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FESTIVAL: A Multiscale Visualization Tool for Solar Imaging Data

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Abstract Since 4 December 2006, the SECCHI instrument suites onboard the two STEREO A and B probes have been imaging the solar corona and the heliosphere on a wide range of angular scales. The EUVI telescopes have a plate scale of 1.7 arcseconds pixel^{-1}, while that of the HI2 wide-angle cameras is 2.15 arcminutes pixel^{-1}, *i.e.* 75 times larger, with the COR1 and COR2 coronagraphs having intermediate plate scales. These very different instruments, aimed at studying Coronal Mass Ejections and their propagation in the heliosphere, create a data visualization challenge. This paper presents FESTIVAL, a SolarSoftware package originally developed to be able to map the SECCHI data into dynamic composite images of the sky as seen by the STEREO and SOHO probes. Data from other imaging instruments can also be displayed. Using the mouse, the user can quickly and easily zoom in and out and pan through these composite images to explore all spatial scales from EUVI to HI2 while keeping the native resolution of the original data. A large variety of numerical filters can be applied, and additional data (*i.e.* coordinate grids, stars catalogs, *etc.*) can be overlaid on the images. The architecture of FESTIVAL is such that it is easy to add support for other instruments and these new data immediately benefit from the already existing capabilities. Also, because its mapping engine is fully 3D, FESTIVAL provides a convenient environment to display images from future out-of-the-Ecliptic solar missions, such as *Solar Orbiter* or *Solar Probe*.

Keywords Data analysis · Instrumentation

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1. Introduction

The SECCHI A and B instrument suites (Howard *et al.*, 2006) onboard the two STEREO mission spacecraft (Kaiser, 2005) are each composed of: one Extreme Ultra-Violet Imager (EUVI), two white-light coronagraphs (COR1 and COR2), and two wide-angle heliospheric imagers (HI1 and HI2). Technical descriptions of EUVI, COR1 and the HIs can be found in Wuelser *et al.* (2004), Thompson *et al.* (2003), and Defise *et al.* (2003), respectively. The images produced by SECCHI represent a data visualization challenge: *i*) the images are 2048 × 2048 pixels (except for the HIs, which are usually binned onboard 2 × 2), thus the vast majority of computer displays are not able to display them at full frame and full resolution, and *ii*) more importantly, the five instruments of SECCHI A and B were designed to be able to track Coronal Mass Ejections from their onset (with EUVI) to their propagation in the heliosphere (with the HIs), which implies that a set of SECCHI images that covers the propagation of a CME from its initiation site to the Earth is composed of images with very different spatial resolutions – from 1.7 arcseconds pixel^{-1} for EUVI to 2.15 arcminutes pixel^{-1} for HI2, *i.e.* 75 times larger. A similar situation exists with the angular scales of the physical objects, since the size of a CME varies by orders of magnitude as it expands in the heliosphere. This makes it difficult to have an undistorted view of the whole phenomenon using a fixed spatial resolution and a fixed field of view. The challenge of a visualization software for SECCHI data is to: *i*) generate composite images from all five instruments from each SECCHI suite, and *ii*) allow the user to easily zoom and pan across the resulting large composite. In addition, the software has to be able to manage the various cadences of the five instruments (from 2.5 minutes or higher for EUVI to two hours for HI2).

FESTIVAL (http://www.ias.u-psud.fr/stereo/festival/), an open-source browser written in IDL, distributed as a SolarSoftware (SSW) package, was originally designed for simultaneous, fast, and easy manipulation of SECCHI data from STEREO, and of EIT (Delaboudinière *et al.*, 1995) and LASCO (Brueckner *et al.*, 1995) data from SOHO (Domingo, Fleck, and Poland, 1995). FESTIVAL works with FITS files installed locally on the user's computer or on remote disks mounted via NFS. It automatically builds dynamic composite images of the sky as seen by the STEREO A, B, and SOHO spacecraft by interpreting the information stored in the FITS headers (date, plate scale, roll angle, pointing). The composites preserve the native resolution of all of the instruments and the user can zoom in and out to explore the full range of angular scales covered by SECCHI and EIT-LASCO: from the arcsecond (EUVI/EIT) to tens of degrees (HI1/HI2).

