HELIOSEISMOLOGY WITH SOLAR ORBITER: SCIENCE OBJECTIVES, OBSERVATIONAL STRATEGIES AND REQUIREMENTS

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ABSTRACT

Solar Orbiter will offer novel perspectives for helioseismology. The most interesting aspects of the mission reside in the unique vantage points from which the Sun will be viewed. Not only will out-of-the-ecliptic observations enable us to reach higher heliographic latitudes into the solar convection zone but Solar Orbiter in combination with Earth-side observations will also mean the advent of stereoscopic helioseismology. The science objectives, observational strategies and science requirements are discussed.

Key words: Solar Orbiter; Helioseismology.

1. INTRODUCTION

The most interesting aspects of the Solar Orbiter mission clearly reside in the unique vantage points from which the Sun will be viewed. Although the exact orbit of the spacecraft is still under discussion, the orbit design will include two main characteristics, both of which offer novel perspectives for helioseismology. First, Solar Orbiter will make observations away from the ecliptic plane to provide views of the Sun's polar regions. The inclination of the spacecraft's orbit to the Ecliptic will incrementally increase at each venus swing-by manoeuvre to reach up to about 30° toward the end of the mission. Second, Solar Orbiter will cover a large range of spacecraft-Sun-Earth angles. In combination with data collected from the ground or near-Earth orbit, Solar orbiter will mark the advent of steroscopic helioseismology.

2. UNEXPLORED TERRITORY

Helioseismology owes its spectacular progress over the last ten years to the GONG and MDI-SOHO time series of high spatial resolution Doppler images of the Sun's surface. Thanks to global-mode helioseismology [1], the solar differential rotation has been mapped as a function of unsigned latitude and radial distance throughout most of the convection zone with a very good level of precision, while the sound speed profile averaged over spheres has been measured down to the solar core. The picture of the solar interior, however, is far from complete at high heliographic latitudes and is fuzzier with greater depth. In particular, global mode frequency inversions for rotation cease to be accurate above 70° latitude and are uncertain in the radiative interior.

The developing science of local helioseismology [2], which aims at producing three-dimensional images of the solar interior, has provided information in the upper third of the convective envelope and only at relatively low latitudes (less than 50° latitude). High latitudes are difficult to study because the sensitivity of the line-of-sight Doppler measurements to the nearly radial pulsations drops as a function of center-to-limb distance. In addition, the reduction of the effective spatial sampling on the Sun toward the solar limb implies that moderate to high degree modes are more difficult to detect away from disk center in the center-to-limb direction (smaller local spatial Nyquist frequency: foreshortening).

The combined effect of the foreshortening and the projection of the oscillation displacement vector onto the line of sight is illustrated in Figure 1, which shows the temporal power spectrum in each MDI CCD pixel along the central meridien. The power of the solar oscillations in the frequency band 1.7-5.5 mHz is below noise level for angular distances from disk center greater than about 70° (Figure 1). That measurements are difficult to make close to the solar limb has implications not only for studies at high latitudes, but also for probing deep into the interior. Indeed, acoustic ray bundles that penetrate deep inside the Sun connect surface locations that are separated by large horizontal distances: less signal at high latitudes means a reduced ability to probe deep at moderate latitudes. In short, much remains to be learned above 50° heliographic latitude and for radial distances less than, say, $0.9R_\odot$.

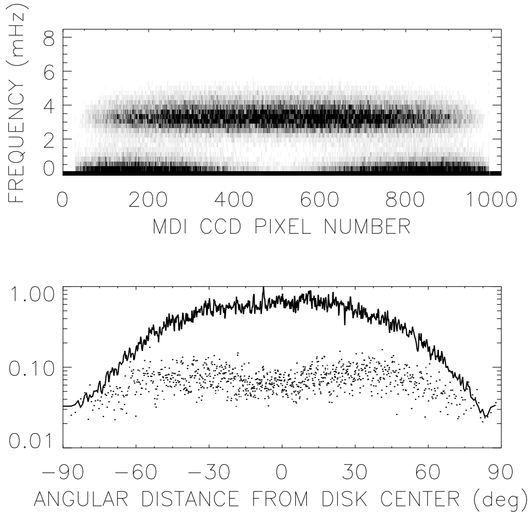

Figure 1. Top: Temporal power spectrum in MDI CCD pixels along the central meridian. The power in the solar oscillations peaks around 3 mHz, while the low frequency component is mostly caused by supergranulation. Bottom: Power in solar oscillations (black line) versus angular distance measured from disk center. The dots give estimates of the solar background noise.

