A large sample of calibration stars for Gaia: log g from 
Kepler and CoRoT fields

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ABSTRACT

Asteroseismic data can be used to determine stellar surface gravities with precisions of < 0.05 dex by using the global seismic quantities $\langle \Delta \nu \rangle$ and $\nu_{\text{max}}$ along with standard atmospheric data such as $T_{\text{eff}}$ and metallicity. Surface gravity is also one of the four stellar properties to be derived by automatic analyses for 1 billion stars from Gaia data (workpackage GSP_Phot). In this paper we explore seismic data from main sequence F, G, K stars (solar-like stars) observed by the Kepler spacecraft as a potential calibration source for the methods that Gaia will use for object characterisation (log g). We calculate log g for some bright nearby stars for which radii and masses are known (e.g. from interferometry or binaries), and using their global seismic quantities in a grid-based method, we determine an asteroseismic log g to within 0.01 dex of the direct calculation, thus validating the accuracy of our method. We also find that errors in adopted atmospheric parameters (mainly [Fe/H]) can, however, cause systematic errors on the order of 0.02 dex. We then apply our method to a list of 40 stars to deliver precise values of surface gravity, i.e. uncertainties on the order of 0.02 dex, and we find agreement with recent literature values. Finally, we explore the typical precision that we expect in a sample of 400+ Kepler stars which have their global seismic quantities measured. We find a mean uncertainty (precision) on the order of better than 0.02 dex in log g over the full explored range $3.8 < \log g < 4.6$, with the mean value varying only with stellar magnitude (0.01 − 0.02 dex). We study sources of systematic errors in log g and find possible biases on the order of 0.04 dex, independent of log g and magnitude, which accounts for errors in the $T_{\text{eff}}$ and [Fe/H] measurements, as well as from using a different grid-based method. We conclude that Kepler stars provide a wealth of reliable information that can help to calibrate methods that Gaia will use, in particular, for source characterisation with GSP_Phot where excellent precision (small uncertainties) and accuracy in log g is obtained from seismic data.

Key words: asteroseismology – stars: fundamental parameters – stars: late-type – surveys: Gaia – surveys: Kepler – Galaxy: fundamental parameters –

1 INTRODUCTION

Large-scale surveys provide a necessary homogenous set of data for addressing key scientific questions. Their science-driven objectives naturally determine the type of observations that will be collected. However, to fully exploit the survey, complementary data, either of the same type but measured with a different instrument or of a different observable, needs to be obtained. Combining data from several large-scale surveys can only result in the best exploitation of both types of data.

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The ESA Gaia mission\textsuperscript{1} is due to launch in Autumn 2013. Its primary objective is to perform a 6-D mapping of the Galaxy (3 dimensional and 3 velocity data)\textsuperscript{2} by observing over 1 billion stars down to a magnitude of $V = 20$. The mission will yield distances to these stars, and for about 20/100 million stars distances with precisions of less than 1%/-10% will be obtained.

Gaia will obtain its astrometry by using broadband $G$ photometry\textsuperscript{3}. The spacecraft is also equipped with a spectrophotometer comprising both a blue and a red prism BP/RP, delivering colour information. A spectrometer will be used to determine the radial velocities of objects as far as $G = 17$ (typical precisions range from 1-20 kms\textsuperscript{-1}), and for the brighter stars ($G < 11$) high resolution spectra (R\textasciitilde11,500) will be available.

One of the main workpackages devoted to source characterisation is GSP\_Phot whose objectives are to obtain stellar properties for 1 billion single stars by using the $G$ band photometry, the parallax $\pi$, and the spectrophotometric information BP/RP (Bailer-Jones et al. 2010). The stellar properties that will be derived are effective temperature $T_{\text{eff}}$, surface gravity $\log g$, and metallicity $[\text{Fe/H}]$, and also extinction $A_G$ in the astrometric $G$ band to each of the stars. Liu et al. (2012) discuss several different methods that were developed to determine these parameters using Gaia data and we refer to this paper and references within for details. In brief, they discuss the reliability of determining the four parameters by using simulations, and in particular, they conclude that they expect typical precisions in $\log g$ on the order of 0.1 - 0.2 dex for main sequence late-type stars, with mean absolute residuals (true value minus inferred value from simulations) no less than 0.1 dex for stars of all magnitudes, see Figure 14 and 15 of Liu et al. (2012). We note that the stellar properties derived by GSP\_Phot will be used as initial input parameters for the workpackage devoted to detailed spectroscopic analysis of the brighter targets GSP\_Spec (Recio-Blanco et al. 2008; Bijaoui et al. 2010; Kordopatis et al. 2011; Worley et al. 2012) using the Radial Velocity Spectrometer data (Katz 2003). Spectroscopic determinations of $\log g$, $T_{\text{eff}}$ and [Fe/H] in general can have large correlation errors, and if $\log g$ is well constrained, $T_{\text{eff}}$, [Fe/H] and chemical abundances can be derived much more precisely.

The different algorithms for GSP\_Phot discussed by Liu et al. (2012) used to determine the stellar properties in an automatic way have naturally been tested on synthetic data. However, to ensure the validity of the stellar properties, a set of 40 bright benchmark stars have been compiled and work is still currently underway to derive stellar properties for all of these in the most precise, homogenous manner (e.g. Heiter, et al. in prep.). Unfortunately, these benchmark stars will be too bright for Gaia, and so a list of about 500 primary reference stars has also been compiled. The idea is to use precise ground-based data and the most up-to-date models (known from working with the benchmark stars) to determine their stellar properties as accurately (correct) and precisely (small uncertainties) as possible. These primary reference stars will be observed by Gaia and thus will serve as a set of calibration stars. A third list of secondary reference stars has also been compiled. These consist of about 5000 fainter targets.

In the last decade or so, much progress in the field of asteroseismology has been made, especially for stars exhibiting Sun-like oscillations. These stars have deep outer convective envelopes where stochastic turbulence gives rise to a broad spectrum of resonant oscillation modes (e.g. Ulrich 1970, Leibacher & Stein 1971, Brown & Gilliland 1994, Salabert et al. 2002, Bouchy & Carrier 2002). The power spectrum of such stars can be characterised by some global seismic quantities; $\langle \Delta \nu \rangle$, $\nu_{\text{max}}$, and $\delta \nu$. The quantity $\langle \Delta \nu \rangle$ is the mean value of the large frequency separations $\Delta \nu_{l,n} = \nu_{l,n} - \nu_{l,n-1}$ where $\nu_{l,n}$ is a resonant oscillation frequency with degree $l$ and radial order $n$, $\nu_{\text{max}}$ is the frequency corresponding to the maximum power in the spectrum, and $\delta \nu$ is the mean value of the small frequency separations $\delta \nu_{l,n} = \nu_{l,n} - \nu_{l+2,n-1}$. Figure 1 shows the power (frequency) spectrum of a solar-like star, observed by the Kepler spacecraft, depicting these quantities.

