Solar Phys (2010) 261: 215–222
DOI 10.1007/s11207-009-9476-9

Use of the FITS World Coordinate System by STEREO/SECCHI

W.T. Thompson · K. Wei

Received: 20 April 2009 / Accepted: 20 October 2009 / Published online: 15 December 2009

Abstract The World Coordinate System (WCS) is a standard for embedding coordinate information in a Flexible Image Transport System (FITS) header. Its first extensive use within solar physics is by the *Sun Earth Connections Coronal and Heliospheric Investigation* (SECCHI) telescope suite onboard the *Solar Terrestrial Relations Observatory* (STEREO). The WCS formalism assists in SECCHI data analysis in several ways: First of all, the spherical effects associated with the extremely wide fields-of-view of the *Heliospheric Imager* (HI) telescopes can be handled in a completely unambiguous and standard fashion. Of particular importance is that WCS positional keywords allow spacecraft-ephemeris information to be embedded within the FITS header without depending on mission-specific keywords. Ephemeris data is critical to the three-dimensional analysis that the STEREO mission is designed for. We also show how the WCS software in SolarSoft can be used to relate STEREO data to other missions such as the *Solar and Heliospheric Observatory* (SOHO). The ability of WCS to support a parallel celestial right ascension (R.A.)/declination (Dec) coordinate system and the use of WCS for COR1 synoptic maps are also discussed. The advantages that STEREO derived from WCS can equally be applied to other solar missions, in particular *Solar Orbiter*, and should be adopted by all future missions.

1. Introduction

The Solar Terrestrial Relations Observatory (STEREO: Kaiser *et al.*, 2008) consists of two virtually identical spacecraft (*Ahead* and *Behind*) sent out in opposite directions to study the three-dimensional properties of coronal mass ejections. Onboard each spacecraft is an extreme-ultraviolet imaging telescope, two coronagraphs, and two *Heliospheric Imager* (HI) telescopes, which together make up the *Sun Earth Connection Coronal and Heliospheric*

W.T. Thompson (✉)
Adnet Systems Inc., NASA Goddard Space Flight Center, Greenbelt, MD, USA
e-mail: William.T.Thompson@nasa.gov

K. Wei
Adnet Systems Inc., University of Maryland, College Park, MD, USA

Investigation (SECCHI: Howard *et al.*, 2008). Analysis of SECCHI data presents new challenges in solar physics. First and foremost, the STEREO mission represents the first time the Sun was viewed from a significant angle off the Sun – Earth line. This makes precise knowledge of the three-dimensional position of each spacecraft critical to the data analysis. Another challenge is the extremely wide fields-of-view of the HI telescopes.

To address these problems, the SECCHI team adopted the use of the World Coordinate System (WCS) to encode positional information in the Flexible Image Transport System (FITS) file headers. The original FITS article (Wells, Greisen, and Harten, 1981) outlined a fairly simple coordinate labeling system involving the keywords `CRPIX`*n*, `CRVAL`*n*, `CDELT`*n*, `CROTA`*n*, and `CTYPE`*n*. This was then expanded upon in the first WCS article (Greisen and Calabretta, 2002), which better formalized the definition of the original keywords, and introduced additional keywords to more fully characterize the coordinate system. The second WCS article (Calabretta and Greisen, 2002) introduced the concept of spherical projections. Thompson (2006) extended the WCS system to solar images and introduced keywords for encoding ephemeris information. In the present work, we will show how the WCS system assists with STEREO/SECCHI data analysis.

STEREO is the first solar mission to fully embrace the WCS system. The concepts used by STEREO are equally applicable to other solar missions and ground-based data. By demonstrating the usefulness of WCS to STEREO, we show that WCS offers a migration path for better standardization of all solar data.

2. Spherical Projections

The traditional approach in solar physics is to assign a pixel scale to the image (typically in arcseconds per pixel), and apply this scale linearly across the image. For most solar images, encompassing a degree or less in width, this is usually an adequate simplifying assumption. However, as the width of the field-of-view increases, one starts to have to take into account the fact that one is dealing not with linear distances, but with spherical angles. This is particularly true for the wide angular ranges of the SECCHI/HI telescopes, which are 20° for HI-1 and 70° for HI-2. It is here that the WCS concept of spherical projections fully comes into play.