3. OUTSTANDING QUESTIONS

3.1. Internal rotation at high latitudes

The large-scale differential rotation is an essential dynamical property of the Sun. Inversions of global-mode frequency splittings support the idea that rotation is special at heliographic latitudes above 70°. In particular, some inversions suggest the existence of a buried jet-like zonal flow [3] and a surprisingly slow rotation rate above 75° compared to a smooth extrapolation from lower latitudes [4, 5] (Fig. 2). In addition, the near-surface radial gradient of the angular velocity, may switch sign near latitude 50° [6]. These results have been derived using global-mode techniques, which do not necessarily require local observations at high latitudes. Using observations out of the Ecliptic plane together with techniques of local helioseismology, Solar Orbiter may offer the opportunity to check the validity of the global-mode frequency inversions at high latitudes. Of course, direct Doppler measurements will also give important information about the surface rotation rate.

We note that the apparent slow polar rotation is in contradiction with the naive expectation of a spin up due to the conservation of angular momentum and the existence of a poleward meridional flow [7]. Spectroscopic observations in the infrared by Ye & Livingston [8] suggest that rotation very close to the Sun's poles may occasionaly be peculiar: apparent cessation of rotation in some sample data, sharp velocity signal (a vortex?) within 1° of the pole in other.

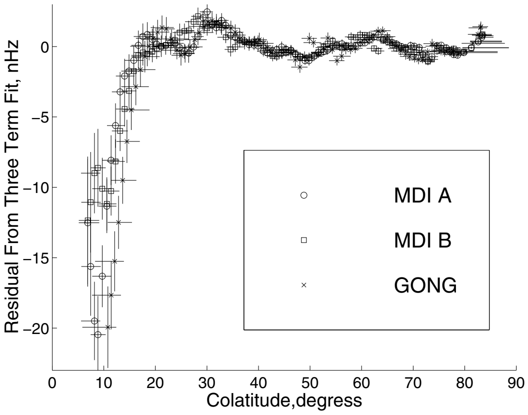

Figure 2. Residuals of the solar differential rotation from a smooth fit, showing a sharp deviation for co-latitudes less than 20° *[5].*

3.2. Meridional circulation

Surface Doppler measurements have shown the existence of a meridional flow from the equator to the poles with a maximum amplitude of about 15 m/s near 30° latitude. Meridional circulation plays a role in the evolution of the large-scale surface magnetic field. In flux-transport dynamo models based on the Babcock-Leighton mechanism, it carries the poloidal field generated at the surface down to the bottom of the convection zone, transports the toroidal magnetic field equatordward, and sets the period of the solar cycle [9]. Due to mass conservation, the meridional flow amplitude at the base of the convection zone is expected to be extremely small: it has been estimated to be as low as 1.2 m/s by Hathaway et al. [10] from the equatorial drift of sunspots.

Techniques of local helioseismology are sensitive to the first order effect of meridional circulation. Giles et al. [11] were first to infer the horizontal meridional flow at moderate latitudes down to about $0.8R_\odot$, with time-distance helioseismology. The meridional flow at latitudes above 50°, however, is poorly known and should be an important target for Solar Orbiter. One question is whether the meridional flow has a single- or multi-cell structure. The determination of the latitudinal component of the meridional flow in the near polar regions is likely to be extremely difficult (a very small signal is expected). There, it may even be preferable to try to detect the radial component of the meridional flow with time-distance, holographic, or Fourier-Hankel analyses.

