SOFTWARE USER GUIDE VERSION 3.2.0

e-CALLISTO
FITS Analyzer

Visualization, processing and analysis of solar radio dynamic spectra, solar images, coronal mass ejections and their geomagnetic response

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e-CALLISTO FITS Analyzer — User Guide
For software version 3.2.0
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Data acknowledgment. The radio spectra described in this guide are recorded by the stations of the e-CALLISTO network. Solar images, X-ray and particle fluxes, geomagnetic indices and event catalogs are retrieved from the archives listed in Appendix C; users should acknowledge those data providers as their policies request.

Disclaimer. Every effort has been made to make this guide accurate and complete. The software and this guide are provided "as is", without warranty of any kind. Physical quantities derived with the software depend on models and assumptions that are described in the relevant chapters; results should be validated independently before they are used for scientific conclusions.

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Preface

The e-CALLISTO FITS Analyzer began as a tool for looking at the solar radio dynamic spectra recorded by the e-CALLISTO network and for measuring the drift of Type II bursts. Over successive releases it has grown into a framework that also retrieves archive data from several radio instruments, places a radio event in its wider solar and geophysical context, analyzes solar images from space-borne observatories, reconstructs coronal mass ejections in three dimensions, and follows an event to its geomagnetic response at Earth. This guide describes all of that functionality as it exists in version 3.2.0.

About this guide

This is a *user guide*: a reference to what each window, menu, panel and control does, what it expects as input, what it produces, and which limits apply. It is not a tutorial and does not teach solar radio physics or image analysis. Where an operation consists of several steps, the steps are given as a short numbered procedure; otherwise each feature is described in the place where you meet it in the interface. Short *Background* boxes summarize the models behind computed quantities so that results can be interpreted and reported correctly; the full set of equations is collected in Appendix D.

The guide is written for observers, students and researchers who work with e-CALLISTO data and related space-weather observations. No programming knowledge is required.

How this guide is organized

Part I, Getting Started introduces the software, explains installation on Windows, macOS and Linux, tours the main window, and describes the help, update, citation and bug-report tools.

Part II, Working with Dynamic Spectra covers opening and combining FITS files, the sidebar processing panels, display, RFI cleaning, annotation and measurement tools, the Type II drift and shock analysis, band-splitting analysis, and the single project file, reports and export.

Part III, Radio Data Access describes the e-CALLISTO FITS Downloader, the Multi-Station Comparison workspace, and the Learmonth and STEREO/SWAVES loaders.

Part IV, Solar-Event Context describes the GOES X-ray, GOES proton, Dst, Kp and SOHO/LASCO CME catalog viewers; the Geomagnetic Response, the Event Context Strip and the Event Figure composer; and the SunPy Multi-Mission Explorer.

Part V, Solar Image Analysis covers the multi-mission imaging workspace: data retrieval, display and processing, measurement and CME kinematics, and potential-field source-surface modeling.

Part VI, Three-Dimensional CME Reconstruction describes the GCS CME Fitting window for flux-rope and shock reconstruction from several coronagraph viewpoints.

The appendices list keyboard shortcuts, file formats and outputs, data sources, models and formulas, and troubleshooting advice, followed by a glossary, the bibliography and an index.

Conventions

Table 1 lists the typographic conventions used throughout the guide.

Table 1 Typographic conventions used in this guide.

Example	Meaning
File → Export As → Export Figure	A command reached through a menu and its submenus.
Subtract Background	A button, field, check box, tab, panel or window as labeled in the interface.
Ctrl+S	A keyboard shortcut. On macOS, Ctrl in a shortcut corresponds to the Command key Cmd.
`project.efaproj`	A file name, file extension or folder.
③	A numbered callout in a screenshot, explained in the accompanying table.
Note, **Tip**, **Caution**	Boxes with additional detail, a quicker way of doing something, or a warning about lost work or results that need care. **Background** boxes summarize the model behind a computed quantity.

The screenshots were taken with the macOS version of the software in the light theme. On Windows and Linux the window frames, fonts and menu placement follow the conventions of the operating system, and in the dark theme the colors differ, but the controls and their behavior are identical on all platforms.

Acknowledgments

The e-CALLISTO FITS Analyzer relies on data from the e-CALLISTO network and its archive, and on the many public archives listed in Appendix C. It is built on open-source scientific software, including Qt for Python (PySide6), NumPy, SciPy, Matplotlib, PyQtGraph, Astropy (Astropy Collaboration et al. 2022), SunPy (The SunPy Community et al. 2020), aiapy (Barnes et al. 2020), sunkit-magex (Stansby et al. 2020) and reproject. Their authors and maintainers are gratefully acknowledged.

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Colombo, October 2026

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Part I

Getting Started

What the software does, how to install it, and a tour of the main window, its menus and the built-in help.

1

Introduction

1.1 What the e-CALLISTO FITS Analyzer is

The e-CALLISTO FITS Analyzer is a cross-platform desktop application for visualizing, processing and analyzing solar radio dynamic spectra recorded in FITS format by the e-CALLISTO spectrometer network, and for placing those observations in their solar and geophysical context. It runs natively on Windows, macOS and Linux (Debian and Ubuntu) and is distributed as self-contained installers, so no separate Python installation is required.

e-CALLISTO is a world-wide network of CALLISTO radio spectrometers that monitors the Sun around the clock (Benz et al. 2009). Each station records dynamic spectra — radio intensity as a function of frequency and time — in FITS files that normally span 15 minutes. A station may operate several receivers or frequency bands, each identified by a two-digit *focus code*. File names follow the pattern `STATION_YYYYMMDD_HHMMSS_FC.fit.gz`, for example `Australia-ASSA_20261004_000000_63.fit.gz` for focus code 63 of the Australia-ASSA station starting at 00:00:00 UT on 4 October 2026.

The application merges fragmented observations across time and frequency, removes the receiver background, mitigates radio-frequency interference (RFI), and isolates solar radio bursts with an interactive mask. Dedicated tools derive the frequency drift rate and shock parameters of Type II bursts and estimate the coronal magnetic field from band-split emission. Around this core, the software retrieves archive data from several radio instruments, displays X-ray, particle, geomagnetic and coronal mass ejection (CME) data for the same interval, analyzes solar images from space-borne observatories, models the coronal magnetic field, and reconstructs CMEs in three dimensions. It follows an event to Earth with its geomagnetic response, draws the flare, CME and storm catalogs beside the spectrum, composes a figure of the whole event, and keeps the radio, solar-image and CME work of one event in a single project file.

1.2 Capabilities at a glance

Table 1.1 summarizes the main modules, where they are opened, and where they are described in this guide.

Table 1.1 Main modules of the e-CALLISTO FITS Analyzer.

Module	Opened from	Purpose	Chapter
Main window	Application start	Display and process dynamic spectra	3–7
Type II analysis	Toolbar; Analysis	Burst isolation, maxima, drift and shock parameters	8
Band-splitting analysis	Analysis → Type II Band-splitting	Compression ratio, Alfvén speed, magnetic field	9
Projects and export	File	One project for every window, figures, FITS, reports, batch export	10
FITS Downloader	Download; toolbar	e-CALLISTO archive search, preview and import	11
Multi-Station Comparison	View	Stacked spectra from several stations	12
Learmonth, STEREO/SWAVES	Solar Events → Radio Bursts	Additional radio spectra	13
Solar-event viewers	Solar Events	GOES X-rays and protons, Dst, Kp, CME catalog	14
Geomagnetic Response	Solar Events → Geomagnetic; sidebar	Dst, Kp, IMF, solar wind and auroral indices around the event	15
Event Context Strip	View	Flare, CME, DONKI and burst catalogs above the spectrum	15
Event Figure	File → Export As	One publication figure of the whole event	15
SunPy Explorer	Solar Events → Archives	Multi-mission archive search and plots	16
Solar Image Analysis	Analysis → Solar Image Analysis	Imaging, measurement, CME kinematics, PFSS	17–20
GCS CME Fitting	Analysis → GCS CME Fitting…	3-D flux-rope and shock reconstruction	21–22

1.3 Supported data

The application reads and retrieves the data types listed in Table 1.2. The archives behind each retrieval tool are listed in Appendix C.

Table 1.2 Data types handled by the e-CALLISTO FITS Analyzer.

Data	Use in the application
CALLISTO FITS (`.fit`, `.fits`, `.fit.gz`, `.fits.gz`)	Loaded, combined, processed and analyzed in the main window.
ARTEMIS-IV `ARTLOOK` FITS	Loaded in the main window with instrument-specific time and intensity scaling (Section 5.1.1).
Learmonth Solar Radio Spectrograph archive	Converted to FIT files and imported (Section 13.1).
STEREO/SWAVES level-2 spectra	Displayed below the CALLISTO spectrum on a shared time axis (Section 13.2).
Solar image FITS (SDO/AIA, SDO/HMI, SOHO/EIT, SOHO/LASCO, STEREO/SECCHI, GOES/SUVI)	Displayed, processed and measured in Solar Image Analysis (Part V).
Helioviewer JPEG2000 images	Quicklook image sequences and near-real-time previews in Solar Image Analysis (Part V), the coronagraph images used for GCS fitting (Part VI), and Event Figure thumbnails.
Synoptic magnetograms (GONG, HMI, ADAPT)	Boundary condition for PFSS modeling (Chapter 20).
GOES XRS and SGPS, Kyoto Dst, GFZ Kp, SOHO/LASCO CME catalog	Context viewers and overlays (Chapter 14).
OMNI, DSCOVR and SWPC solar-wind data; SYM-H and AE indices	Geomagnetic Response (Section 15.2).
GOES/SWPC flare list, CDAW CMEs, NASA DONKI, e-CALLISTO burst lists	Event Context Strip, Event Figure and the report's Event Story (Chapter 15).

1.4 Workflow overview

Figure 1.1 shows how the main components relate to each other. Data enter the main window from local files, the downloaders or a saved project; they are processed in the sidebar; analysis windows take the processed spectrum as input; and every stage can be saved in a project or exported. The context and imaging tools can be synchronized to the time window of the loaded spectrum, and the event-context tools follow the event time of the loaded data.

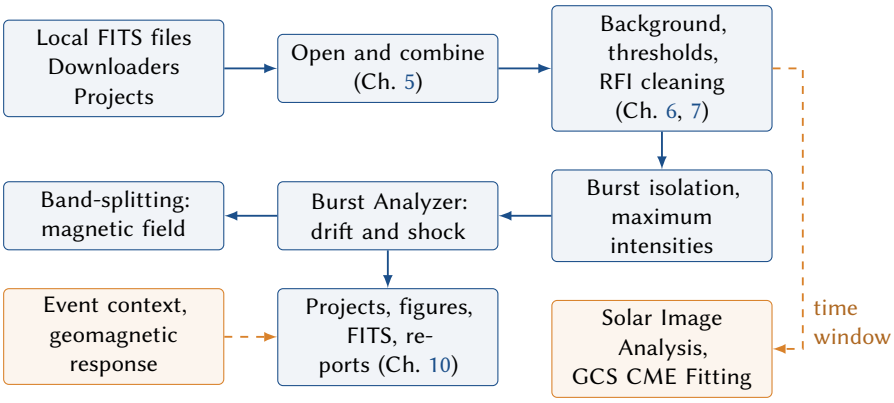


Figure 1.1 Relationship between the main components of the e-CALLISTO FITS Analyzer. Solid arrows show the radio-analysis chain; dashed arrows show context and imaging tools that use the time window of the loaded spectrum.

1.5 What is new in version 3.2.0

Version 3.2.0 turns a radio burst into the story of a whole event. It adds or substantially extends the following features, all of which are described in this guide:

- **One project for every window:** a single `.efaproj` file holds the radio analysis, the Solar Image Analysis frames and measurements, and the GCS fits, with the images linked or embedded (Section 10.1);
- **Geomagnetic Response:** Dst, SYM-H, Kp, the IMF, solar wind and auroral indices from one day before to seven days after the event, as a sidebar card and a window (Section 15.2);
- **Event Context Strip and Event Figure:** flare, CME, DONKI and burst catalogs above the spectrum, and one composed publication figure of the event (Sections 15.3 and 15.4);
- **Project reports** that open with an Event Story and include Solar Image Analysis and GCS sections (Section 10.6);
- **Solar Image Analysis:** a choice of full-resolution FITS, reduced-size FITS or JPEG2000 quicklook products, download progress based on the real transfer, the AIA 193 Å Sun in LASCO's occulter, and labelled north-up movies (Chapters 17 and 18);
- Reset All, which returns the application to its start-up state (Section 3.2).

Version 3.1.0 introduced ridge tracking, the selectable power-law time origin and density models, the Timeline panel, the logarithmic frequency axis, the Burst List, PFSS modeling and GCS fitting; they are described in the chapters concerned.

> **Caution.** Projects saved by version 3.2.0 cannot be opened by version 3.1. Keep a copy of any project you still need to open in version 3.1 before saving it again. Version 3.1 radio projects open unchanged, and a version 3.1 `.ecsolar` Solar Image Analysis session opens as a new, unsaved project.

1.6 Citing the software

If you use the e-CALLISTO FITS Analyzer in your research, please cite Liyanage et al. (2026). The citation and a BibTeX entry can be copied from the application with the Cite this Software button (Section 4.2). The BibTeX entry is:

```
@article{liyanage2026ecallistofitsanalyzersoftware,
   title={e-CALLISTO FITS analyzer: a software framework for CALLISTO solar radio data},
   author={Liyanage, G L S S and Adassuriya, J and Jayaratne, K P S C and Monstein, C and Manoharan,
P K},
   journal={RAS Techniques and Instruments},
   volume={5}, pages={rzag056}, year={2026},
   doi={10.1093/rasti/rzag056}
}
```

When you publish results that depend on archive data retrieved through the application, acknowledge the corresponding data providers as well (Appendix C).

2

Installation and Startup

Native installers are available for Windows, macOS and Linux. Each bundles the application with everything it needs to run, including the Python runtime and all scientific libraries, so no separate Python installation is required. Installers can be downloaded from the official website, https://ecallistoanalyzer.org, from the e-CALLISTO software page, https://www.e-callisto.org/Software/Callisto-Software.html, or from the project's GitHub releases page, https://github.com/SaanDev/e-Callisto_FITS_Analyzer/releases.

> **Full application and Lite.** Each release also carries *e-CALLISTO FITS Analyzer Lite*, a separate, lighter application that contains only the radio analysis. Its installers have `-lite` in their names. This guide describes the full application: download the installer *without* `-lite`. The two can be installed side by side.

2.1 System requirements

Table 2.1 System requirements for version 3.2.0.

Item	Requirement
Windows	64-bit Windows able to run x64 applications. Installation needs administrator approval.
macOS	macOS 15 (Sequoia) or later on a Mac with Apple silicon (arm64).
Linux	Debian, Ubuntu or a derivative on 64-bit x86 (`amd64`), with the Qt/OpenGL runtime libraries `libgl1`, `libegl1`, `libxkbcommon-x11-0` and `libxcb-cursor0` (installed automatically by `apt`).
Disk space	About 3 GB for the application, plus space for the download caches. Solar image sequences can occupy several gigabytes.
Display	1280 × 800 pixels or larger. A resolution of at least 1440 × 900 is recommended for the Solar Image Analysis and GCS CME Fitting windows.
Network	Required for the downloaders, archive searches, context viewers, the geomagnetic response and event catalogs, update checks and bug reports. Local files, saved projects (including embedded ones) and cached downloads can be analyzed offline.

2.2 Installing on Windows

1. Download the installer, `e-CALLISTO_FITS_Analyzer_v3.2.0_Setup.exe`.
2. Run the installer and approve the Windows administrator prompt.
3. Follow the installation steps. The installer can optionally create a desktop shortcut.
4. Start the application from the Start menu or the desktop shortcut.

> **Note.** If a save location chosen by the application is not writable — for example a folder inside `C:\\ProgramFiles` — the application asks you to choose another folder.

2.3 Installing on macOS

1. Download the disk image, `e-callisto-fits-analyzer_3.2.0_macOS_arm64.dmg`.
2. Quit any running instance of the application.
3. Open the disk image and drag the application to the `Applications` folder, replacing the previous version if asked.
4. Eject the disk image and start the application from `Applications` or Launchpad.

> **Note.** The macOS application is not notarized, so macOS blocks it the first time it opens. Try to open the application, close the warning, then open System Settings → Privacy & Security and click Open Anyway next to the message about the e-CALLISTO FITS Analyzer, and confirm with your password. macOS remembers the choice, so this is needed only once for each installed version.

2.4 Installing on Linux

Download the Debian package and install it from a terminal in the download folder:

```
sudo apt install ./e-callisto-fits-analyzer_3.2.0_amd64.deb
```

The package installs a desktop entry, so the application appears in the desktop environment's application menu. Using `apt` rather than `dpkg` also installs any missing runtime libraries.

2.5 Running from source

The source code is openly available at https://github.com/SaanDev/e-Callisto_FITS_Analyzer. Running from source is intended for developers and for platforms without an installer. With Python 3.12 or newer:

1. Clone or download the repository and create a virtual environment in it.
2. Install the pinned dependencies with `python scripts/install_requirements.py`.

3 Start the application with `python src/main.py`.

On Windows, if Qt reports `DLL load failed` at start-up, the script `packaging/windows/repair_windows_venv.ps1` rebuilds the virtual environment with the supported Python version.

2.6 Starting the application

When the application starts it shows a splash screen and then opens the main window (Chapter 3) with an empty plotting area. Shortly after start-up it checks GitHub for a newer release and reports the result on the right of the status bar, for example Updates: up to date (Section 4.3).

If the previous session ended unexpectedly while it had unsaved work, the application offers to recover the latest autosave snapshot (Section 10.2).

With Solar Events → Fetch Event Context Automatically on (the default), loading data also fetches the event's geomagnetic response and, when the Event Context Strip is shown, the event catalogs (Section 15.1). Turn it off if you prefer that nothing is downloaded on your behalf.

The application remembers your preferences between sessions, including the theme and rendering mode, which sidebar sections are expanded, the frequency-axis scale, the recent files and projects, processing and display-range presets, the Event Context Strip and its sources, automatic event-context fetching, the Geomagnetic Response panels, and the JSOC e-mail address and download product used by Solar Image Analysis.

2.7 Updating and uninstalling

Use About → Check for Updates... to look for a newer version; if one exists, the installer can be downloaded from within the application (Section 4.3). Installing a new version over an existing one keeps your preferences. Before saving an existing project in a new version, check the compatibility notes of that version: projects saved by version 3.2.0 cannot be opened by version 3.1.

To uninstall, use Settings → Apps on Windows, move the application from `Applications` to the Trash on macOS, or run `sudo apt remove e-callisto-fits-analyzer` on Linux. Downloaded data remain in the cache folders; empty them first with the Clear Cache buttons of the downloaders if you want to reclaim the space.

3

The Main Window

The main window is where dynamic spectra are displayed, processed and measured, and from where every other tool is opened. This chapter describes its layout, toolbar, menus and status bar. The sidebar panels are described in Chapter 6.

3.1 Layout

The main window (Figure 3.1) consists of the regions listed in Table 3.1.

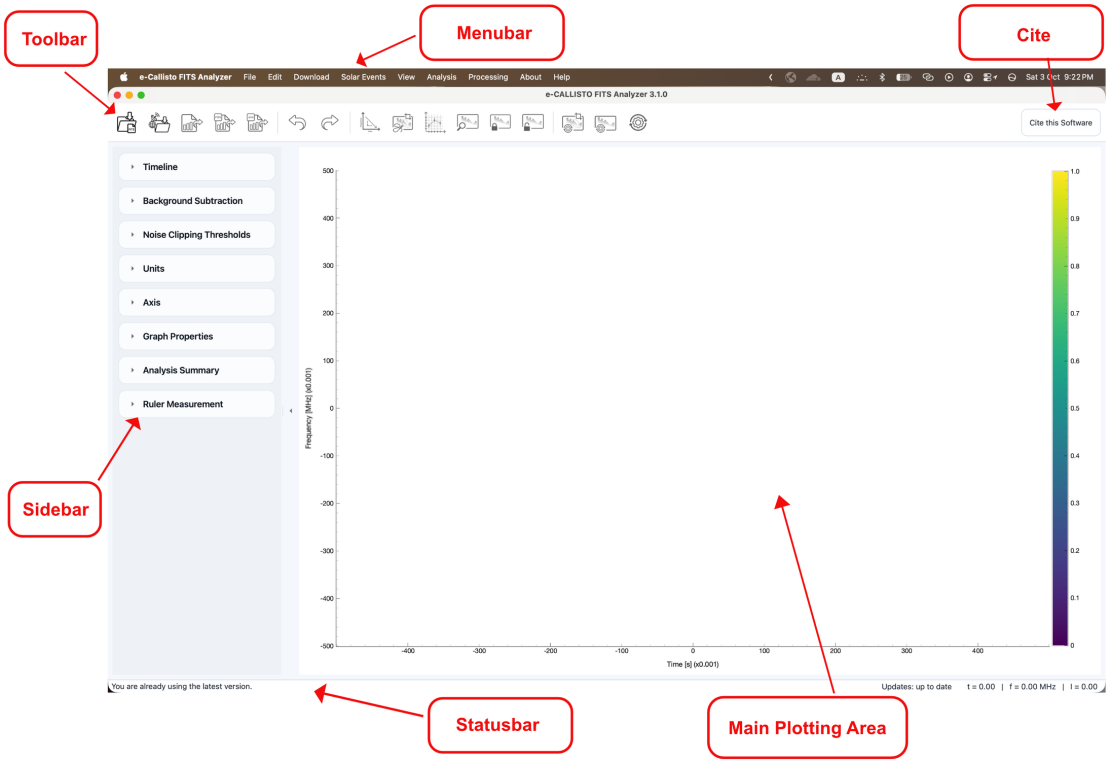


Figure 3.1 Main window of the e-CALLISTO FITS Analyzer before a file is loaded.

A narrow arrow handle on the left edge of the plotting area hides or shows the sidebar to give the plot more room. The divider between the sidebar and the plot can also be dragged.

Table 3.1 Regions of the main window.

Region	Description
Menu bar	Access to every function, including those not on the toolbar (Section 3.4). On macOS the menu bar is at the top of the screen.
Toolbar	Icon buttons for the most frequent actions (Section 3.2).
Cite this Software	Opens the citation dialog (Section 4.2).
Sidebar	Collapsible panels for the timeline, background subtraction, display thresholds, units, axis scale, graph properties, the analysis summary, the geomagnetic response and the ruler readout (Chapter 6).
Main plotting area	The dynamic spectrum with its color bar, and optionally the Event Context Strip above it (Section 15.3). Interactive tools act here.
Status bar	Messages on the left; the update status and the live cursor readout on the right (Section 3.5).

3.2 Toolbar

The toolbar (Figure 3.2) contains 16 tools, described in Table 3.2. Hovering over a tool shows its name. Tools that need loaded or processed data remain disabled until they can be used.

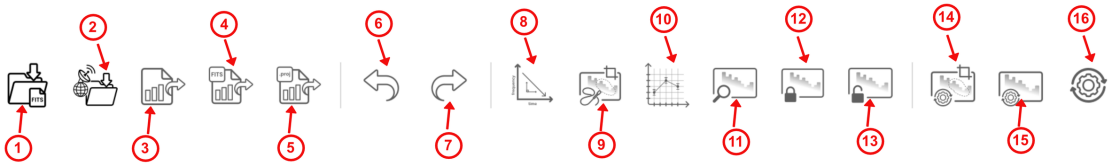


Figure 3.2 The main toolbar with its tools numbered.

Table 3.2 Toolbar tools.

No.	Tool	Function	Shortcut
1	Open / Load	Load one or more CALLISTO FITS files from disk (Section 5.2).	Ctrl+O
2	Download	Open the e-CALLISTO FITS Downloader (Chapter 11).	
3	Export	Export the displayed spectrum as a figure (Section 10.3).	Ctrl+E
4	Export as FITS	Export the processed spectrum as a FITS file (Section 10.4).	Ctrl+F
5	Save Project	Save the complete workspace as an `.efaproj` project (Section 10.1).	Ctrl+S
6	Undo	Undo the last processing change.	Ctrl+Z
7	Redo	Redo the last undone change.	Ctrl+Shift+Z

No.	Tool	Function	Shortcut
8	Estimate Drift Rate	Estimate the drift rate from points clicked along a burst (Section 7.7).	
9	Isolate Burst	Draw a freehand mask around a burst (Section 8.2).	
10	Plot Maximum Intensities	Open the Maximum Intensities window (Section 8.3).	
11	Rectangular Zooming	Drag one rectangle to zoom into the plot. Available while navigation is locked (Section 7.1).	
12	Lock zooming and panning	Disable scroll-wheel zooming and panning, freezing the view and enabling rectangle zoom.	
13	Unlock zooming and panning	Re-enable scroll-wheel zooming and panning.	
14	Reset Selection	Clear the isolated-burst selection and drift markers.	
15	Reset to Raw	Discard all processing and show the raw spectrum.	
16	Reset All	Return the application to its start-up state (see below).	

Reset All (also Edit → Reset All) returns the application to how it starts: the loaded data, processing, graph settings, sidebar readouts and undo history are cleared, and the analysis, Geomagnetic Response, Event Figure, Solar Image Analysis and GCS windows are closed. Your preferences, including the View-menu event-strip choices, and the download cache are kept.

> **Caution.** With unsaved changes, Reset All asks whether to Save, Discard or Cancel, as when opening a project or quitting. With everything saved but work open in the Solar Image Analysis or GCS window, it asks you to confirm.

3.3 Plotting area and renderers

The plotting area shows the dynamic spectrum with frequency on the vertical axis, time on the horizontal axis and intensity as color. The plot title shows the source file name and the processing state, for example -Background Subtracted or -Isolated Burst. With View → Event Context Strip on, catalog lanes are drawn above the spectrum on their own time axis (Section 15.3).

Two renderers are available and are selected with View → Mode:

Modern uses a hardware-accelerated canvas (PyQtGraph) for fast zooming and panning of large or combined spectra. This is the default.

Classic uses Matplotlib.

Processing → Hardware Acceleration → Enable switches the accelerated live canvas on or off. Both renderers support the same tools, annotations and overlays, and exported figures look the same whichever renderer is in use (Section 10.3).

3.4 Menu bar

Table 3.3 summarizes the menus of the main window. The tables that follow list every command, with its shortcut and the section where it is described.

Table 3.3 Menus of the main window.

Menu	Main functions
File	Open and combine FITS files; recent files and projects; open, save and recover projects; project reports; figure, FITS, provenance, analysis-log and Event Figure export.
Edit	Undo and redo; extend the timeline with adjacent observations; reset to raw data; reset the workspace.
Download	Launch the e-CALLISTO FITS Downloader.
Solar Events	CME catalog, GOES X-ray and proton flux, geomagnetic indices and the Geomagnetic Response, SunPy Explorer, radio-burst downloaders, time-window synchronization, GOES overlay, the SWAVES panel and automatic event-context fetching.
View	FITS header, display range and its presets, view configurations, Multi-Station Comparison, the Event Context Strip and its sources, theme and rendering mode.
Analysis	Solar Image Analysis, GCS CME Fitting, maximum intensities, Type II band-splitting, light curves and the ruler.
Processing	Hardware acceleration, RFI cleaning, annotations, presets, automatic outlier cleaning, restored analysis sessions and batch processing.
About	Update check, bug report and version information.
Help	The built-in user guide and the official website.

Table 3.4 File menu.

Command	Function	Shortcut, see
Open	Load one file, or combine a compatible multi-file selection.	Ctrl+O, §5.2
Recent Files	Reopen one of the last ten FITS selections.	§5.2.1
Combine FITS Files...	Validate, preview and import time, frequency or time × frequency combinations.	§5.4

Command	Function	Shortcut, see
Open Project...	Open a project and restore every window it needs; also imports a version 3.1 `.ecsolar` session.	Ctrl+Shift+O, §10.1
Recent Projects	Reopen one of the last ten projects.	§10.1
Save Project	Save the radio, Solar Image Analysis and GCS work to the current project file.	Ctrl+S
Save Project As...	Save to a new project file, choosing to link or embed the images.	Ctrl+Shift+S, §10.1.1
Recover Last Session...	Restore the most recent autosave snapshot.	§10.2
Generate Project Report...	Create a PDF report that opens with the Event Story.	§10.6
Export As → Export Figure	Save the plot as an image or vector figure.	Ctrl+E, §10.3
Export As → Export to FIT	Save the processed spectrum as a FITS file.	Ctrl+F, §10.4
Export As → Export Provenance Report...	Write Markdown and JSON provenance summaries.	§10.5
Export As → Export Analysis Log...	Write CSV and text summaries of the fit and shock results.	§10.5
Export As → Event Figure…	Compose one publication figure of the whole event.	§15.4

Note. The disabled File → Save As entry in the main window is reserved; projects are saved with Save Project and Save Project As....

Table 3.5 Edit menu.

Command	Function	Shortcut, see
Undo	Undo the last processing or timeline change.	Ctrl+Z
Redo	Redo the last undone change.	Ctrl+Shift+Z
Add Previous Observation	Prepend the preceding 15-minute observation.	Ctrl+Shift+Left, §6.1
Add Next Observation	Append the following observation.	Ctrl+Shift+Right, §6.1

Command	Function	Shortcut, see
Prefetch Adjacent Observations	When ticked (default), download neighboring observations in the background so the next timeline step is instant.	§6.1
Reset to Raw	Remove all processing and return to the loaded data.	
Reset All	Return the application to its start-up state.	§3.2

Table 3.6 Download and Solar Events menus.