2. FESTIVAL Basics

2.1. Layers

The traditional way to create composite images from multiple-instrument data is to build a large matrix, which greatly limits the range of angular scales that can be covered simply because of the amount of computer memory required. For example, a bitmap composite image covering the fields of view from EUVI to HI2 with the resolution of EUVI would be 190 000 × 150 000 pixels, which represents 26 GB at eight bits. Using the mapping capabilities of modern graphics cards, FESTIVAL does not need to build such a huge matrix. Instead, FESTIVAL composite images are made of superimposed layers. One layer is associated with each instrument: one for EUVI, one for COR1, one for COR2, *etc.* FESTIVAL sends the images to the graphics card along with the pointing and scaling information read in the FITS headers. The graphics hardware then takes care of the compositing. The full SECCHI composite image described above therefore requires only 14 MB of RAM instead of 26 GB. A layer can contain either a 2D textured polygon or 2D vector data. Textured polygons are used to display images, while vectors are used to display context information on the images. At present, the available context information sources are: Carrington, Stonyhurst, polar, and sky coordinates grids, stars from the *Hipparcos* catalogue (see Section 2.4), and the position of planets. The display order of the layers associated with the instruments can be modified. EUVI and COR1, for example, have a region of overlap. By changing the order of the layers, one can choose to visualize EUVI or COR1 data in this region. The information layers are always on top of the instrument layers. The visibility of the layers can be switched on and off. Note that EUVI and EIT are imaging EUV emission lines, while LASCO, the CORs, and the HIs take broadband visible-light images. A composite can therefore contain information from physically different emission processes and this has to be kept in mind when interpreting the images.

2.2. Systems of Coordinates and Projections

Considering the very large total field of view covered by the SECCHI telescopes (up to 90° from the Sun to the outer edge of HI2), the composites are not mere images of the solar corona – they can cover large portions of the sky. So whether looking at a small portion of the solar disk or at a large-angle composite of HI images, FESTIVAL is always building a map of a full hemisphere of the sky as seen from either STEREO A, B, or SOHO. The data from different probes cannot be overlaid. For example, STEREO and SOHO data cannot be overlaid because these data are not taken from the same vantage point. FESTIVAL uses two possible frames of reference called Heliocentric Ecliptic North Up (HENU) and Heliocentric Solar North Up (HSNU). The z-axis is Sun centered, the x-axis is pointing toward either ecliptic north or solar north, and the y-axis is completing a right-handed orthogonal coordinate system.

The type of projection used to map the sky on the computer display can be chosen by the user and applies to all the instruments of a given probe. Projection types can be different for each probe. All the projection types that allow the mapping of a full hemisphere (*e.g.*, Equirectangular, Mercator, Aitoff, *etc.*) and that are supported by IDL are available.

2.3. Data Handling

An image undergoes the following operations before it is displayed:

1. Preparation: call to the appropriate SSW routine, *e.g.*, EIT_PREP, SECCHI_PREP. This includes reading the corresponding FITS file.
2. Rotation: rotation to solar north up or ecliptic north up, depending upon the choices made in the projection options.
3. Filtering: apply the user-defined sequence of filters, if any.
4. Difference: subtraction of the previous image of the same instrument if in running-difference mode. If the previous image is not already present in memory, it is computed by going through steps 1 – 3.
5. Enhancement: conversion from 16 bits to 8 bits according to the parameters defined in the enhancement options.
6. Projection: mapping of the data on the sky according to the settings defined in the projection options.
7. Storing in the history stack.

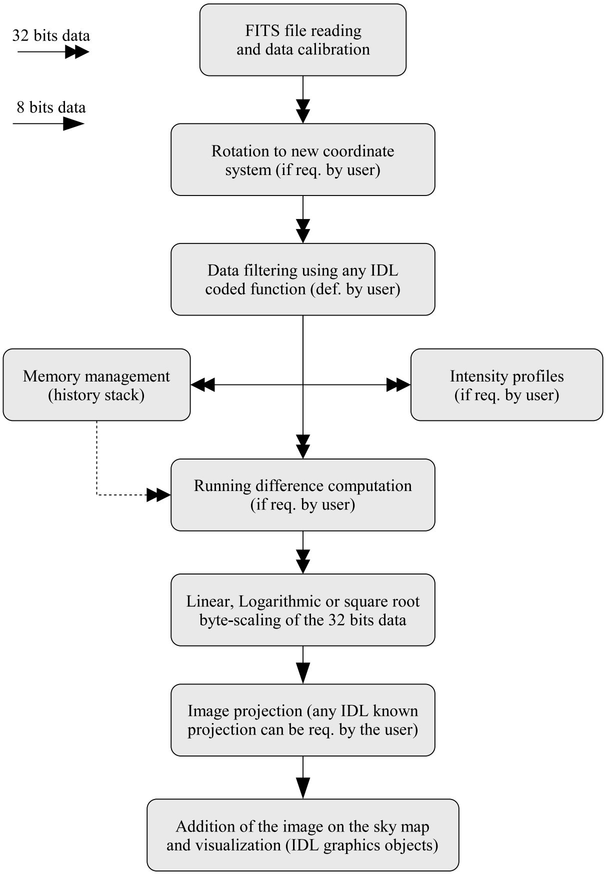


Figure 1 Illustration of the data flow in FESTIVAL.