3.3. Polar region variability

The polar regions appear to be very dynamical. There is evidence that the differential rotation near the poles may vary on a short time scale [8]. The magnetic properties of the polar regions at solar minimum determine the strength of the forthcoming solar maximum [12]; a new sunspot

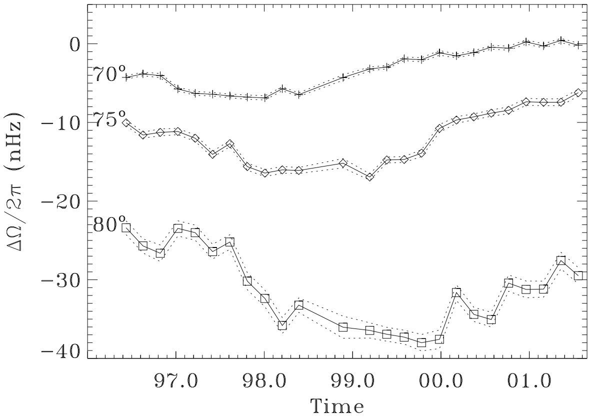

Figure 3. Near polar rotation rate from MDI f-mode frequency splittings as a function of time [13].

cycle starts in the polar regions. Thus, studying the dynamics and variability of the polar regions will help us understand how the solar dynamo works.

Using global-mode helioseismology, Birch & Kosovichev [5] and Schou [13] found that there may be a significant variation of the subsurface high-latitude rotation as a function of the phase of the solar cycle (polar branch of the torsional oscillation, Fig. 3). Does the meridional circulation, which is known to vary with time near active latitudes, also vary at high latitudes? In particular, does it exhibit multi-cell structures that come and go with the phase of the solar cycle? We may also ask about flow patterns across the poles. Answering these questions will require long-term monitoring of the polar regions.

3.4. Convection at high latitudes

Near-surface convective flows act as an important driver of solar activity. By controling the evolution of the magnetic network, supergranulation affects chromospheric and coronal activity. Near-surface convective flows could support local dynamo action too. Is the dynamics of supergranulation different in the polar regions where the effect of the Coriolis force is expected to be much stronger that at lower latitudes? What is the dynamical coupling between near-surface flows in the near polar regions and photospheric/coronal magnetism? There are several reasons to want to study convective flows in the polar regions. Flows at supergranular scales can be measured with seismic holography or time-distance helioseismology with sufficient temporal resolution. A good spatial resolution does require, however, that f-modes be observed [14]. As discussed by Gonzalez Hernandez et al. [15], flows at larger spatial scales than supergranulation can be measured with the technique of ring diagram analysis.

3.5. Structure and variability of the Tachocline, dynamo flows

The solar tachocline is a thin transition layer between the latitudinal differential rotation of the convection zone and the nearly uniform rotation of the radiative interior. It is believed to be the seat of the generation of the global magnetic field [16] and is thus an important target for helioseismological studies. The tachocline has been measured by helioseismology to be prolate [17]. Its shape and thickness are expected to be affected by a toroidal field stored there. A proper determination of the figure of the solar tachocline obviously requires high latitude information. It has recently been suggested by Rempel & Dikpati [18] that prograde fluid jets may be generated in the solar tachocline at high latitudes, which may be measurable by helioseismology [19]. The tachocline also appears to support quasi-periodic oscillations with a period of approximately 1.3 year [20], which may be a deep extension of the torsional oscillations.

There are indications that surface magnetic fields often cluster at a few specific longitudes for several rotation periods [21]. The preferred longitudes manifest themselves in the interplanetary magnetic field. A recent analysis by Berdyugina & Usoskin [22] supports the idea that sunspots in both the northern and southern hemispheres appear preferentially at two persistent active longitudes separated by 180°. This may indicate the presence of an underlying non-axisymmetric magnetic structure and could be a manifestation of non-axisymmetric modes of the dynamo [23, 24].

Local helioseismology is the appropriate tool to search for longitudinal variations deep in convection zone. Attempts by Birch [25] and Duvall [26] have proven difficult. Ruzmaikin & Lindsey [27] predict that stereoscopic local helioseismology will be an important advance to detect the signature of deep dynamo flows and their longitudinal variations inside the Sun.

4. BASIC REQUIREMENTS FOR HELIOSEISMOLOGY

4.1. Observables

The fundamental data of modern helioseismology are series of high resolution Doppler images of the Sun's surface, recorded at a cadence of 1 min or less. In addition to Doppler images, it is essential to collect intensity images and magnetograms at a smaller cadence (30 min, say) to locate regions of magnetic activity and make possible studies of the relationships between the Sun's interior and surface magnetism.

