We report detection of oscillations in brightness temperature, size and horizontal velocity of three small bright features in the chromosphere of a plage/enhanced-network region. The observations, which were taken with high temporal resolution (i.e. 2 s cadence) with the Atacama large millimetre/submillimetre array (ALMA) in Band 3 (centred at 3 mm; 100 GHz), exhibit three small-scale features with oscillatory behaviour with different, but overlapping, distributions of period on the order of, on average, $90 \pm 22$ s, $110 \pm 12$ s and $66 \pm 23$ s, respectively. We find anti-correlations between perturbations in brightness temperature and size of the three features, which suggest the presence of fast sausage-mode waves in these small structures.
In addition, the detection of transverse oscillations (although with a larger uncertainty) may also suggest the presence of Alfvénic oscillations which are likely representative of kink waves. This work demonstrates the diagnostic potential of high-cadence observations with ALMA for detecting high-frequency magnetohydrodynamic waves in the solar chromosphere. Such waves can potentially channel a vast amount of energy into the outer atmosphere of the Sun.

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1. Introduction

The solar atmosphere consists of a large variety of magnetic structures capable of maintaining different types of magnetohydrodynamic (MHD) waves [1–4]. While these could be in part responsible for the plasma heating in the upper solar atmosphere (by means of energy deposition in those layers), the exact physical mechanisms of this still remain unclear (see [5,6] and references therein for a wider picture). In particular, direct detection of MHD-wave-energy release in the solar chromosphere has been rare, thus, their detection in structures with various spatial scales and in a wide range of frequencies is of vital importance.

Notably, compressible and incompressible MHD-wave modes can be excited in magnetic flux tubes, which act as waveguides, by reoccurring perturbations at their footpoints at photospheric heights [7]. Signatures of both standing and propagating incompressible (transverse) kink waves, as oscillatory pattern of velocities perpendicular to the assumed waveguides, have been observed in various structures in the solar photosphere and chromosphere such as small-scale bright points, spicules, fibrils and mottles (e.g. [8–16]). These have been reported to have periods on the order of 30–350 s and velocity amplitudes of about 1–29 km s$^{-1}$ (see table 3 in [5] for a detailed summary of the observed properties of kink waves). In the case of the compressible sausage modes, the observed signature is a periodic fluctuation of the waveguide’s cross-section accompanied by a corresponding out-of-phase oscillation of the intensity [17,18]. Morton et al. [19] reported evidence of the sausage mode in a magnetic pore with a clear anti-phase relation of the width of the magnetic structure (waveguide) and the intensity observed at 4170 Å by the Rapid Oscillations in the Solar Atmosphere (ROSA; [20]) instrument at Dunn Solar Telescope. Furthermore, Gafeira et al. [21] reported the anti-phase behaviour in Slender Ca II H Fibrils observed at 3969 Å with the SuFI instrument onboard the SUNRISE balloon-borne solar observatory [22,23].

Both kink- and sausage-mode waves have been observed in large magnetic structures such as sunspots and pores, as well as in small-scale elongated structures. Their observations in small magnetic features, particularly in the mid-to-high solar chromosphere, have not been so common. Such waves, if propagating, can significantly contribute to the heating of the outer solar atmosphere where they can be dissipated. Thus, their detection in the chromosphere is of high interest for understanding the energy budget in this atmospheric region and beyond.

The Atacama Large Millimetre/Submillimetre Array (ALMA; [24]) started regular observations of the Sun in late 2016, with a capability of providing high-cadence observations of the solar chromosphere at millimetre wavelengths. This is obviously a crucial factor for observing high-frequency (short period) waves. These will, however, be limited to spatial scales detectable by currently provided antenna configurations of ALMA, since the spatial resolution is also important in detecting high-frequency oscillations [25]. Additionally, ALMA is a powerful diagnostic tool for the solar chromosphere, since the radiation is formed under the condition of local thermodynamic equilibrium (LTE) at these wavelengths. Hence, the observable brightness temperature constitutes a direct proxy of the local gas temperature of the plasma [26–30]. Thus, temperature perturbations due to e.g. propagating waves, can be directly examined.