Figure 1 illustrates this sequence. After an image is displayed, FESTIVAL stores in the history stack the 32-bit filtered image, the 8-bit projected image and detailed information (filter sequence, calibration options, projection parameters, *etc.*) about its processing through steps 1 – 7. The history stack is a first in, first out (FIFO). Any modification by the user (except panning and zooming) of the rendered scene leads to a request for new data. This includes modifying the rotation, filter sequence, enhancement parameters, projection type, *etc.* When new data are requested, FESTIVAL looks up the history stack for previously processed data that have the right properties: roll, filter sequence, enhancement parameters, projection type, *etc.* If the data are found, the projected image is displayed instantaneously. If not, FESTIVAL will find the data closest to that requested. For example, if the user displays an image and then changes the projection type, data that are correctly calibrated and filtered are already present in memory. In this case, FESTIVAL does not process the data from scratch (step 1), but uses the existing information and proceeds directly from step 4; the resulting new data are pushed onto the history stack. Its default size is 400 MB, but with more RAM more data can be stored in memory and the processing will execute more rapidly.

2.4. Coalignment Calibration

Stars were used to investigate the accuracy of FESTIVAL's mapping engine and the coalignment of the coronagraphs onboard SOHO and STEREO.

Table 1 Pitch, yaw, and roll corrections for HI images derived from visual matching of stars field in FESTIVAL.

	Pitch	Yaw (degrees)	Roll
HI1A	0.03	−0.025	−0.05
HI2A	−0.20	0.11	−0.09
HI1B	−0.05	−0.06	0.0
HI2B	0.25	0.05	−0.2

FESTIVAL provides a reference frame that can be used to calibrate the accuracy of the absolute positioning of the images on the sky. The software can therefore be used as a tool for investigating the alignment and/or coalignment of instruments. The projected views of the sky can contain both imaging data (*e.g.* SECCHI images) and vectorial overlays (*e.g.* lines, polygons). A vectorial overlay is used to display a set of polygons representing stars. Knowing the position of the stars, the orientation of the ecliptic plane, the orientation of the solar equator, and the position of the spacecraft in a common system of coordinates, it is possible to compute the position of the stars in the two frames of reference used by FESTIVAL and to display them on top of SECCHI or EIT-LASCO data for comparison. We have done this for LASCO C2 and C3, and for SECCHI COR2, HI1 and HI2 (A and B spacecraft).

For the position of stars, we used the *Hipparcos* catalogue (Perryman *et al.*, 1997). It contains 118 218 entries, is complete down to visual magnitude 7 (15 405 stars), and includes stars down to magnitude 14. The position of stars are given in the International Celestial Reference System (ICRS) for epoch J1991.25. The axes of the ICRS are consistent within 0.1 arcsecond with the J2000.0 equatorial celestial coordinates. For our application, we do not distinguish between the two systems. The proper motion of stars in right ascension and declination is used to compute their position at epoch J2000.0. The position of the spacecraft (SOHO or STEREO) is known in the J2000.0 Heliocentric Aries Ecliptic system. For STEREO, this information is listed in the FITS headers, while for SOHO it is read in the orbit files via the `GET_ORBIT` IDL function. In J2000.0, the solar-rotation axis has equatorial celestial coordinates (R.A. $= +286.11^\circ$, DEC $= +63.85^\circ$) and the inclination of the ecliptic is 23.4392911°. With these parameters, the positions of the stars are computed in one of the two possible frames of reference (HENU or HSNU). Note that annual aberration is not taken into account. However, this effect is small (30 arcseconds at most for an observer on the Earth), and since the frames of reference of FESTIVAL are Sun centered, the aberration of the Sun should be subtracted, resulting in a minute correction.

We present results for the comparison between the theoretical and observed position of stars. We used stars down to visual magnitude 15. The alignment of LASCO data was visually checked for 20 dates between December 2005 and January 2007. Figure 2 shows an example of a LASCO C2/C3 composite image for 21 November 2006 with stars overlaid (circles). The diameter of the stars is proportional to their magnitude. The top panel is an enlargement of the C2 field of view, while the bottom panel shows the whole composite. Overall, the match between computed and observed stars was found to be on average within one pixel in both C2 and C3 (*i.e.* 11.9 arcseconds and 56.0 arcseconds, respectively). Note that FESTIVAL is also able to display planets and their satellites. The top right inset shows Callisto correctly positioned at the East of Jupiter. The other satellites are masked by the CCD blooming. Venus is also circled in the C3 field of view (bottom panel).