Two telescopes on the Visible-light Imager and Magnetograph (VIM) on Solar Orbiter will provide the data for helioseismology. VIM will produce Doppler velocity images and maps of the vector magnetic field. It will consist of two telescopes and a filtergraph. The Full Disk Telescope (FDT) will obtain 2k×2k full-disk images. The High Resolution Telescope (HRT) will deliver 1 arcsec angular resolution images over a field of view of 17×17 arcmin^2.

4.2. Important parameters

Our ability to probe the solar interior depends on a number of parameters. Assuming that well-calibrated, nearly-continuous time-series of Doppler images will be made available, these parameters are mainly the observation duration, the temporal sampling, the field of view, and the spatial resolution. At fixed data volume, we may have a little bit of freedom to choose between trade-off solutions. We may, for example, choose to transmit to Earth a smaller field of view at full spatial resolution, or the opposite (just one example).

The observation duration is a critical parameter: the larger T, the smaller the contribution of random noise to helioseismic measurements. For nearly all quantities of interest, the level of random noise due to the stochastic nature of solar oscillations behaves like $T^{-1/2}$. Near-surface helioseismic inferences require less data (typically, days to weeks) than investigations of the deep interior for which long time averages are required (typically, weeks to months or even years). The current mission baseline allows observations to be carried out for about $T = 10$ days during each orbit, near perihelion.

The temporal sampling needs to be at least as short as $\Delta t = 1$ min to make possible observations of all solar waves with significant power; a smaller value of, say, 40 s may be desirable to detect the highest frequency waves. The use of high-frequency waves is potentially important to study magnetic effects and to provide more localized information.

The field of view must be large to resolve the low-degree modes (large horizontal wavelengths) that penetrate deep into the interior, as well as to make possible the study of large scale solar inhomogeneities. A large field of view also gives the ability to track local areas on the Sun over long periods of time to compensate for the spacecraft motion in frames that co-rotate with the Sun. A full-disk view is ideal, especially to make the most of stereoscopic analyses.

The spatial resolution measured on the Sun's surface is a function of ccd pixel size and center-to-limb distance. Solar oscillations have significant power at all wavelengths above, say, 5 Mm (f-mode frequency at 3 mHz). Typically, a spatial sampling of 1 Mm (measured on the Sun) is sufficient for nearly all applications of helioseismology. A higher spatial sampling is not needed, while a lower one is still acceptable for a large range of applications that involve long-wavelength deep-penetrating modes of oscillation. Spatial sampling is most critical to detect, close to the solar limb, waves that propagate in the center-to-limb direction (foreshortening, Sec. 2).

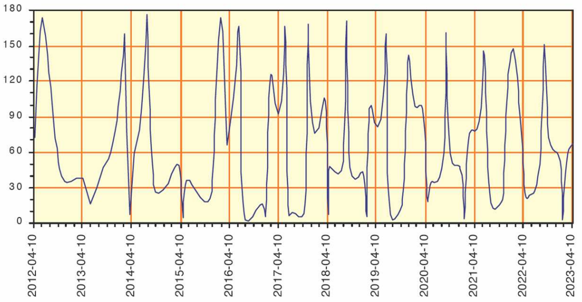

Figure 4. Sun-spacecraft-Earth angle as a function time for a particular mission profile.

5. STEREOSCOPIC HELIOSEISMOLOGY

Helioseismic data analysis includes global and local methods. Global helioseismology is based on the interpretation of the eigenfrequencies of the resonant modes of oscillations. The aim of local helioseismology is to make three-dimensional images of the Sun's interior, using the full wave field observed at the surface, not just the eigenmode frequencies. Here we comment on stereoscopic helioseismology, which would benefit both global and local methods of helioseismolgy.

By definition, stereoscopy requires several observatories. Both SDO-HMI and GONG (or another ground-based facility) are expected to be operational at the time of Solar Orbiter operations. Combining Solar Orbiter with any one of them will open new windows into the Sun. Figure 4 is a plot of the Sun-spacecraft-Earth angle as a function of time for a particular mission profile. Note that how well the data can be merged will depend critically on timing accuracy and geometry knowledge.

