

A Catalogue of Solar-Like Oscillators Observed by TESS in 120-second and 20-second Cadence

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ABSTRACT

Context. The Transiting Exoplanet Survey Satellite (TESS) mission has provided photometric light curves for stars across nearly the entire sky. This allows for the application of asteroseismology to a pool of potential solar-like oscillators that is unprecedented in size.

Aims. We aim to produce a catalogue of solar-like oscillators observed by TESS in the 120-second and 20-second cadence modes. The catalogue is intended to highlight stars oscillating at frequencies above the TESS 30-minute cadence Nyquist frequency with the purpose of encompassing the main sequence and sub-giant evolutionary phases. We aim to provide estimates for the global asteroseismic parameters ν_{\max} and $\Delta\nu$.

Methods. We apply a new probabilistic detection algorithm introduced by Nielsen et al. (2022) to the 120-second and 20-second light curves of over 250,000 stars. This algorithm flags targets that show characteristic signatures of solar-like oscillations. We manually vet the resulting list of targets to confirm the presence of solar-like oscillations. Using the probability densities computed by the algorithm, we measure the global asteroseismic parameters ν_{\max} and $\Delta\nu$.

Results. We produce a catalogue of 4,177 solar-like oscillators, reporting $\Delta\nu$ and ν_{\max} for 98% of the total star count. The asteroseismic data reveals vast coverage of the HR diagram, populating the red giant branch, the subgiant regime and extending toward the main-sequence.

Conclusions. A crossmatch with external catalogs shows that 27 of the detected solar-like oscillators are a component of a spectroscopic binary, and 29 are confirmed planet host stars. These results provide the potential for precise, independent asteroseismic constraints on these and any additional TESS targets of interest.

Key words. Asteroseismology – Catalogs – Stars: oscillations – Methods: data analysis

1. Introduction

Asteroseismology, the study of the intrinsic oscillations of stars, has revealed the physical properties of thousands of stars to high precision (e.g. Metcalfe et al. 2014; Lebreton & Goupil 2014; Lagarde et al. 2015; Serenelli et al. 2017; Yu et al. 2018; Yıldız et al. 2019). Solar-like oscillators, where-in modes are excited and damped by the turbulent motion of gas in the outer convection zone, have been of particular interest due to the host of identifiable overtones present in their oscillation power spectra. The spectra of such stars can be characterized via two global parameters, the large frequency separation ($\Delta\nu$) and the frequency at maximum power (ν_{\max}). The former describes the regular frequency interval separating overtone modes of a given angular degree. The latter refers to the central frequency of the Gaussian-like envelope describing the visible power excess caused by the

modes. These two parameters are the most readily available in the spectrum of a solar-like oscillator and, when combined with an independent measure of effective surface temperature (T_{eff}), can be exploited to determine the mass and radius of a star to within a few percent (Silva Aguirre et al. 2012; Huber et al. 2012; Guggenberger et al. 2016; Gaulme et al. 2016; Yıldız et al. 2016; Li et al. 2021; Mathur et al. 2022).

With the only requirement for the excitation of modes being the presence of an outer convection zone, solar-like oscillations have been observed in stars on the main sequence (e.g. Chaplin et al. 2014), in the subgiant phase (e.g. Appourchaux et al. 2012b; Mathur et al. 2022), and on the red giant branch (e.g. Bedding et al. 2010; Yu et al. 2018; Çelik Orhan et al. 2021). As a given star evolves through these phases, structural changes will affect the properties of the oscillations. The least evolved stars oscillate at a few thousand μHz . This decreases as the star evolves off the main-sequence, dropping to below $\sim 100 \mu\text{Hz}$ on the red giant branch. Despite the large cover-

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age of the Hertzsprung-Russell (HR) diagram, current catalogues are disjoint in evolutionary state. Detections are dominated by a large number of red giants and a much smaller set of main-sequence stars, with the subgiant phase only sparsely sampled. Although a decrease in numbers is expected during this phase, given their rapid evolution, observational constraints have magnified the discrepancy.

Relying predominantly on space-based photometry means observations of solar-like oscillators are mostly limited to data collected by a handful of missions. Of these, the *Kepler* (Borucki et al. 2010) mission provides the longest time series for a large number of available targets. Observing the same patch of sky for four years, the mission monitored approximately 196,000 targets (e.g. Huber et al. 2014). Data were collected in two modes - long and short-cadence, with the associated sampling rates corresponding to Nyquist frequency limits of 283 μHz and 8496 μHz , respectively. The short-cadence data spans the full range in frequency where solar-like oscillations are located. However, due to telemetry constraints, the number of targets observed in the longer cadence greatly outnumbered those in short. Indeed, of the total observed targets only a few thousand were selected for short-cadence (Thompson et al. 2016). Therefore, of the tens of thousands of solar-like oscillators detected using *Kepler* data, the vast majority are more evolved stars (Stello et al. 2013; Hekker et al. 2011; Yu et al. 2018).

Although sparse in comparison, detections of solar-like oscillators were made in the short-cadence data (Chaplin et al. 2011b). Due to the reduced capacity for such observations, these slots were reserved for targets most suited to the main aims of the mission: the detection of exoplanets via the transit method. This led to the preferential selection of cool main sequence stars (Batalha et al. 2010). The combination of the selection criteria for the short-cadence observations and the Nyquist frequency in the long cadence data resulted in the asteroseismic yield lacking a significant number of subgiant stars. The largest list of such stars was constructed by Li et al. (2020) and numbers only 50 subgiants.

The TESS mission (Ricker et al. 2014) launched in 2018 and has been surveying the majority of the sky, providing an extensive database of potential solar-like oscillators. The nominal mission lasted two years and observations continue during the first extended mission, which will finish observing in September of 2022. To maximise the sky coverage, observations are made in sectors with an average length of 27.4 days. Most targets are captured in one or two sectors, while a small number of stars are located where the sectors overlap at the ecliptic poles (known as the *continuous viewing zones*). Similarly to *Kepler*, the majority of the stars monitored by TESS in the nominal mission were observed at 30-minute cadence (referred to as Full Frame Images, or FFIs), corresponding to a Nyquist frequency of 278 μHz . Currently the largest systematic searches for solar-like oscillators have been performed with observations at this cadence, and therefore restricted to the more evolved stars (Silva Aguirre et al. 2020; Hon et al. 2021; Mackereth et al. 2021; Stello et al. 2022). Shorter cadences are available for a smaller set of targets, with the nominal mission including a 120-second integration time (double the *Kepler* short-cadence). The extended mission introduced 20-second data for a reduced target list while the FFI cadence was shortened to 10-minutes. With Nyquist frequencies of 4167 μHz and 25000 μHz respectively, the 120-second and 20-second cadence data allow us to detect solar-like oscillations in less evolved solar-like oscillators.