We performed similar tests on SECCHI HI1 and HI2 data taken between 15 March 2007 and 15 August 2007. We have not yet performed these tests on COR1 and COR2. However,

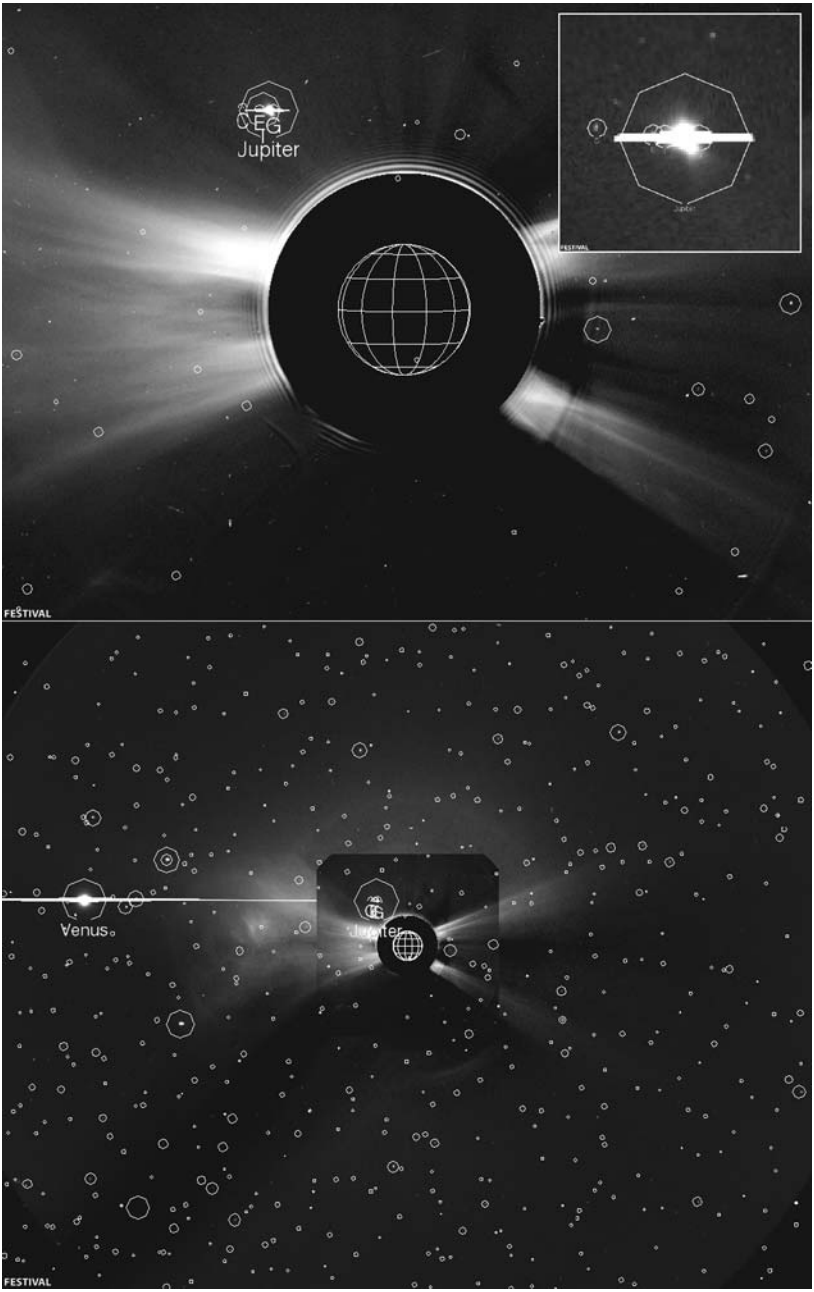


Figure 2 Star field and planets (circles) overlaid on a LASCO C2/C3 composite image for 21 November 2006. The observed stars are, on average, within one pixel of their computed positions.

we verified that sharp coronal structures, such as streamer edges or large coronal loops, are well connected from EUVI to COR1 to COR2, to within the resolution of the instruments. According to the results obtained with LASCO data, we could expect FESTIVAL to position

