Proposed plan and needed effort to improve the leakage of SDO orbit velocity into HMI high level data products.

The physical quantities calculated from HMI filtergrams exhibit small but important systematic errors related to the SDO orbital velocity that show up in line-of-sight (LOS) Doppler velocity V, LOS magnetic field M, and the vector field B. Results show a c. 1% not-quite-linear scale error in velocity and somewhat larger 24- and 12-hour periodic variations in reported magnetic field values. Though small they are systematic and hinder some analyses of some solar quantities that depend on frame-to-frame differences in the reported magnetic field such as energy and helicity transport through the photosphere. The periodic variations do not have much if any effect on helioseismic studies or other investigations that have resulted in more than a thousand research publications, but they can interfere with quantitative analysis of active region magnetic field evolution.

Three types of approaches have been employed by researchers at Stanford and other institutions to resolve the problem. We believe that the fundamental problem is insufficient knowledge of the spectral profiles of the instrument, which is needed to convert the observed filtergrams into products such as line-of-sight velocity and magnetic field, and vector field maps. To date a completely satisfactory solution has not been developed.

See accompanying note on HMI Measurement Principles (below) for a more complete description of how the HMI instrument measures the magnetic and velocity fields.

Approaches to Calibration

The first and most satisfying approach is to improve the knowledge of the instrument spectral profiles and use that knowledge to calibrate out the periodic signals. Much of the work at Stanford in the HMI calibration team has focused on this approach, but has suffered for lack of a staff member who has sufficient uninterrupted time to work on it, due to limited funding available after the first two years of the mission. This method also requires a more accurate simulated solar line profile to be used in the LOS calibrations and in the calibration of the filters on orbit. The HMI team has learned much about the problem, but has yet to find a robust fix. Related work is already underway in collaboration with NSO, where similar topics arise with calibration of the GONG instruments.

A second approach taken by some users of the data has been to recognize the close correlation between the artifacts in the data and the orbital velocity, with its clear 12- and 24-hour periods. (The 12-hour component comes from a slightly non-symmetrical instrument profile.) The typical magnetic and velocity variations that depend on velocity have been characterized. The empirical methods can be used for individual datasets over times where there are not large changes in the solar quantities themselves. The method has been used in a number of publications at Stanford and other institutions.

A more recent approach is to employ machine learning (ML) techniques to find either better methods for the ad-hoc post-calibration method, and/or to use ML to help determine adjustments to the measured filter element profiles (“phase maps” described in the attached note.) This technique has been suggested by both the Stanford calibration team and others, including some connected with the SOLSTICE DRIVE Science Center phase-1 study and earlier by Pete Schuck at GSFC working with Stanford.

This approach shows great promise, but requires additional steps to understand the instrumental and physical causes of the variations.

Goals for Improvement

The goal of this HMI calibration effort is to find a robust method to calibrate both future and past data by removing the 12/24-hour artifacts in both the LOS and vector data products. The problem is less critical for helioseismology, the primary original purpose for HMI, but impedes some types of investigations into the evolution of magnetic active regions using the unique continuous, otherwise uniform vector field data that HMI provides. Progress on understanding the Doppler velocity variations will help with the LOS field measurements, and may help with the vector field as well.

Institutions and people are added for each goal/task with colors: Stanford, NSO, GSFC, and others. Stanford people: Phil H Scherrer, Charles Baldner, Yang Liu, Tom Duvall, NSO Gordon Petrie, Luca Bertello, Valentin M-P; GSFC: Pete Schuck; Other: Jesper Schou at MPS; and for not yet determined TBD.

We identify five basic goals for this project.

1. Document and improve the characterization of the 24- and 12-hour variations in B (vector field), M (LOS magnetic field), and V (LOS Doppler velocity).
    a. Collect and refine known 12- and 24-hour issues in B, M, and V. *[SU: YL, PHS; NSO: LB]*
    b. Fill gaps discovered in development of 1.a. *[SU: YL, PHS; NSO: LB]*
    c. Document in a useful way what the pipeline codes for calibration and inversion currently do. E.g. what is the fitted model? Where do phasemaps and line profiles come from? I.e. fill in gaps in published descriptions of HMI processing. *[SU: PHS, CB, YL]*
    d. Inventory relevant ground and space calibration measurements. A lot of data were taken. *[SU: CB, PHS]*
    e. Compile a list of calibration efforts that have already been tried, indicate what worked and what failed, identify known issues that still exist, and describe where we believe issues are not important for the 24-hour problem. *[SU: PHS, YL; MPS: JS; GSFC: PS]*
    f. Verify that most if not all of these investigations can be adequately accomplished using lower resolution averages of HMI observed filtergrams. *[SU: PHS]*
2. Develop ML or other empirical methods to determine B, M, and V and to mitigate the 24- 12-hour variations in B, M, V.
    a. Include direct use of the known orbital velocity vector and instrument temperatures as well as results from existing code. ***[GSFC: PS, SU: CB, YL]***
    b. Develop fast methods for replicating and testing inversion code results and for investigating the effects of instrument parameter changes. ***[GSFC: PS, SU: CB, YL]***
3. Develop improved synthetic line profiles and use them in a model of the HMI instrument.
    a. Generate accurate synthetic line profiles for a range of field strengths and center-to-limb angles. *[NSO: GP]*
    b. Develop an end-to-end HMI instrument model of sufficient accuracy and fidelity to reproduce the existing 24-hour problems with synthetic spectra and actual orbit data. *[NSO: GP, VMP]*
4. Refine the details of the HMI optical elements that affect the measurements of V, M, and B.