To that end, we used 120-second and 20-second TESS data to search for oscillations in stars observed during Sectors 1 to

46. Starting with a smaller set of targets that were identified as the most likely to oscillate above the 30-minute FFI Nyquist frequency (Schofield et al. 2019), we have identified 400 candidate solar-like oscillators by eye. These were used to optimise a detection algorithm presented in Nielsen et al. (2022) (henceforth referred to as N22). We then passed the remaining stars observed during the aforementioned sectors to this tuned pipeline. Although the main aim of this work is to construct a list of solar-like oscillators, we found we could exploit the probability distributions calculated by the algorithm to measure the global properties (ν_{max} and $\Delta\nu$). Therefore, we provide these values for the majority of the detected solar-like oscillators.

2. Target Selection

The full list of targets observed in 120-second cadence by TESS exceeds 300,000. The Asteroseismic Target List (ATL, Schofield et al. 2019) gives some indication of which stars are most likely to be solar-like oscillators prior to running the algorithm. By separating this sample from the full set of 120-second cadence targets we can loosen detection constraints whilst keeping the required manual validation to manageable levels. To distinguish the stars in the ATL from the remaining targets observed in 120-second cadence we will refer to the latter sample as ‘the Large Sample’.

The ATL was constructed prior to the launch of TESS to provide a prioritised list of targets most likely to yield detections of solar-like oscillations (Schofield et al. 2019; see also Fausnaugh et al. 2021; Godoy-Rivera et al. 2021). Aimed at 120-second cadence data, the list was restricted to stars which would oscillate above the 30-minute FFI Nyquist frequency. To select targets the authors employed asteroseismic scaling relations for ν_{max} (Campante et al. 2016). This allowed them to locate stars in the TESS field-of-view predicted to have $\nu_{\text{max}} > 240 \mu\text{Hz}$. Calculating the expected power excess caused by the modes, the authors estimated the probability that the oscillations would be detectable. Only those targets with at least a 5% probability of making a detection were retained, which constituted $\approx 25,000$ targets. Of these, 11,220 had been observed at the time of this work. In the following analysis, values of parallax and T_{eff} (required by the detection algorithm) were taken from the ATL. The ATL used parallaxes from Gaia data release 2 (GDR2, Gaia Collaboration et al. 2018), supplemented at bright magnitudes with values from the eXtended Hipparcos Catalogue (XHIP, Anderson & Francis 2012). Effective temperatures in the ATL were computed from a polynomial in dereddened (B-V) colour, using coefficients according to Torres (2010).

The Large Sample consists of the remaining 120-second cadence targets. We selected stars brighter than 11th magnitude in 2MASS K_S magnitude, and used T_{eff} from the TESS Input Catalogue (TIC, Stassun et al. 2019) to restrict to the range 4500K $< T_{\text{eff}} < 6500\text{K}$. This includes the typical ranges in T_{eff} of stars from the main sequence to the red giant branch, and removes stars that are likely too faint for modes to be visible (Stello et al. 2017). In this set we analysed light curves for 255,089 stars. We applied the same cuts to all of the targets observed in 20-second cadence, which yielded light curves for 6157 stars. Parallaxes for both sets were again drawn from GDR2.

For reference, we also identified targets with a published detection of solar-like oscillations and some measure of the global asteroseismic parameters. A set of 13 such stars was produced, which is shown in Table 1 and referred to in the following as the ‘literature sample’. We prioritized targets oscillating at frequencies above the *Kepler* long-cadence Nyquist as per the main

aim of the catalogue. Parallaxes and effective temperatures were drawn from GDR2.

3. Data Selection

We used detrended light curves produced by the TESS Science Processing Operations Center (SPOC) pipeline (Jenkins et al. 2016), which carries out the simple aperture photometry and removes instrumental trends. We used light curves recorded in 120-second cadence, except when 20-second data were available. In the literature sample, we used 120-second cadence light curves for all but three stars (γ Pav, π Men and α Men), where we used 20-second cadence light curves. We used the open source package *Lightkurve* (Lightkurve Collaboration et al. 2018) to stitch sectors together, and remove flux values exceeding 5σ . As TESS observes in 27.4 day sectors, there are gaps present in the light curves. Both leaving the gaps and methods to fill the gaps (such as linear interpolation, Stello et al. (2015)) introduce strong correlations between frequency bins. Assuming mode lifetimes follow the relation given by Appourchaux et al. (2012a) (see also Lund et al. 2017), at $T_{\text{eff}} = 5000\text{K}$, we expect mode lifetimes on the order of weeks. Therefore, if a star is observed in the nominal mission and then a year later in the extended, we expect the modes have been re-excited so that the variability in the time series is no longer correlated, and hence we removed the gap in the data by shifting the timestamps. We then used the *Lightkurve* package to produce a power density spectrum via the ‘fast’ Lomb-Scargle method (Lomb 1976; Scargle 1982; Press & Rybicki 1989).

4. Detection of Solar-Like Oscillators

In the following section we briefly review the methods used in the detection algorithm of N22, before discussing the detections made in each set of targets. The detection test consists of two modules, which exploit different properties of solar-like oscillators:

1. **Power excess test:** The first module uses the power spectral density of the time series. Given the assumption that the noise in each frequency bin follows a χ^2 distribution with 2 degrees of freedom, the probability that only noise is present in a given bin is calculated (the H_0 probability). The probability that an envelope is present is then computed via a prediction of the expected power in a hypothetical envelope centered on each frequency bin (the H_1 probability). The prediction is calculated via the methods of Chaplin et al. (2011a) and Schofield et al. (2019), requiring T_{eff} . Prior information on ν_{max} is used, guided by parallax and 2MASS K_S -band magnitude.
2. **Large separation test:** The second module looks for the signature of the regularly spaced overtones. This is achieved using the methods described in Mosser & Appourchaux (2009), who used the autocorrelation function (ACF) of the time series. A band-pass filter is placed on the power spectrum at a test frequency and the ACF of this filtered time series is calculated via an inverse Fourier transform. Repeating this for other test frequencies, we produce a 2D ACF in test frequency (a proxy for ν_{max}) and lag (related to the large frequency separation via $\tau = 1/\Delta\nu$). This 2-dimensional map is collapsed along the lag axis to produce a 1-dimensional distribution in frequency. To evaluate whether the probability the observed collapsed ACF is inconsistent with noise, N22 approximate the response due to noise by a Γ distribution.

Using 400 solar-like oscillators and non-detections manually identified from the ATL, N22 established the performance of the pipeline for a range of detection thresholds. They found the pipeline was able to attain a true positive rate of 94.7% and a false positive rate of 8.2% when asking for a response at least one of the two modules¹.

In the following sections we discuss the detections made in the four samples via this algorithm. All of the reported solar-like oscillators have been manually vetted to check for false positives. We retain only targets in which we are confident we can identify the presence of oscillations, prioritizing a reduced false positive rate over maximising the yield. This may cause an under-representation of targets with very low signal-to-noise. A break down of the total counts, and which sample they belong to, can be seen in Table 2. Cross referencing with NASA’s Exoplanet Archive², we found 29 of the stars in our catalogue are confirmed planet hosts. The majority of these stars have not yet been studied asteroseismically. Asteroseismic inferences on these targets are reserved for an upcoming work. We also cross-referenced with the *Ninth Catalogue of Spectroscopic Binary Orbits* Pourbaix et al. (SB9, 2004) discovering a further 27 stars are components in spectroscopic binary systems.

