Solar MAgnetized Regions Tomograph (SMART) Mission

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Science Questions addressed by the SMART mission

I. How do magnetic fields evolve with height in the solar atmosphere?

Information on the height-evolution of solar magnetic fields presently relies exclusively on the extrapolation of photospheric or chromospheric magnetic fields, rather than measurements. The photospheric and chromospheric magnetograms are used as the required lower boundary condition. Different assumptions result in various sophistication levels of the extrapolation of the same boundary magnetogram: current-free field (Schmidt 1964), linear force-free (LFF) field (Alissandrakis 1981; Gary 1989), and nonlinear force-free (NLFF) field (Schrijver et al. 2006, 2008; Metcalf et al. 2008 and references therein). NLFF extrapolation provides more accurate field topologies but they are computationally demanding.

Further inconsistencies arise when photospheric magnetic fields are used without preprocessing. These inconsistencies are due to the non-force-free nature of the magnetic field at the photospheric level (Georgoulis and LaBonte 2004). As such, they cannot be used in force-free field extrapolations. This problem is tackled by "preprocessing" the photospheric fields to bring them closer to a force-free equilibrium (Wiegelmann et al. 2006, 2008). The realism of the preprocessing methods is, however, still questionable (Schrijver et al. 2008).

The photosphere being non-force-free, chromospheric magnetic fields are believed to be much closer to a NLFF equilibrium (Metcalf et al. 1995—see, however, Socas-Navarro 2005a for a challenging finding). As a result, there should be a layer between the photosphere and the chromosphere where the transition from forced and force-free fields occurs. We call this layer the *magnetic transition region* (MTR), not to be confused with the radiative/thermal solar transition region. The evolution of solar magnetic fields through and above the MTR is completely unknown. Extrapolations have little to offer in this respect, given their problems and crude spatial sampling. Investigating this layer - where thermodynamic mechanisms of heating and acceleration chromospheric and low-coronal plasma take plane- require systematic multi-height and nearly simultaneous vector field measurements (see e.g. Figure 1). This approach has never been attempted due to the lack of dedicated instruments.

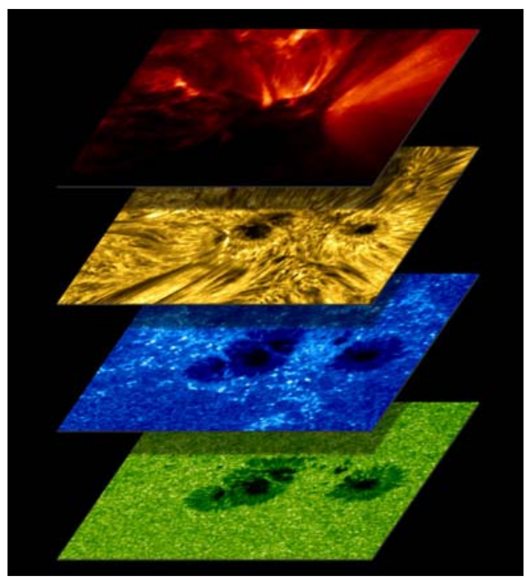

Figure 1: The proposed vector magnetograph will measure the variation of the solar magnetic field vector with altitude from the photosphere to well into the chromosphere, covering also the

Present vector magnetograms are predominantly photospheric, although chromospheric vector magnetography has recently seen some advances (Metcalf et al. 2005; Socas-Navarro 2005b; Lagg 2007). Coronal magnetography is still in its infancy. **The SMART mission proposes to probe the atmosphere between the photosphere through the MTR and into the chromosphere through near-simultaneous, multi-height measurements of the vector magnetic fields.**

II. When, and how much magnetic energy is released in solar eruptions?

Understanding the physical processes leading to transient solar activity (flares/CMEs) is extremely important for space-weather studies and predictions. The lack of significant breakthrough in this field is mainly due to the lack of measurement of the magnetic field at atmospheric layers where most of the free energy that powers solar eruptions resides. Most solar activity takes place well above the photosphere, where most available measurement capability exists. Regnier and Priest (2007) provided evidence for non-even distribution of the magnetic free energy in an active region and showed that it is predominantly accumulated within a few Mm to a few tens of Mm above the lower photospheric boundary (see also Figure 2).

These chromospheric altitudes are exactly the ones at which the proposed vector magnetograph will deliver measurements of the magnetic field vector. The availability of such measurements will allow accurate calculation of the magnetic free energy in a straightforward fashion by means of, say, the magnetic Virial theorem (Molodensky 1974; Aly 1984). These measurements are also very important for constraining extrapolation techniques and consequently the determination of coronal magnetic fields. Measurements before and after an eruption will determine the amount of magnetic energy released during the eruption. This task is so sensitive that it cannot be accomplished using seeing-dependent, ground-based vector magnetograms (see Metcalf et al. 2005 for an attempt).