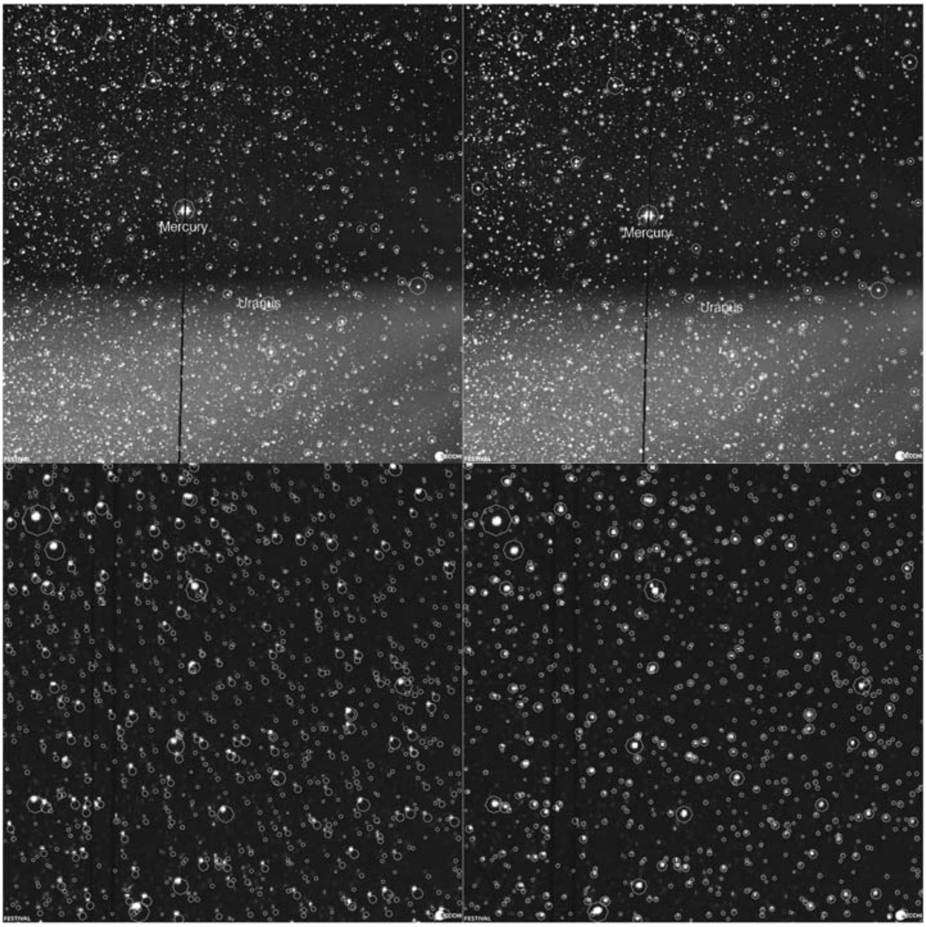
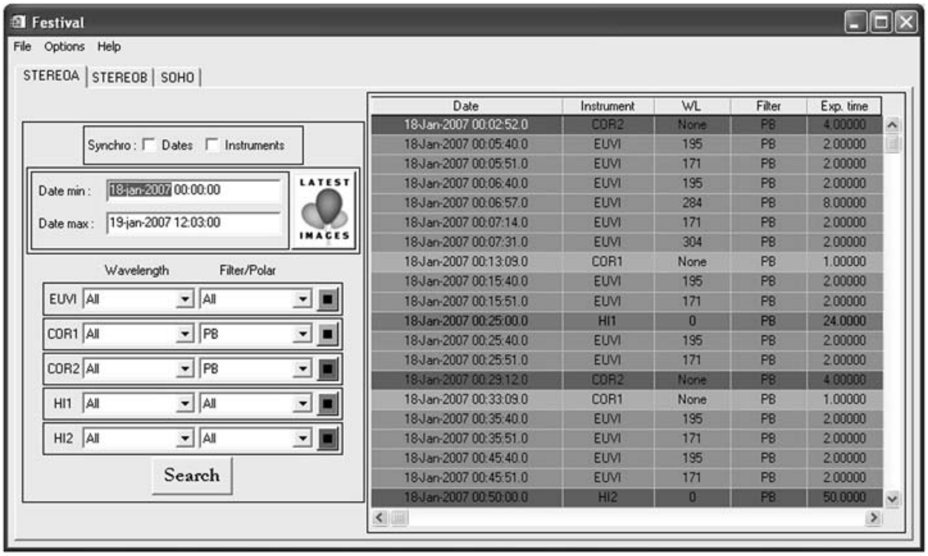


Figure 3 Left panels: HI1A (top) and HI2B (bottom) images with overlaid star fields (circles). Only a 17 × 17 degree position of the HI2 field of view is shown. The discrepancies are about one arcminute in HI1 and 15 arcminutes in HI2. Right panels: same images after correction using the angles given in Table 1.

SECCHI data to within a pixel of the theoretical star positions. The star fields were found to be off by about 1 arcminute in HI1A and HI1B, and by about 15 arcminutes in HI2A and HI2B. The top left and bottom left panels of Figure 3 illustrate the observed discrepancies for HI1A and HI2A, respectively. Only a fraction (17 × 17 degrees) of the HI2A field of view is shown. The stars are displayed as circles. From such images, we estimated the corrections in pitch, yaw, and roll to apply to the images in order to visually match the star fields. Results are listed in Table 1. We estimate the accuracy of this manual procedure to be about 0.01 degrees. The HI1B values should be used with caution because the pointing of HI1B is known to be unstable; its boresight being erratically shifted by a still-unidentified mechanism (one hypothesis being interplanetary dust impacts). The top right and bottom right panels of Figure 1 show the images of the left panels after pointing correction. Future updates of the HI headers with measured pointing information are expected to reduce the observed discrepancies.