Fig. 1 shows the value of 2MASS K_S magnitude against the predicted value of ν_{max} . In grey we show targets observed in 120-second cadence with a detection probability greater than 10% using the methods described by Chaplin et al. (2011a) and Schofield et al. (2019). We did not detect solar-like oscillations in any targets with $\nu_{\text{max}} < 5 \mu\text{Hz}$, regardless of magnitude. As discussed in N22, the predicted mode amplitude used in the power excess module included the observed decrease near the red edge of the δ Scuti instability strip. This is included via a factor which depends on ν_{max} and T_{eff} , so that at a given temperature amplitudes decrease as a function of frequency. At $T_{\text{eff}} = 4800\text{K}$ the factor decreases to approximately zero at frequencies below $5 \mu\text{Hz}$. Therefore, we did not expect to make detections in the most evolved red giants.

4.1. Literature Sample

Of the 13 solar-like oscillators drawn from the literature, the algorithm flagged a detection in both modules for 11 stars. μ Ara produced a response in the power excess module, but not the repeating pattern. Oscillations in this star have thus far only been detected in Doppler velocity (Bouchy et al. 2005). As the signal from granulation is lower relative to the modes in velocity measurements than in photometry (Basu & Chaplin 2017), the single module response is likely just an effect of the decreased signal-to-noise. The remaining star, HD19916, did not produce a flag in either module. Although oscillations in HD19916 have been detected in TESS 120-second cadence data the authors note that a custom aperture had to be used, expanding to include more of the stellar flux (Addison et al. 2021). To maintain consistency with the rest of our catalogue, we did not mimic this approach. We note that the stars with detections reported in 20-second data (γ Pav, π Men and α Men) produced flags in both modules. However, if we use the available 120-second data for the same stars, one is not detected at all (π Men) and the others are only detected in the power excess module, despite oscillating at frequencies well below the corresponding Nyquist frequency limit. The im-

¹ This is achieved when taking a threshold of 0.77 on the power excess module and 0.73 on the frequency spacing module.

² <https://exoplanetarchive.ipac.caltech.edu>

Table 1: Global asteroseismic parameters of stars in the literature sample.

Common Name	TIC	ν_{\max} [μHz]	$\Delta\nu$ [μHz]	Source
HD 19916	TIC200723869	1188 ± 40	61.4 ± 1.5	TESS 120-second ¹
HD 222416	TIC441462736	430 ± 18	28.94 ± 0.15	TESS 120-second ²
λ^2 For	TIC122555698	≈ 1280	69.76 ± 0.23	TESS 120-second ³
HD 212771	TIC12723961	226.6 ± 9.4	16.25 ± 0.19	TESS 30-minute FFI ⁴
HD 222076	TIC325178933	203.0 ± 3.6	15.60 ± 0.13	TESS 120-second ⁵
94 Aqr	TIC214664574	875 ± 12	50.2 ± 0.4	TESS 120-second ⁶
γ Pav	TIC265488188	2693 ± 95	119.9 ± 1.0	TESS 20-second ⁷
π Men	TIC261136679	2599 ± 69	116.7 ± 1.1	TESS 20-second ⁷
ν Ind	TIC317019578		25.08 ± 0.10	TESS short ⁸
β Hyi	TIC267211065	≈ 1000	57.24 ± 0.16	HARPS and UCLES, WIRE ⁹
μ Ara	TIC362661163	≈ 2000	89.68 ± 0.19	HARPS ¹⁰
μ Her	TIC460067868	1216 ± 11	64.2 ± 0.2	SONG ¹¹
α Men	TIC141810080	3134 ± 440	140 ± 2	TESS 20-second ¹²

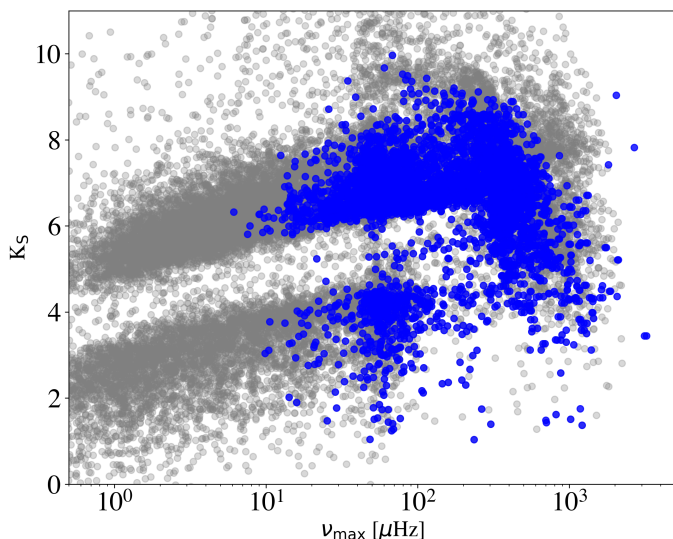
¹ Addison et al. (2021)² Huber et al. (2019)³ Nielsen et al. (2020)⁴ Campante et al. (2019)⁵ Jiang et al. (2020)⁶ Metcalfe et al. (2020)⁷ Huber et al. (2022)⁸ Chaplin et al. (2020)⁹ Bedding et al. (2007), Karoff et al. (2007)¹⁰ Bouchy et al. (2005)¹¹ Grundahl et al. (2017)¹² Chontos et al. (2021)

Fig. 1: 2MASS K_S Magnitude and predicted ν_{\max} for stars observed in 120-second cadence with a detection probability exceeding 10% (grey). The targets which we identified as solar-like oscillators are marked in blue.

provement made by the 20-second data was highlighted by Huber et al. (2022).

4.2. Asteroseismic Target List

To construct the set of stars used to establish the performance of the detection algorithm in N22, a manual inspection of the 11,220 spectra discussed in Sect. 2 was performed. On the construction of the the sets of 400 oscillators and 400 ‘non-oscillators’, several stars fell into the category of targets where, although some excess power was present in the spectrum, we were unable to unambiguously classify the target as a solar-like oscillator. Since that work was done, new sectors of data had become available, which could facilitate unambiguous classification. We therefore re-ran the algorithm on the full set of 11,220 spectra. In total 2651 stars were flagged in just one module and

490 in two. Of the first group, the vast majority presented some large non-solar type signal (such as periodic dips caused by a transit, eclipse, or classical oscillations). Such stars were not included in the metrics stated in N22. Including these stars in the false-positive metric for a single module response increases the percentage to $\approx 20\%$. With the false positives removed an additional 383 targets passed the manual vetting step in total. This increased our yield from 369 to 752 solar-like oscillators.

4.3. Large Sample

Of the 255,089 stars for which we analysed light curves, 37,250 flagged in at least one module. With an expected false positive rate of 8.2%, if we assume the majority of the stars observed are not detectable as solar-like oscillators then false positives exceeding 10,000 are entirely possible. Therefore we took the more conservative approach and performed a manual inspection of stars that produced a flag in both modules. Of the 5,781 stars which produced flags in both modules, we found 2,927 clear solar-like oscillators.

