Solar Physics
DOI: 10.1007/•••••-•••-•••-••••-•

# RHESSI Solar Shape Morphology

**M. Fivian**[1] · **H. Hudson**[1] · **J. Zahid**[1]

**Abstract** The RHESSI[2] mission includes precise astrometric measurements of the solar limb shape at optical wavelengths as a part of its aspect-determination system. These data have precisions below 1 mas and extend over the full lifetime of the mission (from February, 2002). Synoptic maps of the limb shape reveal facular regions as increases, and sunspots as decreases, in the apparent radius. We compare these signatures with synoptic SOHO images for a 3-month period in 2004. The patterns are strongly similar, but the EUV synoptic maps have contributions from features not at the exact limb, which dominates the RHESSI data. This study anticipates making use of such high-contrast coronal or chromospheric measurements to provide a masking function to screen against these features in determinations of the true solar oblateness and higher-order permanent shape features. We also explore the possibility of cross-correlating RHESSI sunspot images against those of other optical telescopes, such as MDI, as a means of calibrating the roll coordinate of the telescope pointing.

**Keywords:** Solar Photosphere, Astrometry, Sunspots, Faculae

## 1. Introduction

The radius of the Sun is a fundamental observable quantity of astrophysics, and its variation around the limb (the shape) contains much interesting information. The shape reflects the interior mass distribution and motions of the Sun, predominantly its rotation. The rotational distortion is an oblateness[3] with a magnitude of about 4 mas ($4 \times 10^{-3}$ arc sec) assuming constant angular velocity (Dicke, 1970). This is small by comparison with the width of the intrinsically ill-defined edge of the Sun (a finite scale height of about 67 mas and a poorly characterized rough structure caused by convective and seismic motions). Knowledge of the shape can in principle help us to understand the physics of the solar interior, and its implications for the gravitational potential of the Sun external to its surface, for example in the precession of the perihelion of Mercury, also contribute to understanding relativity (Dicke, 1970).

---

[1] SSL/UC Berkeley email: hhudson@ssl.berkeley.edu

[2] The Reuven Ramaty High Energy Solar Spectroscopic Imager

[3] We use the term "oblateness" in this paper always to refer to the amplitude of the axisymmetric quadrupole term in the Fourier expansion of the full limb

The modern history of solar shape measurements began with Dicke's observations from Princeton (Dicke and Goldenberg, 1974), which was a highly differential ground-based observation utilizing rotating optics. This has proved to be a key requirement for this kind of astrometry, which requires precisions better than one ppm to be really interesting. Subsequent to this initial measurement, still better observations were done from the ground (Hill *et al.*, 1974) and then from telescopes above the Earth's atmosphere: balloons (Egidi *et al.*, 2006) and the Michelsen Doppler Imager (MDI) on board SOHO (Emilio *et al.*, 2007). The RHESSI (Lin *et al.*, 2002) observations discussed in this paper are in the same tradition of rotating optics and have greatly improved the precision of the measurement (Fivian *et al.*, 2007).

We have recently published results from the initial reduction of our data, which show the limb to have clearly-defined distortions due to spots and faculae (Fivian *et al.*, 2007). In addition there is an excess oblateness, also magnetic in nature, that appears to fluctuate with time. Below these distorting features we believe that the non-magnetic body of the Sun may have a "true" shape that is essentially hydrodynamic in origin. If this can be measured well, it will contribute information about the solar interior structure and dynamics that would be complementary to the information gleaned from helioseismology (Thompson *et al.*, 2003).

This paper gives a general overview of the morphology of the RHESSI limb observations in comparison with limb features seen in SOHO magnetograms and EUV images. We discuss the problems involved with the eventual development of techniques for data masking, whereby high-contrast EUV features might be used to identify magnetic features in the RHESSI limb, thus allowing us better views of a hypothetical non-magnetic solar figure.

