Coronal Seismology with ATST

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**Abstract.** We give a brief summary on the current status of coronal seismology and anticipate research opportunities for ATST in this discipline. Given the optical/infrared spectral range and the high-resolution magnetic field capabilities of ATST ($\approx 0.05'' - 0.1''$), the potential of exploring coronal seismology includes: (1) Optical detection of coronal waves and oscillations, (2) high-resolution magnetic field modeling with accurate determination of Alfvénic speeds, and (3) correlative studies that investigate the coupling between photospheric waves (detected in optical wavelengths) and coronal waves, which will provide insights into the generation mechanism of coronal waves, the origin and efficiency of coronal heating by waves, and diagnostics on flare and CME processes by global waves.

1. Introduction

Coronal seismology studies a host of oscillatory and transient phenomena that are generated by standing and propagating magnetohydrodynamic (MHD) waves in the solar corona. The theory of MHD waves in high-temperature plasmas, such as their dispersion relations and wave solutions in homogeneous plasmas and in wave ducts, have been studied in laboratory plasma physics, magnetospheric physics, as well as in the interpretation of solar transients since the beginning of radio observations ($\approx 1942$) and space exploration ($\approx 1957$). Oscillatory phenomena in the solar corona have been initially detected with radio spectrometers in the frequency-time domain (e.g., see review by Aschwanden 1987), without any imaging information. The first imaging observations of coronal waves and oscillations were enabled with SoHO/EIT, interpreted as slow (acoustic) MHD waves (Deforest & Gurman 1998; Berghmans & Clette 1999), and with TRACE, interpreted as fast kink-mode oscillations in coronal loops (Aschwanden et al. 1999; Nakariakov et al. 1999). Since then, imaging observations of MHD waves and oscillations have been reported in almost all wavelengths, especially in EUV and soft X-rays, but also in optical, H$\alpha$, and radio wavelengths. An overview of the most important identified MHD wave types is given in Table 1, along with a few examples of observations with the measured periods and wave phase speeds. The literature on observations and theory of oscillations and waves in the solar corona has grown to over 700 refereed publications at the time of writing (Aschwanden 2011). Reviews on the subject can be found in Aschwanden (2004, Chapters 7 and 8), Nakariakov & Verwichte (2005), Space Science Reviews Vol. 149/1-4 (Nakariakov & Erdélyi 2009) and 158/2-4 (Erdélyi & Goossens 2011), or IAU Symposium Vol. 247, (Erdélyi & Mendoza-Briceño 2008).
Table 1. MHD wave types identified in the solar corona.

<table>
<thead>
<tr>
<th>MHD wave type</th>
<th>Period range</th>
<th>Observations</th>
<th>References of examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHD Oscillations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast kink mode</td>
<td>≈ 3 – 5 min</td>
<td>TRACE</td>
<td>Aschwanden et al. (1999)</td>
</tr>
<tr>
<td>Fast sausage mode</td>
<td>≈ 1 – 10 s</td>
<td>Radio</td>
<td>Nakariakov et al. (1999)</td>
</tr>
<tr>
<td>Slow (acoustic) mode</td>
<td>≈ 10 – 20 min</td>
<td>SoHO/SUMER</td>
<td>Wang et al. (2002)</td>
</tr>
<tr>
<td>Propagating MHD Waves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow (acoustic) waves</td>
<td>75 – 150 km/s</td>
<td>SoHO/EIT</td>
<td>Deforest &amp; Gurman (1998)</td>
</tr>
<tr>
<td></td>
<td>75 – 200 km/s</td>
<td>SoHO/EIT</td>
<td>Berghmans &amp; Clette (1999)</td>
</tr>
<tr>
<td></td>
<td>65 – 150 km/s</td>
<td>TRACE</td>
<td>De Moortel et al. (2000, 2002b)</td>
</tr>
<tr>
<td>Fast (Alfvénic) waves</td>
<td>2100 km/s</td>
<td>SECIS</td>
<td>Williams et al. (2001)</td>
</tr>
<tr>
<td></td>
<td>1000 – 4000 km/s</td>
<td>CoMP</td>
<td>Katsiyannis et al. (2003)</td>
</tr>
<tr>
<td>Fast kink waves</td>
<td>100 – 500 km/s</td>
<td>TRACE</td>
<td>Verwichte et al. (2005)</td>
</tr>
</tbody>
</table>