The simplest spherical projection is the gnomonic projection. This is the native projection for simple optical systems. In the WCS system, the gnomonic projection is also known as the TAN projection, because the pixel position scales as the tangent of the angle away from a central reference point. The TAN projection is used for the SECCHI/*Extreme-ultraviolet Imager* (EUVI), and for the inner and outer coronagraphs (COR1, COR2).

However, the TAN projection breaks down for the two HI telescopes. Instead, it turns out that the optical properties of these telescopes are well described by a closely related projection known as zenithal (or azimuthal) perspective (AZP). An additional parameter (μ) describes the deviation away from gnomonic; when $\mu = 0$, the AZP projection simplifies to the TAN projection. The application of this projection to HI data is described by Brown, Bewsher, and Eyles (2009).

Figure 1 demonstrates the importance of proper handling of the spherical projection for HI-2. The solid lines show contours of equal helioprojective-Cartesian (HPC) longitude and latitude. The coordinate system is clearly not linear. Some curvature is due to the spherical aberration in the system as described by the AZP projection, but much of it is intrinsic to the spherical nature of the coordinates.

Although the combined effects of the spherical coordinates and the instrumental aberration expressed by the parameter μ are somewhat complex, the fact that the coordinates are

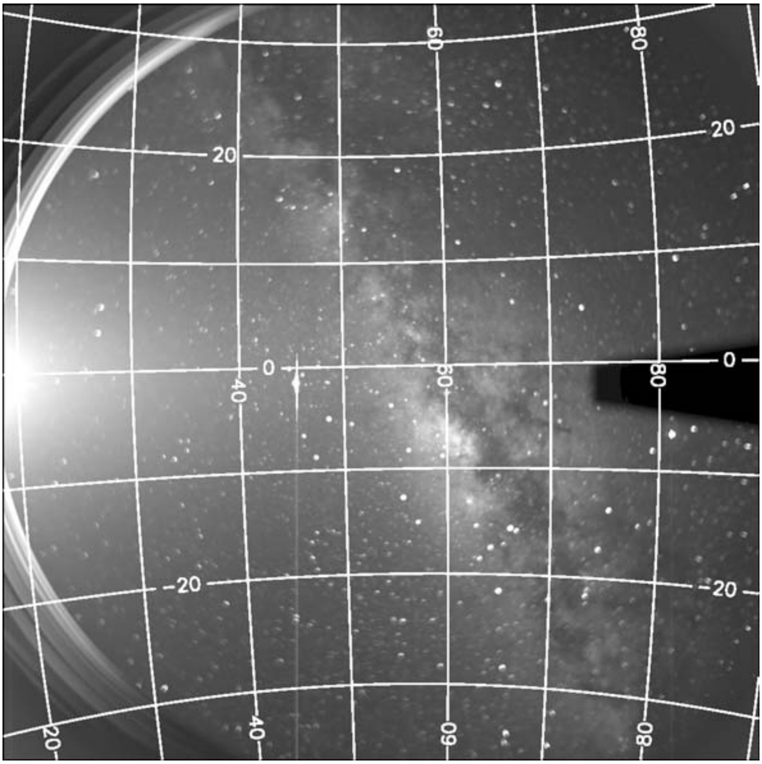

Figure 1 Sample HI-2 image from the STEREO *Behind* spacecraft. The solid lines show contours of equal helioprojective-Cartesian longitude and latitude, in degrees.

expressed using standard WCS keywords makes extracting the coordinates quite simple. In IDL™, the following SolarSoft (Freeland and Handy, 1998) calls are sufficient to derive the coordinates over the entire image:

```
wcs = fitshead2wcs(header)
coord = wcs_get_coord(wcs).
```

The importance of these calls is that they are not specific to HI, but can be used with any SECCHI telescope, or indeed with just about any solar image stored in a FITS file (see Section 5). There are also non-IDL packages available capable of interpreting the WCS information embedded in the HI headers, such as SAOimage (Mink, 1996) and WCSTools (Mink, 1997).