## 2. The RHESSI observations

### 2.1. SAS

The RHESSI spacecraft rotates around an axis that points approximately at the Sun, with a nominal rotation period of 4 sec but a time-variable pointing offset and nutation amplitude, each typically a few arc min or less. It contains a Solar Aspect System (SAS) whose job is to provide sub-arcsec attitude information, in real time, for the operation of the primary instrument (a set of X-ray/$\gamma$-ray modulation collimators). The SAS consists of three linear CCDs, 2048 × $1.73''$ square pixels, with 4-cm lenses forming images on them in a narrow spectral band ($\sim$12 nm) at 670 nm; each image nominally provides two limb locations per readout. In normal operation SAS gives 16 samples, hence 96 total measurements, per second. This high cadence is necessary to provide sufficient aspect information, but it clearly helps with our secondary application of these data to solar shape measurements. Please refer to earlier papers for detailed information regarding SAS (Fivian *et al.*, 2002; Zehnder *et al.*, 2003). Note that SAS was not designed for astrometry as such, but RHESSI provides an excellent platform for solar shape measurements because of its rotation and the high cadence of SAS measurements.

### 2.2. Preliminary data reduction

The data reduction essentially consists of constructing the perpendicular bisectors of the three pairs of limb positions, inferring a Sun center location from their intersection, and then determining a differential radius for each limb point relative to the

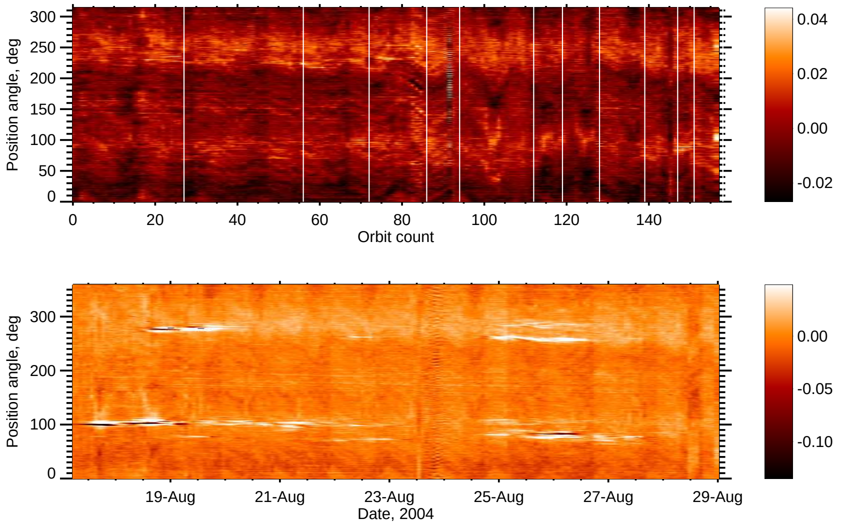

**Figure 1.** Stackplot views of RHESSI solar limb shape. The Y-axis represents position angle around the limb, in the order NWSEN bottom to top, and the time binning is one orbit (96 min). The lower plot shows about two weeks of data with a color range of 150-mas; the upper plot shows the same number of orbits but only ones selected, over a three-month time range in late 2004, to have minimal magnetic effects. In the upper plot the grayscale range is 60 mas total.

ephemeris value. As RHESSI rotates, the points distribute themselves around the limb; they are then integrated in time (typically one 96-min orbit) and in position angle (one degree bins for the present, but SAS has higher resolution that we plan to exploit in the future). This description grossly oversimplifies the data reduction and analysis, since we have found it necessary to fit many instrument parameters to be consistent with the data; for example, slow drifts of optical efficiency have had to be determined by reference to the quiet Sun and the assumption of constant luminosity in these regions. Ground-based calibrations exist, but the data are far stabler than their precision.

### 2.3. First results

Grayscale views of the preliminary reduction of RHESSI limb data appear in Figure 1. The lower panel shows sunspots as dark (reduced apparent radius) and facular regions as bright (increased apparent radius). The magnet features appear on the limb at the positions expected from the active-region database, ie in narrow latitude ranges near the solar equator in these late-phase conditions. The sunspots give us a view of the Wilson depression (de La Lande, Wilson, and Maskelyne, 1783), but not a complete one: even for the largest sunspot umbra, the tangent ray would only penetrate a small fraction of the depth (of order 10 km) of the Wilson depression (Solanki, 2003). In fact, the prevalence of an apparent radius deficit in the active regions shown in Figure 1 presumably means that an effective depression already commences in the penumbra.