2. Overview on MHD Oscillations and Waves

It is customary to subdivide oscillatory wave phenomena into (1) standing waves with fixed wave nodes (also called eigen-modes; Section 2.1), and (2) into propagating waves (Section 2.2). Both wave phenomena can be characterized by wavelengths and periods, but the waves are reflected at fixed spatial nodes in the former case, such as between the footpoints of closed magnetic field lines (e.g., in active region loops and postflare loops), while they propagate away from the exciter source in the latter case, such as in open magnetic field regions (e.g., in coronal holes, plumes, and in the solar wind).

2.1. MHD Oscillation Eigen-Modes

The dispersion relation of MHD waves in an unbound homogeneous medium has three branches of solutions for the phase speed \( v_{\text{ph}} \), one is called the fast-mode regime near the Alfvén speed \( v_A = B/\sqrt{4\pi\rho_0} \) (with \( B \) the magnetic field strength, \( \rho_0 = \mu m_p n_e \) the mass density, \( n_e \) the electron density, \( m_p \) the proton mass, and \( \mu \) the mean atomic weight), a second one is called the slow-mode regime near the acoustic or sound speed \( c_s = 1.66 \times 10^4 \sqrt{T_e/\mu} \) (with \( T_e \) the electron temperature), and a third one is the incompressible Alfvén wave. Furthermore, the slow and fast-mode regime have solutions for multiple harmonics, where the lowest harmonic mode is called the sausage mode \( m = 0 \), corresponding to symmetric radial oscillations of a flux tube, and the kink mode \( m = 1 \), corresponding to asymmetric oscillations of a flux tube that appear as a periodic transverse displacement. For the slow modes, both the kink and sausage modes have an almost identical solution \( \omega(k) \) of the dispersion relation and thus are generally not distinguished. An important discriminating property of the MHD modes is the com-
pressibility in the case of the magneto-acoustic wave, which is detectable as a density variation, and the incompressibility in the case of an Alfvén wave, which can only be detected by velocity and magnetic field fluctuations.

Fast kink modes have been discovered in coronal loops in a flaring active region with the EUV-imaging telescope TRACE (Aschwanden et al. 1999; Nakariakov et al. 1999), which exhibited standing eigen-mode oscillations of the fundamental harmonic with a period of \( P \approx 5 \) minutes, corresponding to the Alfvén crossing time back and forth of the loop, displacing the loop apex in transverse direction with a period of \( P \approx \frac{2L}{v_A} \) (with \( L \) being the full loop length). Due to the dependence of the kink-mode period on the Alfvén speed, the coronal magnetic field strength \( B \) in an oscillating loop can directly be measured from its period \( P \), length \( L \), and densities \( n_0 \) and \( n_e \),

\[
B = \frac{L}{P} \sqrt{8\pi \rho_0 (1 + \rho_e/\rho_0)},
\]

(1)

where \( \rho_0 = \mu m_p n_0 \) and \( \rho_e = \mu m_p n_e \) are the inner and outer mass densities. Typical magnetic field values found in oscillating loops are in the order of \( B \approx 10 - 40 \) G (see Table 7.1 in Aschwanden 2004).

The fast sausage mode is harder to detect, because the eigen-mode periods are much shorter under coronal conditions, i.e., \( P \approx 1 - 10 \) s (Roberts et al. 1984; Aschwanden 1987) than the cadence of existing imaging telescopes allow to measure. Moreover, the sausage mode has a long-wavelength cutoff that predicts that this mode can only occur in either very dense or relatively short loops, a condition that is only fulfilled in some extreme flare loops. Plausible imaging detections of sausage mode oscillations have been reported by Asai et al. (2001), Nakariakov et al. (2003), and Melnikov et al. (2005) using the Nobeyama radio interferometer, based on radio flux pulsations and the approximate flare loop geometry, although no direct measurement of the radial loop width oscillations has succeeded yet to-date.

