Do the fundamental constants of nature vary in spacetime?

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Presented in fulfillment of the requirements of the degree of Doctor of Philosophy

2019

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Abstract
One of the limitations of currently accepted physical theory, the Standard model of particle physics, arises due to our lack of understanding of the fundamental constants. We do not know the source of these numbers that lie in the core of our understanding of the Universe and, therefore, we must consider their variation as a possibility. The purpose of this thesis is to test the variability of one such constant, the fine-structure constant $\alpha$, by measuring its relative deviation, $\Delta\alpha/\alpha$, from the current value on Earth, in quasar absorption systems. Previous studies showed some evidence of $\alpha$ variation and its dependency on time, distance and/or angle across the sky and vigorously tried to examine possible systematic effects that could spuriously cause this. Indeed, it was recently found that one such systematic effect, long-range wavelength distortions, caused by stretches or compressions of the wavelength scale could potentially explain measured variation, making previous results unreliable.

This thesis addresses this observational situation by:

1. Making new reliable measurements of $\Delta\alpha/\alpha$ in quasar absorption systems.
2. Enabling reliability of future measurements by devising a method to easily correct for the long-range wavelength distortions.
3. Further exploration of associated systematic effects.

For this purpose $\Delta\alpha/\alpha$ was measured in a total of 23 absorption systems, towards four quasars, using UVES/VLT and HIRES/Keck spectra. This almost doubled the number of reliable measurements and almost tripled the precision in the weighted mean result $-1.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}}$ parts per million (ppm), leading to the main conclusion from this thesis, that there is no evidence for cosmological variation in the fine-structure constant at $z \sim 0.576$–1.916. The increase in precision is dominated by the most precise measurement of $\Delta\alpha/\alpha$ from the absorption system at $z_{\text{abs}} = 1.508$ towards HE 0515–4414 quasar $\Delta\alpha/\alpha = -1.42 \pm 0.55_{\text{stat}} \pm 0.65_{\text{sys}}$ ppm. This analysis required the formulation of a new method for strongly suppressing systematic errors associated with long-range wavelength distortions: we corrected the UVES wavelength calibration using lower signal-to-noise ratio spectra of the same quasar from the well-calibrated HARPS instrument on the ESO 3.6-meter telescope. This method will be suitable for suppressing distortions of the existing UVES spectra using short
\(~3\,\text{h}\) quasar exposures from new and future well-calibrated spectrographs. By using the highest S/N quasar spectrum from high-resolution echelle spectrographs we identified that systematic effects associated with CCDs and spectral reduction techniques are likely to be important for the spectra observed with the \(~30\,\text{m}\) class telescopes.
Acknowledgements

First of all, I would like to present my sincere appreciation for the help given by my coordinating supervisor, Professor Michel Murphy. I am enormously thankful for all those hours spent on leading me through the understanding of physical processes from the distant quasars through absorption systems and all the way to the giant telescopes and spectrographs. I also thank you for trying to polish my writing, often in the after work hours. I am also thankful that I had such a great associate supervisor Associate Professor Emma Ryan-Webber who was the most understandable person I met in my life. Thanks Emma for understanding that it is not easy to cope with the PhD and being a parent at the same time.

I am also grateful to other Centre for Astrophysics and Supercomputing staff and students for their enormous help with dealing with both scientific and personal life during my PhD. I really appreciate the help from Alex Codoreanu and Daniel Berke in proofreading my writing and Dr Manodeep Sinha for his comments about my work. I also thank to my colleges Uroš Meštrić and Robert Džudžar for letting me stay at their apartment in a few months leading to my submission.

I would also like to mention other people who I’ve met during my PhD and without whom I would not be able to get this far. Thank you Jonathan, Neil, Angela, Glenn, Colin, Elisa, Darren, Jeff, Gonzalo, Rob and all others. It would be much harder to get through all this without you.

Finally, I would like to thank to my wife Ana Kotuš and my children Anakin and Alisa Kotuš who supported me throughout the past five years. I really appreciate everything and I dedicate this thesis to you!
Declaration

The work presented in this thesis has been carried out in the Centre for Astrophysics & Supercomputing at Swinburne University of Technology between September 2013 and September 2018. This thesis contains no material that has been accepted for the award of any other degree or diploma. To the best of my knowledge, this thesis contains no material previously published or written by another author, except where due reference is made in the text of the thesis. All work presented is primarily that of the author.

- Chapters 2 and 3 have been published as ‘High-precision limit on variation in the fine-structure constant from a single quasar absorption system’. S. M. Kotuš, M. T. Murphy and R. F. Carswell, 2017, MNRAS, 464, 3679. Minor alterations have been made to the published papers in order to maintain argument continuity and consistency of spelling and style. I would like to specifically point the typographical errors in Section 3.1.2.3 where I have quoted an order of magnitude wrong dispersion corrections in the publication.

- Chapters 4 and 5 have not appeared in a refereed journal, but are expected to be submitted for publication in the near future.

Where the contributions to the work in this thesis are not my own, this is acknowledged in the Foreword section of each chapter, if applicable.

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Melbourne, Victoria, Australia

25 September 2018
Abstract

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1.1 Purpose of the thesis

The aim of this thesis was to investigate the possibility that the fundamental constants of nature vary throughout cosmic history. In particular, I have made a series of high-precision measurements of the fine-structure constant’s variability using some of the highest signal-to-noise (S/N) quasar echelle spectra available from 10 m class telescopes. With these measurements I account for all known systematic effects by utilising established and new techniques that I develop in this thesis. In addition I anticipate the main challenges likely to arise when working with high-quality spectra from improved instruments and future, larger telescopes.

The first project presented in this thesis is a detailed re-analysis of possible variation in the fine structure constant in the $z_{\text{abs}} = 1.1508$ absorption system towards quasar HE 0515–4414. The second project focuses on sight lines towards three quasars from a Very Large Telescope (VLT) Large Program, which is specifically designed to measure variation in the fine-structure constant. These two projects advance the field by almost doubling the number of reliable measurements, including the two most precise measurements from two individual absorption systems.

1.2 Why do we measure fundamental constants?

Fundamental constants are numbers that are essential for all physical theories, but those numbers cannot be derived and fully understood from within currently ac-
cepted theories. In other words, the Standard Model of particle physics uses fundamental constants as input and does not provide any explanation about their origin. The only reason why we assume that fundamental constants are constants is because, so far, experiments seem to find the same value, regardless of the epoch and location of the measurement. However, we must ensure that measurements continue because of several reasons. Firstly, we cannot know \textit{a priori} where or when they can vary. Secondly, we develop new experiments that allow us to measure fundamental constants in different places and times throughout the Universe. Finally, the precision of our existing experiments is increasing with technological development so we need to search at these new levels of precision.

The fine-structure constant \( \alpha \equiv \frac{e^2}{4\pi\varepsilon_0c} \approx \frac{1}{137.036} \) is one of these numbers. It was originally introduced by Sommerfeld (1911) as a measure of the relativistic correction to a Bohr model of the atom. According to quantum electrodynamics it is defined as a measure of the strength of the electromagnetic force that governs how electrons and photons interact. One of its very important features is that it does not have units; it is a dimensionless quantity. In contrast, the speed of light has units, and if we were to attempt to measure its variation, we could not say whether the actual speed of light has changed, or whether time has slowed/accelerated, or whether the measuring rods have changed their lengths. Therefore, it is meaningless to measure \( c \)'s variation (Ellis & Uzan, 2005).

Milne (1935) and Dirac (1937) first considered variation in one of the modern fundamental constants, \( G \). Dirac noted several coincidences between large numbers, such as the age of the universe \( t \) (in units where the light crossing time of the classical electron radius is one) and the ratio of the electric to gravitational forces, both of which have values of \( \sim 10^{40} \). He therefore proposed his Large Number Hypothesis according to which the gravitational constant \( G \propto 1/t \). Inconsistency of this theory with the fairly constant temperature of the Sun and therefore the existence of life on Earth in the past 500 million years was eventually shown by Teller (1948).

Various theories which extend beyond the Standard model by including gravity have been proposed in the last century. Some of them involve variation in fundamental constants (reviewed in Uzan 2003, 2011), sometimes including predictions of relationships between different fundamental constants (Dent et al., 2008). For example, the scalar field theory proposed by Bekenstein (1982) suggests that space-
1.3 Methods of measurements of the fine-structure constant variability

Considering that the main focus of this thesis is to measure possible fine-structure constant variation, the rest of the introduction will concentrate on $\alpha$, with a short overview of measurements of the variation in the proton-to-electron mass ratio

$$\mu \equiv \frac{m_p}{m_e} \approx 1836.153,$$  \hspace{1cm} (1.1)

where $m_p$ is mass of proton and $m_e$ is mass of electron. This is because the proton-to-electron mass ratio is measured using a similar method to the one that we use for measurements of variation in the fine-structure constant $\Delta \alpha/\alpha$, i.e. by analysing high resolution optical quasar spectra.

As pointed out in the previous section, we do not know at which time and/or distance in space fundamental constants might vary, so it is essential to measure them on different temporal as well as spatial scales. All of the methods used so far to constrain possible variations in the fundamental constants are reviewed in depth in Üzan (2003, 2011). The Many Multiplet (MM) method, which is used in this work, will be described in more detail in Section 1.4.2. Here I review alternative methods which are used to constrain $\alpha$ and $\mu$.

1.3.1 Atomic clock constraints

Atomic clock measurements of fine-structure constant variability are among the most precise measurements in physics, at a precision level of $10^{-17}$ year$^{-1}$. They use atomic clocks based on different transitions, in different atoms, whose frequency ratios are proportional to $\alpha^2$ to determine $\Delta \alpha/\alpha$. Although this method can be used to measure
\( \Delta \alpha / \alpha \) directly (e.g. Rosenband et al. 2008), in some studies it is only possible to constrain \( \Delta \alpha / \alpha \) and \( \Delta \mu / \mu \) jointly (e.g. Godun et al. 2014). These two studies reported \( \dot{\alpha} / \alpha = (-1.6 \pm 2.3) \times 10^{-17} \text{ year}^{-1} \) and \( \dot{\mu} / \mu = (0.2 \pm 1.1) \times 10^{-16} \text{ year}^{-1} \), respectively. \( \dot{\alpha} / \alpha \) denotes here to the variation in \( \alpha \) over time. The Rosenband et al. (2008) measurement, which uses the frequency ratio of singly ionised aluminium and mercury atomic clocks is currently the best independent constraint on \( \Delta \alpha / \alpha \). However, if Godun et al. (2014) used long-term measurements (over a whole year) as Rosenband et al. (2008), they would be able to reach higher precision on \( \dot{\alpha} / \alpha \). Dzuba et al. (2012) reported the possibility of increasing the precision of \( \Delta \alpha / \alpha \) measurements by using Nd\(^{13+} \) and Sm\(^{15+} \) atomic clocks to the level of \( 10^{-20} \text{ year}^{-1} \), which is similar to the precision of proposed nuclear clocks (e.g. Kazakov et al. 2012).

1.3.2 Oklo and meteoritic constraints

Other fairly local measurements of \( \Delta \alpha / \alpha \) use data from the Oklo natural fission reactor (e.g. Gould et al. 2006) and meteorite dating (e.g. Olive et al. 2004). Even though the precision of these measurements (\( \sim 10^{-17} \text{ year}^{-1} \)) can be a few orders of magnitude better than the precision acquired from the MM method, assuming linear variation with time\(^1 \), these methods are dependent on at least one other parameter and can also be influenced by the physical properties of the system.

Oklo constraints introduced by Shlyakhter (1976) are based on measuring the abundance ratios of different rare-earths (e.g. \(^{149}\text{Sm} \) / \(^{147}\text{Sm} \)) which are related to the resonant energy of neutron capture by \(^{149}\text{Sm} \) and, through it, to \( \alpha \). It is clear from these relations that this method is based on a series of assumptions and models, such as nuclear models and geometry and temperature of the reactor. The best current measurement from Oklo is \( \Delta \alpha / \alpha = (0.65 \pm 1.75) \times 10^{-8} \) at the 2\( \sigma \) confidence level by Gould et al. (2006).

The meteorite dating method introduced by Peebles & Dicke (1962) uses long-lived species’ \( \beta \) decays, such as \(^{187}\text{Re} \) to constrain \( \Delta \alpha / \alpha \). The best current measure-

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\(^1\)Considering that still unknown physics lies behind the explanation of possible variation in the fundamental constants, it is unclear how to compare these local measurements to the longer timescales of MM method measurements. The simplest way to do this is to compare the rate of change in \( \alpha \) per year that they imply, with a potentially incorrect assumption of linear variation of \( \alpha \) with time.
1.3. Methods of measurements of the fine-structure constant variability

Measurement from the meteorite dating method is $\Delta \alpha / \alpha = (-0.8 \pm 1.6) \times 10^{-8}$ at the 2$\sigma$ confidence level by [Olive et al. 2004]. Unfortunately, $\Delta \alpha / \alpha$ constrained with this method is degenerate with the weak interaction coupling constant [Fujii & Iwamoto 2005].

1.3.3 Big bang nucleosynthesis and cosmic microwave background constraints

Other measurements of the possible variation in the fine-structure constant, with significantly lower precision than the MM method (by three orders of magnitude), have been made from the Big Bang Nucleosynthesis (BBN) and the Cosmic Microwave Background (CMB) methods.

Constraints from the BBN method are based on measurements of the light element abundances and their ratios ($H$, $D$, $^3$He, $^4$He, Li, Be). Changing the fine-structure constant would affect the Coulomb barrier of reactants, which is correlated with reaction rates and therefore the abundances. However, there is high dependence on other constants (e.g. Higgs vacuum expectation value, baryon-to-photon ratio and other couplings). If these degeneracies are accounted for, the best constraint is $\Delta \alpha / \alpha = (3 \pm 7) \times 10^{-2}$ [Nollett & Lopez 2002]. Since 2002 measurements of the abundances of the light elements have been considerably improved in the works of Cooke et al. (2014) and Riemer-Sørensen et al. (2017), it would be useful to revise these results.

The possibility of measuring variation in the fine-structure constant from the CMB angular power spectrum was introduced by Kaplinghat et al. (1999) and Hannestad (1999). Possible variation of $\alpha$ would manifest itself as a change in the hydrogen binding energy and Thomson scattering cross section, leading to different recombination rates and a different time period of recombination. Currently the best constraint from the CMB is $\Delta \alpha / \alpha = (3.6 \pm 3.7) \times 10^{-3}$ at $z \approx 1100$ measured by the Planck Collaboration et al. (2015).
1.4 Quasar constraints on $\Delta \alpha/\alpha$

In this section I give an overview of the constraints on the variation in the fine-structure constant that use absorption or, in the pioneer studies, emission lines in quasar or galaxy spectra. Figure 1.1 illustrates a simulated quasar spectrum in the lower panel with a schematic diagram showing the sources of emission and absorption in the upper panel. Quasar absorption/emission methods are based on the influence of a possible variation in the fine-structure constant on the observed velocity of spectral transitions. In particular, relativistic corrections to the particular energy levels in atoms/ions are differently affected by the possible variation in $\alpha$, causing distinctive shifts for each transition. In other words, atoms/ions (except hydrogen) consist of many electrons, so the influence of possible $\alpha$ variation on different electronic transitions can be significantly different in both size and sign. Figure 1.2, below, represents an exaggeration of how various transitions would shift if $\alpha$ varied, with appropriate $q_i$ coefficients (see equation (1.2)) reviewed in Murphy & Berengut (2014). This causes a specific pattern of velocity shifts among various transitions which can be detected if there is $\alpha$ variation. It is preferable to use high resolution echelle spectra because they cover a very wide range of wavelengths and at the same time small shifts of the absorption features can be detected with high precision. Additionally, this method offers the advantage of no real degeneracies between $\alpha$ variation and other parameters, such as redshift.

1.4.1 Alkali Doublet (AD) method

The alkali doublet method is based on the proportionality between $\alpha^2$ and the relative wavelength separation between the two transitions of an alkali doublet. The AD method was first demonstrated by Savedoff (1956). He investigated Seyfert galaxy emission lines and compared the relative wavelength separation between doublet transitions and constrained variation in $\alpha$. The best current constraints that use quasar and galaxy emission lines were made by Albareti et al. (2015). They used O\textsc{iii} lines in spectra of $\sim 13000$ quasars from the SDSS–III/BOSS DR12 survey and spectra of $\sim 4000$ galaxies from the DEEP2 survey and measured $\Delta \alpha/\alpha$ of $(0.9 \pm 1.8) \times 10^{-5}$ and $(-0.9 \pm 1.6) \times 10^{-5}$, respectively. Measurements from future low resolution galaxy surveys will include millions of galaxies and will be able to
1.4. Quasar constraints on $\Delta \alpha/\alpha$

Figure 1.1: Illustration of the quasar spectrum and its origin. Upper panel shows the origin of emission and absorption lines in a quasar spectrum and lower panel represents an illustration of quasar spectrum with its most distinctive features. For quasar constraints on $\Delta \alpha/\alpha$ we are interested in relative shifts between metal emission or absorption lines. Metal emission lines originate from the quasar, and are much broader than absorption lines which originate in the intergalactic or circumgalactic environment. This leads to more precise constraints on $\Delta \alpha/\alpha$ from absorption lines than from emission lines. It is also important to note that the lines usually consist of many velocity components, which need to be modelled, before a distinctive pattern of velocity shifts between different transitions can be acquired and possible $\Delta \alpha/\alpha$ can be measured. Diagram by Michael Murphy, based on another by John Webb, and used with permission.
Figure 1.2: Sensitivity of commonly used transitions to the exaggerated variation in the fine-structure constant. There are a variety of transitions which can shift towards higher or lower wavelengths, as well as those which are quite insensitive to the change in $\alpha$. There are three types of transitions (positive shifters, negative shifters and anchors). This figure was taken from King (2012).
reach higher precision on $\Delta \alpha/\alpha$.

Bahcall et al. (1967) were the first to use the similar method to constrain $\Delta \alpha/\alpha$ from absorption systems between the Earth and background quasars. They measured $\Delta \alpha/\alpha = (-2 \pm 5) \times 10^{-2}$ at $z \approx 1.95$. The precision was significantly increased compared to Savedoff (1956) due to much narrower absorption lines from galactic or intergalactic gas clouds than quasar emission lines. The most precise reliable constraint from the AD method reported in the literature is $\Delta \alpha/\alpha = (0.5 \pm 1.3) \times 10^{-5}$ at $2.33 \leq z \leq 3.08$ by Murphy et al. (2001d).

1.4.2 Many Multiplet (MM) method

A more sensitive and precise generalization of the AD method, the MM method, was introduced by Dzuba et al. (1999) and Webb et al. (1999). The MM method compares the relative velocity spacing between different metal transitions and relates it to possible variation in $\alpha$. For example, considering just a single transition, variation in $\alpha$ is related to the velocity shift $\Delta v_i$

$$\Delta \alpha/\alpha \equiv \frac{\alpha_{\text{obs}} - \alpha_{\text{lab}}}{\alpha_{\text{lab}}} \approx \frac{-\Delta v_i \omega_i}{2c q_i},$$

where $c$ is the speed of light, $q_i$ is the sensitivity of the transition to $\alpha$ variation, calculated from many-body relativistic corrections to the energy levels of ions, and $\omega_i$ is its wavenumber measured in the laboratory.

Comparison of different ground levels in ions is much more sensitive to possible variation in $\alpha$ than comparison of different excited levels. This leads to an increased sensitivity of the MM method over the AD method, because for the AD method excitation originates from the same ground level. The possibility of using many transitions with different $q$ coefficients also makes the MM method more precise by enhancing the statistics of the measurement compared to the AD method. The transitions used in the MM method are presented in Murphy & Berengut (2014). The MM method was applied for the first time in Webb et al. (1999) on 30 absorption systems between redshifts $0.5 < z < 1.6$ observed with High Resolution Echelle Spectrometer (HIRES) mounted on Keck telescope. They fitted 8 transitions of Mg I, Mg II and Fe II, yielding tentative evidence for a smaller $\alpha$ in the past, with $\Delta \alpha/\alpha = (-10.9 \pm 3.6)$ parts per million (ppm), on average.
1.4.2.1 HIRES sample

In [Webb et al. (2001) and Murphy et al. (2001c)] the previous sample was extended to 49, by adding absorption systems at higher redshift, yielding a $0.5 < z < 3.5$ redshift range. Therefore, additional transitions were included in the analysis, with redshifted wavelengths in Keck’s optical range, such as Ni II, Cr II, Zn II, Si II, Al II and Al III. They measured weighted mean $\Delta \alpha/\alpha = (-7.2 \pm 1.8)$ ppm with 1σ uncertainty. In the rest of the thesis 1σ uncertainties will be quoted, unless specified otherwise. Possible systematic effects were thoroughly investigated in [Murphy et al. (2001a)] and most of them were found to be negligible, except for atmospheric dispersion effects and isotopic abundance variations. However, if simple models of these systematic effects were used to account for them, the significance of the result increased rather than decreased. In subsequent publications the sample was almost tripled, firstly by adding 78 more absorption systems in [Murphy et al. (2003a)] and finally by adding 15 more in [Murphy et al. (2004)], totaling 143 over the redshift range $0.2 < z < 4.2$. This final sample led to the weighted mean result, $\Delta \alpha/\alpha = (-5.7 \pm 1.1)$ ppm, which has 5σ significance of $\alpha$ being smaller at high redshift. [Murphy et al. (2003a, 2004)] further investigated possible systematic effects, but none was found that could cause this result.

1.4.2.2 First constraints from UVES

Since all the data for [Murphy et al. (2004)] was observed on Keck/HIRES, any systematic effect intrinsic to the telescope/spectrograph could not be ruled out. Because of this, work was continued on Ultraviolet and Visual Echelle Spectrograph (UVES) mounted on VLT. In the next few years, other groups applied the MM method to search for variation in $\alpha$ using spectra observed with UVES. Chand et al. (2004) reported $\Delta \alpha/\alpha = (-0.60 \pm 0.60)$ ppm from the sample of 23 absorbers in the redshift range $0.4 < z < 2.3$. These results were also summarised in Srianand et al. (2004). There were two attempted measurements [Levshakov et al. 2005, 2007] of $\alpha$ in the absorber $z_{\text{abs}} = 1.839$ towards Q 1101–264 and three attempted measurements [Quast et al. 2004, Levshakov et al. 2006, Chand et al. 2006] hereafter Q04, L06, C06) of $\alpha$ in the very complex absorber $z_{\text{abs}} = 1.1508$ towards the extremely bright quasar HE 0515–4414, which all reported $\alpha$ variation consistent with zero.
The results of these latter studies are summarised in Table 3.3. However, all these studies were demonstrated to be critically flawed in [Murphy et al. (2008b)]. The main arguments for the faulty results in [Chand et al. (2004), Srianand et al. (2004) and C06] were that the $\chi^2$ minimisation algorithm failed to find the correct $\chi^2$ curve, and the real minimum was not returned, leading to significantly underestimated errors and results strongly biased towards zero. On the other hand, other publications mentioned in this paragraph were criticised by [Murphy et al. (2008b)] to have either oversimplified their modelled velocity structure or have underestimated their statistical uncertainty due to some unidentified issue. [Murphy et al. (2008b)] also reanalysed the [Chand et al. (2004)] spectra and reported the weighted mean $\Delta \alpha/\alpha = (-6.4 \pm 3.6) \text{ ppm}$. These systems have also been reanalysed (with newly reduced and calibrated UVES spectra) by [Wilczynska et al. (2015)], leading to the weighted mean result $\Delta \alpha/\alpha = (2.2 \pm 2.3) \text{ ppm}$. The differences between [Murphy et al. (2008b)] and [Wilczynska et al. (2015)] arise from different reductions of the spectra and different models.

Table 1.1: Summary of the constraints on $\Delta \alpha/\alpha$ from the $z_{\text{abs}} = 1.1508$ absorption system towards QSO HE 0515$-4414$ in the literature.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>S/N</th>
<th>Resolving power</th>
<th>$\Delta \alpha/\alpha$ [ppm]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVES</td>
<td>~ 100</td>
<td>55000</td>
<td>$-0.40 \pm 1.90 \pm 2.70$</td>
<td>Q04</td>
</tr>
<tr>
<td>UVES</td>
<td>~ 40</td>
<td>55000</td>
<td>$-0.07 \pm 0.84$</td>
<td>L06</td>
</tr>
<tr>
<td>HARPS</td>
<td>~ 35</td>
<td>112000</td>
<td>$+0.50 \pm 2.40$</td>
<td>C06</td>
</tr>
<tr>
<td>UVES</td>
<td>~ 100</td>
<td>55000</td>
<td>$+1.00 \pm 2.20$</td>
<td>C06</td>
</tr>
</tbody>
</table>

1.4.2.3 UVES sample and possible spatial variation in $\alpha$

The first significantly large sample of 154 absorption systems observed with the UVES spectrograph was analysed in [Webb et al. (2011)] and [King et al. (2012)]. They measured a weighted mean value of $\Delta \alpha/\alpha = (2.29 \pm 0.95) \text{ ppm}$. At first, this result seems to be in contradiction with the previous 143 absorption systems from Keck/HIRES. However, the Keck and VLT telescopes are in different hemispheres so they mostly observe different parts of the sky. When those two data sets were combined to search for spatial variations in $\alpha$, a significant dipole pattern (angular variation) in $\Delta \alpha/\alpha$ was found across the sky. The maximal increase of $\alpha$ occurred in the direction $\text{RA} = (17.3 \pm 1.00) \text{ hr}$, $\text{dec.} = (-61 \pm 10)^\circ$, with amplitude $9.7^{+0.22}_{-0.20} \text{ ppm}$,
and this model was preferred with 4.1σ significance over a monopole model with the same value of α across the sky (but possibly different to the current laboratory value). Clearly, this possibility needed extensive critical assessment and investigation of systematic effects.

1.5 Systematic errors

1.5.1 Early considerations

The crucial question is whether a systematic effect, or some combination of multiple systematic effects, could mimic the possible evidence for varying α. After a very thorough assessment of various possible causes of systematic errors in early studies (Murphy et al., 2001a, 2003b; Fenner et al., 2005), none were reported that could strongly affect aforementioned large samples of Δα/α measurements. This thesis will focus on recent discoveries of systematic effects in the quasar spectra, but it is worth reviewing systematic effects considered in these earlier studies:

- **Laboratory wavelength errors** – If the laboratory wavelengths of the transitions used for Δα/α measurements were systematically incorrect it would automatically lead to errors in Δα/α measurements. However, it was explained in Murphy et al. (2001a) that similar values of laboratory wavelengths have been measured in different independent experiments, which points towards no systematically incorrect laboratory wavelengths. The current uncertainty of these measurements is in the range between 0.04 m s⁻¹ and ~20 m s⁻¹ (Murphy & Berengut, 2014). If we consider only Mg II 2796 and Fe II 2382 transitions the largest of these could possibly lead to errors on Δα/α of the order of 1–2 ppm. However, this effect is further diluted by the use of several transitions.

- **Heliocentric velocity variation** – Heliocentric velocity may change up to ~0.1 km s⁻¹ during a ~1 h exposure. This can only lead to smearing of the features in the spectrum that will only affect uncertainties in the redshift and not the Δα/α measurement.

- **Differential isotopic saturation** – This effect arises from using only the abundance weighted mean (composite) wavelengths for saturated transitions. Arti-
1.5. Systematic errors

Fictitious velocity shifts occur due to different influence of weaker isotopes on the absorption centroid when the strongest isotope saturates. Based on Mg I, Mg II and Si II transitions, for which both composite and individual wavelengths were known, Murphy et al. (2001a) showed that these systematic effects are very small.

- **Isotopic abundance variation** – This effect is caused by possibly non-terrestrial isotopic abundance ratios in absorption systems. Murphy et al. (2001a) and Murphy et al. (2003b) found that isotopic abundance variation, in particular lower amount of the heavier Mg II isotopes in absorption systems, could affect results reported for the lower redshift HIRES sample of Murphy et al. (2003b). However, their conclusion was that correction for these systematic effects would make $\Delta \alpha / \alpha$ measurements more statistically significant. This effect is still very important because there is no direct method of measuring evolution of isotopic ratios of different elements with redshift. Fenner et al. (2005) assessed the possibility of an overabundance of heavier isotopes of Mg II by using chemical evolution models of Milky Way type galaxies. They found that nitrogen would also be overproduced in this case, which is opposite to abundances of nitrogen observed in quasar absorption systems used for $\Delta \alpha / \alpha$ measurements (e.g. Centurión et al., 2003). This means that overproduction of Mg II is unlikely.

I return to this and test our results for the sensitivity to this effect in Section 3.1.3.4 and Section 5.1.3.

- **Magnetic fields** – Magnetic fields could possibly shift energy levels of ions, which would lead to systematic errors in $\Delta \alpha / \alpha$. However, their strength would need to be at least of the order of 100 G (Murphy et al. 2001a). This is unlikely because measurements of the large-scale magnetic fields inside clusters of galaxies do not exceed 10 $\mu$G (Govoni & Feretti 2004).

- **Kinematic effects** – This systematic effect is caused by different redshift among ions used for $\Delta \alpha / \alpha$ measurements. I consider this in detail in Section 3.1.3.4 and find it to be an implausible explanation.

- **Wavelength miscalibration** – It is possible to set the wavelength scale for
quasar spectra improperly, due to some faults of the wavelength calibration software. Although it was subsequently found (as described in Section 1.5.2) that calibration errors significantly affect $\Delta \alpha / \alpha$ measurements, early considerations by Murphy et al. (2001a) and Murphy et al. (2003b) did not reveal this. This was mainly because these studies assessed only the goodness of ThAr calibration, but not the possibility of different light paths between the ThAr calibration lamp and quasar light. This possibility was recognised as a potential problem but the specific analyses and tests conducted were not sensitive to this particular problem. Their conclusion was that misidentification of ThAr lines can influence $\Delta \alpha / \alpha$ at the level of $\sim 0.1$ ppm.

- **Hyperfine-structure effects** – There are two different effects related to hyperfine structure which can cause systematic errors on $\Delta \alpha / \alpha$. One is caused by differential saturation of different hyperfine components of odd mass number isotopes, similar to differential isotopic saturation. The other effect is caused by variations in hyperfine level population. Both of them have the largest effect on Al$\text{II}$ and Al$\text{III}$ ions due to their large magnetic moment. Differential hyperfine saturation is, however mostly eliminated because Al$\text{III}$ transitions are usually not saturated and Al$\text{II}$ has a zero spin electron in both its excited and ground state and, hence, no hyperfine structure. On the other hand, hyperfine level population variations in Al transitions can affect $\Delta \alpha / \alpha$ by up to 4 ppm when estimate is done using only Fe$\text{II}$ 2382 and Al$\text{III}$ transitions. However, this effect is significantly diluted by other transitions (Murphy et al., 2001a) and Al$\text{III}$ transitions are often not used in MM analysis because of their weakness.

- **Air–vacuum wavelength conversion** – This effect is caused by use of two different dispersion formulae in different HIRES spectral reduction packages. It was shown in Murphy et al. (2001a) that this effect is negligible.

- **Temperature changes during observations** – If the temperature changes during a quasar exposure it would affect the refractive index of air inside the spectrograph leading to distortions of the spectrum relative to the calibration exposure taken immediately afterwards. However, Murphy et al. (2001a) showed that these changes are much smaller than current statistical errors on
• **Line blending** – This effect occurs due to possibility of some transitions being contaminated by weak lines. This effect can be random or systematic. The random effect occurs due to interloping transitions from different redshifts than the absorption system under consideration. Due to the random nature of this effect its influence on $\Delta \alpha/\alpha$ is randomized when considering a large number of absorption systems. On the other hand, systematic blending is caused by transitions in the same absorption system, which have slightly different rest wavelengths from the transition which is being modelled. [Murphy et al. (2001a)] did not find any interloping transitions that could cause significant changes in $\Delta \alpha/\alpha$. However, the existence of some unidentified, highly ionised species is considered as a possibility because we cannot know at which wavelength this unknown specie will be interloping.

• **Atmospheric dispersion effects** – Atmospheric dispersion effects are caused by two different sources. The first effect is caused by dispersion of light across the slit prior to entering the spectrograph. The second effect is caused by the wavelength-dependent seeing profile truncation by the slit edges. Both of these effects should only manifest themselves in the spectra observed in the pre-rotator era (before installation of image rotator on the HIRES spectrograph) of the HIRES spectrograph and, therefore, do not affect any spectra observed after August 1996 or UVES spectra. [Murphy et al. (2001a)] examined these effects in depth and found that they are not able to explain the results from the whole sample of [Murphy et al. (2001c)].

• **Instrumental profile variations** – Intrinsic asymmetries of the instrumental profile (IP) can cause incorrect estimates of the absorption line centroids, and if this asymmetry changes with wavelength it could affect $\Delta \alpha/\alpha$ measurements. Indeed, these variations in the asymmetries of the instrumental profiles were detected by [Valenti et al. (1995)] along the HIRES echelle orders. However, it was found in [Murphy et al. (2001c)] that this effect is negligible.

Although early considerations of systematic effects did not reveal any that can significantly affect $\Delta \alpha/\alpha$ measurements at the precision level which is currently
achievable, it would be essential to assess these same effects when precisions of the order of ~0.1 ppm become achievable from the new generation of 25–40-m class telescopes.

1.5.2 Wavelength calibration problems

Out of the early considerations summarised in the previous subsection remains the possibility of a difference between quasar and thorium-argon (ThAr) light paths through the spectrograph. As explained further in the rest of this subsection, this difference causes calibration errors that are the particular focus of this thesis and will be explored in detail in Chapter 2 and Chapter 4. Recent studies (Whitmore & Murphy, 2015) suggested that a possible explanation of the previously measured variation in the fine-structure constant may indeed be these wavelength calibration errors.

Most of the spectra used for measurements of $\Delta \alpha / \alpha$ in the large samples of HIRES and UVES spectra were observed for other purposes, and therefore did not include additional wavelength calibration techniques that are necessary for accurate $\Delta \alpha / \alpha$ measurements. This means that only traditional wavelength calibration was performed. It involves acquiring the wavelength scale of quasar spectra from the thorium emission lines from the standard ThAr arc lamp exposure. Preferably this ThAr exposure is observed in the same setting and immediately after the quasar exposure. However, in some cases it was necessary to use the ThAr exposure observed in the morning following the night on which the quasar was observed. Acquisition of the quasar wavelength scale is done by assigning known thorium emission line wavelengths to the specific pixels on the charged couple device (CCD) and using that wavelength–pixel conversion for the quasar exposure (Fig. 1.3). The wavelength solution for the gaps between ThAr lines is acquired in the calibration step of the spectral reduction as a two-dimensional polynomial solution.