Although the spherical effects are less than for HI, standard WCS keywords are also used for EUVI, COR1, and COR2, so that these effects are properly accounted for. For COR2, the difference between a full spherical treatment and a linear approximation can be as large as an arcminute in the corners of the image. For COR1 and EUVI, the maximum differences drop to 1.2 and 0.1 arcseconds respectively, and are essentially negligible. Some instrumental aberrations are present in the COR2 telescope, but the standard SolarSoft processing routine `secchi_prep` resamples the image to agree with the WCS parameters in the header (R. Colaninno, private communication, 2009). No aberration corrections have yet been es-

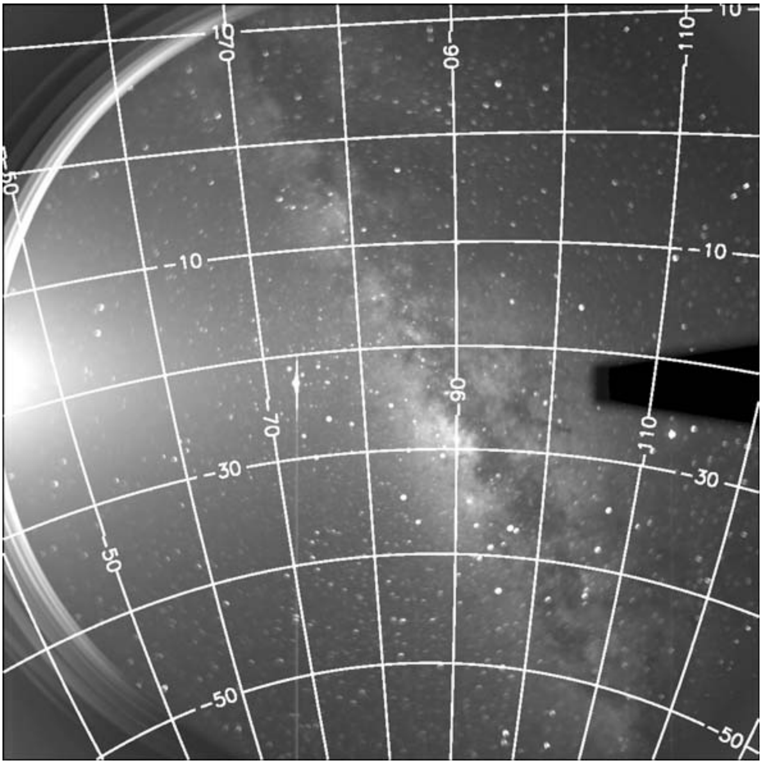

Figure 2 Same image as in Figure 1, but with contours of equal right ascension and declination taken from the alternative WCS "A" coordinate system in the FITS header.

tablished for COR1 or EUVI; given the much smaller fields-of-view of these telescopes, any aberrations are likely to be negligible.

3. Alternative Coordinates

One of the things that WCS allows one to do is to express data in more than one coordinate system. Along with the regular keywords `CRPIX1`, `CRVAL1`, and so on, one can also include alternative coordinate systems by appending a letter of the alphabet after each keyword, *e.g.*, `CRPIX1A`, `CRVAL1A`, and so on. In the SECCHI FITS files, the letter "A" is used for celestial coordinates expressed as right ascension and declination, in degrees. In IDL, these can be accessed using the following SolarSoft calls:

```
wcs = fitshead2wcs(header, system='A')
coord = wcs_get_coord(wcs).
```

The purpose of this alternative coordinate system is to make it simpler to determine the positions of stars and other celestial objects in the coronagraph and HI images. This coordinate system is illustrated in Figure 2.

```
DSUN_OBS=        150231969710. /[m]   Distance to Sun
HGLN_OBS=       -23.8768623852 /[deg] Stonyhurst longitude
HGLT_OBS=       -6.98514129731 /[deg] Stonyhurst latitude
CRLN_OBS=        41.7285219512 /[deg] Carrington longitude
CRLT_OBS=       -6.98514129731 /[deg] Carrington latitude

HCIX_OBS=        38147157598.1 /[m] Heliocentric Inertial
HCIY_OBS=        144154937995. /[m]
HCIZ_OBS=       -18270001144.7 /[m]
HAEX_OBS=       -131467098855. /[m] Heliocen. Aries Ecliptic
HAEY_OBS=        72705167376.8 /[m]
HAEZ_OBS=        72652363.7251 /[m]
HEEX_OBS=        137569035263. /[m] Heliocen. Earth Ecliptic
HEEY_OBS=       -60368864306.9 /[m]
HEEZ_OBS=        74040472.6719 /[m]
HEQX_OBS=        136355106993. /[m] Heliocen. Earth Equatorial
HEQY_OBS=       -60358401057.0 /[m]
HEQZ_OBS=       -18270001144.7 /[m]
```

Figure 3 Sample ephemeris data from a SECCHI FITS header. Comments were added for clarity.