Even when individual frequencies can not be determined from the frequency spectra both $\langle \Delta \nu \rangle$ and $\nu_{\text{max}}$ can still be extracted quite robustly. Many methods have been developed to do this using Kepler-like data (Bonanno et al. 2003; Huber et al. 2003; Mosser & Appourchaux 2009; Mosser & Appourchaux 2009; Hekker et al. 2010; Campante et al. 2010; Mathur et al. 2010; Karoff et al. 2010) and these have been compared in Verner et al. (2011) (see references therein). The global seismic quantities have been shown to scale with stellar parameters such as mass, radius, and $T_{\text{eff}}$, e.g. Brown & Gilliland (1994); Bedding & Kjeldsen (2003); Stello et al. (2008); Huber et al. (2011); Bedding (2011); Miglio et al. (2012); Silva Aguirre et al. (2012). By comparing the theoretical seismic quantities with the observed ones over a large grid of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{High SNR power/frequency spectrum of a Kepler solar-like star KIC 6603624. Some individual frequencies $\nu$ are denoted with their degree $l$ and radial order $n$ in parenthesis (Appourchaux et al. 2012). The reference radial order $n_0$ usually corresponds to orders similar to 20 for these stars. We also show the individual large and small frequency separations, $\Delta \nu(l,n)$ and $\delta \nu(l,n)$ respectively, for three cases, and the approximate frequency corresponding to the maximum power in the spectrum, $\nu_{\text{max}}$. For much lower SNR spectra, the mean value $\langle \Delta \nu \rangle$ of the large frequency separations and $\nu_{\text{max}}$ can usually be determined even if individual frequencies $\nu$ can not be resolved.}
\end{figure}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Parameter & Value & Unit \\
\hline
$G$ & 17 & \textdegree \\
$\log g$ & 4.0 & \textdegree \\
$T_{\text{eff}}$ & 5770 & K \\
$[\text{Fe/H}]$ & -0.5 & \\
$A_G$ & 1 & \\
\hline
\end{tabular}
\caption{Example of stellar properties derived by GSP\_Phot.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Example of stellar properties derived by GSP\_Phot.}
\end{figure}
stellar models, very precise determinations of \( \log g \) (< 0.05 dex) and mean density (< 2%) can be obtained for main sequence F, G, K stars \( ^\text{32} \)\( ^\text{10} \). Kepler is a NASA mission dedicated to characterising planet-habitability \( ^\text{32} \)\( ^\text{10} \). It obtains photometric data of approximately 150,000 stars with a typical cadence of 30 minutes. However, a subset of stars (less than 1000 every month) acquire high-cadence data with a point every 1 minute. This is sufficient to detect and characterise Sun-like oscillations in many stars. \( ^\text{32} \)\( ^\text{10} \), \( ^\text{11} \); \( ^\text{11} \). recently showed the detections of the global seismic quantities for a sample of 600 F, G, K main sequence and subgiant (V/IV) stars with typical magnitudes \( 7 < V < 12 \), while both CoRoT and \( ^\text{11} \)\( ^\text{12} \) have both shown their capabilities of detecting these same seismic quantities in 1000s of red giants, e.g. \( ^\text{12} \)\( ^\text{13} \), \( ^\text{11} \)\( ^\text{12} \), \( ^\text{11} \)\( ^\text{12} \), \( ^\text{11} \)\( ^\text{12} \), \( ^\text{13} \), \( ^\text{11} \)\( ^\text{12} \).

With the detection of the global seismic quantities in hundreds of main sequence stars (and 1000s of giants), the \( ^\text{13} \)\( ^\text{11} \) field is very promising for helping to calibrate Gaia GSP_Phot methods. In particular, the global seismic quantities deliver one of the four properties to be extracted by automatic analysis, namely \( \log g \). \( ^\text{11} \)\( ^\text{11} \) studied the distribution of errors for a sample of simulated stars using seismic data and a grid-based method based on stellar evolution models. They concluded that \( \log g \) derived from seismic properties ("seismic \( \log g \)) is almost fully independent of the input physics in the stellar evolution models that are used. More recently, \( ^\text{12} \)\( ^\text{13} \) compared classical determinations of \( \log g \) to those derived alone from a scaling relation (see Eq. \[ \text{2} \]), and concluded that the mean differences between the various methods used is \( \sim 0.05 \) dex, thus supporting the validity of a seismic determination of \( \log g \). While some studies have focused on comparing seismic radii or masses with alternative determinations, for example, \( ^\text{11} \)\( ^\text{10} \), no study has been done focussing on both the accuracy and precision of a seismic \( \log g \) using one or more grid-based methods for stars with independently measured radii and masses. The accuracy and precision in \( \log g \) for these bright stars has also not been tested while considering uncertainties in data such as those obtained by \( ^\text{12} \). Such a study could validate the use of seismic data as a calibration source for Gaia. For the rest of this work the term precision refers exclusively to the derived uncertainty in \( \log g \), while accuracy refers to how true the value is.

With these issues in mind, the objectives of this paper are to (i) test the accuracy and precision of a seismic \( \log g \) from a grid-based method using bright nearby targets for which radii and masses have been measured (Sect. 3), (ii) determine \( \log g \) for an extended list of stars whose global seismic properties and atmospheric parameters are available in the literature using the validated method (Sect. 4), and (iii) study the distribution of \( \log g \) and their uncertainties of over 400 F, G, K V/IV \( ^\text{11} \)\( ^\text{11} \) stars derived by a grid-based method while concluding on realistic uncertainties (precisions) and possible sources of systematic errors for this potential sample of Gaia calibration stars (Sect. 5). In this work, our analysis is restricted to stars with \( \log g > 3.75 \) primarily due to the very limited sample of stars for which we can test the accuracy of and validate our method. For ease of reading, Table \[ \text{1} \] summarises the frequently used notation in this work. We begin in Sect. 2 by summarising the different methods available for determining \( \log g \).

## 2 DIRECT METHODS TO DETERMINE \( \log g \)

In this section we summarise the various methods that are used to determine the surface gravity (or the logarithm of this \( \log g \)) of a star. Comparing each of these methods directly would be the ideal approach for unveiling shortcomings in our models (systematic errors) and reducing uncertainties by decoupling stellar parameters.

### 2.1 Derivation of \( \log g \) from independent determinations of mass and radius

The most direct method of determining \( \log g \) involves measuring the mass \( M \) and radius \( R \) of a star in an independent manner. Surface gravity \( g \) is calculated using Newton’s Law of Gravitation: \( g = GM/R^2 \) where \( G \) is the gravitational constant.

#### 2.1.1 Mass and radius from eclipsing binary systems

For detached eclipsing spectroscopic binaries, both \( M \) and \( R \) can be directly measured by combining photometric and radial velocity time series \( ^\text{32} \)\( ^\text{11} \); \( ^\text{32} \)\( ^\text{11} \); \( ^\text{11} \)\( ^\text{12} \). The orbital solution is sensitive to the mass ratio and the individual \( M \sin i \) of both components, where \( i \) is the inclination. The photometric time series displays eclipses (when the orbital plane has a high enough inclination) that are sensitive to \( i \) and the relative \( R \). Once \( i \) is derived, then the individual \( M \) are solved. Kepler’s Law relates the orbital period of the system \( \Pi \), the system’s \( M \), and the separation of the components. \( \Pi \) is known from either eclipse timings or observing a full

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**Table 1. Summary of the frequently used notation in this study.**

| Notation | Definition |
|----------|------------|
| \( g \) | gravity |
| \( \log g \) | logarithm of \( g \) |
| \( T_{\text{eff}} \) | effective temperature |
| \( \langle \Delta \nu \rangle \) | mean large frequency separation |
| \( \nu_{\text{max}} \) | frequency of maximum power |
| \( \text{[Fe/H]} \) | metallicity |
| \( R \) | stellar radius |
| \( M \) | stellar mass |
| \( \sigma \) | uncertainty in \( \log g \) |
| \( s \) | systematic error in \( \log g \) |
| \( A_G \) | extinction in the Gaia G band |
| \( r \) | stellar magnitude in the SDDS system |

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[^32]: \url{http://kepler.nasa.gov}

radial velocity orbit. Once the individual $M$ are known then $K$ scales the system (providing the separation) and thus the individual $R$, and $g$ can be then calculated.

2.1.2 Mass and radius from interferometry and global seismic quantities

$R$ is measured by combining the angular diameter $\theta$ from interferometry with the distance to the star. The distance (or its inverse the parallax) has been made available using data from the Hipparcos satellite for stars with $V < \sim 8$ mag (Perryman et al 1997; van Leeuwen 2007; Kervella et al 2003). Indirect methods also exist for determining the angular diameter of a star, such as combining $T_{\text{eff}}$ with measurements of bolometric flux (Silva Aguirre et al 2012), or from calibrated relations using photometry (Kervella et al 2004). Using $R$ and $\langle \Delta \nu \rangle$ a model-independent mass determination can be obtained by using the asteroseismic relation which links mean density $\langle \rho \rangle$ and $\langle \Delta \nu \rangle$

$$\langle \Delta \nu \rangle_{\odot} \approx \sqrt{\frac{\rho}{\rho_{\odot}}} = \sqrt{(M/M_{\odot})/(R/R_{\odot})^3}$$

where $\langle \Delta \nu \rangle_{\odot}$ is the solar value (e.g. Kjeldsen & Bedding 1992; Huber et al 2011).