Command	Function	See
Download → Launch FITS Downloader	Open the e-CALLISTO FITS Downloader.	Ch. 11
Solar Events → CMEs → SOHO/LASCO CME Catalog	Daily CME lists, parameters and movies.	§14.7
Solar Events → Flares → GOES X-Ray Flux	GOES XRS viewer and flare parameters.	§14.3
Solar Events → Energetic Particles → GOES SEP Proton Flux	GOES SGPS proton flux viewer.	§14.4
Solar Events → Geomagnetic → Kyoto Dst Index	Dst index viewer.	§14.5
Solar Events → Geomagnetic → GFZ Kp Index	Kp index viewer.	§14.6
Solar Events → Geomagnetic → Geomagnetic Response…	Dst, Kp, IMF, solar wind and auroral indices around the event.	§15.2
Solar Events → Archives → SunPy Multi-Mission Explorer	Multi-mission archive search and plotting.	Ch. 16
Solar Events → Radio Bursts → e-CALLISTO	The e-CALLISTO FITS Downloader.	Ch. 11
Solar Events → Radio Bursts → Learmonth	Learmonth spectrograph browser.	§13.1
Solar Events → Radio Bursts → SWAVES	STEREO/SWAVES loader.	§13.2
Solar Events → Sync Current Time Window	Send the time range of the loaded spectrum to open context windows.	§14.2
Solar Events → GOES Overlay → Short(XRS-A), Long(XRS-B)	Draw GOES X-ray curves on the spectrum.	§14.3.1

Command	Function	See
Solar Events → SWAVES Panel	Show or hide the loaded SWAVES panel.	§13.2
Solar Events → Fetch Event Context Automatically	When ticked (default), fetch the geomagnetic response and catalogs when data are loaded or an event is selected.	§15.1

Table 3.7 View menu.

Command	Function	See
View FITS Header	Show the primary header of the loaded file.	§5.5
Set Display Range...	Enter exact time and frequency limits.	§7.2
Save / Apply / Delete Display Range Preset...	Store and reuse named display ranges.	§7.2
Export View Config..., Import View Config...	Share display settings as `.efaview.json`.	§7.2.2
Multi-Station Comparison...	Open the comparison workspace.	Ch. 12
Event Context Strip	Show catalog lanes above the spectrum.	§15.3
Event Context Sources → …	Choose the lanes; Refresh Event Context fetches them again.	§15.3
Theme → System / Light / Dark	Choose the color theme.	§3.6
Mode → Classic / Modern	Choose the Matplotlib or hardware-accelerated renderer.	§3.3

Table 3.8 Analysis menu.

Command	Function	See
Solar Image Analysis	Open the multi-mission imaging workspace.	Ch. 17
GCS CME Fitting…	Open the GCS window for the visible time range.	Ch. 21
Maximum Intensities → Open Maximum Intensities	Extract the peak frequency of each time channel.	§8.3
Type II Band-splitting → Open Type II Band-splitting	Open the band-splitting analyzer.	Ch. 9

Command	Function	See
Plot Light Curves → Enter frequency	Plot a light curve at a typed frequency.	§7.6
Plot Light Curves → Click on a frequency	Toggle click mode for light curves.	§7.6
Plot Light Curves → Settings...	Light-curve appearance.	§7.6
Plot Light Curves → Clear light curve(s)	Remove all light curves.	§7.6
Ruler Measurement	Measure duration, frequency change and slope between two points.	§7.8
Clear Ruler Measurement	Remove the ruler.	§7.8

Table 3.9 Processing, About and Help menus.

Command	Function	Shortcut, see
Processing → Hardware Acceleration → Enable	Toggle the accelerated live canvas.	§3.3
Processing → RFI Cleaning → Open RFI Panel / Apply RFI / Reset RFI	RFI cleaning pipeline.	§7.3
Processing → Annotations → …	Polygon, line and text annotations.	§7.5
Processing → Presets → …	Processing presets and the default preset.	§7.4
Processing → Maximum Intensity → Auto-Clean Isolated Burst Outliers	Remove outliers automatically when maxima are taken from an isolated burst.	§8.5
Processing → Analysis Session → Open Restored Analysis	Reopen the analysis windows of a restored session.	§10.1.3
Processing → Batch Processing → Open Batch Processor	Export many files with consistent settings.	§10.8
About → Check for Updates...	Look for a newer release.	§4.3
About → Report a Bug...	Prepare a bug report with diagnostics.	§4.4
About → About	Version and author information.	§4.5
Help → User Guide	Open the built-in user guide.	F1, §4.1
Help → Official Website	Open https://ecallistoanalyzer.org in your web browser.	§4.6

3.5 Status bar

The left part of the status bar shows messages from the current operation, for example the result of a drift-rate estimate or a reminder of how to finish a tool. The right part shows:

- the update status, for example Updates: up to date; and
- the live cursor readout t = … | f = … MHz | I = …, giving the time, frequency and intensity (in the selected units) under the mouse pointer.

The readout allows quick quantitative inspection of the spectrum without clicking.

3.6 Themes

View → Theme selects System (follow the operating system), Light or Dark. The theme applies to all windows of the application and to on-screen plots. Exported figures and PDF reports are always drawn on a white page, whichever theme is in use.

3.7 Drag and drop

FITS files and `.efaproj` projects can be dropped anywhere on the main window, including the plot. A single FITS file opens on its own; several are combined exactly as with File → Open; a project file opens the project, and a version 3.1 `.ecsolar` session is imported as a new project. Other file types are refused. If the current work has unsaved changes, you are asked whether to save them first.

4

Help, Updates and Support

This chapter describes the built-in user guide, the citation dialog, the update check, the bug-report tool and the version information.

4.1 The built-in user guide

Help → User Guide (F1) opens a condensed version of this guide in a separate window (Figure 4.1). The guide follows the application theme and offers:

- a linked table of contents and cross-references between sections;
- Home and Back buttons for navigation;
- a Find in guide… field with Find Next; and
- Close.

The GCS CME Fitting window has its own help, opened with F1 in that window (Section 21.7).

4.2 Citing the software

The Cite this Software button at the right end of the toolbar opens the citation dialog (Figure 4.2). It shows the recommended citation and a BibTeX entry, with Copy Citation and Copy BibTeX buttons that place the text on the clipboard. The citation is reproduced in Section 1.6.

4.3 Checking for updates

The application checks GitHub for a newer release shortly after it starts and shows the result in the status bar (Updates: checking…, Updates: up to date, or a notice that a new version is available). About → Check for Updates… repeats the check on demand:

- if a newer version exists, the dialog shows the current and latest version numbers with a summary of the release notes, and offers to download the installer of the full application for your platform to a folder you choose;
- if you are up to date, the dialog confirms the installed version;

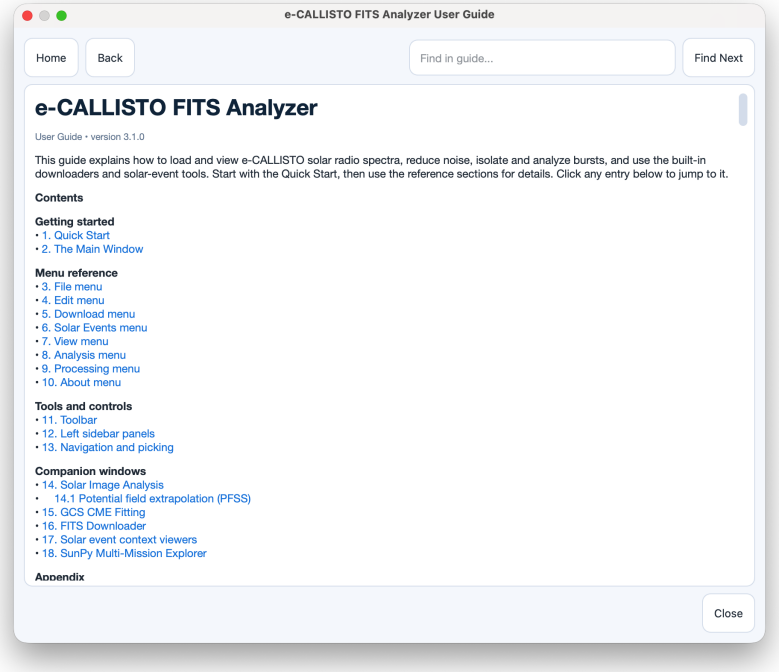


Figure 4.1 The built-in user guide window.

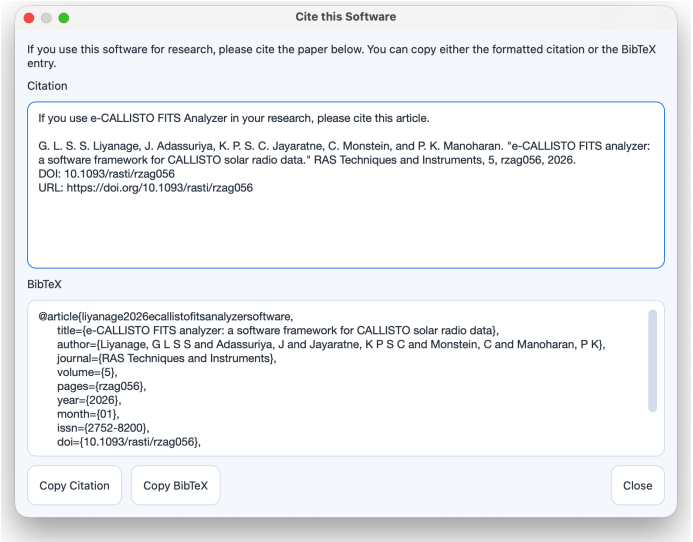


Figure 4.2 The Cite this Software dialog.

- if the check fails, for example without a network connection, an error message explains why.

Install the downloaded package as described in Chapter 2.

4.4 Reporting a bug

About → Report a Bug... opens the bug-report dialog (Figure 4.3). It contains:

Bug Title
a short summary, for example *Crash when exporting PNG*.

What happened / Steps to reproduce / Expected behavior
a free-text description, pre-filled with a template.

Generate Diagnostics...
creates a ZIP bundle with a summary of the current session (loaded file, plot type, units, color map, combination state and project path), environment information (application version, operating system and Python version), the operation log, the processing and RFI settings, and a structured provenance summary of the loaded data. The path of the bundle is shown below the text.

Copy Issue Text
copies a formatted issue description, including the environment summary, to the clipboard.

Open GitHub Issue
opens a pre-filled issue draft on the project's GitHub page in your web browser, where you can attach the diagnostics bundle before submitting.

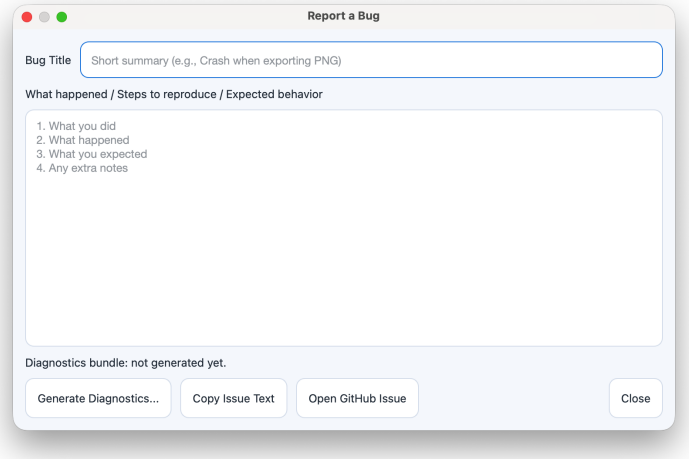


Figure 4.3 The Report a Bug dialog.

> **Note.** Nothing is sent automatically. The issue is created only when you submit it on GitHub. Review the diagnostics bundle before attaching it if your file names or paths are confidential.

4.5 About

About → About shows the version number, the developer, the affiliation and the address of the official website. The Solar Image Analysis and Maximum Intensities windows have their own About menus with information about those tools.

4.6 Official website

Help → Official Website opens https://ecallistoanalyzer.org in your web browser. The website offers the installers for all platforms, an online version of the user guide, tutorials, and the recommended citation. If the browser cannot be opened, a message shows the address so that it can be copied.

Part II

Working with Dynamic Spectra

Loading, combining, processing and measuring CALLISTO dynamic spectra, the Type II analysis tools, and saving and exporting your work.

5

Opening and Combining Data

This chapter describes the file types the main window reads, the ways of opening them, and the rules and options for combining several files into one dynamic spectrum.

5.1 Supported files

The main window reads CALLISTO dynamic spectra in FITS format, compressed or uncompressed:

- uncompressed files: `.fit`, `.fits`;
- gzip-compressed files: `.fit.gz`, `.fits.gz`.

Upper-case suffixes such as `.FITS` are accepted. Combination relies on the standard CALLISTO file name, `STATION_YYYYMMDD_HHMMSS_FC`, from which the station, start time and focus code are read. Files converted from the Learmonth spectrograph (Section 13.1) follow the same conventions.

5.1.1 ARTEMIS-IV files

FITS files from the ARTEMIS-IV radio spectrograph (Thermopylae, Greece) in its `ARTLOOK` format are recognized automatically. On loading:

- the hours-based UT time axis is converted to the internal time axis;
- intensities are labeled and scaled as ADC counts, with the instrument's conversion of 58.51 counts per dB used for the dB scale; and
- the observation opens background subtracted, because the receiver's channel gains span more than an order of magnitude.

5.2 Opening files

Use any of the following:

- File → Open, the Open / Load toolbar tool, or Ctrl+O;
- drag the files onto the main window;
- File → Recent Files (Section 5.2.1);
- the Import button of a downloader (Chapters 11 and 13).

When one file is selected, it is displayed at once. When several files are selected, the application determines whether they can be combined in time, in frequency, or in both (Section 5.3) and, if so, combines them into a single spectrum. If the selection cannot be combined, a message explains why (Figure 5.1). If the current work has unsaved project changes, you are asked whether to save them first.

After loading, the analysis controls and the Graph Properties panel become active, and the sidebar's Timeline panel lists the observations that make up the dataset. The observation start becomes the event time of the Geomagnetic Response and the event-context tools (Section 15.1).

5.2.1 Recent files

File → Recent Files lists the last ten FITS selections. A combined set is a single entry, combined again when reopened; hovering over an entry shows its files. An entry whose files have been moved or deleted is removed from the list with a message. Clear Recent Files empties the list.

5.3 Combining files

CALLISTO observations are fragmented in time (15-minute files) and often in frequency (several receivers or focus codes). The application can merge them along either axis or both. The rules are summarized in Table 5.1.

Table 5.1 Requirements for combining FITS files.

Combination	Requirements
Time	Same station and focus code; consecutive observations whose start times are 750–1050 s apart (normally 15 minutes). Sequences may continue across UTC midnight.
Frequency	Same station, date and observation start time; distinct focus codes; identical time axes. Bands may be separated by a gap or may overlap (Section 5.3.1).
Time × frequency	A complete grid of at least two consecutive timestamps and at least two focus codes, with the same set of focus codes at every timestamp.

A selection that contains extra files is searched for a combinable subset; for example, selecting a whole day of files together with one stray file still finds the grid within it. All files of one combined dataset must come from the same station.

For a time × frequency grid, the bands are first combined at each timestamp with one shared gap and overlap policy; the application checks that every result has the same frequency grid, and then joins the results in time order. Incomplete grids, duplicate timestamp and focus-code pairs, non-consecutive timestamps and incompatible axes are rejected with a detailed message.

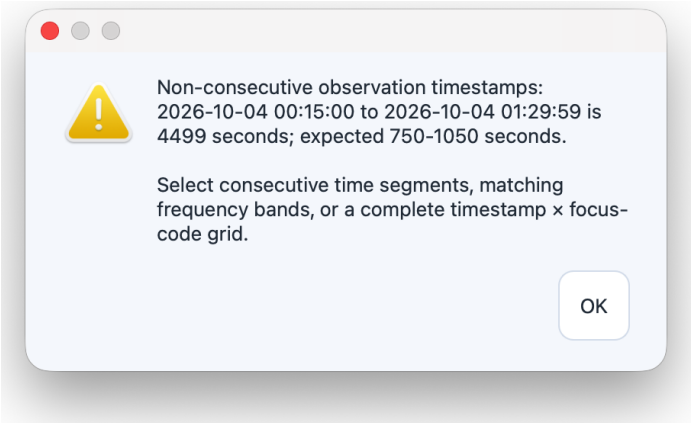


Figure 5.1 Error message for files that cannot be combined.

Combined datasets keep their provenance: exported FITS files, projects and reports record the original list of source files and the combination method (`time`, `frequency` or `time_frequency`).

5.3.1 Frequency gaps and overlaps

When the selected bands leave a gap between them, or overlap, the Frequency Combine Options dialog asks how to handle it before the combined spectrum is imported (Figures 5.2 and 5.3). The detected gap or overlap range is shown at the top of the dialog. The chosen option is stored in the metadata of the combined dataset.

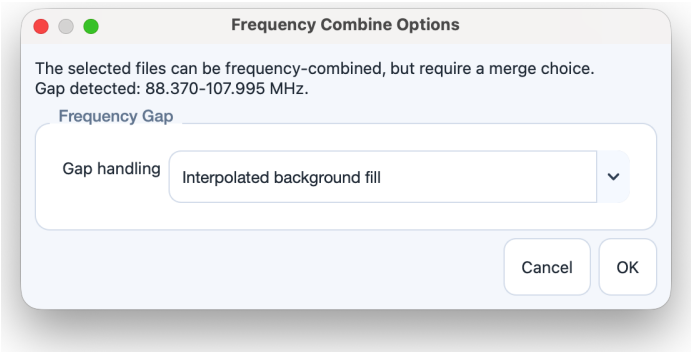


Figure 5.2 Gap handling in the Frequency Combine Options dialog.

Interpolated background fill fills the gap with background values interpolated between the edges of the two bands.

Gray-hatched blank gap leaves the gap without data and displays it as a gray-hatched region, so that it is clearly distinguished from observed data.

Average edge background fill fills the gap with the average background level of the band edges on either side.

Zero fill fills the gap with zeros.

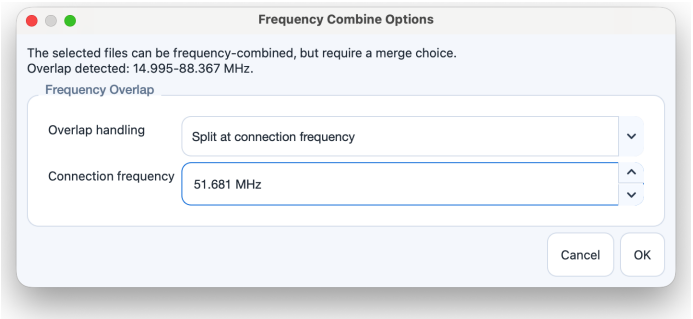


Figure 5.3 Overlap handling with a connection frequency.

Split at connection frequency uses the lower band below the Connection frequency and the higher band above it. The connection frequency is proposed automatically and can be edited.

Use lower-frequency file keeps the data of the lower-frequency file in the overlapping region. The file name is shown in the option when there is a single overlap.

Use higher-frequency file keeps the data of the higher-frequency file in the overlapping region.

Reject overlap cancels the combination.

5.4 The Combine FITS Files dialog

File → Combine FITS Files... opens a dialog for selecting, validating and previewing a combination before it is imported (Figure 5.4).

1. Click Select FITS Files and choose the files. The dialog inspects them and reports whether they form a valid time, frequency or time × frequency combination.
2. For a frequency combination, choose the gap and overlap handling and, if needed, the connection frequency in the Frequency Combine Options group. In this dialog the overlap choices are labeled Keep low band in overlap and Keep high band in overlap.
3. Click Combine and Preview to see the combined spectrum in the dialog.
4. Click Import to Analyzer to load the result into the main window.

5.5 Viewing the FITS header

View → View FITS Header shows the primary header of the loaded file (Figure 5.5). Save as .txt writes the header to a text file.

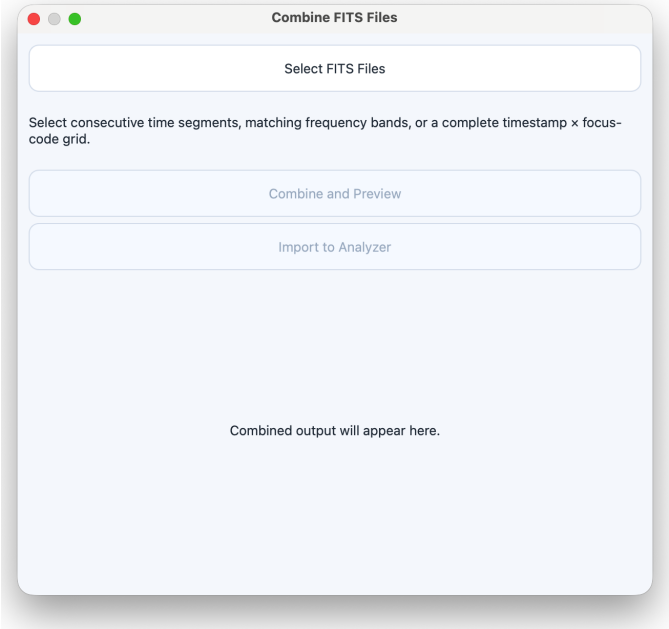


Figure 5.4 The Combine FITS Files dialog.

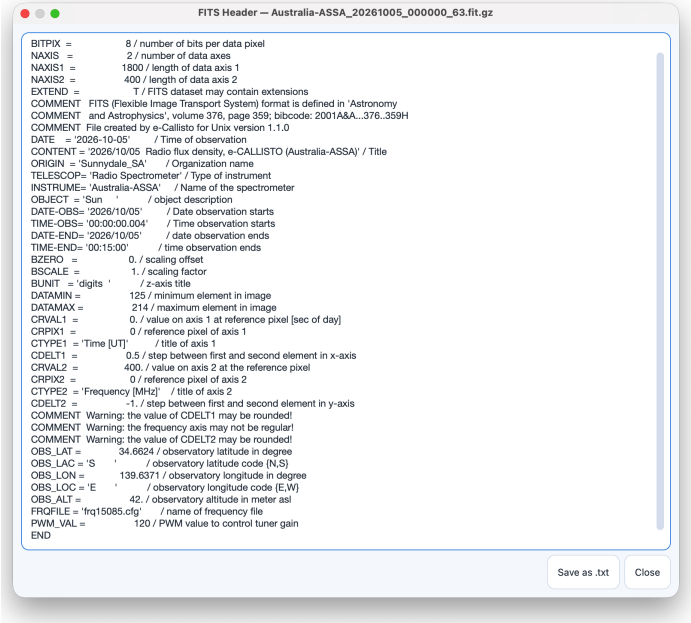


Figure 5.5 The FITS header viewer.

6

The Sidebar Panels

The sidebar on the left of the main window groups the controls used most often while working on a spectrum. It contains nine sections, from top to bottom: Timeline, Background Subtraction, Noise Clipping Thresholds, Units, Axis, Graph Properties, Analysis Summary, Geomagnetic Response and Ruler Measurement. Each section is a card with a clickable header that collapses or expands it; the state of every card is remembered between sessions. The whole sidebar can be hidden with the arrow handle on the left edge of the plot.

6.1 Timeline

A loaded dataset knows which station, focus codes and observation times it came from. The Timeline panel (Figure 6.1) lists them and extends or trims the dataset in place, without returning to the downloader.

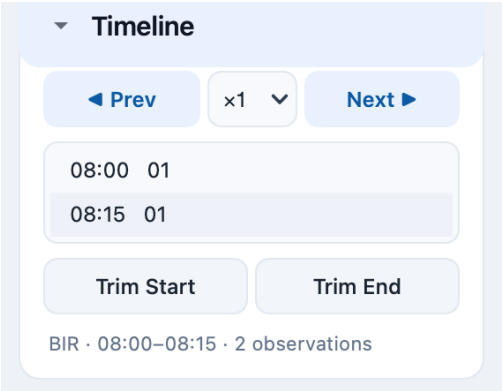


Figure 6.1 The Timeline panel.

◂ Prev / Next ▸ Fetch the observation before the first, or after the last, and time-combine it into the spectrum (Ctrl+Shift+Left and Ctrl+Shift+Right, also in the Edit menu).

Step selector (×1, ×2, ×4, ×8) The number of observations added per click.

Observation list One row per observation, giving its start time and focus code(s).

Trim Start / Trim End Remove the earliest or the latest observation. Trimming down to a single observation returns to a plain single-file load.

Status line The station, the covered time range and the number of observations, for example BIR · 08:00–08:15 · 2 observations. When a direction is unavailable the panel says why, for example the end of the archive day or a timestamp that supplies only part of the focus-code set.

Adjacent observations are looked for first among the loaded file's neighbors on disk, and only then in the e-CALLISTO archive, so a set that has already been downloaded extends without network access. Day listings are cached during the session. With Edit → Prefetch Adjacent Observations ticked (the default), neighboring files are downloaded in the background so that the next step is instant; untick it to avoid unrequested archive traffic.

Extending and trimming preserve your work:

- annotations, the ruler measurement and drift picks are kept, and their time coordinates shift with the axis when an earlier observation is prepended;
- the active background subtraction and RFI cleaning are recalculated over the longer array rather than returning the view to the raw data;
- the display thresholds are kept;
- every extension or trim is a single undo step (Ctrl+Z), restoring the arrays, the source list and the annotations together.

After an extension or trim the plot is rescaled to show the full spectrum.

6.2 Background Subtraction

The receiver background varies strongly from channel to channel, producing horizontal stripes in a raw spectrum. The Background Subtraction panel (Figure 6.2) removes it.

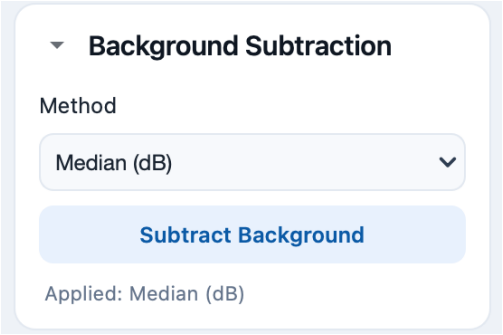


Figure 6.2 The Background Subtraction panel.

Choose a Method and click Subtract Background. The background is computed for each frequency channel over the whole observation time:

Mean subtracts the mean of each frequency channel; the result stays in the raw intensity unit (Digits).

Median subtracts the median of each frequency channel; the result stays in Digits. The median is less affected by bursts and RFI than the mean.

Median (dB) subtracts the median of each channel and converts the result to decibels above that background, following the CALLISTO Plotutil recipe used by the batch processor. This method is recommended for analysis.

The status line below the button names the method in use, for example Applied: Median (dB). The subtraction is always computed from the raw data, so choosing another method and clicking again replaces the previous result rather than stacking on it. Re-applying the subtraction also clears any RFI cleaning or isolated burst that was derived from the previous result. While a Median (dB) result is shown, the intensity unit is locked to dB because the data are already in decibels. Edit → Reset to Raw removes the subtraction.

6.3 Noise Clipping Thresholds

The Noise Clipping Thresholds panel (Figure 6.3) sets the limits of the color scale.

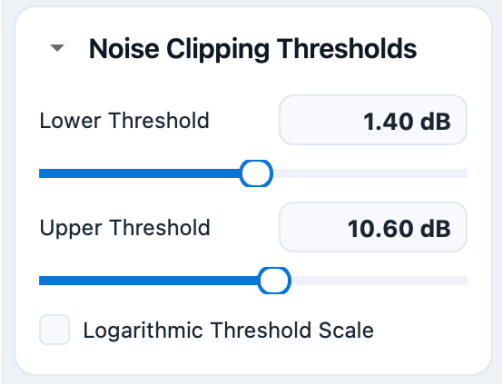


Figure 6.3 The Noise Clipping Thresholds panel.

Lower Threshold / Upper Threshold High-resolution sliders for the lower and upper limits of the color scale (Vmin and Vmax). The display updates live while you drag; no Apply button is needed. The value card beside each label shows the limit. When the intensity is shown in Digits, a second line gives the corresponding dB value.

Logarithmic Threshold Scale Makes the sliders logarithmic for finer control near zero.

The thresholds change the contrast only; the data are never clipped or modified. With both sliders at zero the color scale spans the whole data range. Limits chosen on the raw data are reset when you subtract the background, because they would saturate the new scale. Processing → Presets → Raw FITS Percentile (5-98%) sets the limits from the distribution of the data on show (Section 7.4).

6.4 Units

The Units panel (Figure 6.4) selects the units of the intensity and time axes.

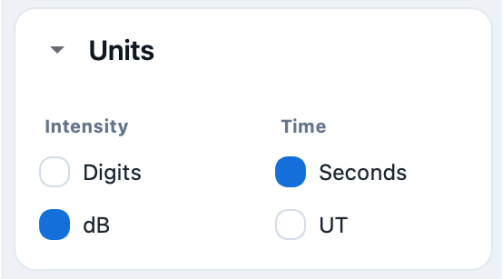


Figure 6.4 The Units panel.

Intensity: Digits / dB Digits shows raw CALLISTO ADC values as stored in the file. dB converts them with the CALLISTO receiver scale (see the glossary entry *Digit*).

Time: Seconds / UT Seconds measures time from the start of the loaded data; UT shows Universal Time. UT requires the observation start time (`TIME-OBS`) in the FITS header.

Switching units does not modify or lose data; it only changes the axis labels, the color-bar label and the cursor readout.

6.5 Axis

The Axis panel (Figure 6.5) switches the frequency axis between Linear (proportional to MHz) and Log (proportional to $\log_{10}$ MHz).

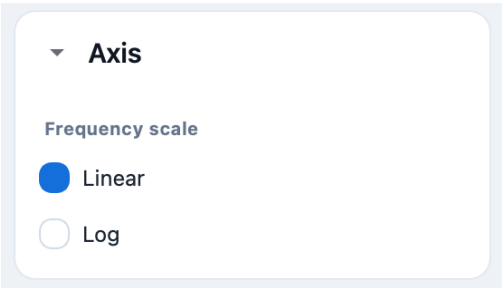


Figure 6.5 The Axis panel.

A logarithmic axis spreads out the decametric end of the band, where Type II and Type III bursts spend most of their drift, and places a fundamental–harmonic pair at a constant separation. Ticks are anchored to the decades and labeled in MHz (for example 20, 30, 40, 50, 60, 70, 80 across a 20–80 MHz band), thinning as the span widens. Both renderers support the logarithmic axis, and annotations, the ruler, light-curve picks and drift points behave identically in both scales because their coordinates remain in MHz. The choice is remembered between sessions. The STEREO/SWAVES panel always uses its own logarithmic axis (Section 13.2).

6.6 Graph Properties

The Graph Properties panel (Figure 6.6) controls the appearance of the plot. It becomes active once a file is loaded. The settings apply to the on-screen plot and to exported figures and reports.