4.4. 20-second Cadence

Of the 6157 stars in this set, the algorithm produced a single module response for 1585, and a double module response for 421. Upon visual inspection of these targets, we were able to clearly identify 490 solar-like oscillators.

5. Global Asteroseismic Parameters

Alongside enabling detection, the probability distributions calculated in the detection process allow us to measure the global asteroseismic parameters $\Delta\nu$ and ν_{\max} . There are already a number of pipelines dedicated to measuring these parameters via different methods (Huber et al. 2009; Hekker et al. 2010; Kallinger et al. 2010; Mathur et al. 2010; García et al. 2014; Elsworth et al. 2017; Zinn et al. 2019). However, as the main aim of this work is the construction of a list of solar-like oscillators, a full comparison between our method and such alternatives is reserved for future work.

Table 2: Detection counts in each sample. ‘Double’ refers to cases where the star flagged a detection in both the power excess and repeating pattern modules. ‘Single’ refers to cases where the star flagged in one module only.

Sample	Double	Single	Total
Literature	11	1	12
ATL	494	258	752
Large	2927	-	2927
20-sec	288	198	486
Total	3720	457	4177

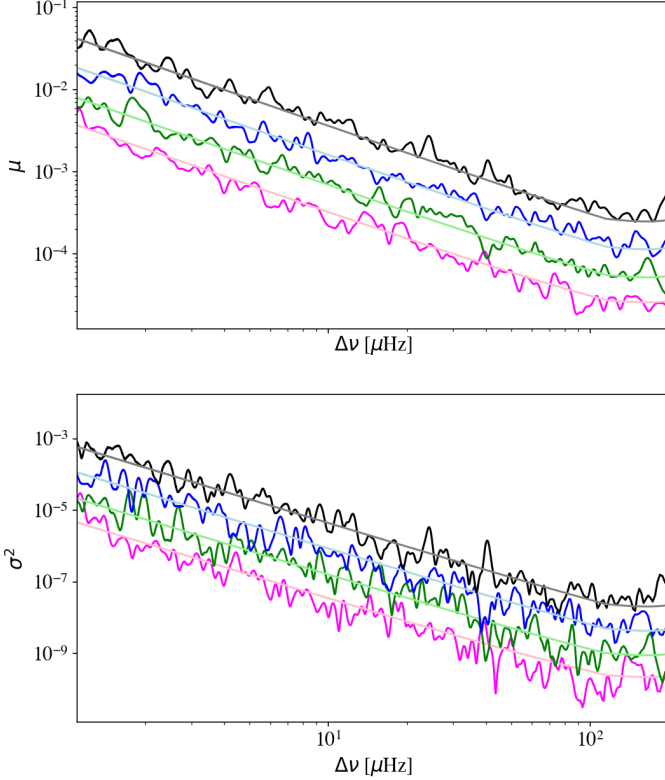


Fig. 2: Top panel: Mean simulated collapsed ACF as a function of $\Delta\nu$ for filtered white noise. Colours represent time series of different lengths, with one sector in black, four in blue, nine in green and twelve in magenta. Pale lines show the predictions for each length according to Eq. 2. Bottom panel: Variance on the simulated collapsed ACF presented in the top panel.

The probability distribution as a function of frequency calculated by the frequency spacing method (see Sect. 4) was normalized to unit integral over the spectrum, producing a probability density. The 50th percentile of this was used to measure ν_{\max} ,

Table 3: Parameters for Eq. 2 and 3.

Parameter	Value
B	1.54
α	0.65
β	0.36
c	0.34

with the 16th and 84th percentiles giving the confidence interval.

N22 only required the ACF collapsed along the lag (τ) axis to perform a detection. To determine $\Delta\nu$ we instead collapsed along test frequency. Rather than summing the ACF for all test frequencies at a given lag, we exploited the approximate relation between ν_{\max} and $\Delta\nu$ (Stello et al. 2009),

$$\frac{\tilde{\nu}_{\max}}{\nu_{\max,\odot}} = \left(\frac{\Delta\nu}{\Delta\nu_{\odot}} \right)^a, \quad (1)$$

where we took the value $a = 0.791$ as in N22. This estimate of ν_{\max} at a given $\Delta\nu$ ($\tilde{\nu}_{\max}$) allowed us to restrict the range of frequencies summed. Accordingly, we only summed bins in the range $|\nu_{\max} - \tilde{\nu}_{\max}| < 0.2\tilde{\nu}_{\max}$.

To calculate the expectation from a spectrum devoid of oscillations we utilized 10^3 white noise realizations. Similarly to N22 we found that, for filtered white noise, the noise statistics can be well approximated by a Γ distribution in lag. The mean of this distribution can be described by the empirical relation

$$\mu(\tau) = A(B + \tau^\alpha / N_v^\beta), \quad (2)$$

where N_v is the number of frequency bins included in the calculation of the ACF at a given τ . Utilizing the emcee package (Foreman-Mackey et al. 2013) we fitted for the parameters B , α and β , the results of which can be found in Table 3. The parameter A is a calibration constant which depends on the time series length and was determined on a star-by-star basis. Using Eq. 1 to estimate the value of $\Delta\nu$ ($\tilde{\Delta\nu}$) given the measured value of ν_{\max} , we masked the ACF in the range $0.7\tilde{\Delta\nu} < \Delta\nu < 1.3\tilde{\Delta\nu}$. The calibration factor A was then estimated by the ratio of the modelled to observed ACF in the first 5 μHz and final 50 μHz (with the latter range accounting for the decrease in frequency resolution at small lag).

We found that the variance in the collapsed ACF can be approximated by,

$$\sigma(\tau)^2 = c\mu(\tau)^2, \quad (3)$$

with the value of c determined by a fit to the white noise simulations (see Table 3). A comparison of the predictions from Eq. 2 and 3 to simulations of different time series length can be seen in Fig. 2. We also tested the model on data binned to different effective lengths. The net effect of the binning is an additional multiplicative factor, which is accounted for in the calibration.

We used Eq. 2 and 3 to establish the probability ($P_{\Delta\nu}$) that the collapsed ACF (r) at a given value of τ is inconsistent with noise. Logarithmic probabilities were used for numerical stability. Given that the envelope will cause an excess above the mean, we can label any divergences below the mean as noise. Therefore the natural choice is the survival function,

$$\log P_{\Delta\nu} = -\log \left(\int_r^\infty \frac{\beta^\alpha}{\gamma(\alpha)} r'^{\alpha-1} \exp(-\beta r') dr' \right), \quad (4)$$

where the shape parameter is $\alpha(\tau) = (\mu(\tau)/\sigma(\tau))^2$ and the scale parameter $\beta(\tau) = \mu(\tau)/\sigma(\tau)^2$. Normalizing $P_{\Delta\nu}$ to unit integral over the $\Delta\nu$ axis produces a probability density. The 50th percentile of this was used to measure $\Delta\nu$, with the 16th and 84th percentiles giving the confidence interval.