The apparent radius increase in faculae do not have an obvious explanation, since the “hot wall" model now seems to have been confirmed by the highest-resolution observations of (for example) the Swedish Solar Telescope (Lites *et al.*, 2004). This then would mean that there do not need to be any facular "hillocks" (Schatten *et al.*, 1986), and yet this at first guess would be the natural interpretation of the apparent radius excesses seen in faculae in these new data. Numerical simulations (Steiner, 2005) thus far do not seem to suggest the presence of these excesses, whereas they do reveal Wilson depressions even for slender flux tubes.

The most interesting new result from the RHESSI shape measurements (Fivian *et al.*, 2007) is the presence of a large apparent oblateness, i.e. a smooth term clearly distinguishable from the facular excesses. This apparent oblateness term appears to vary in phase with the solar cycle, based on comparisons of the RHESSI data with previous balloon-borne (Egidi *et al.*, 2006) and SOHO (Emilio *et al.*, 2007) measurements. If the solar-cycle dependence is confirmed, this large-scale shape component also would have to have a magnetic origin (Withbroe, 2006). This could imply a mechanism within the outer convection zone, or else a surface effect that we could hope to track with independent signatures of magnetic activity, as discussed in Section 3.

## 3. Limb synoptic data for mask definition

We now turn to the practical motivation for this paper, namely the development of a mask by which we can identify magnetic activity and thus hope to avoid confusion in precise limb shape measurements. The SOHO data provide synoptic charts in four UV/EUV bands (304Å, 171Å, 195Å, and 284Å) as well as the MDI "white light" and (line-of-sight) magnetic field. We have experimented with the EUV images to find an optimal annular region near the limb that best discriminates against magnetic features. The approach is to define an annular zone in the vicinity of the limb. For reference the RHESSI sampling is normally four pixels at the limb, roughly corresponding to one width of the core of the point-spread function of the SAS lens. We experiment with similar annulus widths for the comparison data, noting that generally the resolution is much higher. Figure 2 shows an example of this, based on the 284Å data, in which we vary the size and location of the annulus. In general these variations do not matter much, and qualitatively, at least, all provide good matches with the RHESSI limb-shape features. Figure 3 intercompares five bands ( the UV/EUV and MDI "continuum" bands in this manner.

## 4. Roll calibration

[How to use the RHESSI spot signatures to define a roll angle in somebody else's images]