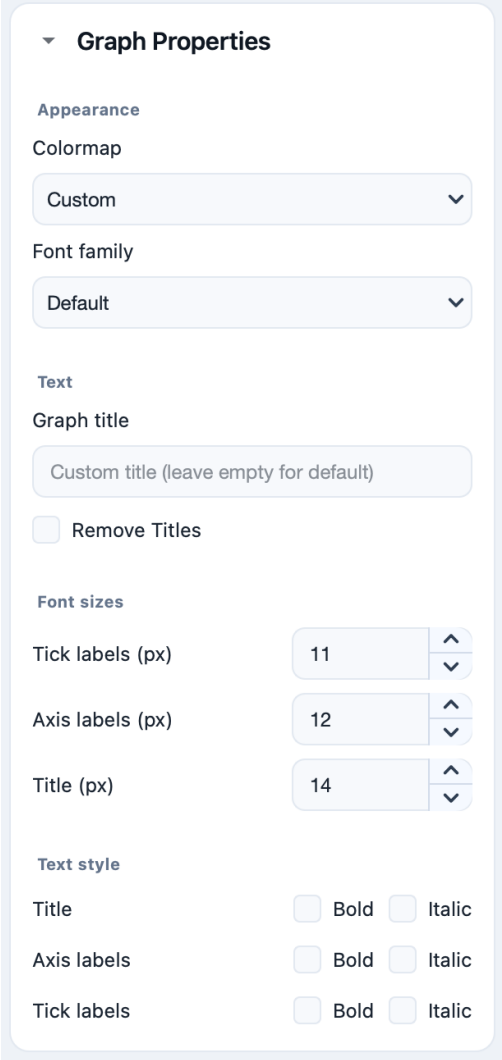


Figure 6.6 The Graph Properties panel.

6.7 Analysis Summary

The Analysis Summary panel (Figure 6.7) is a read-only summary of the current analysis session: the fitted equation, R^2, the fold number and the average shock speed and height from the Burst Analyzer (Section 8.7). It also reports when a saved session has been restored. Before any analysis it reads No analysis session loaded.

Table 6.1 Controls of the Graph Properties panel.

Group	Control	Function
Appearance	Colormap	Custom (blue–red–yellow), viridis, plasma, inferno, magma, cividis, turbo, RdYlBu, jet, cubehelix or bone_r.
	Font family	Typeface of all plot text; Default or any installed font.
Text	Graph title	A custom title; leave empty for the default title.
	Remove Titles	Hide the plot title.
Font sizes	Tick labels (px)	6–60 px (default 11).
	Axis labels (px)	6–60 px (default 12).
	Title (px)	6–80 px (default 14).
Text style	Title, Axis labels, Tick labels	Bold and Italic for each text element.

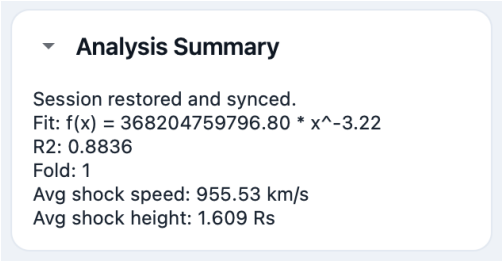


Figure 6.7 The Analysis Summary panel.

6.8 Geomagnetic Response

The Geomagnetic Response card (Figure 6.8) summarizes what Earth's environment did after the current event (Section 15.1). Its first line names the event; five rows give the Dst min (with its time and the hours after the event start), the Kp max and its NOAA G level, the Bz min, the V max of the solar wind, and the Storm class. A status line reports loading, missing data or that fetching is off.

Refresh fetches the response for the event again.

Open window opens the Geomagnetic Response window with every panel (Section 15.2).

Use loaded data shown after a burst-list or downloader selection; returns to the event of the loaded file.

6.9 Ruler Measurement

The Ruler Measurement panel (Figure 6.9) shows the result of the ruler tool, started with Analysis → Ruler Measurement (Section 7.8): the two points P1 and P2 (time and frequency), the Duration, the Frequency drift and the Slope in MHz/s. Copy copies the readout to the clipboard and Clear removes the measurement.

Screenshot placeholder

`figures/event-context/geomagnetic_card.png`

The Geomagnetic Response sidebar card after loading a file followed by a storm: the event line, the Dst min, Kp max, Bz min, V max and Storm rows filled in, the status line, and the Refresh and Open window buttons.

Figure 6.8 The Geomagnetic Response card.

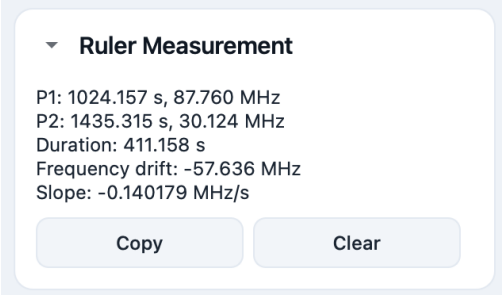


Figure 6.9 The Ruler Measurement panel.

7

Viewing, Processing and Annotation Tools

This chapter describes how to navigate the spectrum, set an exact display range, clean radio-frequency interference, use processing presets, annotate the plot, overlay light curves, and make quick drift-rate and ruler measurements.

7.1 Navigating the spectrum

Table 7.1 lists the mouse interactions available in the plotting area.

Table 7.1 Navigation and picking in the plotting area.

Interaction	How
Zoom	Scroll the mouse wheel over the plot; the zoom is centered on the pointer.
Pan	Hold the left mouse button and drag.
Rectangle zoom	Click Lock zooming and panning on the toolbar, then Rectangular Zooming, and drag a rectangle. Repeat Rectangular Zooming for each further zoom.
Freeze or release the view	Lock zooming and panning disables wheel zoom and panning; Unlock zooming and panning re-enables them.
Cursor readout	Move the pointer over the plot; time, frequency and intensity appear in the status bar.
Estimate drift rate	Click points along the burst; right-click or double-click to finish (Section 7.7).
Isolate burst	Press, drag a loop around the burst and release (Section 8.2).
Ruler	Click two points (Section 7.8).
Light curve by click	With click mode on, click a frequency (Section 7.6).
Annotations	Line: click the start and end. Text: click the position. Polygon: click the vertices and right-click to close (Section 7.5).

Reset Selection clears an isolated-burst selection and drift markers; Reset to Raw discards all processing; Reset All clears the workspace (Table 3.2).

7.2 Setting an exact display range

View → Set Display Range... sets the visible window numerically, which is useful for comparing several stations over identical axes (Figure 7.1).

- Choose Use seconds from file start or Use UT clock time, then enter the start and stop times in the Seconds or UT group. UT input is unavailable when the file has no `TIME-OBS` value.
- Enter the lower and upper limits in the Frequency group (MHz).
- The full time and frequency ranges of the data are shown for reference.

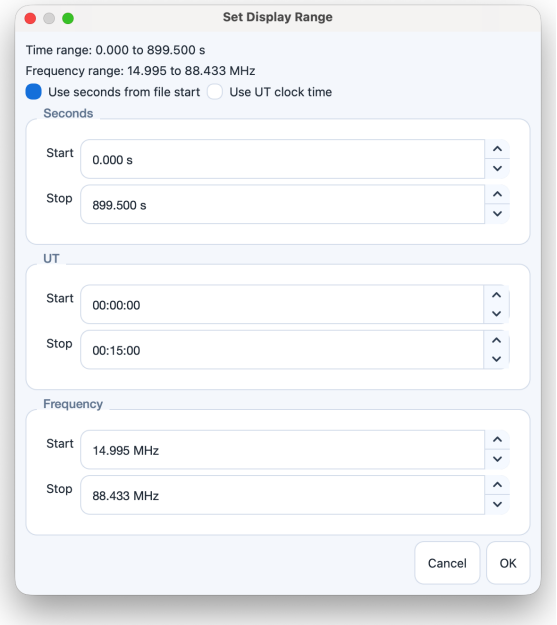


Figure 7.1 The Set Display Range dialog.

7.2.1 Display-range presets

A display range can be stored under a name with View → Save Display Range Preset..., applied later to another file with Apply Display Range Preset..., and removed with Delete Display Range Preset.... Presets are stored in your preferences and are available in every session.

7.2.2 View configurations

View → Export View Config... saves the display range, units, thresholds, color map and graph styling to a portable `.efaview.json` file; View → Import View Config... applies such a file. View configurations can be shared with colleagues and are also accepted by the batch processor (Section 10.8) and the Multi-Station Comparison (Chapter 12), so that many spectra can be rendered with identical axes and appearance.

7.3 RFI cleaning

Radio-frequency interference appears as bright horizontal streaks (persistent narrow-band emitters) and short spikes. Processing → RFI Cleaning offers Open RFI Panel, Apply RFI and Reset RFI. The RFI Cleaning panel (Figure 7.2) applies a deterministic pipeline to the dynamic spectrum:

1. two-dimensional median smoothing with a window of Kernel (freq) × Kernel (time);
2. detection of hot channels from a robust Z-score of each channel's level and variability;
3. repair of the masked channels from their neighbors;
4. per-channel clipping of high outliers above an upper percentile (the low side is preserved).

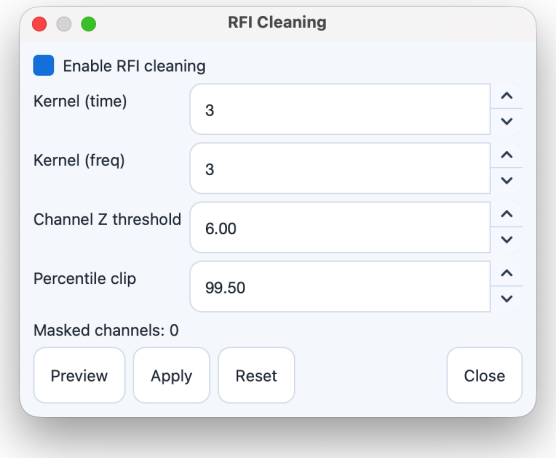


Figure 7.2 The RFI Cleaning panel.

Table 7.2 RFI cleaning parameters.

Parameter	Range (default)	Effect
Enable RFI cleaning	on/off (on)	Includes RFI cleaning in the processing chain.
Kernel (time)	1–31, odd (3)	Median window along time. Larger values suppress short spikes more strongly but can blur fast burst structure.
Kernel (freq)	1–31, odd (3)	Median window across frequency channels. Larger values reduce narrow-band striping but can widen spectral features.
Channel Z threshold	0.5–20 (6.0)	Cut-off for hot-channel masking. Lower values mask more channels.
Percentile clip	90–99.99 (99.5)	Upper cap applied to each channel. Lower values clip peaks more aggressively.

Preview shows the result without committing it. The Masked channels line reports the number and indices of the channels flagged as hot.

Apply commits the cleaning to the processed data.

Reset restores the default parameters in the panel.

Close closes the panel.

If channel streaks remain, lower the Channel Z threshold gradually (for example from 6.0 to 5.0 and then 4.0). If burst detail looks over-smoothed, reduce the kernel sizes or raise the threshold. Edit → Reset to Raw reverts all applied processing, including RFI cleaning.

7.4 Processing presets

A processing preset stores the display thresholds and their scale, the background subtraction method, the intensity and time units, the color map, the graph styling, the RFI settings and the default annotation style. Presets are managed from Processing → Presets:

Raw FITS Percentile (5-98%) sets the threshold limits to the 5th and 98th percentiles of the data currently shown — a quick starting range for raw files.

Save Current as Preset... stores the current settings under a name.

Apply Preset... applies a stored preset to the loaded data.

Set Default Preset... chooses a preset that is applied automatically to every file loaded afterwards.

Clear Default Preset stops applying a default preset.

Delete Preset... removes a stored preset.

7.5 Annotations

Annotations mark features on the spectrum. They are drawn in both renderers, saved in projects, and included in exported figures and reports. Processing → Annotations (Figure 7.3) contains:

Add Polygon click the vertices; right-click to close the polygon.

Add Line click the start point and then the end point.

Add Text click where the label should go, then enter it in the text dialog.

Edit Text Label... choose an existing label and change its text and style.

Move Text Label... choose a label, then click its new position.

Toggle Visibility show or hide all annotations.

Delete Last remove the most recent annotation.

Clear All remove every annotation.

The text dialog sets the Text, Font, Font Size, Font Style (Bold, Italic) and Color of a label.

7.6 Light curves

A light curve is the intensity at one frequency as a function of time. Light curves are drawn on top of the spectrum (Figure 7.4) from Analysis → Plot Light Curves:

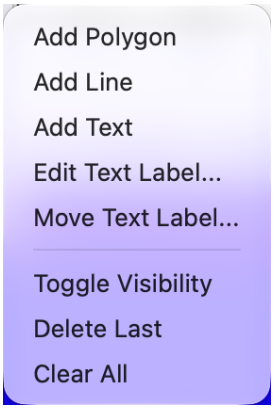


Figure 7.3 The Processing → Annotations menu.

Enter frequency opens a dialog for typing a frequency in MHz; the available range of the data is shown.

Click on a frequency toggles click mode. While it is on, clicking the spectrum plots the light curve at the clicked frequency.

Settings... opens the Light Curve Settings dialog (Table 7.3).

Clear light curve(s) removes all light curves without affecting the data.

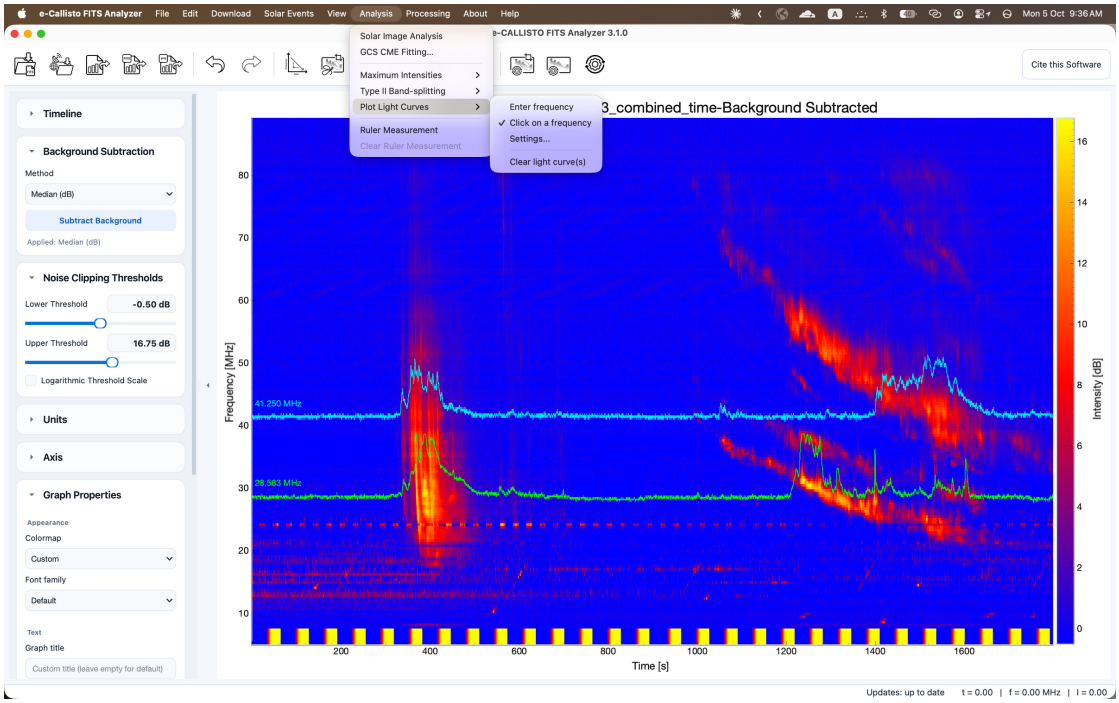


Figure 7.4 Light curves at two frequencies overlaid on a dynamic spectrum, with the Analysis → Plot Light Curves submenu open.

Apply applies the settings, Reset to Defaults restores the defaults and Close closes the dialog. Light curves are saved in projects and can be included in project reports.

Table 7.3 Light-curve settings.

Setting	Range	Effect
Mode	Single / Multiple	Single light curve replaces the previous curve; Multiple light curves keeps adding curves.
Color	color picker	Color of the curve.
Thickness	0.5–12	Line width.
Vertical Scale	0.1–5	Height of the curve relative to the plot.
Opacity	0.1–1	Transparency of the curve.
Line Style	solid, dashed, dotted	Line pattern.
Labels	on/off	Show frequency labels next to each curve.

7.7 Estimating the drift rate

The Estimate Drift Rate toolbar tool gives a quick estimate of a burst's frequency drift from points that you click.

1. Click Estimate Drift Rate.
2. Click two or more points along the burst.
3. Right-click or double-click to finish.

The points are joined by dashed segments, and the status bar shows the Average Drift Rate in MHz/s (the mean of the segment drift rates), the start and end frequencies, and the duration. Segments of zero duration are ignored. Reset Selection clears the drift markers. For a fitted drift rate and shock parameters, use the Type II analysis tools (Chapter 8).

7.8 Ruler measurement

Analysis → Ruler Measurement measures between two points clicked on the spectrum. The readout appears in the sidebar's Ruler Measurement panel (Section 6.9): the coordinates of both points, the duration, the frequency change and the slope. Analysis → Clear Ruler Measurement or the panel's Clear button removes it. The ruler is kept when the timeline is extended.

7.9 Overlays from other instruments

Two overlays add context directly to the main plot:

- the GOES X-ray flux curves, enabled from Solar Events → GOES Overlay (Section 14.3.1); and
- the STEREO/SWAVES spectrum below the CALLISTO spectrum (Section 13.2).

8

Type II Burst Analysis

Type II solar radio bursts are slowly drifting emission lanes produced by shock waves traveling outward through the corona. The plasma frequency falls with height, so the drift of the emission to lower frequencies traces the shock's motion. The Type II tools fit the burst backbone and convert its frequency and drift into a shock height and speed using a coronal electron-density model.

8.1 The analysis chain

The analysis uses four tools, normally applied in this order:

1. **Burst isolation** restricts the data to the emission of interest (Section 8.2).
2. **Maximum intensities** extracts the frequency of peak emission in each time channel, or tracks the burst ridge (Sections 8.3 and 8.4).
3. **Outlier removal** discards points that do not belong to the burst (Section 8.5).
4. **The Burst Analyzer** fits the backbone and derives the drift rate, shock speed and shock height (Section 8.7).

Each tool works on the spectrum as currently displayed: background-subtracted, RFI-cleaned or isolated. Figure 8.1 shows a background-subtracted spectrum containing a Type II burst.

8.2 Burst isolation

The Isolate Burst toolbar tool (tool 9) draws a freehand lasso mask around the emission region of a burst. Background subtraction must be applied first.

1. Click Isolate Burst.
2. Press the mouse button, drag a loop around the burst, and release.

Only the data inside the loop are retained; everything outside is set to zero, which is the background level of the background-subtracted spectrum. This removes unrelated emission and residual noise from the analysis (Figure 8.2). Isolation can be undone with Ctrl+Z. The plot title changes to -Isolated Burst. The mask follows the drawn path on the displayed spectrum. Reset Selection (tool 14) clears the selection.

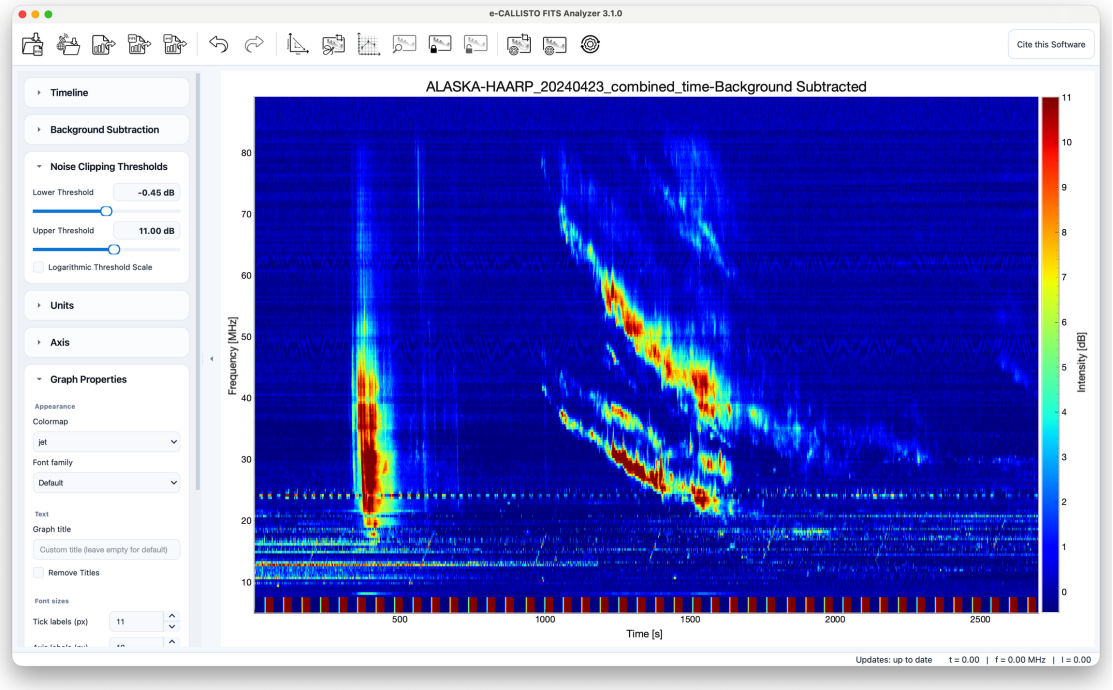


Figure 8.1 A background-subtracted dynamic spectrum containing a Type II burst.

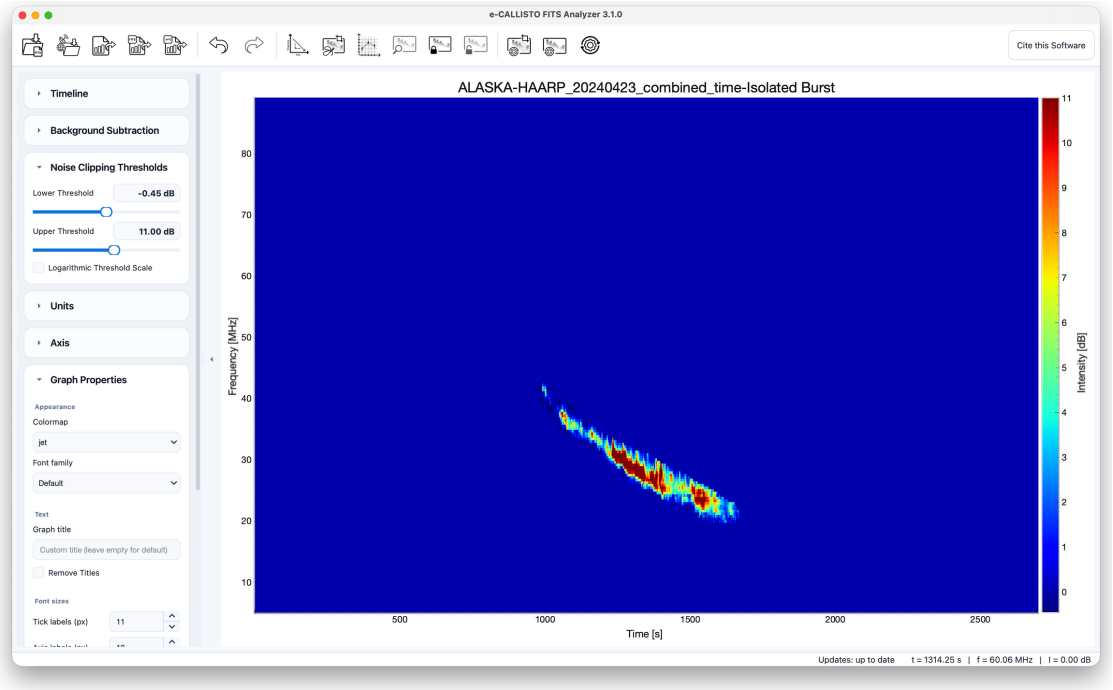


Figure 8.2 An isolated Type II burst lane.

8.3 The Maximum Intensities window

The Maximum Intensities window (Figure 8.3) shows, for each time channel of the displayed spectrum, the frequency at which the intensity is highest. These points trace the burst backbone that the Analyzer fits. Open it with the Plot Maximum Intensities toolbar tool (tool 10) or Analysis → Maximum Intensities → Open Maximum Intensities. When the maxima are taken from an isolated burst, time channels with no emission inside the mask are excluded.

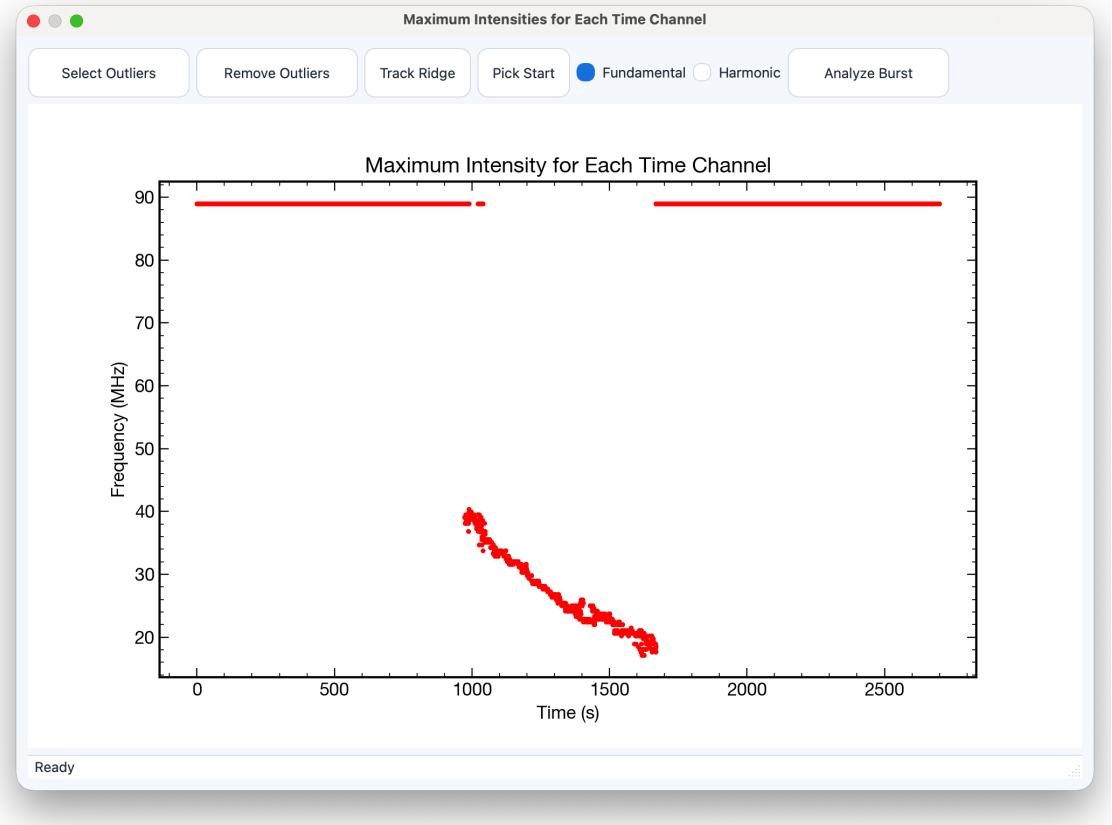


Figure 8.3 The Maximum Intensities window. Without isolation, a persistent RFI channel near 89 MHz produces spurious points.

The status bar at the bottom of the window reports the result of each action, for example the number of selected points.

8.4 Ridge tracking

Taking the brightest channel in every time column picks up RFI, a second burst or noise, leaving scattered points to remove by hand. Track Ridge follows the burst itself instead:

- Tracking starts from the brightest point of the burst, or from a point chosen with Pick Start (marked with a star), and continues forwards and backwards in time, searching only a few channels around the ridge position in the previous column.

Table 8.1 Controls of the Maximum Intensities window.

Control	Function
Select Outliers	Draw a lasso around points to remove.
Remove Outliers	Remove the selected points.
Track Ridge	Replace the per-column maxima by an automatically tracked ridge (Section 8.4).
Pick Start	Click a point on the burst from which ridge tracking starts.
Fundamental / Harmonic	Whether the lane is fundamental or harmonic plasma emission (Section 8.6).
Analyze Burst	Open the Burst Analyzer with the current points.
File → Save As	Save the points as CSV: time channel, time (s) and frequency (MHz).
File → Export As	Save the plot as a figure (PNG, PDF, EPS, SVG, TIFF or JPG).
Edit → Reset All	Clear the selection, the ridge start point and the stored Analyzer state.
Edit → Restore Per-Column Maxima	Bring back the points replaced by ridge tracking.
Analyze → Open Analyzer	Open the Burst Analyzer.
Analyze → Ridge Tracking Settings...	Parameters of the ridge tracker (Table 8.2).

- A channel that is bright for most of the file is treated as RFI and is not chosen as a starting point. An error is reported if a picked start point is not above the background.
- Short dropouts in the burst are bridged. After a gap, tracking continues only once two consecutive columns show signal, so a single noise spike cannot extend the ridge. Tracking stops once the signal has stayed below the threshold for longer than the allowed gap.
- Each peak is refined to sub-channel frequency.

The tracked points replace the per-column maxima; outlier removal, the fundamental/harmonic choice and Analyze Burst work on them as before. Edit → Restore Per-Column Maxima brings the original points back.

Table 8.2 Ridge Tracking Settings.

Setting	Description	Default
Search window (channels)	Maximum movement of the ridge between two consecutive time columns (1–100).	3
Threshold (σ)	Minimum height of a peak above the background, in robust standard deviations (0–50).	3.0
Allowed gap (columns)	Number of consecutive columns below the threshold before tracking stops (0–1000).	8
Only follow drift to lower frequency	Restricts the ridge to move toward lower frequencies with time, as in Type II and Type III bursts.	Off

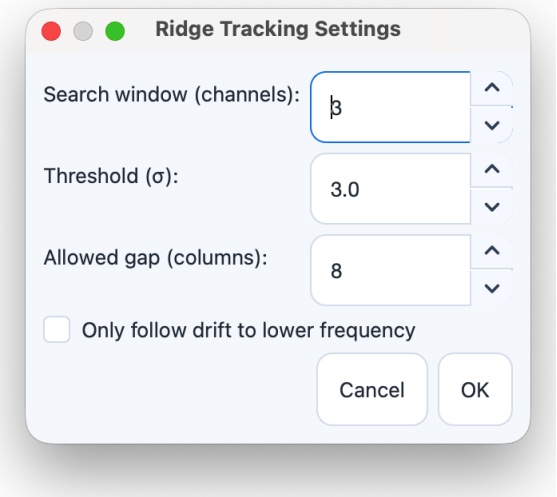


Figure 8.4 The Ridge Tracking Settings dialog.