Synchro : ☐ Dates ☐ Instruments

Date min : 18-jan-2007 00:00:00

Date max : 19-jan-2007 12:03:00

	Wavelength	Filter/Polar
EUVI	All	All
COR1	All	PB
COR2	All	PB
HI1	All	All
HI2	All	All

Date	Instrument	WL	Filter	Exp. time
18-Jan-2007 00:02:52.0	COR2	None	PB	4.00000
18-Jan-2007 00:05:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:05:51.0	EUVI	171	PB	2.00000
18-Jan-2007 00:06:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:06:57.0	EUVI	284	PB	8.00000
18-Jan-2007 00:07:14.0	EUVI	171	PB	2.00000
18-Jan-2007 00:07:31.0	EUVI	304	PB	2.00000
18-Jan-2007 00:13:09.0	COR1	None	PB	1.00000
18-Jan-2007 00:15:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:15:51.0	EUVI	171	PB	2.00000
18-Jan-2007 00:25:00.0	HI1	0	PB	24.0000
18-Jan-2007 00:25:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:25:51.0	EUVI	171	PB	2.00000
18-Jan-2007 00:29:12.0	COR2	None	PB	4.00000
18-Jan-2007 00:33:09.0	COR1	None	PB	1.00000
18-Jan-2007 00:35:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:35:51.0	EUVI	171	PB	2.00000
18-Jan-2007 00:45:40.0	EUVI	195	PB	2.00000
18-Jan-2007 00:45:51.0	EUVI	171	PB	2.00000
18-Jan-2007 00:50:00.0	HI2	0	PB	50.0000

Figure 4 The selection GUI. Each of the three tabs is associated with a probe: STEREO A, STEREO B, and SOHO. In each tab, the search criteria are entered in the left area, and on the right is a table that summarizes the result of the search.

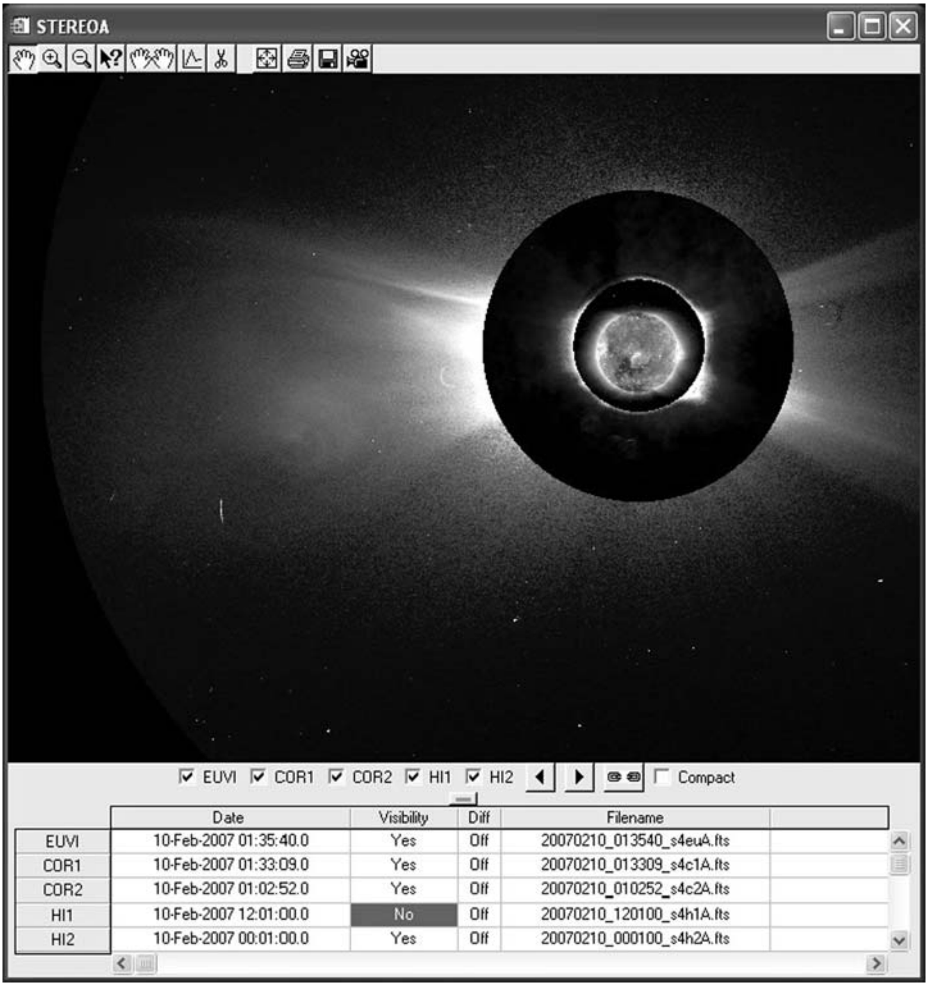
2.5. The Interface

The Graphical User Interfaces (GUI) vary slightly from one operating system/window manager to another. The screenshots shown in this paper were taken running Windows XP and IDL 6.2. FESTIVAL presents two main kinds of GUIs to the user:

1. The selection GUI, where the user makes selective searches for the data of interest (Figure 4).
2. The visualization GUIs, where the selected data are visualized. Up to three can be opened simultaneously, one per probe (Figure 5).