Slow (acoustic) modes have first been identified in spatially resolved observations with the SoHO/SUMER imaging spectrograph in soft X-ray wavelengths (Wang et al. 2002; Kliem et al. 2002). Acoustic oscillations result from periodic density variations caused by acoustic waves that travel back and forth in a loop, where the period \( P = \frac{2L}{c_s} \) depends only on the loop length \( L \) and sound speed \( c_s = 1.66 \times 10^5 \sqrt{T_e/\mu} \), or electron temperature \( T_e \). These acoustic oscillations are most likely excited by a CME or flare-induced pressure disturbance, as it has been reproduced in numerical MHD simulations also (e.g., Nakariakov et al. 2004). Thus, detection of acoustic oscillations provide an excellent diagnostic of the coronal sound speed or temperature.

### 2.2. Propagating MHD Waves

The standing or eigen-modes described in the foregoing section require a symmetric structure or cavity that reflects the waves on opposite sides, so that incoming and reflected waves add coherently to a standing wave, like a plucked violin string or a laser device (or even the solar interior in the case of helioseismology). However, there are a lot of asymmetric structures in the solar corona, such as large-scale loops in the quiet Sun, diverging fans above sunspots, or open field lines in coronal holes, which act as waveguides. If such structures are impulsively disturbed, an outgoing (longitudinal) wave propagates along the field lines, usually decaying after some distance without noticeable reflection. Depending on the wave speed we distinguish between slow (acoustic) and fast (Alfvénic) propagating waves. Pure incompressible Alfvén waves are also
Table 2. Coronal waves and oscillations detected in optical wavelengths.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Wavelength $\lambda$ [Å]</th>
<th>Period P [s]</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koutchmy et al. (1983)</td>
<td>5303</td>
<td>43, 80, 300</td>
<td>Sac Peak coronagraph</td>
</tr>
<tr>
<td>Pasachoff &amp; Landman (1984)</td>
<td>5303</td>
<td>0.5-2 (?)</td>
<td>Hyderabad (eclipse)</td>
</tr>
<tr>
<td>Pasachoff &amp; Ladd (1987)</td>
<td>5303</td>
<td>0.5-4 (?)</td>
<td>East Java (eclipse)</td>
</tr>
<tr>
<td>Pasachoff et al. (2000)</td>
<td>5303</td>
<td>-</td>
<td>Chile (eclipse)</td>
</tr>
<tr>
<td>Pasachoff et al. (2002)</td>
<td>5303</td>
<td>-</td>
<td>Romania (eclipse)</td>
</tr>
<tr>
<td>Sakurai et al. (2002)</td>
<td>5303</td>
<td>0.14-250, &gt;300</td>
<td>Norikura coronagraph</td>
</tr>
<tr>
<td>Williams et al. (2001, 2002)</td>
<td>5303</td>
<td>6</td>
<td>Bulgaria (eclipse), SECIS</td>
</tr>
<tr>
<td>Singh et al. (2011)</td>
<td>5303, 6374</td>
<td>29-64</td>
<td>Anji, China (eclipse)</td>
</tr>
<tr>
<td>Ofman et al. (1997)</td>
<td>360, 1200-3000</td>
<td>372, 1200, 3000</td>
<td>SoHO/UVCS, WLC</td>
</tr>
<tr>
<td>Ofman et al. (2000)</td>
<td>400, 625</td>
<td>400-625</td>
<td>SoHO/UVCS, WLC</td>
</tr>
</tbody>
</table>

called torsional waves, which are only detectable by Doppler shifts in non-thermal line broadening.

Slow (acoustic) propagating waves have been noticed on the Sun first with the SoHO/EIT imager in extreme-ultraviolet wavelengths, based on diagonal features in space-time slice diagrams, which corresponded to speeds of $v \approx 50 - 150$ km s$^{-1}$ and thus have been attributed to the sound speed at coronal temperatures of $T \approx 1$ MK (Deforest & Gurman 1998; Berghmans & Clette 1999; De Moortel et al. 2000, 2002b; Robbrecht et al. 2001). Interestingly, propagating waves emanating from plages of active regions exhibited periods of $P \approx 5$ min, while waves from sunspots exhibited periods of $P \approx 3$ min, which gave strong evidence that these acoustic waves are excited by the global subphotospheric acoustic p-mode oscillations known in helioseismology (De Moortel et al. 2002a). The detected acoustic waves have also been found always to propagate in upward or outward direction, so they are clearly generated at or below the solar surface, which pinpoints their origin either to subphotospheric magnetohconvection or global p-mode oscillations.