Recent studies have shown the potential of ALMA to examine distinct phenomena both in quiet and active regions [31–40]. In particular, Eklund et al. [41] found signatures of shock-wave events in Band 3 (2.8–3.3 mm) observations from December 2016, coming to the conclusion that
there are numerous small-scale dynamic structures with lifetimes of 43–360 s present in the ALMA field of view (FOV), with excess temperatures of more than 400 K and a correlation between their occurrence and the magnetic field strength. Characterization of such events at millimetre wavelengths has also been studied in detail from numerical simulations [42]. Nindos et al. [40] presented a survey of transient brightenings with a mean lifetime of 51.1 s in ALMA Band 3 data observed in March 2017, which show light curves such that their origin is strongly suggested to be thermal, meaning that the observed brightness temperature variations are indeed caused by variations of the gas temperature and not other effects such as optical depth variations. In April 2017, Chintzoglou et al. [43] reported the detection of an on-disk chromospheric spicule in a plage region observed simultaneously by IRIS and ALMA Band 6 (1.1–1.4 mm). Therefore, ALMA observations have been demonstrated to possess sufficient quality and temporal resolution to search for various long-lived and transient phenomena (within its current spatial-resolution limits), and likewise, to study MHD-wave signatures in the solar chromosphere. An overall study of temperature oscillations in the solar chromosphere with ALMA (using ten different datasets in both Band 3 and Band 6) has shown the dependency of the oscillation properties on the magnetic configurations in the mid-to-high chromosphere [44].

In this paper, we present evidence of MHD-wave signatures in three small bright features traced in time within the FOV of an ALMA Band 3 dataset. In §2, the data were described. The method of selection of the three bright features as well as the tracking algorithm are presented in §3. In §4, the properties of the features and the wave analysis are detailed. Lastly, our interpretation of the observed oscillations as well our concluding remarks are presented in §5.

2. Observations

The ALMA Band 3 (2.8–3.3 mm) observations used here were carried out on 22nd April 2017 between 17:20 and 17:54 UTC as part of program 2016.1.00050.S. The set-up of the receiver bands consists of four sub-bands centred on 93 GHz (SB1), 95 GHz (SB2), 105 GHz (SB3) and 107 GHz (SB4), corresponding to 3.224 mm, 3.156 mm, 2.855 mm and 2.802 mm, respectively. The reconstruction of the interferometric data has been done with the Solar ALMA Pipeline (SoAP). A detailed description of the pipeline will be provided in a forthcoming publication (Szydlarski et al., in prep.; see also [39]). One of the modes of SoAP enables the creation of a full-band time sequence in which all the four sub-bands are combined into one. Because of the higher signal-to-noise ratio (as a result of better sampling of Fourier space during the image reconstruction) of the full-band time series, this mode of SoAP was used to reconstruct the data used for the present work (instead of the four sub-bands).

The data consist of 3 scans, 10 min long each, with 2 s cadence. There are gaps of approximately 140 s between the scans used for calibration measurements. The column of precipitable water vapour (PWV) in the Earth’s atmosphere during the observation was 0.4 mm, on average. The pixel size is chosen during the reconstruction process; for this observation, the sampling resolution is 0.34 arcsec. The synthetic elliptical median beam size (which defines the spatial resolution of the observations) depends on the observed frequency and, therefore, changes depending on the sub-bands or full-band used. For the full-band, the synthetic elliptical median beam size which is representative of the whole observation is 2.21 arcsec × 1.70 arcsec (1607 km × 1235 km) with an anticlockwise inclination angle of 54.06° with respect to the solar north. In addition, observations from the Solar Dynamics Observatory (SDO), consisting of photospheric magnetograms from the Helioseismic and Magnetic Imager (HMI, [45]), and images at 1700 Å and 304 Å from the Atmospheric Imaging Assembly (AIA, [46]) have been spatially co-aligned with the ALMA observations in order to gain context information. The co-alignment was carried out by comparing the ALMA time-averaged image for the whole observation with a time-averaged combined image of SDO/HMI, SDO/AIA1600, SDO/AIA1700 and SDO/AIA304 in the same time range. The initial point of comparison was taken from the coordinates provided by ALMA.
Figure 1. (a) A full-band ALMA Band-3 image at 17:35:48 UT. The small ellipse in the bottom-left-corner of the panel (a) illustrates the synthetic elliptical median beam. (b) Line-of-sight magnetogram from SDO/HMI. (c,d) SDO/AIA 1700 Å and SDO/AIA 304 Å, respectively. The white/red contours delimit the network-internetwork regions and the yellow/green circles mark the ALMA field-of-view. The observing time of each image has been indicated on its top-left corner. The locations of the three small bright features of interest are labelled with A, B and C. (Online version in colour.)