2.1.3 Mass and radius from interferometry and/or high precision seismic data

When high signal-to-noise ratio seismic data are available, individual oscillation frequencies (see Fig. 1) can be used to do detailed modelling, and hence determine $M$ (e.g. Doğan et al 2010; Brandão et al 2011; Bigot et al 2011; Metcalfe et al 2012; Miglio et al 2012). When combined with an independently measured $R$, the uncertainties in mass $\sigma(M)$ can reduce to $< 3\%$ (Creevey et al 2007; Bazot et al 2011; Huber et al 2012). If an independently determined $R$ is not available, then stellar modelling also yields $R$ to between $2-5\%$ and $M$ with less precision. However, this method depends on the physics in the interior stellar models unlike the methods mentioned above, and using different input physics may result in different values of mass. Typical uncertainties/accuracies in $M$ does not usually exceed about $5\%$ for bright targets when more constraints are available, and this translates to less than a $0.02$ dex error in $\log g$ for stars that we consider in this work. As $g$ is sensitive to seismic data, then $R$ and $M$ are correlated and $\log g$ can be determined with a precision of $\sim 0.02$ dex with a very slight dependence on the physics in the models, e.g. Metcalfe et al (2010).

2.2 Spectroscopic determinations of $\log g$

The surface gravity of a star is usually derived from an atmospheric analysis with spectroscopic data (e.g. Thévenin & Jasniwicz 1994; Bruntt et al 2010; Lebzelter et al 2010; Sousa et al 2012). There are two usual approaches for deriving atmospheric parameters ($\log g$, $T_{\text{eff}}$, and [Fe/H]). The first approach is based on directly comparing a library of synthetic spectra with the observed one, usually in the form of a best-fitting approach. A shortcoming of this method is that combinations of parameters can produce similar synthetic spectra so that many correlations between the derived parameters exist. The more classical method for determining atmospheric parameters relies on measuring the equivalent widths of iron lines (or other chemical species). This method assumes local thermodynamic equilibrium (LTE) and requires model atmospheres. Once $T_{\text{eff}}$ is determined (by requiring that the final line abundance is independent of the excitation potential or for stars with $T_{\text{eff}} > 5000$ K, measuring the Balmer H line profiles), then $g$ is the only parameter controlling the ionisation balance of a chemical element in the photospheric layers, which acts on the recombination frequency of electrons and ions. $g$ is then determined by requiring a balance between different ionized lines e.g. Fe-I and Fe-II. Spectroscopically determined $\log g$ can have large systematic errors especially for more metal-poor stars where NLTE effects must be taken into account. This can change $\log g$ by $\sim 0.5$ dex, e.g. Thévenin & Jasniwicz (1992).

2.3 $\log g$ derived from Hipparcos data

An alternative method for determining $\log g$ relies on knowing the distance $d$ (in pc) to the star from astrometry, its bolometric flux (combining these gives the luminosity of a star) and $T_{\text{eff}}$. Then substituting $M$ and $\log g$ for $R$ in Stefan’s Law, one obtains the following $\log g = -10.5072 + \log M + 0.4(V_0 + BC_V) - 2 \log d + 4 \log T_{\text{eff}}$, where $V_0$ is the de-reddened V magnitude and $BC_V$ the bolometric correction in $V$ and $M$ (in $M_{\odot}$) a fixed value that is estimated from evolution models, e.g. Thévenin et al 2003; Barbuy et al 2004. This Hipparcos $\log g$ is often used as a fixed parameter for abundance analyses of stars. Typical uncertainties are no less than 0.08 dex where especially the error in $M$ is large, and errors from $d$ and $T_{\text{eff}}$ are not insignificant. We note that Gaia will deliver unmistakeably accurate distances for much fainter stars and these will provide a much improved $\log g$ using this method for individual stars.

2.4 $\log g$ from evolutionary tracks

2.4.1 Classical constraints in the H-R diagram

When H-R diagram constraints are available ($T_{\text{eff}}$, $L$, metallicity) then stellar evolution tracks can be used to provide estimates of some of the other parameters of the star, e.g. mass, radius, and age. While correlations exist between many parameters, e.g. mass and age, these correlations also allow us to derive certain information with better precision, e.g. mass and radius gives $g$. Exploring a range of models that pass through the error box thus allows us to limit the possible range in $\log g$ (e.g. Creevey et al 2012).

2.4.2 Grid-based asteroseismic $\log g$

Apart from performing detailed modelling using asteroseismic data (Sect. 2.1.2), one can rely on grids of stellar models to estimate stellar properties such as mass and radius with precisions on the order of $2-12\%$. However, because asteroseismic data are extremely sensitive to the ratio of these two parameters, then very precise determinations of $\log g$ and $\langle \rho \rangle$ can be obtained in an almost model-independent manner (e.g. Gai et al 2011 in Sect. 5.3 we address this issue).
Such a grid-based asteroseismic log $g$ can be obtained in the following manner: a large grid of stellar models that spans a wide range of mass, age, and metallicity is constructed. Each model in the grid has a corresponding set of theoretical observables, such as log $g$, $T_{\text{eff}}$, individual frequencies $v_{n,l}$, $\langle \Delta \nu \rangle$ and $v_{\text{max}}$. A scaling relation is used to obtain $v_{\text{max}}$:

$$
\frac{v_{\text{max}}}{v_{\text{max,\odot}}} \approx \frac{(M/M_{\odot})}{(R/R_{\odot})^2 \sqrt{T_{\text{eff}}/T_{\text{eff,\odot}}}}
$$

where $v_{\text{max,\odot}}$ is the solar value (e.g., Vandakurov 1968, Tassoul 1980, Kiekebsen & Bedding 1997). The quantity $\langle \Delta \nu \rangle$ can be obtained either from Eq. 1 or calculated directly from the oscillation frequencies derived from the structure model. Differences, however, on the order of 2% in $\langle \Delta \nu \rangle$ may be found by adopting one or the other method (e.g., White et al. 2011, see also Mosser et al. 2013). A set of input observed data, e.g., $\{\langle \Delta \nu \rangle$, $T_{\text{eff}}$, and $[\text{Fe/H}]\}$, is compared to the theoretical one, and the models that give the best match to the data are selected and the value of log $g$ and its uncertainty is derived using these best selected models. Such a precise value for this seismic log $g$ comes, in fact, from the very close relation between $v_{\text{max}}$ and the cut-off frequency, and recent work has made progress on understanding this relation (Bellacem et al. 2011). Several seismic grid-based approaches for determining stellar properties have been discussed and applied in the recent literature (Stello et al. 2009, Olivier et al. 2010, Basu et al. 2010, Gai et al. 2011, Creevey et al. 2012, Metcalfe et al. 2012, Silva Aguirre et al. 2012), and for the rest of this paper we use the term seismic log $g$ to refer specifically to the grid-based method for determining log $g$.