2.6. Navigation in Time

The user can move back and forth in time either with the “back” and “next” buttons in the visualization GUI or by clicking on an entry of the table in the selection GUI. The effect of this action will depend on which of the two navigation modes (“normal” or “compact”) is selected. In normal mode, any image can be composited with any other, while in compact mode, the images are always forced to be as close together in time as possible with each other. Selecting one image in the selection GUI table (or hitting the “next” button) will not only bring up the selected (or the next) data, but also the images from the other selected instruments that are closest in time to it. The compact mode is the most used since it guarantees the best simultaneity of the data. However, due to the different cadences of the instruments (up to few tens of seconds for EUVI, two hours for HI2), and in order to study the propagation of an event through the FOVs, it is convenient to be able to go backward or forward in time with one instrument only without affecting the others. This is possible in the normal mode in which there is no constraint on simultaneity. The added flexibility permits,



☑ EUVI ☑ COR1 ☑ COR2 ☑ HI1 ☑ HI2 ☐ Compact

	Date	Visibility	Diff	Filename
EUVI	10-Feb-2007 01:35:40.0	Yes	Off	20070210_013540_s4euA.fts
COR1	10-Feb-2007 01:33:09.0	Yes	Off	20070210_013309_s4c1A.fts
COR2	10-Feb-2007 01:02:52.0	Yes	Off	20070210_010252_s4c2A.fts
HI1	10-Feb-2007 12:01:00.0	No	Off	20070210_120100_s4h1A.fts
HI2	10-Feb-2007 00:01:00.0	Yes	Off	20070210_000100_s4h2A.fts

Figure 5 The visualization GUI. Up to three visu-GUIs can be opened simultaneously, one for each STEREO probe and one for SOHO. This screenshot of the STEREO A GUI shows a composite of EUVI 19.5 nm, COR1, and COR2. The user can dynamically pan and zoom through the composite image with the mouse.

for example, the creation of an EUVI/COR1/COR2 composite in which the images of the instruments are as close as possible in time (as in the compact mode), but with the added condition that the dates are increasing from EUVI to COR1 to COR2. Finally, the normal and compact modes are complemented by the “linked” mode, in which the navigation in time is synchronized between the selected probes. The linked mode allows for easy creation of movies of simultaneous STEREO and SOHO composites.

2.7. Filters and Enhancements

Before they are put together as a composite, the projected images are converted from 32-bit floating point numbers to eight-bit integers, using a choice of three response curves: linear, square root, or logarithmic. Also, a large variety of digital filters can be applied to the data.

A filter is any IDL function, either built-in or user-written. The filters are input using a command line in the filter dialogue box. The only constraint is for the function to accept one matrix parameter. Built-in IDL functions that can be used as filters are, *e.g.*, smooth (image, 10) or median (image, 3). The straightforward application is to enhance the data with, for example, an unsharp mask, a wavelet filter, *etc.* Complex operations can be achieved with user-defined filters, such as processing the input matrix, computing physical parameters, and reading and writing files. Any number of filters can be applied sequentially to the data.

2.8. Graphical Output

2.8.1. Images

The content of a visualization GUI can be stored either in postscript format or in several bitmap formats (JPEG, TIFF, *etc.*). In postscript format, each image forming the composite is stored at its native resolution. The grid is rasterized, even though it is a vector object within FESTIVAL. In the bitmap formats, the content of the visualization GUI (including the coordinate grid if present) is rasterized before it is saved. By default, the scene is rasterized to produce an output of size equal to that of the visualization area of the GUI. But the width and height of the output can be changed. The maximum resolution is $10\,000 \times 10\,000$ pixels.

2.8.2. Movies

FESTIVAL is able to save at once a whole sequence of images that can later be put together in a movie (*i.e.*, MPEG or animated GIF) using video-encoding software. The sequence of images saved is equivalent to what would be obtained by clicking the “next” button through the list of images, as defined by current mode (normal, compact, or linked).