4. Ephemeris Data

It is critical for SECCHI data analysis to know the exact position of the spacecraft at the time of the exposure. Only by knowing where each spacecraft is can one triangulate between the views of the *Ahead* and *Behind* spacecraft to derive a three-dimensional position. Thompson (2006) outlined a system of keywords forming a FITS convention for storing ephemeris data in the header. Figure 3 shows the keywords used by SECCHI. The main keywords give the distance from the Sun (DSUN_OBS), followed by the heliographic longitude and latitude in Stonyhurst (HG) and Carrington (CR) coordinates. Augmenting these are the three-dimensional x, y, z coordinates in several heliocentric coordinate systems (Fränz and Harper, 2002). Following FITS standards, all distance keyword values are given in meters and all angles are given in degrees.

To illustrate the use of the ephemeris data in the header, consider the case where one wants to map the pixel position of an active region on an *Ahead* image to the corresponding position on the *Behind* image. This can be accomplished with the following SolarSoft commands:

```
wcs_a = fitshead2wcs(header_a)
wcs_b = fitshead2wcs(header_b)
coord_a = wcs_get_coord(wcs_a, pixel_a)
wcs_convert_from_coord, wcs_a, coord_a, 'HG', hgln, hglt
wcs_convert_diff_rot, wcs_a, wcs_b, hgln, hglt
wcs_convert_to_coord, wcs_b, coord_b, 'HG', hgln, hglt
pixel_b = wcs_get_pixel(wcs_b, coord_b).
```

This process is demonstrated in Figure 4. In this example, the *Ahead* pixel coordinates (pixel_a) are first converted into HPC coordinates in arcseconds. These are then converted into Stonyhurst heliographic longitude and latitude. A correction for differential rotation is applied to account for any time difference between the *Ahead* and *Behind* images.

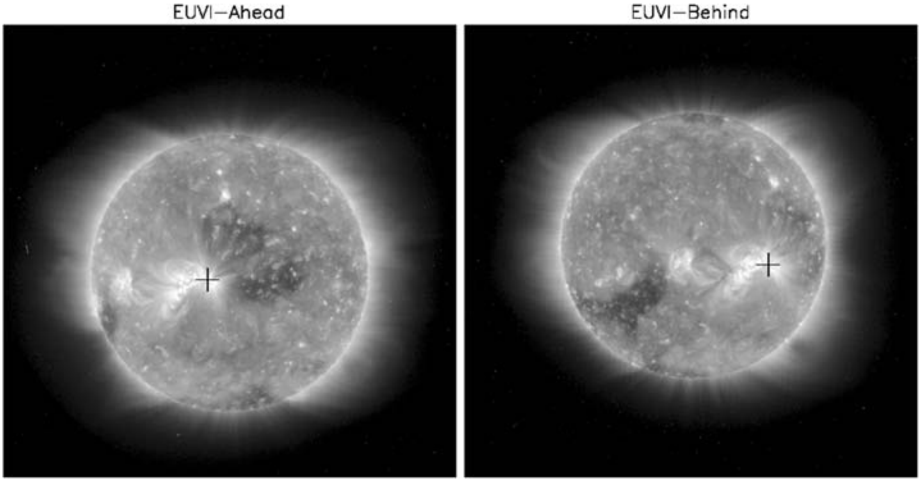

Figure 4 Sample EUVI images from the STEREO *Ahead* and *Behind* spacecraft. The "+" symbols mark the same point on the surface as seen in both images, calculated using the WCS information in the FITS headers.

Then the heliographic coordinates are converted back into HPC coordinates as seen by *Behind*. Finally, these are converted into pixel positions on the *Behind* image. All of these transformations are possible because of the keywords `DSUN_OBS`, `HGLN_OBS`, and `HGLT_OBS` in the header. Without this information, it would be very difficult to relate the images from two such different viewpoints.