8.5 Outlier removal

Outliers are removed manually in the Maximum Intensities window:

1. Click Select Outliers and draw a lasso around the unwanted points (Figure 8.5).
2. Click Remove Outliers.

When Processing → Maximum Intensity → Auto-Clean Isolated Burst Outliers is ticked (the default), outliers are also removed automatically whenever the maxima are taken from an isolated burst. The manual tools remain available in either case.

8.6 Fundamental and harmonic emission

Type II emission occurs at the local plasma frequency (fundamental) and at twice that frequency (harmonic). Select Harmonic when the fitted lane is the harmonic. The observed frequencies and drift rates are then divided by two before the shock parameters are calculated, so that heights and speeds always refer to the plasma frequency. Saved summaries keep both the converted values and the observed reference values.

8.7 The Burst Analyzer

The Burst Analyzer (Figure 8.6) fits the burst backbone with a power law and derives the frequency drift rate, shock speed and shock height, with the goodness of fit. Open it with Analyze Burst or Analyze → Open Analyzer in the Maximum Intensities window.

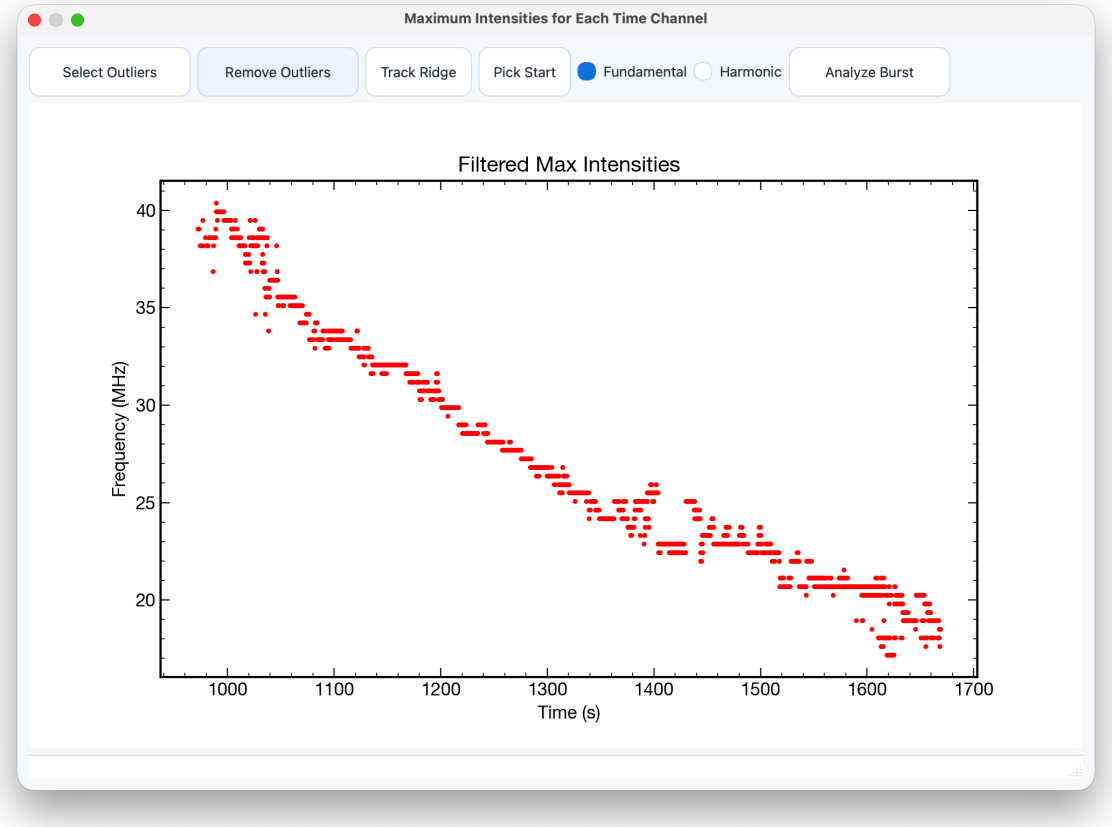


Figure 8.5 Selecting outliers with the lasso in the Maximum Intensities window.

Table 8.3 Controls and displays of the Burst Analyzer.

Control or display	Function
Maximum Intensities	Plot the extracted points.
Best Fit	Fit the points with a power law and plot the fit.
t_0	Time origin of the power law (Section 8.7.1).
Density model	Coronal density model for heights and speeds (Section 8.7.3).
Fold-number	Multiplier 1–4 applied to the model density; press Calculate after changing it.
Best Fit Equation	The fitted power law.
Fit Metrics	R^2 and RMSE of the fit.
Shock Parameters	Derived quantities with uncertainties (Table 8.4).
Density model comparison	Initial and average shock speed and height from all five models (Section 8.7.4).
Save Graph	Save the plot on show as a figure.
Save Data	Save the results to an Excel workbook (Section 8.7.6).
Existing Excel File	Append to an existing workbook instead of creating a new one.
Extra Plots and Plot	Additional plots (Section 8.7.5).

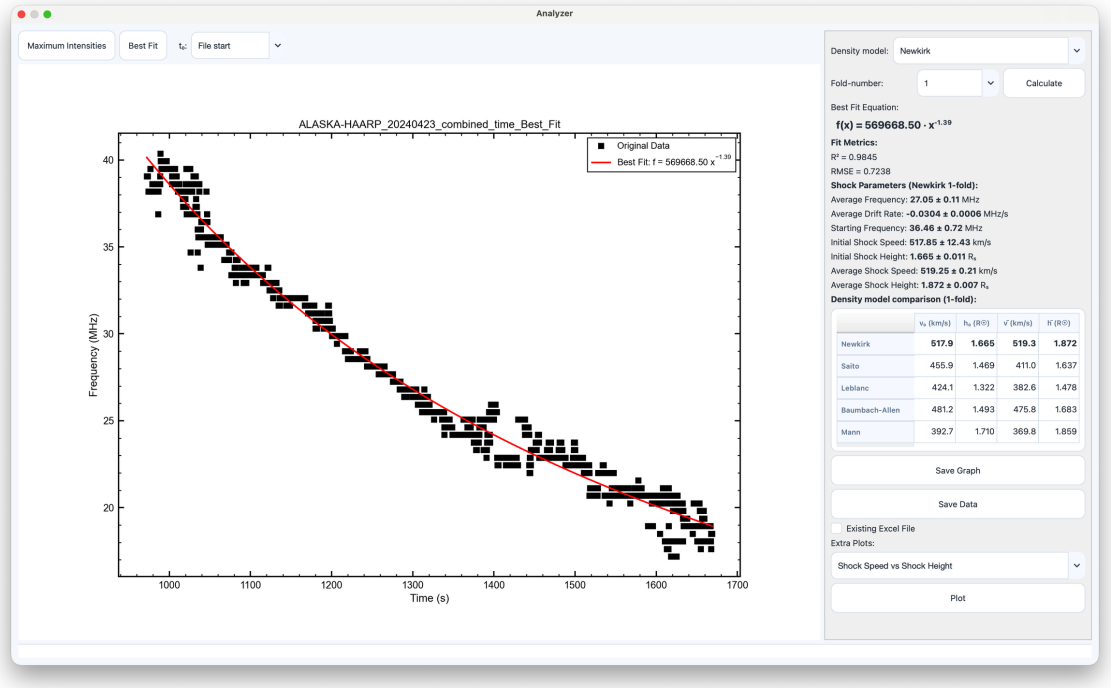


Figure 8.6 The Burst Analyzer window with the best fit, shock parameters and density-model comparison.

8.7.1 Power-law fit and the time origin

The backbone is fitted as

$$f(t) = a\,(t - t_0)^{-b}, \tag{8.1}$$

where f is the frequency in MHz, t the time in seconds, and a and b the fitted parameters. The drift rate at each point follows from the derivative, $\mathrm{d}f/\mathrm{d}t = -ab\,(t - t_0)^{-b-1}$. On the Best Fit graph the points are drawn as filled black squares and the fitted power law as a red curve, with a boxed legend.

Because a power law depends on where $t = 0$ lies, the fitted exponent, drift rate and shock parameters depend on the chosen time origin. t_0 is selected from the t_0 list next to Best Fit:

File start measures time from the start of the loaded data (the default).

Burst onset places t_0 one time sample before the first fitted point, so that every point lies on the curve.

Custom time uses a time that you enter, in UT when the start time of the file is known and otherwise in seconds from the start of the file.

Changing t_0 re-runs the fit automatically. The graph keeps the data's own time axis, and the equation shows $(x - t_0)$ whenever t_0 is not the file start.

8.7.2 Shock parameters

Table 8.4 defines the quantities in the Shock Parameters block. The heading names the density model and fold in use, for example Shock Parameters (Newkirk 1-fold).

Table 8.4 Shock parameters reported by the Burst Analyzer.

Quantity	Definition
Average Frequency	Mean frequency of the maximum-intensity points (MHz), with its standard error.
Average Drift Rate	Mean of the fitted drift rate along the backbone (MHz/s).
Starting Frequency	The 90th percentile of the fitted frequencies, taken as the start of the burst (MHz).
Initial Shock Speed	Shock speed at the starting frequency (km/s).
Initial Shock Height	Heliocentric height at the starting frequency ($R_\odot$).
Average Shock Speed	Mean shock speed along the backbone (km/s), with its standard error.
Average Shock Height	Mean height along the backbone ($R_\odot$), with its standard error.

Background: from drift rate to shock speed

The emission frequency is identified with the local plasma frequency, $f_p \approx 8.98 \times 10^{-3}\sqrt{n_e}$ MHz for an electron density n_e in cm^{-3}. A density model $n_e(r)$ therefore maps each frequency to a heliocentric height r, and the drift rate to a radial speed,

$$v = \left|\frac{\mathrm{d}f}{\mathrm{d}t}\right|\left|\frac{\mathrm{d}r}{\mathrm{d}f}\right|, \qquad \frac{\mathrm{d}r}{\mathrm{d}f} = \frac{2\,n_e}{f\,|\mathrm{d}n_e/\mathrm{d}r|}.$$

Uncertainties are propagated linearly from the drift-rate and frequency errors. The results are only as good as the density model, which describes an average corona and can differ from the actual medium by large factors; the fold number scales the model density to account for denser structures such as streamers.

8.7.3 Density models

Shock heights and speeds are calculated from one of five coronal electron-density models (Table 8.5). Changing the model recalculates the shock parameters immediately. The fold number (1–4) multiplies the model density; press Calculate after changing it. The formulas are given in Appendix D.

Models other than Newkirk are evaluated between the photosphere (1 $R_\odot$) and 1 AU. A frequency that a model cannot reach in this range — for example above about 116 MHz for the 1-fold Saito model — has no height, and is shown as a dash rather than an extrapolated value.

8.7.4 Density-model comparison

The Density model comparison table below the shock parameters lists the initial shock speed v_0, initial height h_0, average speed $\bar{v}$ and average height $\bar{h}$ obtained with every model at the

Table 8.5 Coronal electron-density models.

Model	Reference
Newkirk (default)	Newkirk (1961)
Saito	Saito et al. (1977)
Leblanc	Leblanc et al. (1998)
Baumbach–Allen	Baumbach (1937); Allen (1947)
Mann	Mann et al. (1999)

current fold, with the selected model in bold. It shows at a glance how strongly the derived kinematics depend on the assumed corona.

8.7.5 Additional plots

Choose an entry in Extra Plots and click Plot to show: Shock Speed vs Shock Height, Shock Speed vs Frequency or Shock Height vs Frequency. These plots use the selected density model.

8.7.6 Saving graphs and data

Save Graph writes whichever plot is on show — maximum intensities, best fit or an additional plot — as an OriginPro-style graph on a white page in PNG, PDF, EPS, SVG, TIFF or JPG format.

Save Data writes one row of results to an Excel workbook (`.xlsx`). With Existing Excel File ticked, you choose a workbook and the row is appended, which builds an event table over many analyses. The columns are listed in Table 8.6.

Table 8.6 Columns of the Burst Analyzer Excel export.

No.	Column
1–2	Observation date; station
3–5	Best-fit equation; R^2; RMSE
6–9	Average frequency and error; average drift rate and error
10–11	Starting frequency and error
12–15	Initial shock speed and error; initial shock height and error
16–19	Average shock speed and error; average shock height and error
20	Absolute value of the average drift rate
21	Density model
22	t_0 in seconds from the start of the file

The density model and t_0 are also saved in projects and named in project reports. Projects saved before these options existed open with the Newkirk model and the file start as t_0, matching how they were calculated.

9

Type II Band-Splitting Analysis

The emission lanes of many Type II bursts are split into two parallel bands, interpreted as emission from the plasma ahead of (upper band) and behind (lower band) the shock front. The frequency ratio of the two bands gives the shock's density compression ratio, from which the Alfvén Mach number, the Alfvén speed and the coronal magnetic field can be estimated (Vršnak et al. 2002). The Type II Band-splitting window performs this analysis directly on the current noise-reduced dynamic spectrum.

9.1 Opening the window

Open the window with Analysis → Type II Band-splitting → Open Type II Band-splitting. The calculation needs the shock speed and the starting frequency from the Burst Analyzer, so run the Analyzer (Section 8.7) first. The Analyzer Reference panel reports Analyzer reference data loaded. when these values are available, and Analyzer input missing. otherwise.

9.2 Window layout

The tools and panels of the window are numbered in Figure 9.1 and described in Table 9.1.

9.3 Picking and fitting the bands

1. Select the Active Band in the Controls panel (9).
2. Switch on Add Points (1) and click points along that band on the spectrum. Points of the upper and lower bands are drawn in different colors.
3. Select the other band and add its points.
4. Fit each band with Fit Active Band (4), or both at once with Fit Both Bands (5).

Each band is fitted with a power law $f(t) = a\,t^{-b}$, where t is measured from the start of the file. At least two points with positive time and frequency are needed per band. The Fitted Bands panel shows each fitted equation, R^2, RMSE and the number of selected points.

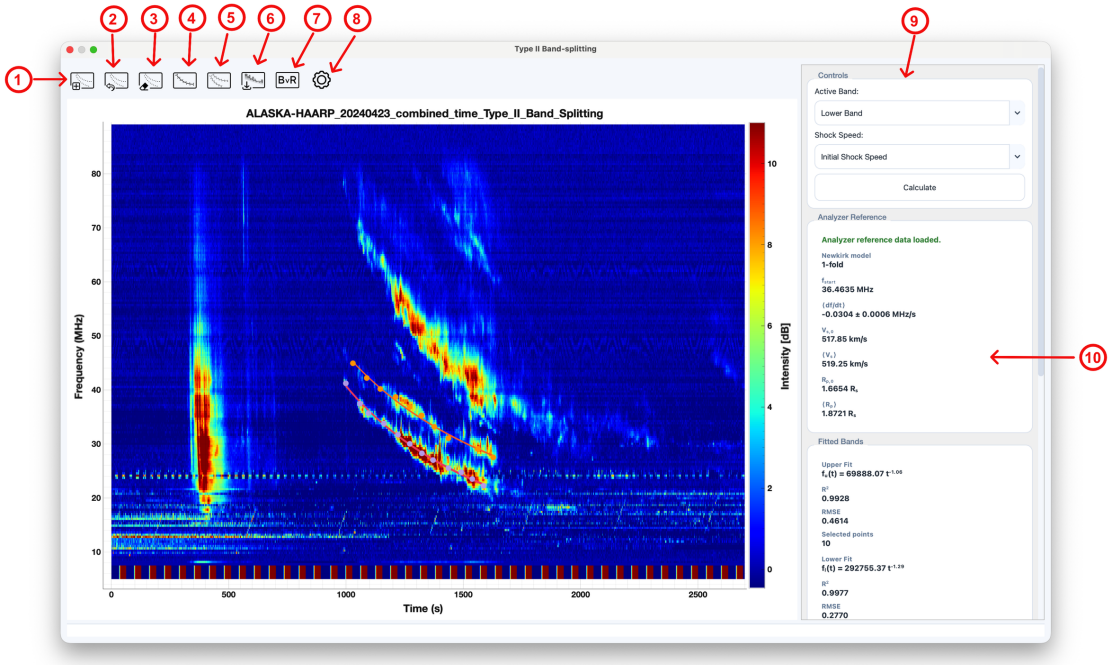


Figure 9.1 The Type II Band-splitting window with its tools and panels numbered.

Table 9.1 Tools and panels of the Type II Band-splitting window.

No.	Tool or panel	Function
1	Add Points	Toggle point picking; click along the active band on the spectrum to add points.
2	Undo Last Point	Remove the last point added to the active band.
3	Clear Active Band	Remove all points of the active band.
4	Fit Active Band	Fit the points of the active band with a power law.
5	Fit Both Bands	Fit the upper and the lower band.
6	Save Plot	Save the fitted lanes over the spectrum, or the magnetic field versus height plot, as a figure.
7	BvR	Toggle the plot of magnetic field versus shock height (Section 9.5).
8	Settings	Graph settings: fonts, lane colors, line widths and marker sizes (Section 9.6).
9	Controls panel	Active Band (Upper Band or Lower Band), Shock Speed (Initial Shock Speed or Average Shock Speed) and Calculate.
10	Results panels	Analyzer Reference, Fitted Bands and Averaged Band-Splitting Quantities (Section 9.4).

9.4 Calculation and results

Choose whether the Initial Shock Speed or the Average Shock Speed from the Analyzer is used, and click Calculate. The results panels contain:

Analyzer Reference the reference values imported from the Burst Analyzer: the fold number, the starting frequency f_{start}, the average drift rate $\langle \mathrm{d}f/\mathrm{d}t \rangle$, the initial and average shock speeds $V_{s,0}$ and $\langle V_s \rangle$, and the initial and average shock heights $R_{p,0}$ and $\langle R_p \rangle$.

Fitted Bands the fitted equation, R^2, RMSE and number of points of each band.

Averaged Band-Splitting Quantities the averaging interval, the start time t_{start} and band frequencies, the mean upper and lower frequencies, the bandwidth $\langle \Delta f \rangle = \langle f_u - f_l \rangle$, the mean upper-band drift $\langle \mathrm{d}f_u/\mathrm{d}t \rangle$, the compression ratio $X = (\langle f_u \rangle / \langle f_l \rangle)^2$, the Alfvén Mach number M_A, the Alfvén speed V_A and the magnetic field B.

The averaging interval is the time span of the upper-band points; the two fitted curves are sampled over it. If the lower-band fit has to be extrapolated over part of the interval, a warning is shown. The calculation is refused if the compression ratio does not stay between 0 and 4 over the interval.

Background: band-splitting relations

For a perpendicular shock in a low-β plasma the compression ratio X and the Alfvén Mach number are related by (Vršnak et al. 2002)

$$X = \left(\frac{f_u}{f_l} \right)^2, \qquad M_A = \sqrt{\frac{X\,(X+5)}{2\,(4-X)}}.$$

The Alfvén speed follows from the shock speed V_s taken from the Analyzer, $V_A = V_s / M_A$, and the magnetic field from $B = V_A \sqrt{\mu_0 \, m_p \, n_e}$, with the electron density obtained from the plasma frequency, $n_e = (f / 8.98 \times 10^{-3}\,\mathrm{MHz})^2\ \mathrm{cm}^{-3}$. In the averaged result the density is taken at the Analyzer's starting frequency.

9.5 Magnetic field versus height

After a successful calculation, the BvR tool (7) plots the magnetic field against shock height (Figure 9.2). Along the averaging interval the field is computed at each sample time from the local compression ratio, with the density taken from the upper-band frequency. The heights are calculated with the Newkirk model and the Analyzer's fold number, and the profile is fitted with a power law $B = a\,R^{-b}$. Click BvR again to return to the spectrum.

Note. The shock speed is taken from the Burst Analyzer and therefore follows the density model selected there (Section 8.7.3). The heights of the magnetic field versus height profile always use the Newkirk model, with the fold number set in the Analyzer.

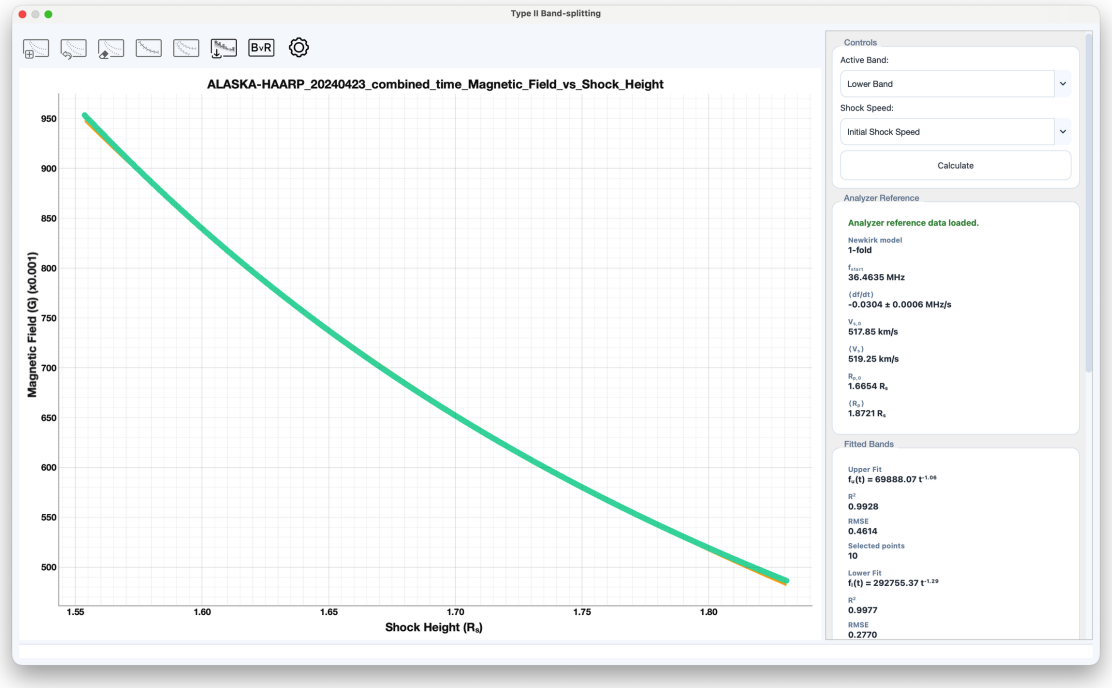


Figure 9.2 Magnetic field versus shock height in the band-splitting window.

9.6 Graph settings

The Settings tool (8) opens the Type II Graph Settings dialog (Figure 9.3):

Text Formatting font family, and size, bold and italic for the title, the axis labels and the tick labels.

Upper Band, Lower Band color and width of the fit line, and color and size of the picked points.

B vs R color and width of the fit line, and color and size of the markers.

Apply applies the settings, Reset to Defaults restores the defaults and Close closes the dialog.

9.7 Saving plots

Save Plot (6) exports either the fitted lanes over the dynamic spectrum or the magnetic field versus height fit, whichever is on show, as an OriginPro-style graph in PNG, PDF, EPS, SVG, TIFF or JPG format. The lane colors and fonts from the graph settings are kept.

> **Caution.** Derived magnetic-field values may not be accurate for all events or under all assumptions. They depend on the shock geometry, the density model and the interpretation of the split bands. Confirm results against known or independently validated events before using them for scientific conclusions.

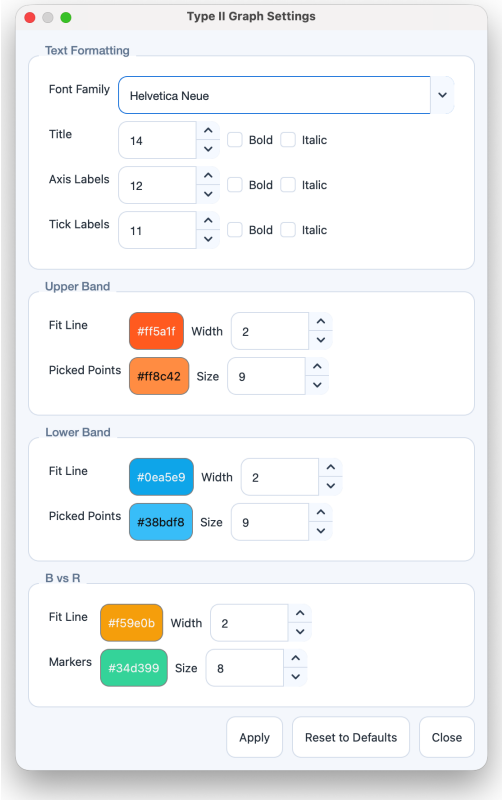


Figure 9.3 The Type II Graph Settings dialog.

10

Projects, Reports and Export

This chapter describes how the state of an analysis is saved and recovered, and how figures, processed data, reports and batches of files are exported.

10.1 Projects

A project file (`.efaproj`) keeps everything about one event in one file, so that work can be resumed exactly where it was left. Since version 3.2.0 it holds the work of every window; a project may hold any of these parts on its own, without a radio spectrum:

Radio analysis the loaded or combined data with the list of source files and the combination method; the processing state (background subtraction, RFI cleaning, isolated burst); the view (display range, thresholds, units, axis scale, color map and graph properties); annotations, light curves and a loaded STEREO/SWAVES panel; the active processing preset, the operation log and the last time-window synchronization; and the analysis session (maximum-intensity points, the fundamental/harmonic choice, the Analyzer's fit, density model, fold and t_0, and band-splitting points and fits).

Solar Image Analysis the frames, the data source, display, crop and playback settings, the CME measurements and the PFSS settings (Chapter 17).

GCS CME Fitting the channels, display settings, front points and recorded fits of both models (Chapter 21).

Event context the geomagnetic response, the Event Context Strip with its source choices, and the Event Figure settings (Chapter 15).

Projects are managed from the File menu of the main window:

Save Project (Ctrl+S, or the toolbar tool) saves to the current project file, asking for a name the first time. Ctrl+S in the Solar Image Analysis or GCS window saves the same project.

Save Project As... (Ctrl+Shift+S) saves to a new file. When the project holds solar or GCS images, you choose how to keep them (Section 10.1.1).

Open Project... (Ctrl+Shift+O) opens a project and every window it needs: Solar Image Analysis and the GCS window open and are restored. A project file can also be dropped onto the main window.

Recent Projects lists the last ten projects opened or saved; Clear Recent Projects empties the list, and an entry whose file is missing is removed with a message.

Before a project is opened, new data are loaded, or the application is reset or closed, you are asked whether to save unsaved changes. Changes in any of the three windows count.

10.1.1 Linking or embedding images

When a project holds solar or GCS images, Save Project As... asks how the project should keep them (Figure 10.1):

Link data (small) the project refers to the image files on this computer and stays a few hundred kilobytes. If the files are later moved, or the download cache is cleared, they are fetched again from the archive when the project is opened.

Embed data (portable) the images are stored inside the project; the button shows the expected size. The project opens anywhere, even offline.

The radio arrays are always stored in the project. The choice is kept in the file, so Ctrl+S does not ask again.

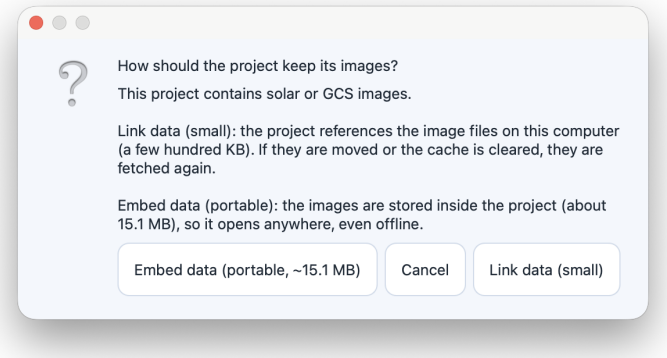


Figure 10.1 Choosing how a project keeps its images.

10.1.2 Reopening projects

- A part of a project that cannot be read is skipped and named in a message, while the rest opens.
- Solar Image Analysis measurements are matched to the reloaded frames by observation time.
- An overlay composite that was built when the project was saved, such as the AIA Sun in the LASCO occulter, is built again once the frames are in.
- The geomagnetic response, the catalogs and the Event Figure settings are restored without fetching anything.

> **Compatibility.** Projects saved by version 3.2.0 cannot be opened by version 3.1. Version 3.1 radio projects open unchanged. A version 3.1 `.ecsolar` Solar Image Analysis session can be opened

with Open Project...: it is imported as a new, unsaved project. `.ecsolar` files are no longer written.

10.1.3 Restored analysis sessions

When a project with an analysis session is opened, the Analysis Summary panel reports that the session has been restored. Processing → Analysis Session → Open Restored Analysis reopens the windows that were open when the project was saved — the Maximum Intensities window, the Burst Analyzer and the Type II Band-splitting window — with their points, fits and settings.

10.2 Autosave and recovery

While a project has content and unsaved changes, the application writes a recovery snapshot every three minutes. Snapshots always link solar and GCS images rather than embed them, so they stay small and fast. The ten most recent snapshots are kept. If the application did not close normally, it offers to recover the latest snapshot at the next start. File → Recover Last Session... restores the most recent snapshot at any time.

10.3 Exporting figures

File → Export As → Export Figure (Ctrl+E, or the Export toolbar tool) saves the main plot as a PNG, PDF, EPS, SVG, TIFF or JPG file. Whatever renderer and theme are on screen, the exported figure is drawn as a publication-style (“OriginPro-style”) graph in light mode:

- Arial type, a closed black frame with inward major and minor ticks on all four sides, a framed color scale, and time ticks on whole UT minutes;
- the current zoom, color map, display range, linear or logarithmic frequency axis, and the titles and font sizes from Graph Properties;
- every visible overlay: light curves, annotations, the GOES X-ray overlay, the ruler measurement, the STEREO/SWAVES panel and the Event Context Strip.

The plot on screen keeps its own look. On Windows, if the proposed folder is not writable (for example inside `C:\\ProgramFiles`), you are asked to choose another folder.

The Maximum Intensities window, the Burst Analyzer, the band-splitting window, the Multi-Station Comparison and the Solar Image Analysis tracking panel export their graphs in the same style.

10.4 Exporting FITS files

File → Export As → Export to FIT (Ctrl+F, or the Export as FITS toolbar tool) writes the spectrum on show as a new FITS file, for downstream analysis or machine learning. The processed data are exported if processing has been applied, and the raw data otherwise; combined datasets are exported as one file.