3 COMPARISON OF DIRECT AND SEISMICALLY DETERMINED log $g$.

3.1 Observations and direct determination of log $g$

In order to test the reliability of an asteroseismically determined log $g$, the most correct method is to compare it to log $g$ derived from mass and radius measurements of stars in eclipsing binaries (Sect. 2.1.1), apart from the Sun. Unfortunately the number of stars whose masses and radii are known from binaries, where seismic data are also available, is quite limited. For this sample of stars we have ο Cen A and B, and Procyon. Following this, we rely on the combination of asteroseismology and interferometry to determine log $g$, and use the scaling relation which links density to the observed properties of $\langle \Delta \nu \rangle$ and $R$ to provide an independent $M$ measurement (Sect. 2.1.2). However, since this scaling relation is used explicitly in the grid-based method, we have opted to omit stars where this method provides the mass, except for the solar twin 18 Sco, which was included because of its similarity to the Sun. To complete the list of well-characterised stars we have then chosen some targets for which an interferometric $R$ has been measured and detailed seismic modelling has been conducted to determine the star’s $M$ by several authors (Sect. 2.1.3). The stars which fall into this group are HD 49933 and β Hydri. The seven stars are listed in order of log $g$ in Table 4 along with $\langle \Delta \nu \rangle$, $v_{\text{max}}$, $T_{\text{eff}}$, $[\text{Fe/H}]$, $M$, and $R$. When several literature values are available these are also listed. The final column in the table gives the direct value of log $g$ as derived from $M$ and $R$. For HD 49933 and β Hydri we adopt the weighted mean values of log $g$ which are 4.214 and 3.958 dex respectively (see Table 4), and these are summarized in column 2 of Table 5. For the rest of the paper we refer to these determinations of log $g$ as the direct determinations.

3.2 Seismic method to determine log $g$

We use the grid-based method, RadEx10, to determine an asteroseismic value of log $g$ (Creevey et al. 2012a). The grid was constructed using the ASTEC stellar evolution code (Christensen-Dalsgaard 2008) with the following configuration: the EFF equation of state (Eggleton et al. 1973), without Coulomb corrections, the OPAL opacities (Iglesias & Rogers 1996), supplemented by Kurucz opacities at low temperatures, solar mixture from Grevesse & Noels (1993), and nuclear reaction rates from Bahcall & Pompousault (1992). Convection in the outer convective envelope is described by the mixing-length theory of Böhm-Vitense (1958) and this is characterised by a variable parameter $\alpha_{\text{MLT}}$ (where $f = \alpha_{\text{MLT}} H_p$, $f$ is the mixing-length and $H_p$ the pressure scale height). When a convective core exists, there is an overshoot layer which is also characterised by a convective core overshoot parameter $\alpha_{\text{ov}}$ and this is set to 0.25 (an average of values used recently in the literature). We also ignore diffusion effects, although we note that for accurate masses and ages this needs to be taken into account.

The grid considers models with masses $M$ from 0.75 – 2.00 $M_{\odot}$ and ages $t$ from ZAMS to subgiant. The initial metallicity $Z_i$ spans 0.003 – 0.030 in steps of $\sim 0.003$, while initial hydrogen abundance $X_i$ is set to 0.71: this corresponds to an initial He abundance $Y_i = 0.260 – 0.287$. The mixing length parameter $\alpha_{\text{MLT}} = 2.0$ is used, which was obtained by calibration with solar data. We note that to derive other stellar properties, it is very important to allow $\alpha_{\text{MLT}}$ to vary e.g. (Creevey et al. 2012b, Bonaca et al. 2012).

To obtain the grid-based model stellar properties, e.g. log $g$, $M$, and $t$, we perturb the set of input observations by scaling its input error with a number drawn randomly from a normal distribution and add this to the input (observed) value. We compare the perturbed observations to the model ones and select the model that matches best. This is repeated 1,000 times to yield model distributions of best-fit model ones and select the model that matches best. This is repeated 1,000 times to yield model distributions of best-matching stellar parameters. In this method, $\langle \Delta \nu \rangle$ is calculated using Eq. 1 and the input observations consist primarily of $\langle \Delta \nu \rangle$, $v_{\text{max}}$, $T_{\text{eff}}$, and $[\text{Fe/H}]$, although other inputs are possible, for example, $L$ or $R$. The model distributions are then fitted to a Gaussian distribution and the fitted stellar property and its uncertainty ($\sigma$) are defined as the central value and the standard deviation $\sigma$ of the Gaussian fit. In this work we consider just the derived value of log $g$.

3.3 Analysis approach

We determine a seismic log $g$ for the reference stars using the method explained above. We consider different sets of input data in order to test the effect of the different observations on the accuracy (and precision) of a seismic
Table 2. Properties of the reference stars

| Star       | ($\Delta \nu$) (µHz) | $\nu_{\text{max}}$ (mHz) | $T_{\text{eff}}$ (K) | [Fe/H] | $R$ (R$_{\odot}$) | $M$ (M$_{\odot}$) | log $g$ (dex) |
|------------|----------------------|---------------------------|----------------------|--------|------------------|-----------------|----------------|
| $\alpha$CenB | 161.5 ± 0.11$^a$ | 4.0$^{1a}$ | 5316 ± 28$^b$ | +0.25 ± 0.04$^{1b}$ | 0.863 ± 0.005$^{1c}$ | 0.934 ± 0.006$^{1d}$ | 4.538 ± 0.008 |
| 18 Sco     | 134.4 ± 0.3$^a$ | 3.1$^{2a}$ | 5813 ± 21$^a$ | 0.04 ± 0.01$^{2a}$ | 1.010 ± 0.009$^a$ | 1.02 ± 0.03$^{2a}$ | 4.438 ± 0.005 |
| Sun        | 134.9 ± 0.1$^{3a}$ | 3.05$^{3b}$ | 5778 ± 20$^{3c}$ | 0.00 ± 0.01 | 1.224 ± 0.003$^{1c}$ | 1.105 ± 0.007$^{1d}$ | 4.307 ± 0.005 |
| $\alpha$CenA | 105.6$^{4a}$ | 2.3$^{4a}$ | 5847 ± 27$^{b}$ | +0.24 ± 0.03$^{b}$ | 4.347 ± 0.002$^{3d}$ | 3.97 ± 0.005 |
| HD 49933   | 85.66 ± 0.18$^{5a}$ | 1.8$^{5a}$ | 6500 ± 75$^{5b}$ | −0.35 ± 0.10$^{5b}$ | 1.49$^{b}$ | 1.325$^{5b}$ | 2.43 ± 0.02$^{5b}$ |
| Procyon    | 55.5 ± 0.5$^{6a}$ | 1.0$^{b}$ | 6530 ± 90$^{6c}$ | −0.05 ± 0.09$^{6d}$ | 2.067 ± 0.022$^{6e}$ | 1.497 ± 0.037$^{6f}$ | 3.982 ± 0.016 |
| $\beta$Hydri | 57.24 ± 0.16$^{7a}$ | 1.0$^{7a}$ | 5872 ± 44$^{7b}$ | −0.10 ± 0.07$^{7c}$ | 1.814 ± 0.017$^{7c}$ | 1.7 ± 0.03$^{7b}$ | 3.950 ± 0.015 |
|            |                     |                     |                     |        |                  |                 |               |
|            | 5964 ± 70$^{7g}$ | −0.03 ± 0.07$^{7g}$ | 1.69 ± 0.05$^{7g}$ |        |                  |                 | 4.02 ± 0.04$^{7g}$ |

log $g$:
(S1) $\langle \langle \Delta \nu \rangle \rangle$, $\nu_{\text{max}}$, $T_{\text{eff}}$, [Fe/H],
(S2) $\langle \langle \Delta \nu \rangle \rangle$, $\nu_{\text{max}}$, $T_{\text{eff}}$, then
(S3) $\langle \langle \Delta \nu \rangle \rangle$, $T_{\text{eff}}$.

For the potential sample of Gaia calibration stars, [Fe/H] will not always be available, and in some cases, $\nu_{\text{max}}$ is difficult to determine for very low S/N detections.