In the following sections we discuss the values of $\Delta\nu$ and ν_{\max} in each of our samples. We utilize our literature sample to briefly comment on the robustness of our methods in TESS data

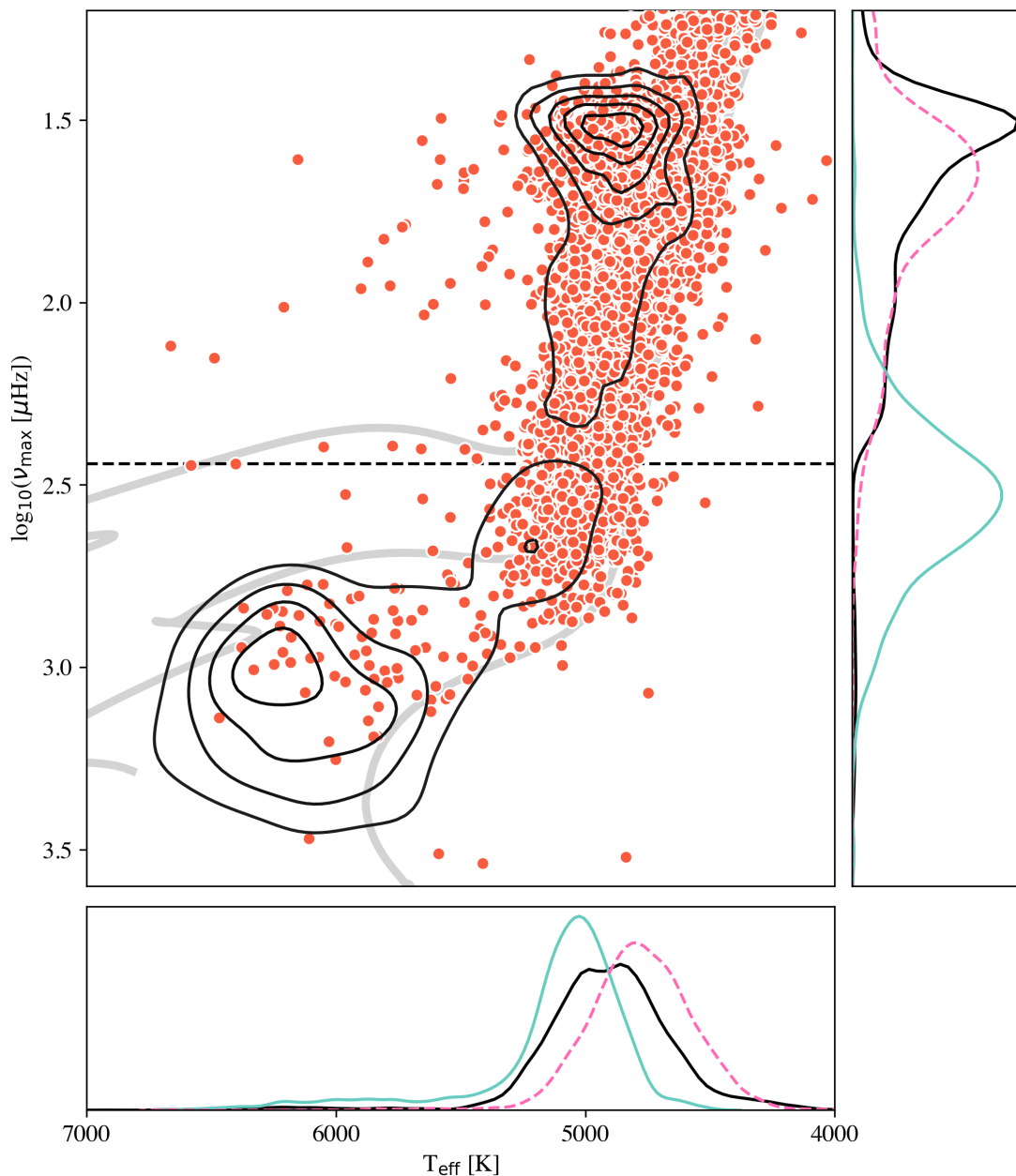


Fig. 3: The main panel shows an asteroseismic HR diagram for the stars in all samples (orange circles). Effective temperatures have been drawn from the TIC in all cases, to maintain consistency. Contour lines represent measurements from *Kepler* data reported in Yu et al. (2018), Lund et al. (2017) and Serenelli et al. (2017), with effective temperatures from GDR2. The horizontal dashed line represents the *Kepler* long cadence Nyquist frequency. Three stellar tracks at masses 1.0, 1.5 and 2.0 M_{\odot} generated by MIST (Choi et al. 2016) are shown in grey. The distributions in T_{eff} and ν_{max} are shown in the bottom and right panels, respectively. Here, the catalogue is split into the ATL set in turquoise and the Large Sample in pink (dashed) with the *Kepler* distribution shown in black.

compared to results produced largely from bespoke analysis of individual stars. We then go on to discuss the results in the remaining new detections. A summary of the catalogue can be seen in Fig. 3. Measurements that were manually identified as clear outliers in the $\nu_{\text{max}}-\Delta\nu$ plane were removed from the final catalogue. The values cleaned are shown in Fig. 1 of the appendix.

5.1. Literature Sample

Of the 13 targets making up the sample, 9 have published ν_{max} values with uncertainties. In the remaining stars, the authors fo-

cussed on determining individual frequencies rather than global parameters, and so estimates of ν_{max} without uncertainties were published. A comparison of the literature values to those measured by our method can be seen in Fig. 4. On average, the measured values of ν_{max} are larger than those reported in the literature by $\approx 2.5\%$. The star with largest fractional difference is HD 212771, where our value of ν_{max} is larger by $\approx 9\%$. The literature value was measured using FFI data processed by the TESS Asteroseismic Science Operations Center (TASOC) pipeline (Handberg et al. 2021). From visual inspection of the signal-to-noise spectrum of HD 212717 we found the envelope extended beyond the FFI Nyquist frequency. The attenuation

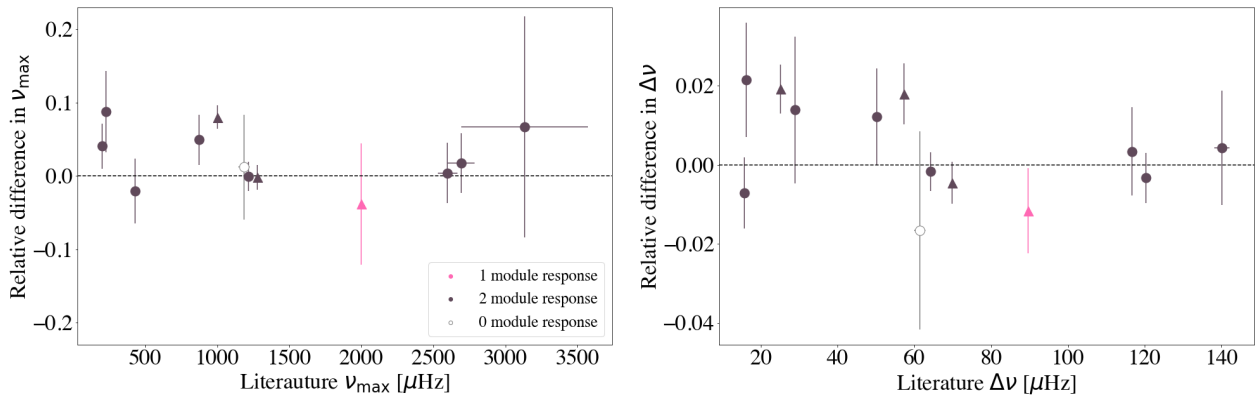


Fig. 4: A comparison of the global asteroseismic parameters measured by our algorithm to those reported in the literature. Stars are coloured by the number of modules in which they produce a flag; pink for a single module, brown for two modules and an open grey marker for none. Triangles represent stars for which no uncertainty on ν_{\max} was reported in the literature. The left and right panels show the fractional difference between the values of ν_{\max} and $\Delta\nu$ as measured by the algorithm versus literature value respectively.