Figure 1 shows a full-band ALMA Band 3 image recorded at 17:35:48 UT (a), along with its co-aligned SDO/HMI line-of-sight magnetogram (b), SDO/AIA 1700 Å (c) and SDO/AIA 304 Å (d). In the ALMA panel, the small ellipse in the bottom-left corner illustrates the beam size. In the magnetogram panel, the blue crosses indicate the locations of three different transient brightenings whose oscillatory behaviours are studied in this work. Each of these brightenings corresponds to one single feature (labelled with A, B and C) whose characteristics are described in §4. These ALMA observations were taken in a plage/enhanced-network region on the east side of NOAA AR12651, with strong photospheric magnetic fields, spanning a range of $[-1819,961]$ Gauss during our observation. In figure 1a–d, the white/red contours depict the network-internetwork boundaries, identified from a combination of the saturated SDO/HMI magnetogram and the 1700 Å image. The circles mark the FOV of ALMA on the SDO images.
3. Method

Characterizing the structure and dynamics of magnetic features in the solar chromosphere, namely, time variations of intensity, size and displacement, can reveal the oscillatory behaviour in this atmospheric region. Moreover, if there exists information about the magnetic-field configuration, it is also possible to inspect whether or not the oscillatory signals are magnetic in nature. In this work, three distinct bright features, one per ALMA scan (see §2), are analysed. The spatial locations of the three features, labelled A, B and C, are marked on the line-of-sight photospheric magnetogram in figure 1. We note that the magnetogram was shown for one particular frame of the observations, whereas the three features were identified at different times throughout the image sequence. However, their locations within the network region suggest their magnetic origin. A one-to-one comparison of these bright features and the magnetic elements in the HMI magnetogram is not straightforward due to the large height difference between the atmospheric layers mapped by ALMA Band 3 and the HMI magnetogram (i.e. the high chromosphere versus the low photosphere, respectively), as well as their relatively low spatial resolutions.

(a) Feature detection

Detection and tracking of small-scale bright features in the ALMA Band 3 time series of images is not trivial, as many of the structures have dimensions comparable to the spatial resolution of the observations (or even smaller). This limits us to features larger than the beam size (i.e. larger than approx. 1.9 arcsec). Several feature-tracking approaches have been developed to address similar situations. Particularly, Crocker & Grier [47] described an algorithm to precisely identify, track, and extract quantitative information for colloidal suspensions in noisy image sequences, where large background brightenings may also exist. This is a similar challenge to that which we face in detecting small chromospheric brightenings in ALMA images. The algorithm has been designed to have a high sub-pixel accuracy in locating the features. According to an error analysis by Crocker & Grier [47], a precision better than 0.05 pixel can be achieved. However, accounting for the rapid size and intensity variations of the small dynamic features in the solar chromosphere, we consider an (overestimated) uncertainty of about 0.5 pixel. This algorithm has been implemented in Python for finding blob-like features in time series of images by means of the TrackPy package [48]. The algorithm has been used in various fields, including solar physics (e.g. [49,50]). In this study, the TrackPy package is used to perform the tracking analysis.