Looking at the Sun from two distinct viewing angles results in an increase of the observed fraction of the Sun's surface. Global helioseismology would naturally benefit from this situation, since the modes of oscillation would be easier to disentangle (reduction of spatial leaks). The precision on the determination of the mode frequencies would improve at high frequencies for all spherical harmonic degrees; it would improve less at low frequencies where solar noise is the main issue. Spatial masks for extracting acoustic modes (and gravity modes [28]) will be closer to optimal.

With stereoscopic local helioseismology, new acoustic ray paths can be considered to probe deeper layers in the interior. Observations from two widely different viewing angles allow the probing of the solar interior at any depth, and in particular the solar tachocline [27]. It even becomes possible to target regions in the solar core: this is illustrated in Figure 5. This aspect of seismic stereoscopy is revolutionary.

The other aspect of stereoscopy is that it is possible to observe a common area from two different viewing angles. This case is useful to understand systematic errors

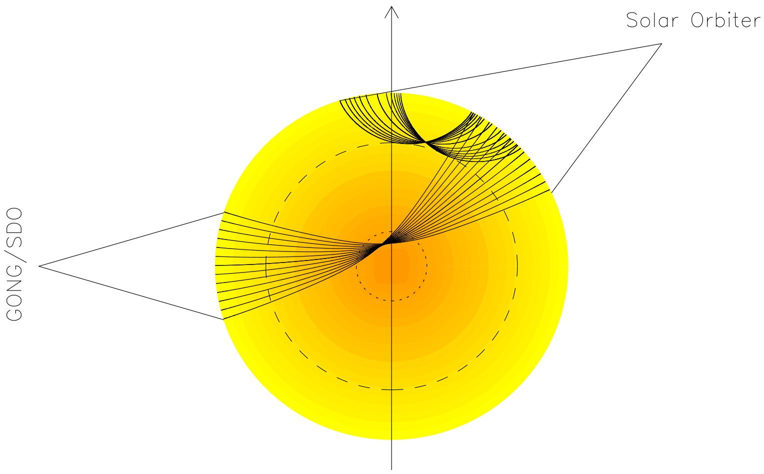

Figure 5. Sketch showing deep-focussing averaging schemes for local helioseismology. Solar Orbiter in combination with SDO or ground-based observatories will give access to local information very deep inside the Sun (stereoscopic helioseismology).

and line-of-sight projection effects in local helioseismology. It is also potentially important to minimize the contribution of convection noise in spectra of solar oscillations. Suppose that the amplitude ratio and the phase relationship of horizontal to vertical velocities is different for solar oscillations and small-scale convection, then the two can at least partially be decoupled. This may result in a significant reduction of noise at low temporal frequencies. Finally, there is the possibility of observing the same area with two different spectral lines formed at two heights in the solar atmosphere to study vertical wave propagation.

6. WHAT SCIENCE OBJECTIVES FOR SOLAR ORBITER?

Section 3 was a long list of (difficult) topics in helioseismology. Whether Solar Orbiter can help us make progress in some of these areas will ultimately depend on the orbital parameters, the instrumentation and the available telemetry, but also on the choice of observational strategies and onboard data processing algorithms.

The broad science objective is to gain a better understanding of solar activity and variability. In practice, it means extending our knowledge of the solar interior to higher latitudes and larger depths, beyond what SDO can achieve. All topics listed in Section 3 are potential targets for investigation. Studying the near-surface layers at high latitudes is a prime objective. Probing the deep interior with sufficient accuracy may, however, require longer observation durations than will be possible.

In addition, demonstrating the concept of stereoscopic helioseismology is an important objective. SDO and/or ground-based facilities together with Solar Orbiter would make a most powerful combination.

7. TECHNICAL REQUIREMENTS

Helioseismology will principally be done with the FDT and occasionally with the HRT. The following requirements are mostly based on the MDI/HMI helioseismology requirements. The exact requirements for helioseismology on Solar Orbiter may not be exactly the same.

7.1. Image stabilization system

The specifications derive from the stability required for a 60 s velocity measurement. The xy jitter must be reduced to 1/10 CCD pixel (FDT) peak to peak. Image offset between line scans shall be less than 0.05 pixel.

Ideally the roll jitter should also be reduced to 1/10 CCD pixel (FDT) peak to peak at the edge of the image. The ISS cannot possibly handle this constraint, which is left to the spacecraft.