The observational errors in our sample are very small due to the brightness (proximity) of the star, so we also derive an astroseismic log $g$ while considering observational errors that we expect for Kepler stars (see Verner et al. 2011) and Figure 5. We consider three types of observational errors while repeating the exercise: (E1) the true measurement errors from the literature, (E2) typically “good” errors expected for these stars, i.e. $\sigma(\langle \Delta \nu \rangle) = 1.1$ µHz, $\sigma(\nu_{\text{max}}) = 5\%$, $\sigma(T_{\text{eff}}) = 70$ K, and $\sigma([\text{Fe/H}]) = 0.08$ dex (see Sect. [4]), and (E3) “not-so-good” measurement errors, primarily considering the fainter targets ($V \sim 11.12$), i.e. $\sigma(\langle \Delta \nu \rangle) = 2.0$ µHz, $\sigma(\nu_{\text{max}}) = 8\%$, $\sigma(T_{\text{eff}}) = 110$ K, and $\sigma([\text{Fe/H}]) = 0.12$ dex.

3.4 Seismic versus direct log $g$

In Figure 2 we compare the grid-based seismic log $g$ with the direct log $g$ for the seven stars. Each star is represented by a point on the abscissa, and the y-axis shows (seismic - direct) value of log $g$. There are three panels which represent the results using the three sets of input data. We also show for each star in each panel three results; in the bottom left corner these are marked by ‘E1’, ‘E2’, and ‘E3’, and they represent the results using the different errors in the observations. The black dotted lines represent seismic minus direct log $g = 0$, and the grey dotted lines indicate ±0.01 dex.

Figure 2 shows that for all observational sets and errors log $g$ is generally estimated to within 0.01 dex in accuracy and with a precision of 0.015 dex. This result clearly shows the validity of the global seismic quantities and atmospheric parameters for providing accurate values of log $g$. It can also be noted that the precision in log $g$ typically decreases as (1) the observational errors increase (from E2 – E3), and (2) the information content decreases (S1 – S2 – S3, for example).

One noticeable result from Figure 2 is the systematic offset in the derivation of log $g$ for HD 49933 when we use [Fe/H] as input (S1). This could be due to an incorrect [Fe/H] or $T_{\text{eff}}$, an error in the adopted direct log $g$ or a shortcoming of the grid of models. This star is known to be active and found clear evidence of spot signatures in line bisectors. More recently Garcia et al. (2010) and Salabert et al. (2013) found frequency and amplitude variations similar to those in the Sun, evidence of the presence of a stellar cycle. Garcia et al. (2014) derived an S-index of about 0.3 corresponding to a very active star, even though no detection of a magnetic field has yet been confirmed (P. Petit, private communication 2012). Fabbian et al. (2012) showed that the magnetic effects in stellar models affect the determination of the metallicity and this, in turn, will affect the determination of other stellar parameters such as mass.
A large seismic sample of calibration stars for Gaia

Figure 2. Accuracy of method. Seismic-minus-direct $\log g$ for the seven sample stars while considering different subsets of input observations (different panels, S1, S2, S3) and different observational errors (E1, E2, E3). See Sect. 3.3 for details.

Table 3. log $g$ derived by RadEx10 for the reference stars using the true measurement errors. $\Delta g = \log g - \log g_{\text{direct}}$.

| Star     | $\log g$  | $\log g_{\text{direct}}$ | $\Delta g$  | $\Delta g$  |
|----------|-----------|---------------------------|--------------|--------------|
|          | (dex)     | (dex)                     | (dex)        | ($\sigma$)   |
| $\alpha$ Cen B | 4.527 ± 0.004 | 4.538                    | -0.011       | -2.8         |
| 18 Sco   | 4.441 ± 0.004 | 4.438                    | 0.003        | 0.8          |
| Sun      | 4.438 ± 0.001 | 4.437                    | 0.001        | 1.0          |
| $\alpha$ Cen A | 4.312 ± 0.004 | 4.307                    | 0.005        | 1.3          |
| HD 49933 | 4.195 ± 0.007 | 4.214                    | 0.019        | 2.7          |
| Procyon  | 3.981 ± 0.006 | 3.982                    | -0.001       | -0.2         |
| $\beta$ Hydri | 3.957 ± 0.010 | 3.958                    | 0.001        | 0.1          |

In their work, they considered large magnetic field strengths of several hundreds of Gauss.

Since no evidence of such a large magnetic field has yet been found for HD 49933 we propose another explanation. We consider the effect of the confirmed presence of spots on the effective temperature. By considering a spot area of about 20 percent of the stellar surface we found that the real effective temperature (that of the non spotted surface of the star) should increase by about 300 K with respect to the non-spotted star. Adding 300 K to $T_{\text{eff}}$ results in a seismic $\log g$ that increases by 0.011 dex for S1 (considering errors E1 and E2), which makes the new value consistent with the direct value within error bars. The increase of 0.011 dex corresponds to a relative increase of 3.7$\sigma$ and 1.2$\sigma$ for both error types E1 and E2. If we add this same 300 K for cases S2 and S3, we also find an increase in $\log g$, but smaller (0.009 and 0.006 dex), corresponding to a relative increase of 0.6$\sigma$ and 0.4$\sigma$, respectively.

3.5 Systematic errors in observations

For all of the calculations we have assumed that the input observations are correct (accurate). While this is certainly more true for brighter nearby targets where high SNR data can be obtained, the same cannot be said for fainter stars. In particular with spectroscopic data, the determination of $T_{\text{eff}}$ and [Fe/H] are correlated and depend on the analysis methods used and the different model atmospheres (see e.g. Creevey et al. 2012, Lebzelter et al. 2012). Additionally for many stars a photometric temperature may be the only available one and while these estimates are very good, systematic errors are still unavoidable (Casagrande et al. 2010).
true observational errors. We highlight the excellent agreement between our seismically determined parameters, and those obtained by direct mass and radius estimates. $\log g$ is matched to within $\sim0.01$ dex, and 0.02 dex for HD 49933. We must also comment on the very small uncertainties given in Table 3; these results were obtained using the true (very small) observational errors given in Table 2 and typically one would not expect to obtain such small errors for fainter stars. As can be seen, the results using the relaxed observational errors give more reasonable parameter uncertainties, i.e. 0.010 – 0.015 dex, see Fig. 2 while still matching the direct log $g$ to within 1$\sigma$.

4 DETERMINATION OF $\log g$ FOR AN EXTENDED LIST OF STARS

We apply our grid-based method to an extended list of stars with measured global seismic quantities and atmospheric parameters. Table 2 lists the star name along with the other measured parameters that are used as the input for our method. The first part of the table comprises primarily bright stars whose oscillation properties have been measured either from ground-based or spaced-based instrumentation (see references given in the table). For most of these stars no errors are cited for $\langle \Delta \nu \rangle$ and $\nu_{\text{max}}$. The second part of the table lists a set of 22 solar-type stars observed by the Kepler spacecraft and studied in Mathur et al. (2012). We have taken the seismic and atmospheric data directly from this paper. To conduct a homogenous analysis of these stars we adopted a 1.1 $\mu$Hz error on $\langle \Delta \nu \rangle$ for all of the stars, and a 5% error on $\nu_{\text{max}}$, typical of what has been found for the large sample of Kepler stars (see Huber et al. 2011 and Sect. 3.6).

Table 2 lists the derived value of $\log g$ and $2\sigma$ uncertainties (to allow for round-up error) for each of the stars using RadEx10. We show two values of $\log g$; the first is obtained by using the four input constraints $\{\langle \Delta \nu \rangle, \nu_{\text{max}}, T_{\text{eff}}, [\text{Fe/H}] \}$ and the second log $g_{\text{MIC}[\text{Fe/H}]}$ is obtained by omitting [Fe/H] from the analysis.