By using Trackpy, it is possible to identify and track blob-like structures which persist in time. The main input for Trackpy is an initial estimate of the size (or diameter), in pixels, of the features of interest, with which the algorithm searches for features within circles with a diameter larger than the input size. The minimum input size was chosen based on two steps: (i) a visual inspection of the time series to identify an approximate size of transient bright features of interest, which was found to be 3 arcsec or larger, corresponding to a minimum of 8 pixels and (ii) we considered the median value of the beam size (i.e. 1.93 arcsec; 6 pixels). With these in mind, the sub-pixel precision function of TrackPy was used to evaluate the best initial estimate size, this being 15 pixels. This is larger by a factor of ≈ 2.5 than the median beam size (i.e. the spatial resolution) and thus ensures the detection of spatially resolved features. The algorithm was then run to track potential candidates in each ALMA scan, which were visually inspected afterwards to select the three features that are analysed here. Particularly, the algorithm did not retain information on the candidate feature from frame to frame, meaning that an event must be present in every single frame to be considered a reliable and unique feature. Thus, the initial detection of a feature is defined as the frame in which it is first observed by the algorithm. The feature is considered extinguished when its intensity goes below the detection limit. Features that merge with other structures, or split into several features, are excluded. In addition, features with lifetimes shorter than 200 s have been excluded too. This decision was made based on a primary exploration, from which a clear manifestation of oscillatory periods on the order of 50 s or longer.
Figure 2. Distributions of brightness temperature of the individual scans are shown in grey. They include the entire FOV for all time steps within the corresponding scan. The orange histogram in each panel corresponds to the temperature distribution of each identified feature during the course of its lifetime. The median brightness temperatures are given for all distributions. (Online version in colour.)

was noted. The features A, B and C have lifetimes of 316 s, 238 s and 389 s, respectively. These three selected features are being analysed in detail in the present work. A statistical and in-depth study of a larger sample is the subject of a forthcoming article.

4. Analysis and results

The Trackpy procedure was applied to the identified features to extract their physical properties. Thus, for each feature at every time step, the properties—namely, size, location and brightness temperature—were determined. The size corresponds to the diameter of a circle with the same area of the feature. The location of each feature is described by its centre-of-gravity of intensity (i.e. brightness temperature). The representative brightness temperature of the feature has been chosen to be the value of the closest pixel to the centre of gravity of intensity. Also, the transverse (horizontal) velocities in solar-X and solar-Y directions (for the centre of gravity of intensity) between two consecutive frames were determined (i.e. the instantaneous horizontal velocities). All time series corresponding to these quantities were detrended (by subtracting a simple linear fit) and apodised (using a Tukey window, with a length of 0.1) prior to wavelet analysis (see §4c).

(a) Size, location and brightness temperature

Figure 2 shows the distributions of brightness temperature of the entire FOV during the whole observation for each scan in grey. The orange histograms correspond to the distributions of brightness temperature for the three features during their lifetimes. The median temperatures of the features A, B and C are 1776 K, 1760 K and 2358 K higher than the median temperatures for the entire FOV, respectively.

Figure 3 illustrates the temporal evolution of the brightness temperature of the features in black and the temporal evolution of their sizes in red. The major axis of the synthetic elliptical median beam is plotted as a horizontal black dotted line in the first panel. It is clear that the three features under study are all spatially resolved in our observations. An anti-correlation between oscillations in the brightness temperature and size of the three features is evident. Time lags between the anti-correlations are also observed, e.g. in the second major extrema in the top panel (i.e. feature A). Anti-phase oscillations between intensity and size of magnetic structures are suggestive signatures of fast sausage-mode waves [51]. A quantitative inspection of the anti-phase behaviour will be described in §4c.
**Figure 3.** Fluctuations in brightness temperature (black) and size (red) of the three small bright features studied in the present work. The horizontal black, dotted line in the top panel marks the size of the major axis of the synthetic elliptical median beam (i.e. the spatial-resolution element). An anti-correlation between oscillations of the two quantities is evident. (Online version in colour.)

(b) Horizontal velocity

The instantaneous horizontal velocities in each direction, i.e. $v_x$ and $v_y$, were also determined by taking the difference between the location of the centre of gravity of intensity in two consecutive frames and dividing it by 2 s, i.e. the cadence of the observations. Figure 4 shows trajectories of the centre of gravity of the three features under study. The colours code the time progression from dark blue to dark red. The total instantaneous horizontal velocity is then calculated as $v_T = \sqrt{v_x^2 + v_y^2}$. Figure 5 shows in black dashed lines the temporal evolution of the velocities $v_x$, $v_y$ and $v_T$ for the three features. The average frame to frame displacements of the gravity centres of the features are of the order of 6–9% of the pixel size of the ALMA observations. Therefore, in order to estimate a time span for which the displacements are at least half of the pixel size, implying that the uncertainty of the measurement is reduced, the total average displacements in a mobile window of 20 s, i.e. adding up all the displacements frame to frame in a range of 20 s, have also been calculated falling in the range of 60–90% of the pixel size. Hence, a boxcar running average of 20 s has been applied to the velocities of the features and is over-plotted as...
Figure 4. Trajectories of the three features studied here. The colours indicate the time progression from the birth time of the features (dark blue) to when they extinguish (dark red). (Online version in colour.)