## 5. Conclusions

**Acknowledgements** The authors thank NASA for patience with our time-consuming efforts

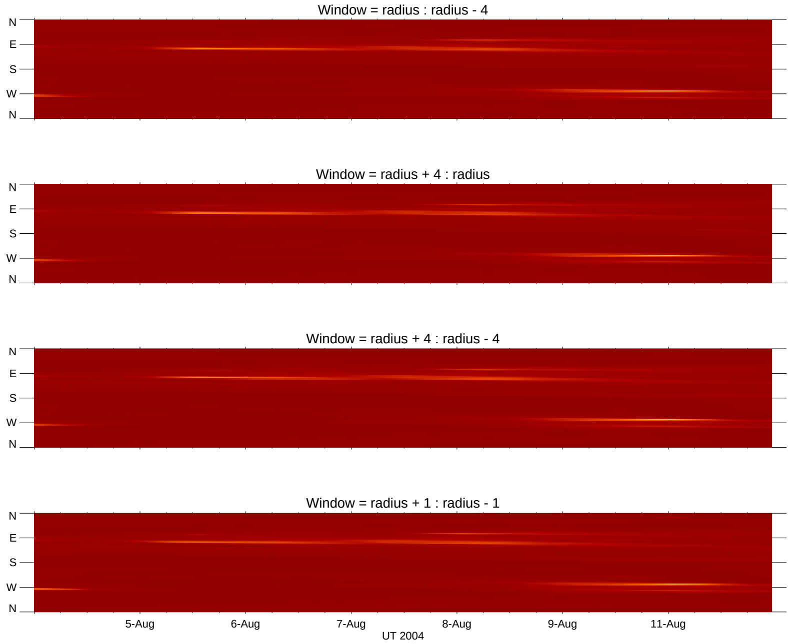

**Figure 2.** Stackplot views of EUV emissions from MDI 284Å, showing different annulus width and locations.

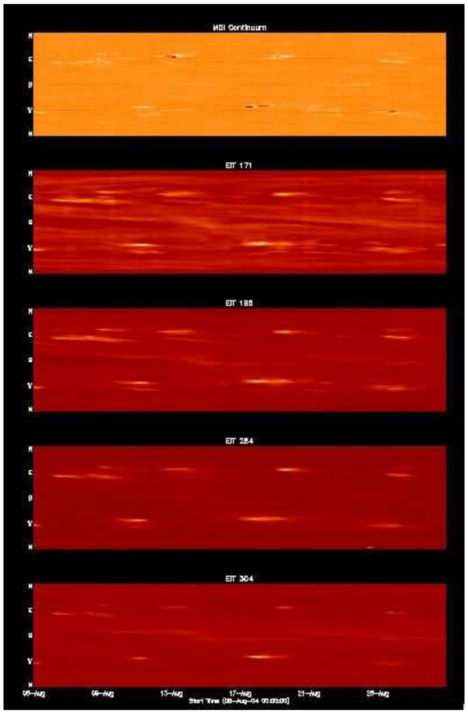

**Figure 3.** Stackplot views of all SOHO bands, as labeled, plus MDI "continuum".

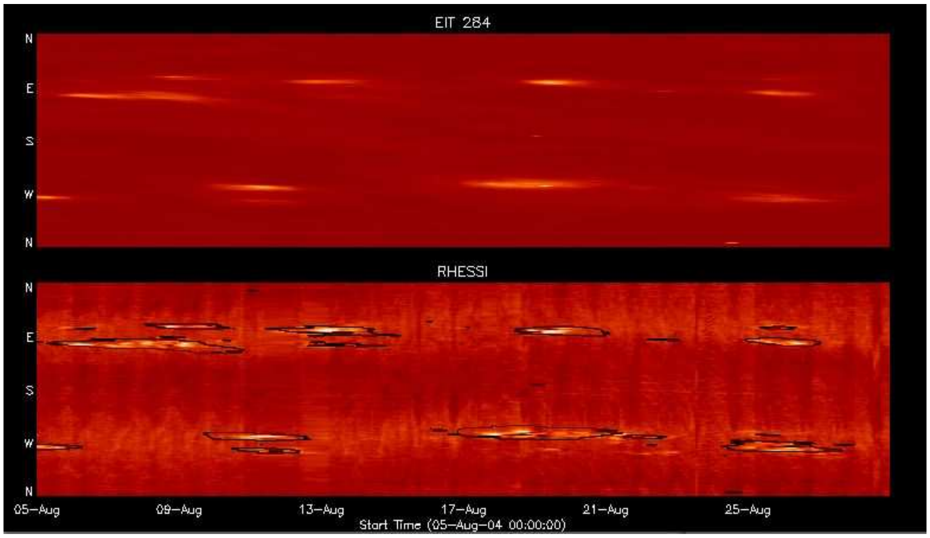

**Figure 4.** Comparison of EUV and RHESSI.

## References

de La Lande, M., Wilson, A., Maskelyne, N.: 1783, An Answer to the Objections Stated by M. De la Lande, in the Memoirs of the French Academy for the Year 1776, against the Solar Spots Being Excavations in the Luminous Matter of the Sun, Together with a Short Examination of the Views Entertained by Him upon That Subject. By Alexander Wilson, M. D. Professor of Practical Astronomy in the University of Glasgow; Communicated by Nevil Maskelyne, D.D. F. R. S. and Astronomer Royal. *Philosophical Transactions Series I* **73**, 144 – 168.

Dicke, R.H.: 1970, The Solar Oblateness and the Gravitational Quadrupole Moment. *Astrophys. J.* **159**, 1 – +.

Dicke, R.H., Goldenberg, H.M.: 1974, The oblateness of the sun. *Astrophys. J. Supp.* **27**, 131 – +.

Egidi, A., Caccin, B., Sofia, S., Heaps, W., Hoegy, W., Twigg, L.: 2006, High-Precision Measurements of the Solar Diameter and Oblateness by the Solar Disk Sextant (SDS) Experiment. *Solar Phys.* **235**, 407 – 418. doi:10.1007/s11207-006-0073-x.