5. Application to Non-STEREO Data

The same techniques used to relate data between the two STEREO spacecraft can also be used to relate STEREO data to other missions. This is done through the SolarSoft routine `fitshead2wcs`, which "compiles" the information in the FITS header to derive the information used by the other WCS routines. Headers using the older Wells, Greisen, and Harten (1981) system are translated into WCS format by making a few simple assumptions. Some other *ad-hoc* FITS coordinate systems commonly used in solar physics are also supported. In the absence of ephemeris information, Earth data are used. An exception is made for the *Solar and Heliospheric Observatory* (SOHO: Domingo, Fleck, and Poland, 1995), which is in a halo orbit about Earth's L_1 Lagrange point. Unfortunately, SOHO FITS files do not contain any ephemeris information in their headers, so when confronted with a FITS header from SOHO, `fitshead2wcs` will first try to find the appropriate SOHO ephemeris file. Failing that, it will choose a position along the Sun – Earth line at 0.99 times Earth's distance from the Sun. Experimentation showed that this assumption introduces negligible error.

Thus, any of the operations discussed in this article can equally be applied to non-STEREO data. For instance, the procedure discussed in Section 4 to relate images between the STEREO *Ahead* and *Behind* spacecraft could equally be used to relate either STEREO spacecraft to SOHO.

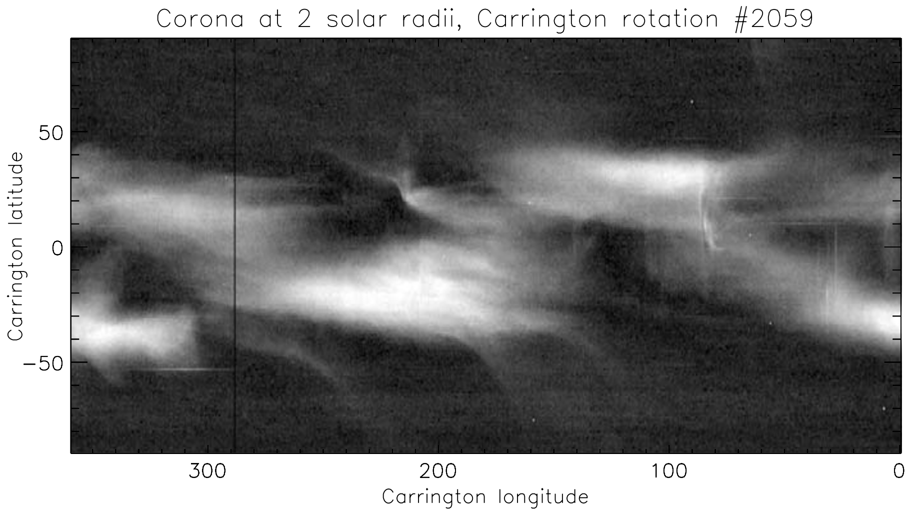

Figure 5 Sample COR1 synoptic map from the STEREO *Ahead* spacecraft. The map is built up from data taken at the east limb.

6. Synoptic Maps

The World Coordinate System can be used not just for solar images, but for other kinds of data as well. For example, the SECCHI/COR1 team recently started generating FITS files containing synoptic maps. These files are available from the COR1 website at cor1.gsfc.nasa.gov. Since the coordinate information is supplied using the same WCS formalism as in the headers for the telescope exposures, one can use the same SolarSoft calls discussed in Section 2 to extract the coordinates. The result is shown in Figure 5. Note that the longitude decreases from left to right. This is because the data are built up from a series of exposures taken over a period of one solar rotation (about 27 days) and the data are displayed as they are stored, with time progressing from left to right. Synoptic maps are stored using one of the WCS cylindrical projections, in this case plate carrée (CAR), although other projections such as cylindrical equal area (CEA) or pseudo-cylindrical projections such as Sanson – Flamsteed (SFL) can also be used.

7. Conclusions

We show that the use of WCS keywords in the FITS headers greatly simplifies analysis of SECCHI data, both in the treatment of the wide fields-of-view of the HI telescopes, and in the comparison of SECCHI *Ahead* and *Behind* data to each other and to data from other observatories. All this is accomplished using standard keywords, thus avoiding mission-specific approaches that cannot be extended to other data sets. Hence, the WCS coordinate system is a robust standard applicable to all future solar missions. The ephemeris encoding aspects of WCS are particularly useful for missions that observe from significant distances away from Earth. This includes missions at L_1, such as SOHO, and those that observe from off the Sun – Earth line, such as *Solar Orbiter*. Telescopes with wide fields-of-view will benefit from the spherical projection capabilities.