Before saving, choose the data type (`BITPIX`): Auto (the recommended type is shown), 8 (unsigned byte), 16 (signed int16) or 32 (signed int32). Integer types are offered because some FITS viewers cannot read 64-bit floating-point data. The exported file keeps the original header, updated with:

- `HISTORY` records naming the application, the plot type, the intensity units and the source file(s);
- `COMBINED`, `COMBMETH` (combination method) and `NFILES` for combined data;
- `BUNIT`, `DATAMIN` and `DATAMAX`;

and an `AXIS` binary-table extension with the `FREQUENCY` and `TIME` columns, as in standard CALLISTO files (see Appendix B).

10.5 Provenance reports and analysis logs

For reproducibility, two structured reports can be exported from File → Export As:

Export Provenance Report... writes a Markdown (`.md`) and a JSON (`.json`) summary with the sections *App*, *Data Source*, *Processing*, *RFI*, *Annotations*, *Time Sync* and *Operation Log*.

Export Analysis Log... writes `<name>_analysis_log.csv` and `<name>_analysis_log.txt` with the Analyzer's fit parameters and the derived shock quantities.

These reports are suitable for laboratory notebooks, collaboration hand-overs and the preparation of papers.

10.6 Project report PDF

File → Generate Project Report... creates a consolidated PDF of the current project. A progress dialog is shown while the report is built. Catalogs and the geomagnetic response that are not yet loaded are fetched first, even when Solar Events → Fetch Event Context Automatically is off; they are then kept, so the sidebar card and the event strip show them and the project saves them. A project without a radio spectrum has a report too: the radio sections are left out.

10.6.1 Event Story

The report opens with an *Event Story* that tells what happened, in order, from the Sun to the Earth (Figure 10.2):

- a headline and a one-line chain, for example *flare* → *radio burst* → *CME* → *shock at Earth* → *storm*;
- the *event chain* graphic: Sun, corona, heliosphere and Earth lanes on a compressed time axis (minutes near the eruption, days at Earth), with the time between the key steps;
- *Key Numbers*;
- *What Happened*, four short chapters: at the Sun, in the corona, through the heliosphere and at Earth;
- a *Timeline* of every milestone; bold rows are the steps joined on the event chain;
- the event overview and Geomagnetic Response figures;
- *Sources and Caveats*.

The pieces are drawn from the loaded radio data, the event catalogs (GOES flares, CDAW and DONKI CMEs, DONKI shock arrivals and storms, the e-CALLISTO burst list), a GCS reconstruction and the geomagnetic response. They are associated by timing and by DONKI's own links, and the story says when they do not fit: a storm that peaked before this event's shock arrived is attributed to earlier eruptions. Without radio data the story starts from the Solar Image Analysis frames or the GCS event.

> **Caution.** The Event Story associates events by timing and by DONKI's links. Check the associations before citing them.

10.6.2 Report sections

After the Event Story the report contains the sections listed below; sections without content are omitted.

- *Data Source* and *Selected FITS Header*;
- *Processing*, and *RFI, Annotations, and Light Curves*;
- *Analysis Summary* and *Type II Results*, including the fit equation (with t_0 when it is not the file start), the density model, and band-splitting output;
- *Figures*: the raw and background-subtracted spectra (with the Event Context Strip when it is shown), light curves with the spectrum, the maximum-intensity fit, the Type II band-splitting plots, the STEREO/SWAVES split view, and any available GOES X-ray, GOES proton, Dst and Kp context plots;
- *Solar Image Analysis*, when that window holds frames: the current frame as on screen, the instrument, product, frames and processing, the overlay layers, and the CME measurements with their kinematics;
- *GCS CME Fitting*, when the GCS window holds work: the viewpoints and a table of the recorded fits (the GCS window's own report draws every fit on its images, Section 22.8);
- *Full FITS Header Appendix*.

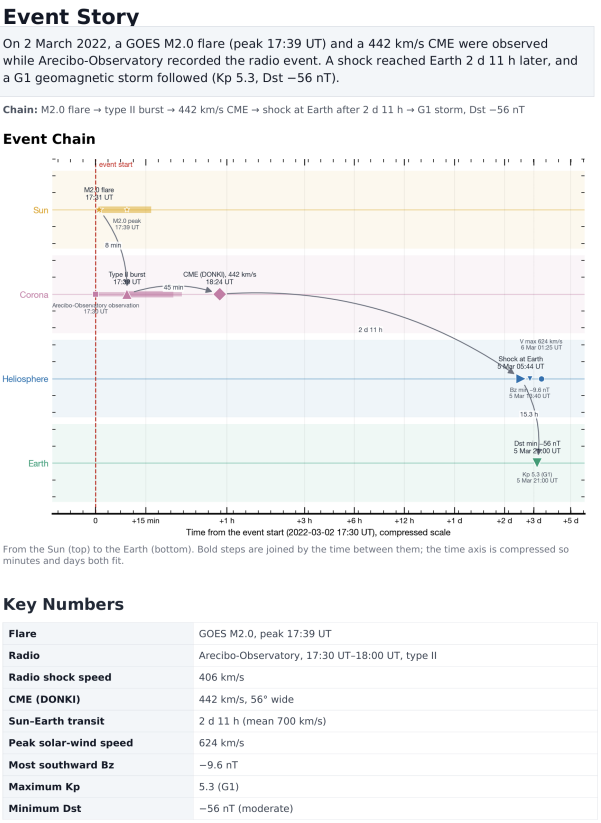


Figure 10.2 The first page of a project report's Event Story.

Every graph in the report is drawn in the same style as Export Figure, on a white page even in the dark theme.

10.7 Event Figure

File → Export As → Event Figure… composes one publication figure of the whole event from the spectrum, other instruments, catalogs, image thumbnails and the geomagnetic response. It is described in Section 15.4.

10.8 Batch processing

Processing → Batch Processing → Open Batch Processor opens the Batch FIT Processing dialog (Figure 10.3), which renders every FIT file in a folder as a PNG image with consistent settings.

Input Folder, Output Folder the folder of FIT files to process and the folder for the PNG images (one per input file, at 300 dpi; existing names are not overwritten).

Output Type Raw or Background Subtracted.

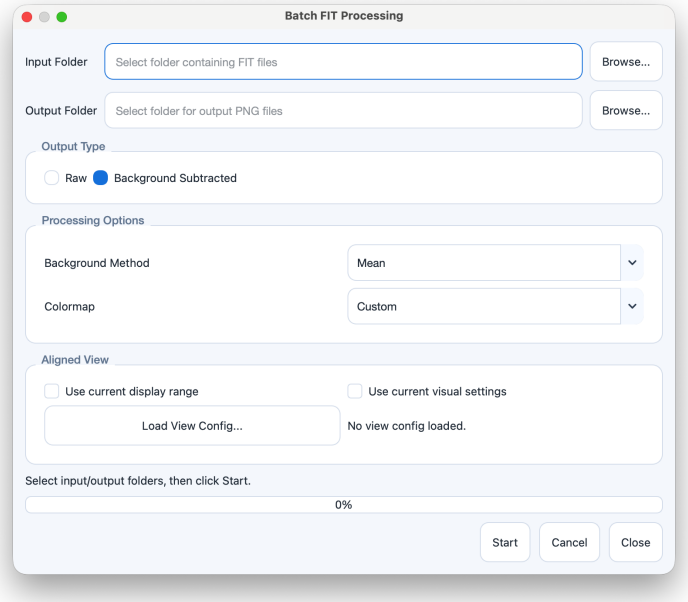


Figure 10.3 The Batch FIT Processing dialog.

Processing Options the Background Method (Mean, Median or Plotutil Median (dB)) and the Colormap. Plotutil Median (dB) converts digits to dB with the CALLISTO scale before subtracting the median, and defaults to a display range of −1 to 8 dB.

Aligned View Use current display range and Use current visual settings apply the main window's display range and appearance; Load View Config... applies a saved `.efaview.json` file instead. These options give many station spectra identical time and frequency axes.

Start, Cancel, Close start the run, cancel it after the current file, or close the dialog. A summary is shown when the run finishes, including any files that failed.

Part III

Radio Data Access

Retrieving radio data from the e-CALLISTO archive, comparing stations, and working with Learmonth and STEREO/SWAVES spectra.

11

The e-CALLISTO FITS Downloader

The e-CALLISTO FITS Downloader retrieves FITS files directly from the e-CALLISTO data archive. Open it with the Download toolbar tool, Download → Launch FITS Downloader, or Solar Events → Radio Bursts → e-CALLISTO.

The window has four tabs — Single Station, Multi-Station Event, Spectral Overview and Burst List — described in the sections below. Station lists are read from the archive whenever a date changes, so they offer only the stations that have data on the chosen UTC days; a line under the date reports how many, for example 42 stations have data on 2026-10-04 (UTC).

11.1 Common features

11.1.1 The download cache

Previewed and downloaded files are kept in a persistent cache on disk, so re-previewing, importing or extending a dataset never fetches the same file twice. The size of the cache is shown at the bottom left of the window (Cache: …). Open Cache Folder opens the cache in the file manager and Clear Cache empties it.

11.1.2 Preview, download, import and compare

The tabs share four actions on the files you have ticked:

Preview opens the FITS Preview window with a background-subtracted spectrogram of the selection. A selection that can be combined in time, in frequency or in both is previewed as it would be imported; otherwise each file appears in its own tab.

Download asks for a folder (Select Download Folder) and saves the files there.

Import loads the selection into the main window, combining it automatically when possible (Section 5.3). Gap and overlap options are requested when needed.

Compare opens the Multi-Station Comparison with the selection (Chapter 12).

During downloads a progress panel shows the overall progress, transfer statistics and an estimated time remaining; Show file details expands a table with the progress, speed and status of every file.

11.2 Single Station

The Single Station tab (Figure 11.1) lists all files of one station for a complete UTC day.

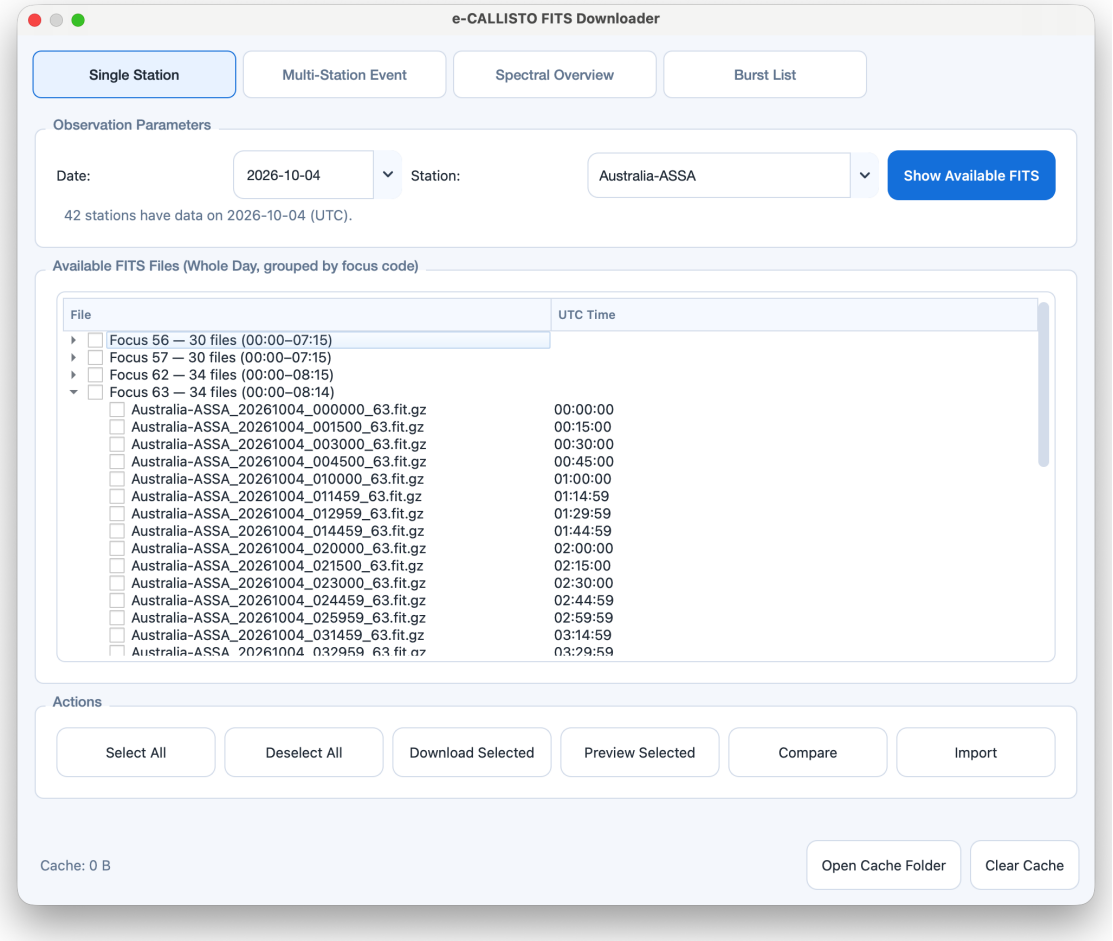


Figure 11.1 The Single Station tab.

1. In Observation Parameters, choose the Date and then the Station.
2. Click Show Available FITS.
3. In Available FITS Files (Whole Day, grouped by focus code), expand a focus code and tick files, or tick a whole focus-code group. Each group heading shows the number of files and the time span covered, for example Focus 63 — 34 files (00:00–08:14), so the receivers that covered an event are visible at a glance.
4. Use the buttons in Actions: Select All, Deselect All, Download Selected, Preview Selected, Compare or Import.

When several files are ticked, the downloader determines whether they can be combined in time, in frequency or in both, using the rules of Section 5.3. Files that cannot be combined are reported with an explanation (Figure 5.1).

Choosing a date, or selecting a file in the list, also sets the event time of the Geomagnetic Response and the event-context tools in the main window (the selected day, or the file's start time), so the geomagnetic response of a day can be inspected before anything is downloaded (Section 15.1).

11.3 Multi-Station Event

The Multi-Station Event tab (Figure 11.2) finds the files recorded by several stations during the same event in a single search.

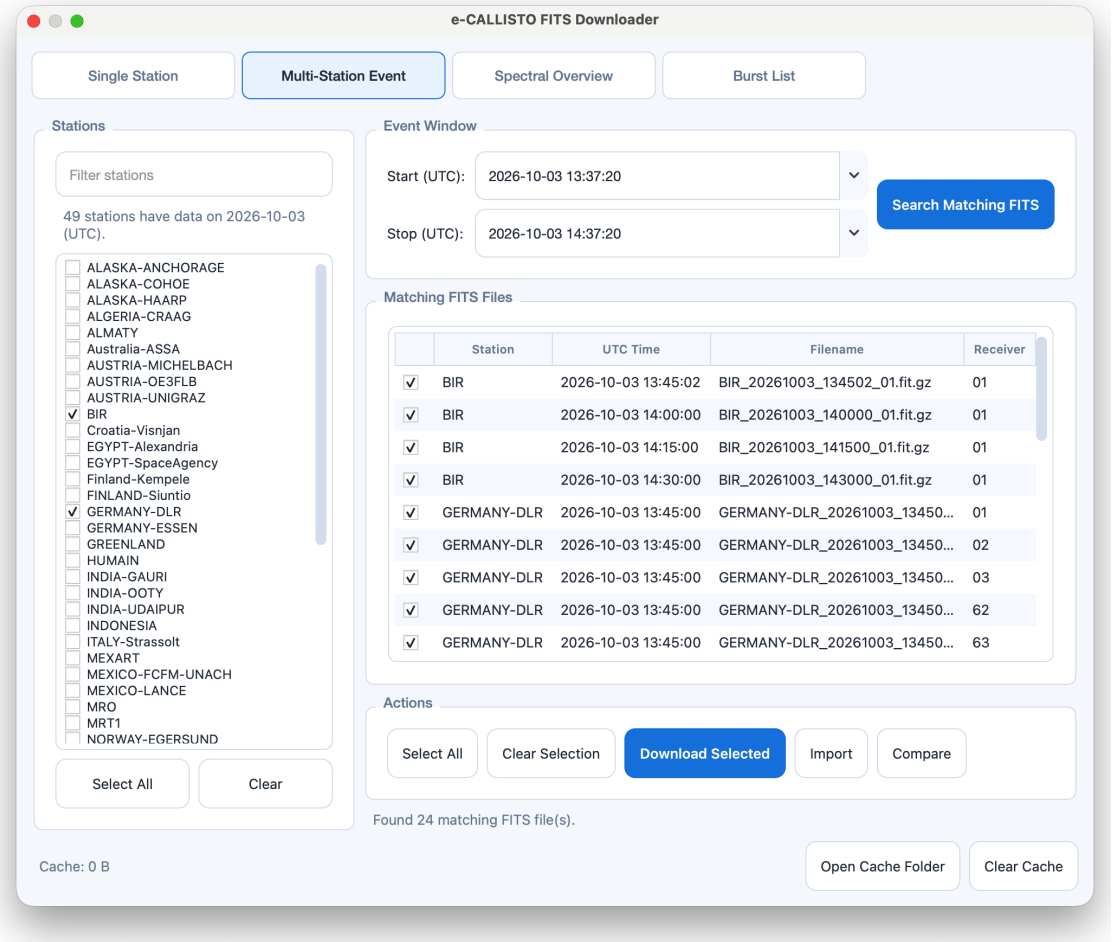


Figure 11.2 The Multi-Station Event tab.

1. In Event Window, set Start (UTC) and Stop (UTC). The station list is updated to the stations with data in that window (windows of up to seven days).
2. In Stations, tick the stations to search. Filter stations narrows the list by name; Select All and Clear tick or untick all stations.
3. Click Search Matching FITS. The Matching FITS Files table lists the station, UTC time, file name and receiver (focus code) of every file overlapping the window.

4 Use Select All, Clear Selection, Download Selected, Import or Compare.

A compatible selection is imported directly into the main window, combined in time, in frequency or in both. Files from several stations cannot be combined into one spectrum; use Compare to view them side by side. The comparison workspace opens only when Compare is clicked.

11.4 Spectral Overview

The Spectral Overview tab (Figure 11.3) assembles a station's observations for a complete UTC day into one overview figure.

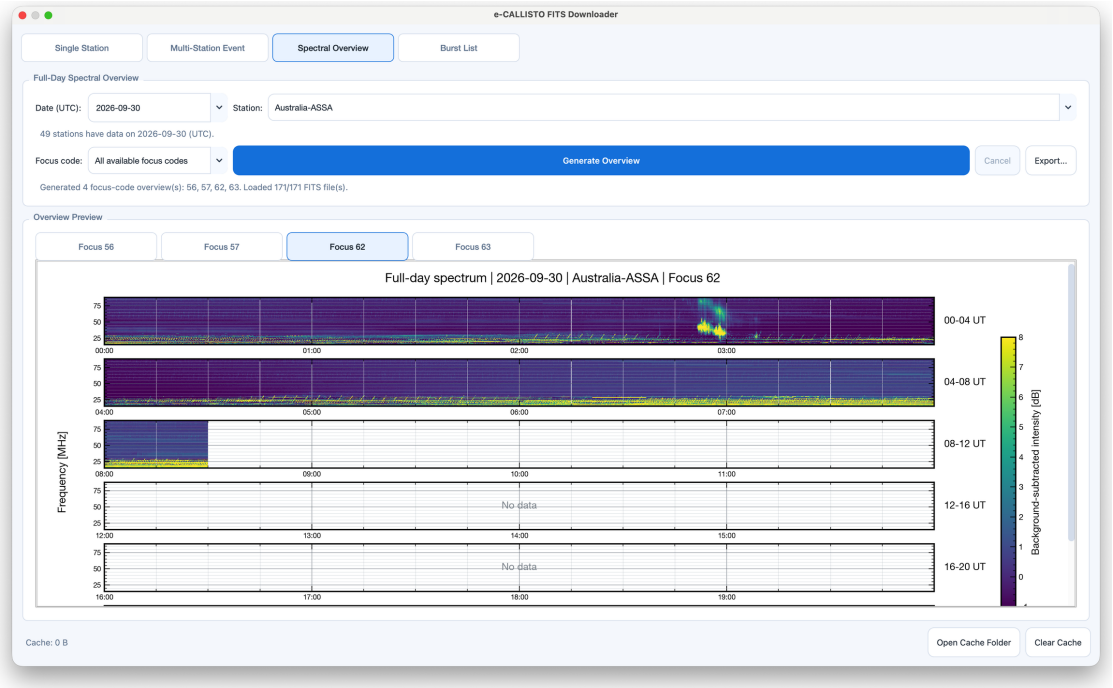


Figure 11.3 The Spectral Overview tab with a full-day overview for one focus code.

Date (UTC), Station the day and station to summarize.

Focus code All available focus codes, or a single focus code to generate or regenerate on its own.

Generate Overview downloads (or reuses from the cache) every file of the day and builds the overview. The status line reports the focus codes generated and the number of files loaded. Cancel stops a running generation.

Overview Preview one tab per focus code. Each overview shows the day as six four-hour panels (00–04 UT to 20–24 UT), background-subtracted with a day-wide median (dB) baseline and a common color scale; intervals without data are marked *No data*.

Export... saves the overview of the selected tab as a PNG, PDF, EPS, SVG or TIFF figure at 300 dpi on a white background.

11.5 Burst List

The Burst List tab (Figure 11.4) gives access to the e-CALLISTO solar radio burst catalog compiled by C. Monstein (Monstein n.d.), so that the FITS files for a listed burst can be found together with its type and reporting stations. The Monstein source catalog link opens the original lists in a web browser.

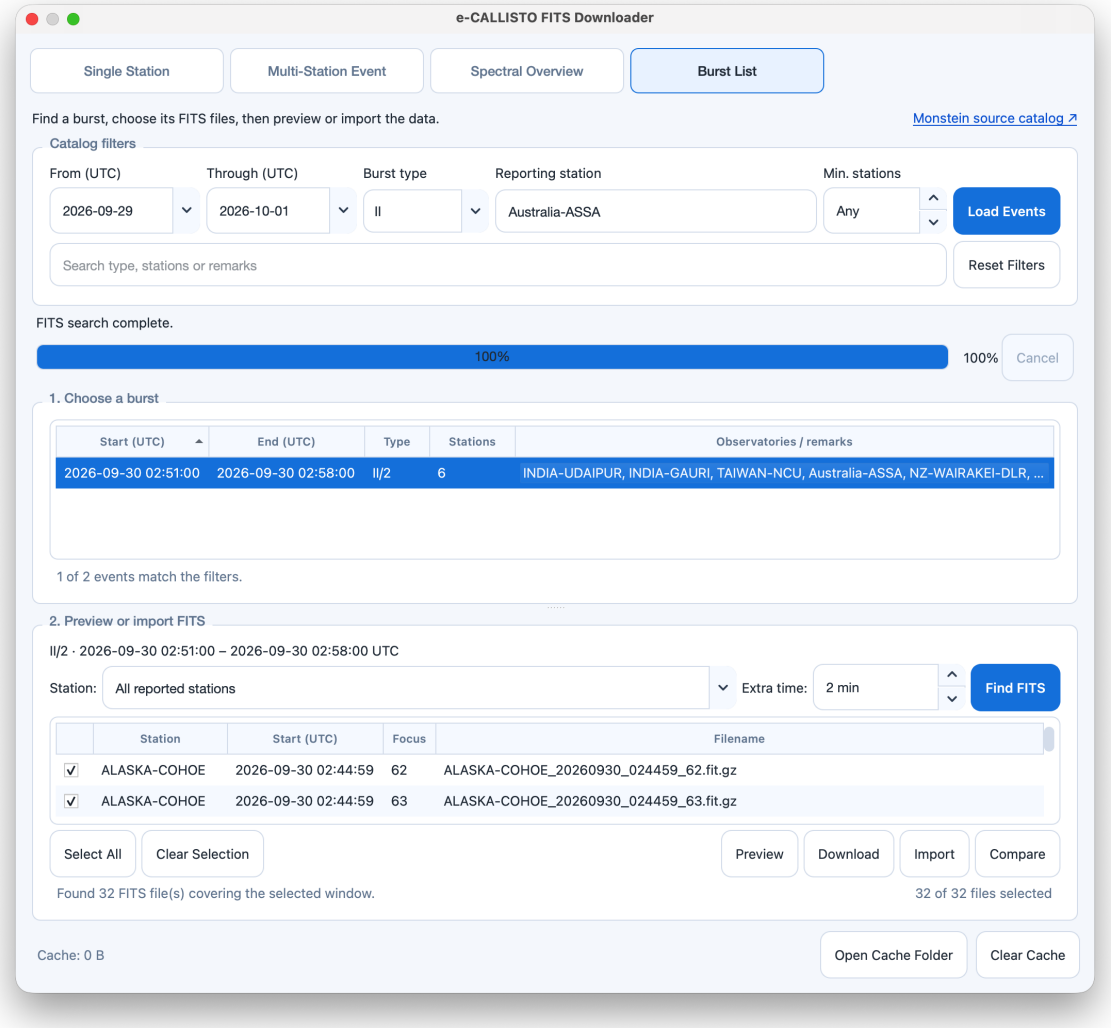


Figure 11.4 The Burst List tab with a selected Type II event and its FITS files.

Catalog filters

From (UTC), Through (UTC) the date range to load; click Load Events.

Burst type All types or one of the burst types found in the loaded catalog (for example II or III).

Reporting station events reported by a given station.

Min. stations events reported by at least this many stations (Any for no limit).

Search free-text search in the type, stations or remarks.

Reset Filters clears the filters while keeping the selected dates.

A progress bar with a Cancel button reports catalog loading, FITS searches, preview preparation and downloads. The final state remains visible after completion.

1. Choose a burst

The event table lists the start and end time (UTC), type, number of stations, and the observatories and remarks of each matching event, with a count such as 1 of 2 events match the filters. Hovering over a row shows the original catalog record and its source URL. Missing periods, source notices and loading errors are reported below the table. Selecting a burst sets the event time of the Geomagnetic Response (Section 15.1).

2. Preview or import FITS

Station All reported stations, one of them, or the name of any archive station typed in the box.

Extra time padding added on both sides of the burst (0–120 min, default 2 min).

Find FITS searches the archive. Overlapping 15-minute files and events that cross UTC midnight are included. The table lists the station, start time, focus code and file name of each file found.

Select All, Clear Selection, Preview, Download, Import, Compare act on the ticked files as described above; the number of selected files is shown.

The divider between the two tables can be dragged to resize them.

> **Note.** Catalog coverage varies by year, station and type information may be unavailable in older lists, and a listed detection does not guarantee that matching FITS data are archived. Catalog times are UTC with one-minute precision.

12

Multi-Station Comparison

The Multi-Station Comparison workspace displays dynamic spectra from several stations in vertically stacked panels with a shared time axis, so that the same event can be compared across stations, receivers and frequency ranges (Figure 12.1). It is opened from View → Multi-Station Comparison… or with the Compare button of the downloader (Chapter 11).

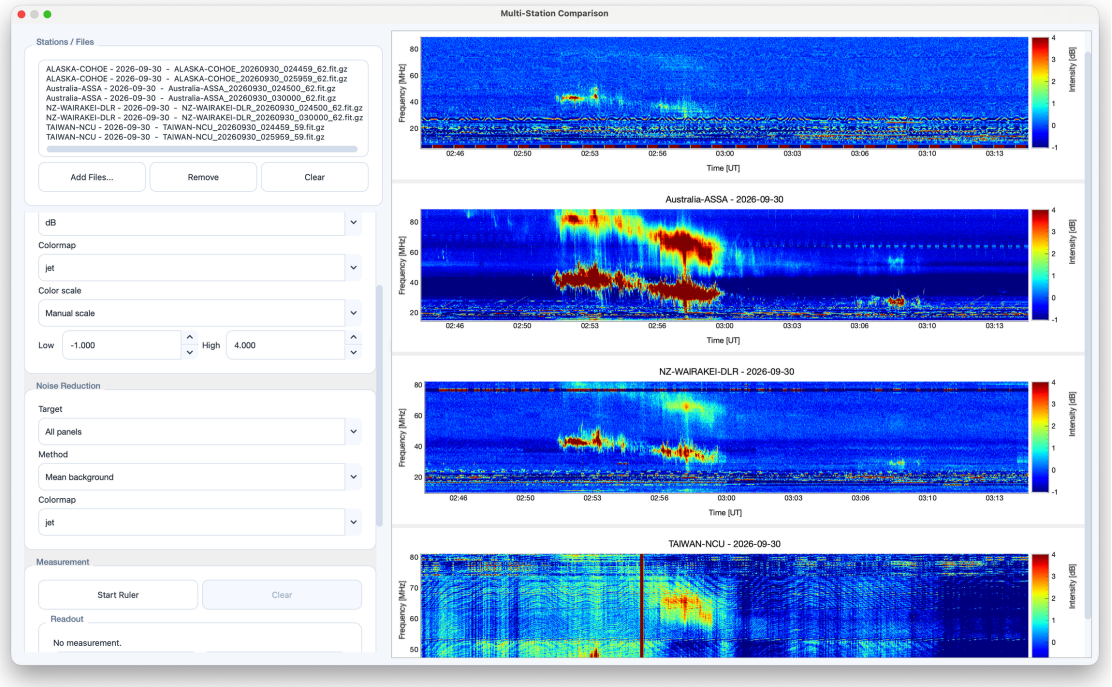


Figure 12.1 The Multi-Station Comparison workspace with four stations observing the same event.

The workspace follows the rendering mode of the application: in Modern mode the panels are hardware-accelerated when available, and in Classic mode they are drawn with Matplotlib.

12.1 Stations and files

The Stations / Files group lists the loaded files as *station – date – file name*. Add Files... adds FITS files from disk, Remove removes the selected entry and Clear removes all entries. Files that can be combined are merged automatically before display: each station's files are combined in time, in frequency, or as a complete time × focus-code grid (Section 5.3), so a mixed-station selection yields one panel per station. Hovering over an entry shows any warning raised while reading it.

12.2 Display controls

Table 12.1 Display controls of the Multi-Station Comparison.

Group	Control	Function
View	Time alignment	UT clock aligns the panels on Universal Time; Seconds from file start aligns each panel on its own start. UT alignment requires `TIME-OBS` in every file; otherwise the workspace switches to seconds and says so.
Appearance	Units	Digits or dB.
	Colormap	Color map of all panels.
	Color scale	Shared scale (one scale for all panels), Per-station auto scale, or Manual scale with Low and High limits.
Noise Reduction	Target	All panels or one panel.
	Method	None, Mean background, Median background, Robust background or Noise clipping.
	Colormap	Color map of the noise-reduced panels.
	Thresholds	With Noise clipping, Lower threshold and Upper threshold sliders and a Logarithmic Threshold Scale option, as in the main window.