Figure 4 top panel compares the derived values of $\log g$ for the Kepler stars with those determined using the individual oscillation frequencies, as given by Mathur et al. (2012), with our 1$\sigma$ error bars overplotted. We see that the grid-based method provides $\log g$ consistent with those derived from a detailed asteroseismic analysis, although a very small trend can be seen. For some of the stars they obtain a fitted initial He abundance significantly below the accepted primordial value, suggesting that the corresponding fitted mass and radius may be slightly biased (grey squares). If we omit these stars, then we fit a slope of $-0.03 \pm 0.02$ to the difference between their and our $\log g$ values. White et al. (2011) and Mosser et al. (2013) point out that a discrepancy may exist between the two different theoretical values of $\langle \Delta \nu \rangle$ (using scaling relations or from individual frequencies), and the two different approaches could also be responsible for this trend. We see, however, that our values agree generally to within 0.01 dex. Silva Aguirre et al. (2012) have analysed 6 of these stars and the lower panel of Fig. 4 shows a comparison between their $\log g$ values with ours. Fitting the differences between our results, we obtain a slope of $0.001 \pm 0.004$.

3.6 Seismic determination of $\log g$ from the global seismic quantities for the reference stars

We summarize $\log g$ for the sample stars in Table 3 derived by RadEx10 using $\langle \Delta \nu \rangle$, $\nu_{\text{max}}$, $T_{\text{eff}}$, and [Fe/H], and the stellar parameters have more weight. In the latter case, an incorrect $T_{\text{eff}}$ will have an offset. In this case biases on the order of up to 6% and 20% in radius and mass can be obtained (Creevey & Thévenin 2012). It must also be noted that a systematic error in the offset does not exceed 0.02 dex. For determining a seismic radius and mass, however, a systematic error in the atmospheric parameters has more weight. In the former case, a systematic error in both $T_{\text{eff}}$ and [Fe/H] will necessarily shift the mass either up or down (in terms of the H-R diagram), and result in a more displaced $\log g$. However, in both cases, we see that the offset does not exceed 0.02 dex. For determining a seismic radius and mass, however, a systematic error in the input observations has a much more profound effect on the offset. In this case biases on the order of up to 6% and 20% in radius and mass can be obtained (Creevey & Thévenin 2012).
0.025 with a systematic offset of -0.003 ± 0.005, indicating no systematic trends.

5 PRECISION IN log g FOR A LARGE SAMPLE OF Kepler STARS OF CLASSES IV/V

Our primary objective was to test the accuracy of a seismic log g by using bright nearby targets that have independent mass and radius measurements. We showed in Sect. 3.4 (see Fig. 2) that our accuracy should be on a level of 0.01 dex with a precision of ~0.02 dex using the set \{(Δν),ν_{\text{max}},T_{\text{eff}}\} for the small sample of stars covering the range 3.9 < log g < 4.6. In this section we investigate the precision in log g for a sample of 403 V/IV stars (log g > 3.75) observed with the Kepler spacecraft by employing the same analysis methods. In particular we pay attention to systematic errors by 1) using different sets of observational constraints, 2) comparing results using two different methods which incorporate different stellar evolution codes and physics, and 3) we also show the distribution of errors as a function of magnitude.
Table 5. Derived seismic log g for an extended list of Sun-like oscillators. log g and log $g_{\text{radex} \text{[Fe/H]}}$ refer to using \{$(\Delta \nu), \nu_{\text{max}}, T_{\text{eff}}, \text{[Fe/H]}$\} and \{$(\Delta \nu), \nu_{\text{max}}, T_{\text{eff}}$\} as the constraints in the analysis. For a homogenous analysis we adopted 1.1 $\mu$Hz and 5% as the errors on $(\Delta \nu)$ and $\nu_{\text{max}}$. We list 2$\sigma$ uncertainties for log g.

| Star Name   | log g (dex) | log $g_{\text{radex} \text{[Fe/H]}}$ (dex) |
|-------------|-------------|------------------------------------------|
| HD 10700    | 4.55 ± 0.02 | 4.57 ± 0.02                              |
| HD 17051    | 4.40 ± 0.02 | 4.39 ± 0.03                              |
| HD 23249    | 3.81 ± 0.02 | 3.78 ± 0.04                              |
| HD 49385    | 3.98 ± 0.02 | 3.97 ± 0.04                              |
| HD 52265    | 4.28 ± 0.02 | 4.24 ± 0.02                              |
| HD 61421    | 3.98 ± 0.02 | 3.97 ± 0.03                              |
| HD 63077    | 4.22 ± 0.02 | 4.25 ± 0.03                              |
| HD 102870   | 4.11 ± 0.02 | 4.10 ± 0.04                              |
| HD 121370   | 3.82 ± 0.03 | 3.82 ± 0.03                              |
| HD 139211   | 4.20 ± 0.02 | 4.21 ± 0.02                              |
| HD 160091   | 4.22 ± 0.02 | 4.21 ± 0.02                              |
| HD 165341   | 4.54 ± 0.02 | 4.54 ± 0.02                              |
| HD 170987   | 3.98 ± 0.02 | 3.98 ± 0.03                              |
| HD 181420   | 4.15 ± 0.02 | 4.15 ± 0.03                              |
| HD 181906   | 4.22 ± 0.02 | 4.23 ± 0.02                              |
| HD 186408   | 4.28 ± 0.02 | 4.28 ± 0.03                              |
| HD 186427   | 4.36 ± 0.02 | 4.35 ± 0.03                              |
| HD 185395   | 4.22 ± 0.02 | 4.23 ± 0.02                              |
| HD 205608   | 4.35 ± 0.02 | 4.37 ± 0.04                              |
| HD 210302   | 4.23 ± 0.02 | 4.24 ± 0.03                              |
| KIC 3632418 | 4.00 ± 0.03 | 4.01 ± 0.04                              |
| KIC 3656476 | 4.23 ± 0.02 | 4.23 ± 0.03                              |
| KIC 4914923 | 4.21 ± 0.02 | 4.21 ± 0.03                              |
| KIC 5184732 | 4.26 ± 0.02 | 4.25 ± 0.02                              |
| KIC 5512589 | 4.05 ± 0.02 | 4.04 ± 0.04                              |
| KIC 6106415 | 4.29 ± 0.02 | 4.30 ± 0.03                              |
| KIC 6116048 | 4.25 ± 0.02 | 4.27 ± 0.03                              |
| KIC 6603624 | 4.32 ± 0.02 | 4.32 ± 0.02                              |
| KIC 6933899 | 4.09 ± 0.02 | 4.09 ± 0.04                              |
| KIC 7680114 | 4.18 ± 0.02 | 4.17 ± 0.04                              |
| KIC 7976303 | 3.89 ± 0.02 | 3.92 ± 0.04                              |
| KIC 8006161 | 4.48 ± 0.02 | 4.48 ± 0.02                              |
| KIC 8228742 | 4.02 ± 0.03 | 4.02 ± 0.04                              |
| KIC 8379927 | 4.36 ± 0.02 | 4.40 ± 0.02                              |
| KIC 8786041 | 4.31 ± 0.02 | 4.35 ± 0.03                              |
| KIC 10018963| 3.96 ± 0.03 | 3.96 ± 0.03                              |
| KIC 10516996| 4.17 ± 0.02 | 4.18 ± 0.03                              |
| KIC 10963065| 4.28 ± 0.02 | 4.29 ± 0.04                              |
| KIC 11244118| 4.09 ± 0.02 | 4.08 ± 0.03                              |
| KIC 11713510| 4.05 ± 0.04 | 4.05 ± 0.03                              |
| KIC 12096504| 4.21 ± 0.02 | 4.21 ± 0.03                              |
| KIC 12258514| 4.12 ± 0.02 | 4.12 ± 0.03                              |

5 Kepler Astroseismic Science Consortium, see http://astro.phys.au.dk/KeASC/.

and log g and summarize the uncertainties and systematics as a function of magnitude.

5.1 Observations

During the first 9 months of the Kepler mission targets to be monitored with a 1 minute cadence during 1 month each were selected by the KASC\(^5\). These stars were chosen based on information available in the Kepler Input Catalog, KIC, \cite{Brown2011} and were expected to exhibit solar-like oscillations. A total of 588 stars with values of log g between 3.0 and 4.5 dex were analysed \cite{Garcia2011} and had their global seismic quantities determined \cite{Huber2011,Verner2011,Chaplin2011}. In this paper we concentrate on a subset of 403 less-evolved stars with log g values between 3.75 and 4.50 dex derived from RadEx10, the range for which we have validated our method.