Emilio, M., Bush, R.I., Kuhn, J., Scherrer, P.: 2007, A Changing Solar Shape. *Astrophys. J. Lett.* **660**, L161 – L163. doi:10.1086/518212.

Fivian, M., Hemmeck, R., Mchedlishvili, A., Zehnder, A.: 2002, RHESSI aspect reconstruction. *Solar Phys.* **210**, 87 – 99.

Fivian, M.D., Hudson, H.S., Lin, R.P., Zahid, H.J.: 2007, Solar Shape Measurements from RHESSI: a Large Excess Oblateness. *Nature*, in press.

Hill, H.A., Clayton, P.D., Patz, D.L., Healy, A.W., Stebbins, R.T., Oleson, J.R., Zanoni, C.A.: 1974, Solar oblateness, excess brightness, and relativity. *Physical Review Letters* **33**, 1497 – 1500.

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., Curtis, D.W., Pankow, D., Turin, P., Bester, M., Csillaghy, A., Lewis, M., Madden, N., van Beek, H.F., Appleby, M., Raudorf, T., McTiernan, J., Ramaty, R., Schmahl, E., Schwartz, R., Krucker, S., Abiad, R., Quinn, T., Berg, P., Hashii, M., Sterling, R., Jackson, R., Pratt, R., Campbell, R.D., Malone, D., Landis, D., Barrington-Leigh, C.P., Slassi-Sennou, S., Cork, C., Clark, D., Amato, D., Orwig, L., Boyle, R., Banks, I.S., Shirey, K., Tolbert, A.K., Zarro, D., Snow, F., Thomsen, K., Henneck, R., Mchedlishvili, A., Ming, P., Fivian, M., Jordan, J., Wanner, R., Crubb, J., Preble, J., Matranga, M., Benz, A., Hudson, H., Canfield, R.C., Holman, G.D., Crannell, C., Kosugi, T., Emslie, A.G., Vilmer, N., Brown, J.C., Johns-Krull, C., Aschwanden, M., Metcalf, T., Conway, A.: 2002, The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). *Solar Phys.* **210**, 3 – 32.

Lites, B.W., Scharmer, G.B., Berger, T.E., Title, A.M.: 2004, Three-Dimensional Structure of the Active Region Photosphere as Revealed by High Angular Resolution. *Solar Phys.* **221**, 65 – 84. doi:10.1023/B:SOLA.0000033355.24845.5a.

Schatten, K.H., Mayr, H.G., Omidvar, K., Maier, E.: 1986, A hillock and cloud model for faculae. *Astrophys. J.* **311**, 460 – 473. doi:10.1086/164786.

Solanki, S.K.: 2003, Sunspots: An overview. *Astron. Astrophys. Rev.* **11**, 153 – 286. doi:10.1007/s00159-003-0018-4.

Steiner, O.: 2005, Radiative properties of magnetic elements. II. Center to limb variation of the appearance of photospheric faculae. *Astron. Astrophys.* **430**, 691 – 700. doi:10.1051/0004-6361:20041286.

Thompson, M.J., Christensen-Dalsgaard, J., Miesch, M.S., Toomre, J.: 2003, The internal rotation of the sun. *Ann. Revs. Astron. Astrophys.* **41**, 599 – 643.

Withbroe, G.L.: 2006, Quiet Sun Contribution to Variations in the Total Solar Irradiance. *Solar Phys.* **235**, 369 – 386. doi:10.1007/s11207-006-0070-0.

Zehnder, A., Bialkowski, J., Burri, F., Fivian, M., Henneck, R., Mchedlishvili, A., Ming, P., Welte, J., Thomsen, K., Clark, D., Dennis, B.R., Hurford, G.J., Curtis, D.W., Harvey, P.R., Pankow, D.H.: 2003, RHESSI imager and aspect systems. In: *Innovative Telescopes and Instrumentation for Solar Astrophysics. Edited by Stephen L. Keil, Sergey V. Avakyan . Proceedings of the SPIE, Volume 4853, pp. 41-59 (2003).*, 41 – 59.