12.3 Display range and view configurations

The Actions group contains:

Set Range... enter a shared time and frequency range for all panels.

Reset Range return to the full range of the data.

Load View Config... apply a `.efaview.json` view configuration (Section 7.2.2). The visual settings are applied; when the files differ in date, set UT bounds with Set Range....

Export... export the comparison (Section 12.5).

12.4 Ruler measurement

In the Measurement group, Start Ruler activates a ruler: click two points in one panel to measure the duration, frequency drift and slope, shown under Readout. Clear removes the measurement.

12.5 Exporting a comparison

Export... opens the Export Comparison dialog (Figure 12.2):

Visible View exports the comparison exactly as it appears in the window.

Grid / Table Layout exports a compact publication-style matrix of all panels, with a shared time axis, each station's native frequency range and a white background. Its options are the number of Columns (Auto or a fixed number), an Overall title, and the Raster resolution (DPI) for bitmap formats.

The figure can be saved as PNG, PDF, EPS, SVG or TIFF.

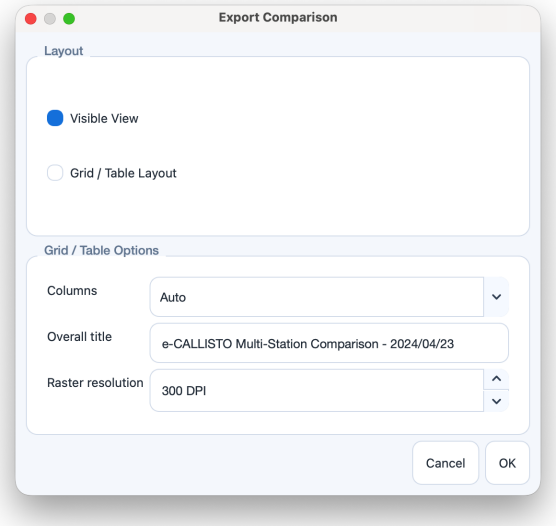


Figure 12.2 The Export Comparison dialog.

13

Learmonth and STEREO/SWAVES Data

Besides the e-CALLISTO archive, the application reads data from two further radio instruments: the ground-based Learmonth Solar Radio Spectrograph in Western Australia, and the space-based STEREO/WAVES (SWAVES) radio receivers. Both are opened from Solar Events → Radio Bursts.

13.1 Learmonth Solar Radio Spectrograph

The Learmonth Solar Radio Spectrograph, operated by the Australian Bureau of Meteorology, records daily archive files (`.srs`) in two receiver bands. Solar Events → Radio Bursts → Learmonth opens the Learmonth Solar Radio Browser (Figure 13.1), which converts selected parts of a daily file into FIT files for the main window.

Observation Parameters choose the Date and a Time, then click Show Available Data. The daily file is read from the local cache when available and downloaded otherwise. The chunk containing the chosen time is highlighted.

Daily Raw File information about the daily archive file. Download saves the raw `.srs` file to a folder you choose.

Available 15-Minute Chunks the time ranges into which the day is divided. Select All and Deselect All change the selection.

Convert to FIT converts the selected chunks to CALLISTO-style FIT files in a folder you choose.

Convert and Import converts the selected chunks and imports them into the main window, combined in time when consecutive.

Converted files carry a standard FITS header with the frequency and time axes and the observatory position, so they can be processed and analyzed exactly like e-CALLISTO data.

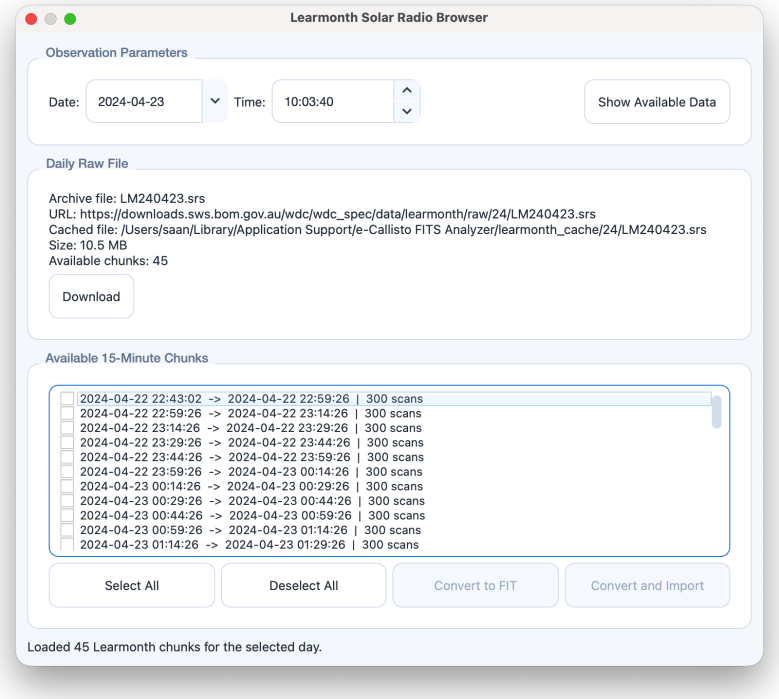


Figure 13.1 The Learmonth Solar Radio Browser.

13.2 STEREO/SWAVES

SWAVES on the twin STEREO spacecraft (Bougeret et al. 2008) records radio spectra from 2.6 kHz to 16 MHz, directly below the CALLISTO band. A burst that drifts out of the ground-based range can therefore be followed into the interplanetary medium on the same figure. Solar Events → Radio Bursts → SWAVES opens the STEREO/SWAVES Radio Spectrograph dialog (Figure 13.2).

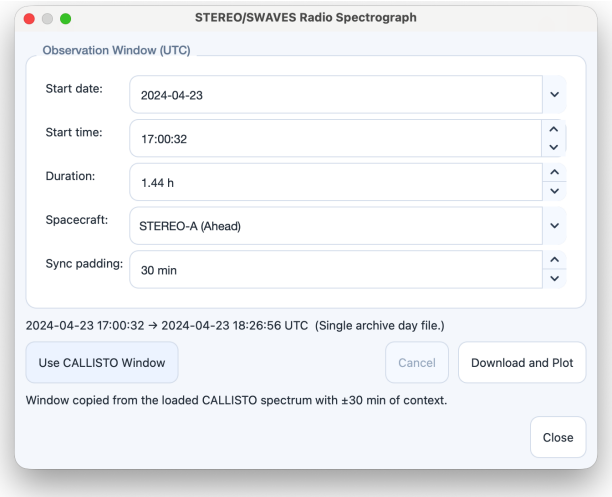


Figure 13.2 The STEREO/SWAVES dialog.

Start date, Start time, Duration the UTC window to load (0.1–24 h; default 4 h). The data are NASA/SPDF level-2 one-minute averages served as one file per UTC day; a window that crosses midnight fetches and joins both days. The archive starts on 27 October 2006, and downloaded day files are cached and reused.

Spacecraft STEREO-A (Ahead) or STEREO-B (Behind). STEREO-B is unavailable for dates after 1 October 2014, when contact with the spacecraft was lost.

Sync padding extra time added on each side when the window is taken from the CALLISTO spectrum (0–720 min; default 30 min). A Type II or Type III burst takes tens of minutes to hours to drift from the corona into the SWAVES band, so an exact match would cut off the part you want to see.

Use CALLISTO Window copies the time range of the loaded CALLISTO spectrum, widened by the sync padding. Solar Events → Sync Current Time Window updates an open SWAVES dialog in the same way.

Download and Plot loads the data; Cancel stops a running load.

13.2.1 The split view

Once SWAVES data are loaded, the plotting area of the main window splits into two panels: CALLISTO above and SWAVES below, on a shared time axis, so that panning or zooming either panel moves both (Figure 13.3). The CALLISTO interval is outlined on the SWAVES panel. The SWAVES frequency axis is always logarithmic and its intensity is in decibels above the instrument background, so the panel keeps its own color bar and color scaling while following the color map chosen in the sidebar. Loading SWAVES with no CALLISTO file open plots it across the whole area; it moves into the split view as soon as a FITS file is loaded.

Solar Events → SWAVES Panel hides and restores the panel without discarding the loaded data. The split view is included in exported figures, saved in and restored from projects without downloading the data again, and added to project reports.

> **Note.** The drawing, lasso, drift and measurement tools act on the CALLISTO panel only, and the data-reduction controls of the sidebar do not apply to the SWAVES panel.

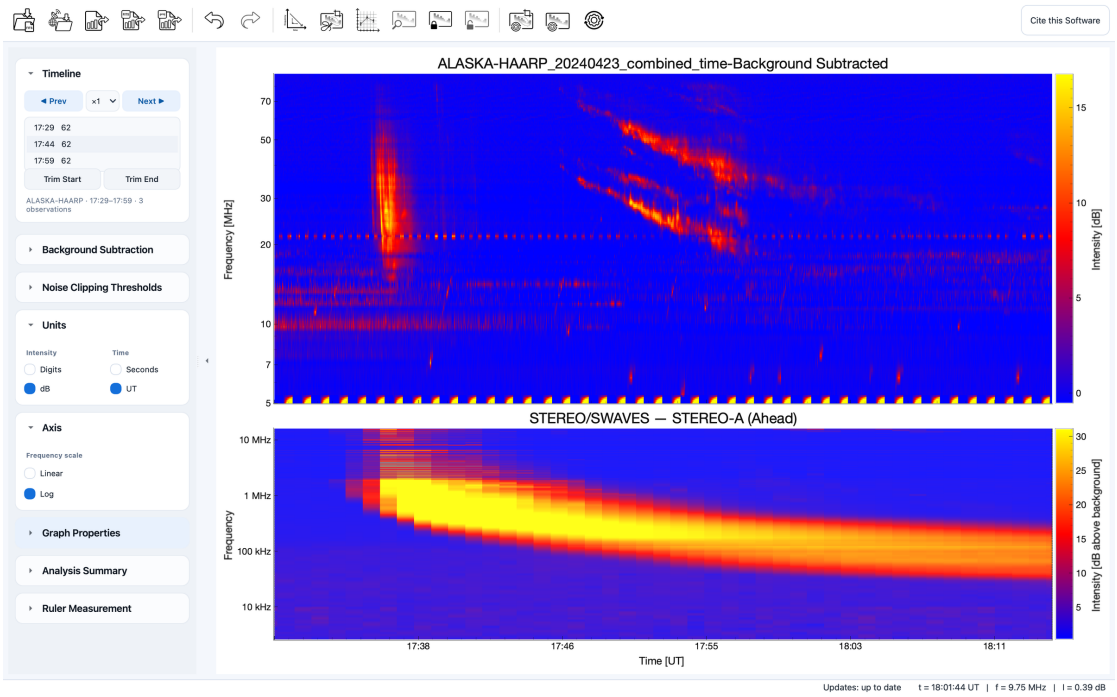


Figure 13.3 CALLISTO and STEREO/SWAVES spectra in the split view.

Part IV

Solar-Event Context

The event's context from the Sun to the Earth: X-ray, particle, geomagnetic and CME catalog viewers, the geomagnetic response, the event context strip and event figure, and the SunPy Multi-Mission Explorer.

14

Solar-Event Viewers

The viewers in the Solar Events menu place a radio event in its wider context: the X-ray flare, energetic protons, the geomagnetic response and any associated coronal mass ejection. Each viewer is an independent window that fetches its data from the archive listed in Appendix C. The viewers can also be started from source as standalone programs (Section 2.5). The Geomagnetic Response, which combines Dst, Kp, the solar wind and auroral indices around the loaded event, and the catalog-based event tools are described in Chapter 15.

14.1 Common controls

The GOES and geomagnetic viewers share a common layout:

- a time-range selector with Start and End rows (date, and hour, minute or three-hour slot) and, where applicable, the spacecraft;
- a Preset list with Apply for common ranges;
- a plot button that fetches and plots the data, with a progress indicator;
- Save Plot (PNG) and Save Data (CSV);
- a reset or clear button; and
- an information panel summarizing the plotted data or a selected interval.

14.2 Synchronizing the time window

Solar Events → Sync Current Time Window sends the time range of the spectrum loaded in the main window to every open context window: the GOES X-ray and proton viewers, the Dst and Kp viewers and the STEREO/SWAVES dialog plot the new range; the SOHO/LASCO CME catalog searches the day of the middle of the range; and the SunPy Explorer takes the range as its query window. The status bar reports which windows were updated, or that none were open.

14.3 GOES X-ray flux

Solar Events → Flares → GOES X-Ray Flux opens the GOES XRS Plotter (Figure 14.1), which plots the soft X-ray flux measured by the GOES X-Ray Sensor in its short (XRS-A, 0.05–0.4 nm) and long (XRS-B, 0.1–0.8 nm) channels.



Figure 14.1 The GOES XRS Plotter with a selected flare interval.

Start, End, Use the UTC range and the spacecraft (GOES-8 to GOES-19; default GOES-16). Preset: Whole day (00:00–23:59) selects the whole of the start day.

Plot XRS Data downloads the daily science files from NOAA and plots both channels on a logarithmic flux axis.

Selection drag across the plot to select a flare interval. The Flare Information panel then shows the Selection window, the Peak X-ray Flux (W/m²) and Peak Time (UTC) of the long channel, the Rise Time (selection start to peak), the Decay Time (peak to selection end), the Flare Duration and the GOES Class derived from the peak flux.

Save Plot, Save Data, Reset save the figure as PNG, save the fluxes as CSV, or clear the plot and selection.

14.3.1 GOES overlay on the spectrum

Solar Events → GOES Overlay → Short(XRS-A) and Long(XRS-B) draw the GOES X-ray curves directly on the dynamic spectrum in the main window (Figure 14.2), with a flare-class guide (A, B, C, M, X) on the right. The overlay does not modify the spectrum data. The application chooses a GOES satellite appropriate for the date automatically, falling back across legacy and modern satellites when a file is unavailable. The overlay is included in exported figures.

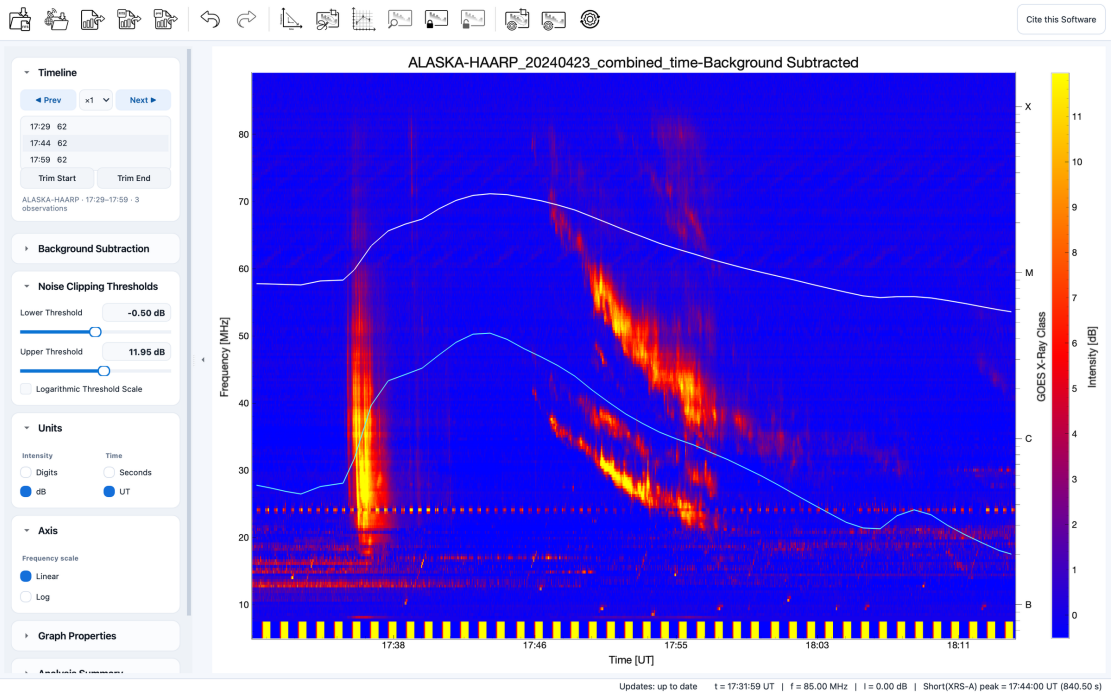


Figure 14.2 GOES X-ray curves overlaid on a dynamic spectrum.

14.4 GOES proton flux

Solar Events → Energetic Particles → GOES SEP Proton Flux opens the GOES SEP Proton Flux Plotter (Figure 14.3), which plots proton fluxes from the GOES Solar and Galactic Proton Sensor (SGPS) archive at NOAA over multi-day UTC ranges.

Start, End, Use the UTC range and the spacecraft: Auto (GOES-19 -> GOES-16) tries the newest spacecraft first, or a specific GOES satellite can be chosen.

Preset Last 24 hours, Last 72 hours, Last 7 days or Current UTC day.

Plot SEP Proton Flux fetches and stitches the daily files and plots the channels closest to about 10 MeV and 100 MeV, with hover readouts.

Selection drag across the plot to measure an event.

SEP Analysis the spacecraft, channels, number of samples and source files, the peaks of both channels in the plot, and for the selection its window, peak (low channel), peak time, rise time, decay time and duration.

Save Plot, Save Data, Clear Selection save the figure as PNG, save the stitched flux table as CSV, or clear the selection.

14.5 Kyoto Dst index

Solar Events → Geomagnetic → Kyoto Dst Index opens the Dst Index viewer (Figure 14.4) for the hourly Dst index from the World Data Center for Geomagnetism, Kyoto (Nosé et al. 2015).

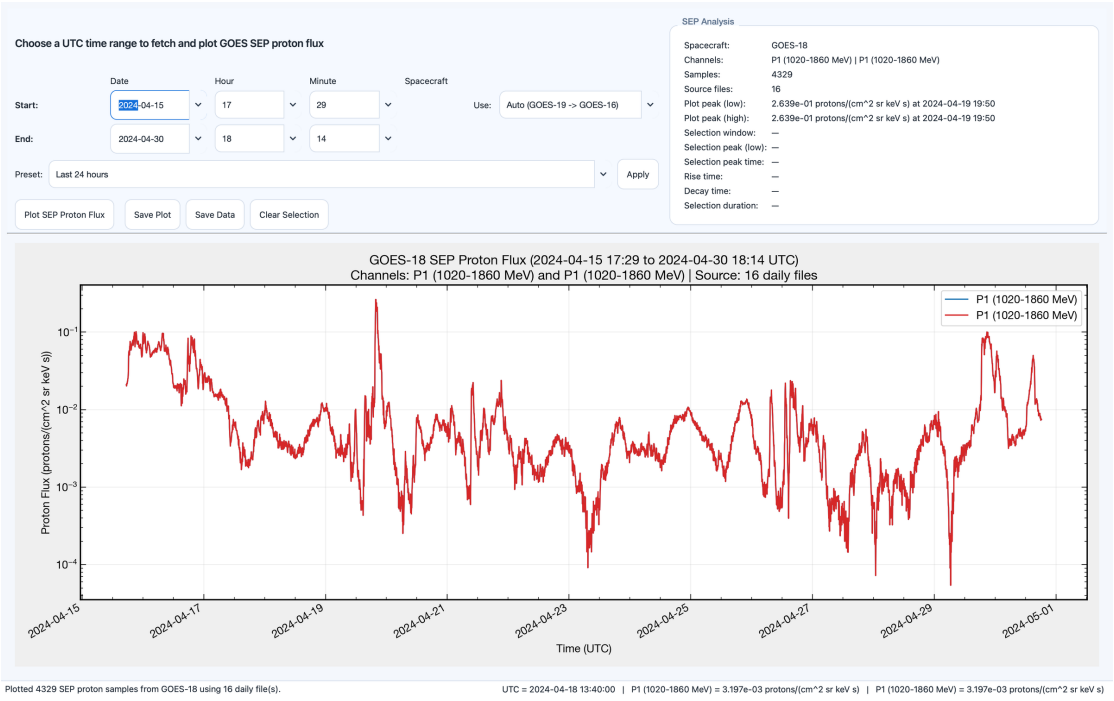


Figure 14.3 The GOES SEP Proton Flux Plotter.

Dst measures the strength of the ring current; large negative values indicate geomagnetic storms.

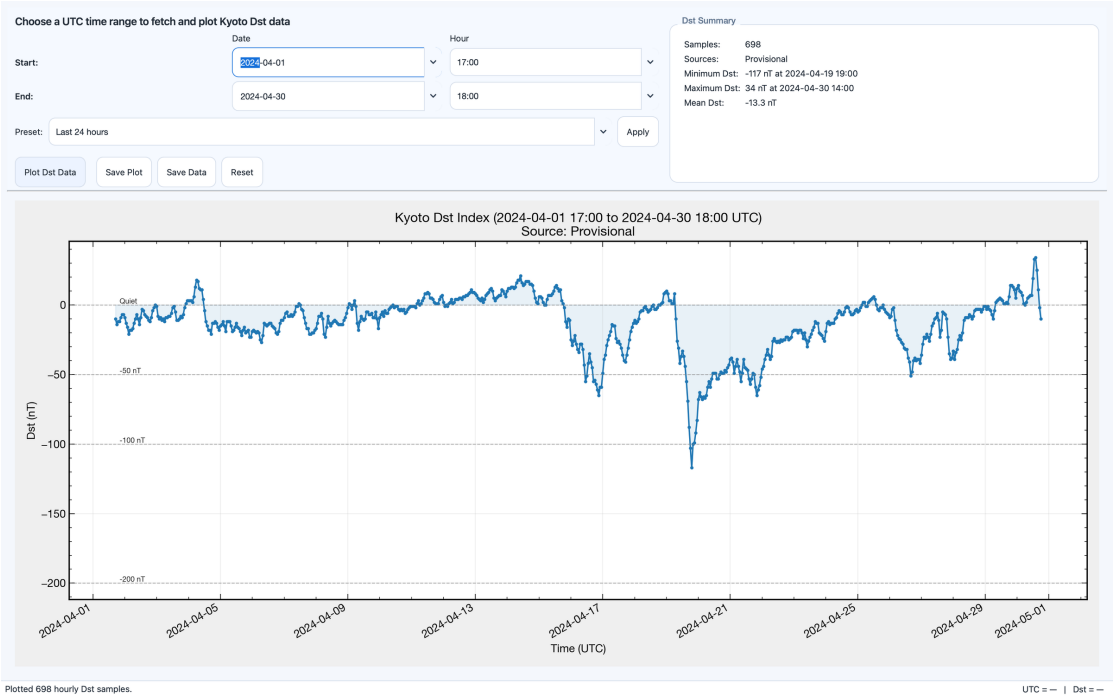


Figure 14.4 The Kyoto Dst Index viewer.

Start, End date and hour. Preset: Last 24 hours, Last 7 days, Current month or Previous month.

Plot Dst Data fetches and plots the index with storm-level guides at 0 (quiet), −50, −100 and −200 nT. Hours that Kyoto has not filled in are shown as gaps.

Dst Summary the number of samples, the data sources (final, provisional or real-time), and the minimum, maximum (each with its time) and mean Dst.

Save Plot, Save Data, Reset PNG figure, CSV table, or clear.

14.6 GFZ Kp index

Solar Events → Geomagnetic → GFZ Kp Index opens the Kp Index viewer (Figure 14.5) for the three-hourly planetary Kp index from GFZ Potsdam (Matzka et al. 2021).

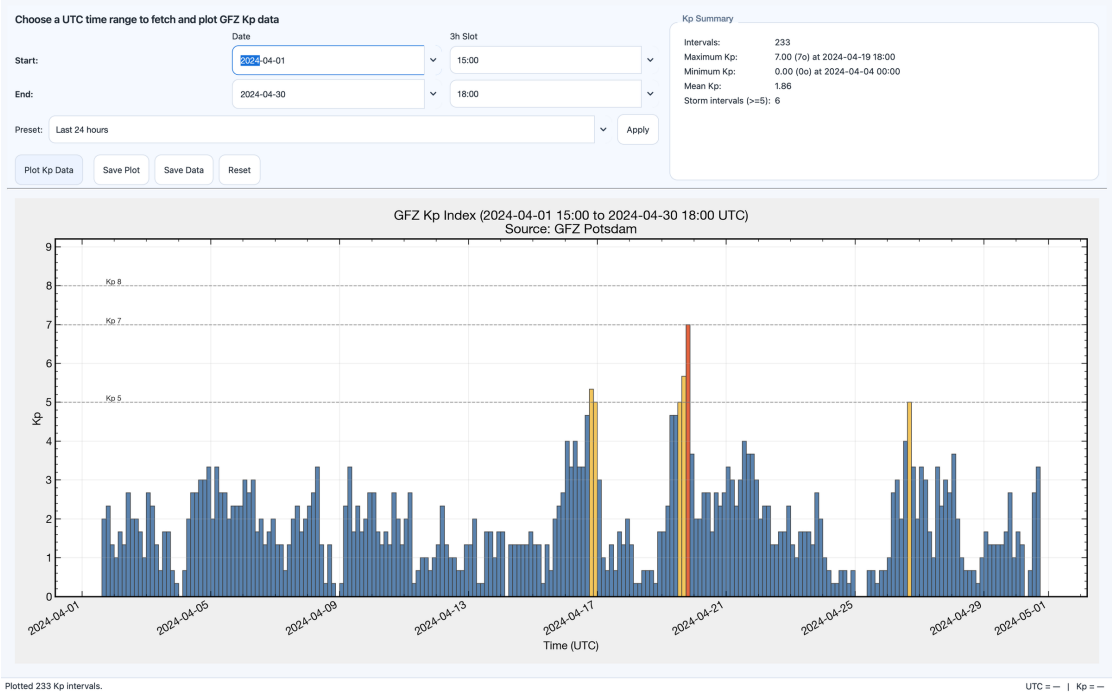


Figure 14.5 The GFZ Kp Index viewer.

Start, End date and three-hour slot (3h Slot). Preset: Last 24 hours, Last 7 days, Current month or Previous month.

Plot Kp Data plots the index as bars colored by activity (quiet below 5, storm from 5, severe from 7), with guide lines at Kp 5, 7 and 8.

Kp Summary the number of intervals, the maximum, minimum and mean Kp, and the number of storm intervals (Kp $\geq$ 5).

Save Plot, Save Data, Reset PNG figure, CSV table, or clear.

14.7 SOHO/LASCO CME catalog

Solar Events → CMEs → SOHO/LASCO CME Catalog opens the SOHO/LASCO CME Catalog Tool (Figure 14.6), which reads the CDAW catalog of CMEs observed by SOHO/LASCO (Yashiro et al. 2004).

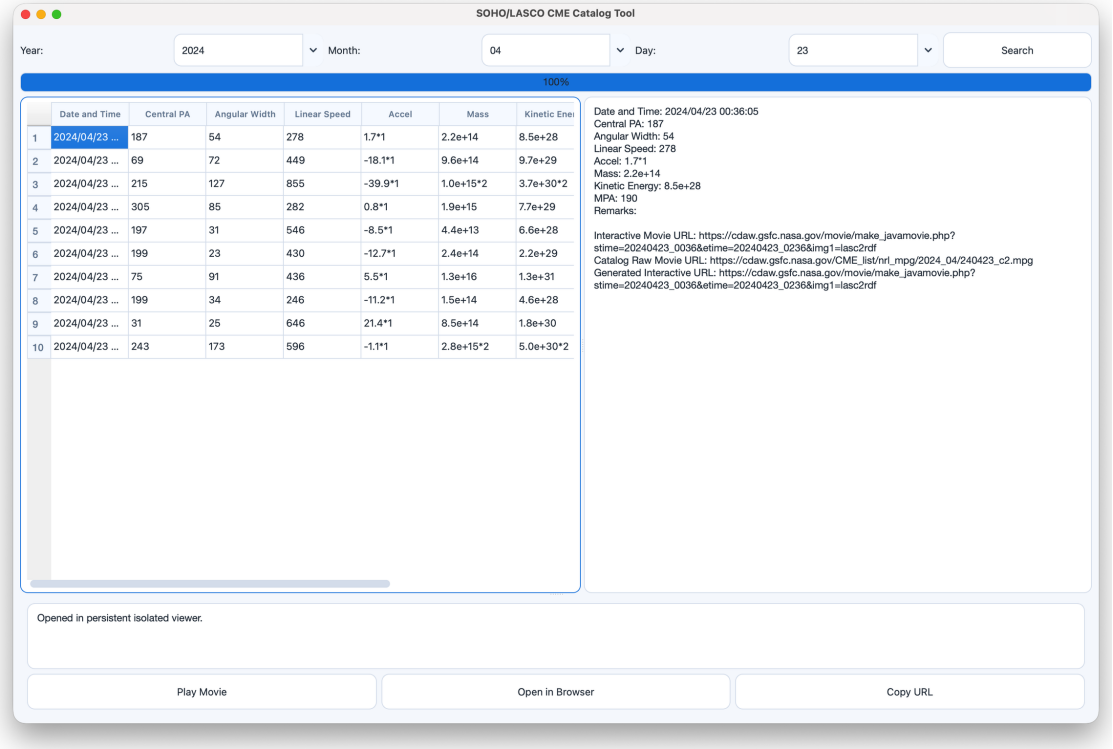


Figure 14.6 The SOHO/LASCO CME Catalog Tool.

Year, Month, Day, Search list the CMEs of the chosen day. A progress bar shows the retrieval.

CME table one row per CME with the columns Date and Time, Central PA, Angular Width, Linear Speed, Accel, Mass, Kinetic Energy, MPA (measurement position angle) and Remarks. Clicking a row shows its details beside the table.

Play Movie plays the LASCO movie associated with the selected CME (double-clicking a row does the same) in a viewer with Back, Forward, Reload, Open in Browser, Open Raw Movie and Copy URL.

Open in Browser, Copy URL open the CDAW page of the selected CME, or copy its address.