The global seismic quantities have been determined using the SYD pipeline as described by \cite{Huber2009}, which uses the reference values of $(\Delta \nu)_{\odot} = 135.1$ $\mu$Hz and $\nu_{\text{max,}\odot} = 3,090$ $\mu$Hz. To avoid systematic errors (Chaplin, et al. in prep.), we adopted these same values in our grid. The uncertainties on the seismic quantities include a contribution from the scatter between different analysis pipelines \cite{Verner2011, Chaplin2011}. Figure 5 shows the cumulative distribution for the errors in the seismic observations, $(\Delta \nu)$ (top) and $\nu_{\text{max}}$ (bottom) in units of $\mu$Hz and $\%$, respectively, for the 403 stars. Our choice for absolute and relative errors is for consistency with units used in the recent literature. We show the cumulative distribution of the errors in order to see the typical errors for 50% and 80% of the sample, which justifies the errors that we used in Sect. 5.3. These are less than 1.1/2.0 $\mu$Hz for $(\Delta \nu)$, and less than 5%/8% for $\nu_{\text{max}}$, respectively.

The $T_{\text{eff}}$ derived by the KIC have been shown not to
be accurate on a star-to-star basis [Molenda-Zakowicz et al. 2011], and so the ground-based Kepler support photometry [Brown et al. 2011] was re-analysed by Pinsonneault et al. (2012) to determine more accurate $T_{\text{eff}}$ for the ensemble of Kepler stars. These are the temperatures that we adopt for our first analysis and we refer to them as $T_{\text{eff Pin}}$. In their work they consider a mean $\text{[Fe/H]} = -0.20 \pm 0.30$ for all of the stars. Silva Aguirre et al. (2012) adapt an infra-red flux method presented by Casagrande et al. (2010) for determining stellar temperatures. In their work they apply this method to the large ensemble of Kepler stars to provide an alternative determination of $T_{\text{eff}}$. We also adopt their $T_{\text{eff}}$ in determinations in order to study the effect of biases in temperature estimates on the derived value of log $g$. We refer to these temperature estimates as $T_{\text{eff irfm}}$. Support spectroscopic data have also been obtained for 93 of the stars and the metallicities are presented in Bruntt et al. (2012). We further include these data to study the effects of possible biases arising from lack/inclusion of metallicity information.

5.2 Seismic log $g$ from different sets of observations

Using our validated method described in Sect. 3.2 we calculated values of log $g$ and their uncertainties for the sample of 403 stars using the set of observations comprising \{\(T_{\text{eff Pin}}, \langle \Delta \nu \rangle, v_{\text{max}}\)\} while adopting a mean $\text{[Fe/H]} = -0.20 \pm 0.30$ dex. We refer to this as the set of observational constraints comprising \{\(T_{\text{eff Pin}}, \langle \Delta \nu \rangle, v_{\text{max}}\)\}. The accuracy of those for the reference set are 0.015 dex. The subset is shown in Fig. 6. Here it can be seen that typical uncertainties in log $g$ for this set of 403 Kepler stars is below 0.02 dex (there is one star with an error of 0.05 dex), with a mean value of 0.015 dex.

In Figure 5 we show the difference in the fitted log $g$ while considering different input observational sets compared to the reference set \{log $g_{\text{ref}}$\}. The subsets are: Set 1 which considers \(\langle \Delta \nu \rangle\) and $T_{\text{eff Pin}}$ only and Set 2 which considers \(\langle \Delta \nu \rangle\), $v_{\text{max}}$, and $T_{\text{eff irfm}}$. We note that for all of the analyses \[\text{[Fe/H]}\] was constrained to $-0.20 \pm 0.30$ dex, which corresponds to 90% of the models of the grid.

Inspecting the top panel of Fig. 1 (Set 1) one can see that by omitting $v_{\text{max}}$ as an observed quantity can result in differences of over 0.05 dex for a very small percentage of the stars, but the absolute difference between the full set of results is $+0.005$ dex with an rms of 0.01 dex. Here, we note that several authors have investigated the relation between \(\langle \Delta \nu \rangle\) and $v_{\text{max}}$ and find tight correlations [Bedding & Kjeldsen 2003; Stello et al. 2009]. The uncertainties arising from a set of data with less constraints usually increases and we indeed find an increase in the uncertainties $\sigma$ of $\sim 0.01$ dex. The extra scatter of 0.01 dex is taken care of in the larger $\sigma$.

Inspecting the lower panel of Fig. 2 (Set 2) one can see that the $T_{\text{eff}}$ derived by using different photometric scales results in a mean difference in log $g$ of $-0.002$ dex (i.e. no significant overall effect) with an rms of 0.006 dex. This latter fact implies that we can expect to add just under 0.01 dex to the error budget in log $g$ by considering $T_{\text{eff}}$ derived from different methods. We found a similar result in Sect. 5.3 for $\beta$ Hydri.

The mean value of the derived uncertainties ($\sigma$) in log $g$ for Set 1 and 2 are 0.023 and 0.015 dex, respectively, while those for the reference set are 0.015 dex. The accuracy of these log $g$ (if we consider the reference set to be correct) is within a precision of 1$\sigma$.

Figure 3 compares the derived log $g$ using the reference set of observations, to those with measured $T_{\text{eff}}$ and \[\text{[Fe/H]}\] from Bruntt et al. (2012). The absolute mean residual is 0.002 dex and is highlighted by the dotted grey line. We find that log $g$ can differ by up to 0.02 dex by including \[\text{[Fe/H]}\]. This 0.02 dex is also consistent with what we found in Sect. 5.3 for $\beta$ Hydri when we considered different metallicity constraints.

5.3 Comparison of results using different codes

To investigate the possible source of systematics arising from using a different evolution code and input physics, we determined log $g$ using a second pipeline code, Yale-
Bham (Gai et al. 2011; Creevey et al. 2012a). Details of the code can be found in the cited papers. Here, it suffices to know that the method is very similar to that of RadEx10, but the evolution code is based on YREC (Demarque et al. 2005) in its non-rotating configuration, with the following specifications: OPAL EOS (Rogers & Nyfond 2002) and OPAL high-temperature opacities (Iglesias & Rogers 1996) supplemented with low-temperature opacities from Ferguson et al. (2007), and the NACRE nuclear reaction rates (Angulo et al. 1999). Diffusion of helium and heavy elements were included, unlike RadEx10.

Figure 7 shows the difference in the derived value of log g between RadEx10 and Yale-Bham using \( \langle \Delta \nu \rangle, \nu_{\text{max}}, T_{\text{eff PIN}} \). We show the normalised difference, i.e. divided by the Yale-Bham errors, which are very similar to the RadEx10 errors. As can be seen from the figure the agreement in log g between the different methods is within 1σ or \(< 0.01\) dex for 98% of the stars and 2σ for all stars except one. A small absolute difference of 0.005 is found with an rms of 0.005 (units of σ). This is most likely due to the different physics adopted in the codes. A very slight systematic trend is present with a slope of \(-0.005 \pm 0.005\). The agreement between the results using the different codes and methods is very encouraging. We can consider an upper limit of 0.01 dex as a typical systematic error arising from employing different codes.

Figure 9. The difference between the values of log g obtained by RadEx10 and Yale-Bham as a function of Radex10 log g and normalised by the Yale-Bham errors. See Sect. 5.3 for details.

Figure 10. Distribution of derived uncertainties in the seismic log g from RadEx10 for 403 Kepler V/IV stars as a function of SDDS r magnitude.