3. 3D Visualization

Most users will use FESTIVAL with a standard computer display, and when working with multiple probes, it is much more comfortable to use one display per probe in order to maximize the viewing area for each. Many graphics card are able to do so. FESTIVAL can also be used with 3D visualization hardware to display stereoscopic images. A sample setup using a passive technology system with left/right circular polarizers is illustrated by Figure 6. In order to achieve stereoscopic viewing, FESTIVAL is run as usual, but the STEREO A visualization GUI is simply sent to one projector, and the STEREO B GUI to the other. For use with such devices, FESTIVAL includes a 3D mode in which the panning and zooming are synchronized between STEREO A and B. In this mode, the user can navigate through the image or enlarge a region of interest without losing the stereo vision effect. There is no intrinsic limitation of the stereoscopic mode with EUVI data. However, stereoscopic vision is much easier to obtain and much more comfortable for EUVI images than for coronagraphic data. Filaments are most prominent and easy to see “above” the chromosphere. Interestingly, some faint filaments would not be (or barely) identified as such using 2D images only, but they appear clearly in 3D. This suggests that the accuracy of the measurement of filament altitudes by tie-point methods (see, *e.g.*, Aschwanden *et al.*, 1999) could be improved by working in a 3D visualization environment. Finally, it is worth noting that even though the resolutions of the instruments are different, it is possible to use FESTIVAL for stereoscopic viewing of, for example, EUVI B and EIT data. This naturally doubles the duration of the period during which stereoscopic vision is achievable.

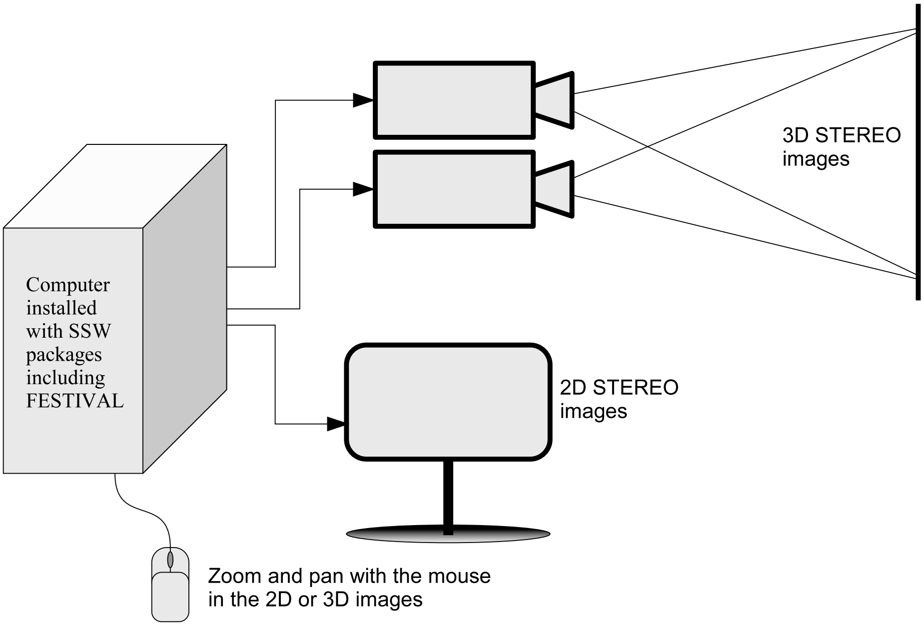


Figure 6 A sample hardware setup with one standard computer display and two projectors for 3D stereoscopic viewing.

4. Perspectives

FESTIVAL is a novel tool for the visualization of multispacecraft solar imaging data. The quick panning and zooming capability makes it easy to navigate through large images or composite of images, and this functionality is compatible with stereoscopic displays. After a few months of tests, several directions for improvements can be envisioned.

FESTIVAL currently supports images from SECCHI, EIT-LASCO, the Nançay Radioheliograph (NRH), and the MkIV coronagraph. The addition of other instruments is a natural evolution which we are pursuing. As is usually done, by neglecting the small parallax with the L_1 halo orbit of SOHO as seen from the Sun, images provided by spacecraft in Earth orbit or by ground-based observatories can be displayed in the SOHO visualization GUI. However, if a new spacecraft were to be launched on an interplanetary orbit (such as STEREO), the images would have to be displayed in a separate visualization GUI, for they could not be meaningfully combined with the data from other probes. One can also think of the visualization of simulated data overlayed, or not, on top of real observations.

Today, the user needs expensive 3D display hardware to be able to view stereoscopic images with FESTIVAL. A useful addition would be the ability to create red/cyan anaglyphs. These are not the best way to visualize 3D images because ghost images can never be totally eliminated, but they require only inexpensive red/cyan glasses.

At present, FESTIVAL works with local data, which means that the user has to access one of the solar databases to get the data before visualizing them. The capability to query remote databases and download the data would render this process transparent to the user.

Finally, FESTIVAL was designed to be able to be run from a command line, without the graphical interface, with the possibility to set the main visualization parameters. Even though this feature is not implemented yet, it opens a large range of perspectives. The kernel of FESTIVAL could then become a powerful visualization segment of a pipeline processing chain.

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