In addition, high-quality measurements of chromospheric magnetic fields that are not too dependent on photospheric line-tying may establish well-defined, conspicuous eruption-associated magnetic patterns (on the photosphere, generally subtle magnetic field changes have been found after the eruptions; see Sudol and Harvey 2005). Such a finding would (i) significantly advance our understanding of solar magnetic eruptions and (ii) possibly lead to the identification of pre-eruption magnetic patterns that are telltale as to the imminent triggering of solar eruptions. Currently, all these capabilities are strongly desired but can only be envisioned as future accomplishments.

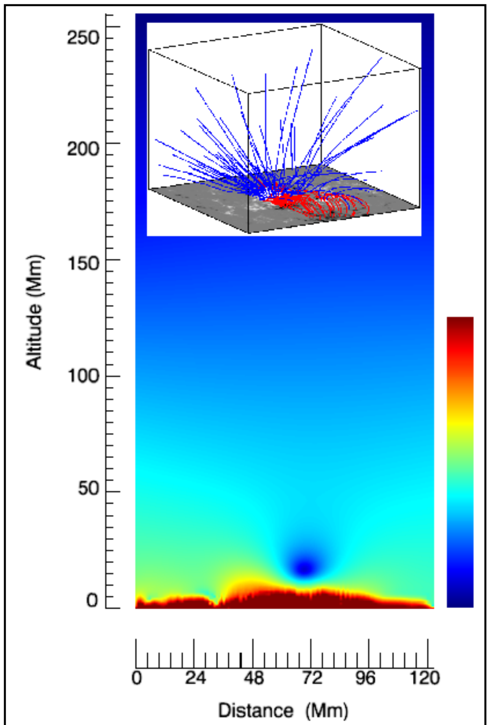

Figure 2: Spatial distribution of the free magnetic energy in a cross-section of the NLFF extrapolated magnetic fields in NOAA AR 10930 (inset). The color code corresponds to the logarithm of the free energy. About 98% of this energy resides

III. What heats the solar chromosphere and corona?

Ever since the discovery of the million-degree solar corona by Grotrian and Edlen (Grotrian 1939; Saha 1942) coronal heating remains a mystery. Even more puzzling is the fact that the corona cannot be maintained without a chromosphere. Chromospheric heating and mass supply are very challenging problems that need to be addressed in order to advance our understanding of the solar corona.

Recent findings link the supply of chromospheric mass to the "leakage" of p-mode resonant acoustic oscillations through upward flows and spicules (De Pontieu et al. 2004). It has been established later that the damping of acoustic oscillations is decisively insufficient to provide the required power (Fossum and Carlsson 2005; Carlsson et al. 2007). Alfven waves (Tomczyk et al. 2007) and small-scale dissipation of magnetic free energy (the *nanoflare* concept of Parker 1988) may play a role in the heating of the chromosphere. Lites et al. (1998) showed that photospheric magnetic fields are not correlated with chromospheric brightenings, contrary to the findings of Sivaraman and Livingston (1982). We now know that the photospheric fields below the MTR have quite different properties compared to those of the chromospheric fields above the MTR. Therefore, a possible magnetic heating discovery in the chromosphere may await the flight of our proposed magnetograph.

Doppler velocity and magnetic field measurements must be taken with cadence <30 s in order to isolate any wave motions, and this speed would be achievable only with an imaging magnetograph that can switch rapidly from one spectral line to another. Our measurement strategy is to combine images of the vector magnetic field, line intensity, and velocities in the photosphere and MTR over a large field of view (>100 Mm). High resolution (~100 km) and high sensitivity (30 G, transverse) are called for in the Heliophysics Roadmap.

SMART Mission Concept

SMART is a space based solar observatory either in Geosynchronous or Sun synchronous orbit aiming at producing 3D tomographic magnetic field measurements of the solar active regions and the quiet Sun. It will map the solar vector magnetic field at different heights from the photosphere through the chromosphere. The measurement of the polarization Stokes vector (I, Q, U, & V) of several magnetic-sensitive spectral lines will be carried out at 5 to 7 positions across the profiles of every line. Several spectral lines in the red and near infrared wavelength range will be selected for this mission. The filter measurements at a single wavelength yield 2D spatial information both in intensity and polarization at one height in the atmosphere. The 3D map is built by combining the 2D observations from the different spectral lines. The spatial resolution will be from 0.15 arcsec in the photosphere to about 0.25 arcsec in the chromosphere, which is sufficient to resolve single flux-tubes both in the photosphere and in the chromosphere. The cadence will be on the order of 5 to 8 minutes per full tomographic scan, which is also sufficient to capture dynamic processes in the solar atmosphere.

SMART Instrument Description

The SMART instrument is composed of a light-weight 1-m solar telescope feeding an imaging vector magnetograph that uses two Lithium Niobate ($LiNbO_3$) Fabry-Perot etalons for the wavelength selection, a polarization analyzer based on two liquid crystal variable retarders and a linear polarizer, and two 4Kx4K CCD cameras, one for high resolution imaging and vector magnetic field mapping at 0.05 arcsec/pixel, and the second one for full-disk imaging and global vector magnetic field mapping at 0.5 arcsec/pixel resolution. A summary of the instrument characteristics is given in Table I.