Figure 10 shows the uncertainties in log g as a function of magnitude (obtained from the KIC) while using the reference set of observations. As the figure shows, precision improves with apparent brightness, where more reliable measurements have smaller error bars. We can expect typical uncertainties in log g of less than 0.03 dex for the full sample with a mean value of \(< 0.02\) dex.

In Table 6 we summarize for different apparent magnitude bins 1) the mean uncertainties \( \langle \sigma \rangle \) and 2) the mean
systematic errors $\langle s \rangle$ arising from adopting different temperature scales $\langle \sigma_{\text{eff}} \rangle$, metallicities $\langle \sigma_{[\text{Fe/H]}_\text{s}} \rangle$ and different pipeline codes $\langle \sigma_{\text{code}} \rangle$. Note that the sample size for the bin with $r < 9$ is much smaller than the others and this is the reason we find a larger $\sigma_{[\text{Fe/H]}_\text{s}}$ for $r < 9$. In the last row we give the mean uncertainty and the adopted systematic errors over the full sample.

5.5 Summary of results for the sample of Kepler stars

From the sample of Kepler data with $3.75 < \log g < 4.50$ derived from seismic data, we obtain a mean precision $\sigma$ of between 0.01 and 0.02 dex (max 0.03 dex for 99% of stars) when $\left< \Delta v \right>$, $v_{\text{max}}$, and $T_{\text{eff}}$ are used as the input constraints for the pipeline analysis. A typical systematic error $s$ of 0.01 dex can be added to account for a possible systematic error in $T_{\text{eff}}$, such as that obtained by applying different calibration methods to photometry. Similarly, we can add a systematic error of 0.02 dex due to an incorrect or lack of a [Fe/H] measurement. We also showed that using different models and physics in the pipeline analyses yields results in log $g$ consistent to within 0.01 dex i.e. almost no model dependence.

Eliminating one of the seismic indices from the set of data yields a zero offset in the results for the full sample of stars and a typical scatter of 0.01 dex, although differences of over 0.05 dex were found for $< 1\%$ of the stars.

6 DISCUSSION

The first objective of this study was to investigate if we can determine log $g$ reliably using global seismic quantities and atmospheric data. We showed that our method is reliable by comparing our results with values of log $g$ derived from direct mass and radius estimates of seven bright nearby stars. We then applied our method to a list of 40 Sun-like stars and derived log $g$ to within 1σ ($\sim 0.01$ dex) of those from Mathur et al. (2012) and Silva Aguirre et al. (2012). We also showed that for a sample of 400+ Kepler stars ($6 < r < 12$) with log $g$ between 3.75 and 4.50 dex typical uncertainties $\sigma$ of less than 0.02 dex can be expected and we estimated systematic errors $s$ of no more than 0.04 dex arising from errors in $T_{\text{eff}}$ and [Fe/H] measurements and using different codes.

Table 6. Summary of uncertainties $\sigma$ and systematic errors $s$ in the seismic log $g$ from the Kepler sample of stars as a function of magnitude. We give the mean values $\langle \rangle$ of each over the sample that falls into the corresponding magnitude bin. The systematic errors $s$ have subscripts which refer to possible sources of errors in the input $T_{\text{eff}}$, [Fe/H], and the code that is used to generate the stellar models (see Sects. 4 and 5 for details). In the final row we summarize the mean uncertainties and adopted systematic errors for the full sample.

| $r$ (mag) | $\langle \sigma \rangle$ (dex) | $\langle \sigma_{\text{eff}} \rangle$ (dex) | $\langle \sigma_{[\text{Fe/H]}_\text{s}} \rangle$ (dex) | $\langle \sigma_{\text{code}} \rangle$ (dex) |
|----------|-------------------------------|----------------------------------------|-------------------------------|----------------------------------------|
| $6 < r < 9$ | 0.012 | 0.004 | 0.014 | 0.005 |
| $9 < r < 10$ | 0.014 | 0.004 | 0.009 | 0.004 |
| $10 < r < 11$ | 0.016 | 0.009 | ... | 0.006 |
| $11 < r < 12$ | 0.017 | 0.009 | ... | 0.006 |

All of the Kepler stars will be observed by the Gaia mission, and for this reason they provide a valid set of calibration stars, by constraining log $g$ with precisions and accuracies much better than spectroscopic or isochrone methods provide for the current list of calibration stars for Gaia. The astrophysical parameters to be determined from Gaia data using the astrometry, photometry and BP/RP spectrophotometry are $T_{\text{eff}}$, $A_G$, [Fe/H], and log $g$. By ensuring that the GSP__Phot methods deliver log $g$ consistent with the seismic value will reduce the uncertainties and inaccuracies in the other parameters. Moreover, an independent log $g$ provides an extra constraint for the determination of the atmospheric parameters from GSP__Spec where degeneracies between $T_{\text{eff}}$ and log $g$ severely inhibit the precision of atmospherically extracted parameters and chemical abundances.

While in this paper we concentrated primarily on using Kepler data to determine log $g$, we note that both the CoRoT and Kepler fields have great potential in other aspects. For example, Miglio et al. (2012) and Miglio et al. (2013) determine distances, masses, and ages of red giants from the CoRoT fields to constrain galactic evolution models, while Silva Aguirre et al. (2012) develop a method which couples asteroseismic analyses with the infrared flux method to determine stellar parameters including effective temperatures and bolometric fluxes (giving angular diameters), and hence distances. The distances obtained by both Miglio et al. (2013) and Silva Aguirre et al. (2012) can be compared directly with a Gaia distance for either calibration of Gaia data or stellar models. By combining data from CoRoT and Kepler with those from Gaia we can also determine extremely precise angular diameters by coupling a seismically determined radius with the Gaia parallax. Finally, these stars will also be excellent calibrators for the FLAME workpackage of Gaia, which aims to determine masses and ages for one billion stars.

7 CONCLUSION

In this work we explored the use of F, G, K IV/V stars observed in the Kepler field as a possible source of calibration stars for fundamental stellar parameters from the Gaia mission. Our first objective was to test the reliability/accuracy of a seismically determined log $g$, and using a sample of seven bright nearby targets we proved that seismic methods are accurate (see Fig. 2) by obtaining results to within 0.01 dex of the currently accepted log $g$ values. We showed, however, that the accuracy of the input atmospheric parameters does play a role in the accuracy of the derived parameters. For $\beta$ Hydri we found that errors in the atmospheric parameters, and in particular [Fe/H], can change log $g$ by 0.02 dex.

We then applied our grid-based method RadEx10 to an extended sample of stars from the literature. We derived their seismic log $g$ and these are given in Table 4. We showed that a grid-based log $g$ is consistent with the values of log $g$ obtained by detailed seismic analysis from Mathur et al. (2012) for 22 stars and in excellent agreement.
with the results from Silva Aguirre et al. (2012) for the 6 common stars. We find typical precisions in \( \log g \) of 0.02 dex.

We finally studied the distribution of errors in \( \log g \) from two analysis methods for a sample of 403 *Kepler* stars with 3.75 < \( \log g \) < 4.5, and we obtained a typical uncertainty of between 0.01 and 0.02 dex in \( \log g \) for F, G, K IV/V stars (see Table 5). We can add a total of 0.04 dex as a systematic error which arises from the adopted temperature scales (0.01 dex) and measured metallicities (0.02 dex) as well as the grids of models used (0.01 dex), which differ in evolution codes and input physics. The precisions in the data are unprecedented, and the systematic errors are much smaller than those stemming from any other method, especially for 7 < \( V \) < 12 stars (see e.g. Creevey et al. 2012a Figure 1 and Table 3 which compare spectroscopically derived \( \log g \) for five *Kepler* stars with \( V \approx 11 \)).

As a final remark, we highlight that while there are >500 IV/V stars in the *Kepler* field and some in the CoRoT fields that exhibit Sun-like oscillations, there are also 1000s of red giants in both CoRoT and *Kepler* fields with these same measured quantities, however, the accuracy of these stars’ seismic \( \log g \) is yet to be studied.

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