Considering that movements of the telescope and/or spectrograph can influence the difference between quasar and ThAr lamp light paths, it is very important to acquire calibration exposures just before and/or after the quasar exposure. Further accuracy of the wavelength calibration can be gained by observing additional calibrators (“supercalibration”) such as observing quasars through the iodine cell or extra exposures of solar-like spectra (Fig. 1.3). In other words “supercalibration”
1.5. Systematic errors

Figure 1.3: Illustration of different calibration methods used to assign the wavelength scale to the high resolution quasar spectra. The traditional ThAr calibration spectrum is shown as black line in the lower panel. Known ThAr wavelengths are assigned to specific pixels on a CCD and quasar spectrum (black line in the upper panel). This method can induce systematic errors due to possibly different light paths through the spectrograph between the quasar and the ThAr lamp light. As such, additional “supercalibration” (investigation of the possible errors in the ThAr calibration) is very useful. This figure illustrates two “supercalibration” approaches. The red line in the lower panel represents the molecular iodine (I$_2$) absorption spectrum, which is acquired by placing the iodine cell in the quasar light path. The wavelength scale acquired from the ThAr calibrator is assigned to this spectrum. Iodine absorption features are then compared to the iodine Fourier Transform Spectrum (FTS) absorption features and shifts between them are measured. These shifts represent velocity shifts induced by different light paths between quasar and ThAr exposures. Unfortunately, the iodine absorption spectrum covers a short range of wavelengths making it impossible to measure shifts in the whole quasar wavelength range. Another disadvantage of this approach is that the iodine cell additionally absorbs quasar light and blends with quasar features making the quasar spectrum useless for $\Delta \alpha/\alpha$ measurements. The other type of “supercalibration” is performed in a similar fashion. The only difference is that it uses the solar-like spectrum (red line in the top panel) instead of the iodine cell. A solar-like spectrum is a spectrum of reflected sun light (asteroid) or a spectrum of star that is similar to Sun. This type of “supercalibrator” is superior to the iodine-cell because it covers a wide wavelength range. The only assumption here is that the difference in the light path through the telescope and spectrograph does not change while changing the target. Therefore, it is recommended to observe the solar-like spectrum immediately before, or after (at least in the same night as) the quasar exposure. Illustration used with premission of author – Michael Murphy.
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enables us to measure how good the wavelength scale acquired from the standard calibrator is.

Iodine cell exposures are useful, because they are observed at the same time as the quasars and therefore are not affected by the motions that can occur in between exposures. Moreover, the iodine cell calibration spectrum is imprinted on the quasar spectrum itself, which means that the light paths of the quasar and the calibrator are the same. However, the iodine cell is in the path of the already faint quasar light making it even fainter and possibly affecting particular transitions of interest for $\Delta \alpha/\alpha$ measurements. As such, it is not possible to use quasar exposures overlaid with the iodine cell spectrum to measure $\Delta \alpha/\alpha$. However, it is possible to estimate distortions of the wavelength scale by comparing the wavelength scales acquired from the ThAr lines and the iodine cell. This was done for the first time by Griest et al. (2010) and Whitmore et al. (2010). They identified saw-tooth shaped intra-order distortions of the wavelength scale (distortions over the range of one echelle order) with a peak-to-peak amplitude of up to 300–800 m s$^{-1}$ and 100–200 m s$^{-1}$ for HIRES and UVES spectra, respectively. Although systematic errors caused by these distortions become randomized when considering a large number of absorption systems, they can be very important in studies of individual absorption systems (e.g. Murphy et al., 2016).

Rahmani et al. (2013) and more recent studies identified another type of calibration error, that of long-range distortions of the wavelength scale established from traditional ThAr calibration lamp spectra. These were discovered via “supercalibration” techniques in which solar or solar-like spectra from asteroids or “solar twin” stars were used to establish an alternative, likely much more accurate, wavelength scale. Earlier similar “supercalibration” checks by Molaro et al. (2008a), Griest et al. (2010) and Whitmore et al. (2010) did not reveal such long-range distortions. However, Whitmore & Murphy (2015) analysed two decades of archival solar twin spectra from UVES and HIRES and found that significant long-range distortions were common, typically in the range $\pm 200$ m s$^{-1}$ per 1000 Å. These values are the linear approximation to the long-range distortions, derived from a fit, while ignoring intra-order distortions.

Whitmore & Murphy (2015) also found that these long-range distortions provide a compelling explanation for some of the non-zero values of $\Delta \alpha/\alpha$ found in the large
1.6 Variation in the proton-to-electron mass ratio \( \mu \)

A similar method to the MM method can be used to measure possible variation in the proton-to-electron mass ratio. This method computes \( \Delta \mu/\mu \) by comparing velocity shifts of various \( \text{H}_2 \) ro-vibrational transitions from the Lyman and Werner bands. If only a single transition is considered, \( \mu \) is related to the velocity shift \( \Delta v_i \) of a transition:

\[
\Delta \mu/\mu \equiv \frac{\mu_{\text{obs}} - \mu_{\text{lab}}}{\mu_{\text{lab}}} \approx \frac{\Delta v_i}{cK_i},
\]

where \( c \) is the speed of light and \( K_i \) is the sensitivity of the transition to \( \mu \) variation, similar to the \( q_i \) coefficients in the MM method.

A thorough review of the literature related to \( \Delta \mu/\mu \) measurements from \( \text{H}_2 \) is presented in Ubachs et al. (2016). The weighted mean of measurements in 10 absorption systems in the redshift range \( z_{\text{abs}} = 2.0 - 4.2 \) is \( \Delta \mu/\mu = (3.1 \pm 1.6) \) ppm, with a 1.9\( \sigma \) significance of \( \Delta \mu/\mu \) being higher in the past. Given that the method involves using high resolution spectra, \( \Delta \mu/\mu \) measurements are also prone to wavelength distortion systematic effects. Indeed, the first publication which identified the long-range wavelength distortions, Rahmani et al. (2013), was focused on \( \Delta \mu/\mu \) measurement. Unfortunately, most of the measurements summarized in Ubachs et al.
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(2016), except Rahmani et al. (2013), Bagdonaite et al. (2014), Bagdonaite et al. (2015) and Daprà et al. (2015) have not been corrected for the long-range distortions, which might contribute to the weighted mean $\Delta \mu/\mu$ being non-zero. As such, Ubachs et al. (2016) estimated the conservative result consistent with no variation, $|\Delta \mu/\mu| < 5$ ppm. Recently, one more measurement from H$_2$ consistent with this estimate was published in Daprà et al. (2017). This constraint used HD in addition to H$_2$ transitions and supercalibration techniques to correct for the long-range wavelength distortions. Other molecules, such as ammonia and methanol have also been used to measure $\Delta \mu/\mu$ (e.g. Murphy et al., 2008a; Bagdonaite et al., 2013), with order-of-magnitude tighter constraints than achieved with H$_2$. These two single absorber measurements were probing $\Delta \mu/\mu$ at much lower redshifts 0.68 and 0.89, respectively.

1.6.1 Other methods for measurement of possible joint variation in $\alpha$ and $\mu$

Several other methods that measure possible variation in combinations of $\alpha$, $\mu$ and/or other fundamental constants have been proposed and used. These methods involve millimeter and/or radio wave astronomy in addition to optical spectroscopy. One of these constraints is from comparison between the 21 cm transition of neutral hydrogen and the ultraviolet (UV) heavy element transition wavelengths. In this way $x \equiv \alpha^2 g_p/\mu$ is constrained, where $g_p$ is the proton’s g-factor. This method was introduced by Wolfe et al. (1976), and the best current constraint is $\Delta x/x = (-0.1 \pm 1.3)$ ppm measured in 4 absorption systems by Rahmani et al. (2012). Another combination of constants, $y \equiv \alpha^2 g_p/\mu$, can be measured by comparing the redshifts constrained from the 21 cm transition of neutral hydrogen and the CO molecular absorption lines. The method of measuring $\Delta y/y$ was introduced by Varshalovich & Potekhin (1996). The best current constraints from this method are $\Delta y/y = (1.6 \pm 5.4)$ ppm and $\Delta y/y = (-2.0 \pm 4.4)$ ppm from two absorption systems at $z = 0.6847$ and $z = 0.247$, respectively, reported in Murphy et al. (2001b). Other measurements found in the literature (e.g. Chengalur & Kanekar 2003, Kozlov et al., 2008, Kanekar & Chengalur 2004) probe possible variation of $F \equiv g_p(\alpha^2 \mu)^{1.57}$, $F' \equiv \alpha^2 \mu$ and $G \equiv g_p(\alpha \mu)^{1.85}$ from 18 cm OH and far infrared
fine-structure lines with precision in the range 10–100 ppm.

1.7 Motivation for and aim of the thesis

At the outset of my PhD the observational status of the field was that the effect of long-range distortions on the $\Delta \alpha/\alpha$ measurements from the large samples of HIRES and UVES spectra was still being explored. It was still unknown whether and, if so, to what extent the previous measurements of $\Delta \alpha/\alpha$ were affected by long-range distortions. It was also not clear whether they were ubiquitous or only occurring in a few spectra. As such, there were no published studies of $\Delta \alpha/\alpha$ that were corrected for long-range distortions. Most of the researchers who work in the field realized very soon that correction was necessary, so that new measurements of $\Delta \alpha/\alpha$ could be considered reliable. This motivation lead to the first and most important aim of my PhD: to make a series of reliable measurements of possible variation in the fine-structure constant, which have been corrected for the most important systematic effect, that of long-range wavelength distortions.

During my PhD there was some progress in the field. Evans et al. (2014) made 9 measurements of $\Delta \alpha/\alpha$ in 3 absorbers using 3 different telescopes, and robustly corrected for the long-range distortions. The weighted mean combining all these measurements was $\Delta \alpha/\alpha = -5.4 \pm 3.3_{\text{stat}} \pm 1.5_{\text{sys}}$ ppm. Murphy et al. (2016) published the weighted mean measurement of $\Delta \alpha/\alpha = 0.4 \pm 1.4_{\text{stat}} \pm 0.9_{\text{sys}}$ ppm from 8 absorption systems. Three of these absorbers were observed with both the HIRES and UVES spectrographs. These measurements were resistant to long-range distortions because they used only Cr II and Zn II transitions, which are nearby to each other on the wavelength scale. Murphy & Cooksey (2017) reported a weighted mean measurement of $\Delta \alpha/\alpha = 3.0 \pm 2.8_{\text{stat}} \pm 2.0_{\text{sys}}$ ppm from 6 absorption systems from two quasar sightlines observed with the High Dispersion Spectrograph (HDS) on the Subaru telescope and supercalibrated with solar-twin observations. Not counting the work detailed in this thesis, these three publications are the only ones that correct for the long-range distortions to date.

Unfortunately, it is not possible to correct for long-range wavelength distortions in most of the quasar spectra previously used for $\Delta \alpha/\alpha$ measurements. Only a small portion, up to 5 per cent, of these existing spectra have “supercalibration” taken in
the same night as the quasar exposure, which are necessary for the correction. This leads to the second aim of this thesis: to devise a method to enable future researchers to correct for long-range distortions in existing spectra which do not have attached “supercalibrations”.

The experience gained from the last 15 years of systematic error analysis related to $\Delta \alpha/\alpha$ measurements teaches us to carefully search for undiscovered systematics but also to re-examine previously analysed systematics. This is particularly important in view of the higher quality spectra that will be available from future spectrographs and telescopes (e.g. the high resolution spectrographs planned for 25–40-m class telescopes). Given that the precision of these new measurements will be higher than that of previous measurements, we must ensure that all systematic errors at that level of precision are accounted for. For this reason, it is crucial to understand relevant systematic effects at this higher precision level, to be able to use this information for future spectrograph designs. This leads to the final aim of my thesis: to further explore systematic effects related to $\Delta \alpha/\alpha$ measurements that will be important in spectra with S/N > 100.

1.8 Thesis outline

Chapters 2 and 3 of this thesis focus on addressing the second and third aim discussed above (Section 1.7). In this work I explored a very high signal-to-noise ratio (S/N) spectrum of quasar HE 0515–4414 with the aim of finding systematics, correcting for them and measuring a very precise value of $\Delta \alpha/\alpha$ that is not limited by these systematics. This measurement is currently the most precise measurement of $\Delta \alpha/\alpha$ from a single absorption system. Additionally, these chapters develop a method of correcting for the long-range wavelength distortions by comparing the extremely high S/N UVES spectrum with a well calibrated lower S/N spectrum from another spectrograph. Moreover, possible systematic effects that could affect $\Delta \alpha/\alpha$ measurements from future spectrographs and telescopes are assessed.

Chapters 4 and 5 address the first aim above. They present measurements of $\Delta \alpha/\alpha$ in eight absorption systems in the sightlines towards two quasars using spectra observed with both HIRES and UVES. In this work I also re-measured $\Delta \alpha/\alpha$ in six absorption systems towards quasar HE 2217–2818 after correction of the spec-
trum for the long-range distortions (cf. Molaro et al. 2013b). All of these three spectra were observed in the “Large Program for Testing Fundamental Physics”, which was particularly designed for $\Delta \alpha / \alpha$ and $\Delta \mu / \mu$ measurements, with attached ThAr exposures and, in some cases, additional “supercalibrations”. The main motivation of the work done in chapters 4 and 5 was to significantly increase the number of new reliable measurements of $\Delta \alpha / \alpha$.

The conclusions of this thesis and opportunities for future work are given in Chapter 6.
2

Stringent limit on $\Delta \alpha/\alpha$ from the brightest southern quasar above redshift 1 - part I

2.1 Introduction

In this work we report the most robust and precise constraint on $\alpha$-variation in the well-studied $z_{\text{abs}} = 1.1508$ absorption system towards QSO HE 0515–4414. This is the brightest quasar at redshift above $z = 1$ in the southern sky, so it offers the best opportunity to minimize statistical errors and study systematic effects beyond those discernible in lower-fidelity spectra. So far, three constraints on $\Delta \alpha/\alpha$ have been attempted in this absorber (Quast et al., 2004 [Q04], Levshakov et al., 2006 [L06], Chand et al., 2006 [C06]). The L06 result was revised in Molaro et al. (2008b [M08b]). We discuss the results from these studies in the context of our new results in Section 3.2.1, suffice it to say here that there are several motivations to measure $\Delta \alpha/\alpha$ in this absorption system again.

Firstly, significantly more observational spectra are now available, including 3 times the number of UVES exposures previously used. Table 2.1 summarises all the available spectra obtained with the UVES spectrograph used in this study. When all the UVES spectra are combined, it results in the highest S/N spectrum taken with a high-resolution optical spectrograph of a quasar, to our knowledge. This allows a thorough investigation of systematic effects which provides an insight into...
the problems likely to be faced when similar high-quality spectra are obtained from upcoming new spectrographs and telescopes.

Secondly, the previous work on this absorber has used only 6 Fe II transitions to constrain $\Delta \alpha / \alpha$, of which only one transition, 1608, has a velocity shift in the opposite direction from the other transitions if $\alpha$ varies. If there exists a systematic error (e.g. a calibration error) that causes the 1608 line to shift, it would be seen as a non-zero $\Delta \alpha / \alpha$. Artificial shifts between this and other Fe II transitions are possible, particularly because it falls in a different arm of the UVES spectrograph in this absorption system. Artificial velocity shifts may also be due to the aforementioned long-range distortions. Therefore, in this work we include all transitions identified by Murphy & Berengut (2014) that are useful for measuring $\Delta \alpha / \alpha$, which fall in the wavelength region of our spectra and which are not blended with absorbers from different redshifts. This somewhat increases the information available to reduce the statistical error on $\Delta \alpha / \alpha$, with the main motivation being the possibility of greater resistance to systematic effects.

Thirdly, it is apparent that the absorption profile models used in previous work significantly ‘under-fitted’ the spectra, with 36 or fewer velocity components. According to Murphy et al. (2008b, figure 8), under-fitting the spectra may lead to a substantial systematic error in the measured $\Delta \alpha / \alpha$ value. For this reason, we try to avoid this problem in our model by fitting as much of the statistically significant velocity structure as possible. This implies using 106 velocity components – see Section 2.3.4 – which is much larger than used in any previous MM analysis. We explore the possibility that we may still be under-fitting or somewhat ‘over-fitting’ the spectra in Section 3.1.2.

Finally, we use complementary observations from the High Accuracy Radial velocity Planet Searcher (HARPS) on the ESO 3.6 m La Silla telescope of the same object to recalibrate the wavelength scales of the UVES spectra. The supercalibration studies of Molaro & Centurión (2011) and Whitmore & Murphy (2015) demonstrated that the HARPS wavelength scale has much smaller (if any) long-range distortions than UVES and HIRES. By directly comparing the HARPS and UVES spectra we effectively transfer the relatively accurate HARPS wavelength scale onto the UVES spectra – see Section 2.3.3. Additionally, we use the HARPS and complimentary Bench-mounted High Resolution Optical Spectrograph (bHROS) on the Gemini
Table 2.1: Summary of the observations from UVES/VLT used in this work. ‘Project ID’ represents the internal ESO project number in which exposures were taken. ‘Exposure time’ represents the total observing time in each project, divided into dichroic (when both arms of the spectrograph were in use) and single-arm observations. The blue and red S/N correspond to neighbouring continuum to the Fe\textsuperscript{II}1608 and Mg\textsuperscript{II} doublet transitions, respectively. The seeing is the average during the project, with its range in parentheses. Years 1999a and 1999b correspond to 1×2 and 1×1 CCD binning, respectively. In year 1999a, the exposures in the 346-nm setting were taken in the blue arm only, while the 437-nm and 860-nm exposures were taken together in dichroic mode.

<table>
<thead>
<tr>
<th>Project ID/Year</th>
<th>Number of exposures</th>
<th>Exposure time [s]</th>
<th>S/N</th>
<th>Slit width [&quot;]</th>
<th>Seeing [&quot;]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>346 437 520 580 860</td>
<td>346 437 520 580 860</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.A-9022(A)/1999a</td>
<td>3 2 0 0 2</td>
<td>9500 14200</td>
<td>80</td>
<td>0.8 0.8</td>
<td>0.7 0.86 (0.6–1.4)</td>
</tr>
<tr>
<td>60.A-9022(A)/1999b</td>
<td>0 0 1 3 0</td>
<td>16600</td>
<td>103</td>
<td>0.7 0.7</td>
<td>0.61 (0.5–0.8)</td>
</tr>
<tr>
<td>66.A-0212(A)/2000</td>
<td>7 6 0 4 9</td>
<td>53100</td>
<td>70</td>
<td>0.8 0.8</td>
<td>0.8 0.61 (0.4–0.8)</td>
</tr>
<tr>
<td>072.A-0100(A)/2003</td>
<td>0 0 0 2 0</td>
<td>6120</td>
<td>68</td>
<td>0.7</td>
<td>0.81 (0.8–0.9)</td>
</tr>
<tr>
<td>079.A-0404(A)/2007</td>
<td>3 0 0 3 0</td>
<td>9900</td>
<td>22</td>
<td>0.7</td>
<td>0.7 1.77 (1.7–1.8)</td>
</tr>
<tr>
<td>082.A-0078(A)/0809</td>
<td>16 0 0 16 0</td>
<td>46400</td>
<td>79</td>
<td>0.6</td>
<td>0.5 1.00 (0.6–1.7)</td>
</tr>
</tbody>
</table>
South Telescope, of very high resolution, \( R \sim 140000 \), but with lower signal-to-noise ratio (S/N), to search for extra velocity structure (Section 2.3.5). Complementary observations from the HARPS and bHROS are described in Sections 2.2 and 2.3, respectively.

## 2.2 Observations, data reduction and calibration

HE 0515–4414 is a bright quasar with \( V \approx 14.9 \) mag and redshift \( z_{\text{em}} = 1.71 \) which was first identified in Reimers et al. (1998). We have used a large set of publicly available observations taken with three instruments: the UVES/VLT, HARPS/ESO–3.6 m and bHROS/Gemini. We also publish the reduced spectra in Kotuš et al. (2016).

### 2.2.1 UVES/VLT

The largest data set comprises 90 separate exposures from UVES/VLT (Dekker et al., 2000), which were observed between 1999 and 2009 in five different projects. The main \( \Delta \alpha / \alpha \) constraint is from this dataset because it collectively has much higher S/N ratio (per km s\(^{-1}\)) than the other spectra. In all of the UVES exposures, the slit was at the paralactic angle, projected perpendicular to the horizon. Three exposures in 2003 were taken with an iodine cell in the light path (Whitmore et al., 2010) and have significantly lower S/N ratio and the expected forest of I\(_2\) absorption features; they have been excluded from this analysis. Ten exposures do not have “attached” ThAr exposures, which means that the echelle or cross-disperser gratings were likely reset between the quasar and ThAr exposures. This can cause velocity shifts and possibly distortions in the wavelength scale of a quasar spectrum and so we exclude these exposures as well. After these selections, the total number of useful UVES exposures reduces to 77 which have attached calibrations for measuring \( \Delta \alpha / \alpha \) (Table 2.1). These 77 exposures can also have velocity shifts and distortions in their wavelength scales, which we will account for in Section 2.3.3. Most of the exposures were taken by observatory staff (i.e. “service mode”), except the three exposures taken in 2007, which were taken by visiting astronomers (i.e. “visitor mode”). The exposure time of individual exposures is in the range between 2700 and 5400 s with a mean of \( \sim 1 \) h. The continuum around the bluest transition that we use in our study, Fe\(_{\text{II}}\) 1608 which falls near 3460 Å in the 346-nm setting, has a S/N in the
range between 9 and 26 per 1.3-km s$^{-1}$ pixel in individual exposures. The S/N in the continuum near the Mg II doublet at $\approx 6030$ Å in the red 580-nm setting is much higher, ranging between 28 and 62 per pixel in individual exposures. The object is very bright so it was not necessary to observe it only during dark nights. Therefore, all exposures have moon illumination between 0 and 100 per cent, with a mean of 43 per cent.

For data reduction we used the ESO UVES Common Pipeline Library (CPL 4.7.8). Initially it bias-corrects and flat-fields the quasar exposures. The quasar flux is then extracted with an optimal extraction method over the several pixels in the cross dispersion direction where the source flux is distributed. The wavelength calibration, which is a very important step for our measurements, was performed using an attached ThAr lamp exposure, taken immediately after each quasar exposure, and the air wavelengths and calibration procedure described by Murphy et al. (2007a). Instead of using the spectra which are automatically redispersed onto a linear wavelength scale by the CPL code, we used only un-redispersed flux and corresponding error arrays for individual echelle orders in the rest of the reduction procedure.

After the wavelength calibration, the air wavelength scale of individual echelle orders, in all quasar exposures, was corrected to vacuum using the (inverse) Edlen (1966) formula. It was then converted to the Solar System heliocentric reference frame using the date and time of the mid-point of the exposure integration, using a custom code, \texttt{UVES\_POPLER} (Murphy, 2016). This code was also used to redisperse the flux from individual exposures onto a common log-linear wavelength scale with dispersion 1.3 km s$^{-1}$ pixel$^{-1}$ for 1×1 binning and 2.5 km s$^{-1}$ pixel$^{-1}$ for 2×1-binned exposures. The rebinned flux arrays from all exposures were scaled to match that of overlapping orders and then combined with inverse-variance weighting and outlier rejection.

We also used \texttt{UVES\_POPLER} to automatically fit a continuum to the spectrum using low-order polynomial fits to overlapping 2000 km s$^{-1}$ wide sections. This continuum was generally acceptable, though some local adjustments were made using customised low-order polynomial fits in the vicinity of our transitions of interest. \texttt{UVES\_POPLER} automatically rejects pixels at the edges of echelle orders which have uncertainties in flux above some threshold, but we have rejected all pixels at the edges of echelle orders if they overlapped with our transitions of interest. We
Figure 2.1: Example transitions from the combined UVES spectrum of HE 0515–4414. The upper panel shows the Fe\textsc{ii} 1608 transition, which represents the blue part of the spectrum, with S/N \sim 140 per 1.3-km s\(^{-1}\) pixel. The middle and lower panels show the Fe\textsc{ii} 2374 and 2382 transition pair and the Mg\textsc{ii} doublet, respectively, with S/N \sim 240 per pixel; these represent the red part of the spectrum. Blue, green and red colours in each panel represent the three fitting regions in our analysis, referred to as the left, central and right region. The combined spectrum here includes all UVES exposures except those with 2\times1 binning and is available in Kotuš et al. (2016).
2.2. Observations, data reduction and calibration

have also manually rejected some pixels from individual exposures around cosmic rays and other obvious artifacts.

The final reduced spectrum, with all exposures combined except those with 2×1 binning, is publicly available in Kotuš et al. (2016). It covers all wavelengths from 3051 to 10430 Å except for a small inter-chip gap at 8537–8664 Å. Its resolving power is higher at redder wavelengths – ≈63500 at ≈4500 Å compared with ≈75000 at ≥5000 Å – because a smaller slit width was typically used for the UVES red arm, though the many exposures contributing to the final spectrum had a range of resolving powers at all wavelengths, ranging between 53500–70000 at ≤4500 Å and 62000–93500 at ≥5000 Å. We discuss the resolving power in more detail in Section 2.3.2. Example sections of the spectrum are shown in Fig. 2.1, which cover 5 of the transitions used in our MM analysis. The continuum around the bluest transition, Fe ii 1608 shown in the top panel, falling near 3460 Å in the 346-nm setting, has a S/N of ≈140 per 1.3-km s⁻¹ pixel. The strongest transitions of Fe ii and Mg i/ii, which dominate our analysis, fall in the wavelength range 5000–6400 Å (middle and bottom panels), are covered by many exposures in the 580-nm setting and all have a S/N of ≈240 per pixel. The S/N peaks at ≈250 per pixel around the Mg ii doublet falling around 6015 Å. To our knowledge, these represent the highest S/N values for a quasar absorption system in an echelle spectrum at z > 1.

Our spectra were observed over ten years, in five separate projects, with different charge-coupled device (CCD) on-chip binning and a variety of slit widths. This variety determines a range of different nominal resolving powers. This, combined with the very high S/N of the spectra, means that modelling the absorption profiles accurately enough to measure Δα/α is only possible if the combined spectrum is separated into five ‘sub-spectra’ – i.e. combined sub-sets of exposures taken in different ‘epochs’ with different resolving power and on-chip binning. These sub-spectra are summarised in Table 2.1. Observations from project 60.A-9022(A) are separated into two sub-spectra, 1999a and 1999b, because exposures in 1999a have 2×1 binning, while those in 1999b are not binned. Observations from projects 072.A-0100(A) and 079.A-0404(A) are combined together into sub-spectrum 0307 because they used the same slit width. Other observations were combined according to the project; we refer to these as sub-spectra taken in epochs 2000 and 0809. We do not notice any obvious deviations in the absorption profile shapes between the different
epochs. However, this possibility could be investigated further with the published sub-spectra.

2.2.2 HARPS/ESO-3.6 m

HARPS (Mayor et al., 2003) is a fiber-fed spectrograph with resolving power of $R \approx 112000$. It is contained in an enclosure in which very stable conditions are maintained, such as very low and stable pressure and constant temperature. It is calibrated with ThAr lines and uses optical fibres, instead of a slit, to introduce light into the spectrograph. However, some of the systematic effects seen in the UVES and HIRES spectrographs also seem to be present in the HARPS wavelength scale. These systematic effects were first identified in the frequency comb study of Wilken et al. (2010) as short-range distortions that are repeated from echelle order to echelle order. Molaro et al. (2013a) measured the amplitude of these ‘intra-order’ distortions in each echelle order to be $\pm 40 \text{m s}^{-1}$. Molaro et al. (2013a) did not identify any significant long-range distortions, as were found subsequently in UVES and HIRES. While Whitmore & Murphy (2015) identified small $\sim 45 \text{m s}^{-1}$ per 1000 Å long-range distortions in their analysis of HARPS solar twin spectra, they are most likely caused by systematic errors in the solar FTS spectrum used as the reference spectrum in that analysis.

The HARPS spectrum used in this work consists of 18 exposures, with exposure times between 1 h and 1.75 h taken during six nights in 2003 and 2009 in ESO Projects 60.A-9036(A) and 072.A-0244(A), with a total exposure time of 93000 s. A ThAr calibration exposure, taken before each night, was used to derive a wavelength solution for all quasar exposures on that night. The HARPS wavelength scale is stable to within just 15 cm s$^{-1}$ over several hour time-scales (Wilken et al., 2010) so this approach does not limit the calibration uncertainty. The observations used one fibre on the quasar while the other was on a nearby sky position to allow sky subtraction.

The quasar, sky and ThAr flux, together with an estimate of the blaze correction from flat-field exposures, were all automatically extracted by the standard HARPS data reduction software. This software also derived the wavelength calibration solution from the extracted ThAr flux. These products were then combined using UVES_POPLER in the same way as the UVES exposures. However, the sky-
subtraction, construction of a flux error spectrum, and blaze correction are not performed by the HARPS reduction software, so these steps were performed within UVESPOPLER. The sky flux was redispersed onto the same common wavelength grid and subtracted from the quasar flux in the same echelle order before the (sky-subtracted, blaze-corrected) flux from all orders and exposures was combined. The error spectrum for each exposure was estimated, assuming Gaussian statistics, from the combination of the quasar CCD electron counts and an estimate of the read noise in each extracted pixel.

The final reduced HARPS spectrum that we use in our analysis, which we make publicly available in [Kotuš et al. (2016)], covers the wavelength range between 3791 and 6905 Å with a small gap between 5260 and 5338 Å due to the physical gap between the HARPS blue and red CCD chips. The S/N around 5050 Å is ≈29 per 0.85-km/s pixel but at the position of the Mg II doublet it peaks at ≈33 per pixel.

2.2.3 bHROS/Gemini

bHROS (Margheim 2008) was bench-mounted in the gravity-invariant pier of the Gemini South Telescope and fed by a 0′.9 × 0′.9 optical fibre that, via an image slicer, projected a 0′.14-wide pseudo-slit into the spectrograph to achieve a resolving power of R ≈ 140000. A total of 37 × 3600-s exposures of HE0515–4414 were obtained during bHROS “science verification” in November and December 2006 and January 2007 during variable conditions. Each quasar exposure was followed immediately by a ThAr lamp exposure. Unfortunately, one of the two CCD chips failed before the observations and the efficiency of bHROS appeared well below specifications during them. The former meant that observations in 2 separate wavelength settings were required to cover most strong transitions in the $z_{abs} = 1.1508$ absorber. The spatial profile of light from the image slider was spread over a large number of pixels (≈50), so the contribution of CCD read noise was significant and further reduced the S/N of the spectra considerably. ThAr lamp observations also revealed instabilities that caused ∼0.5 km/s shifts in the spectrum over several hours. These factors dramatically reduced the S/N of the spectra and rendered them useless for directly measuring Δα/α. However, the very high resolution may still assist in revealing additional velocity structure, and we explore this possibility in Section 3.1.2.4.

No dedicated data reduction pipeline is available for bHROS spectra, so we used
our own custom codes, based loosely on the REDUCE suite of routines \citep{Piskunov:2002}. The two-dimensional shifts between quasar exposures was determined from their corresponding ThAr exposures and the heliocentric velocity at the mid-point of the quasar exposure integration. These shifts were used to combined the low-S/N, individual (dark current, bias and flat-field corrected) quasar exposures into a single, higher-S/N one upon which the flux extraction procedure was performed. The flux in each echelle order containing a transition of interest was extracted with a custom optimal extraction routine which accounted for bad pixels and cosmic rays. Error arrays were estimated in the same process. No sky-subtraction was possible because only a single fibre was available. However, the observations were conducted with typically \( \sim 25\text{--}50 \text{ per cent moon illumination, so the sky background flux is expected to be negligible.} \)

The final, reduced bHROS spectrum is publicly available in \cite{Kotuš:2016} for the transitions of Mg\textsc{i} 2852, Mg\textsc{ii} 2796/2803 and Fe\textsc{ii} 2383, 2586 & 2600 that could be covered in two separate wavelength settings. The spectra around these transitions were extracted to a linear wavelength grid with 0.012\,Å dispersion and the final S/N for, e.g., the Fe\textsc{ii} 2382 at 5123\,Å is \( \approx 24 \) per 0.70-\text{km\,s}^{-1} \text{ pixel.} \)

\section*{2.3 Analysis}

\subsection*{2.3.1 Identification of absorption systems and transitions}

To measure \( \Delta \alpha/\alpha \) we may use all available transitions for which the \( q \) coefficients are known and for which the rest wavelengths are measured with high enough precision. Such transitions were reviewed in \cite{Murphy:2014} and those used in our analysis are summarised in Table \ref{table:transitions}. We only constrain \( \Delta \alpha/\alpha \) in the absorption system at \( z = 1.1508 \). However, we need to identify absorption systems at other redshifts that overlap with those of the \( z = 1.1508 \) system to understand the effect of their transitions, if any.

For absorption system identification we used a custom-made code which searches for absorption from different metal transitions of different species in redshift space. We have identified 8 other absorption systems towards QSO HE 0515−4414 at redshifts 0.2223, 0.2818, 0.4291, 0.9406, 1.3849, 1.5145, 1.6737 and 1.6971.
In the absorption system of interest the strongest transitions show very wide (~750 km s\(^{-1}\)) and very complex velocity structure (e.g. bottom panel of Fig. 2.1) providing a reasonable probability of a blend with transitions from these other redshifts. We have identified 3 such blends. Al\(II\) 1670 at \(z = 1.1508\) is blended with Mg\(II\) 2803 at \(z = 0.2818\), and because of that we do not fit Al\(II\) 1670 redwards of \(-140\) km s\(^{-1}\) (see Section 2.3.4). Al\(III\) 1862 at \(z = 1.1508\) is blended with Mg\(II\) 2803 at \(z = 0.4291\), so we do not fit Al\(III\) 1862 redwards of \(-100\) km s\(^{-1}\). Fe\(II\) 2344 at \(z = 1.1508\) is blended with Ca\(II\) 3934 at \(z = 0.2818\), hence the former is not fitted above 70 km s\(^{-1}\). We also do not fit parts of other weak transitions where we do not formally detect any absorption (e.g. Fe\(II\) 1611).

### 2.3.2 Modelling the resolving power

Even small inaccuracies in the estimated resolving power can yield statistically significant differences between the profile model and spectral data, especially when fitting a large number of velocity components in very high S/N spectra. Therefore, it is very important to accurately estimate the resolving power. Studies of even the best spectra (e.g. Evans et al., 2014) have previously been able to simply assume nominal resolving power values. However, our spectrum has such high S/N that a more sophisticated approach is needed. Further, even the “quality control” information available from ESO (plots of resolving power versus slit width) was not accurate enough for our purposes, because the resolving power can vary by up to 20 per cent depending on the position along the echelle order, the seeing, and/or the slit width.