    a. Using the results of 2 and 3, improve the characterization of the HMI filter elements, measure or compute the sensitivity to errors in the element descriptions to the final calibration, includes phases, contrast, and intensity-ripple. *[NSO: GP, VMP; GSFC: PS; SU: CB, TD]*
    b. Document the impact of the fringes produced in the blocker, front window, and other HMI optics and their effects on calibration and observations. *[SU:CB; MPS: JS; NSO: GP]*
    c. Determine the impact of imperfect on-orbit thermal control of the front window and other elements. . *[SU:CB; MPS: JS; NSO: GP]*
    d. Incorporate better instrument knowledge into the JSOC pipeline. *[SU: CB, PHS]*
5. Understand the limitations of the inversion codes for determining physical quantities
    a. Understand physics of inversion code (LOS and Vector) and how the inversion results may depend on velocity and viewing angle in the linear and saturated regimes for the given instrument parameters and solar signals. *[NSO: GP; SU: YL]*
    b. Understand how the instrument characteristics (e.g. limited spectral resolution, spectral sampling, and spatial resolution) affect the inversion, with an eye toward improving the observing scheme and/or the calibration algorithms. This could include using the well-known orbit velocity vectors in the inversions directly vs removing them from the finished product (if some non-linear aspects of inversion process). *[NSO: LB; GSFC: PS; SU: YL, TD]*

We believe that focusing effort on both the "forward problem" and the empirical approach will be most effective for both LOS and vector field calibrations. The 'forward problem' will determine improved instrument filter profiles using algorithms that take advantage of the precisely known orbital velocity. The empirical approach, including ML methods, can use the known absence of exact 12/24-hour periods in the Sun to determine 'corrections' to physical quantities and help determine the filter-element profiles that remove the artifacts. Both methods rely on better estimates of solar line profiles, which vary with center-to-limb angle and with field strength.

Methods that use ML may require more computing capability than is available at the Stanford JSOC, but is available at GSFC or at Ames. Experience in calculating better line profiles for calibration and experience in instrument simulations that go from a model solar atmosphere through to complete instrument simulation exists at NSO, where we have a small trial effort already in place (0.5 FTE for 1 year).

Work Estimates

We propose a project that includes four types of effort at Stanford: to follow through on the team's current approach to provide the most satisfying 'forward' instrument model, to collaborate with other teams to develop reliable and believable mitigations of the periodic variations, to support generation of robust code to include in the processing pipeline, and to recalibrate the 10 years of existing data. We estimate approximately on additional FTE of effort for two years. We also anticipate support for this calibration effort from former key Stanford team members who continue to support the project as time permits, including Jesper Schou and Rock Bush.

The proposed work would also support collaborative efforts of NSO and GSFC researchers to work with solar atmospheric models through to a simulated HMI and to examine machine learning approaches.

Existing recently (re)started efforts at GSFC presently rely on modest support from the SOLSTICE DRIVE center phase-1 effort and could well benefit from a longer-term commitment at a higher effort level. We estimate at two-year effort at 0.XXX FTE by Pete Schuck.

Work already begun at NSO involves Gordon Petrie and Valentin Martinez-Pillet and will consume 0.5 FTE in several months is based on valuable experience in calibration issues from work for Solar Orbiter's PHI and GONG. This will be supplemented by additional work involving G. Petrie and Luca Bertello to develop synthetic line profiles, improve instrument models, and cross-calibrate with SOLIS, GONG, DKIST, PHI, and other data sets. We estimate 2 years of effort at a level of 0.9 FTE.

Implementation: A mod to HMI contract is easy to implement quickly and easy to manage as a new WBS element. There is already a subcontract from Stanford to NSO for the HMI calibration effort that is in progress -- 0.5 FTE ending on Oct 1 2020, but we expect to extend it after an HMI mod to allow completion. This effort could be enhanced and extended with increased support with little administrative effort. GSFC related efforts are presumably easy to implement.