Figure 5. Oscillations in horizontal velocities for the features A, B and C. In each column (associated with one feature), $v_x$ is shown in the top panel, $v_y$ in the middle panel, and the total horizontal-velocity in the bottom. The red lines are the boxcar averages of 20 s.

Moreover, in order to examine the validity of the signals (i.e., the boxcar-averaged oscillations), a statistical significance of the total velocities was performed by using the Monte Carlo (randomization) test described by Linnell Nemec & Nemec [52] and O’Shea et al. [53]. In this method, the global wavelet spectrum of the boxcar averaged total velocity time series for each feature is compared with the global wavelet spectrum obtained from a random permutation of the values in the time series. Doing this process for $N$ times, the probability $p$ with which the periodicities were produced by noise (and not a real signal) would be $M/N$, where $M$ is the number of times that the power at each frequency bin in the permuted signal is larger than the power measured from the original time series. The confidence level of the calculated periodicities from the original signal is then estimated as $1 - p$. The confidence levels of the total velocity periods found with the randomization test with $N = 10000$ were 0.97, 0.99 and 0.99 for features A, B and C, respectively, meaning that they are not noise originated. Table 1 summarizes the minimum, mean, median and maximum values of the boxcar averaged total velocity amplitudes for the three features.
Figure 6. Wavelet power spectra for oscillations in brightness temperature (top row) and size (middle row) of the three features A–C from left to right, respectively. The cross-wavelet power spectrum between the two power spectra of each feature is shown in the bottom row. In each panel, the power was plotted using a log$_2$ scale to enhance the contrast of colours. In each panel, the y-axis corresponds to the oscillation period, and the x-axis represents the observation time of each feature in seconds. The hashed black cone region represents the cone of influence for each spectrum and the black solid contours mark the 95% confidence levels. The white dashed contours mark the 75% confidence level. The arrows depicted on the cross-wavelet power spectra mark phase lags between the oscillations in brightness temperature and size (arrows pointing straight down represent anti-phase relationship; pointing left indicate perturbations of brightness temperature follows that of size).

Table 1. The minimum, mean, median and maximum boxcar averaged total horizontal-velocity amplitudes for the three features under study.

| Feature | $v_{\text{min}}$ (km s$^{-1}$) | $v_{\text{mean}}$ (km s$^{-1}$) | $v_{\text{median}}$ (km s$^{-1}$) | $v_{\text{max}}$ (km s$^{-1}$) |
|---------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| A       | 1.0                           | 2.0                           | 1.9                           | 3.0                           |
| B       | 1.1                           | 2.1                           | 2.6                           | 2.6                           |
| C       | 0.6                           | 2.6                           | 2.4                           | 5.9                           |

(c) Wavelet analysis

To determine the periods of the oscillation for temperature, size and velocity, as well as the phase lags between them, we perform a wavelet analysis. Torrence & Compo [54] presented a comprehensive description of the method which is used as the basis for this analysis. Accordingly, the time-varying signals are decomposed into time-frequency space components making it possible to determine the dominant oscillation modes in a power spectrum. Moreover, it is also possible to calculate the cross-wavelet spectrum between two signals which in turn gives information about their correlations, hence, the phase lags between the two signals (cf. e.g. [21]).