To obtain a more accurate first-guess resolution, we estimated the resolving power for each transition in each sub-spectrum from the FWHM of ThAr lines used in our calibration. We performed a linear fit to FWHM versus wavelength and FWHM versus position along the echelle orders of the different chips in each sub-spectrum. From these fits we calculated the FWHM of ThAr lines at the specific wavelengths in each sub-spectrum for our transitions of interest. A similar, but to some extent simplified approach was used in Molaro et al. (2013b).

Quasar and ThAr light have slightly different light paths through the optics of the spectrograph. Quasar light is blurred by the atmosphere, forming a seeing disc at the slit entrance. We model this in the spectral direction as a Gaussian function, with a FWHM equal to the seeing. The seeing disc is truncated by the edges of the
Table 2.2: Spectral resolution for different sub-spectra and transitions used in the $\Delta \alpha/\alpha$ analysis. Specific FWHMs for each transition (its wavelength and echelle order position) are estimated from the FWHMs of ThAr lines observed in the attached exposures.

<table>
<thead>
<tr>
<th>Ion Transition</th>
<th>1999</th>
<th>2000</th>
<th>0307</th>
<th>0809</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg I 2026</td>
<td>5.308</td>
<td>4.363</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Mg I 2852</td>
<td>4.199</td>
<td>4.670</td>
<td>4.736</td>
<td>3.768</td>
</tr>
<tr>
<td>Mg II 2796</td>
<td>4.262</td>
<td>4.714</td>
<td>4.818</td>
<td>3.876</td>
</tr>
<tr>
<td>Mg II 2803</td>
<td>4.234</td>
<td>4.696</td>
<td>4.780</td>
<td>3.824</td>
</tr>
<tr>
<td>Al II 1670</td>
<td>5.296</td>
<td>4.660</td>
<td>4.361</td>
<td>4.340</td>
</tr>
<tr>
<td>Al III 1854</td>
<td>5.395</td>
<td>4.349</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Al III 1862</td>
<td>5.597</td>
<td>4.394</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Si II 1808</td>
<td>5.423</td>
<td>4.356</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Cr II 2056</td>
<td>5.223</td>
<td>4.335</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Cr II 2062</td>
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<td>4.389</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Cr II 2066</td>
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<td>4.354</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Mn II 2576</td>
<td>3.933</td>
<td>4.366</td>
<td>4.302</td>
<td>3.309</td>
</tr>
<tr>
<td>Mn II 2594</td>
<td>3.850</td>
<td>4.338</td>
<td>4.227</td>
<td>3.212</td>
</tr>
<tr>
<td>Mn II 2606</td>
<td>3.900</td>
<td>4.340</td>
<td>4.269</td>
<td>3.264</td>
</tr>
<tr>
<td>Fe II 1608</td>
<td>5.310</td>
<td>4.667</td>
<td>4.363</td>
<td>4.396</td>
</tr>
<tr>
<td>Fe II 1611</td>
<td>5.263</td>
<td>4.728</td>
<td>4.361</td>
<td>4.385</td>
</tr>
<tr>
<td>Fe II 2260</td>
<td>3.848</td>
<td>4.359</td>
<td>4.295</td>
<td>3.294</td>
</tr>
<tr>
<td>Fe II 2344</td>
<td>3.841</td>
<td>4.361</td>
<td>4.300</td>
<td>3.311</td>
</tr>
<tr>
<td>Fe II 2374</td>
<td>3.829</td>
<td>4.356</td>
<td>4.290</td>
<td>3.283</td>
</tr>
<tr>
<td>Fe II 2382</td>
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<td>4.305</td>
<td>3.316</td>
</tr>
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<td>3.928</td>
<td>4.366</td>
<td>4.302</td>
<td>3.311</td>
</tr>
<tr>
<td>Ni II 1709</td>
<td>5.374</td>
<td>4.696</td>
<td>4.359</td>
<td>4.302</td>
</tr>
<tr>
<td>Ni II 1741</td>
<td>5.595</td>
<td>4.780</td>
<td>4.356</td>
<td>4.269</td>
</tr>
<tr>
<td>Ni II 1751</td>
<td>5.331</td>
<td>4.519</td>
<td>4.356</td>
<td>4.269</td>
</tr>
<tr>
<td>Zn II 2026</td>
<td>5.327</td>
<td>4.368</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
<tr>
<td>Zn II 2062</td>
<td>5.411</td>
<td>4.385</td>
<td>no spectra</td>
<td>no spectra</td>
</tr>
</tbody>
</table>
slit jaws, which we model in the spectral direction as a hat function. We therefore represent the quasar light after the slit as the product of the Gaussian (seeing) and hat (slit) functions. On the other hand, ThAr light fully illuminates the slit, so it can be modelled just with the hat function. Both signals subsequently pass through similar optics, so to represent their 1-dimensional point-spread functions at the CCD, we convolve them with the same instrumental profile, represented by a Gaussian with a 0.13 arcsec width, which is smaller than the smallest slit width of UVES.

To understand the difference between the quasar and ThAr resolving powers, we calculate the ratio of the measured FWHMs of these final two 1-dimensional profiles. We found this ratio of ThAr FWHM and QSO absorption line FWHM to be between 0.8 and 1. However, in this modelling process we did not account for two-dimensional effects or additional blurring caused by imperfect tracking of the quasar. The latter will be largest for very small values of the seeing-to-slit ratio, because in that situation the observer cannot see any part of the seeing disc reflected from the slit jaws to track the quasar’s position. Therefore, we have imposed a lower limit of 0.9 for the ratio of ThAr-to-quasar resolving powers. The final resolving powers for the different sub-spectra and transitions are shown in Table 2.2.

After refining the resolving power for each transition in the above way, the $\chi^2$ of our fits to their absorption profiles improved even before rerunning the $\chi^2$ minimization procedure again. This justifies the procedure and should be taken into account in future measurements with high S/N and should possibly involve taking into account two dimensional effects, which will improve the fits further.

2.3.3 Correcting the UVES wavelength scale with HARPS spectra

To establish the correct wavelength scale and to measure $\Delta \alpha / \alpha$ accurately, long-range distortions in the wavelength scales of the UVES spectra need to be accounted for. Evans et al. (2014) did this by supercalibrating asteroid spectra (reflected sunlight), taken with the same instrument as their quasar spectra, with Fourier transform spectra (FTS) of the Sun. Whitmore & Murphy (2015) demonstrated that similar supercalibration can be accomplished using spectra of solar twin stars. How-
ever, the UVES spectra of HE 0515—4414 were observed over many widely-separated epochs, mostly in service mode, without appropriate solar twin stars or asteroid exposures within the same nights. Therefore, we must use a different approach and, fortunately, due to the quasar’s brightness, the HARPS spectra are of sufficient quality to provide a similar supercalibration.

The solar twin supercalibration of HARPS by Whitmore & Murphy (2015) revealed a \( \sim 45 \, \text{m s}^{-1} \) per 1000 Å long-range distortion. This is consistent with the first asteroid supercalibration results for HARPS by Molaro & Centurión (2011), though that study employed fewer lines and the long-range distortion was less clear. However, in the frequency comb calibration of HARPS by Molaro et al. (2013a), no long-range distortion was apparent. It is therefore likely that the long-range distortion seen in Whitmore & Murphy (2015) results from a small distortion in the solar FTS spectra used and not HARPS itself. Therefore, in this work we regard the HARPS spectra as having no long-range distortion.

Our approach is to directly compare the HARPS spectrum of the same quasar to its UVES counterpart to transfer its much more accurate wavelength scale. This is schematically presented in Fig. 2.2. This will correct the long-range distortions in the UVES spectrum’s wavelength scale and allow an accurate \( \Delta \alpha / \alpha \) measurement which utilizes the high S/N of the UVES spectrum. In other words, we use the Direct Comparison (DC) method (Evans & Murphy, 2013) to transfer the HARPS wavelength scale, which is more accurate, to the UVES spectra.

The DC method compares corresponding small sections (“chunks”) of two spectra and robustly measures the velocity shift between them using all available absorption features which contribute information beyond some specified significance threshold (typically 5–10\( \sigma \)). It is used to find the weighted mean shift between the sections and any change in this shift over long wavelength ranges. A velocity shift may be caused by the quasar being positioned differently across the slit during different exposures and this shift should not vary substantially with wavelength. We refer to these as “slit-shifts” below. However, it is not known what specifically causes the long-range distortions identified in Rahmani et al. (2013) and explored by Whitmore & Murphy (2015) in detail, but, in general terms, they are likely caused by the differences in the light paths of the quasar and the ThAr lamp light through the spectrograph. In the following subsections we use the DC method to find velocity
Figure 2.2: Schematic diagram of the correction of the UVES wavelength scale with a HARPS spectrum using the DC method.

shifts and slopes (stretch or compression of the wavelength scale) between different UVES exposures in each sub-spectrum (Section 2.3.3.1), between the combined UVES sub-spectra from different epochs (Section 2.3.3.2), and between the combined UVES sub-spectrum from each epoch and the HARPS spectrum of the same quasar (Section 2.3.3.3).

2.3.3.1 Velocity shifts between UVES exposures within each sub-spectrum

To measure and correct for slit-shifts between exposures within a given sub-spectrum, we used the DC method to compare each of them with the combined sub-spectrum from that epoch. The DC method was applied using 200-km s\(^{-1}\) chunks and a feature-selection threshold of 7\(\sigma\). These are similar to the parameters used by Evans & Murphy (2013) for non-Lyman-\(\alpha\) forest regions of spectra, with a slightly higher selection threshold because of the much higher S/N of our spectra. In principle, the individual exposures within each sub-spectrum may have long-range distortions between them which should first be measured and corrected before the slit-shifts. However, from the DC method comparison, we found that these distortions had slopes that were all consistent with zero, albeit with large statistical uncertainties (typically
Chapter 2. Stringent limit on $\Delta \alpha /\alpha$ - part I

$\sim 190 \text{ m s}^{-1}$ per 1000 Å) because of the relatively low S/N per exposure ($\lesssim 40$ per pixel). Therefore, we did not correct for long-range distortions and proceeded to measure and correct the slit-shifts only.

We found shifts typically in the range between $-100$ and $100 \text{ m s}^{-1}$, with extreme values of $300 \text{ m s}^{-1}$, which is consistent with both cross-correlation measurements of Rahmani et al. (2013) and DC method measurements of Evans et al. (2014). It is very important to correct for slit-shifts because they can influence how the spectra are combined within UVES_PoPLER. For example, if the S/N varies differently as a function of wavelength in two different exposures, the combined spectrum will have a wavelength-dependent relative contribution from those exposures and, thus, a wavelength-dependent residual slit-shift. Transitions at different wavelengths will therefore have a spurious velocity shift between them. Therefore, the slit-shift for each exposure was corrected within UVES_PoPLER, by applying the opposite of the shifts to all exposures in every sub-spectrum. After re-combination, there were no shifts left among different exposures in each sub-spectrum. This was checked with a repeated DC method analysis.

2.3.3.2 Velocity shifts between UVES sub-spectra

At this stage, individual exposures that are combined to create the sub-spectra had been corrected for the slit-shifts. However, different sub-spectra could still have shifts between them. This kind of shift is even more important to correct for, due to the different wavelength coverage of each sub-spectrum. For example, some sub-spectra do not contribute to some transitions, while other sub-spectra contribute to all transitions. If there is a shift between two such sub-spectra, it will directly influence the velocity shift between these two sets of transitions, leading directly to a spurious $\Delta \alpha /\alpha$ measurement.

The higher S/N of the sub-spectra (compared to their constituent exposures) also allows us to estimate relative wavelength distortions between them. These can be checked against the absolute (and more precise) long-range wavelength distortions measured in Section 2.3.3.3. We have chosen to compare all the sub-spectra with the 2000 sub-spectrum, because it consists of exposures in all the different settings that we use in our analysis and therefore has the largest wavelength coverage. We used the same DC method parameters as in the previous subsection.
2.3. Analysis

We found slit-shifts between sub-spectra in the range between $-200$ and $200$ m s$^{-1}$, consistent with shifts found in previous works of Rahmani et al. (2013) and Evans et al. (2014) and our shifts found in Section 2.3.3.1. We corrected for these relative shifts and recombined the sub-spectra using UVES\_POPLER by adding the additional correction to the slit-shift for each exposure from Section 2.3.3.1. Upon re-combination, no shifts remained between any of the exposures, which was again checked with a repeated DC method analysis.

The relative long-range distortions of all the sub-spectra, except one, have slopes that are statistically consistent with zero: For the red settings the average slope was $\approx 25$ m s$^{-1}$ per 1000 Å with the uncertainty of $\approx 30$ m s$^{-1}$ per 1000 Å and for the blue settings the average was $\approx 200$ m s$^{-1}$ per 1000 Å with uncertainties in the range $\approx 170$–$560$ m s$^{-1}$ per 1000 Å. This average uncertainty is typical of the magnitude of the distortions found in UVES spectra (Whitmore & Murphy, 2015). Assuming a simple MM analysis involving only the Mg\textsc{ii} 2796 and Fe\textsc{ii} 2382 transitions, this would correspond to an uncertainty in $\Delta \alpha / \alpha$ of $\approx 10$ ppm. This is still an order of magnitude larger than the final systematic error budget of $\lesssim 1$ ppm which we measure in this work (see Section 3.1). In a single exceptional case, the 0307 red 580-nm setting, the long-range distortion relative to the 2000 sub-spectrum had a slope of $119 \pm 30$ m s$^{-1}$ per 1000 Å. If converted to $\Delta \alpha / \alpha$ in the same way as above, it would represent a $\Delta \alpha / \alpha$ of $\approx 6$ ppm. That is, left uncorrected, such a distortion could contribute a significant systematic error. We return to this case in Section 2.3.3.3 below.

2.3.3.3 Correction of each UVES sub-spectrum to the HARPS wavelength scale

Finally, we directly compared the combined UVES sub-spectra with the HARPS spectrum. The HARPS spectrum has the disadvantage of limited wavelength coverage, 3780–6915 Å, compared to 3040–10430 Å for the UVES spectrum, so only the limited, overlapping wavelength range of the two spectra can be compared. This corresponds to the wavelengths covered by the UVES 580-nm setting. Therefore, we cannot determine the size of any velocity shift between the red and blue arms of UVES from our spectra and/or whether the long-range distortions in the red and blue arms are the same. In the analysis of Whitmore & Murphy (2015), the slopes of
the distortions in UVES’s red and blue arms were indeed found to be very similar in most cases, so we make this assumption below. We assume that the distortion slopes from the UVES 580-nm setting applies to all other UVES settings in the 1999, 0307 and 0809 sub-spectra. We test this assumption in Section 3.1.3.1.

The slopes of the distortions we find between the HARPS spectrum and the UVES sub-spectra are provided in Table 2.3 and fall between 110 and 220 m s$^{-1}$ per 1000 Å. The larger slopes correspond to $\Delta \alpha / \alpha \approx 10$ ppm if we consider the same two transitions used in Section 2.3.3.2 for the conversion, so it is clearly important to correct for these distortions. This also indicates the size of the systematic error expected in previous analyses of the 1999 and 2000 spectra. The distortions in Table 2.3 are comparable to the relative distortions found in the DC method comparison of the UVES sub-spectra from different epochs in Section 2.3.3.2. They are typical of the long-range distortions found in UVES spectra for the epochs probed (Whitmore & Murphy, 2015).

Another relevant disadvantage of the HARPS spectrum is its much lower S/N compared to the UVES spectrum (e.g. $\approx 35$ per 0.85 km s$^{-1}$ pixel at 6000 Å), and this limits the precision of the slope determined from the DC method analysis. However, the statistical uncertainties in the distortion slopes reported in Table 2.3 are relatively small, between 35 and 53 m s$^{-1}$ per 1000 Å, meaning that the distortions themselves are detected with 2.2–6.0σ significance.

While the 1999, 2000 and 0809 sub-spectra all have similar distortion slopes, the slopes found for the 0307 and 2000 sub-spectra differ by $\approx 109$ m s$^{-1}$ per 1000 Å. This is consistent with the relative difference found by directly comparing the UVES 0307 and 2000 sub-spectra in Section 2.3.3.2. This demonstrates the robustness of the DC method and HARPS supercalibration approach, and increases confidence in the final wavelength scale of our UVES spectrum. We have therefore corrected for the distortions listed in Table 2.3 by applying an opposing long-range distortion slope to the each corresponding exposure in UVES_popler. We use the error bars associated with these slopes to estimate the remaining systematic uncertainty budget in Section 3.1.2.1.

After correcting for the long-range wavelength distortions, the DC method was run again to determine any newly-introduced velocity shifts between the corrected UVES sub-spectra and the HARPS spectrum. These shifts will be introduced be-
Table 2.3: Long-range distortion slopes identified in the DC method comparison of different UVES sub-spectra in the 580-nm setting with the HARPS spectrum. It is important to correct for the long-range wavelength distortions with this magnitude because they can lead to spurious $\Delta \alpha/\alpha$ measurements of up to $\sim 10$ ppm.

<table>
<thead>
<tr>
<th>Sub-spectrum</th>
<th>Slope [m s$^{-1}$ Å$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.209 ± 0.035</td>
</tr>
<tr>
<td>2000</td>
<td>0.221 ± 0.053</td>
</tr>
<tr>
<td>0307</td>
<td>0.112 ± 0.051</td>
</tr>
<tr>
<td>0809</td>
<td>0.203 ± 0.041</td>
</tr>
</tbody>
</table>

due to the different UVES sub-spectra cover different wavelength ranges and the slopes are corrected around different ‘pivot’ wavelengths. That is, they are artifacts of our procedure. They are found to be $< 185$ m s$^{-1}$ corrections. Shifts were measured for the 437, 520 and 580-nm settings, but for the 346-nm setting we used the shifts from the 580-nm setting from the same sub-spectrum. This should be correct if the previous assumption of similar long-range wavelength slopes in the blue and red settings is valid, and we test this in Section 3.1.3.1. We also checked that the 437 and 580-nm settings have consistent shifts and we found them to be consistent. However, the uncertainties on the shifts in the 437-nm settings are much larger than for the 580-nm settings. Therefore, we cannot make a definitive conclusion that these shifts, as well as the long-range wavelength distortion slopes, are similar in the blue and red settings from this information alone. The final velocity shift corrections were added to the previously measured offsets in all exposures from the relevant sub-spectra and they were recombined with UVES_popler.

As a last step in this part of the analysis, we have confirmed that a DC method analysis returns negligible, insignificant shifts and distortion slopes between the UVES sub-spectra and the HARPS spectrum after all of these corrections.

2.3.4 Fitting procedure

Due to the very complex and broad velocity structure of the $z_{abs} = 1.1508$ absorber, we have separated the absorption profile into three regions, which we fit separately: ‘left’, ‘central’ and ‘right’. These velocity regions are defined such that there appears to be no absorption in the strongest transition (Mg II 2796) at the region edges, and that they have approximately the same velocity width. The re-
regions are indicated by different shading in Fig. 2.1, where left, central and right regions are between $-565 \text{ km s}^{-1}$ and $-360 \text{ km s}^{-1}$, $-360 \text{ km s}^{-1}$ and $-100 \text{ km s}^{-1}$, $-95 \text{ km s}^{-1}$ and $150 \text{ km s}^{-1}$, respectively, where $v = 0 \text{ km s}^{-1}$ is at $z = 1.1507930$. If there is no absorption in some parts of a weak transition its regions are narrowed to avoid fitting many pixels of unabsorbed continuum unnecessarily.

To be able to measure $\Delta \alpha/\alpha$ we need to construct a model of the absorption profile, jointly for all fitted transitions, which comprises many individual velocity components. These are represented as Voigt profiles convolved with Gaussian instrumental profiles. We use vpfit version 9.5 (Carswell & Webb, 2014) to minimize the $\chi^2$ between this model and the spectra. This is a non-linear least-squares algorithm which varies the column densities ($N$), Doppler $b$-parameters and redshifts ($z$) of individual components. We allow column densities to vary freely, but we tie $b$-parameters and redshifts for each velocity component between different transitions.

We assume that all velocity components in our fits are turbulently broadened, i.e. the $b$-parameters of corresponding components are the same for all species. However, previous work has demonstrated that $\Delta \alpha/\alpha$ is not sensitive to the broadening mechanism assumed, either purely thermal (where the $b$-parameter scales with the atomic mass) or a mix of turbulent and thermal (e.g. Murphy et al., 2003a; King et al., 2012). This is especially the case with a fitting approach that seeks to fit all statistically significant structure (Evans et al., 2014), so we expect that systematic errors from the assumption of turbulent broadening are negligible. Vpfit can also vary the additional $\Delta \alpha/\alpha$ parameter, but initially we fix $\Delta \alpha/\alpha$ to zero until our preferred models of the absorption profiles are finalized.

Before fitting we blinded our spectra by introducing random small shifts between transitions in Uves_popler. This blinding approach was the same as employed by Evans et al. (2014): random intra-order and long-range distortions were introduced into each exposure, with some common elements between exposures (to prevent the distortions averaging out over many exposures). The amplitudes and magnitudes of the distortions were such that no value of $\Delta \alpha/\alpha$ derived from the sub-spectra could be trusted, but not large enough to significantly affect the profile fitting approach below. The blinding was only removed once the preferred profile fits were finalized and $\Delta \alpha/\alpha$ was to be determined.

Our approach to fitting is similar to recent analyses of variation in $\alpha$ (e.g. Molaro...
Figure 2.3: Combined, continuum-normalized UVES 0809 sub-spectrum [ESO project 082.A-0078(A)] (black histogram) overlaid with our preferred model (red curve) in the left region. For transitions not covered by the 0809 sub-spectrum (see Table 2.2), the 2000 sub-spectrum is plotted. Blue tickmarks represent centroids of individual velocity components. Dotted light blue lines below and above the spectra represent the zero level and continuum, respectively. The grey line represents the residuals between the spectrum and the model, with the ±1σ deviations marked by the dark green lines. The fitting region is narrowed down in weak transitions due to the lack of absorption, or they are not fitted at all.
Figure 2.4: Same as Fig. 2.3 but for the central region. The fitting region for Al\textsc{ii} is not modelled above $-160\ \text{km s}^{-1}$ because of the blend discussed in Section 2.3.1.
Figure 2.5: Same as Fig. 2.3 but for the strong transitions in the right region. The fitting region for Fe II 2344 is not modelled above 65 km s$^{-1}$ because of the blend discussed in Section 2.3.1.
Figure 2.6: Same as Fig. 2.3 but for the weak transitions in the right region. Pink tickmarks in the second and third panel represent velocity components of Zn II transitions and blue tickmarks are components of Mg I 2026 and Cr II 2062 transitions.
2.3. Analysis

However, we had to divide the fitting process into several steps due to the high complexity of the absorption system. Firstly, we fitted just the Fe\text{\textsc{ii}} transitions because they cover a variety of optical depths (because they have a variety of oscillator strengths). In an iterative process we trialed many models by reducing $\chi^2$ using \textsc{vpfit} and adding more components in places where the residuals were not satisfactory. Once a statistically satisfactory fit was established using just the Fe\text{\textsc{ii}} transitions we incorporated the weaker transitions, one by one, by using the same velocity structure as in Fe\text{\textsc{ii}} and minimizing $\chi^2$ in \textsc{vpfit}. In this process we also narrowed the velocity width of regions in parts of the weak transitions where we did not identify any absorption. In all such weak transitions (i.e. those of Zn\text{\textsc{ii}}, Cr\text{\textsc{ii}} etc.), the weaker velocity components were not typically required to provide a statistically acceptable fit, so \textsc{vpfit} removed them. We were careful to check each time such a component was removed that it corresponded to the weakest of any close grouping of Fe\text{\textsc{ii}} components. Typically, many fewer components are required to fit these much weaker transitions, but our fit maintains the components corresponding to the strongest Fe\text{\textsc{ii}} components. After inspecting the residuals again, we tried to incorporate additional components if possible. Finally, we incorporated the somewhat saturated Mg\text{\textsc{ii}} transitions by copying the Fe\text{\textsc{ii}} velocity structure, including some additional velocity components and minimizing $\chi^2$, iteratively trialing more complex models until we achieved the statistically preferred model for $\Delta\alpha/\alpha$ measurements.

The 5 different sub-spectra have somewhat different resolving powers. Therefore, rather than fitting the combined spectrum, the sub-spectra were fit separately but simultaneously with the same model. For each sub-spectrum the model is convolved with a Gaussian line-spread function with the appropriate FWHM shown in Table 2.2.

Our preferred models of the absorption profiles are shown in Figs. 2–5 overlaid on the 0809 sub-spectrum – i.e. the combination of all exposures from the new 2008/2009 epoch (see Table 2.1) – for all the fitted transitions in the left, central and right regions, respectively. For transitions not covered by the 0809 sub-spectrum (see Table 2.2), the 2000 sub-spectrum is plotted.

Due to the high resolution and (mainly) very high S/N of the spectrum, plus the complexity and breadth of the absorption system, a very large number of compo-
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ments, 106, was required to fit the statistically significant velocity structure in all the transitions. To our knowledge, this is a much larger number than has been used to fit any metal absorption system before. Fitting such a large number of components was extremely challenging and time-consuming, even though we fitted the three different regions separately. This raises the question of how robustly we can determine the velocity structure and how to be sure that all statistically significant structure in the profile is fitted.

The difficulty in establishing the preferred velocity structure was compounded by data artifacts. Figures 2–5 show the residuals between our model and the spectrum, normalized by the 1$\sigma$ error array. Note that, in some parts of some transitions, even our very complex model leaves significant residuals in several neighboring pixels (e.g. around +100 km s$^{-1}$ in Mg $\text{II} 2803$ in the right region, Fig. 2.5). In many cases, especially in the redder transitions (e.g. Mg 12852, the Mg $\text{II}$ doublet and the Fe $\text{II}$ lines redwards of 2344 Å in the absorber rest-frame), these significant runs of residuals are most likely caused by low-level CCD fringing (i.e. internal reflections within the CCD substrate). An example of the fringing effect is shown in Fig. 2.7. In other parts of the spectrum we also find evidence for artifacts from the flux extraction, sky subtraction and flat-fielding. These effects are not normally significant in quasar spectra with $S/N \lesssim 100$ but likely dominate over the statistical noise in some places of our much higher $S/N$ spectrum. These artifacts may drive a requirement to fit more velocity components, so this complicated our approach to determining when to stop adding new components to our model profile.

Previous studies have used several different criteria to decide the best number of components to fit, e.g. minimizing the $\chi^2$ per degree of freedom, $\chi^2_n$, (e.g. Murphy et al., 2008b; Molaro et al., 2013b; Evans et al., 2014), or minimizing the Akaike information criterion (e.g. King et al., 2012), and by ensuring that no significant structures in the residuals are common among the different fitted transitions (by constructing “composite residual spectra”, Malec et al., 2010). However, the data artifacts discussed above force us to adopt a different approach to avoid fitting too many components; the $\chi^2$ minimization algorithm cannot sustain an arbitrarily large number of components due to the degeneracies that develop between neighboring components. Therefore, our approach was to stop adding more velocity components when doing so reduced $\chi^2_n$ by less than $\approx 0.002$ and when no correlated structures
in the residuals were present across the fitted transitions (as visualized through the composite residual spectrum). We discuss the implications of these data artifacts for analyses of high-S/N spectra from future telescopes in Section 3.2.3.

After preferred models were established, we unblinded the sub-spectra by removing the artificial shifts and distortions applied in the blinding process, and began the \( \chi^2 \) minimization with \( \Delta \alpha / \alpha \) introduced as a free parameter. We constructed five models with different starting values for \( \Delta \alpha / \alpha \), \(-5, -1, 0, 1\) and \(5\) ppm, to assess whether the \( \chi^2 \) minimization converged towards the same value of \( \Delta \alpha / \alpha \). Convergence was complete in all regions, from all starting values, except for the right region with starting values \( \pm 5 \) ppm and in the left region for the \(-5\) ppm starting value. This is to be expected for the right region: the final value of \( \Delta \alpha / \alpha \) for this region is close to zero with a statistical uncertainty \(<0.6\) ppm (see Section 3.1), so the starting values of \( \pm 5 \) ppm are far from this solution; coupled with the complexity of the fit, and the covariance between the column densities and \( b \)-parameters of closely-spaced velocity components, achieving convergence in a reasonable number of iterations (\( \sim 1000 \)) is not expected. Nevertheless, these two models in the right region were converging towards the same \( \Delta \alpha / \alpha \) value as the other models; given a longer computation time, it is evident that these extreme models would eventually converge to the same \( \Delta \alpha / \alpha \) value as the others in the right region. However, in the left region the \(-5\) ppm model converged towards a somewhat different \( \Delta \alpha / \alpha \) value to the models with other starting values. In this case, the final statistical error on \( \Delta \alpha / \alpha \) (Section 3.1) is \(>3\) ppm, so, together with the fact that all other models converged, this suggests that the multidimensional \( \chi^2 \) space around the solution is very flat, possibly due to some degeneracy between \( \Delta \alpha / \alpha \) and the redshift parameters of one or more velocity components. This is further explored and the systematic error associated with this is examined in Section 3.1.2.5. Given the overall convergence of the models in most cases, we derived our estimates of \( \Delta \alpha / \alpha \) using fits that begin with the \( \Delta \alpha / \alpha = 0 \) as the starting value. We refer to them as our “fiducial” models and to the values of \( \Delta \alpha / \alpha \) derived from them as fiducial \( \Delta \alpha / \alpha \) values. We use fiducial models to estimate our final \( \Delta \alpha / \alpha \) values (by including the isotopic structures of the fitted transitions – see Section 3.1.1), and for all subsequent analyses in this study.
Figure 2.7: Example of the fringing effect in the red part of the combined 0809 sub-spectrum. Red shading represents the reddest half of the right fitting region of the Mg\textsc{ii} 2803 transition. Many fringes are evident as significant, low-level (note the zoomed vertical axis range) variations in the unabsorbed continuum flux over \(~20–100\) pixel ranges. These fringes are likely to be present in the fitting regions of the Mg\textsc{i/ii} transitions as well. Fringing with similar magnitude, but uncorrelated structure, is evident in all sub-spectra.
2.3. Analysis

2.3.5 Implications for velocity structure from higher-resolution spectra

Here we explore whether additional information about the velocity structure can be obtained from the higher-resolution HARPS and bHROS spectra. Specifically, can we determine whether the fiducial model, based on the lower-resolution but considerably higher-S/N UVES spectra, contains too few components spaced too far apart, or perhaps too many components spaced too closely together? That is, can the HARPS and/or bHROS spectrum be used to assess whether we have over-fitted or under-fitted our UVES spectrum?

As a first step, we compared the UVES, HARPS and bHROS spectra in each transition, an example of which is shown in Fig. 2.8 for Fe II 2382. The main difficulty in comparing the spectra is already evident in this figure: the much lower S/N ratio for the two highest-resolution spectra masks any possible evidence for different velocity structure, especially for the bHROS spectrum. The HARPS spectrum possibly shows some difference to the UVES spectrum at $\pm 5$ and $\pm 15$ km s$^{-1}$. Even though these differences are small and the S/N per km s$^{-1}$ is $\sim 6.5$ times lower for HARPS than for UVES, they may reveal information about unresolved velocity components, so we explore these differences further below. However, for this reason, it is already clear that the HARPS and bHROS spectra offer much less precise constraints on $\Delta \alpha / \alpha$ and no firm constraint on the reality of any individual velocity component in our fiducial model, so we do not directly include the HARPS and bHROS spectra for our $\Delta \alpha / \alpha$ measurement.

As a second step, we tried to assess a different, more collective property of the velocity structure: how closely velocity components are spaced relative to their widths. We constructed two simulated models, consisting of more and fewer velocity components than in the fiducial model, in a velocity range between $-15$ and $28$ km s$^{-1}$. The first model was constructed from our fiducial model by merging narrow velocity components into a smaller number of 4-km s$^{-1}$-wide (i.e. $b = 4$ km s$^{-1}$) velocity components. The second model was constructed from our fiducial model by separating each component broader than 1 km s$^{-1}$ into two or more, 1-km s$^{-1}$-wide components. We minimized $\chi^2$ between these new ‘resolved’ and ‘unresolved’ models and the UVES spectrum, using the Fe II transitions only, while holding the redshifts
and b-parameters fixed and allowing the column densities to vary. We converted the instrumental profile width in both models to that of the bHROS spectrograph (i.e. $R = 140000$) and converted the resulting flux profiles into apparent column density profiles according to

$$
\log N_a = \log \frac{\ln(1/F)}{(f\lambda_0)\pi e^2/m_e c}
$$

(2.1)

where $F$ is the continuum-normalized flux, $f$ and $\lambda_0$ are the oscillator strength and the transition’s rest wavelength, and $m_e$ and $e$ are the mass and charge of the electron.

Figure 2.9 compares the apparent column density profiles of the Fe II 2382 and 2600 transitions, for both resolved and unresolved models at both UVES and bHROS resolution. By offering a comparison of the apparent column density profiles of these transitions, both in saturated and unsaturated parts of the profile, the Fe II 2382 and 2600 transitions give the best opportunity for understanding how tightly velocity components are packed. We find that these transitions’ $N_a$ profiles match well even in saturated regions when the velocity structure comprises many closely-packed components that are not individually resolved, i.e. the UVES-resolution model (pink and black solid lines) in the middle panel of Fig. 2.9. There is no such match when all velocity components are resolved, either if we increase the resolving power of the spectrograph (orange and blue dashed lines in the middle panel of Fig. 2.9), or decrease the number of components and increase their widths (pink and black solid lines in the upper panel of Fig. 2.9).