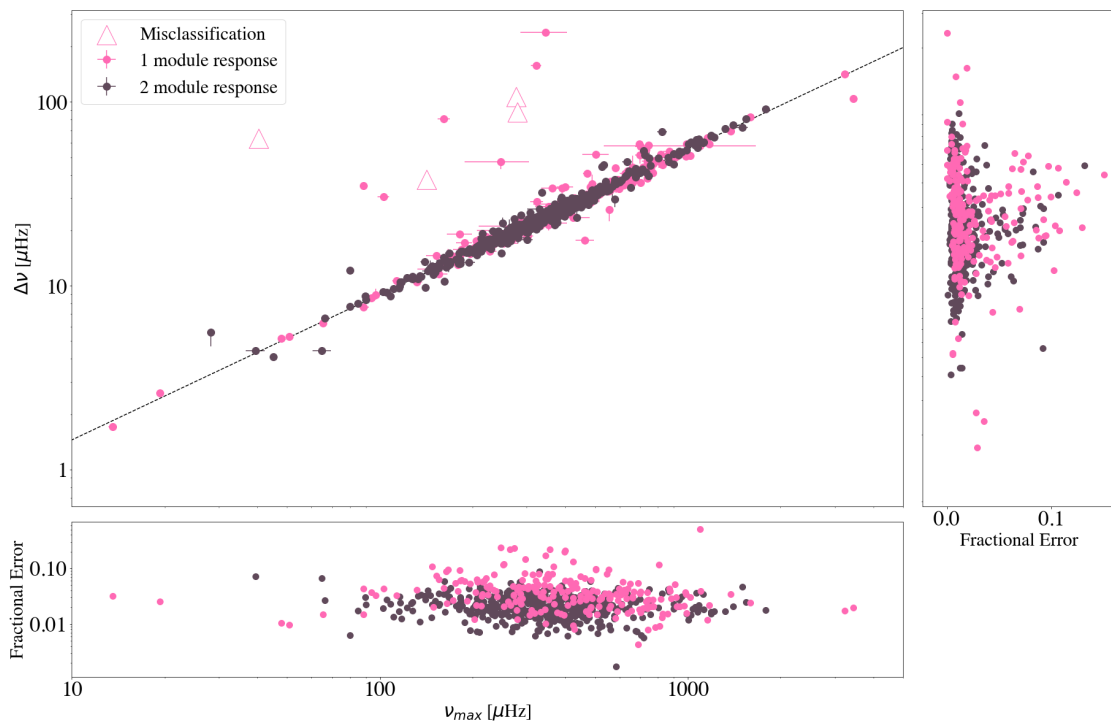


Fig. 5: The main panel shows $\Delta\nu$ as a function of ν_{\max} measured by the algorithm for validated solar-like oscillators from the ATL set. Stars producing flags in only one module are shown in pink, those producing flags in both modules are shown in brown. Triangles mark stars that were likely misclassified as solar-like oscillators. The black dotted line shows Eq. 1. Additional panels show the fractional uncertainties on $\Delta\nu$ and ν_{\max} .

caused by the sampling integration causes a decrease in power near the Nyquist frequency, which could have caused an underestimate on ν_{\max} in Silva Aguirre et al. (2020). Visual inspection of the power spectra confirms our higher value is more accurate.

In total 11 stars have measurements of $\Delta\nu$ in the literature. In the case of ν Ind, the most recent asteroseismic study was made in Chaplin et al. (2020), where the authors used a single sector of TESS data to fit individual modes. We measured $\Delta\nu$ from the gradient of a linear fit to the radial mode frequencies as a function of order (White et al. 2011). We took the same approach for λ^2 For where the authors also did not provide estimates of $\Delta\nu$ (Nielsen et al. 2020). A comparison of the values with those

from the algorithm can be seen in the right panel of Fig. 4. The agreement is better than for ν_{\max} , with a mean fractional difference on $\Delta\nu$ of 0.24%.

5.2. Asteroseismic Target List

Of the 752 validated solar-like oscillators, we report both $\Delta\nu$ and ν_{\max} for 739. In the majority of cases the determination of the two goes hand-in-hand, with both coming from the autocorrelation function collapsed along the relevant axis. However it is possible to detect the envelope without a signal from the frequency spacing.

In order to assess the quality of the measured ν_{\max} and $\Delta\nu$ values, we exploit the approximate scaling relation between the two (Eq. 1). Although there is a slight mass dependence in the exponent a (Stello et al. 2009), the general trend remains such that stars disagreeing significantly with the rest of the population may indicate an error in one (or both) of the measured values.

Fig. 5 shows the relation between the values of ν_{\max} and $\Delta\nu$ for the targets in the ATL sample. The majority of the stars with detections in both modules follow Eq. 1. The star with smallest $\Delta\nu$ is TIC 381975502 (CD-56 1110). Here, a background eclipsing binary introduced several harmonic peaks in the power spectral density at low frequency. These appear in the ACF as a large response at a test frequency corresponding to the frequency of the orbital harmonics, resulting in the algorithm incorrectly assigning both $\Delta\nu$ and ν_{\max} . This is also the case for TIC 271701447 (HR 4749; HD 108570).

For targets detected in just one module there is a larger scatter about the scaling relation as shown on Fig. 5. Using an exponent on Eq. 1 of $a = 0.791$ as calculated in N22, $\Delta\nu$ for 13 targets differs by more than 30% from the value predicted by the scaling relation and measured value of ν_{\max} . We performed a manual inspection of these stars and found four are likely misclassifications. A further two passed the detection threshold, both at the envelope and at a much lower frequency, biasing the resulting parameters. In three stars, the estimated ν_{\max} used in the prior was significantly higher than the observed value, being overestimated by factors of three, five and two. In these cases, the parallaxes reported in the ATL were drawn from XHIP rather than GDR2. The ν_{\max} predicted using GDR2 parallaxes produced a prior more consistent with the measured ν_{\max} . The remaining stars could be divided into two sets: Targets with less than one full sector of data and high- ν_{\max} targets with low mode amplitudes. The resulting low signal-to-noise could impact the determination of $\Delta\nu$.