Fast (Alfvénic) propagating waves, also called impulsively generated fast waves (Roberts et al. 1984), imply a magnetic field disturbance that travels at Alfvénic speeds. They are difficult to detect because of the fast speed (which requires a high imaging cadence) and the absence of density modulations (that modulates the EUV or soft X-ray emission measure). Theoretically, Alfvén waves can be detected only by Doppler shifts (of velocity variations) or magnetic field measurements (of the magnetic field fluctuations). However, the slow- and fast-mode types of magneto-acoustic waves are essentially compressible, which can be detected by density modulations. Interestingly, the first propagating fast wave was detected in optical wavelengths during a solar eclipse, using the high-cadence SECIS instrument, yielding a speed of $v_{ph} \approx v_A = 2100$ km s$^{-1}$ (Williams et al. 2001; Katsiyannis et al. 2003).

Fast kink waves have possibly been detected in the outflow regions of coronal magnetic reconnection sites in solar flares, based on the rapid initial wave speed of $v_{ph} \approx 500$ km s$^{-1}$ and the periodic transverse displacements of the outflow jets, detected as tadpole-like features in supra-arcadal flare loop systems (Verwichte et al. 2005).

Observations of spatially and temporally ubiquitous waves detected with the Coronal Multi-channel Polarimeter (CoMP) in the form outward and inward propagating wave features in $k - \omega$ diagrams have been attributed to propagating Alfvén waves...
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( Tomczyk et al. 2007; Tomczyk & McIntosh 2009 ). However, it was also argued that these observations can be explained in terms of guided kink magneto-acoustic modes, based on the lack of collective behavior for torsional Alfvén waves expected in MHD theory (Van Doorsselaere et al. 2008). The amount of energy carried by these propagating waves was found to be too weak to heat the solar corona, but a possibly sufficient amount hidden in unresolved Alfvén waves cannot be excluded (Tomczyk et al. 2007).

In summary, the key observations summarized in these two Sections demonstrate that coronal seismology bears enormous potential for the diagnostics of coronal magnetic field strengths, temperatures, and energy transport from the solar surface (or interior) upward to the corona.

2.3. Previous Detections of Coronal Waves in Optical Wavelengths

The detection of coronal waves and oscillations in optical wavelengths seems to be rather difficult due to the turbulent fluctuations in the Earth atmosphere, but the advanced technology of adaptive optics (AO) designed for ATST will allow us to push the frontiers of wave detection in the solar corona in optical wavelengths. To set the scene, let us start with a brief review of previous studies in optical and Hα wavelengths (Table 2), which were mostly motivated by the theoretical possibility of coronal heating by waves. Such measurements of waves in the optical corona succeeded only above the limb, either during eclipses or using coronagraphs, so that the much brighter light from the solar disk was occulted.

Early searches for coronal waves have been conducted in power spectra of the Fe xiv green line (5303 Å) recorded above the solar limb (Koutchmy et al. 1983). No significant period was found in the intensity, but significant power was detected in the Dopplershift signal with periods of 43, 80, and 300 s, the latter being coincident with global p-mode oscillations. Koutchmy et al. (1983) suggested that the Doppler velocity oscillations could be due to resonant Alfvén waves. Then there were searches for high-frequency oscillations ($P = 0.5 – 10$ s) performed in a number of total solar eclipse observations (Pasachoff & Landman 1984; Pasachoff & Ladd 1987; Pasachoff et al. 2000, 2002), but none or only a marginal excess (at the $\lesssim 1$% level) was found in power spectra of the 5303 Å green line.

Spectroscopic observations of coronal waves have been pursued with the Norikura coronagraph in the green line (5303 Å), with the finding of excess power in the 1-3 mHz and 5-7 mHz range in Doppler velocities (Sakurai et al. 2002). Wave speeds of $v \approx 100$ and $\approx 500$ km s$^{-1}$ were derived; the slower ones are likely to be associated with sound waves, and the faster ones possibly with Alfvénic or magneto-acoustic waves.