We compare this model prediction with the real apparent column density profiles of Fe II 2382 and 2600 transitions in the UVES and HARPS spectra in the lower panel of Fig. 2.9. We use the HARPS spectrum here, even though the bHROS spectrum has somewhat higher resolution, because the S/N of the bHROS spectrum is substantially lower than for the HARPS spectrum. The apparent column density profiles match well in the saturated regions of the UVES spectrum (pink and black solid lines in the lower panel of Fig. 2.9), similar to the UVES-resolution models in the middle panel. This may provide some evidence that the real velocity structure has even more closely-spaced, narrow velocity structure than our fiducial model. As such, our approach of fitting a larger number of velocity components is supported to some extent by Fig. 2.9.
Figure 2.8: Comparison of the UVES, HARPS and bHROS spectra for the right region of the Fe\textsc{II} 2382 transition. The S/N ratios per km\,s$^{-1}$ are 200, 31 and 29 in the continuum, respectively, and it is clear that there is little evidence, if any, for additional velocity structure from the higher-resolution spectra because of their much lower S/N per km\,s$^{-1}$. 
Figure 2.9: Apparent column density as a function of velocity in the near-saturated regions of the absorption profile for the Fe II 2382 and Fe II 2600 transitions. The upper and middle panels show two different models with the $b$-parameters of all velocity components from our fiducial model converted to 4 km s$^{-1}$ and 1 km s$^{-1}$, respectively. The lower panel shows the apparent column density of the real UVES and HARPS spectra (pixels in which noise fluctuations gave negative flux values are not plotted). The profiles match very well between the Fe II 2382 and Fe II 2600 transitions at UVES resolution in the saturated regions at 0, 10 and 24 km s$^{-1}$ (pink and black solid lines in the middle panel). However, they do not match as closely at higher, bHIROS resolution, or in the case of broader velocity components which are resolved at UVES resolution. This implies that, if we have a closely-packed velocity structure in reality, with individually-unresolved components at UVES resolution, we should expect Fe II 2382 and Fe II 2600 apparent column density profiles to match well. This is what we observe in the lower panel, providing some evidence for a closely-packed velocity structure in reality.
2.3. Analysis

Unfortunately, from comparison of the same two transitions in the HARPS spectrum (orange and blue dashed lines in the lower panel of Fig. 2.9) we are unable to reveal how well the apparent column density profiles match. The main reasons for this are the low S/N of the HARPS spectrum, which is immediately evident in Fig. 2.9, and that this causes many pixels in highly saturated regions to have flux values lower than zero (missing in Fig. 2.9). These cannot be converted to apparent column density with equation (2.1). However, even if we had a high S/N per km s\(^{-1}\) spectrum at higher resolution, and the real velocity structure comprised very closely-packed, narrow velocity components, we would still not be able to resolve them individually – they would be too closely packed to produce anything but smooth features in the spectrum. Therefore, increasing the resolution would only slightly increase the amount of ‘centroiding information’ and the precision with which we can measure \(\Delta \alpha / \alpha\) is proportional to this. In other words, even with a similar S/N per km s\(^{-1}\) as our UVES spectrum, observing at higher resolving power would not substantially increase the precision on \(\Delta \alpha / \alpha\).
3

Stringent limit on $\Delta \alpha/\alpha$ from the brightest southern quasar above redshift 1 - part II

3.1 Results

3.1.1 Results from VPFIT and statistical errors

The best-fitting value of $\Delta \alpha/\alpha$, its $1\sigma$ statistical error and the $\chi^2$ per degree of freedom, $\chi^2_\nu$, for each of the three regions are shown in Table 3.1. These values were derived by minimizing $\chi^2_\nu$ in VPFIT from the fiducial model for each region. The statistical errors are determined from the diagonal terms of the final parameter covariance matrix and, for a given profile model, derived only from the statistical flux noise in the spectra. Systematic errors are discussed in Section 3.1.2 below. Section 3.1.4 explains how we combined the values from the individual regions to form a combined $\Delta \alpha/\alpha$ estimate and error budget for the entire absorber.

The final results in Table 3.1 were derived using the laboratory wavelength information recommended by [Murphy & Berengut, 2014], including the isotopic structures (where known from measurements or theoretical calculations). We assume terrestrial isotopic abundances, even though we cannot be sure that the same isotopic abundance pattern exists in this absorbing cloud at $z = 1.15$. We discuss the impact of different isotopic abundances in the cloud, especially for Mg, in Section 59.
The final fitted parameters and their uncertainties from vpfit are provided in electronic format in Kotuš et al. (2016).

The ESO UVES Common Pipeline Library, which we used to reduce the spectra, fails to correctly estimate the flux errors in near or fully saturated parts of the spectra (King et al., 2012). Therefore, we used the modified version of vpfit (King et al., 2012) which increases the error array appropriately in such regions for the correct estimate of the $\chi^2$ in the Table 3.1.

It is evident in Table 3.1 that the right region measurement is by-far the most precise among the three measurements. This is mainly because this is the most complex, highest column-density part of the absorption system: there are more sharp, deep features from which constraints on the relative velocity between the transitions can be derived. While more transitions are also utilized in this region (i.e. those of Ni II, Mn II, Cr II and Zn II), they are all very weak and consequently contribute little to the statistical precision on $\Delta\alpha/\alpha$ in this region (see analysis in Section 3.1.3.2 in which these transitions are removed). The complexity of the absorption in the right region, combined with the data artifacts discussed in Section 2.3.4, especially fringing effects, lead to a higher $\chi^2$ in that region. Indeed, among the 25 transitions fitted in this region, $\chi^2_\nu$ is largest for the Mg II transitions where the fringing is most important. However, the larger $\chi^2$ for the Mg II transitions may also be due to the difficulty in fitting these much stronger and somewhat saturated transitions; there may exist weak velocity components that are not fitted and which contribute negligibly to absorption in other species (e.g. Fe II).

The statistical uncertainties on $\Delta\alpha/\alpha$ range between 0.592 and 3.381 ppm across the three regions. The latter is comparable with the most precise previous measurements of $\Delta\alpha/\alpha$ in individual absorption systems (Q04; Levshakov et al., 2007; M08b; Agafonova et al., 2011; Molaro et al., 2013b; Evans et al., 2014) and the former is comparable with, though smaller than, the statistical error in the weighted mean $\Delta\alpha/\alpha$ values reported for the large samples of absorbers studied in (Murphy et al., 2004; King et al., 2012).

Using only the statistical errors, the $\Delta\alpha/\alpha$ values in the three regions are marginally inconsistent with each other: the values from the left and central regions are 1.5 and 2.1$\sigma$ from that of the right region. The $\chi^2$ around the weighed mean value, $-1.37 \pm 0.55$ ppm, is 6.42. Formally, this value (or higher) has a 4 per cent chance of
3.1. Results

Table 3.1: Final measurements of \( \Delta \alpha / \alpha \) for the three fitting regions and the combined value with 1\( \sigma \) statistical and systematic uncertainties. \( \chi^2 \) is given in the last column. We provide additional significant figures here to allow reproducibility of our calculations only.

<table>
<thead>
<tr>
<th>Region</th>
<th>( \Delta \alpha / \alpha ) [ppm]</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>(-6.153 \pm 3.381_{\text{stat}} \pm 2.055_{\text{sys}} )</td>
<td>1.086</td>
</tr>
<tr>
<td>Central</td>
<td>(-4.692 \pm 1.743_{\text{stat}} \pm 1.612_{\text{sys}} )</td>
<td>1.171</td>
</tr>
<tr>
<td>Right</td>
<td>(-0.843 \pm 0.592_{\text{stat}} \pm 0.554_{\text{sys}} )</td>
<td>1.262</td>
</tr>
<tr>
<td>Combined</td>
<td>(-1.422 \pm 0.553_{\text{stat}} \pm 0.645_{\text{sys}} )</td>
<td></td>
</tr>
</tbody>
</table>

occurring randomly, but with just 3 values to compare, this estimate is not reliable. More importantly, systematic effects have not yet been included, and we discuss these below. Some of those effects are correlated between the absorbers, so combining them and discussing their consistency requires further analysis in Section 3.1.4.

3.1.2 Systematic error estimates

Given that we study only a single absorption system in this study, an important goal is to identify all systematic effects that can influence our results and to quantify them. VPFIT calculates statistical errors on \( \Delta \alpha / \alpha \) very robustly (King et al., 2009), but it is unable to provide any information about the possible presence of systematic errors. In this Section we estimate the effect on \( \Delta \alpha / \alpha \) of the four most important systematic errors: long-range wavelength distortions, intra-order distortions, redispersion of exposures onto the common wavelength scale, and inaccuracies in the modelled velocity structure. These are discussed in the following subsections, and Section 3.1.2.5 discusses the additional systematic error in the left region caused by a relatively flat \( \chi^2 \) space. The systematic uncertainties are summarized in Table 3.2, which also shows the total systematic error for each region (calculated as the quadrature sum of individual systematic uncertainties for each region). Several other consistency checks, which limit the cumulative effect of these main systematic errors, are conducted in Section 3.1.3 together with other possible effects, such as isotopic abundance variations and real velocity shifts between ionic species. However, those consistency checks do not modify our systematic error budget.
3.1.2.1 Long-range wavelength distortions

In our analysis we have compared UVES sub-spectra with the HARPS spectrum of the same object to correct for the long-range wavelength distortions before measuring $\Delta \alpha/\alpha$. Here we use the uncertainties in the distortion slopes derived in that comparison (using the DC method), which are shown in Table 2.3 to estimate the systematic uncertainty implied for $\Delta \alpha/\alpha$.

For each sub-spectrum, we imposed an additional distortion slope on each of its constituent exposures, equal to the slope uncertainty, $+1\sigma$, and recombed the sub-spectrum again in UVES_POPER. We also created another sub-spectrum with a $-1\sigma$ correction applied. VPFIT is then used to optimize the fiducial model (separately) on the two new sets of sub-spectra ($+1\sigma$ and $-1\sigma$) to determine how much $\Delta \alpha/\alpha$ differs from the fiducial value in each of the 3 fitting regions. The long-range distortion systematic error is then computed as the mean of the two estimates in each region. The systematic errors calculated from this analysis are $\pm 1.22$, $\pm 1.05$ and $\pm 0.51$ ppm, for the left, central and right regions, respectively, and these are shown in Table 3.2.

It is also interesting to determine how large the systematic effect from the long-range distortions would have been if we had not corrected them in the UVES spectra. To assess this we remeasured $\Delta \alpha/\alpha$ in the right region after recombing the sub-spectra without correcting them for the distortions found in Section 2.3.3.3. After optimizing the model in VPFIT we found that $\Delta \alpha/\alpha$ was 2.1 ppm lower than our fiducial value for the right region. In Section 2.3.3.3 we estimated that the long-range distortions we find (i.e. a slope of $\approx 200 \text{ m s}^{-1}$ per 1000 Å) could affect a $\Delta \alpha/\alpha$ measurement by up to $\approx 10$ ppm if, as an example, only the Mg II 2796 and Fe II 2382 transitions were considered. Comparing that estimate with our measured value of 2.1 ppm, it is clear that the constraints on $\Delta \alpha/\alpha$ in our absorption system are not solely dominated by the comparison of Mg and Fe II transitions redwards of (rest-frame) 2340 Å like, for example, many of the absorbers in the large samples of Murphy et al. (2004) and King et al. (2012), particularly those at redshifts $z_{\text{abs}} < 1.6$.

As we show below in Sections 3.1.3.1 and 3.1.3.2 the comparison between those red Fe II transitions and Fe II 1608 is more important in our absorber. A simple estimate of the expected effect on $\Delta \alpha/\alpha$ considering only the Fe II 1608 and 2382 transitions, similar to the previous one using Mg II 2796 and Fe II 2382, demonstrates that a
2 ppm systematic error is expected for our absorber. This estimate takes into account the fact that these transitions fall in the two different arms of UVES and assumes that the long-range distortions are separate in the two arms but approximately aligned (with zero velocity difference) near the centres of their respective wavelength ranges.

### 3.1.2.2 Intra-order wavelength distortions

Intra-order wavelength distortions are those on scales of, and which tend to be repeated across, individual echelle orders. They were identified for the first time in Griest et al. (2010), Whitmore & Murphy (2015), using many supercalibration spectra of asteroids and solar twins from UVES, found that the intra-order distortions were typically very similar across all echelle orders in a single exposure, with little change between exposures over several-day timescales. They found their typical amplitude to be $\Delta v \sim 100 \text{ m s}^{-1}$. Previous studies (Malec et al., 2010; Molaro et al., 2013b; Evans et al., 2014; Bagdonaite et al., 2014) have estimated the systematic error on varying-constant measurements by modelling the intra-order distortion as a simple “saw-tooth” function, with the velocity shift varying linearly from a peak, $\Delta v$, at the centre of each echelle order to $-\Delta v$ at the order edges. The value of $\Delta v$ was estimated from the intra-order distortions observed in supercalibrations observed as close as possible to the quasar exposures.

In this work, we follow the same modelling approach, but we are unable to estimate the intra-order distortion amplitude, $\Delta v$, because we do not have complementary supercalibration exposures. Therefore, we assume typical values for the distortion amplitude for UVES found in previous supercalibration studies (Whitmore & Murphy, 2015), $\Delta v = 100 \text{ m s}^{-1}$. To simplify the analysis we assume the same distortion in all of our exposures. We introduce this distortion for each echelle order, recombine the spectra in `UVES_POPLER` and use these adjusted spectra to measure $\Delta \alpha/\alpha$. The difference between the fiducial $\Delta \alpha/\alpha$ and the $\Delta \alpha/\alpha$ measured in this analysis provides the intra-order systematic error estimate: $\pm 0.12$, $\pm 0.37$ and $\pm 0.16$ ppm, for left, central and right regions, respectively.

One might at first expect this effect to be larger than we measure it to be because we study a single absorber and some transitions of interest should be at the edges of echelle orders and highly susceptible to this distortion. However, this is not the
Table 3.2: Contribution of individual systematic errors to the systematic error budget on $\Delta\alpha/\alpha$ in each region and the total systematic error estimate in each region, in units of ppm. The systematic error for the entire absorption system is also presented, together with the contributions from the individual effects, as described in Section 3.1.4. We provide additional significant figures here to allow reproducibility of our calculations only.

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Region</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Central</td>
<td>Right</td>
<td></td>
<td>Entire system</td>
<td></td>
</tr>
<tr>
<td>Long-range distortions</td>
<td>1.220</td>
<td>1.047</td>
<td>0.512</td>
<td></td>
<td>0.593</td>
<td></td>
</tr>
<tr>
<td>Intra-order distortions</td>
<td>0.119</td>
<td>0.372</td>
<td>0.159</td>
<td>0.185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redispersion</td>
<td>0.510</td>
<td>0.369</td>
<td>0.041</td>
<td>0.070</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity structure</td>
<td>0.393</td>
<td>1.108</td>
<td>0.131</td>
<td>0.160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convergence</td>
<td>1.518</td>
<td></td>
<td></td>
<td>0.069</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrature sum</td>
<td>2.055</td>
<td>1.612</td>
<td>0.554</td>
<td>0.645</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

case because, as we described in Section 2.2.1 we have rejected pixels at the edges of echelle orders if they overlapped with our transitions of interest. The effect is also reduced by using a large number of transitions, as we do here, with the main constraints on $\Delta\alpha/\alpha$ contributed by the 9 Mg i/ii and Fe ii transitions shown in Fig. 2.5. Furthermore, the intra-order distortions in the combined spectrum should average out in the real spectra to some extent if they vary to some degree over the many years of exposures. Therefore, our intra-order systematic error estimates may be even somewhat conservative.

3.1.2.3 Spectral redispersion effects

To construct our sub-spectra we used a dispersion of $1.3 \text{ km s}^{-1} \text{ pixel}^{-1}$ for $1 \times 1$-binned exposures and $2.5 \text{ km s}^{-1} \text{ pixel}^{-1}$ for $2 \times 1$-binned exposures. The dispersion defines the binning grid and, when each exposure is redispersed onto the common wavelength grid of the final spectrum, the “phasing” of the binning grid changes. This causes slight shifts in the fitted line centroid position. Furthermore, the rebinning of individual exposures onto the same wavelength grid introduces correlations between the fluxes and flux uncertainty estimates of neighboring pixels.

To estimate the systematic error caused by these two effects we re-combine the sub-spectra in UVES_POPLER with dispersions differing from the fiducial sub-spectra by $\pm 0.005$ and $+0.01 \text{ km s}^{-1}$ for $1 \times 1$-binned exposures and $\pm 0.01$ and $+0.02 \text{ km s}^{-1}$
3.1. Results

for 2×1-binned exposures. We then measure $\Delta \alpha/\alpha$ by rerunning VPFIT with these newly created sub-spectra and our fiducial models as starting points. We estimate the systematic errors caused by spectral redispersion effects as the mean of the difference between the fiducial value and these estimates of $\Delta \alpha/\alpha$. The results are $\pm 0.51$, $\pm 0.37$ and $\pm 0.04$ ppm, for the left, central and right regions, respectively.

3.1.2.4 Velocity structure modelling errors

Our fitted velocity structure in each region consists of a large number of velocity components. While we thoroughly explored many different possible velocity structures, and the normalized residuals in our fiducial fits, shown in Figs. 2.2–2.5, show no strong evidence of additional, unfitted structure, it remains likely that different velocity structures, with slightly more or fewer components, may provide equally satisfactory fits. It is also possible that some velocity components used in our fiducial models were required by the data artifacts that, at the very high S/N of our spectra, cause statistically significant structure in some transitions (albeit uncorrelated from transition to transition). That is, overall, we cannot be sure that our fitted velocity structure is unique or correct, even though it provides a statistically acceptable fit, so we explored many alternative velocity structures to estimate the systematic uncertainty related to these effects.

To measure possible uncertainties in the velocity structure we trialed several deviations from our fiducial model by adding/removing several velocity components one by one, while still trying to achieve reasonable residuals between the sub-spectra and the new model. We have two approaches to decide which components to add/remove: (1) if the component is very close to another component and/or (2) if it is missing from some of the weaker species. We measure $\Delta \alpha/\alpha$ by minimizing $\chi^2$ in VPFIT and calculate the velocity structure systematic error for each case as the difference between our fiducial $\Delta \alpha/\alpha$ value and the value after removal of the component. We obtain the systematic error by averaging these differences among different models.

We have excluded several cases from this analysis if they did not pass certain criteria. Firstly, we required a reasonably low $\chi^2$, i.e. similar to that associated with our fiducial fit. This was necessary to avoid accepting fits that would not have passed our original criteria for selecting our fiducial model. Secondly, we did not accept models which left substantial deviations from zero in the normalized
residual spectra, particularly when those were clearly (anti-)correlated across several transitions. Usually these cases also showed higher $\chi^2_\nu$. Finally, we did not accept models from which strong velocity components (i.e. those with high optical depths in Mg I/II and Fe II) were removed by $\text{vpfit}$ during the $\chi^2$ minimization process.

For each trial velocity structure, we detail the components that were removed and which models remained ‘viable’ (in terms of the criteria above) in subsequent paragraphs.

**Left region:** Firstly, we removed one of the two components in the strongest ‘feature’ (i.e. region of the spectrum between its local maxima) at $-535 \, \text{km s}^{-1}$. Removing either of the two components produces similar results. The only requirement is to remove the same component from different species. After its removal, the component in the wing of this feature, which is relatively strong in Mg II, drops from Fe II during the $\text{vpfit}$ $\chi^2$ minimization process. However, after the minimization was complete, we did not observe significant or correlated residuals and the $\chi^2_\nu$ was only larger than that of our fiducial model by 0.006. Therefore, we include this result for the systematic uncertainty estimate.

Secondly, if we remove the leftmost component in the feature at $-415 \, \text{km s}^{-1}$, the rightmost component in this feature drops from Fe II during the $\chi^2$ minimization process. In this case the $\chi^2_\nu$ increases by only 0.003 and we do not see any strong correlations between residuals. Therefore, we include this result for the estimate of the uncertainty.

Thirdly, we removed one of the components in the feature at $-400 \, \text{km s}^{-1}$. After $\chi^2$ minimization the component from Mg I in the feature at $-415 \, \text{km s}^{-1}$ dropped during the $\chi^2$ minimization process and the other component from this same feature shifted towards the initial velocity of the removed component. This indicates that the removed component is statistically important for the fit. Because of this drop and shift, this case is very similar to the previous case. On the other hand, the $\Delta\alpha/\alpha$ estimate is significantly different from the previous case, which appears to be due to the convergence difficulties described in Section 3.1.2.3. Furthermore, the residuals do not increase significantly and are not correlated between transitions, and $\chi^2_\nu$ increases by only 0.003. Therefore, we include this result for the estimate of the uncertainty.

Finally, we removed the middle component from the feature at $-495 \, \text{km s}^{-1}$,
which resulted in the same $\chi^2$ as for the fiducial fit, without any components dropped. This result is also included in the uncertainty estimate.

When we combine these four systematic error estimates by averaging them, we measure the velocity structure modelling error in the left region to be $\pm 0.39$ ppm.

**Central region:** Firstly, we removed one of the two components in the strongest feature at $-235$ km s$^{-1}$. During the $\chi^2$ minimization procedure several components dropped and $\chi^2$ increased by more than 1 from its fiducial value; this was also reflected in a large increase and strong correlation in the residuals. Therefore, we exclude the result of this trial from the estimate of the systematic uncertainty.

Secondly, we removed one of the components in the $-135$ km s$^{-1}$ feature. The $\chi^2$ minimization in this trial produced a $\chi^2$ which was 0.03 larger than the fiducial value. However, the residuals did not increase substantially and no strong correlations were apparent across many transitions, so we include this $\Delta \alpha/\alpha$ value in the uncertainty estimate.

Thirdly, we removed the middle component at $-185$ km s$^{-1}$ in the left wing of the feature at $-180$ km s$^{-1}$. In this case one unimportant component dropped from Al III. The $\chi^2$ even decreased in this case in comparison to our fiducial $\chi^2$ and the residuals did not increase noticeably or become more correlated between transitions. Therefore, we include this value in the uncertainty estimate.

Finally, we removed the left component in the weak feature at $-300$ km s$^{-1}$. The $\chi^2$ was the same in this case and there was no apparent change in the residuals, so we include this value in the uncertainty estimate.

We use the average of these measurements, $\pm 1.11$ ppm, as the velocity structure modelling error in the central region.

**Right region:** The right region has two features, at 0 and 25 km s$^{-1}$, where several components are fitted in the fiducial model. In both features, removing any of these components from the model produces much larger $\chi^2$ values than our fiducial model. This was expected because fitting these features required many different velocity structures to be trialed while establishing our fiducial model. Therefore, we do not include these trial fits with one or more of those components removed in our modelling uncertainty estimate for the right region.

We investigated the effect of removing other components located at $-18$, 12, 43 and 78 km s$^{-1}$. All of them produced $\chi^2$ values close enough to the fiducial fit.
However, for the 12 km s\(^{-1}\) case, several components in other parts of the region dropped from weak ionic species during the \(\chi^2\) minimization process, and for the 78 km s\(^{-1}\) case the component at 77 km s\(^{-1}\) was dropped from Mg II. Regardless, we decided to keep these results, mainly because we observed no substantial changes in the residuals.

After averaging the estimates of the deviations in \(\Delta \alpha/\alpha\) we find a systematic uncertainty associated with velocity structure modelling for the right region of \(\pm 0.13\) ppm.

### 3.1.2.5 Convergence error

Due to the very complex velocity structure in all regions, our models have a large number of velocity components and free parameters. VPFIT has been used previously to fit systems with far fewer components. However, to test whether VPFIT minimizes \(\chi^2\) correctly for our much more complex model, we tested whether the models converge towards the same \(\Delta \alpha/\alpha\) value when we start the fitting procedure from different values of \(\Delta \alpha/\alpha\) in Section 2.3.4. The relevant models converged in the central and right regions to within 0.2 and 0.08 ppm of our fiducial values, so we do not incorporate an additional term in the systematic error budget for these regions.

However, as described in Section 2.3.4, a convergence problem became evident in the left region, where the model that started from \(-5\) ppm converged towards \(-7.2\) ppm and all other models converged to within 0.4 ppm of \(-4.2\) ppm. This implies that variation in \(\chi^2\) with \(\Delta \alpha/\alpha\) in the vicinity of the best solution is almost entirely compensated by variations in other parameters, a degeneracy which seems to be caused, at least in part, by the 3 strongest components in the strongest feature in this region at \(-535\) km s\(^{-1}\). Indeed, when conducting other consistency checks and tests for other systematic errors, \(\Delta \alpha/\alpha\) often converged to values close to one of these two values, \(-7.2\) and \(-4.2\) ppm.

Our fiducial value in the left region is therefore the mid-point between these two extreme values, and we include an additional systematic error term – a convergence error – of \(\pm 1.52\) ppm for this region. When deriving the other terms in the systematic error budget for this region, we measured the deviation of \(\Delta \alpha/\alpha\) from the closest of these two extremes. It is therefore possible that the other elements of the systematic error budget for this region also include some degree of this convergence error and
3.1. Results

may therefore be somewhat overestimated.

This highlights a particular problem with fitting very high S/N spectra with multi-component Voigt profile models and may indicate that we are reaching a limitation of this approach.

3.1.3 Consistency checks and astrophysical systematic effects

Here we conduct several consistency checks and discuss the potential for astrophysical systematic effects in the absorption system. We find that we do not need to include the results of the former into the systematic error budget. However, the extent to which the latter have affected our results is unclear and difficult to incorporate into the formal systematic error budget.

3.1.3.1 Testing the possibility of different long-range wavelength distortions in the blue and red settings

When correcting for the long-range wavelength distortions in Section 2.3.3.3 we assumed that the long-range distortions in the red and blue settings were the same in each sub-spectrum. While Whitmore & Murphy (2015) found this to be a good approximation for most supercalibration exposures from UVES, it was not always true. Therefore, this assumption might not be true for some of the sub-spectra used in this study.

We test this by measuring $\Delta \alpha / \alpha$ using only transitions that fall in the wavelength range of the 580-nm setting. This includes all Mn II, Mg I/II and Fe II transitions, excluding Fe II 1608 and Mg I 2026. This ensures that we include only transitions for which we directly measured the long-range distortion from the DC method. The $\chi^2$ minimization procedure was started from our fiducial fit in the right region but with $\Delta \alpha / \alpha$ reset to 0 ppm. This region provides the most valuable test because it yields the tightest constraint on $\Delta \alpha / \alpha$. The resulting $\Delta \alpha / \alpha$ value was $-2.62 \pm 1.89_{\text{stat}}$ ppm for this fit that includes only transitions that fall in the red arm.

The statistical error bar for this measurement is $\sim 3$ times higher than our fiducial error bar (0.59 ppm). Such a large increase indicates that strong constraints on $\Delta \alpha / \alpha$ come from combining the transitions in the blue and red arms, not just from those in one arm alone. This is reasonable to expect because the Fe II 1608 transition
provides a strongly contrasting \( q \) coefficient to those of the Fe\( \text{II} \) transitions falling in the red arm. This test shows the importance of this specific transition for the \( \Delta \alpha / \alpha \) measurement. On the other hand, the difference between \( \Delta \alpha / \alpha \) from this test and our fiducial measurement (\(-0.92\) ppm) is only a factor of 1.3 larger than the difference between their error bars. Clearly, the measurements are correlated; but in simple terms this indicates that a deviation of this magnitude is expected. We therefore conclude that they are not significantly different. This indicates that there is no evidence that there are substantial differences in the long-range distortions for the blue and red arms.

### 3.1.3.2 Further, unmodelled velocity structure

Some previous studies have claimed that the Many Multiplet method is not appropriate because there is a possibility for different kinematics, and therefore velocity structure differences, between different species (e.g. [Levshakov et al., 2005]). However, this would imply that different ions are physically separated in the individual clouds and have their own distinct parameters (e.g. temperature and turbulent motion). We argue that this is unlikely and, rather, that it is important to distinguish such “kinematic” differences between species from another, much more likely possibility: significant differences in relative column densities in neighboring velocity components in different species. If, for example, there exists two closely-spaced velocity components which are mistakenly fitted as a single component, and the relative column densities in these two components vary substantially between different species, then a spurious velocity shift will be measured between the species. One can generalize that example to cases where the physical conditions vary somewhat across individual clouds. This is another important motivation for our approach to fitting the absorption system with as many velocity components as required to account for all statistically significant structure. Of course, it is possible that we are still under-fitting the absorber to some extent, as discussed in Section 2.3.4.

To check the potential effect this may have had on \( \Delta \alpha / \alpha \), we repeated the \( \chi^2 \) minimization process using only the Fe\( \text{II} \) transitions, excluding all other transitions in the right region. The \( \chi^2 \) minimization procedure was started from our fiducial fit in the right region but with \( \Delta \alpha / \alpha \) reset to 0 ppm. The resulting \( \Delta \alpha / \alpha \) value was \(-0.62 \pm 0.61_{\text{stat}} \) ppm for this Fe-only fit. This is only slightly larger than our
3.1. Results

fiducial value in the right region \((-0.92 \pm 0.59_{\text{stat}} \text{ ppm})\) and we conclude that this effect is not important. This comparison is also sensitive to any residual long-range distortions because the Fe\(\text{II} 1608\) transition’s \(q\) coefficient has an opposite sign to that of the redder Fe\(\text{II}\) transitions. Therefore, the result of this test provides additional confidence that the long-range distortions have been removed adequately and without significant residuals. It is also interesting to note that the Fe\(\text{II}\) velocity structure remains the same after removing the constraints on the velocity structure from other species. No components are excluded by \textsc{vpfit} from the fit during the \(\chi^2\) minimization process. This confirms that the large number of velocity components is necessary even to fit only Fe\(\text{II}\).

3.1.3.3 Measuring velocity shifts between strong transitions

Measuring \(\Delta \alpha/\alpha\) is, at the most basic level, the measurement of a pattern of velocity shifts between several transitions. However, if systematic effects introduce additional velocity shifts between the transitions, this can shift the measured \(\Delta \alpha/\alpha\) value. The intra-order distortions, for example, should typically introduce shifts of \(\sim 100 \text{ m s}^{-1}\) between transitions and, because they seem to follow the same pattern for all orders, the shifts will depend on the transitions’ relative positions along their respective echelle orders. A generic test for such systematic effects is to measure the velocity shifts between transitions using our fit while assuming \(\Delta \alpha/\alpha\) is zero.

We conducted this test in the right region using only the strongest transitions, those of Mg and Fe, because the weak transitions (e.g. of Mn, Ni etc.) provide velocity shift measurements that are not precise enough to be useful. A single velocity shift parameter was introduced for each transition in \textsc{vpfit} and assumed to be the same for all sub-spectra. The Mg\(\text{II} 2852\) transition is taken as the reference (its velocity shift is fixed at zero). The \(\chi^2\) minimization procedure was started from our fiducial fit in the right region.

Figure 3.1 shows the velocity shift measured for each transition versus its position along its echelle order. The typical uncertainties on the velocity shifts are \(\approx 60 \text{ m s}^{-1}\), below the expected level for intra-order distortions (in individual exposures). However, there is no evidence for additional scatter in the velocity shifts beyond that expected from the individual error bars. That is, we do not find evidence in Fig. 3.1 for intra-order distortions in the combined spectrum. Therefore, our estimate of the
systematic error from intra-order distortions in Section 3.1.2.2 \( \approx 0.19 \text{ ppm} \) (see Table 3.2), may well be conservative. Figure 3.1 also demonstrates that the cumulative effect of all systematic effects that may spuriously shift the transitions with respect to each other does not exceed \( \approx 60 \text{ m s}^{-1} \) and, therefore, will not have a significant impact on our measurement of \( \Delta \alpha / \alpha \) in this system.

### 3.1.3.4 Isotopic abundance variations

To measure the correct velocities of individual components we must model transitions using their known isotopic structures and correct relative isotopic abundances. However, the isotopic abundances in the absorbers are unknown and we assume the terrestrial abundance pattern for each species (Murphy & Berengut, 2014). If the relative isotopic abundances are substantially different in the absorbers, this will lead to small, spurious shifts measured between the transitions of interest and, therefore, systematic errors in \( \Delta \alpha / \alpha \) measurements. Some transitions, particularly of light species, and especially Mg II, have widely separated (\( \sim 1 \text{ km s}^{-1} \)) isotopic components, while most others, such as transitions of Fe II, have negligible separation between the isotopic components. Therefore, the possibility of differing Mg II isotopic abundances (compared to terrestrial) is potentially an important systematic effect for \( \Delta \alpha / \alpha \) measurements. This effect was explained and quantified in detail in Murphy et al. (2001a) and Fenner et al. (2005).

In a typical absorption system, in which the 3 strongest Mg I/II transitions and several of the 5 Fe II transitions at 2300–2600 Å are used to measure \( \Delta \alpha / \alpha \), Murphy et al. (2004) showed that if the heavy isotope fraction of Mg (\( ^{25+26}\text{Mg}/^{24}\text{Mg} \)) is zero, instead of 0.21 (the terrestrial value), we should measure \( \Delta \alpha / \alpha \) to be 4 ppm too low. If the heavy isotope fraction is 1, we should measure \( \Delta \alpha / \alpha \) to be too high by 17.5 ppm. Such variations in isotopic abundances are not implausible (Murphy et al., 2001a) so it is important to gauge their possible effect on our measured \( \Delta \alpha / \alpha \) value.

We checked this possibility by removing the influence the Mg transitions have on \( \Delta \alpha / \alpha \) in our analysis of the right region. The Mg transitions were kept in the fit so that they still helped to constrain the velocity structure. However, they were effectively decoupled from influencing the \( \Delta \alpha / \alpha \) parameter by introducing a freely-fit velocity shift between each Mg transition and all other transitions in the fit. The \( \chi^2 \)
Figure 3.1: Measured velocity shift as a function of relative position along the echelle order for the strongest transitions. The order edges correspond to relative displacements of $\pm 0.5$. Transitions are colour-coded depending on their wavelength. No correlation or significant structure is apparent, and uncertainties limit the possible amplitude of residual intra-order distortions in the combined sub-spectra to $\lesssim 50 \text{ m s}^{-1}$.
minimization procedure was started from our fiducial fit in the right region but with \( \Delta \alpha/\alpha \) reset to 0 ppm. The resulting best-fit \( \Delta \alpha/\alpha \) value was \(-0.68 \pm 0.60_{\text{stat}} \) ppm, which is very close to our fiducial value, \( \Delta \alpha/\alpha = -0.92 \pm 0.59_{\text{stat}} \) ppm. Indeed, this comparison demonstrates that the Mg transitions have very little weight in constraining \( \Delta \alpha/\alpha \) in the right region: the statistical uncertainty is almost unaffected when decoupling Mg from \( \Delta \alpha/\alpha \), primarily because the main spectral features are saturated in Mg \( \text{II} \). Therefore, we conclude that isotopic abundance variation, at least in Mg, does not influence our result significantly. This also indicates that fringing (see Section 2.3.4), which is most prominent for the Mg transitions, also has a negligible effect on our \( \Delta \alpha/\alpha \) measurement.

3.1.4 Final result for the entire absorption system

Here we combine the results and error budgets from the three regions to derive our final result for the entire absorption system. The effect of the long-range distortions on \( \Delta \alpha/\alpha \) is correlated across the 3 regions because it influences the wavelength scale similarly at the position of each transition regardless of which region we consider. Furthermore, the intra-order distortions have a correlated influence on \( \Delta \alpha/\alpha \) because the transitions are much narrower than echelle orders. We take these correlated systematic errors into account using a Monte Carlo simulation approach, similar to that in Evans et al. (2014), to calculate the distribution of final \( \Delta \alpha/\alpha \) values, the width of which reflects the full error budget, including the correlated systematic effects.