15

Event Context and Geomagnetic Response

A radio burst is one moment in a chain that can run from a flare and a coronal mass ejection at the Sun to a shock and a geomagnetic storm at Earth one to three days later. The tools in this chapter place the loaded event in that chain: the *Geomagnetic Response* shows what Earth's environment did around the event, the *Event Context Strip* draws the flare, CME, storm and burst catalogs above the spectrum, and the *Event Figure* composer combines everything into one publication figure. The same information opens the project report's Event Story (Section 10.6).

15.1 The event and automatic fetching

The tools work around an *event time*, which is set by the most recent of these actions:

- loading data in the main window — the observation start of the loaded spectrum (*FITS: …*);
- selecting a row in the downloader's Burst List (*Burst list: …*);
- selecting a day or a file in the e-CALLISTO downloader (*Downloader: …*).

The current event is named at the top of the Geomagnetic Response card and window. After a burst-list or downloader selection, Use loaded data returns to the event of the loaded file. Nothing ever pops up on its own: the card updates, and the window opens only when you ask for it.

Solar Events → Fetch Event Context Automatically (on by default, and remembered) fetches the geomagnetic response, and the event catalogs while the strip is shown, whenever data are loaded or an event is selected. Turn it off to download nothing on your behalf: the card then asks you to press Refresh, and Refresh, Refresh Event Context and File → Generate Project Report... still fetch when you ask.

15.2 Geomagnetic Response

The Geomagnetic Response follows the event to Earth. It covers, by default, one day before the event start to seven days after, on a single UTC axis. Two views show it: a summary card

in the main window's sidebar (Section 6.8) and the full window, opened with Solar Events → Geomagnetic → Geomagnetic Response… or the card's Open window button (Figure 15.1).

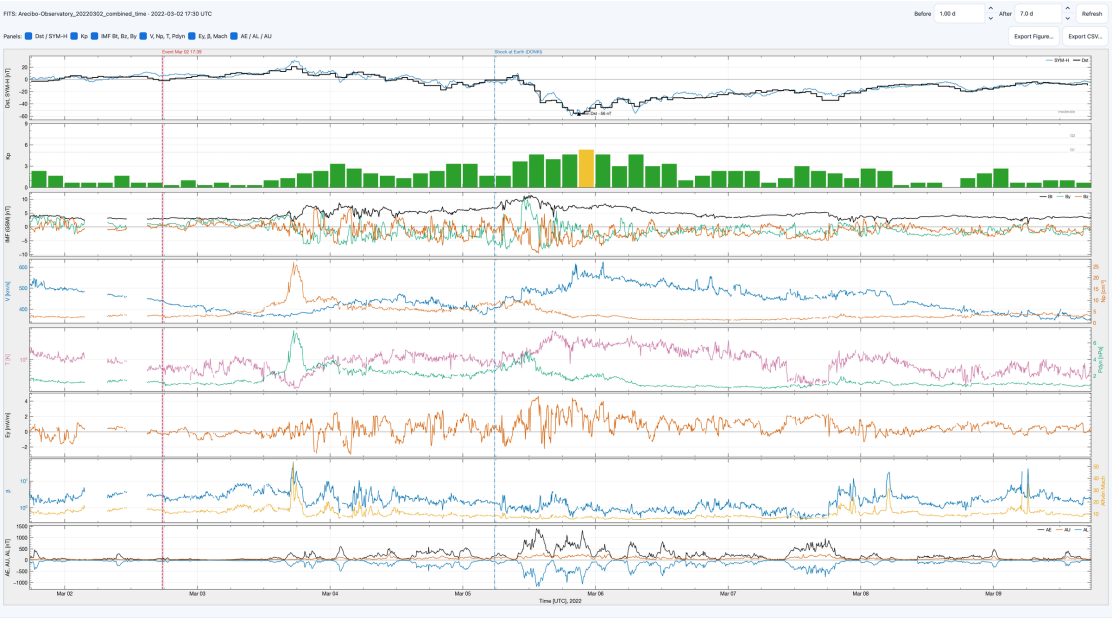


Figure 15.1 The Geomagnetic Response window for the radio event of 2 March 2022, with all six panels; the DONKI shock arrival at Earth and the moderate storm that followed are marked.

15.2.1 Controls

Event the event the response is shown for, with where its time came from.

Before, After the span shown before and after the event start (0.25–10 days before, default 1; 0.5–30 days after, default 7).

Refresh fetches the response again.

Panels check boxes that choose the panels shown (Table 15.1). The choice is remembered between sessions.

Export Figure… saves the selected panels as an OriginPro-style figure (PNG, PDF, SVG, EPS, TIFF or JPG), black on white whatever the application theme.

Export CSV… saves every series as CSV, with a provenance column naming the archive or spacecraft of each value.

A line below the panels lists notes, such as data that are not yet published.

The Dst/SYM-H, Kp, IMF and plasma panels are shown by default.

15.2.2 Markers

The event start is a dashed red line and the interval of the loaded radio data is shaded. DONKI interplanetary-shock arrivals at Earth, geomagnetic storms and the CMEs they are linked to are

Table 15.1 Panels of the Geomagnetic Response.

Panel	Content
Dst / SYM-H	Kyoto Dst (final, provisional or real-time, month by month) with the 1-minute SYM-H index. The scale follows the data; the storm levels it reaches (moderate −50, intense −100, severe −250 nT) are dotted, and the minimum is marked with its value.
Kp	GFZ Kp as bars coloured by NOAA G level, with the G1 (Kp 5) and G3 (Kp 7) levels dotted.
IMF Bt, Bz, By	Interplanetary magnetic field magnitude and components (GSM).
V, Np, T, Pdyn	Solar-wind speed and proton density, temperature and dynamic pressure; each half of the panel has two scales coloured like their lines.
Ey, β, Mach	Dawn–dusk electric field, plasma β and Alfvén Mach number.
AE / AL / AU	Auroral electrojet indices.

marked with labelled vertical lines. When the labels crowd, they are shortened (for example *CME 1330*, *Shock*, *Kp 9.0*) and the least important are left unnamed, though their lines remain. Markers outside the plotted span are not shown.

15.2.3 Data sources

- **Solar wind, IMF and derived parameters** come from the OMNI 5-minute data set (King and Papitashvili 2005), which is time-shifted to the nose of Earth's bow shock and also carries the SYM-H (Iyemori 1990) and AE (Davis and Sugiura 1966) indices.
- OMNI is published with a delay of a few weeks. For the most recent days the measurements of DSCOVR (NOAA NCEI archive) or NOAA SWPC's real-time solar-wind feed are used instead. They are measured at the L1 point, upstream of Earth, and are labelled *L1, not time-shifted to the bow shock*; their Ey, β and Mach number are computed with OMNI's formulas (Appendix D).
- SYM-H and AE have no such stand-in and are reported as not yet published until OMNI includes them.
- **Dst** comes from the World Data Center for Geomagnetism, Kyoto, and **Kp** from GFZ Potsdam, as in the stand-alone viewers (Chapter 14).
- **Markers** come from NASA's DONKI database (NASA Community Coordinated Modeling Center n.d.) (Section 15.3).

A source that fails is reported in the notes while the others still load. The response is saved in the project, so a reopened project shows it without fetching anything, and the project report includes it.

15.2.4 The Geomagnetic Response card

The sidebar card (Section 6.8) summarizes the same response in five rows: the Dst minimum (with when it occurred and how many hours after the event start), the Kp maximum and its

NOAA G level, the most southward Bz, the fastest solar wind and the storm class (Table 15.2). When the event moves to another hour, the previous event's numbers are cleared rather than shown under the new event.

Table 15.2 Storm classes and NOAA G levels used in the summary.

Storm class (Dst min)	G level (Kp max)	Notes
weak: ≤ -30 nT	G1: Kp 5	Classes after Gonzalez et al. (1994).
moderate: ≤ -50 nT	G2: Kp 6	
intense: ≤ -100 nT	G3: Kp 7	
super: ≤ -250 nT	G4: Kp 8	
	G5: Kp 9	NOAA space-weather scales (NOAA Space Weather Prediction Center n.d.).

Caution. A storm within the window is not necessarily caused by the event: it may have been driven by an earlier eruption. Compare the storm's timing with the shock arrivals and the transit time from the Sun before attributing it. The project report's Event Story makes this check (Section 10.6).

15.3 Event Context Strip

View → Event Context Strip adds lanes above the dynamic spectrum, on their own time axis, in both the Classic and the Modern view (Figure 15.2). Each lane shows one catalog (Table 15.3); View → Event Context Sources chooses the lanes, and View → Event Context Sources → Refresh Event Context fetches them again.

Table 15.3 Lanes of the Event Context Strip.

Lane (source menu entry)	Content
Flares (GOES/SWPC)	The NOAA SWPC flare list, through the Heliophysics Event Knowledgebase (HEK), as bars coloured by GOES class.
CMEs (CDAW)	The CDAW SOHO/LASCO CME catalog, at the first C2 appearance, with speed and width.
DONKI	NASA DONKI CMEs, flares, interplanetary shocks, geomagnetic storms and SEP events.
Bursts (e-CALLISTO)	The e-CALLISTO (Monstein) burst lists, as bars with their burst type.

- Hover over a marker to read its details.
- Events up to six hours outside the plotted time range are counted at the edge of their lane, for example *2 more nearby*.
- The catalogs are cached on disk, one file per source and UTC day. Days within the last 30 days are refreshed after a day, because catalogs are still being filled in; older days never expire.

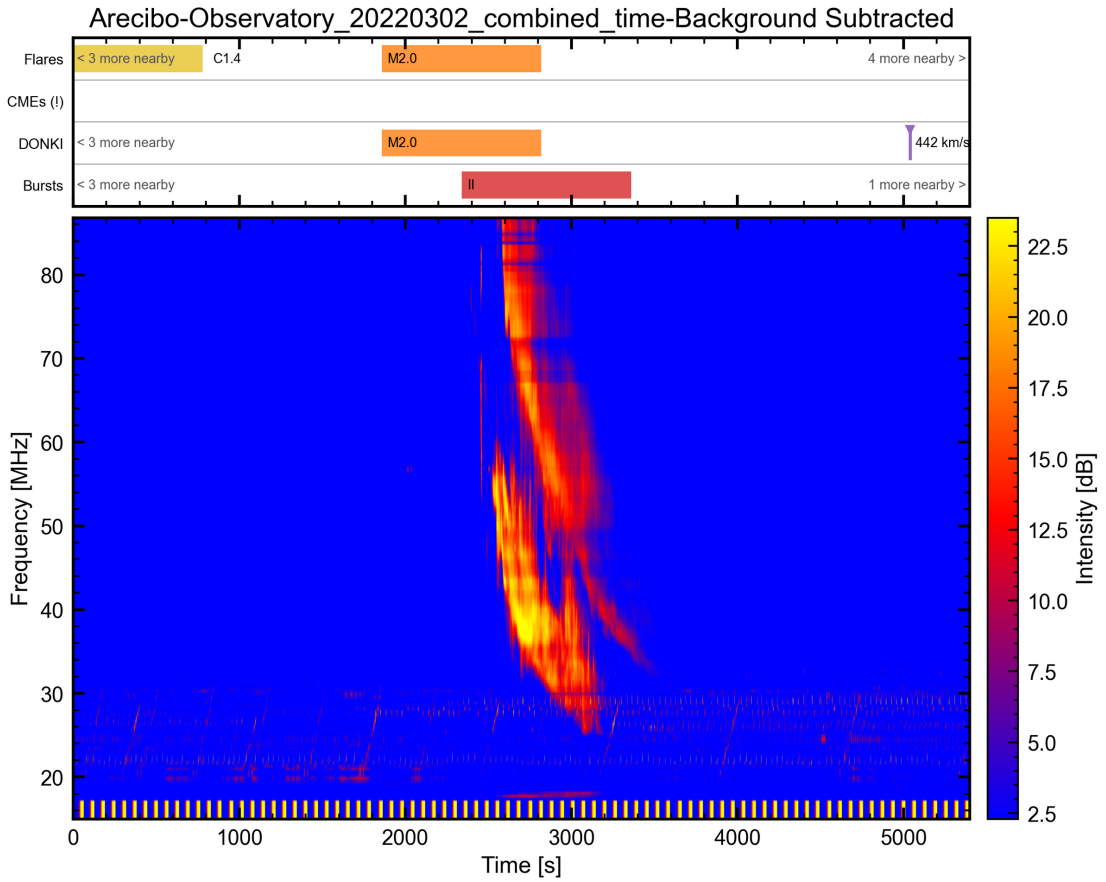


Figure 15.2 The Event Context Strip above a dynamic spectrum, as saved with Export Figure. Edge labels count events just outside the plot; the CMEs lane is marked (!) because its catalog could not answer for that day.

- A day that a catalog cannot answer for yet — a CDAW month that has not been published, or a DONKI service that failed — is not cached. It is asked for again next time, and its lane is marked **(!)** with the reason in the status bar.

While it is shown, the strip is included in Export Figure and in the project report, and it is saved in the project. A project keeps its own strip and source choices without changing your View-menu preference.

15.4 Event Figure

File → Export As → Event Figure… opens the Event Figure Composer (Figure 15.3), which builds one publication figure of the whole event with a live preview. Figure 15.4 shows an example.

Event panels (top to bottom) tick the panels to include — CALLISTO dynamic spectrum, STEREO/SWAVES, GOES X-ray flux, GOES proton flux (SEP) and Event catalogs — set each

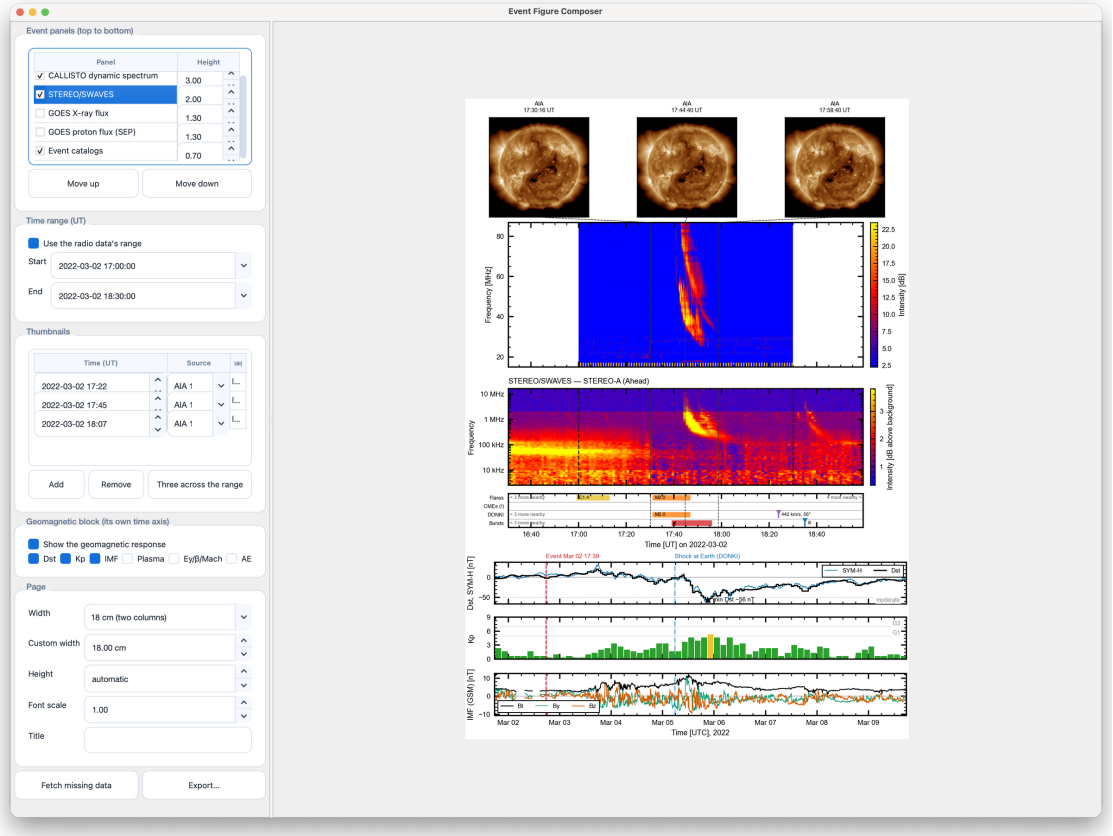


Figure 15.3 The Event Figure Composer.

panel's height, and reorder them with Move up and Move down. The spectrum, GOES X-rays and catalogs are selected by default.

Time range (UT) Use the radio data's range, or a Start and End of your own.

Thumbnails a table of images (Time (UT), Source, Image) drawn as a row above the panels. Add and Remove edit the list and Three across the range adds three evenly spaced thumbnails. Sources are AIA, EIT, LASCO C2 and C3, and STEREO COR1 and COR2. A frame already loaded in Solar Image Analysis or the GCS window near the chosen time is used as it is processed there; otherwise a Helioviewer image is fetched. Each thumbnail's time is drawn as a dashed line down through the panels.

Geomagnetic block (its own time axis) Show the geomagnetic response adds the Geomagnetic Response panels below the event panels, on their own days-long axis, with the radio interval shaded and the DONKI markers; check boxes choose its panels.

Page Width: 8.8 cm (one column), 12 cm, 18 cm (two columns) or custom (4–40 cm); Height: automatic or fixed; Font scale (0.5–2); and a Title.

Fetch missing data downloads what the chosen panels and thumbnails need and is not yet loaded (GOES X-rays and protons, thumbnails). The status line reports what was fetched.

Export… saves the figure as PNG, PDF, EPS, SVG, TIFF or JPG.

The composer's settings are saved in the project. Fetched GOES and proton series are used only

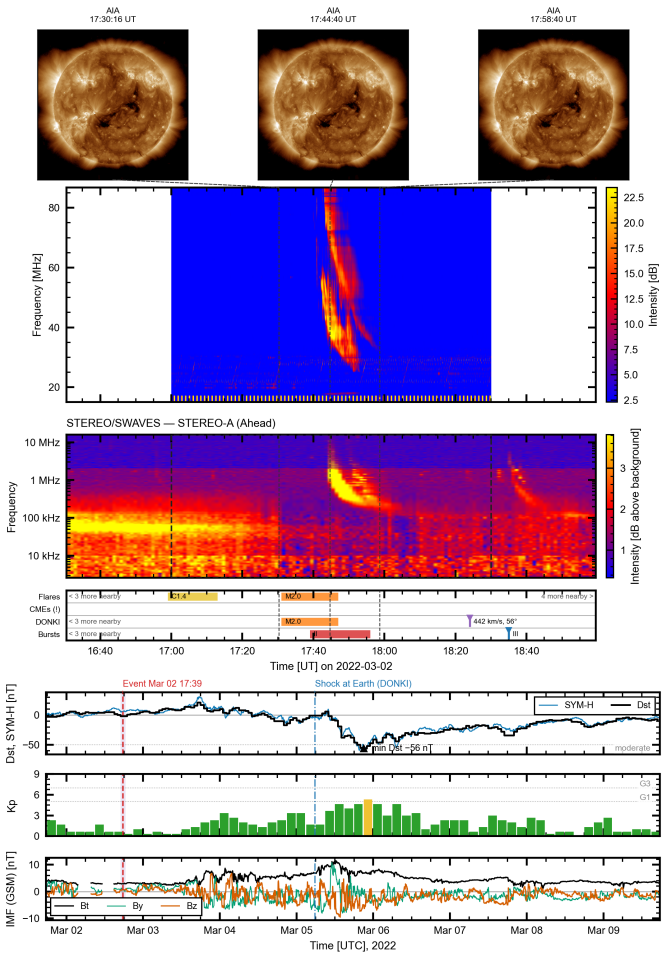


Figure 15.4 An exported Event Figure (18 cm wide) for the event of 2 March 2022: AIA thumbnails, the CALLISTO and STEREO/SWAVES spectra, the catalog lanes and the geomagnetic block.

for the event and time range they were fetched for, so after loading another file press Fetch missing data again.

16

SunPy Multi-Mission Explorer

The SunPy Multi-Mission Explorer searches public solar archives through SunPy (The SunPy Community et al. 2020), downloads the selected records into an application-managed cache, and plots images and time series for quick inspection. Open it with Solar Events → Archives → SunPy Multi-Mission Explorer. For in-depth image analysis, use Solar Image Analysis (Part V).

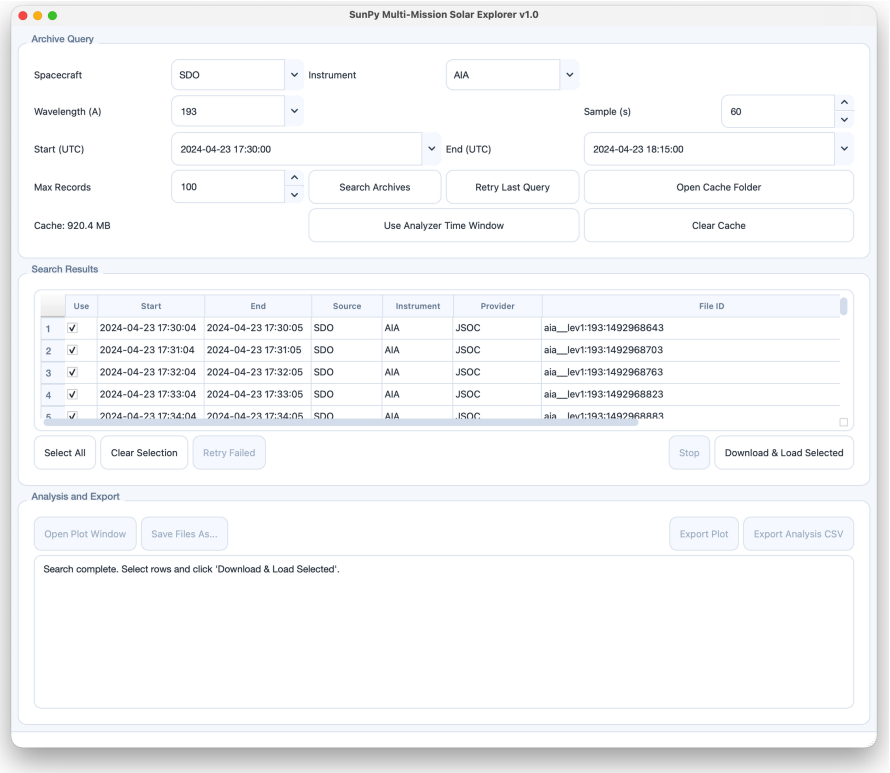


Figure 16.1 The SunPy Multi-Mission Solar Explorer.

16.1 Supported instruments

Table 16.1 lists the instruments that can be searched. Map (image) products are shown in the plot window as image sequences; GOES/XRS is a time series.

Table 16.1 Instruments available in the SunPy Multi-Mission Explorer.

Instrument	Type	Selectable options
SDO/AIA	Map	Wavelength 94, 131, 171, 193, 211, 304, 335, 1600, 1700 Å
SDO/HMI	Map	Product: magnetogram, continuum, dopplergram
SOHO/EIT	Map	Wavelength 171, 195, 284, 304 Å
SOHO/LASCO C2, C3	Map	Detector
STEREO-A/B SECCHI	Map	Detector EUVI (171, 195, 284, 304 Å), COR1, COR2, HI1, HI2
GOES/SUVI	Map	Wavelength 94, 131, 171, 195, 284, 304 Å; level 1b or 2
PROBA2/SWAP	Map	—
GOES/XRS	Time series	GOES satellite

STEREO-B entries return data only for 2007–2014, before contact with the spacecraft was lost.

16.2 Searching the archives

The Archive Query group contains:

Spacecraft, Instrument the observatory and instrument. The Detector, Wavelength (A), GOES Satellite, product and Level fields appear when they apply to the selected instrument.

Sample (s) the sampling cadence in seconds; 0 requests the full archive cadence, which is slower and returns more records.

Start (UTC), End (UTC), Max Records the time range and the maximum number of records returned.

Search Archives runs the query. Retry Last Query repeats it, for example after a network error.

Use Analyzer Time Window sets the time range from the spectrum in the main window and searches.

Open Cache Folder, Clear Cache manage the download cache; its size is shown.

The Search Results table lists, for each record, the start and end time, source, instrument, provider, file identifier and size. Tick the records to download with the Use column or Select All and Clear Selection, then click Download & Load Selected. Retry Failed downloads again only the rows that failed, and Stop cancels a running search or download. Cached files can be reopened without a network connection.

16.3 The plot window

Open Plot Window in the Analysis and Export group opens the SunPy Plot and Animation window with the loaded data (Figure 16.2).

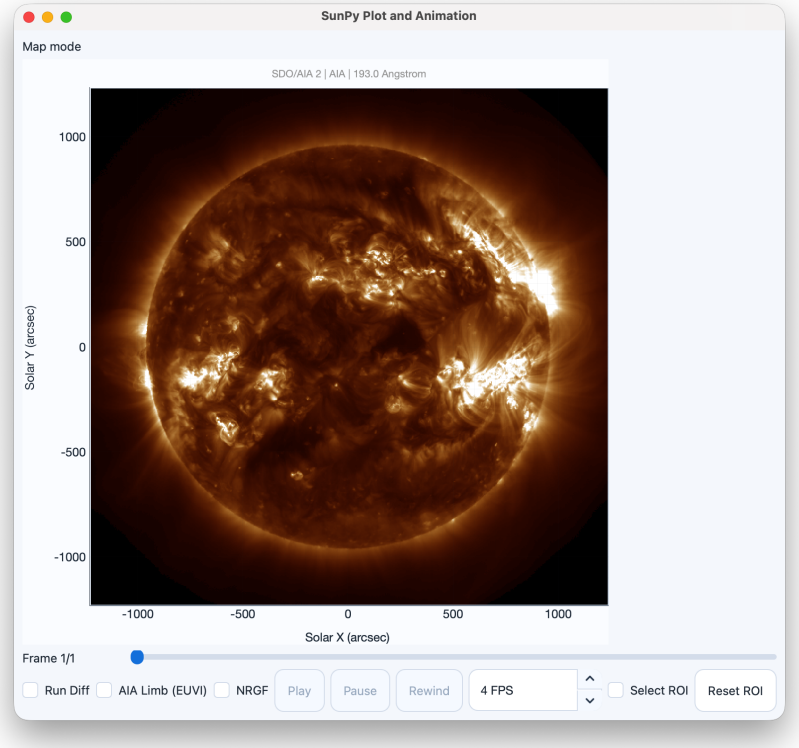


Figure 16.2 The SunPy Plot and Animation window in map mode.

In *map mode* the controls are:

Frame slider steps through the sequence; the frame number is shown.

Run Diff shows running differences between consecutive frames. Difference → Base Difference shows each frame minus the first.

AIA Limb (EUVI) on STEREO/EUVI images, draws the solar limb as seen from Earth, showing which part of the disk is visible to SDO/AIA.

NRGF applies the normalizing-radial-graded filter (Morgan et al. 2006) to coronagraph images (COR1, COR2, LASCO), flattening the radial fall-off of brightness to reveal faint CME fronts.

Play, Pause, Rewind, FPS animate the sequence at 1–30 frames per second.

Select ROI, Reset ROI draw a rectangular region of interest on the map, for which the minimum, maximum, mean, median, standard deviation and 95th and 99th percentiles are computed.

In *time-series mode* (GOES/XRS) the window plots the X-ray channels and derives basic flare summary metrics.

16.4 Exporting

The Analysis and Export group of the explorer provides Save Files As..., which copies the downloaded data files to a folder of your choice; Export Plot, which saves the current plot as PNG, PDF, SVG, TIFF or JPG; and Export Analysis CSV, which saves the ROI statistics or flare summary.

Part V

Solar Image Analysis

The multi-mission imaging workspace: obtaining and displaying solar images, measuring eruptions, and modeling the coronal magnetic field.

17

The Solar Image Analysis Window

Solar Image Analysis is a multi-mission imaging workspace for extreme-ultraviolet (EUV) disk images, magnetograms, coronagraph images and heliospheric images. It retrieves image sequences from the solar archives or reads local FITS files, displays and processes them, measures eruptions and their kinematics, and models the coronal magnetic field. Open it with Analysis → Solar Image Analysis in the main window.

This chapter describes the window, its menus, how image data are obtained, and how its work is saved in the project. Display and processing are described in Chapter 18, measurements in Chapter 19 and magnetic-field modeling in Chapter 20.

17.1 Supported observables

Table 17.1 lists the observables that can be retrieved. Local FITS files from these and other solar instruments can be loaded as well.

Table 17.1 Observables available in Solar Image Analysis.

Instrument	Class	Observables
SDO/AIA (Lemen et al. 2012)	EUV/UV disk	94, 131, 171, 193, 211, 304, 335, 1600 and 1700 Å
SDO/HMI (Scherrer et al. 2012)	Magnetograph	Magnetogram, Continuum (Intensitygram), Dopplergram; vector field (Section 18.10)
SOHO/EIT	EUV disk	171, 195, 284 and 304 Å
SOHO/LASCO (Brueckner et al. 1995)	Coronagraph	C2, C3
STEREO-A/B SECCHI (Howard et al. 2008)	EUV disk, coronagraph, heliospheric imager	EUVI 171, 195, 284 and 304 Å; COR1, COR2; HI1, HI2
GOES/SUVI	EUV disk	94, 131, 171, 195, 284 and 304 Å

The sidebar shows only the tool groups that apply to the instrument class of the loaded data (or, before loading, of the selected observable); see Table 17.4.

17.2 Window layout

The window is divided into the regions numbered in Figure 17.1 and described in Table 17.2.