High-cadence observations of a solar eclipse was conducted with the SECIS instrument in the Fe xiv green line (5303 Å) during the 1999 Aug 11 eclipse in Bulgaria, which provided evidence for oscillations at a period of $P = 6$ s (Williams et al. 2001, 2002). Williams et al. (2001) and Katsiyannis et al. (2003) identified the location of the coronal oscillation in a small-scale loop (with a length of $L \approx 50$ Mm) and measured a propagation speed of $v_A \approx 2100$ km s$^{-1}$ at the location of the oscillating signal. Based on these observables they interpreted the phenomenon as an impulsively generated fast mode wave that is generated at one footpoint of the loop and propagates along it. A more extended Fourier spectral analysis in the frequency range of 1-10 Hz (periods of $P = 1 – 10$ s) in thousands of (4′′) pixels of the same SECIS data was unsuccessful in finding more significant periodicities (Rudawy et al. 2004). A similar search in eclipse data of 2001 June 21, which had considerably better data quality than the 1999
Aug 11 data with the same (SECIS) instrument yielded a similar null-result (Rudawy et al. 2010). It was concluded that the pervasive Alfvén wave-like phenomena discovered with polarimetric Dopplershift observations using the CoMP instrument (Tomczyk et al. 2007) do not give rise to significant oscillatory intensity fluctuations (Rudawy et al. 2010).

A similar (wavelet) analysis of the 2009 July 22 solar eclipse observed in Anji (China) with a spectrograph at wavelengths of 5303 Å and 6374 Å revealed oscillations in intensity, velocity, and line width with periodicities in the range of \( P = 29 - 64 \text{ s} \), possibly caused by Alfvénic or magneto-acoustic waves (Singh et al. 2011).

Quasi-periodic brightness fluctuations were also measured in polarized brightness time series in the solar wind emanating from coronal holes at heights of \( \geq 2R_\odot \) with the white-light channel of UVCS onboard SOHO, exhibiting significant peaks in the Fourier power spectrum at \( P \approx 6 - 10 \text{ min} \), and possibly at \( P \approx 20 - 50 \text{ min} \) (Ofman et al. 1997, 2000). These oscillation have been interpreted in terms of slow magnetosonic waves propagating in coronal plumes (Ofman et al. 2000).

We have not mentioned waves and oscillations in prominences and filaments here, which can also show periodicities in the 3-5 min range (e.g., Balthasar et al. 1986) and can carry oscillation energy into the corona. For a review of observations and the theory of oscillations in quiescent prominences see, e.g., Oliver & Ballester (2002).

3. Research Opportunities for ATST

Given the optical/infrared spectral range and the high-resolution magnetic field capabilities of ATST (\( \approx 0.05'' - 0.1'' \)), we anticipate the following research foci in coronal seismology: (1) Optical detection of coronal waves and oscillations (Section 3.1), (2) high-resolution magnetic field modeling with accurate determination of Alfvén speeds (Section 3.2), and (3) correlative studies in the coupling of photospheric and coronal waves (Section 3.3).

3.1. Optical Detection of Coronal Waves with ATST

What are the chances that ATST can detect waves in the solar corona? The relative brightness of the lower corona (above the limb) to the optical disk (photosphere) is about a factor of \( 10^{-6} \) (K-corona) and drops to \( 10^{-9} \) in the outer F-corona at a height of several solar radii. The contrast \( \delta I/I \) of sound waves in the solar corona is related to the density change \( \rho' / \rho \) and the ratio of the velocity \( v \) (in direction of propagation) to the sound speed \( c_s \) (e.g., Sakurai et al. 2002),

\[
\frac{\delta I}{I} = 2 \frac{\rho'}{\rho} = 2 \frac{v}{c_s} , \tag{2}
\]