For each of the three features (in each column), figure 6 presents the wavelet power spectra for the oscillations in brightness temperature (top row) and size (middle row) shown in figure 3, as well as the cross-wavelet power spectrum between these two quantities (bottom row). For
each case, only periods which fall outside the cone of influence (the hashed areas) and the 95% confidence-levels (being significant at 5%; the solid contours) are considered to be representative of the oscillations. The cone of influence excludes those periods which are subject to edge effects. From the figure, a wide range of (relatively short) periods are found, of which those within 60–136 s (for the three features) are significant at 5%. Only these values enter in table 2, where the statistics of all periods extracted from the wavelet spectra for the three types of oscillations are summarized. For comparison, the white dashed contours in figure 6 represent the 75% confidence level. Periods in the ranges of 34–136 s for temperatures and 40–136 s for sizes (for features A and B) fall within this confidence level, suggesting the possible existence of shorter period oscillations in the ALMA data which will be explored in a forthcoming publication. In the present work, only period and phase-angle values within contours of 95% confidence are analysed.

In the third row of figure 6, the small black arrows indicate the phase lags between the two oscillations, being in phase when the arrows point upward and anti-phase when they point downward. If the arrows point to the right then the temperature perturbations leads that of size, and vice versa. Hence, it is possible to confirm that features C and B show a strong anti-phase behaviour for (some of) their dominant, correlated periods of oscillation while other phase differences are also evident in the case of feature A. Figure 7 shows the distributions of the phase lags for each of the three features extracted from the cross-wavelet spectra (i.e. those outside the cone of influence and a 95% confidence level). Again, features B and C present a clear anti-phase as their phase lags are mostly populated around ±180°. For feature A, although the phase lags are distributed over a wider range, there is also a considerable portion of the oscillations in anti-phase relationships. Other phase lags are also observed for the three features. Whether there are any differences in the nature of the oscillations observed in the three features, in particular, between the fluctuations in feature A and those in B and C, further information about e.g. their magnetic fields would be required.

![Figure 7](https://royalsocietypublishing.org/journal/rsta/article-figures/Figure7_Distributionof..07c59f0c6.png)

**Figure 7.** Distribution of phase lags (in degrees) between the oscillations in brightness temperature and size for each feature.

**Table 2.** The range, mean and median periods of oscillation of the temperature, size and total velocity are presented for the three features.

|                 | temperature periods (s) | size periods (s) | velocity periods (s) |
|-----------------|-------------------------|-----------------|----------------------|
|                 | range mean median       | range mean median | range mean median |
| feature A      | 60–114 77 76           | 85–114 96 96    | 40–108 69 72        |
| feature B      | 64–85 72 72            | 64–85 74 72    | 30–85 46 43         |
| feature C      | 102–136 118 120       | 96–136 115 114 | 34–136 65 64        |
Figure 8. Wavelet power spectra of the oscillations in boxcar averaged total horizontal velocities ($v_T$) for features A–C from left to right, respectively. The solid black contours mark the 95% confidence levels and the hashed areas indicate the cone of influence (excluding regions subject to edge effect). (Online version in colour.)

Figure 8 shows the wavelet spectra of the boxcar averaged total horizontal velocity for each of the three features. The cone of influence and the 95% confidence levels are marked with the hashed areas and solid black contours, respectively. In comparison to the brightness temperature and size, shorter periods dominate the horizontal-velocity oscillations. Nevertheless, there also exist longer periods within the significance levels, compared to those for fluctuations in the other two parameters. The statistics (providing minimum, mean, median and maximum values of the periods of velocity oscillations) are summarized in table 2. The three features have an average period on the order of 66 s for the perturbations in horizontal velocity.

5. Discussion and conclusion

We have analysed three small chromospheric bright features (transient brightenings) in ALMA Band 3 observations of a plage/enhanced-network region, revealing short-period oscillations in their brightness temperatures, sizes, and horizontal velocities. Limited by the observation’s beam size (of about 1.93 arcsec), the smallest fully (spatially) resolved features under study benefited from the high quality and high temporal-resolution (i.e. 2 s cadence) of the ALMA observations. These advances resulted in reliable characterizations of the identified oscillations by means of a wavelet analysis. However, a relatively low sampling-resolution of the observations (i.e. the pixel size) resulted in some uncertainties in locating the bright features (see §4b), thus, this should be taken into account when the fluctuations in the horizontal velocities are interpreted.