Helioseismology requires offset knowledge: this can be achieved by transmitting the limb position on the CCD. An accurate determination of the center of the solar disk and of the solar radius requires this to be done with intensity images (not velocity images, too noisy). Roll knowledge is provided by the spacecraft (in part) and is important information.

7.2. Doppler velocity images

Timing: The clock shall be stable to one part in one million over several days and there shall be no discontinuity (a science requirement). The time must be known within 100 ms at all times.

Cadence: 60 s (8.33 mHz Nyquist). Preferably 40 s (12.5 mHz Nyquist) , but not absolutely required.

Field of view: The complete limb should be visible on the velocity image (FDT).

Data coverage: As said above, studies of the solar near-surface layers require days to weeks of data. Investigations of the deep interior typically require durations from weeks to months. In practice, the longer the data coverage, the better. It would be very meaningful to at least consider the possibility of making observations during the cruise phase and outside perihelion passages, even at a very low telemetry rate. Line-of-sight vectors other than Earth-Sun are prefered for stereoscopic helioseismology.

Data completeness: 95% during observing windows. Telemetry issues may not allow this. Should time-series have gaps, these gaps should be chosen with care if possible. In general, periodic observation windows introduce systematic errors in the analysis of solar oscillations (side lobes in power spectra, or blind spots in local helioseismology). It would be preferable to consider pseudo-random observation windows with flat power spectra. Magnetograms should be regularly spaced, say one or two every hour.

Spatial resolution: Many science objectives can be achieved with a relatively low spatial resolution, say 256×256 full-disk images, or even a little less if telemetry demands it. The study of regions close to the limb (e.g. near polar regions) requires, however, the full available FDT/HRT resolution.

Photon noise shall be less than 10 m/s in the quite Sun.

Spacecraft requirement: No orbital artifact above 500 μHz.

Disk averaged noise shall be less than 1 m/s. This refers to the large scale spatially coherent noise.

Disk averaged non white noise shall be less than 0.1 m/s above 500 μHz. This refers to the slowly time-varying component of the above large-scale spatially coherent noise.

Dynamic range in velocity with respect to velocity of spacecraft: ±6 km/s. This means that the measurement shall not saturate or become ambiguous within this range, in particular for pixels in places where the magnetic field is in the range ±3 kG.

The zero point velocity is not relevant for helioseismology, but is important for other applications.

Velocity scale: The systematic error on the velocity scale factor and its spatial variation shall be less than 5%.

Flat field and point spread function knowledge: Good.

8. DATA COMPRESSION, DATA RATE

8.1. Lossless compression

A standard spatial compression algorithm shall be applied to each individual image (compression factor of about 2). Little can be gained from compression schemes in the time domain. In particular nothing can be gained by transmitting first-difference images. A small gain would result from transmitting the difference between an image and its prediction using the previous N images (linear prediction based on stationarity assumption). My estimate is a compression factor of 1.1 for $N = 10$ and $\Delta t = 60$ s.

8.2. Lossy “compression”

Onboard lossy compression algorithms must be well understood and low risk. In a sense, lossy compression should be understood as data selection (essentially lossless, given a particular science application).

Spatial “binning”. The single most powerful form of data selection. Likely to be required to meet telemetry requirements. Example: select desired spatial sampling on the Sun (e.g. 2 Mm), then “bin down” CCD pixels to preserve local sampling on Sun. A proper application of this compression scheme requires a proper spatial filtering algorithm to avoid aliasing. The ideal way of doing this may be to project images onto a truncated basis of spherical harmonics functions.

Fourier filtering. One obvious lossy compression scheme is to transmit Fourier coefficients only in the range, say, 2-4.5 mHz, where solar oscillations have appreciable power, as well as a mean image every, say, 30 min. The compression factor in this case is 3.3.

Low-pass filtering. Example: record one image every 30 s, apply FIR filter with a Kaiser window (50 db) with a 4.8 mHz cutoff (60 coefficients), then transmit 1 out of 3 filtered images (5.6 mHz Nyquist). No folding of the spectrum at high frequencies and essentially lossless from a science perspective. The compression factor is 1.5 compared to a 1 min cadence time series.

8.3. Data rate

The estimated data rate needed to achieve most science objectives is less than 10 kb/s. For probing the deep convection zone and for stereoscopic analyses, a data rate of 3 kb/s may be sufficient.

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