which amounts typically to \( (\delta I/I) \approx 0.05...0.1 \), based on measurements in soft X-rays with SoHO/SUMER (e.g., Wang et al. 2003). Thus, the contrast of the brightness variation caused by an acoustic wave would be a factor of \( 10^{-7} \) at best, which is the reason why all previous wave detections in optical wavelengths succeeded only above the limb, either during a solar eclipse or using disk-occulting coronagraphs. Hence, the same is true for ATST, requiring an occulter and a strong suppression of straylight above the limb. The specifications of ATST quote a scattered light level of \( < 2.5 \times 10^{-6} \) at an altitude of 0.1 solar radii (70 Mm) above the limb at a wavelength of \( \lambda = 10,000 \) Å. If
an acoustic wave has a contrast as measured by SUMER, which amounts to a fraction of $(0.5 - 1) \times 10^{-7}$ of the disk brightness, it would be a factor of $\approx 25 - 50$ below the straylight level, which should still be detectable, since the straylight should form a uniform background that can be accurately subtracted with the proper radial gradient. The possibility of detecting acoustic waves of this magnitude with ATST is also plausible if we believe the positive detections of wave signals with less sensitive instruments, such as the Sac Peak coronagraph (Koutchmy et al. 1983) or the Norikura coronagraph (Sakurai et al. 2002). An example of loop fine structures that can be seen in a white-light image, possible wave ducts of acoustic and Alfvénic waves, is shown in Figure 1 (Druckmüller 2009).

The detection and localization of acoustic waves with ATST is mostly helped by the higher spatial resolution. The contrast for a linear structure (say the loop width $w_{\text{loop}}$) scales linearly with the width of the pixel ($w_{\text{pixel}}$), if unresolved,

$$
(\delta I_{\text{obs}}/I) = (\delta I/I) \times \begin{cases} 
\frac{w_{\text{loop}}}{w_{\text{pixel}}} & \text{for } w_{\text{loop}} \leq w_{\text{pixel}} \\
1 & \text{for } w_{\text{loop}} \geq w_{\text{pixel}}
\end{cases}.
$$

(3)

Thus, ATST allows us to resolve loop strands, and hence density perturbations that propagate in these loop strands, down to the resolution limit of $w_{\text{pixel}} \approx 0.05'' - 0.1''$ (35-70 Mm), which is a factor of 40-80 better than the 4'' resolution of the SECIS instrument, for instance. Thus, ATST would theoretically improve the contrast of the smallest resolved loop strands, after local background subtraction, up to a factor of 40-
compared with the SECIS instrument, and thus would be much more sensitive in detecting periodicities and wave motions with Fourier and wavelet analysis techniques. Let us consider the detection of Alfvénic or magneto-acoustic waves, based on the previous CoMP observations (Tomczyk et al. 2007). The authors reported no intensity variation down to a level of \((\delta I/I) < 3 \times 10^{-3}\), but detected a peak at \(v \approx 3.5\) mHz (5-min period) in the Fourier spectrum of the velocity power. Hence, ATST may not detect density variations either, but should detect the periodic Dopplershift signal \((v/c_s)\). A correlation analysis of neighbored pixels in the study of Tomczyk et al. (2007) revealed coherent motion in narrow structures \((\approx 9\) Mm \(\times 45\) Mm), which could be the result of either density compressions caused by Alfvénic waves that were converted into magneto-acoustic waves, or density compressions caused by torsional or transverse (horizontally or vertically polarized) kink-mode oscillations. Torsional kink-mode oscillations of a helically shaped loop, for instance, have been inferred from 3D reconstructions based on stereoscopic triangulation with STEREO/EUVI (Aschwanden 2009). The higher spatial resolution of ATST could reveal the exact geometry of the spatial structures that oscillate, which could be helical compression zones for torsional magneto-acoustic waves, or a semi-circular displacement for transverse kink-mode oscillations (with horizontal or vertical polarization). Accurate information on the substructuring of oscillating loops has also intriguing consequences for understanding the physics of wave coupling, resonant absorption, Alfvén wave phase mixing, and twisting by electric currents. Hence, a higher spatial resolution with sufficient cadence clearly would clarify the geometric and physical identification of the observed wave types.

### 3.2. High-Resolution Magnetic Field Modeling

ATST will have capabilities to measure the magnetic field with high resolution in the photosphere (Fe \(\text{I} 6303\) Å , Mg \(\text{I} 12320\) Å line) and chromosphere (Ca \(\text{II} 8542\) Å line). Measurements of the magnetic field in the corona, in contrast, is a prime task of coronal seismology that needs to be demonstrated and corroborated with theoretical magnetic field modeling based on photospheric and chromospheric magnetogram data, that can be routinely obtained. However, the two methods entail different challenges and thus are the subject of intense ongoing research.