For each realization of the Monte Carlo simulation, we draw a random \( \Delta \alpha/\alpha \) value, \((\Delta \alpha/\alpha)^{\text{rand}}_i\), from a Gaussian distribution for each region \( i \). For a given region, the Gaussian is centered on its final \( \Delta \alpha/\alpha \) value (Table 3.1) and its 1\( \sigma \) width is the quadrature sum of the statistical (Table 3.1) and uncorrelated systematic error terms (Table 3.2; specifically, the redispersion, velocity structure and convergence uncertainties). To incorporate the correlated effects of uncertainties in our long-range distortion corrections, we draw a random value from a single Gaussian distribution, centered at zero and width \( \sigma = 1 \), and scale it by the long-range distortion uncertainty in each region (Table 3.2). This produces 3 correlated values of \((\Delta \alpha/\alpha)^{\text{long}}_i\), one for each region \( i \). Similarly, for the intra-order distortions, we derive a value of \((\Delta \alpha/\alpha)^{\text{intra}}_i\) for each region, \( i \), which is correlated with
that for the other regions. The simulated value of $\Delta \alpha / \alpha$ in each region is then $(\Delta \alpha / \alpha)^{\text{sim}}_i = (\Delta \alpha / \alpha)^{\text{rand}}_i + (\Delta \alpha / \alpha)^{\text{long}}_i + (\Delta \alpha / \alpha)^{\text{intra}}_i$. The simulated value for the entire absorption system is then the weighted sum of $(\Delta \alpha / \alpha)^{\text{sim}}$ across the 3 regions, with the weight in each region equal to the inverse sum of variances from all error sources in that region (Tables 3.1 & 3.2).

The procedure above is repeated for a large number of realizations to form a (symmetric), Gaussian-like distribution of weighted mean $\Delta \alpha / \alpha$ values. This distribution has a mean of $\Delta \alpha / \alpha = -1.42 \text{ ppm}$ and a width $\sigma_{\text{tot}} = 0.85 \text{ ppm}$ which represents the total uncertainty, including statistical and systematic error components. The statistical component of this is just the normal error in a weighted mean of the 3 regions considering only the statistical errors, i.e. $\sigma_{\text{stat}} = 1/\sqrt{\sum_i 1/(\sigma_{\text{stat}}^i)^2} = 0.55 \text{ ppm}$. The systematic error component is therefore the quadrature difference, $\sigma_{\text{sys}} = \sqrt{\sigma_{\text{tot}}^2 - \sigma_{\text{stat}}^2} = 0.65 \text{ ppm}$. This gives the final result for the entire absorption system (also provided in Table 3.1),

$$
\Delta \alpha / \alpha = -1.42 \pm 0.55_{\text{stat}} \pm 0.65_{\text{sys}}. 
$$

This final result shows no strong evidence for a deviation from the current, laboratory value of $\alpha$ in the absorption cloud. The result is consistent with zero, at the $1.7 \sigma$ level, with a total uncertainty of 0.85 ppm.

In Table 3.2 we also present the contribution that each type of systematic error makes to the $\sigma_{\text{sys}}$ for the whole absorption system. For each type of systematic error, $s$, the same Monte Carlo approach above is followed but with that type of error removed from the process. This provides a new, smaller value of the total error, $\sigma_{\text{tot}}^s$. The contribution for each type of systematic error is calculated as the quadrature difference $\sigma_{\text{sys}}^s = \sqrt{\sigma_{\text{tot}}^2 - (\sigma_{\text{tot}}^s)^2}$. For example, when removing the long-range distortions from the Monte Carlo simulation, we found the simulated $\Delta \alpha / \alpha$ distribution had a width of 0.61 ppm. The quadrature difference between the total error budget (0.85 ppm) and this reduced value is 0.59 ppm. This contribution from uncertainties in the long-range distortion corrections is the dominant systematic error term. The next largest contribution (0.19 ppm) is from intra-order distortions. This demonstrates the importance of removing these sources of systematic error for future, more precise measurements of $\Delta \alpha / \alpha$ using new spectrographs and telescopes.
(see Section 3.2.3 for discussion).

3.2 Discussion

3.2.1 Comparison with previous measurements of \( \Delta \alpha/\alpha \) in the same absorption system

Comparison of our result with previous measurements of \( \Delta \alpha/\alpha \) in the same absorption system, reported in Q04, L06, C06 and M08b, is presented in Table 3.3. All of these previous measurements are consistent with our new measurement and with zero variation. However, in Section 2.3.3.3 we used the HARPS spectrum to demonstrate that the spectra used in the previous studies were all affected by the long-range distortions of \( 110-220 \text{ m s}^{-1} \) per 1000 Å. These studies used the comparison of \( \text{Fe}^{\text{II}} \) 1608 with the redder \( \text{Fe}^{\text{II}} \) transitions to constrain \( \Delta \alpha/\alpha \) so the long-range distortions should have caused systematic shifts in \( \Delta \alpha/\alpha \) of order \( \approx 2 \text{ ppm} \), as we found for our constraint in Section 3.1.2.1. That is, if corrected, these previous measurements would likely be larger by \( \approx 2 \text{ ppm} \). This shift is generally similar to the uncertainties in the values of \( \Delta \alpha/\alpha \) derived from UVES spectra by Q04, L06, C06 and M08b. In this work we corrected the wavelength scales of the previous and new UVES spectra for these distortions, leaving a residual contribution to the systematic error budget of only 0.6 ppm (see Table 3.2).

Table 3.3 also shows how our new fit contains a much larger number of velocity components than previous fits. Our fit to the entire absorption system has 106 velocity components, but the only region common to all previous studies corresponds to our right region, in which Table 3.3 shows we fitted 49 components. This is more than 3 times larger than in any previous fit in that region. We demonstrated in Section 2.3.4 that our fitting approach was not able to strictly satisfy the normal information criterion of minimizing \( \chi^2 \). In this sense, our 106 fitted velocity components may represent a lower limit to the actual number in the absorption profile. Indeed, we stopped adding components to avoid compensating for data artifacts we identified (e.g. fringing). Our analysis of the higher-resolution HARPS and bHROS spectra in Section 2.3.3 also provides no evidence that the absorption profile contains fewer components than we fit. It therefore appears that previous analyses significantly
Table 3.3: Comparison of the constraints on $\Delta \alpha / \alpha$ from the $z_{\text{abs}} = 1.1508$ absorption system towards QSO HE 0515$-$4414 in the literature (Quast et al., 2004; Levshakov et al., 2006; Chand et al., 2006; Molaro et al., 2008b) with our measurements. The independence and overlap between different data sets used is defined in the column ‘Exposures used’. The S/N ratio reported corresponds to the continuum near the Fe $\text{II}$ $\lambda$2600 transition and is expressed on a per pixel basis. L06 and M08b report S/N ratio for the individual exposures that they use in their analysis. The value reported in this table is the quadrature sum of these individual values. Pixel sizes for the UVES and HARPS spectra used in this work are 1.3 km s$^{-1}$ and 0.85 km s$^{-1}$, respectively. The column labeled ‘Components’ represents the number of velocity components fitted in the right region; in our analysis we fitted 32 and 25 components to the left and central regions, respectively.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Instrument</th>
<th>Exposure time [s]</th>
<th>Exposures used$^a$</th>
<th>S/N</th>
<th>Resolving power</th>
<th>Components</th>
<th>$\Delta \alpha / \alpha$ [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q04</td>
<td>UVES</td>
<td>53100</td>
<td>1</td>
<td>$\sim$130</td>
<td>55000</td>
<td>12</td>
<td>$-0.40 \pm 1.90_{\text{stat}} \pm 2.70_{\text{sys}}$</td>
</tr>
<tr>
<td>L06</td>
<td>UVES</td>
<td>32400</td>
<td>2</td>
<td>$\sim$135</td>
<td>55000</td>
<td>13</td>
<td>$-0.07 \pm 0.84_{\text{stat}}$</td>
</tr>
<tr>
<td>M08b</td>
<td>UVES</td>
<td>32400</td>
<td>2</td>
<td>$\sim$135</td>
<td>55000</td>
<td>13</td>
<td>$-0.12 \pm 1.79_{\text{stat}}$</td>
</tr>
<tr>
<td>C06</td>
<td>HARPS</td>
<td>78600</td>
<td></td>
<td>$\sim$35</td>
<td>112000</td>
<td>15</td>
<td>$+0.50 \pm 2.40_{\text{stat}}$</td>
</tr>
<tr>
<td>C06</td>
<td>UVES</td>
<td>53100</td>
<td>1</td>
<td>$\sim$130</td>
<td>55000</td>
<td>9</td>
<td>$+1.00 \pm 2.20_{\text{stat}}$</td>
</tr>
<tr>
<td>This work</td>
<td>UVES</td>
<td>155800</td>
<td>3</td>
<td>$\sim$250</td>
<td>53500$-$93300</td>
<td>49</td>
<td>$-1.42 \pm 0.55_{\text{stat}} \pm 0.65_{\text{sys}}$</td>
</tr>
</tbody>
</table>

$^a$Sub-spectra:
1: All exposures from our 2000 sub-spectrum;
2: Three exposures from 1999 sub-spectrum, which we have not used in this work because they do not have attached ThAr exposures, and 4 out of 13 exposures from our 2000 sub-spectrum;
3: All five sub-spectra (see details in Section 2.2.1).
underestimated the number of components, even taking into account the lower S/N of the spectra used in those studies (see also discussion of Q04’s fit in Murphy et al. 2008b). Murphy et al. (2008b) and Wilczynska et al. (2015) have shown that underfitting in this way often leads to spurious shifts in varying-constant measurements from absorption profiles. On the other hand, Murphy et al. (2008b) showed that over-fitting, to the very small extent allowed by \( \chi^2 \) minimization codes like \textsc{vpfit}, yields accurate \( \Delta\alpha/\alpha \) values with slightly overestimated statistical errors.

The statistical errors reported by Q04 and C06 are significantly larger than ours, as expected considering that the total S/N of our spectra is \( \approx 2 \) times that in those studies. However, the statistical error quoted by L06 is similar to ours. Murphy et al. (2008b) demonstrated that the “limiting precision” on \( \Delta\alpha/\alpha \) available from the spectra used by L06 was worse than the statistical uncertainty quoted in that study. M08b revised the L06 measurement by taking into account the correlations between the series of pair-wise velocity measurements between transitions used to measure \( \Delta\alpha/\alpha \). They reported an increased statistical error of 1.79 ppm, which is in agreement with the limiting precision calculated by Murphy et al. (2008b). Following the formalism in Murphy et al. (2008b), the limiting precision on \( \Delta\alpha/\alpha \) available from the S/N of our UVES spectra in the right region is 0.34 ppm, which is significantly smaller than our measured statistical error, 0.59 ppm, as expected.

Finally, as detailed in Murphy et al. (2008b), the measurement of \( \Delta\alpha/\alpha \) from both the UVES and HARPS spectra studied in C06 was compromised by problems in the \( \chi^2 \) minimization process. On the other hand, the algorithm used in \textsc{vpfit} has been tested extensively with Monte Carlo Markov Chain analyses (King et al., 2009) and shown to return accurate (even slightly conservative) statistical errors on \( \Delta\alpha/\alpha \).

3.2.2 Comparison of our results with other previous \( \Delta\alpha/\alpha \) measurements

The only other \( \Delta\alpha/\alpha \) measurements from absorption lines that have been corrected for the long-range distortions are from a single quasar sight-line with 3 absorption systems, studied using the Keck, VLT and Subaru telescopes by Evans et al. (2014). Figure 3.2 compares our new measurement with the best estimate of \( \Delta\alpha/\alpha \) in each
of those 3 absorbers (averaged across the 3 independent spectra). Our new result is clearly consistent with all three previous measurements. Our combined result of $-1.42 \pm 0.55_{\text{stat}} \pm 0.65_{\text{sys}}$ differs by $1.1\sigma_{\text{comb}}$ from the combined [Evans et al. (2014)] result of $-5.40 \pm 3.25_{\text{stat}} \pm 1.53_{\text{sys}}$, where $\sigma_{\text{comb}}$ is the quadrature sum of the statistical and systematic errors in both studies. The statistical and systematic errors are 5.9 and 2.4 times smaller, respectively, in our new measurement compared with the combined measurement from [Evans et al. (2014)].

Comparison with other previous measurements of $\Delta \alpha/\alpha$ from quasar spectra is very difficult because they will all have been affected by long-range wavelength distortions; none of them is corrected for this important systematic error and, therefore, none can be considered reliable. This includes the large statistical samples from the VLT [King et al. (2012)] and Keck [Murphy et al. (2004)] which showed significant deviations in $\Delta \alpha/\alpha$ from zero. Indeed, [Whitmore & Murphy (2015)] used archival supercalibration exposures over two decades to demonstrate that a simple model of the long-range distortions can adequately explain the VLT results and partially explain those from Keck.

Nevertheless, disregarding those important concerns, the uncorrected VLT and Keck results together imply a dipole-like variation of $\alpha$ across the sky [King et al. (2012)] which can, in principle, be ruled out with new, distortion-corrected measurements like ours. The simplest model proposed by [King et al. (2012)] is a dipole (with no monopole term) in which $\Delta \alpha/\alpha = 10.2^{+2.2}_{-1.5} \cos(\Theta)$ ppm where $\Theta$ is the angle between the dipole direction (RA = 17.4 ± 0.9 h, Dec. = −58 ± 9°) and a selected position on the sky. For the direction towards HE 0515−4414, $\Theta = 77.8^\circ$ and the model implies $\Delta \alpha/\alpha$ should be $2.2 \pm 1.6$ ppm. Our measured value differs by $2.0\sigma_{\text{comb}}$ from this expectation. If a monopole term is allowed in the dipole model, [King et al. (2012)] find it to be $-1.8$ ppm – similar to our total uncertainty – and the expected value in the direction of HE 0515−4414 becomes $0.8 \pm 1.9$ ppm, differing by $1.1\sigma_{\text{comb}}$ from our measurement. That is, our new measurement cannot be used to confirm or rule out the dipole explanation for the non-zero Keck and VLT large-sample results, mainly because the direction to HE 0515−4414 is not well aligned with the dipole (or anti-pole) direction. However, a small number of very precise measurements like ours, towards quasars located $\Theta \approx 90^\circ$ away from that direction would certainly have that potential.
Figure 3.2: Comparison of our measurement with the combined measurements for each absorber from [Evans et al.] (2014). Thick error bars represent statistical errors and thin error bars represent systematic errors (that is, the error from quadrature combination of these error components is smaller than the total error bar represented on this figure).
3.2. Discussion

3.2.3 Next-generation spectrographs and telescopes: expected systematic effects

Our measurement of $\Delta \alpha/\alpha$ includes four different systematic uncertainty terms. We have also identified different data artifacts that can cause systematic shifts in $\Delta \alpha/\alpha$ measurements. To prepare for the high quality of spectra expected from the next generation of telescopes and spectrographs, it is important to assess all of these effects in that context. This will help us understand which of these effects will still be present in future measurements and what improvements can be made to the spectrographs, telescopes and data reduction pipelines, so that a better measurement of $\Delta \alpha/\alpha$ can be made.

One category of effects is associated with CCDs and data reduction techniques: fringing effects and artifacts from flux extraction, sky subtraction and flat-fielding. Avoiding or mitigating these effects would require using new types of detectors which are not prone to these problems and/or new approaches to reducing echelle spectra. These problems may be addressed on the longer timescales involved in preparing for and building G-Clef on the Giant Magellan Telescope (GMT) (Szentgyorgyi et al., 2014) and HIRES on the European Extremely Large Telescope (E-ELT) (Zerbi et al., 2014). These telescopes will have much higher light collecting area which will enable significant improvements in S/N ratio and, therefore, statistical uncertainties in $\Delta \alpha/\alpha$ measurements. Therefore, it is very important to reduce systematic effects and data artifacts commensurately.

In the short-term future, the next spectrograph that will improve $\Delta \alpha/\alpha$ measurements will be the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), to be mounted on the VLT (Pepe et al., 2010). ESPRESSO will be thermally and pressure stabilized and will use optical fibres instead of a slit, similar to the HARPS spectrograph. Therefore, spectra taken with ESPRESSO should be free from long-range wavelength distortions. Furthermore, it will be calibrated with laser frequency combs (Murphy et al., 2007b; Pepe et al., 2010). Laser frequency combs are expected to establish the wavelength calibration with relative precision better than $10^{-12}$ by using narrow modes which are evenly spaced. As such, we do not expect ESPRESSO spectra to be prone to intra-order distortions either (Wilken et al., 2010). In this work, the systematic error terms as-
associated with the uncertainties in the long-range wavelength distortion corrections and the intra-order wavelength distortions contribute the most to our systematic error budget. If we exclude these two terms, which we could do if we were using ESPRESSO spectra instead of UVES, our systematic error would be reduced by a factor of three to \( \sim 0.2 \) ppm.

Using ESPRESSO to reobserve quasar spectra that have already been observed with UVES to avoid long-range and intra-order distortions will require approximately the same observing time as already invested. For example, to achieve the same statistical precision from the \( z_{\text{abs}} = 1.1508 \) absorption system towards HE 0515–4414 as we achieve here would require approximately 4 nights of ESPRESSO observations. To be more specific, due to ESPRESSO’s wavelength coverage (3800–6860 Å), which does not cover Fe\textsc{ii} 1608, the statistical precision on \( \Delta \alpha / \alpha \) measurements will weaken to \( \approx 1.8 \) ppm so substantially more observing time would be needed to compensate for this. This means that quasars with appropriate absorption systems that fall between \( z_{\text{abs}} \sim 1.37 \) and \( \sim 1.85 \) should be chosen for observations with ESPRESSO. Similarly, the quasar providing the \( \Delta \alpha / \alpha \) measurement with the next smallest statistical error (2.4 ppm), HE 2217–2818 \cite{Molaro2013b}, would require 20 hours of new ESPRESSO observations. The absorption system in the sight-line towards this quasar falls into the aforementioned redshift range so the new observations do not need to be much longer than those of \cite{Molaro2013b}.

An alternative approach would be to recalibrate the existing UVES spectra with new ESPRESSO observations and the DC method comparison, just as we used the HARPS spectra to correct the long-range distortions in the UVES spectra of HE 0515–4414. In this approach, new ESPRESSO spectra would only require a relatively low S/N ratio, and consequently shorter total exposure times, because they would be used primarily to correct the long-range distortions in the UVES spectra. The key assumptions in this approach are that the long-range distortions of UVES spectra are approximately linear and with similar slopes in the blue and red arms, which was shown to be typical by \cite{Whitmore2015}, and that the intra-order distortions do not contribute a large systematic error (as demonstrated in this paper). Provided these assumptions, an ESPRESSO spectrum with a S/N of \( \sim 35 \) per km s\(^{-1} \), similar to the HARPS spectrum in this paper, would allow the long-range distortions in the UVES spectra to be corrected and contribute a residual
long-range distortion systematic error of only $\sim$0.6 ppm to $\Delta\alpha/\alpha$. This could be achieved with just 2–3 hours of ESPRESSO observations for bright objects like HE 0515–4414.

The main advantage of this approach is in cases where the existing UVES spectra provide a statistical uncertainty on $\Delta\alpha/\alpha$ of $\geq$1 ppm – in these cases, a residual calibration error in $\Delta\alpha/\alpha$ of $\sim$0.6 ppm would not be dominant (though the assumptions above must be carefully assessed). This includes all absorbers previously observed except for the one studied here towards HE 0515–4414. For example, by correcting the previously studied UVES spectra of HE 2217–2818 (Molaro et al., 2013b) with just $\sim$3 hours of ESPRESSO observations, a residual calibration error of 0.6 ppm would be very small compared to the statistical error of 2.4 ppm from the UVES spectra of the $z_{\text{abs}} = 1.6919$ absorber. The assumption that the blue and red arm long-range distortion slopes are the same is not required for that absorber because the Fe II 1608 transition falls in the red UVES arm.

Approximately 20 other quasars with S/N $> 100$ per pixel are available from the UVES data archive mainly from two previous Large Programs. If we adopt the method proposed in the previous paragraph, we could recalibrate the existing spectra of all 20 quasars by observing for only $\sim$40 h with ESPRESSO. For comparison, 40 hours of exposures would enable a S/N of $\sim$100 for just two quasars with entirely new ESPRESSO observations. That is, using the existing UVES spectra of these quasars, we could make the first sample of reliable measurements very efficiently, with this alternative approach. Most of the absorbers in these UVES spectra already have modelled velocity structures, which will make the analysis even simpler.

### 3.2.4 Improving S/N ratio or resolution?

From the perspective of designing future spectrographs for measuring $\Delta\alpha/\alpha$ it is crucial to understand whether it is more important to improve resolution or S/N per km s$^{-1}$. The key for obtaining a reliable $\Delta\alpha/\alpha$ measurement is the ability to decompose the metal absorption profiles accurately; once that is achieved, the statistical precision is determined by the S/N per km s$^{-1}$ of the spectrum. It is often implicitly assumed, and sometimes stated (e.g. C06), that absorption profiles are more easily decomposed into sub-components, and/or the precision on $\Delta\alpha/\alpha$ is improved, if the resolution is improved. However, as discussed below, the extent to which that is true
depends critically on the S/N ratio and to some extent on the nature of the velocity structure itself.

In Section 2.3.5 we addressed this issue by examining three different spectra with different resolutions and S/N per km s\(^{-1}\). We were not able to identify additional velocity structure in the higher-resolution spectra (from HARPS and bHROS), mainly because of their very low S/N per km s\(^{-1}\), particularly for bHROS. This effectively hid any information about additional velocity structure. The very firm conclusion from this comparison is that at least similar S/N per km s\(^{-1}\) is necessary in the higher-resolution spectra of this absorber to enable identification of any additional velocity structure. Furthermore, it is clear that obtaining, for example, a HARPS spectrum with the same S/N per km s\(^{-1}\) as our UVES spectrum of HE0515–4414 would not provide a substantially improved precision on \(\Delta \alpha/\alpha\).

The main reason for the conclusion above was that the velocity components are packed closely together, relative to their \(b\)-parameters, in the particular absorber studied here. This implies that increasing the resolving power does not assist in decomposing the absorption profile; any additional structure revealed will be subtle and, therefore, will not provide a substantially more precise \(\Delta \alpha/\alpha\) measurement. There are also possibly harmful effects of moving to higher resolution. For example, consider a spectrograph with adjustable resolving power, from \(R = 60000\) (typical of UVES) to \(R = 120000\) (like bHROS and the lower-resolution mode of ESPRESSO), or even to \(R = 240000\) (the high-resolution mode of ESPRESSO). For absorption systems like the one studied here, in which the velocity components are evidently closely packed, moving from \(R = 60000\) to 120000 would not provide much increase in precision on \(\Delta \alpha/\alpha\). However, if the spectrograph is fibre-fed then achieving the higher resolution mode may involve spreading the quasar light across a larger number of spatial pixels. This was the case in bHROS (see Section 2.2.3), where the spatial extent of the quasar signal was \(\approx 50\) pixels. This increases the read-noise per spectral pixel so that observing for the same time at \(R = 60000\) and \(R = 120000\) provides a lower S/N per km s\(^{-1}\) at \(R = 120000\). This ultimately decreases the precision on \(\Delta \alpha/\alpha\), a loss that may well outweigh the small gain from the increased resolving power. The loss may be even greater for the \(R = 240000\) mode. These conclusions will only apply to other absorption systems if their velocity components are distributed similarly to those of HE0515–4414, i.e. packed closely together relative to their \(b\)-
parameters. This can be tested by acquiring high resolution spectra of other quasars and comparing them to the spectra already observed with UVES.

### 3.2.5 Measuring $\Delta \alpha/\alpha$ from a single absorption system versus an ensemble of absorption systems

Our measurement of $\Delta \alpha/\alpha$ is currently the most precise from any absorption system towards any quasar, and is comparable to the ensemble precision from the large samples of Keck and VLT spectra from Murphy et al. (2004) and King et al. (2012) ($\sim 1.1$ ppm). However, the fact that this measurement is made in a single absorption system has a potentially important disadvantage: many systematic effects can be expected to be random in sign and magnitude from absorber to absorber, so analysing a single system requires careful treatment of the systematic errors presented here. For example, apart from the possibility of isotopic abundance variations, all of the systematic errors discussed here (see Table 3.2) would randomize in a large sample of absorbers. In principle, it is also possible that we have missed a potential source of systematic errors, even though we have empirically corrected the wavelength scale using the HARPS spectra, and the consistency checks in Section 3.1.3 did not reveal any significant, unknown effects. Therefore, a larger sample of measurements, with similar precision to that obtained here, would be desirable.

However, at present the UVES spectrum of HE 0515−4414 has much higher S/N than any other in the UVES archive. Very few ($\lesssim 10$) archival UVES spectra have $S/N > 120$ per pixel, but another $\sim 10$ have $S/N \sim 100$. Assuming that $\sim 20$ $\Delta \alpha/\alpha$ measurements can be made from UVES spectra with peak $S/N \sim 100$, a precision of $\sim 0.55 \text{ ppm} \times 250/100/\sqrt{20} = 0.3 \text{ ppm}$ would be available (taking our spectrum’s peak $S/N$ to be 250 per pixel). This is similar to our measurement’s statistical precision (0.55 ppm) but, if long-range distortions were corrected in each of these $\sim 20$ new measurements, the main advantage would be that the remaining systematic errors would randomize to a negligible residual value. Significantly reducing the statistical error budget would require a much larger number of $S/N \sim 100$ spectra, and obtaining a sample of $\sim 20$ much higher S/N spectra, like that of HE 0515−4414 used here, does not seem possible in the next decade.
3.3 Conclusions

In this work we have measured the relative variation in the fine-structure constant in the \( z_{\text{abs}} = 1.1508 \) absorber towards the quasar HE 0515–4414. Because of its brightness \( (V \approx 14.9 \text{ mag}) \) this quasar has been observed frequently with UVES, so a large number of archival spectra are available \((\approx 30 \text{ h})\). Here we add 13h of new UVES exposures to obtain a total \( \text{S/N} \approx 250 \text{ per } 1.3\text{-km} \text{s}^{-1} \text{ pixel (at its peak)} \), the highest for any echelle spectrum of a quasar at \( z_{\text{em}} > 1 \). This, and the large number of narrow features in the Mg I/II and Fe II absorption profiles, provide a very small statistical uncertainty on \( \Delta \alpha/\alpha \) of 0.55 parts per million (ppm).

Most importantly, we have corrected a large systematic error in the UVES spectra, from long-range distortions of the wavelength calibration, by using a HARPS spectrum of the same quasar. Left uncorrected, these would have caused a spurious shift in \( \Delta \alpha/\alpha \) of \( \approx 2.1 \text{ ppm} \). However, by directly comparing the UVES and HARPS spectra the correction leaves a residual systematic uncertainty of just 0.59 ppm. This assumes that the distortions are linear with wavelength and that they have the same slope in the red and blue arms of the UVES spectrograph. Previous studies of these distortions in UVES spectra generally support these assumptions (Whitmore & Murphy, 2015). Other systematic errors, mainly from short-range (i.e. intra-order) distortions and uncertainties in the absorber’s velocity structure, contribute a further 0.26 ppm uncertainty. A series of consistency checks suggest that our total systematic error budget of 0.65 ppm is reliable and that astrophysical systematic errors, such as isotopic abundance variations, are unimportant.

Our final result for this absorber is \( \Delta \alpha/\alpha = -1.42 \pm 0.55_{\text{stat}} \pm 0.65_{\text{sys}} \) ppm. This is consistent with no variation in the fine-structure constant and is the most precise measurement from a single absorption system to date. The precision is comparable to the ensemble precision from the large Keck and VLT samples of absorption systems studied by Murphy et al. (2004) and King et al. (2012). It is unlikely that measurements of \( \Delta \alpha/\alpha \) in other, individual absorption systems, will match the precision obtained here until new 25–40-m telescopes become available. Indeed, this work provides a preview of effects that must be addressed in the very high S/N spectra from those future telescopes. For example, accurate knowledge of the resolving power was required to model the absorption profile in this work, and CCD
and/or data-reduction artifacts were evident in our S/N $\sim$ 250 pix$^{-1}$ spectrum.

Finally, given that all previous $\Delta \alpha / \alpha$ measurements (except those of Evans et al. [2014]) will have been significantly affected by long-range distortions, it is crucial to obtain new measurements which are corrected for (or resistant to) this important systematic effect. In this context, the upcoming ESPRESSO spectrograph on the VLT is very important because it should provide spectra free of this effect (and the intra-order distortions). This work provides two insights for using ESPRESSO most efficiently for precise and reliable $\Delta \alpha / \alpha$ measurements. Firstly, the recalibration approach demonstrated in this work could be applied: existing, high-S/N UVES spectra could be recalibrated with relatively short ESPRESSO observations ($\sim$2–3 h) of the same quasars. This would produce a sample of $\sim$20 reliable, high-precision measurements in $\sim$20 per cent of the time required to build the same S/N with all new ESPRESSO spectra. Secondly, comparison of the UVES and higher-resolution HARPS and bHROS spectra of HE 0515–4414 implies that the absorber comprises many closely-packed, narrow velocity components; the increased resolution provides little additional information about the velocity structure or a significant increase in precision on $\Delta \alpha / \alpha$. Therefore, if the velocity structures of most other absorbers also comprise many closely-packed, narrow components, it is unlikely that a resolving power $R > 100000$ will benefit varying-$\alpha$ measurements, especially if S/N is compromised to obtain the higher resolution.
4

Two–telescope, supercalibrated sample of $\Delta \alpha/\alpha$ measurements - part I

4.1 Introduction

One of the main aims of this thesis (see Section 1.7) is to establish a larger set of reliable measurements of possible variation in the fine-structure constant. Our current understanding of reliability assumes correction of the initial ThAr calibration for the long-range wavelength distortions. Two recent studies, Evans et al. (2014) and Murphy et al. (2016), measured $\Delta \alpha/\alpha$ after correcting for the long-range distortions or were insensitive to them (due to the proximity of the transitions used). They established a first sample of 20 separate distortion-free measurements from 12 absorption systems. Unfortunately, only a small number of quasar spectra are available for which it is possible to correct for the long-range distortions with the established methods. In the following two chapters we will double this set by using “supercalibrated” spectra of two quasars, HE 1341–1020 (hereafter J1344–1035) and PG 0117+213 (hereafter J0120+2133). In addition to this we will acquire these results from spectra observed with two different telescopes, Keck and VLT. In such a way we will be able to compare two independent results for all absorption systems.

The UVES spectra used in this work were observed as part of the ESO Large Program (“The UVES Large Program for testing Fundamental Physics”, program ID 185.A–0745, PI Paolo Molaro). This program was particularly designed to obtain spectra of twelve quasars with $S/N \gtrsim 100$ per pixel. The aim was to measure $\Delta \alpha/\alpha$
with precision better than 10 ppm in at least 25 absorbers. In addition to this, each quasar was selected to have at least one absorber in which $\Delta \alpha / \alpha$ could be measured with precision close to 2 ppm. We also return to the first publication from the “Large Program” (Molaro et al., 2013b) and re-measure the possible variation of the fine structure constant in HE 2217–2818 (hereafter J2220–2803), after correction of the long-range distortions. An additional nine quasar spectra from the “Large Program” have been observed in the same night as asteroid supercalibration. However we have focused on these quasars because of their lowest angular separation from the King et al. (2012) dipole and antipole among “Large Program” quasars.

4.2 Observations

Sight-lines towards three quasars J0120+2133, J1344–1035 and J2220–2803 were used in this work. Table 4.1 shows information about these quasars and absorption systems in the sight-lines towards them. Not all of the absorption systems identified in the lines of sight were used to constrain $\Delta \alpha / \alpha$. Those that have been used are listed in the final column of the table.

4.2.1 UVES

All quasar exposures taken with UVES were part of the Large Program. The exposures were all taken without CCD binning and with a slit width of 0′′8, which corresponds to a resolving power of 60000. They were observed in a mixture of service and visitor mode. Service mode observation means that the quasar is observed by a support astronomer, usually without extra calibration exposures. On the other hand, visitor mode is when an observer from the Large Program team is present at the telescope, which usually means that additional calibration exposures were taken. The observation journal of UVES exposures is presented in Table 4.2.

Exposures of J0120+2133 were taken during 4 nights between 31/10/2010 and 3/11/2010 with the total exposure time of $\sim$36600s. Seeing was in the range 0′′68–1′′27 with an average seeing of 0′′93. Nine out of eleven exposures were taken in the 390+580 nm dichroic mode and two in the 346+564 nm dichroic mode. The combined spectrum covers a spectral range from 3100 to 6800 Å with a gap between 4520–4625 Å (due to a gap between 390 and 564 nm settings).
Table 4.1: Basic information about quasars used in this work. The column “magnitude” represents $V$ magnitude. The column “absorption redshifts” represents redshifts of all intervening systems, while “used absorbers” represent those that are suitable for measuring $\Delta \alpha/\alpha$. For these absorbers fairly strong absorption is detected in at least several transitions and they do not fall in the Lyman forest region of the spectrum.

<table>
<thead>
<tr>
<th>Quasar</th>
<th>Magnitude</th>
<th>Emission redshift</th>
<th>Absorption redshifts</th>
<th>Used absorbers</th>
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</thead>
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<td>J0120+2133</td>
<td>16.1</td>
<td>1.490</td>
<td>0.752, 0.786, 0.873, 1.277, 1.700,</td>
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<td>1.915, 2.042, 2.085, 2.116, 2.147</td>
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</tr>
<tr>
<td>J1344−1035</td>
<td>16.7</td>
<td>2.134</td>
<td>0.576, 0.729, 1.048, 1.325, 1.343</td>
<td>0.576, 0.729, 1.048, 1.325, 1.343</td>
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<tr>
<td>J2220−2803</td>
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<td>2.414</td>
<td>0.600, 0.787, 0.941, 0.942, 1.054,</td>
<td>0.787, 0.941, 0.942, 1.556, 1.628, 1.692, 2.181</td>
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<tr>
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<td>1.083, 1.200, 1.556, 1.628, 1.692, 2.181</td>
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</tbody>
</table>
Exposures of J1344–1035 were taken on eleven nights on seven runs in 2010, 2011 and 2012. The total exposure time is \( \sim 77500 \) s. Seeing was in the range 0\".56–1\".53 with an average seeing of 1\".02. Ten out of fourteen exposures were observed in the 390+564 nm dichroic mode and the rest were observed in the 437+860 nm dichroic mode. The combined spectrum covers the wavelength range from 3300 to 10250 Å with several small gaps of \( \sim 100 \) Å. These include 564 and 860 nm setting chip gaps between 5600–5670 Å and 8520–8660 Å and a gap between 6650–6710 Å.

For J2220–2803 we use the same reduced exposures that were used and described in [Molaro et al. (2013b)], but in Section 4.4.1 it is explained how we “supercalibrated” these with asteroid exposures.