The advantages that STEREO derived from using WCS apply equally well to the upcoming *Solar Orbiter* mission. Like STEREO, *Solar Orbiter* will observe from off the Sun – Earth line and will benefit from the ephemeris encoding aspects of WCS. In addition, *Solar Orbiter* will include a *Heliospheric Imager* package, where the precise spherical projection handling aspects of WCS will come into play.

The use of WCS for COR1 synoptic maps demonstrates that it is useful for other kinds of data besides telescopic images. Another potential use would be for whole-sky maps; projections commonly used for these kinds of data, such as Hammer – Aitoff, are handled natively by WCS. In addition, a recent WCS extension supports spectrometer data (Greisen *et al.*, 2006), which could also prove useful for *Solar Orbiter*.

Acknowledgements The STEREO/SECCHI data used here are produced by an international consortium of the Naval Research Laboratory (USA), Lockheed Martin Solar and Astrophysics Lab (USA), NASA Goddard Space Flight Center (USA), Rutherford Appleton Laboratory (UK), University of Birmingham (UK), Max-Planck-Institut für Sonnensystemforschung (Germany), Centre Spatiale de Liège (Belgium), Institut d'Optique Théorique et Appliqueé (France), and Institut d'Astrophysique Spatiale (France). This work was supported by NASA grant NNG06EB68C.

References

Brown, D.S., Bewsher, D., Eyles, C.J.: 2009, Calibrating the pointing and optical parameters of the STEREO heliospheric imagers. *Solar Phys.* **254**, 185 – 225.

Calabretta, M.R., Greisen, E.W.: 2002, Representations of celestial coordinates in FITS. *Astron. Astrophys.* **395**, 1077 – 1122.

Domingo, V., Fleck, B., Poland, A.I.: 1995, The SOHO mission: an overview. *Solar Phys.* **162**, 1 – 37.

Fränz, M., Harper, D.: 2002, Heliospheric coordinate systems. *Planet. Space Sci.* **50**, 217 – 233.

Freeland, S.L., Handy, B.N.: 1998, Data analysis with the SolarSoft system. *Solar Phys.* **182**, 497 – 500.

Greisen, E.W., Calabretta, M.R.: 2002, Representations of world coordinates in FITS. *Astron. Astrophys.* **395**, 1061 – 1075.

Greisen, E.W., Calabretta, M.R., Valdes, F.G., Allen, S.L.: 2006, Representations of spectral coordinates in FITS. *Astron. Astrophys.* **446**, 747 – 771.

Howard, R.A., Moses, J., Vourlidas, A., Newmark, J., Socker, D., Plunkett, S., Korendyke, C., Cook, J.W., Hurley, A., Davila, J.M., Thompson, W.T., Cyr, O.S., Mentzell, E., Mehalick, K., Lemen, J., Wuelser, J., Duncan, D., Tarbell, T., Wolfson, C., Moore, A., Harrison, R.A., Waltham, N.R., Lang, J., Davis, C., Eyles, C., Mapson-Menard, H., Simnett, G., Halain, J., Defise, J., Mazy, E., Rochus, P., Mercier, R., Ravet, M.F., Delmotte, F., Auchere, F., Delaboudiniere, J., Bothmer, V., Deutsch, W., Wang, D., Rich, N., Cooper, S., Stephens, V., Maahs, G., Baugh, R., Mcmullin, D.: 2008, Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI). *Space Sci. Rev.* **136**, 67 – 115.

Kaiser, M., Kucera, T., Davila, J., St. Cyr, O., Guhathakurta, M., Christian, E.: 2008, The STEREO mission: an introduction. *Space Sci. Rev.* **136**, 5 – 44.

Mink, D.J.: 1996, Browsing Images in World Coordinate Space with SAOimage. In: Jacoby, G.H., Barnes, J. (eds.) *Astronomical Data Analysis Software and Systems V* **CS-101**, Astron. Soc. Pac., San Francisco, 96 – 99.

Mink, D.J.: 1997, WCSTools: image World Coordinate System utilities. In: Hunt, G., Payne, H. (eds.) *Astronomical Data Analysis Software and Systems VI* **CS-125**, Astron. Soc. Pac., San Francisco, 249 – 252.

Thompson, W.T.: 2006, Coordinate systems for solar image data. *Astron. Astrophys.* **449**, 791 – 803.

Wells, D.C., Greisen, E.W., Harten, R.H.: 1981, FITS – a flexible image transport system. *Astron. Astrophys. Suppl. Ser.* **44**, 363 – 370.