Magnetic field extrapolation methods have the following caveats: (1) They depend on the theoretical magnetic field model, such as the potential field model or the force-free model, which is further subdivided into linear (LFFF) and nonlinear force-free fields (NLFFF); (2) They depend on the numerical method (e.g., the Green’s function method or the eigenfunction expansion method for potential fields, or the vertical integration method, the boundary integral method, the Euler potential method, the MHD method, the vector Grad-Rubin method, or evolutionary methods in the case of non-potential fields, for references see Aschwanden 2004, Chapter 5; or comparison of 11 NLFFF methods in De Rosa et al. 2009); (3) Most methods are based on the assumption that the magnetic field is force-free in the lower chromosphere, which is often not the case (Metcalf et al. 1995); (4) The accuracy of the extrapolation methods depends on the size of the boundary box and the accuracy of the boundary data; (5) Line-of-sight magnetogram and vector magnetograph data are both subject to data noise, which adds uncertainties that exponentially increase with height in field extrapolations; (6) The absolute value of the magnetic field strength measured with the Zeeman effect and Stokes polarimetry depends on the spatial resolution of the magnetogram, (this is where ATST comes in and could ameliorate the situation).
Figure 2. A line-of-sight magnetogram observed with HMI/SDO (top left), an EUV image observed with AIA/SDO in 171 Å (top right), an HMI-based dipolar potential field model (bottom left), and the observed position and closest magnetic field line (bottom right) of an oscillating loop observed on 2010 Oct 16, 19:22 UT, is shown. The closest matching magnetic field line has a field strength of $B_{11} = 187$ G and $B_{12} = -63$ G at the footpoints (Aschwanden & Schrijver 2011).

Coronal seismology, based on the relationship of the kink-mode period to the Alfvén speed (Equation 1), on the other hand, has completely different difficulties and limitations: (1) The coronal magnetic field can only be determined during time intervals when coronal loops are excited into transverse kink-mode oscillations, which occurs only during a small percentage of time, essentially only after a major flare, CME, or destabilized filament eruption; (2) Coronal seismology is also limited to the locations of oscillating loops, which generally is confined to flaring active regions and applies often only to a subset of resonant loops; (3) The simple relationship of the kink-mode period to the Alfvén speed (Equation 1) ignores the magnetic field $B(s)$ and density variation $n_0(s)$ along the loop, which implies a variation of the Alfvén speed along the loop; (4) MHD simulations and the analytical relationship (Equation 1) disagree within a factor of 2 to-date (De Moortel & Pascoe 2009); (5) The proper measurement of the 3D geometry of kink-mode oscillations requires a 3D capability, such as stereoscopic trian-
gulation with STEREO, which bears some systematic errors also. The proper geometry is particularly important, because the kink-mode period or the inferred magnetic field scale linearly with the loop length $L$ (Equation 1); (6) Measurements of the electron density inside and outside of the oscillating loop are also required to fully constrain the kink-mode relationship with the magnetic field (Equation 1), which can be estimated from emission measure analysis in EUV and soft X-rays, but have substantial systematic errors due to the unknown geometric filling factor. The inferred electron densities depend also on the applied geometric loop cross-section model (for the density inside of the loop) and hydrostatic models of the background corona (for the density outside of the loop).

Most of the problems have been addressed in numerous studies to a varying degree. The ultimate goal of coronal seismology is less to converge to a global solution of the magnetic field in the solar corona (because the diagnostic tracers are too intermittent in space and time anyway), but rather to test our understanding of the underlying physics in a few well-observed cases. Where ATST can help is mostly in the accurate measurement of the magnetic field strength in the photospheric footpoints of oscillating loops using its high spatial resolution, which allows an accurate determination of the Alfvén speed in the loops of interest.