Table 4.2: Journal of the UVES/VLT observations. Exact start of observing (UT) is given for the blue arm and is slightly (~5 s) different for the red arm. \( \lambda_c \) is the central wavelength of the blue and red settings. “Mode” explains if the exposure was taken in Visitor (V) mode, or Service (S) mode. “SW” and \( t_e \) represents slit width and exposure time, respectively. “Shift” represents the sum of the shift measured between individual exposures and combined exposures for a particular quasar and the shift between different settings for both arms of the spectrograph. This is explained in more detail in Section 4.4.3. “Slope” represents the supercalibration slope measured in Section 4.4.1. Entries marked with an asterisk are supercalibrations measured by the DC method.

<table>
<thead>
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<th>Mode</th>
<th>SW [\textquoteleft]</th>
<th>( t_e ) [s]</th>
<th>Shift [m/s]</th>
<th>Slope m s(^{-1}) per 1000 Å</th>
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<td>3600</td>
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<td>372 204 135</td>
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J1344–1035

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<td>435</td>
<td>195</td>
<td>-36* 79* 79*</td>
</tr>
<tr>
<td>2010-05-12 03:56:32</td>
<td>390 564</td>
<td>S</td>
<td>0.8</td>
<td>6250</td>
<td>122</td>
<td>-277</td>
<td>26* -92* -92*</td>
</tr>
</tbody>
</table>
### 4.2. Observations

#### Table 4.2: Journal of the UVES/VLT observations – continued

<table>
<thead>
<tr>
<th>Date UT</th>
<th>λc [nm]</th>
<th>Mode</th>
<th>SW [&quot;]</th>
<th>te [s]</th>
<th>Shift blue [m/s]</th>
<th>Slope ms⁻¹ per 1000 Å</th>
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<td>V</td>
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<td>5250</td>
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<td>860</td>
<td>V</td>
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<td>V</td>
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<td>860</td>
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<td>5250</td>
<td>263</td>
</tr>
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<td>564</td>
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<td>6250</td>
<td>688</td>
</tr>
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<td>564</td>
<td>S</td>
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<td>6250</td>
<td>148</td>
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<tr>
<td>2012-03-23 06:10:07</td>
<td>390</td>
<td>564</td>
<td>S</td>
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<td>6250</td>
<td>148</td>
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<td>2012-03-29 03:21:59</td>
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<td>564</td>
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</tr>
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</tr>
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<td>564</td>
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<td>419</td>
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<td>5000</td>
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<td>580</td>
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<td>45</td>
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<td>580</td>
<td>V</td>
<td>0.8</td>
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<td>-54</td>
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<td>580</td>
<td>V</td>
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<td>3767</td>
<td>50</td>
</tr>
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<td>2010-06-15 07:07:47</td>
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<td>580</td>
<td>V</td>
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<td>124</td>
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<td>2010-06-15 09:21:48</td>
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<td>4000</td>
<td>32</td>
</tr>
<tr>
<td>2010-06-16 07:49:49</td>
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<td>760</td>
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<td>-300</td>
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<td>760</td>
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<td>2010-06-17 06:35:29</td>
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<td>760</td>
<td>V</td>
<td>0.8</td>
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</tr>
<tr>
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<td>0.8</td>
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<td>151</td>
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<td>760</td>
<td>V</td>
<td>0.8</td>
<td>3767</td>
<td>155</td>
</tr>
</tbody>
</table>

### 4.2.2 HIRES

All HIRES exposures were taken by Tyler Evans and Michael Murphy in visitor mode. The observation journal is presented in Table 4.3.
Table 4.3: Journal of the HIRES/Keck observations. “Cross disperser angle” defines the wavelength coverage of the exposure, where -0.3605 and 0.1290 correspond to wavelength ranges from 3610 Å to 7640 Å and from 3740 Å to 8280 Å, respectively. The “slit width” was increased for the last three exposures of J1344—1035 because of poor seeing. “Shift” represents the shift measured between an individual exposure and the combined exposures for a particular quasar. A more detailed explanation is given in Section 4.4.3.

<table>
<thead>
<tr>
<th>Date UT</th>
<th>Cross disperser angle</th>
<th>Slit Width [&quot;]</th>
<th>Exposure time [s]</th>
<th>Shift [m/s]</th>
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<td></td>
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<tr>
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<td>3250</td>
<td>-32</td>
</tr>
<tr>
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<td>2011-10-21 09:57:18</td>
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<td>129</td>
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<td>2011-10-21 10:54:22</td>
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<td>-36</td>
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<tr>
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<td>0.861</td>
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<td>230</td>
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<tr>
<td>2011-10-21 12:47:42</td>
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<td>0.861</td>
<td>3250</td>
<td>261</td>
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<td>J1344—1035</td>
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<td></td>
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</tr>
<tr>
<td>2012-05-25 06:08:14</td>
<td>0.1290</td>
<td>0.861</td>
<td>3100</td>
<td>-639</td>
</tr>
<tr>
<td>2012-05-25 07:03:39</td>
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<td>1.148</td>
<td>3100</td>
<td>-70</td>
</tr>
<tr>
<td>2012-05-25 07:57:47</td>
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<td>1.148</td>
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<tr>
<td>2012-05-25 08:52:07</td>
<td>0.1290</td>
<td>1.148</td>
<td>3800</td>
<td>439</td>
</tr>
</tbody>
</table>
4.3 Data reduction and calibration

Eight exposures of J0120+2133 were observed on the night of 21/11/2011 in fairly uniform seeing of 0\'065. For these exposures the C1 decker provided a 0\'0861 slit width, producing a nominal resolving power $R \approx 50000$. When these eight exposures are combined the resulting spectrum has $S/N \approx 100$ per 1.3-kms$^{-1}$ pixel at 6000 Å. The combined spectrum covers a wavelength range from 3610 to 7640 Å with several small gaps of less than 100 Å. These include chip gaps between 4540–4580 Å and 6130–6200 Å and several gaps between echelle orders above 6300 Å.

Four exposures of J1344–1035 were observed on the night of 24/05/2012. The seeing varied throughout the night from 0\'09 to 1\'8. As such, the C1 decker was used for only one exposure with the smallest seeing and the C5 decker, which provides a slit width of 1\'0148 and $R \approx 37500$, was used for the other three exposures. Combining these exposures results in a spectrum with $S/N \approx 45$ per 1.3-kms$^{-1}$ pixel at 6000 Å. The combined spectrum covers the wavelength range from 3740 to 8280 Å with several small gaps of less than 100 Å. These include chip gaps between 5190–5220 Å and 6770–6880 Å and several gaps between echelle orders above 6300 Å. However, for the purposes of measuring $\Delta \alpha / \alpha$ in this work, two sub-spectra were produced (see Section 2.2.1) that correspond to the low resolution exposures and the high resolution exposure.

4.3 Data reduction and calibration

4.3.1 UVES/VLT

All three UVES spectra were reduced with the ESO UVES Common Pipeline Library (CPL 4.7.8), similar to the reduction in Section 2.2.1. After bias correcting and flat-fielding the quasar exposures the pipeline extracts the quasar flux using an optimal extraction method from the full seeing profile in the cross dispersion direction. Attached ThAr lamp exposures, observed just after the quasar exposures, are used for the wavelength calibration. The wavelength scale of each echelle order is then converted from air to vacuum using the (inverse) Edlen (1966) formula, so it can be converted to the heliocentric reference frame. This is done with a custom code, \texttt{UVES\_POPLER \cite{Murphy2016}} as in Section 2.2.1. \texttt{UVES\_POPLER} also redisperses the flux in individual exposures onto its common pixel grid, automatically fits the
continuum to the spectrum and automatically rejects cosmic rays. The continuum is then refined manually and spectra are visually inspected and corrected for artifacts in the vicinity of transitions which are to be used in the rest of this work.

4.3.2 HIRES/Keck

Both HIRES spectra were reduced in Evans (2015) using the HIRES _REdux_ reduction software following the procedure explained in Malec et al. (2010). It initially extracts the flux from the raw spectra and computes an appropriate statistical error spectrum. The process then involves careful identification of ThAr lines from a list particularly produced for HIRES spectra using procedures explained in Murphy et al. (2007a). In addition to this the default HIRES _REdux_ procedure was enhanced to reliably determine the ThAr centroids. This is an essential step due to the importance of wavelength calibration for the robustness of the final $\Delta \alpha/\alpha$ measurements. The later steps of dispersing spectra onto the common pixel grid, continuum refinements and artifact correction were my responsibility and I followed the same procedure as in Section 2.2.1.

4.4 Analysis

4.4.1 Supercalibration

4.4.1.1 UVES

Asteroid exposures (reflection of the solar spectrum) taken up to 48 h before or after the quasar exposures are used for measuring and correcting for the possible long-range distortions. Table 4.4 summarizes all asteroid exposures, which were taken during the same time periods as the quasars which are used for the $\Delta \alpha/\alpha$ measurements. All these exposures were reduced with the same pipeline as the quasar exposures. Note that these asteroid exposures were observed at the beginning and/or end of night instead of immediately before or after the quasar exposures. This is not optimal because of the unknown nature of the long-range distortions and the possibility that they vary on timescales of several hours (for example, if they depend

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1http://www.ucolick.org/~xavier/HIRedux
4.4. Analysis

strongly on the movements of the spectrograph and/or telescope). At the time of the Large Program observations it was not yet well established that the long-range distortions were ubiquitous and present in all exposures. As such, more frequent “supercalibration” exposures were not observed. However, Whitmore & Murphy (2015) observed changes in the long-range distortion slopes over ~ 10 h timescales. Indeed, this work also shows fluctuations of the long-range distortion slopes of between 70–200 m s\(^{-1}\) per 1000 Å during a night (see Fig. 4.3).

As introduced in Section 1.5.2 asteroid exposures are used to provide a “supercalibration” of the ThAr wavelength scale of the quasar exposure. This was done by comparison of the asteroid spectra with the laboratory solar spectrum observed with a Fourier Transform Spectrograph (FTS). The specific FTS spectrum used in this work was presented in Chance & Kurucz (2010) as KPNO2010.\(^2\) The code and technique of Whitmore & Murphy (2015) was used to calculate the velocity shift between the two as a function of wavelength. This produced a map of the long-range distortions as a function of wavelength for each chip in each asteroid exposure. The linear slope of this line was then measured by simple linear least square fitting to those data points. Parameters were kept the same as in Whitmore & Murphy (2015), measuring ≥10 separate velocity shifts for each echelle order. This includes manual discarding of the chunks affected by sky lines. The only difference to Whitmore & Murphy (2015) is that instead of fitting a single straight line to both red chips we fit a linear slope for each chip separately.

A simplification in this approach is the assumption of linear distortion in each individual chip. This significantly simplifies the correction but in some cases the distortion is evidently not linear. By visually inspecting the range of linear models, estimated deviations from the linear model in the worst cases are ~ 50 m s\(^{-1}\). On top of these long-range distortions there are also intra-order distortions on the scale of individual echelle orders with a repeated pattern from order to order. We estimate these to have an amplitude of \(\Delta v \sim 100\) m s\(^{-1}\) (i.e. peak to peak range of ~ 200 m s\(^{-1}\)). This is typical for most of the previous measurements (e.g. Whitmore & Murphy 2015) and we use it to estimate intra-order systematic uncertainties in Section 5.1.2.

Figs 4.1–4.4 show the values of the distortion slopes as a function of time for

\(^2\)http://kurucz.harvard.edu/sun/irradiance2005/irradthu.dat
Chapter 4. Two-telescope Δα/α measurements - part I

Table 4.4: Journal of the UVES/VLT asteroid observations. Exact start of observing (UT) is shown for the blue arm and is slightly (∼5 s) different for the red arm. \( \lambda_c \) is the central wavelength of the blue and red settings.

<table>
<thead>
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<th>UT</th>
<th>( \lambda_c ) [nm]</th>
<th>exposure time [s]</th>
</tr>
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<td>2010-06-16</td>
<td>22:47:55</td>
<td>437</td>
<td>760</td>
</tr>
<tr>
<td></td>
<td>2010-10-30</td>
<td>23:48:31</td>
<td>390</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>2010-10-31</td>
<td>23:36:18</td>
<td>437</td>
<td>760</td>
</tr>
<tr>
<td></td>
<td>2010-11-01</td>
<td>23:42:08</td>
<td>390</td>
<td>564</td>
</tr>
<tr>
<td></td>
<td>2010-11-03</td>
<td>23:46:36</td>
<td>390</td>
<td>580</td>
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<td>2012-04-01</td>
<td>09:39:49</td>
<td>390</td>
<td>564</td>
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</table>

each of the asteroid exposures (circles or diamonds) as well as adopted values for most of the quasar exposures (crosses). When the asteroid exposure was taken in the same night as its corresponding quasar exposure its distortion slope is adopted for the quasar correction. However, if there is no asteroid exposure in the same night as the quasar exposure we adopt the average slope of all asteroid exposures within the ±48 h period around the quasar exposure. On the other hand, if there are several asteroid exposures within the same night as the quasar exposure we adopt their averaged slopes for the correction of the quasar exposure.

In the cases when nearby asteroid exposures do not exist we have used the DC method to measure long-range distortion slopes between uncorrected spectra and spectra that had previously been corrected using slopes from nearby asteroid exposures. The final measured long-range distortion slopes for which we correct these spectra are marked with an asterisk in Table I.2. Although we make the long-range distortion corrections from asteroid supercalibration for each individual chip (blue, green or red), here we make the same long-range corrections for both chips in the red arm of the spectrograph. We use this approach because there is not enough information in individual chips to reliably measure them individually. Specifically, slopes have lower uncertainties if they are are measured over the whole red arm.
4.4. Analysis

Figure 4.1: Long-range distortion slope corrections for J0120+2133. Circles and diamonds represent distortions of the asteroid spectra with respect to the solar spectrum observed with FTS. Dashed lines represent relevant quasar exposures and crosses the distortions that have been adopted and corrected in these exposures. Red, green and blue marks correspond to specific CCDs of the UVES spectrograph.

Figure 4.2: Same as Fig. 4.1 but for J1344−1035 exposures taken in 2010.
Figure 4.3: Same as Fig. 4.1, but for J1344–1035 exposures taken in 2012.

Figure 4.4: Same as Fig. 4.1, but for J2220–2803 exposures. The first four quasar exposures do not have corresponding asteroid exposures, so we measure their distortions and correct them by comparing them with the DC method to the ones that have previously been corrected.
than two red arm chips independently. We estimate influence of uncertainties of these corrections on systematic error budget in Section 5.1.2.

A useful crosscheck on the above approach is to compare individual spectra of one quasar in order to determine how much the slope varies. Our approach is to compare two sub-spectra, one constructed from a single night of exposures and another which includes all exposures that have been corrected for the distortion slopes as explained in the paragraph above. The comparison of the two sub-spectra is made using the DC method (Evans & Murphy 2013) similarly to the comparison in Section 2.3.3. The DC method provides a series of residual velocity shifts as a function of wavelength between the two sub-spectra. If these shifts change with wavelength, we can measure the slope of this change. In most cases these slopes were consistent with zero. However, in several cases statistically significant residual slopes were found, which could lead to small errors in $\Delta\alpha/\alpha$. The largest of these errors was $-220 \pm 48$ m s$^{-1}$ per 1000 Å for an exposure of J1344–1035 in red setting observed on 23/03/2012. Such a large distortion could potentially cause an error in $\Delta\alpha/\alpha$ of $\sim10$ ppm, but we expect it to be significantly diluted when combined with other corrected exposures. This is further explored by correcting this exposure and measuring $\Delta\alpha/\alpha$ again in Section 5.1.3.

4.4.1.2 HIRES

We applied the same approach from the previous subsection to measure long-range distortions in the HIRES spectra using asteroids observed in the same night as quasars. On the night of 21/10/2011, when J0120+2133 was observed, 14 exposures of asteroids were taken (3 of Vesta, 5 of Ceres, 5 of Eunomia and 1 of Hebe) and on the night of 25/05/2012, when J1344–1035 was observed, asteroids were observed two times (one exposure of Isis and one of Melpomene). Very small long-range distortion slopes were identified with a mean value of $19 \pm 69$ m s$^{-1}$ per 1000 Å. Therefore, we decided not to correct HIRES exposures, but we estimate how the long-range distortion slope of $\pm70$ m s$^{-1}$ per 1000 Å would affect our $\Delta\alpha/\alpha$ measurement in Section 5.1.2.
4.4.2 Identification of absorption systems and transitions

To be able to make better constraints on $\Delta \alpha/\alpha$ it is essential to identify as many transitions as possible from Murphy & Berengut (2014) in absorption systems of interest. These transitions have both the high precision measurements of their rest wavelengths as well as calculated $q$ coefficients. It is also very important to identify if these transitions overlap with some of the transitions from other redshifts and discard affected transitions or their affected parts if necessary. For this purpose we used a custom-made code to search for the most common metal transitions between a redshift of zero and the quasar emission redshift. All identified absorption systems are listed in Table 4.1. We identified several transitions from non-modelled absorption systems that intervene with the absorption systems that we use for measuring $\Delta \alpha/\alpha$. They are explained in Section 4.4.4 where we discuss each fit to the particular absorption system affected by the blend.

4.4.3 Correcting velocity shifts between different exposures

Even though different exposures were previously corrected for long-range distortions it is still possible that the quasar was observed in multiple exposures at different spectral positions across the slit. Additionally, the process of long-range distortion correction can induce an artificial shift to individual spectra, because in the correction process spectra are rotated for the measured slope around different ‘pivot’ points. These shifts do not affect $\Delta \alpha/\alpha$ measurements from individual exposures, because they shift every transition in the same way leading to the change in modelled redshift. However, $\Delta \alpha/\alpha$ is measured from a combined spectrum of multiple exposures and shifts need to be corrected for several reasons. Firstly, if left uncorrected these shifts would induce broadening of the spectral features, which would then lead to higher uncertainties in $\Delta \alpha/\alpha$ measurements. However, this effect is very small. Secondly, relative S/N of multiple exposures is changing as a function of wavelength, leading to a difference in weight between these exposures at the wavelengths of different transitions. If at the same time there is a velocity shift between multiple exposures this would produce wavelength distortion, leading to a systematic error in $\Delta \alpha/\alpha$. Finally, it is possible that two arms of the UVES spectrograph are misaligned. In other terms, quasar is not observed at the same position across the
4.4. Analysis

slit, causing velocity shift between blue and red transitions. This would also cause
systematic error on $\Delta \alpha/\alpha$, especially if transitions with one type of $q$-coefficient fall
in blue and transitions with the other type of $q$-coefficient fall in red setting (see
Fig. 4.2).

We measure and correct for these shifts by using the DC method. The DC method
directly compares small portions (“chunks”) of two spectra and estimates velocity
shift between them from all reliable absorption features. The reliability of specific
velocity shifts depends on a feature being identified above a specified significance
threshold (in our case 7\(\sigma\) for features redwards of Lyman $\alpha$ emission and 8\(\sigma\) for
forest features). After acquiring velocity shift information for all reliable features
the weighted mean shift between different exposures is calculated.

In the first iteration we measured slit shifts between each individual UVES ex-
posure and the combined UVES spectrum in each setting, each individual HIRES
exposure and the whole combined HIRES spectrum. In the second iteration, we
measured the setting shifts between combined UVES spectra in different settings
which had enough features in their overlapping regions. For the J0120+2133 spec-
trum blue and red exposures did not overlap, so we estimated this setting shifts from
the supercalibration plots of asteroid associated with this quasar. We assign average
of the shifts in the 4 asteroid exposures between the central wavelength of blue and
the central wavelength of red settings as this velocity shift. HIRES exposures were
observed with a single cross disperser angle for each quasar, so this step was omitted
for HIRES. The final measured shifts that we correct spectra for are given in Table
4.2 and Table 4.3.

4.4.4 Fitting procedure

It is necessary to construct an appropriate fit to each absorption system in order
to measure $\Delta \alpha/\alpha$. For this we use VPFIT version 9.5 (Carswell & Webb, 2014), a
non-linear least-squares $\chi^2$ minimization algorithm. It minimizes $\chi^2$ by varying the
column density ($N$), Doppler $b$-parameter and redshift ($z$) of each velocity compo-
nent included in the fit. The fitting procedure is similar to the one explained in
Section 2.3.4.

Due to possible differences in the abundances of different ions for each velocity
component, variation of column densities for different species is allowed. However,
it is assumed that each velocity component originates from the same part of the absorption system for every species, and therefore redshifts and $b$-parameters of individual velocity components are tied together in different species. This was previously explained in multiple publications (e.g. Murphy et al. (2003a). In addition to this it was demonstrated in Murphy et al. (2003a) and King et al. (2012) that $\Delta \alpha/\alpha$ does not depend on the choice of the broadening mechanism used in the fitting procedure when all statistically significant structure is fitted. As such, and to be consistent with recent studies in the literature, we chose to fit all absorption systems with the turbulent $b$-parameter (i.e. the same for all species). The only exception to this is the case of the $z = 1.277$ system towards J1344–1035, where it was not possible to achieve a stable fit with turbulent tying of different species. In this case significantly better stability was achieved using thermal tying of $b$-parameters.

One important factor for the construction of fits is a correct estimate of the resolving power which defines the instrumental profile. The detailed study about resolving power estimates for UVES spectra in Section 2.3.2 showed that resolving power significantly varies as a function of the position along the echelle order, the seeing, and the slit width. The spectra analyzed in this and the following chapter have significantly lower S/N than the spectra from Chapter 2 and Chapter 3, so we accept a less stringent approach for the estimate of the resolving power. We acquired the nominal resolving power for UVES from the quality control statistics (which give information about the ThAr line widths) for the specific time periods when our quasars were observed and specific slit width. For the HIRES spectra the resolving power is initially set to the nominal resolving power which corresponds to the particular slit width during observation. Nominal resolving power is then divided by a factor of 0.9 if the average seeing-to-slit ratio is $\lesssim 1$. If on the other hand the average seeing is significantly higher than the slit width we keep the nominal resolving power. These adjustments of resolving power are necessary, because in good seeing the quasar only partially illuminates the slit, giving higher resolving power.

As previously explained, when constructing the fits it is important to model statistically significant structure completely. However, it is possible that some velocity components that are present in the strongest transitions drop out from the

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3https://www.eso.org/observing/dfo/quality/index_uves.html
weaker transitions (if they are statistically insignificant). When this happens we make sure that the fits are constructed in such a way that stronger components from the stronger transitions stay in the weaker species. To clarify, if the stronger of two components in a strong transition drops from a weaker species we replace it and remove the weaker component in the weaker species. If some inconsistencies with this rule are present we give comments in the subsections below when explaining individual fits.

Considering that we model the same velocity structure for HIRES and UVES spectra of J0120+2133 and J1344–1035 it is convenient to use the fits to UVES spectra as first guesses when fitting the HIRES spectra. If some transitions are not covered with HIRES spectra they are excluded. It is important to note here that we do not claim to model the real, underlying velocity structure, so both models are somewhat simplified in respect to the real velocity structure, where the degree of simplification depends on the S/N ratio and resolution of the spectrum. Due to the much wider coverage of UVES spectra no additional transitions which are covered by HIRES but not covered by UVES spectra were identified. The resolving power used in \texttt{vpfit} was also adjusted according to the discussion above. Due to the generally lower S/N, velocity structure appears less complex for the HIRES spectra and \texttt{vpfit} automatically rejected insignificant components. It is important to carefully follow initial \texttt{vpfit} iterations when transferring velocity structure from a UVES spectrum to a HIRES spectrum to avoid dropping of important components. However, if any of important components drops or significantly reduces its column density, we need to take a step back and adjust neighboring weak components or they might need to be removed completely from the model. After this adjustment is made we can restart the $\chi^2$ minimization process. In this way we make sure that the rule of keeping the stronger component is being followed.

In some of the fits below there is some uncertainty about the extent of blends in particular transitions or about specific velocity structure in some transitions, so we conduct tests later in Section 5.1.3 where we remove those transitions or use them as consistency checks. We note these in the subsections below.

While constructing the fit to a given absorber we keep $\Delta \alpha/\alpha$ fixed to zero, and only when a fiducial fit is acquired and the spectrum unblinded we let $\Delta \alpha/\alpha$ vary. Blinding of the spectra involves introduction of random small shifts between transi-
tions. The largest possible distortion allowed is small enough to allow construction of a consistent model, but large enough to significantly affect $\Delta \alpha/\alpha$. This is the same procedure as in Section 2.3.4 and previous publications (e.g. Evans et al., 2014).

We accept the final model and $\Delta \alpha/\alpha$ measurement if the following criteria are met:

1. $\chi^2 < 1.3$

2. Residuals between spectrum and the fit are not larger than $1\sigma$ in 5 or more neighboring pixels.

3. ‘Composite residual spectrum’ (CRS) shows no significant evidence for unmodelled velocity structure.

### 4.4.4.1 J0120+2133

We have constructed the fits to five absorption systems in the sight-line towards quasar J0120+2133. Before constructing these fits the resolving power to be used in the vpfit model was determined. Nominal resolving powers of 60000 and 50000 for UVES and HIRES correspond to slit widths of 0.08 and 0.0861, respectively. Even though the average seeing for the UVES spectra was 0.093 (slightly higher than the slit width) we correct the nominal full width half maximum (FWHM) with a factor of 0.9, resulting in FWHM of 4.496 km s$^{-1}$. The seeing for the HIRES exposures was significantly lower than the slit width, so we decreased FWHM to 5.395 km s$^{-1}$ for these fits by multiplying the nominal FWHM by 0.9. We present fits to these systems in Fig. 4.5–Fig. 4.14.

$z_{\text{abs}} = 0.576$ (Fig. 4.5 and Fig. 4.6) is fitted with 11 velocity components for both UVES and HIRES, in Mg I (the strongest transition that was fitted). Considering that both Mg II transitions and two strong Fe II transitions (2586 and 2600) are all completely saturated, they are excluded from the analysis of the system. This is similar to the analysis in Murphy & Cooksey (2017), where they analyze the same absorber from the High Dispersion Spectrograph (HDS) on the Subaru telescope. This leaves only 11 weaker transitions, in which the absorption profile is fairly smooth. As such, it is not expected to achieve small statistical error on $\Delta \alpha/\alpha$ from this absorption system. The Mn II 2594 transition is blended with an unidentified feature, and therefore we do not fit the complete absorption system for this
transition. Similarly, the Mg\text{\textsc{ii}} 2852 transition is possibly blended with Fe\text{\textsc{ii}} 2600 at $z_{\text{abs}} = 0.729$ below -12 km s$^{-1}$, so it is not fitted below that velocity.

$z_{\text{abs}} = 0.729$ (Fig. 4.7 and Fig. 4.8) is fitted with 10 velocity components for UVES and 9 components for HIRES, in the strongest Mg\text{\textsc{ii}} transitions. It is comprised of a few fairly narrow and strong features at -95, -75 and 0 km s$^{-1}$, so it is expected to place a tight constraint on $\Delta \alpha/\alpha$. This system is blended with Ti\text{\textsc{ii}} 3073 at $z_{\text{abs}} = 0.576$ in the region of the Mg\text{\textsc{ii}} transitions. Therefore, we included a fit to Ti\text{\textsc{ii}} and Mg\text{\textsc{i}} at $z_{\text{abs}} = 0.576$ (the strongest transition at this redshift) while fitting this absorption system.

$z_{\text{abs}} = 1.048$ (Fig. 4.9 and Fig. 4.10) is fitted with 17 velocity components for UVES and 16 components for HIRES, in the strongest Mg\text{\textsc{ii}} transitions. In this system all transitions have consistent velocity structure and there are no apparent blends with transitions at different redshifts. There are no particularly narrow features so we do not expect a high precision $\Delta \alpha/\alpha$ measurement.

$z_{\text{abs}} = 1.325$ (Fig. 4.11 and Fig. 4.12) is fitted with 16 velocity components for UVES and 15 components for HIRES, in the strongest Mg\text{\textsc{ii}} transitions. Similar to the system at $z = 0.729$, features in the system at $z = 1.325$ are strong and narrow, so we expect a relatively strong constraint on $\Delta \alpha/\alpha$. It is blended with sky lines in the region of the Mg\text{\textsc{ii}} 2796 and Mg\text{\textsc{ii}} 2803 transitions. Therefore, we excluded parts of the spectra in which the fit did not match between the two Mg\text{\textsc{ii}} transitions. In the feature at 50 km s$^{-1}$ one or two of the weakest velocity components drop from weak transitions and in the feature at 150 km s$^{-1}$ the weakest component drops from weak transitions.

$z_{\text{abs}} = 1.343$ (Fig. 4.13 and Fig. 4.14) is fitted with 17 velocity components for both UVES and HIRES, in the strongest Mg\text{\textsc{i}} transition. In weaker transitions we fit only the main feature at 0 km s$^{-1}$, due to very weak absorption in the rest of the system.

### 4.4.4.2 J1344–1035

We have constructed the fits to absorption systems at redshifts 0.873, 1.276, 1.277, 1.915 and 2.147 in the sight-line towards the quasar J1344–1035. The nominal resolving power which corresponds to the slit width of 0.8 is 60000 for UVES. Average seeing for these exposures was slightly higher than the slit width, so we estimate
Figure 4.5: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 0.576$ absorber towards J0120+2133. Lower panels show the spectrum (black) overlaid with the modelled fit (red). Tickmarks above show the centroids of separate velocity components in the model. Dark grey line shows the residuals between the spectrum and the fit with green lines showing the range between $-\sigma$ and $\sigma$. Upper panel shows the combined residuals for all transitions.
Figure 4.6: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 0.576$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
Figure 4.7: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 0.729$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
Figure 4.8: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 0.729$ absorber towards J0120+2133. Details are the same as in Fig. 4.5
Chapter 4. Two-telescope $\Delta\alpha/\alpha$ measurements - part I

Figure 4.9: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.048$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
4.4. Analysis

Figure 4.10: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 1.048$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
Figure 4.11: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.325$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
4.4. Analysis

Figure 4.12: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 1.325$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
Figure 4.13: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.343$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
4.4. Analysis

Figure 4.14: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 1.343$ absorber towards J0120+2133. Details are the same as in Fig. 4.5.
FWHM to be 4.496 km s\(^{-1}\) using a factor of 0.9. However, HIRES spectra were observed with two different slit widths of 0\(^{\prime}\)861 (one exposure) and 1\(^{\prime}\)148 (three exposures), because seeing was in the range 0\(^{\prime}\)9–1\(^{\prime}\)8 and it was necessary to increase the slit width when the seeing increased. These slit widths correspond to nominal resolving powers of 50000 and 37500, respectively. Therefore, we decided to use two subspectra, which correspond to all spectra combined for the same resolving powers and we use FWHMs of 5.397 km s\(^{-1}\) and 7.194 km s\(^{-1}\) after their reduction for the seeing-to-slit ratio effect of 0.9, respectively. Below we describe the fits (Fig. 4.15–Fig. 4.20) for each of the absorbers.

\(z_{\text{abs}} = 0.873\) (Fig. 4.15 and Fig. 4.16) is fitted with 16 velocity components for UVES and with 14 velocity components for HIRES, for the strongest Mg\(^ {\text{II}}\) transitions. Additionally, we fit the Fe\(^ {\text{II}}\) 2600, 2586, 2382, 2374 and 2344 and Mg\(^ {\text{I}}\) 2852 transitions. Fe\(^ {\text{II}}\) 2586 is possibly blended with the broad absorption from C\(^ {\text{IV}}\) 1550 which originates near the quasar. Fe\(^ {\text{II}}\) 2600 is possibly blended with C\(^ {\text{IV}}\) 1548 from \(z = 2.147\) and Al\(^ {\text{II}}\) 1670 from \(z = 1.916\). Therefore, we do not fit the complete absorption regions for these two transitions. We also do additional consistency checks by excluding these transitions in Section 5.1.3.

\(z_{\text{abs}} = 1.276\) and \(z_{\text{abs}} = 1.277\) together make one very wide absorption system. However, we fit these as separate systems due to a large gap between the two separate absorption features.

\(z_{\text{abs}} = 1.276\) (Fig. 4.17 and Fig. 4.18) has somewhat complex velocity structure, consisting of 24 velocity components for UVES and 22 components for HIRES in the strongest Mg\(^ {\text{II}}\) transitions. The Mg\(^ {\text{II}}\) transitions are partially saturated, so we had to fix the column density of several velocity components, at some arbitrary high values, so their influence on the nearby velocity components is not unduly high and causes their automatic exclusion from the fit. These are components at -51, -2, 0 and 5 km s\(^{-1}\) for both UVES and HIRES fits. In the HIRES fit we additionally had to fix the column density of the component at 23 km s\(^{-1}\). We also do additional consistency checks by excluding Mg\(^ {\text{II}}\) transitions in Section 5.1.3. Additional transitions that are fitted in this system are: Fe\(^ {\text{II}}\) 2600, 2586, 2382, 2374 and 2344, Mg\(^ {\text{I}}\) 2852, Al\(^ {\text{II}}\) 1862 and 1854, Mn\(^ {\text{II}}\) 2606 and 2576, Si\(^ {\text{II}}\) 1808 and Ni\(^ {\text{II}}\) 1751 and 1741.

\(z_{\text{abs}} = 1.277\) was initially fitted with five velocity components for UVES and four velocity components for HIRES, for the strongest Mg\(^ {\text{II}}\) transitions. Additionally, we
Figure 4.15: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 0.873$ absorber towards J1344−1035. Details are the same as in Fig. 4.5.
Figure 4.16: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 0.873$ absorber towards J1344–1035. Details are the same as in Fig. 4.5.
4.4. Analysis

Figure 4.17: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.276$ absorber towards J1344−1035. Details are the same as in Fig. 4.5
Figure 4.18: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 1.276$ absorber towards J1344–1035. Details are the same as in Fig. 4.5.
attempted to fit $\text{Fe}^{\text{II}}$ 2600, 2382, 2374 and 2344, $\text{Mg}^{\text{I}}$ 2852, $\text{Al}^{\text{III}}$ 1862 and 1854, $\text{Mn}^{\text{II}}$ 2576 and $\text{Si}^{\text{II}}$ 1808 transitions. Initially we tried to acquire turbulently tied velocity structure, but even when we introduced many velocity components we were unable to achieve such a low $\chi^2$ as in the thermally tied case. In thermally tied case $b$-parameter of light species ($\text{Mg}$, $\text{Al}$ and $\text{Si}$) was about 30 per cent lower than for heavier species ($\text{Fe}$, $\text{Mn}$), which was the same as for the turbulent fit. Further modelling of this system led us to an inconclusive measurement of $\Delta \alpha/\alpha$, which varied substantially and was highly dependent on the number of velocity components. This is unusual for $\Delta \alpha/\alpha$ measurements from quasar absorption systems. In particular, problems such as this occur when velocity structure includes a very narrow velocity component next to a wider component. This is the case in the system at $z_{\text{abs}} = 1.277$, with one component having a $b$-parameter of $\approx 1.2 \text{ km s}^{-1}$. Therefore, we exclude this system for both UVES and HIRES spectra from further analysis. As such, we do not show the fit to this absorption system.