Table I: SMART Strawman instrument characteristics

<table>
<tr><th>Major System</th><th colspan="6">Description</th></tr>
<tr><td rowspan="5">Gregorian Telescope</td><td colspan="6">1-m diameter light weight</td></tr>
<tr><td rowspan="2">Focal plane fields of view</td><td colspan="5">200 x 200 arcsec 0.05 arcsec/pixel</td></tr>
<tr><td colspan="5">33 x 33 arcmin, 0.5 arcsec/pixel (full-disk)</td></tr>
<tr><td rowspan="2">Diffraction Limit</td><td>λ [nm]</td><td>630</td><td>850</td><td>1000</td><td>1100</td></tr>
<tr><td>Resolution</td><td>0.15”</td><td>0.21”</td><td>0.25”</td><td>0.27”</td></tr>
<tr><td rowspan="4">Spectral filter</td><td colspan="6">$LiNbO_3$ dual Fabry-Perot etalon</td></tr>
<tr><td>WL range</td><td colspan="5">630 – 1000 nm</td></tr>
<tr><td>Free spectral range</td><td colspan="5">2.6 – 7.4 nm</td></tr>
<tr><td>FWHM bandpass</td><td colspan="5">0.08 – 0.22 nm</td></tr>
<tr><td rowspan="2">Polarimeter</td><td colspan="6">2 Liquid crystal variable retarders + 1 linear polarizer</td></tr>
<tr><td colspan="6">Records Stokes (I,Q,U,V) in 4 seconds with 4 consecutive exposures</td></tr>
<tr><td>Science cameras</td><td colspan="6">2 4Kx4K CCD optimized for Red and NIR</td></tr>
</table>

The two cameras with different fields of view have complementary purposes. The narrow angle camera (200x200 arcsec FOV with 0.05 arcsec pixels) will focus on following the temporal evolution of the vector magnetic fields in single active regions with a spatial resolution sufficient to observe single flux tubes and how they evolve from the photosphere to the chromosphere. The wide angle, full-disk camera will map the vector magnetic fields at a lower resolution (i.e., 0.5 arcsec/pixel) over the entire solar disk to provide context data to the narrow FOV images and for synoptic mapping. Both cameras will simultaneously take measurements at the same wavelength and for the same polarization state. The full disk vector magnetograms will be complementary to the vector magnetograms captured by HMI onboard SDO since they will have nearly the same spatial resolution but SMART will map the vector magnetic fields at different heights in the solar atmosphere.

A selection of the possible spectral lines that the instrument will probe is listed in Table II. For each line images of the full Stokes vector polarization are measured at 5 to 7 different position across the line. It will require about 1 minute to scan one spectral line and about 8 minutes to probe all the lines listed. For faster cadence the number of lines scanned can be reduced to only 3, enough to obtain a 3D representation of the evolution of the magnetic fields from the photosphere to the chromosphere.

Table II: List of candidate spectral lines that SMART may probe

Spectral line [nm]	630.1	630.2	656.3	108.3	849.8	854.2	868.8	769.9
Element	Fe I	Fe I	Hα	He I	Ca II	Ca II	Fe I	K I
Lande *geff*	1.67	2.5	1.05		1.07	1.1	1.66	1.33
Height [km]	330	260	~2000	~2000	~1100	~1000	~500	~450

Mission Implementation

The spacecraft carrying the 1-m telescope and attached vector mangetograph should fly in Sun-synchronous or Geosynchronous orbit allowing continuous viewing the Sun. A Geosynchronous orbit is preferable for reasons of higher data return. The mission baseline should be of at least 5 years to allow observing at least one solar half cycle, with launch timing preferably either at the minimum or at the maximum of solar activity. We have not performed a cost estimation but a good guess would be that such a mission may be in the vicinity of $500M including launch vehicle and phase E costs. Table III summarizes the key mission profile elements.

Table III: Summary of the SMART mission profile

Orbit	Sun synchronous or Geosynchronous
Strawman Payload	1 m telescope with vis/NIR vector magnetograph
Launch timing	Beginning or maximum of solar cycle
Baseline mission duration	5 years
Observations duty cycle	5 to 7 minutes per full 3D mapping 24 h /day
Spacecraft	Single S/C 3-axis stabilized
Telemetry	TBD
Mass	TBD
Cost	~ $500 M

SMART will be an important addition to the Great Heliophysics Observatory

The SMART mission is meant to be an essential complement to the SDO mission. The HMI instrument onboard SDO is providing moderate spatial resolution, high temporal cadence vector magnetic field information at one single height in the solar atmosphere, namely the photosphere. SMART with its full-disk imager will provide vector magnetic field maps with similar spatial resolution, somewhat lower temporal cadence, but at different heights in the atmosphere providing the necessary information to accurately reconstruct the global vector magnetic fields over the atmospheric layer where the magnetic field transitions from being plasma dominated to dominating the plasma, without solely relying on models. The high spatial resolution imager will provide unprecedented extremely detailed information of the spatial and temporal evolution of single flux-tubes in active regions and quiet Sun not only on a plane to the solar surface but also in height.

Such a mission will be an essential addition to the suite of instruments constituting the Great Heliophysics Observatory.

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