We will illustrate this research task with a specific measurement that has been recently obtained with AIA and HMI onboard SDO (Figure 2). A flare has been observed on 2010 Oct 16, which was accompanied by a narrow-cone CME that escaped in westward direction and excited vertical kink-mode oscillations of a highly inclined loop along its way (Aschwanden & Schrijver 2011). This loop was also observed with STEREO and its 3D geometry could be well-determined, including the footpoint positions and the loop length. Therefore, we know exactly the photospheric magnetic field strengths at the footpoints and can model the magnetic field $B(s)$ and Alfvén speed $v_A(s)$ along the loop with the closest matching field line of a theoretical field extrapolation model. However, comparing a fitting potential field line, an apex field strength of $B = 6$ G was found, which corresponds to an average field of $< B > = 11$ G along the loop, which disagrees with the value obtained from the kink-mode relationship (Equation 1), i.e., $B_{\text{kink}} = 4.0 \pm 0.7$ G. It is conceivable that the higher spatial resolution of ATST would measure an even higher magnetic field strength but constrain a different (nonlinear force-free) field solution that can be used for more stringent tests of coronal seismology.

### 3.3. Coupling of Photospheric and Coronal Waves

Since ATST will probe dynamic phenomena mostly in the photosphere and chromosphere, we anticipate also a number of research tasks that are related to the coupling of photospheric/chromospheric waves and oscillations with their coronal counterparts. We enumerate a few examples.

(1) What is the origin of coronal acoustic waves? A number of coronal wave phenomena have been found to be synchronized with the global 3-min and 5-min p-mode oscillation period (De Moortel et al. 2002a), and thus are likely to be excited by them, although there is an acoustic cutoff for the upward transmission of waves, but sufficient wave leakage apparently occurs (De Pontieu et al. 2005) that needs to be understood in terms an improved dynamic chromospheric model. Evidence for leakage of the 3-min umbral oscillation to the corona was presented by Maltby et al. (1999).
ATST could pinpoint the exact locations and physical mechanisms where the coupling occurs.

(2) Are quasi-periodic propagating signals in the corona produced by magneto-acoustic waves or by high-velocity upflows? Spectroscopic Dopplershift measurements suggest evidence for quasi-periodic high-velocity upflows in some cases (De Pontieu & McIntosh 2010), which may play an important role for spicular heating of the corona and of the solar wind (De Pontieu et al. 2004). ATST could disentangle the magnetic topology of the source regions of high-velocity upflows.

(3) Can AC waves heat the corona, e.g., by the process of Alfvénic resonance, resonant absorption, Alfvén phase mixing, current layers, MHD turbulence, or cyclotron resonance? (e.g., see review in Aschwanden 2004, Chapter 9). Most of these processes require the knowledge of the photospheric magnetic field configuration and dynamics, which can be probed with ATST with higher spatial resolution than before. The Poynting flux determines the amount of wave energy that is transported into the corona, which requires high-resolution magnetic field measurements at the footpoints.

(4) The damping of coronal kink-mode oscillations is not understood, although at least 5 different physical mechanisms have been proposed: non-ideal MHD effects, lateral wave leakage, footpoint wave leakage, Alfvén wave phase mixing, and resonant absorption. Some of them depend on chromospheric conditions, such as footpoint wave leakage (De Pontieu et al. 2001), which can only be tested with improved chromospheric density models, that ATST could furnish with sufficient spatial resolution.

(5) A flare with a CME event usually triggers a global surface wave (also known as EIT wave), which contains multiple components, some propagating in the photosphere (sunquakes, Moreton waves) and some in the lower corona (EUV manifestation of a global wave). The coupling between the photospheric and coronal waves, which originate at the same epicenter, but propagate with different speeds, is still poorly understood. ATST could elucidate the photospheric and chromospheric parts with higher sensitivity, which would help to identify the underlying MHD wave types.

All in all, we see that most physical processes in the solar interior, photosphere, chromosphere, transition region, and corona are often coupled and cannot be studied separately. This is the primary reason why ATST, although being mostly a photospheric/chromospheric microscope, can elucidate many coupling mechanisms that are important to understand the origin of coronal seismology. In addition, we envision that there is new discovery space at so far unobserved small spatial scales and high frequencies, which may transform and enlarge the known field of coronal seismology.

Acknowledgments. Part of the work was supported by NASA contract NNG04EA00C of the SDO/AIA instrument and the NASA STEREO mission under NRL contract N00173-02-C-2035.

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