$z_{\text{abs}} = 1.915$ (Fig. 4.19 and Fig. 4.20) is fitted with nine velocity components for UVES and seven components for HIRES in the $\text{Fe}^{\text{II}}$ 2600, 2586, 2382, 2374, 2344 and 1608 transitions. For the HIRES spectrum the $\text{Fe}^{\text{II}}$ 2374 transition falls in the gap between two orders, and is therefore excluded from the fit. Additionally, we fit the $\text{Si}^{\text{II}}$ 1526/1808, $\text{Al}^{\text{III}}$ 1862 and $\text{Mg}^{\text{I}}$ 2852 transitions for UVES spectrum. However, we do not fit the $\text{Mg}^{\text{II}}$ doublet, because it is highly affected by sky absorption features. The $\text{Mg}^{\text{I}}$ 2852 transition is excluded from the HIRES fit, because it falls beyond the range of the spectrum. We noticed sky absorption lines around $\text{Fe}^{\text{II}}$ 2600, 2586 and $\text{Mg}^{\text{I}}$ 2852 transitions, so we exclude these transitions as a consistency check in Section 5.1.3. We additionally exclude the $\text{Fe}^{\text{II}}$ 2600 and 2586 transitions from the UVES fit due to very high $\chi^2$ for these two transitions, which are possibly caused by sky lines. The $\chi^2$ for the fit for these two transitions is similar to the $\chi^2$ for the other transitions in HIRES spectra, so they are kept in the analysis of that spectrum.

In $z_{\text{abs}} = 2.147$ only the $\text{Mg}^{\text{II}}$ and $\text{Al}^{\text{III}}$ doublet and $\text{Al}^{\text{II}}$ transition were detected and fitted. All of these transitions have very small $q$ coefficients and therefore an estimate of $\Delta \alpha/\alpha$ from this system would have extremely low statistical precision. As such, we do not use this system for $\Delta \alpha/\alpha$ measurement. However, we provide our modelled velocity structure in the online repository$^4$.

$^4$https://github.com/kotushsrdjan/alpha_two_telescope_three_quasar
Figure 4.19: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.915$ absorber towards J1344−1035. Details are the same as in Fig. 4.5.
Figure 4.20: Fit to the Keck/HIRES spectrum of the $z_{\text{abs}} = 1.915$ absorber towards J1344–1035. Details are the same as in Fig. 4.5.
4.4.4.3 J2220–2803

Our approach to fitting absorption systems in the line of sight towards this quasar is different from fitting other absorption systems in this study. For these systems we use the previously published fits from Molaro et al. (2013b) as a first guess. The only difference between our first guesses and the fits published in Molaro et al. (2013b) is that we increase the minimal $b$-parameter from $0.5\,\text{km}\,\text{s}^{-1}$ to $1\,\text{km}\,\text{s}^{-1}$. This leads to an initial increase of $b$-parameters that are in the range $0.5 – 1\,\text{km}\,\text{s}^{-1}$ in our first guesses, which can significantly influence neighboring components in the first few iterations. Therefore, it is important to carefully monitor the fitting procedure. In these fits we first fix the $\Delta\alpha/\alpha$ parameter to zero and all redshifts to the values reported in Molaro et al. (2013b). We let $\Delta\alpha/\alpha$ vary only after running VPFIT for 10 iterations, freeing redshifts and running for 10 more iterations. Figs 4.21–4.26 represent fits to the absorption systems in this sight-line. The velocity structure in every absorption system is in very good agreement with the Molaro et al. (2013b) fits.
Figure 4.21: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 0.786$ absorber towards J2220−2803. Details are the same as in Fig. 4.5.
Figure 4.22: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 0.940$ absorber towards J2220–2803. Details are the same as in Fig. 4.5.
Figure 4.23: Fit to the VLT/UVES spectrum of the $z_{abs} = 0.942$ absorber towards J2220$-$2803. Details are the same as in Fig. 4.5.
Figure 4.24: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.556$ absorber towards J2220–2803. Details are the same as in Fig. 4.5.
Figure 4.25: Fit to the VLT/UVES spectrum of the $z_{\text{abs}} = 1.628$ absorber towards J2220–2803. Details are the same as in Fig. 4.5.
Figure 4.26: Fit to the VLT/UVES spectrum of the  $z_{\text{abs}} = 1.691$ absorber towards J2220–2803. Details are the same as in Fig. 4.5.
Two-telescope, supercalibrated sample of $\Delta \alpha/\alpha$ measurements - part II

5.1 Results

5.1.1 Results with statistical errors

Results of $\Delta \alpha/\alpha$ measurements, their 1σ statistical errors and $\chi^2_\nu$ for each spectrograph/absorption system in each line of sight are presented in Table 5.1 and Table 5.2. These results are derived from vpfit after $\chi^2_\nu$ minimization. These tables also include systematic error estimates calculated in Section 5.1.2. Final models are provided in electronic format in online repository.\(^\dagger\) As a starting fit for these measurements we use our fiducial models explained in Section 2.3.4 for J0120+2133 and J1344–1035 and the final model published in Molaro et al. (2013b) for J2220–2803, with $\Delta \alpha/\alpha$ initially set to zero and left free to vary in the $\chi^2_\nu$ minimization process. Similar to convergence testing in Section 2.3.4 we have tested convergence for all absorbers in this work by adding and subtracting 1σ from our measured $\Delta \alpha/\alpha$ values as the starting point for the $\chi^2$ minimization. As expected, considering less complex velocity structures of absorbers in this work, all $\Delta \alpha/\alpha$ values converged towards initial measured values. vpfit calculates statistical errors from the diagonal terms of the covariance matrix, which depend only on S/N for each particular model. The final $\chi^2_\nu$ values quoted in the tables are obtained from another version

\(^\dagger\)https://github.com/kotushsrđjan/alpha_two_telescope_three_quasar
of VPFIT, which incorporates corrections of errors in flux in the saturated regions of the spectra, as in Section 3.1.1, Section 5.1.2 and Section 5.1.4 explain systematic error analysis and combining results in the separate lines of sight, respectively.

The results presented in Table 5.1 and Table 5.2 are obtained using the laboratory wavelengths reviewed by Murphy & Berengut (2014). Similar to the most previous studies (e.g. Evans et al., 2014) we adopt terrestrial isotopic abundance ratios. Considering that we are unable to measure the real isotopic abundances in the absorption clouds this assumption could be wrong, causing significant systematic errors in our measurements. This problem was explored in various studies in the past (e.g. Fenner et al., 2005) and explained in more detail in Section 3.1.3.4. We further explore the impact of this on our most precise measurements in Section 5.1.3.

Measurements of $\Delta\alpha/\alpha$ from these 14 absorbers towards 3 quasars observed with 2 telescopes are in the range between -12.9 and 27.6 ppm. The statistical precision of presented results ranges between 2.4 and 35.9 ppm, where 12 measurements are better than 10 ppm. Interestingly, half of these 12 measurements are more than 1 $\sigma_{\text{stat}}$ away from zero, with the most precise constraint in the sample (in the $z_{\text{abs}}=1.691$ towards J2220–2803) being 2.6 $\sigma_{\text{stat}}$ away. All steps leading to this particular measurement were carefully examined and none was found that could cause a wrong result. In the following two paragraphs we explore whether the scatter among individual measurements is expected and how important this most precise measurement is in our sample.

The weighted mean calculated using only statistical errors is presented in Table 5.3 individually for every quasar and telescope. The combined statistical weighted mean shows no evidence for varying $\alpha$. On the other hand, two individual sightlines observed with UVES show indication of more than 2 $\sigma_{\text{stat}}$ variation in $\alpha$. Considering that the best individual constraint from this sample is also one of the largest deviations from zero, a combined weighted mean value is also calculated by excluding this measurement, leading to the weighted mean $(\Delta\alpha/\alpha)_w = -3.09 \pm 1.38$ ppm. This is a somewhat different result from the weighted mean result which includes the best measurement in the sample, but it still does not show statistically significant evidence for varying $\alpha$. Exclusion of this measurement from the absorber at $z_{\text{abs}}=1.691$ in the line of sight towards J2220–2803 illustrates the importance of
Table 5.1: Main results from each absorption system observed with VLT. First two columns represent quasar name and absorption system redshift. Third and fourth columns are the best-fit value of $\Delta \alpha/\alpha$ and its 1$\sigma$ statistical uncertainty. Next five columns show individual systematic uncertainties caused by: long-range distortion errors, intra-order distortion errors, redispersion errors, setting shift errors and model errors, respectively. Setting shift error is not reported for HIRES spectra where the lack of overlapping spectral coverage between settings precludes a measurement. Model errors are not measured for $\Delta \alpha/\alpha$ measurements with large statistical errors. Last two columns are the total systematic uncertainty (quadrature sum of individual systematic errors) and $\chi^2$ per degree of freedom for the final model. Final row for each line of sight (bold row in the table) is the weighted mean $\Delta \alpha/\alpha$ with associated uncertainties.

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<th>Quasar</th>
<th>$z_{\text{abs}}$</th>
<th>$\Delta \alpha/\alpha$ [ppm]</th>
<th>$\sigma_{\text{stat}}$ [ppm]</th>
<th>Systematic errors [ppm]</th>
<th>$\chi^2$</th>
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<tr>
<td>J2220-2803</td>
<td>0.942</td>
<td>9.95</td>
<td>12.66</td>
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<td>9.84</td>
</tr>
<tr>
<td>J2220-2803</td>
<td>1.556</td>
<td>-1.00</td>
<td>29.73</td>
<td>1.42</td>
<td>3.82</td>
</tr>
<tr>
<td>J2220-2803</td>
<td>1.628</td>
<td>27.60</td>
<td>19.72</td>
<td>-0.89</td>
<td>39.45</td>
</tr>
<tr>
<td>J2220-2803</td>
<td>1.691</td>
<td>6.31</td>
<td>2.40</td>
<td>-0.26</td>
<td>0.84</td>
</tr>
<tr>
<td>J2220-2803</td>
<td>Av</td>
<td>6.41</td>
<td>2.32</td>
<td>0.23</td>
<td>0.81</td>
</tr>
</tbody>
</table>
### Table 5.2: Same as Table 5.1 but for absorption systems observed with Keck.

<table>
<thead>
<tr>
<th>Quasar</th>
<th>$z_{abs}$</th>
<th>$\Delta\Omega$ (ppm)</th>
<th>$\Delta\Omega_d$ (ppm)</th>
<th>$\Omega_d$ (ppm)</th>
<th>$\delta\Omega$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
<th>$\delta\Omega_d$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0120+2133</td>
<td>0.92</td>
<td>2.32</td>
<td>0.44</td>
<td>0.00</td>
<td>0.04</td>
<td>2.20</td>
<td>—</td>
<td>1.48</td>
<td>1.78</td>
<td>—</td>
<td>2.45</td>
<td>1.29</td>
<td>—</td>
<td>1.23</td>
<td>1.08</td>
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<td>1.23</td>
</tr>
<tr>
<td>J1344+1033</td>
<td>1.49</td>
<td>1.33</td>
<td>1.30</td>
<td>0.95</td>
<td>0.10</td>
<td>1.13</td>
<td>0.04</td>
<td>1.48</td>
<td>1.78</td>
<td>—</td>
<td>1.23</td>
<td>1.08</td>
<td>—</td>
<td>1.23</td>
<td>1.08</td>
<td>—</td>
<td>1.23</td>
</tr>
<tr>
<td>J1344+1033</td>
<td>1.33</td>
<td>1.23</td>
<td>1.23</td>
<td>0.93</td>
<td>0.03</td>
<td>1.12</td>
<td>0.06</td>
<td>1.48</td>
<td>1.78</td>
<td>—</td>
<td>1.23</td>
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</tr>
<tr>
<td>J1344+1033</td>
<td>1.23</td>
<td>1.13</td>
<td>1.13</td>
<td>0.89</td>
<td>0.02</td>
<td>1.12</td>
<td>0.05</td>
<td>1.48</td>
<td>1.78</td>
<td>—</td>
<td>1.23</td>
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<td>1.23</td>
<td>1.08</td>
<td>—</td>
<td>1.23</td>
</tr>
<tr>
<td>J1344+1033</td>
<td>1.13</td>
<td>1.03</td>
<td>1.03</td>
<td>0.86</td>
<td>0.01</td>
<td>1.12</td>
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<td>—</td>
<td>1.23</td>
<td>1.08</td>
<td>—</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 5.2: Same as Table 5.1 but for absorption systems observed with Keck.
Table 5.3: Weighted mean $\Delta \alpha / \alpha$ with only statistical uncertainties for every quasar and/or telescope and for all absorbers combined.

<table>
<thead>
<tr>
<th>Telescope/spectrograph</th>
<th>quasar</th>
<th>$(\Delta \alpha / \alpha)_w$ [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLT/UVES</td>
<td>J0120+2133</td>
<td>$-6.5 \pm 2.1$</td>
</tr>
<tr>
<td>VLT/UVES</td>
<td>J1344−1035</td>
<td>$-1.8 \pm 3.4$</td>
</tr>
<tr>
<td>VLT/UVES</td>
<td>J2220−2803</td>
<td>$6.7 \pm 2.3$</td>
</tr>
<tr>
<td>Keck/HIRES</td>
<td>J0120+2133</td>
<td>$-0.5 \pm 2.3$</td>
</tr>
<tr>
<td>Keck/HIRES</td>
<td>J1344−1035</td>
<td>$-3.8 \pm 7.5$</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>$-0.74 \pm 1.20$</td>
</tr>
</tbody>
</table>

this single measurement to the entire sample.

To estimate consistency of these measurements, $\chi^2$ around the weighted mean has been calculated. Its value of 28.67 is approximately what is expected for 21 degrees of freedom. The probability of $\chi^2$ being larger than or equal to this value by chance alone is 12 per cent. This means that the scatter in the sample of $\Delta \alpha / \alpha$ measurements is consistent with that expected from their statistical uncertainties alone. Therefore, it is not expected to measure large systematic errors in the following section. If individual measurements were not in agreement with each other when using only statistical errors we would expect this probability to be low and additional systematic error terms would be required to account for these discrepancies.

As expected, due to an overall larger S/N, constraints from VLT/UVES are better (have lower statistical uncertainties) than the same absorber constraints from Keck/HIRES, except for the $z_{abs} = 1.048$ and $z_{abs} = 1.325$ absorbers towards J0120+2133. For $z_{abs} = 1.048$ this is probably caused by better S/N in Mg I and Fe II transitions. On the other hand, in the $z_{abs} = 1.325$ absorber statistical error for UVES measurement is increased due to discarding constraining pixels from Mg II transitions that were polluted by atmospheric absorption.

### 5.1.2 Systematic error estimates

One of the most important goals of the field is to understand systematic errors, so we can account for them if possible. In this work we estimate some of the most important systematic errors in the absorption systems we study: long-range wavelength distortions, intra-order distortions, redispersion of exposures onto a common wavelength scale, error caused by uncertainty in the estimated shift between dif-
ferent spectrograph settings (setting shift error), and inaccuracies in the modelled velocity structure. Individual systematic errors are explained in the following subsections and summarized with our main results in Table 5.1 and Table 5.2. It is only possible to measure setting shift error for the spectra which have overlapping settings and it is measured only in those cases. Considering that we expect modelled velocity structure errors to be smaller than 5 ppm we measure the model errors in absorption systems where statistical errors are < 5 ppm.

The specific approach for each type of systematic error is explained in the following subsections. The general approach is to modify the spectra or model and run the same $\chi^2$ minimization process, this time starting $\Delta \alpha/\alpha$ from the fiducial value. If the new model after this additional $\chi^2$ minimization is acceptable according to our fitting criteria (see Section 4.4.4), we calculate the systematic error as the absolute difference between the modified $\Delta \alpha/\alpha$ and our fiducial $\Delta \alpha/\alpha$ for the same absorption system. The final systematic error is then calculated as the mean systematic error for several modified models/spectra within the same error category for the same absorber.

Molaro et al. (2013b) have already estimated systematic uncertainties for J2220–2803 that correspond to intra-order distortions, spectral redispersion and uncertainty in the setting shifts. However, they did not publish the values of these systematic terms separately, so we add our terms due to long-range distortion uncertainties and velocity structure modelling errors to their combined systematic error and present them in Table 5.1.

5.1.2.1 Long-range wavelength distortions

As explained in Section 4.4.1 we used two methods of supercalibration to correct our spectra for long-range distortions: asteroid supercalibration and the DC method supercalibration. However, these corrections have uncertainties which need to be accounted for. For this purpose we modify our spectra, by adding or subtracting the uncertainty of the long-range distortion slopes estimated from supercalibration and divided by the square root of the number of contributing exposures.
5.1. Results

5.1.2.2 UVES

For asteroid supercalibration (Section 4.4.1) we estimate the uncertainties on the long-range distortion slopes from the short term (~1 day) variations in distortion slopes in Fig. 4.1–4.4. From these variations we estimate the long-range distortion uncertainties to be $\pm 60 \text{ m s}^{-1} \text{ per 1000Å}$. We divide this by the square root of the number of exposures (11, 9 and 12 for J0120+2133, J1344–1035 and J2220–2803, respectively), which yields $\pm 20 \text{ m s}^{-1} \text{ per 1000Å}$ uncertainty for all exposures corrected with the asteroid supercalibrations. On the other hand, a smaller number of exposures in J1344–1035 and J2220–2803 spectra (5 and 4, respectively) were corrected with the DC method supercalibration in Section 4.4.1. For these exposures we estimate uncertainty in the long-range distortion slope to be $\pm 100 \text{ m s}^{-1} \text{ per 1000Å}$ as the mean of the uncertainties estimated directly from the DC method itself. This provides $\pm 50 \text{ m s}^{-1} \text{ per 1000Å}$ uncertainty for exposures corrected with the DC method supercalibration after division by the square root of the number of exposures.

5.1.2.3 HIRES

We have previously explained in Section 4.4.1 that we do not correct the HIRES spectra for the long-range wavelength distortions because we found them to be consistent with zero. However, the mean error on the long-range wavelength distortions measured for the HIRES spectra is $\pm 70 \text{ m s}^{-1} \text{ per 1000Å}$. Therefore, we account for this systematic error term here by introducing long-range distortion of $\pm 25 \text{ m s}^{-1} \text{ per 1000Å}$ and $\pm 35 \text{ m s}^{-1} \text{ per 1000Å}$ for J0120+2133 and J1344–1035, respectively. This difference is due to division by the square root of the number of exposures 8 and 4, respectively.

After remeasuring $\Delta \alpha / \alpha$ for each quasar/spectrograph with positive and negative correction we subtract from these values the fiducial value of $\Delta \alpha / \alpha$ measured for each absorption system. The average of the absolute value of those two values is then our long-range distortion systematic error estimate. These measurements are presented in Table 5.1 and Table 5.2. The negative values of the long-range distortion systematic errors in these tables represent the cases when signs of the distortion and change in $\Delta \alpha / \alpha$ are opposite (e.g. positive distortion causes negative change in
\( \Delta \alpha / \alpha \). It is important to take this sign into account when we combine our individual results into a weighted mean \( \Delta \alpha / \alpha \) for a single quasar sight-line by averaging the results for the multiple absorbers along its line of sight (Section 5.1.4). This is because the long-range distortions cause the \( \Delta \alpha / \alpha \) values of different absorbers in a single spectrum to be strongly correlated or anti-correlated, depending on this sign.

5.1.2.4 Intra-order wavelength distortions

From the supercalibration graphs (Fig. 4.1–4.4) we estimated intra-order distortion amplitudes to be of the order of \( \Delta v = 100 \text{ m s}^{-1} \). We use the same approach as in Section 3.1.2.2 to estimate intra-order systematic uncertainties. Briefly, this involves modifying the spectra with a saw tooth pattern for each exposure and recalculating \( \Delta \alpha / \alpha \) in the same way as before. We use the absolute values of the difference between these and our fiducial values of \( \Delta \alpha / \alpha \) to estimate the systematic errors involved. Estimated values are presented in Table 5.1 and Table 5.2.

5.1.2.5 Spectral redispersion effects

We use a similar approach to the one explained in Section 3.1.2.3 to account for the systematic effects that originate from spectral redispersion effects. Briefly, we redispense the spectra with a slightly different dispersion and remeasure \( \Delta \alpha / \alpha \). This effectively changes the pixel phases for every exposure in respect to the dispersion grid, causing different correlations between adjacent pixels.

There are two differences between this and the previous analysis. The first difference is that we change the dispersion by \( \pm 0.01 \text{ and } \pm 0.02 \text{ km s}^{-1} \) (instead of \( \pm 0.005 \text{ and } \pm 0.01 \text{ km s}^{-1} \) as in Section 3.1.2.3) for all exposures in this work. Even though this change should not affect the measurements, we choose larger changes in dispersion because the quasar spectra in this work have significantly lower S/N than the spectra from Chapter 2 and Chapter 3.

We initially estimate our dispersion error as the RMS deviation from the mean of our fiducial result and the 4 \( \Delta \alpha / \alpha \) measurements from redispersed spectra. In addition to this we also examine the variation of this systematic error in relation to the statistical error because the size of the redispersion error relates to the S/N of the spectra and, therefore, should be proportional to the statistical error (Murphy et al., 2016). As such, we plot dispersion errors against the statistical errors for all
absorption systems for both Keck and VLT spectra of J0120+2133 and J1344−1035. We include this additional analysis here and not in Section 3.1.2.3 because it involves many more measurements. The similar regression line fitted to the measurements of systematic error associated with spectral redispersion effects in Section 3.1.2.3 would have had extremely large error because it would only include three measurements. Finally, we assign the larger of the value between the actual estimate and the regression line fit to be more conservative, because we used the RMS of only 5 different measurements and so the RMS could be significantly underestimated due to statistical fluctuations. Estimated values are presented in Table 5.1 and Table 5.2.

5.1.2.6 Error due to uncertainty in the setting shifts

Shifts corrected in Section 4.4.3 were measured using the DC method or estimated from the supercalibration plots. During this we also measure/estimate the error in the shift. Here we calculate the systematic error associated with these setting shift errors. For the line of sight towards J1344−1035 in UVES spectra the extracted spectrum of each exposure of the blue UVES arm was shifted by the uncertainty in the setting shift and all exposures were then combined in the usual way. For the line of sight towards J0120+2133 we estimate this error to be \( \pm 60\, \text{m} \, \text{s}^{-1} \) from a single supercalibration plot and when we combine 4 such estimates we estimate setting shift uncertainty to be \( \pm 30\, \text{m} \, \text{s}^{-1} \). Spectra is initially modified for the uncertainty in the setting shift. In such a way we produce two spectra – one from redshifting the blue-arm exposures, the other from blueshifting them — producing in such a way two values of \( \Delta \alpha / \alpha \). The average absolute difference between these values and our fiducial \( \Delta \alpha / \alpha \) for each absorber is taken as the setting shift error presented in Table 5.1.

5.1.2.7 Velocity structure modelling errors

For each absorption system we measure a single value of \( \Delta \alpha / \alpha \) by fitting it as an additional parameter for a particular fiducial velocity structure. However, as stated in Section 4.4.4 our modelled velocity structure is not the real velocity structure as in the absorption cloud. In addition to this velocity structure, it is possible to construct multiple, statistically justified velocity structures that correspond to every
absorption system used in this work. To assess errors in our fiducial velocity structure we constructed multiple velocity structures by adding/subtracting components with lower confidence. This includes components that are very close to another component and/or if component is missing from weaker species. For every alternate structure we measure $\Delta \alpha/\alpha$ and its difference from our fiducial $\Delta \alpha/\alpha$. The mean of the absolute values of all these differences for all alternate models is then taken as the velocity structure modelling error for a particular absorption system (column Systematic error/model in Table 5.1 and Table 5.2). In the following paragraphs we describe the differences between our fiducial and alternate models for those absorption systems.

For the $z_{\text{abs}} = 0.729$ system towards quasar J0120+2133 we constructed 6 alternate models for UVES and HIRES spectra. Comments about added or discarded components are given in respect to the velocity axis on Fig. 4.7 and Fig. 4.8. In the first alternate model we add a velocity component at -90 km s$^{-1}$, which results in absolute values of $\Delta \alpha/\alpha$ which differ from the fiducial values by 0.67 ppm and 2.31 ppm for UVES and HIRES, respectively. In the next model we discard the component at -85 km s$^{-1}$ with $\Delta \alpha/\alpha$ values differing by 2.20 ppm and 0.01 ppm for UVES and HIRES, respectively. In the third model an additional component was inserted at -75 km s$^{-1}$ resulting in $\Delta \alpha/\alpha$ differences of 3.20 ppm and 3.57 ppm. The next model, in which a component at -5 km s$^{-1}$ was discarded, unfortunately did not produce acceptable results, causing high values of $\chi^2$ and extreme shifts in $\Delta \alpha/\alpha$. Adding a component at 0 km s$^{-1}$ did not work for UVES the spectrum (it was rejected by vpfit), but resulted in a 1.63 ppm difference in $\Delta \alpha/\alpha$ for the HIRES spectrum. The final model without one of the components at 5 km s$^{-1}$ produced a model with 3.46 ppm difference in $\Delta \alpha/\alpha$ for UVES, but did not result in an acceptable fit according to criteria 2 from Section 4.4.4.

For the $z_{\text{abs}} = 1.325$ system towards quasar J0120+2133 we constructed 5 alternate models for UVES and HIRES spectra. Comments about added or discarded components are given in respect to the velocity axis on Fig. 4.11 and Fig. 4.12. In the first alternate model we discard the velocity component from the feature at -50 km s$^{-1}$, which results in alternate values of $\Delta \alpha/\alpha$ which differ from the fiducial values by 3.23 ppm and 3.46 ppm for UVES and HIRES, respectively. In the next model we discard the weakest component at 50 km s$^{-1}$ with $\Delta \alpha/\alpha$ values differing by 2.71 ppm and 3.88 ppm for UVES and HIRES, respectively. In the third model...
5.1. Results

the feature at 50 km s\(^{-1}\) was converted to thermal tying while we kept the original number of components. This resulted in \(\Delta \alpha/\alpha\) difference of 0.95 ppm and 2.47 ppm. Changing the number of components in this thermal feature to 2 resulted in 0.45 ppm and 3.54 ppm differences in \(\Delta \alpha/\alpha\) for UVES and HIRES spectra, respectively. In the final model we tried to add a component at 50 km s\(^{-1}\) to the turbulent fit. This produced a model with a 1.49 ppm difference in \(\Delta \alpha/\alpha\) for HIRES, but was rejected from the UVES fit.

For the \(z_{\text{abs}} = 1.276\) system towards quasar J1344–1035 we constructed 3 alternate models for the UVES spectrum. We do not estimate model error for the HIRES spectrum because the statistical error is larger than 5 ppm. Comments about added or discarded components are given in respect to the velocity axis on Fig. 4.17. In the first alternate model we discard the velocity component from the feature at -50 km s\(^{-1}\), which results in an alternate value of \(\Delta \alpha/\alpha\) which differs from the fiducial value by 2.65 ppm. In the next model we discard two components from this same feature, with the resulting \(\Delta \alpha/\alpha\) value differing by 1.87 ppm. In the final model we discard a component at 20 km s\(^{-1}\), producing a model with a 2.13 ppm difference in \(\Delta \alpha/\alpha\).

For the \(z_{\text{abs}} = 1.691\) system towards quasar J2220–2803 we constructed 6 alternate models for the UVES spectrum. Comments about added or discarded components are given in respect to the velocity axis on Fig. 4.26. In the first alternate model we discard the velocity component from the feature at -200 km s\(^{-1}\), which results in an alternate value of \(\Delta \alpha/\alpha\) which differs from the fiducial value by 2.51 ppm. In the next model we discard a component from the feature at -180 km s\(^{-1}\), with the resulting \(\Delta \alpha/\alpha\) value differing by 0.08 ppm. In the third model the component at -80 km s\(^{-1}\) was discarded resulting in a \(\Delta \alpha/\alpha\) difference of 0.94 ppm. The next model in which a component was inserted at 30 km s\(^{-1}\) produced a shift in \(\Delta \alpha/\alpha\) of 0.28 ppm. Adding a component at 0 km s\(^{-1}\) resulted in a 0.40 ppm difference in \(\Delta \alpha/\alpha\). The final model without one of the components at 0 km s\(^{-1}\) produced a model with 0.84 ppm difference in \(\Delta \alpha/\alpha\).

5.1.3 Results with full systematic error budget

Combined systematic errors are also presented in Table 5.1 and Table 5.2. They are calculated as a quadrature sum of the individual systematic error terms es-
timed in Section 5.1.2. As explained previously in Section 5.1.2, this generally includes terms associated with long-range wavelength distortions, intra-order wavelength distortions, spectral redispersion effects, setting shifts and velocity structure modelling for J0120+2133 and J1344–1035. However, for J2220–2803 we do not measure the terms associated with intra-order wavelength distortions, spectral re-dispersion effects and setting shifts, because they were already calculated in Molaro et al. (2013b). In this line of sight we add the long-range wavelength distortion and the velocity structure modelling terms to the total systematic error budget.

Total systematic uncertainties measured in this work are in the range between 1 and 5 ppm. They are generally smaller than the statistical uncertainties or, for cases with the smallest statistical uncertainties, similar in magnitude. As discussed in Section 5.1.1, this was expected because the Δα/α results were statistically consistent with each other based on their statistical errors alone. However, systematic uncertainties for the line of sight towards J2220–2803 are significantly larger than in the other absorbers, except for the z_{abs} = 1.691 absorber. Considering that Molaro et al. (2013b) did not present separate systematic error terms we cannot be sure about the reason behind these high values. Nevertheless, the statistical error term is above 10 ppm in all of these measurements, making them less significant for the further analysis in comparison to our most precise measurements with σ<5 ppm.

In Fig. 5.1 we present our results from every absorber as a function of redshift. It shows no evidence for α being different than zero or any evolution in redshift. This figure also shows the weighted mean value calculated from all measurements with the quadrature sum of statistical and systematic errors as weights. The weighted mean is \((Δα/α)_w = -0.05 ± 1.20_{stat} ± 0.78_{sys} ppm\) and its calculation takes into account the correlation in long-range distortion uncertainties (see Section 5.1.4). We can also do a similar \(χ^2\) analysis to the one from Section 5.1.1 now including statistical and systematic errors in quadrature. The \(χ^2\) value for 21 degrees of freedom is 19.13, which has an associated probability of being lower than or equal to this value of 42 per cent. Comparing this value to the one calculated in Section 5.1.1 shows that including systematic errors marginally improves the consistency of the Δα/α measurements with respect to each other. Only marginal improvement shows that we did not significantly overestimate our systematic error budget. In addition to this there is no evidence of individual results being inconsistent with this weighted
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5.1.3.1 Consistency checks

In order to be confident that these results are reliable it is necessary to further investigate inconsistencies found throughout analysis. As a first consistency check we further investigate the residual slope found in Section 4.4.1 of \(-220 \pm 48\) m s\(^{-1}\) per 1000 Å for an exposure of the J1344\(--1035\) quasar in the red setting observed on 23/03/2012. We do this by adding this slope to the corresponding exposure, recombining the spectra and remeasuring \(\Delta \alpha/\alpha\) from the absorber with the best constraint on \(\Delta \alpha/\alpha\) in the recombined spectrum. The result changed by only 0.35 ppm from our fiducial \(\Delta \alpha/\alpha\) measurement in this absorber at \(z_{\text{abs}}=1.276\). Considering that this change is much lower than the statistical error in this absorber (4.46 ppm) this anomalous slope could not have affected our measurement significantly.

The next check is related to the sky absorption lines which possibly affect several transitions of interest, which was a possible explanation for slight overfitting of several transitions in Section 4.4.4. The check is accomplished by excluding these transitions from the model and remeasuring \(\Delta \alpha/\alpha\). We explored this in absorbers at \(z_{\text{abs}}=0.873\) and \(z_{\text{abs}}=1.916\) in UVES and HIRES spectra of J1344\(--1035\). In the \(z_{\text{abs}}=1.916\) absorber in the UVES spectrum we excluded the Mg\(\text{I}\) 2852 transition and in other cases we excluded Fe\(\text{II}\) 2600 and Fe\(\text{II}\) 2586 transitions. The only substantial change in \(\Delta \alpha/\alpha\) was measured for \(z_{\text{abs}}=1.916\) in HIRES spectrum. After excluding Fe\(\text{II}\) transitions we measured \(\Delta \alpha/\alpha = 1.1 \pm 16.4\) ppm, which changed by \(\sim 14\) ppm from \(\Delta \alpha/\alpha = -12.9 \pm 17.1\) ppm. Further investigation showed that the problem might be due to a shift of the Fe\(\text{II}\) 2600 transition (compare transitions Fe\(\text{II}\) 2600 and Fe\(\text{II}\) 2382 in Fig. 4.20). This indicates that the fiducial model, which includes Fe\(\text{II}\) 2600, may have been affected by telluric absorption features, despite care taken to avoid this. Ultimately, this consistency check in this absorber illustrates that Fe\(\text{II}\) 2600 should have been excluded from the fiducial model. However, we have not modified the fiducial model as a result because the weight of this particular measurement is among the lowest in this study. As such, keeping the current fiducial model would not affect any of our conclusions.

As explained in Section 5.1.1 we measure \(\Delta \alpha/\alpha\) with the assumption of terrestrial isotopic abundances. We made this choice because we cannot be sure about
Figure 5.1: Measurements of $\Delta \alpha/\alpha$ from each absorption system as a function of redshift. Blue points represent measurements from VLT/UVES and orange from Keck/HIRES. Keck/HIRES measurements are shifted in redshift by 0.01 for the sake of clarity. The thicker error bars represent the statistical errors in each measurement while the narrower bars show combined statistical and systematic errors (added in quadrature). Below the measurements we also present our weighted mean $\langle \Delta \alpha/\alpha \rangle_w$ for the entire sample, which takes into account correlation in long-range distortion uncertainties.
particular isotopic abundances in the absorption systems we analyse. However, as summarized in Section 3.1.3.4 this choice could significantly affect our $\Delta \alpha/\alpha$ measurements if isotopic abundance ratios are different than terrestrial. This effect is the largest for Mg transitions, because they have widely separated isotopic components. This separation can be up to $\sim 0.8 \text{ km s}^{-1}$ depending on components, which is around 10 per cent of the FWHM of our spectra. As such, it is important to attempt to estimate how excluding the Mg transitions would influence our $\Delta \alpha/\alpha$ measurements. We do this for absorbers that provide the best constrained $\Delta \alpha/\alpha$ measurements, where statistical errors are below 5 ppm (see Table 5.1 and Table 5.2). Unfortunately, we cannot exclude Mg from analysis from all those absorbers. In some absorbers Mg transitions are the only transitions which have different types of $q$ coefficients (see Fig. 1.2) from other transitions used in the same absorber. If we remove Mg from such absorbers we are left only with one type of $q$ coefficient and we almost completely lose precision in the $\Delta \alpha/\alpha$ measurement. Therefore, we complete this consistency check on the highest precision measurements for which excluding Mg transitions does not affect precision significantly. In addition to this, we cannot do this test in our highest precision measurement in absorber at $z_{\text{abs}}=1.691$ towards J2220–2803, because Mg transitions are already not fitted in this absorber. However, this means that this particular measurement is less likely to be susceptible to isotopic abundance variations. For alternate models Mg transitions are not completely excluded from the fit, but they are disconnected from the $\Delta \alpha/\alpha$ parameter. This is done by fixing the $\Delta \alpha/\alpha$ parameter associated with Mg transitions to zero but keeping the $\Delta \alpha/\alpha$ parameter associated with other species unfixed.