Note about SDO/HMI Measurement Principles and Performance

HMI operates by measuring the relative brightness of each pixel in a set of 24 filtergrams obtained in a sequence of six wavelengths and four polarizations. The HMI filter chain consists of a broadband front window filter followed by an 8-Angstrom blocking filter that narrows the band into the primary filter set. The primary filter consists of a 5-element Lyot filter section and two Michelson interferometers configured to work as Lyot elements so a chain of seven filter elements, each with a factor of two narrower FSR (free spectral range) than the prior one. The transmission profile of each section taken alone is a cosine^2 with the FSR as the distance between the peaks. The position of the peak intensity can be tuned by rotating linear polarizers at each tunable element. The final Lyot element and the Michelson's can be tuned across their FSRs to achieve a 68 mA bandpass that can be tuned over a range of 340 mA. The details are published in several articles in the Solar Physics SDO "Book" special edition and later articles in the journal Solar Physics.

The Lyot and Michelson sections have small but important variations in the central wavelength across the field of view (FOV), meaning that the effective FSR of each element varies a fraction of its bandwidth. The average FSR and the variation of phase of the cosine^2 per-element profile across the field with respect to the element mean is used to calculate the instrument filter profile for each section of the filter set.

The calibration procedure finds the mean FSR, determines phase maps of deviations, and then calculates the combined filter profile for each tuning position. The non-tunable filter sections were measured carefully on the ground prior to instrument delivery, and the tunable sections can be measured on orbit by sampling a known solar line profile at three tuning positions for each of the three tunable elements, resulting in 27 filtergrams. We call that process a "detune sequence". We obtain detune sets each two weeks for the duration of the mission. The FSR of the sections drift slowly with time at a decreasing rate with time. About once per year we alter the tuning sequence used for observations to keep the mean phases synchronized on a zero-velocity solar line.

The calibration line we use is the unfocused solar light in the same spectral line we use for measurements. While that line does vary a bit with all solar velocities averaged over the disk, we have the same averaged wavelength for each pixel in the FOV during each exposure. Analysis of the detune data combined with the non-tuned sections combine to give us the instrument profile as a function of location in the FOV and tuning.

In the case of LOS products, the profiles are used along with a synthetic solar line profile to measure the expected sensitivity to a line position change, i.e. Doppler shift. The sensitivity map is then used to calibrate the measurements for the 45-second set of 12 filtergrams for Stokes I±V for both the LOS Doppler and magnetic flux maps. The LOS magnetic field is simply the difference between Doppler maps made in RCP and LCP polarizations.

The vector field products are made by combining the instrument profile with 24 filtergrams obtained in six wavelengths and 4 polarization states. These are combined with the instrument spectral profiles to generate the Stokes IQUV data, which are used via an iterative Milne-Eddington inversion process using the observed solar 6-point spectra to determine the field components, velocity, and characteristics of the solar atmosphere.

The resulting LOS velocity and magnetic flux measurements *should be* accurate to much better than 1% of the solar velocity dynamic range (c. 3 km/s) combined with the SDO orbit velocity of about 3 km/s that has a one-day period. When we fit averages of solar rotation, differential rotation, and convective blue shift we find a residual c. 40 m/s signal with 24-hour and 12-hour contributions. I.e. about a 1% scale error. If it were a simple scale factor we would have removed it years ago. It is not. It is non-linear and varies across the FOV and also depends on the temperature of the instrument, which also has a one-day period due to the “nearby” presence of the Earth.

We know the orbit velocity to about 1 cm/s, so in principle it is possible to use that as a calibration source. The LOS data does have a post-calibration adjustment derived from 24-hour fits to the image mean values stepping by 12 hours based on the quick-look data to “correct” the final product. This does reduce the LOS 24-hours variations a bit, but has problems of its own and at times when the data is not complete can introduce extra noise and it cannot be used to correct the vector field data. The combination of the orbit velocity and solar motions means that we can only use the orbit velocity for about half the dynamic range and need to extrapolate the rest.

The Zeeman splitting in terms of wavelength splitting measured as equivalent Doppler shift amounts to about 2 m/s per Gauss. So a 2 kG field is equivalent to an additional 4 km/s dynamic range. This varies across the disk, and the strongest solar small-scale convection and oscillation signals vary across the disk as well, so the combined instrument dynamic range of +- 8 km/s should be enough for moderate fields at any location. It was never expected that HMI would measure sunspot umbral fields well. HMI does saturate for strong fields as expected. What was not expected is the residual orbit velocity leakage into the Doppler data and moderate fields.