In Fig. 3 the stars in the ATL sample cluster about the base of the red giant branch and extend toward the main sequence. The peak of the distribution falls just above the *Kepler* long cadence Nyquist frequency, populating the previously sparsely sampled region. The density falls off toward higher ν_{\max} , which is likely a result of the decreasing mode amplitude.

5.3. Large Sample

Here, we report both ν_{\max} and $\Delta\nu$ for all but 62 stars. For these outliers, we found similar issues to those discussed in the previous sample. Additionally we noted 16 stars where the probability distributions in ν_{\max} were multi-modal. The remaining targets vastly outnumber those from the ATL, and span the red giant branch (as seen on Fig. 3). The density increases with decreasing ν_{\max} until it peaks at $\approx 49\mu\text{Hz}$. At the high- ν_{\max} tail, we note an overlap between the ATL and Large Sample. There are 119 stars that did not appear in the ATL, despite showing oscillations at frequencies above $240\mu\text{Hz}$. Of these, just under half lie near the ATL cutoff, with $240 < \nu_{\max} < 300\mu\text{Hz}$. A total of 63 stars, however, are above $300\mu\text{Hz}$ in a region that should be included in the ATL. These stars are, on average, brighter than those in the ATL (see Fig. 6), with the distribution peaking around $K_s \approx 6$ mag. Of these targets, 70% have parallaxes drawn from GDR2 with the remaining from XHIP. Below 6th magnitude astrometric solutions in GDR2 are known to generally have inferior astrometry (Lindegren et al. 2018). Therefore, it is possible the parallax caused an underestimate on the predicted ν_{\max} , pushing the targets outside of the scope of the ATL.

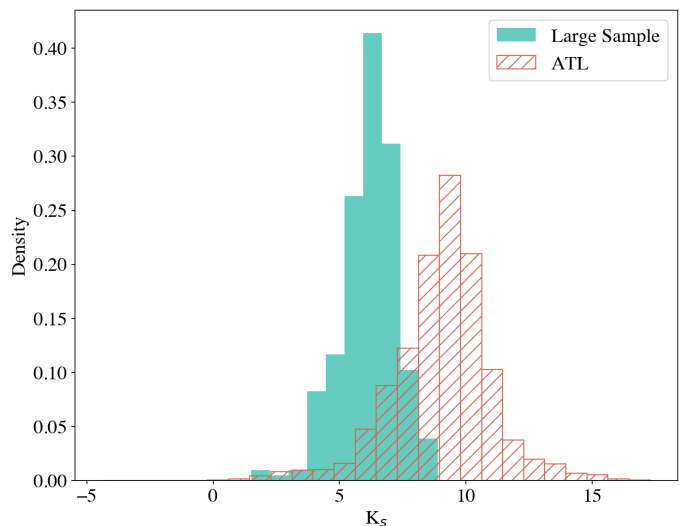


Fig. 6: Distribution in K_s -band magnitude for the detections from the Large Sample which have values of $\nu_{\max} > 240\mu\text{Hz}$, and those made from targets included in the ATL.

According to the main aim of the TESS mission (Ricker et al. 2014), we expected targets proposed for 120-second cadence would be less evolved than the giants presented here. Although targets were also selected if they were brighter than $T_{\text{mag}} = 6$ (where T_{mag} is magnitude of the star for the TESS instrument response), which would preferentially select bright giants, we found that $\approx 80\%$ of the giants in which we detected solar-like oscillations were fainter than this limiting magnitude. We therefore checked that the oscillations occur in the star associated with the TIC number being searched, rather than another star in the mask, by comparing the ν_{\max} value predicted by the prior to the detected value (see Fig. 7). In general, the ratio of the two was close to unity, indicating the detected envelope belongs to the target in question.

5.4. 20-Second cadence

The measured values of $\Delta\nu$ and ν_{\max} can be seen in Fig. 8. A total of 16 stars were removed by manual identification. We note that the uncertainties on $\Delta\nu$ presented in Fig. 8 appear larger than those presented in Fig. 5 (the ATL sample), which is likely due to the population of targets at $\nu_{\max} < 100\mu\text{Hz}$. The mean fractional uncertainty on the measured $\Delta\nu$ in the 20-second cadence sample is 2.1%, approximately consistent with 1.9% in the ATL sample. Again, we find the population is dominated by evolved stars, with the distribution peaking at a ν_{\max} value of $50\mu\text{Hz}$.

We note the presence of a detection in an oscillator observed by *Kepler* (KIC 6106415; HD 177153; "Perky"), which is a clear outlier in Fig. 8. The algorithm reports a $\Delta\nu$ of $131\mu\text{Hz}$ despite measuring a ν_{\max} of $127\mu\text{Hz}$. Using *Kepler* data oscillations were identified at $\nu_{\max} = 2249\mu\text{Hz}$ (Lund et al. 2017). The envelope we detected at $127\mu\text{Hz}$ (which can be visually identified) appears to be on another red giant in the pixel mask. Therefore the prior has caused an erroneous measurement of $\Delta\nu$.

6. Conclusions

Applying the algorithm introduced by Nielsen et al. (2022) to 120-second and 20-second cadence observations from the TESS mission spanning Sectors 1 to 46, we have detected solar-like

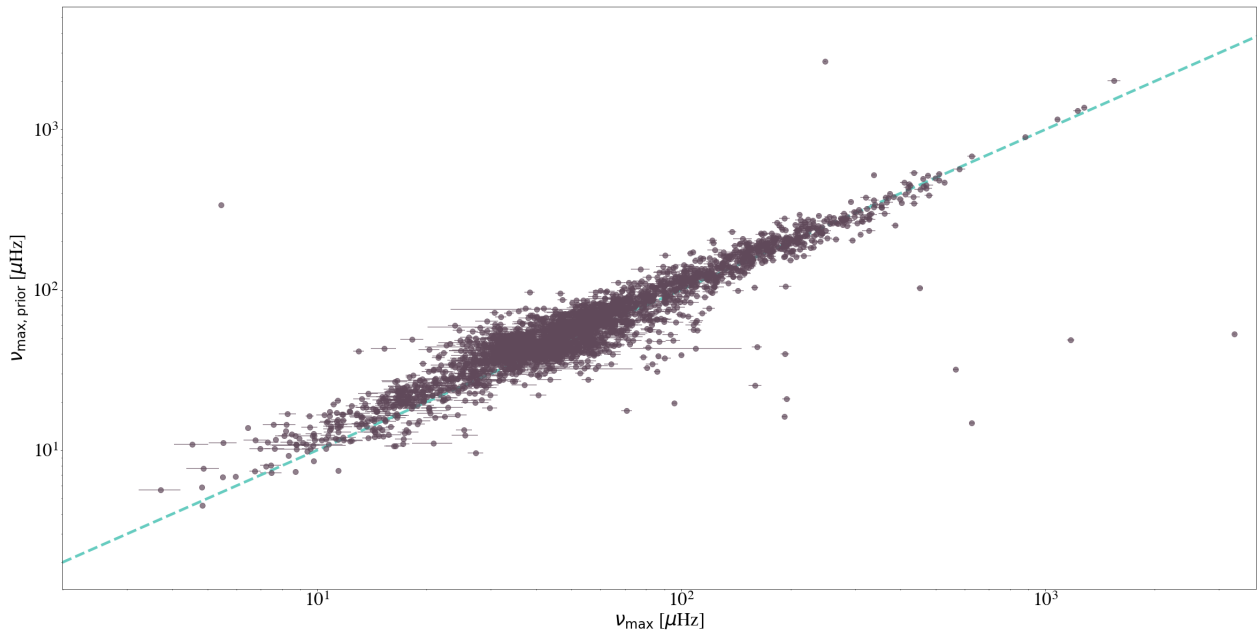


Fig. 7: Prior ν_{\max} ($\nu_{\max,\text{prior}}$) versus measured values in short cadence targets. Blue dashed line represents the 1-1 line.