The results from this analysis are presented in Table 5.4. Individual measurements before and after exclusion of Mg transitions are consistent with each other. We further examine how these results affect the weighted mean by comparing the weighted mean of these results and the weighted mean of our fiducial results which includes only these absorbers. They are also presented in Table 5.4. Considering that these values are highly consistent with each other we could conclude that the possible effect of different isotopic abundance ratios does not affect our measurements. Unfortunately, this is not so simple. Mg transitions are the most important to a particular model in cases where an increase in statistical error on $\Delta \alpha/\alpha$ is the largest when we exclude Mg transitions. However, this large increase in statistical
error means that our precision in measuring this effect diminishes. As such, we can only note that we are unable to assess the real size of this effect and we should always consider it when drawing any conclusions from this work.

5.1.4 Combining results for specific lines of sight

In this subsection we combine $\Delta \alpha/\alpha$ measurements in each line of sight for each spectrograph. We need these combined measurements to be able to compare them with combined lines of sight from other “reliable” measurements and be able to understand if there is any angular dependence of $\Delta \alpha/\alpha$. We assess this question in Section 5.2.

When combining results in particular line of sight we take into account possible correlation between errors (specifically long-range distortion errors). They are correlated within each line of sight because they influence the wavelength scale near the same transitions in different absorbers in a similar way. This does not depend on absorption redshift (to the first order), for absorbers with the same transitions. On the other hand, if completely different transitions are used in different absorbers the effect of the distortions on the absorbers’ $\Delta \alpha/\alpha$ values would not be correlated. In this work most of the constraints on $\Delta \alpha/\alpha$ are coming from Mg$\text{II}$ and Fe$\text{II}$ transitions, so we can say that correlation between long-range distortion errors in all

Table 5.4: Comparison of $\Delta \alpha/\alpha$ measurements from absorbers that provide the best constrained $\Delta \alpha/\alpha$ measurements which include or exclude Mg transitions. Weighted mean value is given in “combined” row. Measurements marked with an asterisk were excluded from the combined analysis because of the significant increase in statistical error due to loss of anchor transitions. They are listed to illustrate the importance of keeping at least two types of transitions (see Fig. 1.2) in the MM analysis.

<table>
<thead>
<tr>
<th>Quasar/ Redshift</th>
<th>Fiducial results</th>
<th>Excluding Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta \alpha/\alpha$ [ppm]</td>
<td>$\sigma_{\text{stat}}$</td>
</tr>
<tr>
<td><strong>UVES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0120+2133/0.729*</td>
<td>-8.67</td>
<td>3.03</td>
</tr>
<tr>
<td>J0120+2133/1.324</td>
<td>-5.06</td>
<td>3.39</td>
</tr>
<tr>
<td>J1344−1035/1.276</td>
<td>-3.12</td>
<td>4.46</td>
</tr>
<tr>
<td><strong>HIRES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0120+2133/0.729*</td>
<td>4.38</td>
<td>4.24</td>
</tr>
<tr>
<td>J0120+2133/1.324</td>
<td>-4.93</td>
<td>3.13</td>
</tr>
<tr>
<td>combined</td>
<td>-5.07</td>
<td>2.04</td>
</tr>
</tbody>
</table>
absorbers in the same line of sight is very high. As such, we use a Monte Carlo simulation approach similar to the one used in Section 3.1.4 to find the distribution of $\Delta \alpha/\alpha$ in each line of sight. The mean of this distribution represents the value of $\Delta \alpha/\alpha$ and its width represents the combined error.

For each redshift, we randomly select 1 million $(\Delta \alpha/\alpha)_\text{rand}^i$ values from a normal distribution centered on the final $\Delta \alpha/\alpha$ value with $\sigma$ set to the quadrature sum of statistical and systematic error terms, excluding long-range distortion errors. For the long-range distortion error term we randomly select 1 million numbers from a normal distribution with a mean of 0 and width of 1 and scale each selected number by the long-range distortion error for each absorber in each spectrum. In such a way we produce correlated values of $(\Delta \alpha/\alpha)_\text{long}^i$. We then add $(\Delta \alpha/\alpha)_\text{rand}^i + (\Delta \alpha/\alpha)_\text{long}^i$ to calculate a simulated value of $\Delta \alpha/\alpha$, the $(\Delta \alpha/\alpha)_\text{sim}^i$. The simulated value for the particular line of sight $(\Delta \alpha/\alpha)_\text{los}^i$ is the weighted mean of $(\Delta \alpha/\alpha)_\text{sim}^i$, where the weights are calculated as the inverse sum of variances of all error types. Finally, the combined value and uncertainty for every line of sight and spectrograph is calculated as the mean and standard deviation of the distribution of $(\Delta \alpha/\alpha)_\text{los}^i$. These values are presented in Table 5.1 and Table 5.2 for UVES and HIRES lines of sight, respectively.

Combined results in each line of sight from both telescopes are mainly consistent with each other. However, a minor concern arises when comparing J0120+2133 and J2220–2803 measurements from UVES spectra. The $\Delta \alpha/\alpha$ measurements from these two lines of sight are 3.3$\sigma$ away from each other. These are mainly caused by deviations seen in the measurements from our three best constraints. We are unable to identify any particular reason for these deviations.

These two tables also show how much each individual systematic error type contributes to the total error and the total systematic error term for each line of sight. Individual systematic error types are calculated as the quadrature difference of the total error estimated in the previous section and the error calculated with the above approach but excluding the specific error type under consideration. For example, if we are calculating the error term associated with intra-order distortions in a particular line of sight, we follow the above approach, excluding intra-order distortion errors for each absorber. The combined error from this calculation is then subtracted in quadrature from the total error which includes all systematics. This results in a systematic error term associated with intra-order distortions in
this particular line of sight. These individual error terms are important estimates because they show the size of particular systematics and the importance of resolving particular causes for future more precise measurements.

In addition to this, we also explore differences between constraints from each individual absorber from UVES and HIRES. Except the two differences in the absorbers at redshifts 0.729 and 1.343 towards J0120+2133 which are 2 and 1.7\(\sigma\) away from each other we are unable to identify any significant difference between individual measurements from two different telescopes/spectrographs. They are all less than 1\(\sigma\) away from each other. The combined result using both telescopes for the lines of sight towards J0120+2133 and J1344–1035 are \((\Delta \alpha/\alpha)_w = -2.87 \pm 1.57_{\text{stat}} \pm 1.18_{\text{sys}}\) ppm and \((\Delta \alpha/\alpha)_w = -2.07 \pm 3.12_{\text{stat}} \pm 1.25_{\text{sys}}\) ppm, respectively. Even though they are both slightly negative they are still consistent with zero variation. Considering that this comparison between two telescopes is important aspect of this project it is further examined in Section 5.2 by taking into account the measurements from the third telescope by Murphy & Cooksey (2017).

5.2 Discussion

In this work we almost double the sample of 27 previous “reliable” constraints on \(\Delta \alpha/\alpha\) by adding 22 new measurements. The reliability means that results either were not prone to long-range distortions due to the proximity of used transitions (Murphy et al., 2016), or were corrected as in Evans et al. (2014), Murphy & Cooksey (2017) and this work. A comparison of our mean result with these previous “reliable” results is given in Table 5.5. While previous measurements showed consistency with each other within 1.7\(\sigma\) our weighted mean measurement is consistent with any of those constraints within 1.3\(\sigma\). The combined result from Table 5.5 is clearly dominated by the extremely precise measurement from Chapter 2 and Chapter 3. If we exclude this measurement the weighted mean result becomes \(-0.3 \pm 0.8_{\text{stat}} \pm 0.5_{\text{sys}}\) ppm. This again illustrates the importance of this single measurement among other “reliable” measurements.

We also provide a comparison of our individual results with other “reliable” measurements in Fig. 5.2. Visual comparison from this plot can be extended to statistical comparison of our weighted mean measurements of \(\Delta \alpha/\alpha\) from two different tele-
Table 5.5: Comparison of our weighted mean measurements with other “reliable” measurements. In addition to this we present a separate measurement from the line of sight towards J0120+2133 from Murphy & Cooksey (2017), hereafter M&C17, for comparison purpose with our J0120+2133 measurement from Table 5.1 and Table 5.2. We also present the weighted mean result from all “reliable” measurements. The “telescopes” column shows which telescopes/spectrographs were used in particular study, where abbreviations K, V and S are Keck/HIRES, VLT/UVES and Subaru/HDS, respectively. Publication Kotuš et al. (2017) is that from Chapter 2 and Chapter 3.

<table>
<thead>
<tr>
<th>Publication/comment</th>
<th>number of quasars/absorbers/measurements</th>
<th>telescopes</th>
<th>$\Delta \alpha /\alpha$ [ppm]</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{sys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evans et al. (2014)</td>
<td>1/3/9 K, V, S</td>
<td>-5.4</td>
<td>3.3</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Murphy et al. (2016)</td>
<td>9/9/11 K, V</td>
<td>0.4</td>
<td>1.4</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Kotuš et al. (2017)</td>
<td>1/1/1 V</td>
<td>-1.4</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>M&amp;C17</td>
<td>2/6/6 S</td>
<td>3.0</td>
<td>2.8</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>M&amp;C17/J0120+2133</td>
<td>1/5/5 S</td>
<td>2.5</td>
<td>2.9</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>This work</td>
<td>3/14/22 K, V</td>
<td>-0.5</td>
<td>1.2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>15/28/49 K, V, S</td>
<td>-1.0</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.6: Comparison of \( \Delta \alpha/\alpha \) measurements from Molaro et al. (2013a) and this work, where long-range wavelength distortions have been corrected.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Molaro results ( \Delta \alpha/\alpha ) [ppm]</th>
<th>( \sigma_{\text{stat}} )</th>
<th>( \chi^2 )</th>
<th>This work ( \Delta \alpha/\alpha ) [ppm]</th>
<th>( \sigma_{\text{stat}} )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6912</td>
<td>1.29</td>
<td>2.35</td>
<td>1.19</td>
<td>6.313</td>
<td>2.404</td>
<td>1.03</td>
</tr>
<tr>
<td>1.6279</td>
<td>37.22</td>
<td>20.62</td>
<td>1.43</td>
<td>27.605</td>
<td>19.723</td>
<td>1.23</td>
</tr>
<tr>
<td>1.556</td>
<td>-0.15</td>
<td>24.9</td>
<td>1.21</td>
<td>-1.004</td>
<td>29.735</td>
<td>1.02</td>
</tr>
<tr>
<td>0.9424</td>
<td>9.32</td>
<td>12.68</td>
<td>1.3</td>
<td>9.947</td>
<td>12.664</td>
<td>1.16</td>
</tr>
<tr>
<td>0.9405</td>
<td>21.4</td>
<td>24.16</td>
<td>1.13</td>
<td>10.416</td>
<td>25.775</td>
<td>1.06</td>
</tr>
<tr>
<td>0.7866</td>
<td>7.32</td>
<td>35.89</td>
<td>1.29</td>
<td>-5.724</td>
<td>35.886</td>
<td>1.10</td>
</tr>
</tbody>
</table>

scopes for J1344−1035 and from three different telescopes for J0120+2133 (including Murphy & Cooksey (2017) measurement). Our measurements from J1344−1035 are consistent with each other within 0.25\( \sigma \). Combining these two measurements results in \( \Delta \alpha/\alpha = -2.1 \pm 3.1_{\text{stat}} \pm 1.2_{\text{sys}} \) ppm. On the other hand, there is an indication of small inconsistencies in \( \Delta \alpha/\alpha \) measurements from J0120+2133 between our UVES and HIRES measurements, as well as our UVES measurement and Murphy & Cooksey (2017) HDS measurement. They are consistent within 1.8 and 1.9\( \sigma \), respectively. Combining these three measurements results in \( \Delta \alpha/\alpha = -1.6 \pm 1.4_{\text{stat}} \pm 1.0_{\text{sys}} \) ppm.

Figure 5.2 also shows that there is no clear indication of evolution of \( \Delta \alpha/\alpha \) with redshift.

We also provide a comparison of our \( \Delta \alpha/\alpha \) measurements in absorbers in the line of sight towards J2220−2803 from this work and Molaro et al. (2013a) in Table 5.6. The best constraints from the absorption system at \( z_{\text{abs}} = 1.691 \) are 1.5\( \sigma \) away from each other, when we add statistical uncertainties in quadrature. This is simplified considering that statistical errors are not independent. In addition to this, we should account for the systematic errors, but Molaro et al. (2013a) has systematic error related to the long-range distortions missing from their analysis. Even though this single measurement does not show extremely significant difference it is at the level of 5 ppm which is similar to the statistical uncertainty in one third of our measurements. As such, this shows the importance of correcting for the long-range wavelength distortions. Measurements in other absorption systems towards J2220−2803 do not show significant difference between these two studies, but their statistical uncertainties are among the largest in this study.

Previous “reliable” studies of \( \Delta \alpha/\alpha \), especially the most recent one by Murphy...
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Figure 5.2: Measurements of $\Delta \alpha/\alpha$ from all “reliable” absorption systems as a function of redshift. The thicker error bar represents the statistical error in each measurement while the narrower bars show combined statistical and systematic error (added in quadrature). For the sake of clarity our VLT/UVES and Keck/HIRES measurements are shifted in redshift by 0.01 and 0.02 from Subaru/HDS measurements, respectively. For the same reason the three telescope measurement of Evans et al. (2014) are shown combined for each of the three different absorbers. Doing this is justified by high consistency of measurements from individual telescopes.
Figure 5.3: All “reliable” measurements of $\Delta \alpha/\alpha$ from Evans et al. (2014), Murphy et al. (2016), Murphy & Cooksey (2017) and this work as a function of angular separation ($\Theta$) from the pole (RA, Dec.)=($17.4 \pm 0.9$ h, $-58 \pm 9$ deg) proposed in the King et al. (2012) dipole model, $\Delta \alpha/\alpha = (10.2 \pm 2.1) \cos(\Theta)$ ppm. For the sake of clarity our VLT/UVES and Keck/HIRES measurements are shifted by 1 and 2 deg from Subaru/HDS measurement of J0120+2133, respectively. The thicker error bars represent the statistical errors in each line of sight while the narrower bars show combined statistical and systematic errors (added in quadrature). The black line with shading shows the dipole model and its $\pm \sigma$ uncertainty.
5.3. Conclusions

& Cooksey (2017), do not support the dipole variation in $\Delta \alpha/\alpha$ introduced in Webb et al. (2011) and King et al. (2012). Our sight-lines lie among the smallest angular separations from the pole and antipole in comparison to other “reliable” measurements (where we would expect the largest deviations from $\Delta \alpha/\alpha = 0$). As such, this work provides an opportunity for comparison with the dipole model. This comparison is illustrated in Fig. 5.3 together with other “reliable” measurements. Even though this figure illustrates previous measurements as the weighted mean of multiple telescopes/spectrographs, our results are separated by telescopes to point out the differences among them. It is interesting to note that our two most significant measurements from the lines of sight towards J2220−2803 and J0120+2133 from UVES spectra lie just 0.3 and 0.7σ away from the dipole model, respectively.

However, if we consider the complete set of 18 “reliable” measurements from Fig. 5.3 the $\chi^2$ around the dipole model is 53.3, with a probability of \(~0.002\) per cent to be exceeded by chance only. By taking this estimate into account we can rule out the King et al. (2012) dipole model with 4.2σ significance. This is just slightly above a similar estimate from Murphy & Cooksey (2017), which measured 4.1σ significance. Nevertheless, if we remove the dominant measurement (from Chapter 2 and Chapter 3) from the sample the $\chi^2$ becomes 35.3, decreasing the dipole rejection significance to 2.8σ. This illustrates how dependent the “rejection” of the dipole model is on this single measurement, and therefore we need to be extremely cautious if we want to reject the dipole model. It is important to note that even this is just an upper limit on rejection significance, because errors on the dipole model were not taken into account. As such, we would require more measurements to make a final conclusion in regards to the dipole. Although we cannot prove or disprove the dipole, we can explore how much current measurements prefer $\Delta \alpha/\alpha = 0$. For this purpose the $\chi^2$ around $\Delta \alpha/\alpha = 0$ has been calculated. For 18 degrees of freedom we calculated $\chi^2 = 23.0$, showing the preference of zero variation over the dipole model.

5.3 Conclusions

After we understood that the long-range wavelength distortions in quasar spectra were usually present in echelle spectra observed with large telescopes, the field had to restart growing the sample of “reliable” $\Delta \alpha/\alpha$ measurements – corrected for, or
insensitive to, long-range wavelength distortions. The main purpose of Chapter 4 and Chapter 5 was to significantly increase the size of this sample from 27 to 49 measurements. It also increased the overall precision of $\Delta \alpha / \alpha$ measurements from 0.71 to 0.62 ppm, by including 22 new measurements among which is the second-most precise measurement from a single absorption system. In this project we analyze five quasar spectra of three quasar sight-lines observed with two telecopes/spectrographs (VLT/UVES and Keck/HIRES), which were corrected for the long-range wavelength distortions using supercalibration asteroid observations. 16 new velocity structure models were constructed for the new absorption systems which were studied and 6 were acquired from previous Molaro et al. (2013a) analysis. Multiple additional models were explored for the purpose of creating the best-fitting velocity structure. The spectra and models are provided online repository.

The weighted mean result of these 22 measurements with absorption systems in the redshift range $z_{\text{abs}}=0.576–1.916$ is $\Delta \alpha / \alpha_{\text{w}} = -0.1 \pm 1.2_{\text{stat}} \pm 0.8_{\text{sys}}$ ppm. This result is clearly consistent with zero, while individual measurements are consistent with each other within 3.0$\sigma$. The total precision of the weighted mean, 1.43 ppm, is slightly larger than the most precise constraint from a single absorption system from Chapter 3 and between 2 and 3 times better than other “reliable” measurements of $\Delta \alpha / \alpha$ (Evans et al. 2014, Murphy et al. 2016, Murphy & Cooksey 2017).

The long-range distortion slopes measured in UVES supercalibrations were similar in size to the slopes previously measured for UVES spectra (e.g. Whitmore & Murphy 2015). On the other hand we identified very small long-range distortion slopes in HIRES spectra. After correcting the UVES spectra the long-range systematic uncertainty was reduced to between 0.02 and 1.4 ppm. It exceeds 1 ppm in only two measurements in the entire sample. The dominant uncertainty is statistical error, with up to several ppm contribution from redispersion and model error in some of the systems. Intra-order distortions were usually small $\lesssim 1$ ppm, with an exception of $\sim 3$ ppm error in one system.

As in most previous studies, we assume terrestrial isotopic abundances in the absorption clouds. Our consistency check which tests this assumption by removing Mg transitions which are the most sensitive to this effect showed no significant changes. However, this test is not sufficient to identify the real size of this effect. Therefore,
5.3. Conclusions

we must consider its possibility whenever we draw conclusions from this work. Other consistency checks in Section 5.1.3—the effect of possible residual slope in one absorber and the exclusion of transitions possibly affected by telluric absorption—do not show any problem that could significantly change our conclusions.

Our new measurements are consistent with previous “reliable” measurements (Evans et al., 2014; Murphy et al., 2016; Kotuš et al., 2017; Murphy & Cooksey, 2017). The combined weighted mean from these measurements and this work is $-1.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}} \text{ ppm}$. This provides evidence of $\Delta \alpha/\alpha$ being consistent with zero within 1.6$\sigma$. Further analysis of possible angular variation of $\alpha$ across the sky, in particular the correlation of “reliable” measurements with dipole variation suggested by Webb et al. (2011) and King et al. (2012), is highly unlikely at 4.2$\sigma$ level. This result is slightly exaggerated by the simplified analysis and more sophisticated calculation is necessary to show the correct discrepancy of this result from the dipole. It is important to mention that both of these analyses are highly dependent on the most precise constraint on $\Delta \alpha/\alpha$ from Section 3. However, even when this measurement is excluded there is evidence that current results do not match with the dipole. From these analyses we can say that zero variation in $\Delta \alpha/\alpha$ is preferable model to the dipole variation.
6.1 Summary

The overall aim of this thesis was to improve the current status of the field of measuring possible variation in fundamental constants, in particular the fine-structure constant $\alpha$, which utilize the Many Multiplet (MM) method. This method uses high resolution ($R > 35000$) quasar spectra and models metal absorption features in these spectra with the purpose to estimate extremely small pattern of shifts between these features which originate in $\alpha$ variations. Considering that propagation of light through absorption systems and telescopes/spectrographs involves many physical processes and that these shifts that we are trying to measure are very small ($<10$ ppm), $\Delta \alpha/\alpha$ measurements are prone to various systematic effects. Indeed, systematic error analysis has been a very important part of the field from its introduction in Dzuba et al. (1999) and Webb et al. (1999). Unfortunately, one of the important systematic effects, the long-range wavelength distortions (Whitmore & Murphy, 2015), appears likely to have affected the series of early works in the field. Considering that distortions of the spectra correlate with inaccuracies of the wavelength calibration, an additional source of calibration information is necessary to account for them. Moreover, they change over time (Whitmore & Murphy, 2015), making it impossible to repeatedly use the same calibrator. As such, it was not possible to correct for these in most of the previously observed spectra (e.g. Murphy et al. 2003a; King et al. 2012).

Considering all of above the overall aim of the thesis was translated into three
specific goals:

1. Substantially increasing the sample of reliable measurements, which have been
corrected for long-range wavelength distortions.

2. Formulation of a new method of measuring and correcting for the long-range
wavelength distortions in existing spectra, which do not have attached “supercalibrations”.

3. Further exploration of systematic effects, in particular those related to spectra
with high signal-to-noise ratio \( (S/N > 100) \).

For this purpose I have worked on two projects. The first project was measure-
ment of \( \Delta \alpha/\alpha \) in the \( z_{\text{abs}} = 1.1508 \) absorption system towards HE 0515–4414 using
the Ultraviolet and Visual Echelle Spectrograph (UVES) mounted on the Very Large
Telescope (VLT) (Chapter 2 and Chapter 3). Considering that HE 0515–4414 is the
brightest quasar at redshift above \( z_{\text{abs}} = 1 \) in the southern sky this analysis gave me
an opportunity to measure \( \Delta \alpha/\alpha \) with the smallest statistical uncertainty currently
achievable (Section 3.1.1). Moreover, such a low statistical error made it possible
to study systematic effects at the levels of concern in measurements from future
telescopes/spectrographs (Section 3.1.2).

Additionally, I used observations of the same quasar from the High Accuracy
Radial velocity Planet Searcher (HARPS) on the ESO 3.6 m telescope to supercali-
brate the UVES spectra. This novel recalibration method (see Section 2.3.3.3) makes
possible to correct for the long-range wavelength distortions even if solar twins or
asteroid exposures were not observed at the time of quasar observations. This makes
it effective in cases where it is impossible to use solar twins or asteroid supercalibrations,
but it requires a well-calibrated new spectrum of the same objects, even if it
has much lower \( S/N \). As such, this is the only method currently available that can be
utilized to make “reliable” measurements of \( \Delta \alpha/\alpha \) from most of the quasar spectra
available on UVES and the High Resolution Echelle Spectrometer (HIRES) archive.
Reliability in this context means that spectra have been corrected for long-range
wavelength distortions.

The measurement from this first project, \( \Delta \alpha/\alpha = -1.4 \pm 0.6_{\text{stat}} \pm 0.7_{\text{sys}} \) ppm,
is the most precise measurement achieved so far from a single absorption sys-
tem. It dominates the current sample of 49 “reliable” measurements of $\Delta \alpha/\alpha$ (including my new 22 measurements in Chapter 5), which have a weighted mean of $-1.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}}$ ppm. The only disadvantage of this project is that it is a measurement from a single absorption system. This is because most of the systematic effects affecting MM measurements randomize between different absorbers. Even though I have carefully explored and measured known systematic effects there is a possibility of additional, unknown, systematic effects that could have affected this measurement. Considering that there is a high chance that this effect is random from absorber to absorber it would be desirable to extend this measurement to a sample. To make a sample of such a high precision measurements, the high S/N $\gtrsim 200$ quasar spectra are required. Unfortunately, the spectrum used in this work is the only currently available spectrum with such a large S/N and making a sample of measurements is currently achievable only from much lower S/N spectra.

As such, making a sample of lower precision “reliable” measurements of $\Delta \alpha/\alpha$ was, indeed, the aim of my second project. For this purpose I measured $\Delta \alpha/\alpha$ in the lines of sight towards J0120+2133, J1344–1035 and J2220–2803 where I used spectra from UVES/VLT and HIRES/Keck for the first two and UVES/VLT for the last quasar. The measurements were made in 5, 3 and 6 absorption systems between redshifts of 0.576 and 1.916 in the lines of sight towards these quasars, respectively. This increased the sample of “reliable” measurements of $\Delta \alpha/\alpha$ from 27 to 49. In this work I measured the long-range wavelength distortions by comparing the complementary asteroid exposures (reflected solar spectrum) to the laboratory solar spectrum observed with a Fourier Transform Spectrograph. The quasar spectra were then corrected for these distortions, which is illustrated in Fig. 4.1–Fig. 4.4. As explained in Section 4.4.1 this “supercalibration” step is essential for making MM method $\Delta \alpha/\alpha$ measurements “reliable”. Long-range distortion slopes found were in the range between -100 and 600 m s$^{-1}$ per 1000 Å for UVES, but we found very small slopes for HIRES. Slopes found for UVES are typical among previous measurements (Whitmore & Murphy 2015) and if simple analysis that involves only Mg and Fe transitions is assumed these slopes could affect $\Delta \alpha/\alpha$ by 10 ppm. By correcting for these long-range distortion slopes I suppressed the long-range distortion uncertainties well below statistical uncertainties and in most cases below other systematic uncertainties estimated in this project. Other systematic uncertainties estimated in
this project include intra-order distortion, redispersion, setting shift and model uncertainties. The largest among these were model uncertainties, ranging between 0.84 and 2.97 ppm. However, they were still well below individual statistical uncertainties.

The weighted mean result from this project \( (\Delta \alpha / \alpha)_w = -0.1 \pm 1.2_{stat} \pm 0.8_{sys} \) ppm is consistent with zero \( \alpha \) variation. It is also consistent with the weighted mean result \( (\Delta \alpha / \alpha)_w = -1.0 \pm 0.5_{stat} \pm 0.5_{sys} \) ppm from the previous 27 absorption system measurements. It is interesting to note that the best constraint in the sample \( \Delta \alpha / \alpha = 6.3 \pm 2.4_{stat} \pm 1.3_{sys} \) ppm, the measurement towards \( z_{abs} = 1.691 \), shows 2.3\( \sigma \) deviation from zero variation. Analysis in this absorber was carefully examined and no particular reason was found that can affect this measurement. Nevertheless, in the sample of \( \sim 20 \) absorbers it is not unexpected to measure such a significant deviation from zero. Other measurements in the sample are consistent with zero variation, within 2.0\( \sigma \).

I also examined how much measurements in the entire reliable sample are supportive of previously proposed dipole variation in \( \alpha \) \cite{King:2012}, which was affected by the long-range distortions. The simplified analysis which did not include dipole error suggests that current reliable measurements are inconsistent with the dipole at 4.2\( \sigma \) level, similarly to previous reliable measurements. However, considering that inclusion of this error and more sophisticated analysis would reduce discrepancies, more evidence (e.g. a larger sample of measurements) is necessary to completely rule out the dipole variation. The significance of this inconsistency is significantly reduced if I exclude measurement from Section 3, again showing the importance of this measurement in the sample.

6.2 Future work

Even though multiple studies in the past (e.g. \cite{King:2012}) suggested possible variation in the fine-structure constant, my work, as well as most of the recent studies \cite{Evans:2014, Murphy:2016, Murphy:2017} are not supportive of such findings. As such, I can conclude that ‘fundamental constants of nature do not vary in spacetime.’ However, this question is much more profound. Current status of the field suggests no variation at the level of \( \lesssim 1 \) ppm and there is no strong theoretical prediction on the actual size of possible variations in \( \alpha \). Therefore,
it is always possible to improve precision of the MM method measurements to the
limit at which we could be able to see its variation. This is actually the primary
motivation of future work in this field. However, for the purpose of this thesis I will
limit discussion about future work to a foreseeable future.

The recalibration method of Section 2.3.3 – in which a well-calibrated, lower
S/N spectrum is used to re-calibrate the wavelength scale of a higher S/N spectrum
from which $\Delta \alpha/\alpha$ is to be measured – requires the well-calibrated spectrum to be
taken. Considering that HARPS is the only functional spectrograph from which well-
calibrated spectra with sufficient S/N are available\(^1\) and that it takes much more
than 10 h to produce such a spectrum I would suggest to leave this method for future
measurements. In other words, continue using this method when it becomes possible
to acquire the recalibration spectrum in a few hours (see explanation below). In
the meantime, I would suggest using available spectra with ‘attached’ supercalibrations.
Unfortunately, only a handful of such a spectra are currently available, mainly
those observed in the “Large Program for Testing Fundamental Physics”. As such,
and taking into account the short amount of time before the next stage in $\Delta \alpha/\alpha$
measurements (see following paragraphs), I do not expect significant improvements
in either statistical precision or further exploration of systematic errors from these
measurements.

Nevertheless, the Echelle SPerctrograph for Rocky Exoplanet and Stable Spec-
troscopic Observations (ESPRESSO) (Pepe et al., 2010) has observed its first light
on VLT in December 2017 (https://www.eso.org/public/australia/news/eso1739/),
and is expected to become fully operational (including its frequency comb) from
April 2019. Similarities to the HARPS spectrograph such as thermal and pressure
stability and optical fiber feeding as well as improvements with the laser frequency
comb calibration (Murphy et al., 2007b; Pepe et al., 2010) make ESPRESSO perfect
for measurements without two systematic effects that affected the past measure-
ments: the long-range and the intra order distortions. As such, this spectrograph
could be used to remeasure the whole sample of quasars previously observed on
UVES. However, this will demand significant observational effort and when we con-

\(^1\)Other spectrographs are capable of producing well-calibrated spectra, but they are either
mounted on even smaller telescopes than HARPS, or they have been recently installed (e.g. Veloce
on AAT).
sider another two science goals of ESPRESSO\textsuperscript{2}, we cannot expect to achieve this in the next decade. Even after this much observational effort has been invested on ESPRESSO, we cannot expect significantly better statistical precision than was achieved in the entire sample of reliable measurements (last column in Table 5.5).

Another approach that would require significantly less observational effort is to use the recalibration method proposed in this work. With the significantly larger collecting area of VLT in comparison to the La Silla Observatory (HARPS), in just a few hour exposure we can observe quasars that have previously been observed with UVES and/or HIRES and make complimentary recalibration exposures. Recalibration of the existing high S/N > 100 spectra would then lead to reliable measurements of $\Delta \alpha / \alpha$. About 20 such high S/N spectra are available on the UVES archive, mainly from the two Large Programs of quasar observations with UVES. As previously stated, whichever method of observing with ESPRESSO we choose it is not expected to significantly increase statistical precision of the $\Delta \alpha / \alpha$ measurements because these spectra will still be observed with $\sim 10 \text{ m}$ telescope.

It was shown in Murphy et al. (2008b) that for a particular absorption system and particular transitions used in the MM analysis the statistical precision of $\Delta \alpha / \alpha$ measurements depends mainly on the S/N of the spectra. My analysis of the higher resolution spectra in Section 2.3.5 explored whether it is possible to completely resolve real velocity structure in the absorption clouds at extremely high resolution of $R \sim 140000$. This would potentially enable us to improve precision of $\Delta \alpha / \alpha$ measurements. Unfortunately, it was found that this is not possible because absorption systems seem to be comprised of very closely-packed, narrow velocity components. As such, the main requirement for the significant improvement of $\Delta \alpha / \alpha$ measurements with the MM method is availability of spectra with S/N > 250. Only a single such spectrum currently exists and that is the HE 0515$-$4414 spectrum used in this work. Total exposure time required to observe this quasar was $\sim 40 \text{ h}$. Considering that this is the brightest southern quasar above redshift 1, considerably more than $40 \text{ h}$ would be required to achieve this S/N spectrum with other quasars. This means that if an enormous amount of observational effort is not invested into varying fundamental constants research such spectra will not be available until echelle spec-

\textsuperscript{2}In addition to the science goal of measuring fundamental constants, ESPRESSO has two more goals: the search for rocky exo-planets and measuring the chemical composition of stars in nearby galaxies.
trographs on a new generation of $\sim$30 m telescopes become operational. Proposed instruments that will be used for measuring possible variation in the fine-structure constant are the GMT Consortium Large Earth Finder (G-CLEF) on the Giant Magellan Telescope (GMT), the High Resolution Spectrograph (HIRES) on the Extremely Large Telescope (ELT) and a high-resolution spectrograph planned for second generation instrumentation on the Thirty Meter Telescope (TMT). Increase of the statistical precision in the 30 m telescope era will require careful consideration of systematic effects associated with CCDs and spectral reduction techniques explored in my work, such as fringing effects and artifacts from flux extraction, sky subtraction and flat-fielding. This would require new approaches to the reduction of echelle spectra. Considering that statistical errors in these measurements will be reduced below 1 ppm some novel approach to modelling absorption systems that will be robust, objective and completely automatic would be necessary to reduce modelling errors. Some examples of prototype algorithms for this have been demonstrated (e.g. Bainbridge & Webb, 2017), but they are not yet fully automatic and currently require very long computation times.

With all this in mind, I expect research in the field of measuring variation in fundamental constants using quasar absorption lines in the next decade to be oriented towards two goals. The first goal will be increasing the sample of reliable $\Delta \alpha/\alpha$ measurements using ESPRESSO. The second goal will be the exploration of systematic errors that are expected to be important in future spectrographs and telescopes. Understanding this would be a great foundation to the future research in the field from 30 m telescopes, which will finally lead to the first sample of results at the sub-ppm level.


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