Clear oscillatory behaviours are observed in both brightness temperature and size of the three features under study (figure 3). Interestingly, the fluctuations in these two parameters show an anti-phase correlation. This suggests the identification of fast sausage modes in the small chromospheric bright features. Periods of both oscillations, as well as the phase lags between them were then identified through wavelet analysis. Thus, the oscillation periods were found to be, on average, 90 ± 22 s and 110 ± 12 s for the brightness temperature and size, respectively. Similar oscillatory behaviours and periods have been reported in observations at other wavelengths in distinct chromospheric structures, such as small bright points, fibrils, spicules and pores (e.g. [5,19,21]). However, oscillations in small bright points were mostly observed in the low chromosphere [16]. We expect that the features presented here (from ALMA Band 3) are formed higher in the chromosphere. It is also worth noting that the elongated structures reported by Gafeira et al. [21] (with similar wave characteristics) have a different nature compared to the small bright features analysed here. The former represent waves in highly inclined magnetic-field lines, whereas the latter (i.e. the features studied here) are likely manifestations of cross sections of nearly vertical flux concentrations.

In addition, the horizontal displacements for all the three features are qualitatively identified in the trajectories of their centres of gravity of intensity (figure 4). Their oscillations in both $x$- and $y$-directions, as well as in the total horizontal velocity, are evident in figure 5. In addition, a preliminary analysis of the phase lags between the horizontal velocities and the temperature
shows a predominant ±90° phase for features B and C, a pattern which has been previously associated with the kink-mode nature of the transverse oscillations [11]. However, detailed analysis of this phase relationship will be a matter of future work. Furthermore, a quantitative determination of periods of the oscillations of the three features we studied revealed an average period of 66 ± 23 s for the horizontal-velocity perturbations and an average horizontal-velocity amplitude of 2.3 ± 1.4 km s\(^{-1}\) among the three features (where the uncertainties are the standard deviations of the distributions), during the course of their lifetimes. We note that due to the large uncertainties in measuring the displacements between consecutive frames, the oscillations of the smoothed signals over 20 s have been analysed. Short periods, in the order of those found here for the transverse velocities, have also been observed in various fibrillar structures (10–500 s; [15,55–58]) and in bright points (43–74 s; e.g. [16]) through the solar chromosphere, though the fibrillar structures have a wider range of periods. We should note that we cannot exclude the presence of longer periods in such small bright features presented here, hence, a statistical study of these features will be required (that is the subject of a forthcoming paper). Other values for the velocity amplitudes and the oscillation periods related to kink waves that have been reported in the literature for different observed structures in the chromosphere span the ranges 5–29 km s\(^{-1}\) and 37–350 s for spicules [8,59–61], 1–10 km s\(^{-1}\) and 100–250 s [11,49] for bright points, 8–11 km s\(^{-1}\) and 120–180 s for mottles [10,62] and for fibrils 1–7 km s\(^{-1}\) and 94–315 s [63,64].

We speculate that the observed anti-phase oscillations are associated with MHD fast sausage-mode waves. While the transverse oscillations in velocity may be associated with MHD kink-mode waves, it may be also possible that the displacements are due to the bulk macroscopic motions, deprecating a noise explanation as the periodicities are significant and the randomization test showed that the velocity oscillation cannot be reproduced randomly. The high-frequency waves identified here are of particular importance because they can penetrate into the outer atmosphere, and thus contribute to the heating budget of the upper chromosphere and corona. Further investigations using the sub-bands capabilities of ALMA might help to determine the propagation characteristics and phase speeds of these waves, and ultimately to the energy flux carried by them into the higher layers of the solar atmosphere. In addition, a systematic analysis of a larger statistically significant sample of features is necessary in order to estimate what the typical attributes of these MHD waves are when propagating throughout the solar chromosphere. Similar studies from radiative MHD simulations will eventually help to better understand the nature of these waves.

**Data accessibility.** The observational data are publicly available in the ALMA Science Archive as part of project no. 2016.1.00050.S.

**Authors’ contributions.** M.S., S.W. and S.J. performed the data reduction and post processing. J.C.G.G. performed scientific analysis, with assistance from S.J., S.W., M.S., B.F. and P.H.K. J.C.G.G. drafted the manuscript. All authors read and approved the manuscript.

**Competing interests.** We declare we have no competing interests.

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