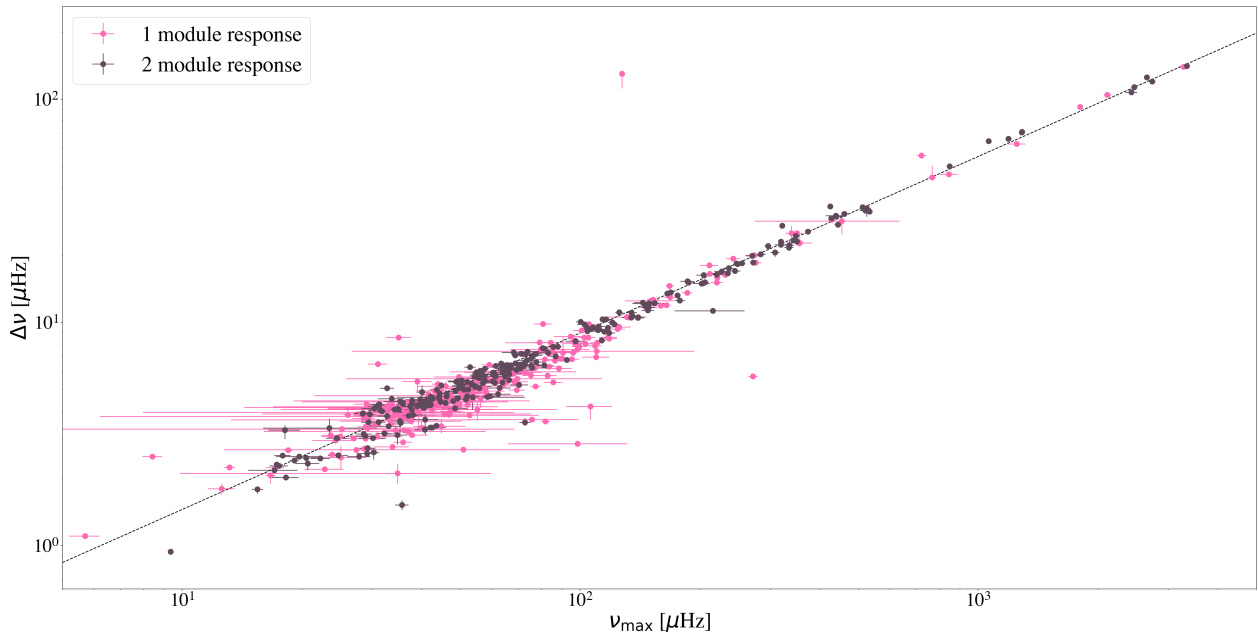


Fig. 8: $\Delta\nu$ versus ν_{\max} for validated solar-like oscillators from the 20-second cadence set. Stars producing flags in only one module in pink, those producing flags in both are in brown.

oscillations in a total of 4177 targets. Of these, 12 belong to a set of previously reported solar-like oscillators, 752 to stars that appeared in the ATL and 486 were detected using 20-second cadence data. The remaining are targets brighter than 11th magnitude in 2MASS K_s , with temperatures in the range $4500\text{K} < T_{\text{eff}} < 6500\text{K}$, observed in 120-second cadence. Since Sector 46, data for additional sectors have been released. We leave the analysis of these and the data collected in upcoming sectors as we approach the end of the first extended mission for future work.

All catalogued targets have been manually vetted to confirm the presence of oscillations. We note that signals from eclipsing binaries, classical pulsators, or transiting planetary bodies can cause false positive detections. Therefore, we highlight that

when using the algorithm presented in N22 with very large data sets, the more conservative approach (asking for responses in both modules) is the most effective at reducing the amount of manual vetting required.

We have extended the work of N22 to include methods to measure the global asteroseismic parameters, ν_{\max} and $\Delta\nu$. We introduced a new model to parameterize the collapsed ACF to produce a probability density for $\Delta\nu$. Applying this technique to the catalogue of detections, we measured the global asteroseismic parameters for 98% of the targets. Overlaying these stars on the asteroseismic HR diagram (ν_{\max} and T_{eff}) allowed us to confirm the ATL successfully identified the least evolved stars, with little overlap in the remaining detections. The small set of stars

that appear to have been missed by the ATL cluster about $K_S = 6$ mag, a region where the GDR2 astrometric solutions are known to have inferior astrometry (Lindegren et al. 2018), suggesting an issue in the parallaxes.

This catalogue has demonstrated the significant contribution the TESS mission can make to the field of asteroseismology. Isolating targets from the ATL, the increase in the number of detections between the 280 μHz cut-off enforced by the 30-minute FFI observations and the upper edge of our catalogue at around 1000 μHz is at least 2-fold on the detections made in *Kepler* data. With the inclusion of the stars detected in 120-second cadence that did not appear in the ATL, we were able to use a homogeneous data set to measure asteroseismic values in solar-like oscillators from the subgiant regime through the red giant branch.

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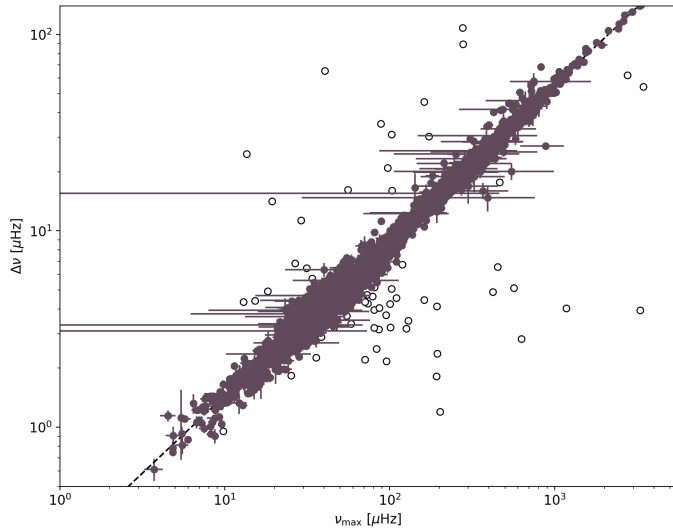


Fig. 1: $\Delta\nu$ as a function of ν_{\max} for targets in the final catalogue in brown. Values that were removed after manual identification are shown as open circles.

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