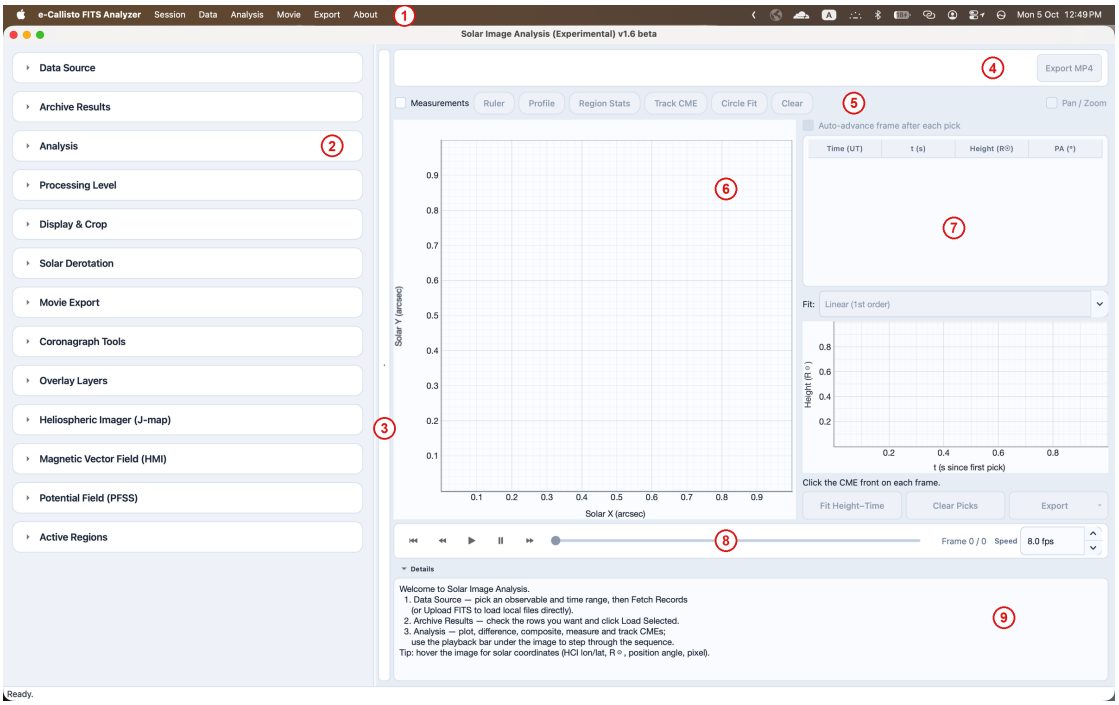


Figure 17.1 The Solar Image Analysis window with its regions numbered.

Table 17.2 Regions of the Solar Image Analysis window.

No.	Region	Description
1	Menu bar	Project, Data, Analysis, Movie, Export and About (Section 17.2.1).
2	Sidebar	Collapsible cards that read from top to bottom as the workflow: get data, choose records, analyze, then display, export and instrument-specific tools.
3	Sidebar handle	Hides or shows the sidebar.
4	Header bar	Live cursor readout — distance from Sun center in $R_\odot$, position angle, heliographic coordinates on the disk, and pixel — and the one-click Export MP4 button.
5	Measure toolbar	The Measurements switch, the Ruler, Profile, Region Stats, Track CME, Circle Fit and Clear tools, and Pan / Zoom (Chapter 19).
6	Image canvas	The current frame, titled with instrument, wavelength and time.
7	CME tracking panel	Measurement table, live height–time graph and kinematic fit; active when Measurements is ticked (Section 19.4).
8	Playback bar	Rewind, previous, play, pause and next buttons, the frame scrubber, the frame counter (Frame n / N) and the Speed in frames per second.
9	Details drawer	Results and warnings of every operation. Click Details to collapse it; drag the divider above it to resize.

The playback speed set in the playback bar is used for playback and for exported movies. While a sequence plays, or while a contrast slider is dragged, the canvas switches to a fast preview that subsamples the display; full resolution returns as soon as playback stops. Measurements, statistics and exports always use the full-resolution data.

17.2.1 Menus

Table 17.3 Menus of the Solar Image Analysis window.

Command	Function
Project → Open Project…	Open a project, or import a version 3.1 `.ecsolar` session (Section 17.4).
Project → Save Project / Save Project As…	Save the project of the main window, including this window's work (Ctrl+S / Ctrl+Shift+S).
Data → Fetch Archive Records	Search the archive (Fetch Records).
Data → Find Latest Available	Find the newest available data (Find Latest).
Data → SOHO Live Preview (Helioviewer)	Near-real-time SOHO quicklook images (Section 17.3.5).
Data → Load Selected (to cache)	Download and load the ticked records.
Data → Save Selected to Disk…	Download the ticked records to a folder.
Data → Upload FITS Files	Load local FITS files.
Data → Use Analyzer Window	Copy the time range of the main window's spectrum.
Data → Stop Download/Search	Cancel the running operation.
Data → Reset All (clear cache & defaults)	Clear the cache and restore default settings.
Analysis → Plot Frames, Running Difference, Composite	Display modes (Section 18.1).
Analysis → Identify Active Regions, Fetch NOAA/HEK Labels	Active-region tools (Section 18.5).
Analysis → Compare Viewpoint…	Compare with a second observer (Section 18.6).
Analysis → GCS CME Fitting…	Open GCS fitting at the time of the displayed frame (Chapter 21).
Analysis → Reset Loaded Frames	Restore the frames as loaded.
Movie → Rewind, Back, Play, Pause, Forward	Playback.
Movie → Build Movie	Export a movie (Section 18.11).
Export → Export Plot, Export Cropped FITS, Export Regions CSV, Export MP4	Exports (Section 18.11).

Command	Function
About → About Solar Image Analysis…	Version information.

17.2.2 Sidebar cards

Table 17.4 lists the sidebar cards in order, and the instrument classes for which each is shown.

Table 17.4 Sidebar cards of Solar Image Analysis.

Card	Shown for	See
Data Source	all	Section 17.3.1
Archive Results	all	Section 17.3.4
Analysis	all (disk tools for disk imagers and magnetographs only)	Section 18.1
Processing Level	AIA and SUVI	Section 17.3.6
Display & Crop	all	Section 18.2
Solar Derotation	all	Section 18.3
Movie Export	all	Section 18.11
Coronagraph Tools	coronagraphs	Section 18.7
Overlay Layers	coronagraphs	Section 18.8
Heliospheric Imager (J-map)	HI1, HI2	Section 18.9
Magnetic Vector Field (HMI)	HMI	Section 18.10
Potential Field (PFSS)	disk imagers, magnetographs, synoptic maps	Chapter 20
Active Regions	disk imagers, magnetographs	Section 18.5

17.3 Obtaining image data

17.3.1 The Data Source card

The Data Source card defines what to retrieve and how.

Observable the instrument and wavelength or product (Table 17.1).

Start (UTC), End (UTC) the time range.

Cadence (s) the sampling interval between frames (0–3600 s; default 120 s).

Max records the maximum number of records to list (1–5000; default 120).

Use Analyzer Time Window copies the start and end times of the spectrum in the main window, so that the images match the radio burst being studied.

Download options

Product what Fetch Records lists and Load Selected downloads (Section 17.3.2): FITS · full resolution, FITS · reduced size or JP2 · quicklook (Helioviewer). The choice is remembered. Products that the selected observable does not have are greyed out, with the reason in their tooltip.

Source (SDO, FITS products) Auto (JSOC → VSO) tries the Joint Science Operations Center (JSOC) first and falls back to the Virtual Solar Observatory (VSO); JSOC (fast) returns direct, compressed AIA files and is usually much faster; VSO (classic) uses the VSO only.

JSOC notify e-mail JSOC requires a one-time, free registration of an e-mail address at https://jsoc.stanford.edu/ajax/register_email.html. The address is remembered.

Frame size for SDO FITS: Full disk (4096^2), Synoptic 1024^2 (no e-mail), Binned ½ (2048^2), Binned ¼ (1024^2) or Cutout (region). The synoptic size reads JSOC's AIA synoptic archive and needs no e-mail. Binned and cutout frames are produced by JSOC, so only the reduced data are transferred; they require the JSOC source and e-mail. For a cutout, enter the Centre X″, Centre Y″, Width″ and Height″ in arcseconds from disk center. For JP2 quicklooks the box offers Native size, Up to 2048 px or Up to 1024 px, which decodes AIA and HMI's 4096-pixel images at a lower resolution to save memory while keeping the coordinates exact.

High resolution AIA (best crop) requests full-resolution AIA products. Files are larger, but cropped views keep more detail.

An estimate of the download size is shown below the options when records are selected.

Actions

Fetch Records searches the archive; the matching records appear in Archive Results. Stop cancels a running search or download; files already completed remain in the cache.

Find Latest scans the archive backwards to find the newest data actually available for the observable. This is useful for SOHO/LASCO, whose calibrated archive can lag real time by many months, and may take a minute or two.

Upload FITS… loads solar FITS files from disk without an archive search.

Live Preview (Helioviewer) shown for SOHO/LASCO and SOHO/EIT (Section 17.3.5).

17.3.2 Download products

FITS · full resolution the archive's own calibrated files: the largest and slowest to download, and the product for photometry.

FITS · reduced size SDO only. The Synoptic 1024^2 (no e-mail) frame size reads JSOC's level-1.5 AIA synoptic archive: 1024-pixel frames at a 2-minute cadence, available about a week after observation, with a near-real-time set covering the latest days (1700 Å is not included). The binned and cutout sizes are made by JSOC on request and need the JSOC notify e-mail.

JP2 · quicklook (Helioviewer) Helioviewer JPEG2000 images for AIA, HMI (magnetogram and continuum), EIT, LASCO and STEREO EUVI, COR1 and COR2. Frames are listed in seconds and are a few hundred kilobytes each, so this is the fast way to inspect an event. GOES/SUVI and the heliospheric imagers have no JP2 product.

Caution. JP2 pixels are 8-bit display values, not calibrated data. Viewing, differences, movies, geometry measurements and derotation work on them, but processing levels, light curves, Region Stats and active-region detection are disabled, and a JP2 quicklook · not calibrated badge above the image and the figure titles say so. Use a FITS product for photometry.

17.3.3 Download progress

The progress bar under the image follows the real transfer from every source: bytes done of the expected total, speed and time remaining, with Show file details listing each file While nothing can be measured — an archive search, or JSOC building binned or cutout frames, which can take minutes — the bar is a busy indicator and the line below it says what is being waited for. After the transfer it counts the frames as they are read, and reaches 100% only when they are on screen. Stop cancels a search, the wait for JSOC or the transfer; files already downloaded stay in the cache.

17.3.4 The Archive Results card

The Archive Results table lists the records found, with the columns Use, Start UTC, Source, Size and File ID. Tick records in the Use column, or use Select All and Deselect All, then:

- Load Selected downloads the ticked records into the working cache and loads them for analysis; or
- Save to Disk… downloads them to a folder you choose, for keeping.

The Analysis card then summarizes what is loaded (instrument, number of frames and configuration).

SOHO data. The archive serves two files for every SOHO/EIT observation, the calibrated Level 1 file and the raw level-zero file. The window chooses one per observation: Level 1 where it exists and the raw file otherwise. Level 1 processing runs about a year behind the raw archive, so recent searches return raw frames and older ones calibrated frames; a window that straddles the boundary loads as two configuration groups. The calibrated SOHO/LASCO archive also lags real time. For a date beyond the newest archived data, the search falls back to the nearest available data and says so. Use Live Preview to see the most recent SOHO images.

17.3.5 Live Preview (Helioviewer)

Live Preview (Helioviewer) opens the SOHO/… Near-Real-Time Preview (Helioviewer) window (Figure 17.2) with the newest quicklook image of SOHO/LASCO C2 or C3 or SOHO/EIT, usually updated within about an hour. These browse images are for situational awareness, not for analysis.

Passband / Detector, Latest Frame choose the EIT passband or LASCO detector, and reload the newest image.

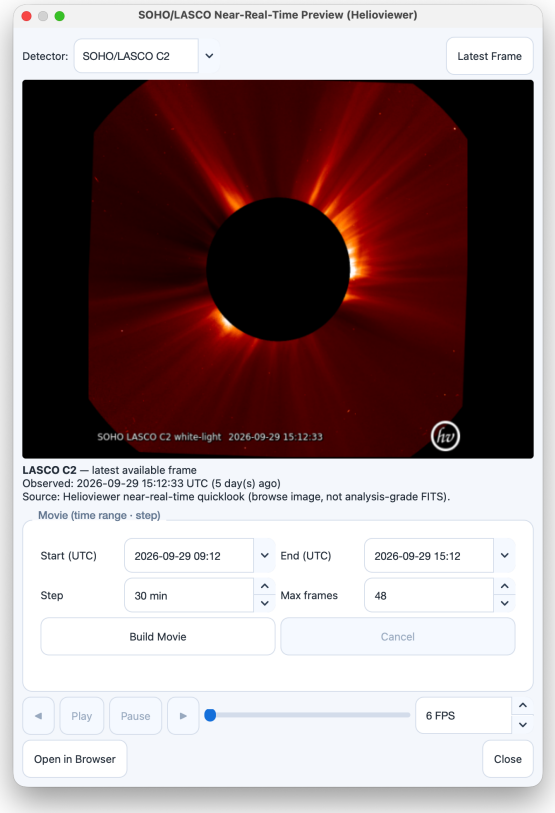


Figure 17.2 The SOHO near-real-time preview.

Movie (time range · step) set Start (UTC), End (UTC), Step (minutes) and Max frames, then Build Movie to fetch one frame per step and play them with ◂, Play, Pause, ▸ and an FPS setting. Cancel stops the fetch. The frame cap protects the Helioviewer service.

Open in Browser opens the view on the Helioviewer web site.

17.3.6 Processing level

Downloads always fetch the archive's base product. For instruments that publish more than one processing level, the Processing Level card selects the level that is displayed and analyzed:

SDO/AIA Level 1 (as downloaded), the archive product; or Level 1.5 (registered here), computed locally with aiapy (Barnes et al. 2020), which applies the master pointing, rotates the image to solar north, rescales it to 0.6 arcsec per pixel and centers the Sun.

GOES/SUVI Level 1b (as downloaded), single calibrated exposures; or Level 2 (archive composite), NOAA's high-dynamic-range composites, which are downloaded separately when selected.

Apply Level re-derives the loaded sequence at the selected level; any crop or derotation is reapplied afterwards. The status line reports the level in use. The card is hidden for instruments that offer only one level.

17.4 Saving the work in a project

The frames, data source, display, crop and playback settings, the CME measurements (height–time picks, circle fits and fit order) and the PFSS settings are part of the main window's project (Section 10.1). Project → Save Project (Ctrl+S) and Save Project As… (Ctrl+Shift+S) in this window save that project. With Link data the project refers to the frames on this computer; a linked project whose frames have been moved or cleared from the cache fetches them again from the archive. With Embed data the frames are stored in the project. Measurements are matched to the reloaded frames by observation time, and an overlay composite built when the project was saved is built again once the frames are in. The PFSS solution itself is not stored; one click on Compute PFSS reproduces it.

A Solar Image Analysis session (`.ecsolar`) from version 3.1 or earlier can still be opened with Project → Open Project…: it is imported as a new, unsaved project. `.ecsolar` files are no longer written.

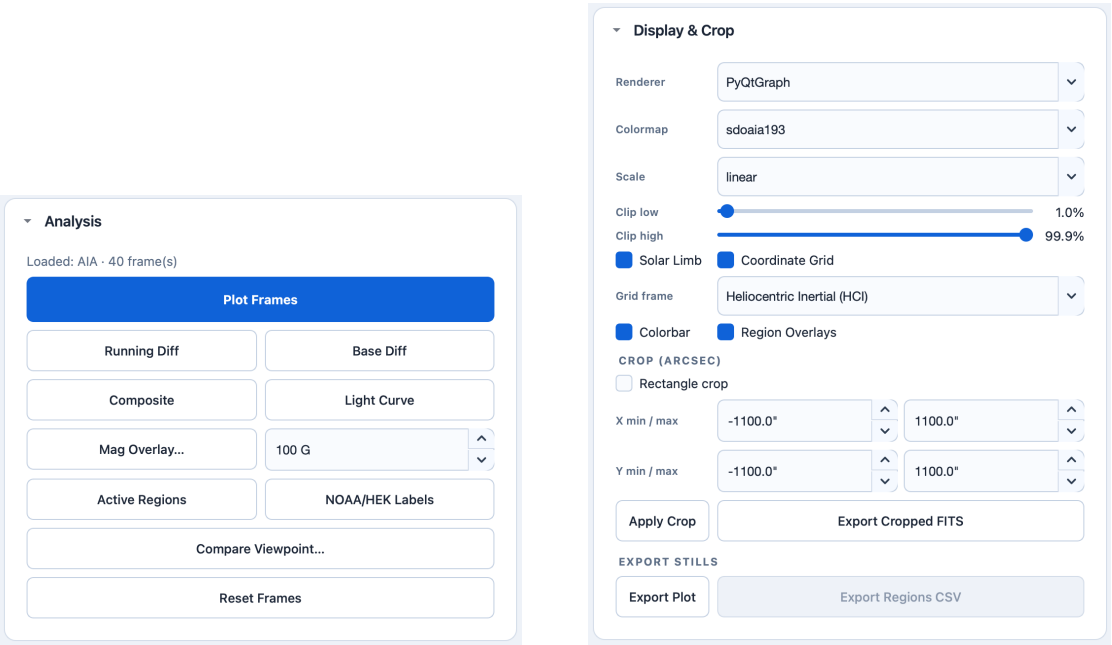
18

Image Display and Processing

This chapter describes the tools of Solar Image Analysis that display, enhance, combine and export image sequences once they are loaded (Chapter 17).

18.1 The Analysis card

The Analysis card (Figure 18.1a) shows a summary of the loaded data and the main display modes and analysis tools.



(a) Analysis card (b) Display & Crop card

Figure 18.1 The Analysis and Display & Crop cards of Solar Image Analysis.

Plot Frames displays the loaded sequence as plain frames.

Running Diff displays each frame minus the previous one, which makes moving and changing features stand out.

Base Diff displays each frame minus the first, showing the total change since the start — useful for eruptions, coronal dimmings and EUV waves.

Composite builds an RGB tri-color image from the first three AIA frames or, when a magnetogram overlay has been loaded, draws HMI polarity contours on the current AIA frame (red positive, blue negative).

Mag Overlay… loads an HMI magnetogram FITS file for the composite; the box beside it sets the contour level (10–2000 G; default 100 G).

Light Curve plots the mean intensity of a region against time (Section 18.4).

Active Regions , NOAA/HEK Labels detect and label active regions (Section 18.5).

Compare Viewpoint… compares the frame with a second observer (Section 18.6).

Reset Frames restores the frames as downloaded, discarding crops, processing levels, derotation, composites and detected regions.

Composite, Mag Overlay…, Active Regions and NOAA/HEK Labels are available only for disk imagers and magnetographs. The difference modes also determine the content of exported movies (Section 18.11).

18.2 Display and cropping

The Display & Crop card (Figure 18.1b) controls the appearance of the image:

Renderer PyQtGraph (default; fast, and required for clicked PFSS seeds and the interactive crop rectangle) or Matplotlib.

Colormap instrument color maps (for example `sdoaia193`, `hmimag`, `soholasco2`, `stereocor2`, `euvi195`, `goes-rsuvi171`) and general ones (`inferno`, `magma`, `plasma`, `viridis`, `cividis`, `gray`, `RdBu_r`, `hot`). A suitable map is chosen automatically for each observable.

Scale linear or log.

Clip low, Clip high the lower and upper percentiles mapped to the ends of the color scale (defaults 1% and 99.9%); dragging gives a live preview.

Solar Limb draws the photospheric limb.

Coordinate Grid, Grid frame overlays a graticule of meridians and parallels in the selected frame — Heliocentric Inertial (HCI, the default), Stonyhurst or Carrington. The same frame is used for the heliographic coordinates of the cursor readout.

Colorbar, Region Overlays show the color bar and the detected active regions.

Cropping

Under Crop (arcsec), enter X min / max and Y min / max in arcseconds from disk center, or tick Rectangle crop to drag a rectangle on the image that fills in the fields. Apply Crop crops all loaded frames to the rectangle. Cropping is done locally after the files are loaded. Export Cropped FITS saves the cropped frames as FITS files with updated coordinate metadata.

The crop rectangle also defines the region used by Region Stats, the light curve, the derotation and the Current crop PFSS seeding.

18.3 Solar derotation

Over a sequence of several hours, a fixed rectangle slowly drifts onto neighboring surface because of solar differential rotation. The Solar Derotation card keeps a selected region on the same piece of the Sun:

Derotate selected area enables derotation of the crop region.

Mode Track region (no resampling) moves the cut-out window with the rotation and keeps the original pixel values, so it is the mode for photometry and light curves. Reproject to reference time resamples every frame onto the reference time's grid, which corrects foreshortening and gives all frames one coordinate system, making differencing meaningful, at the cost of interpolating the data.

Reference First frame, Current frame or Specific frame... (with its number): the frame from which the region is read and to whose time every other frame is rotated.

Padding the extra margin cut around the region before reprojecting (0–600 arcsec; default 60 arcsec), so that the interpolation has data up to the edge. Reproject mode only.

Apply Derotation, Reset to Full Frames apply the derotation, or discard the cut-out and restore the full frames at the current processing level.

The status line reports whether derotation is active.

18.4 Region light curve

Light Curve plots the mean intensity of the crop region (or of the whole frame if Rectangle crop is off), converted to DN/s using the exposure time, against time (Figure 18.2). The time of peak intensity is marked and, when a spectrum is loaded in the main window, its time window is shaded so that the EUV brightening can be timed against the radio burst. At least two frames are needed.

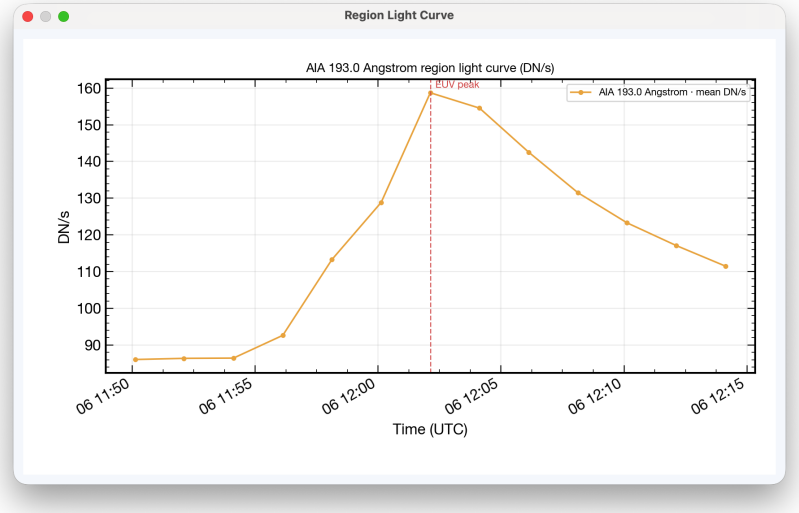


Figure 18.2 The Region Light Curve window.

18.5 Active regions

The Active Regions card detects bright regions in the current frame and lists them:

Threshold the intensity percentile above which pixels count as bright (50–100; default 98).

Min px the minimum area of a region in pixels (default 12).

Region table one row per region with ID, Label, NOAA number, Centroid, Area, Peak intensity and Source.

Click Active Regions in the Analysis card to run the detection, and NOAA/HEK Labels to fetch the NOAA active-region numbers from the Heliophysics Event Knowledge base (HEK) and attach them to the detected regions; the status line reports whether metadata are loaded. Detected regions are drawn on the image when Region Overlays is ticked. Export Regions CSV saves the table with centroids, bounding boxes and intensities. Detection works on local files; the labels need network access.

18.6 Comparing viewpoints

Compare Viewpoint… opens a window that compares the current frame (viewpoint A) with a second observable (viewpoint B) taken near the same time — for example a STEREO image against the Earth view.

1. Choose the Second viewpoint observable and the search window (±, 1–720 min; default 30 min).
2. Click Fetch Viewpoint B. Viewpoint B is downloaded, reprojected onto the coordinate frame of A, and shown beside it.
3. Tick Blink to alternate between the two images in place.

The Observer separation line gives the angle between the two observers.

18.7 Coronagraph tools

For coronagraph data the Coronagraph Tools card offers two tools:

NRGF radial filter the normalizing-radial-graded filter (Morgan et al. 2006). It flattens the steep radial fall-off of coronal brightness so that faint CME fronts become visible at all heights. It applies to the plain frame view; difference images already remove the background.

AIA 193 Sun in the occulter for SOHO/LASCO C2 and C3 frames. One tick fills each frame's occulted center with the SDO/AIA 193 Å image nearest its time, so that an eruption on the disk and the CME in the corona are seen together. The whole AIA image is kept, off-limb corona included, at true scale (it is small in C3), and it never covers LASCO's own field of view. The AIA frames come from Helioviewer's JPEG2000 archive, so a day's series builds in seconds. AIA colormap, below the tick box, recolors the AIA image at once (AIA passband maps, grey, hot, inferno and others), while the LASCO color map stays under Display &

Crop. The layer is also listed in Overlay Layers, where its color map, opacity and midtones can be changed. Untick to return to the plain LASCO frames.

Composites are blended each time a frame is drawn, so the color map, contrast sliders, scale, NRGF filter and running or base difference keep working on them (in a difference view the AIA image is differenced too), and they play, measure and export like plain frames.

18.8 Overlay layers

A CME is never fully visible in one instrument: the eruption starts on the disk (AIA, EIT, EUVI), crosses the low corona (LASCO C2, COR1) and expands into the outer corona (LASCO C3, COR2), and each coronagraph is blind inside its occulter. For coronagraph views the Overlay Layers card blends several instruments into one continuous image from the disk to the outer corona.

Add, Remove choose an observable and add it to the layer list, or remove the selected layer. Layers are painted widest field of view first. Untick a layer to leave it out without losing its settings.

Per-layer settings for the selected layer: Colormap, Scale (log or linear), Opacity, Midtones (gamma; 50 suits most solar images), and the Inner and Outer edges of its field of view in $R_\odot$. Pixels inside the inner edge stay transparent so that the layer below shows through.

Time match how far from each loaded frame's time a layer frame may be taken (1–720 min; default 30 min). Widen it for slow cadences or patchy archives.

Build Composite downloads each layer's matching frames and reprojects them onto the loaded series, in the background with a progress bar. The layers are then blended live on every draw, so the display controls keep working, and the result works with the measurement tools, plot export and movie export. A composite built after a crop is cut to the same crop.

Clear drops the composite and restores the originally loaded frames.

> **Note.** Each layer is color-mapped before blending, because EUV disk images and the white-light corona differ by orders of magnitude. Coronagraph layers are reprojected under a spherical-screen assumption, flagged as approximate in the build notes: cross-observer coronagraph overlays are morphological context, not photometry. SOHO/LASCO files carry no observer position, so an Earth-based observer is assumed (accurate to about 1%).

18.9 Heliospheric imager J-maps

For STEREO HI1 and HI2 data the Heliospheric Imager (J-map) card builds a time–elongation map (Sheeley et al. 1999):

Background Median background removes the static F-corona and star field with the per-pixel temporal median; Previous frame uses a running difference.

PA the position angle of the slit, counter-clockwise from the image $+x$ axis (90° points up; default 90°). Set it along the CME direction.

Build J-map stacks the slit profiles of all frames into the HI J-map window (elongation in degrees against frame index). An outward-moving CME appears as a slanted bright track.

18.10 HMI vector magnetic field

For SDO/HMI data the Magnetic Vector Field (HMI) card overlays the measured photospheric vector field:

Load Vector FITS… loads the `hmi.B_720s` field, inclination and azimuth segments of each time step from disk (with the optional disambiguation segment, applied automatically).

Download Vector (JSOC) downloads `hmi.B_720s` for the query time window through JSOC; this needs the registered JSOC e-mail. Each 720-s time step is four segments of about 50 MB. If no HMI image is loaded, the derived vertical-field (B_z) magnetogram is plotted with the vectors.

Show vector field overlays the field on the HMI frame. The transverse component is drawn as Arrows (length proportional to strength) and/or Streamlines, and |B| layer tints the image by total field strength. Arrows are red where the vertical field points toward the observer ($+B_z$) and blue where it points away.

Spacing, Threshold the arrow grid spacing (16–512 detector pixels; default 64) and the minimum transverse field drawn (50–2000 G; default 200 G). The transverse noise floor of `hmi.B_720s` is about 100 G.

18.11 Movies and still images

Movie Export card choose the Content (Frames, Running Difference or Base Difference) and the Format (MP4 or GIF), and click Build Movie.… Movies play north up, as on screen, and use the playback speed set under the viewer and the current color map, scale, clipping and crop. With Frame labels (instrument, date, time) ticked (the default), each frame carries its instrument and UTC observation date and time on a thin stripe along the bottom, and the difference it shows in a running- or base-difference movie; untick it for a clean movie.

Export MP4 in the header bar makes a one-click MP4 of the loaded sequence with the current display settings.

Export Plot saves the current frame, with its overlays, as an image.

Export Cropped FITS saves the cropped frames as FITS files.

Export Regions CSV saves the active-region table.

The same exports are available from the Export and Movie menus.

19

Measurements and CME Kinematics

The Measure toolbar above the image provides click-driven tools for distances, intensity profiles, region statistics and CME tracking. The CME tracking panel to the right of the image collects the measurements of a sequence and fits their kinematics.

19.1 Enabling the tools

Tick Measurements in the Measure toolbar to enable the tools; the CME tracking panel becomes available at the same time. One tool is active at a time. A right-click or Esc cancels a pick in progress without leaving the tool. Results are shown in the status line and appended to the Details drawer. Pan / Zoom, at the right of the toolbar, enables dragging and scroll-wheel zooming of the image; the zoom is kept while the movie plays, and unticking it returns to the full frame.

Table 19.1 Tools of the Measure toolbar.

Tool	What it does
Ruler	Two clicks give the plane-of-sky distance in arcseconds, $R_\odot$ and Mm, and the position angle (measured from north toward east).
Profile	Two clicks plot the intensity along the cut, for example across a loop, a filament or a CME front, in the Intensity Profile window.
Region Stats	Summarizes the crop rectangle: pixel count, mean, median, minimum, maximum, standard deviation and intensity-weighted centroid (arcsec). Enable Rectangle crop first to choose the region.
Track CME	One click per frame on the leading edge of a CME. The height is its distance from disk center. Best for limb events.
Circle Fit	Three or more clicks along a circular front per frame. Best for eruptions near disk center.
Clear	Resets every measurement: picks, circles, table and overlays.

The 3-D reconstruction of CMEs from several viewpoints is performed in the separate GCS CME Fitting window (Part VI), opened from Analysis → GCS CME Fitting….

19.2 Tracking a CME

Track CME measures a height–time profile with one click per frame (Figure 19.1).

1. Go to the first frame in which the CME front is visible.
2. Select Track CME and click the leading edge. The pick is added to the tracking table and, with Auto-advance frame after each pick ticked (the default), the next frame is shown.
3. Repeat on each frame, then choose the fit order and click Fit Height–Time.

The height is the plane-of-sky distance of the clicked point from Sun center in $R_\odot$; the position angle (PA) is recorded with it. The tool works on any imager — EUVI, AIA, SUVI, COR, LASCO and HI. Clicking again on a frame replaces its pick.

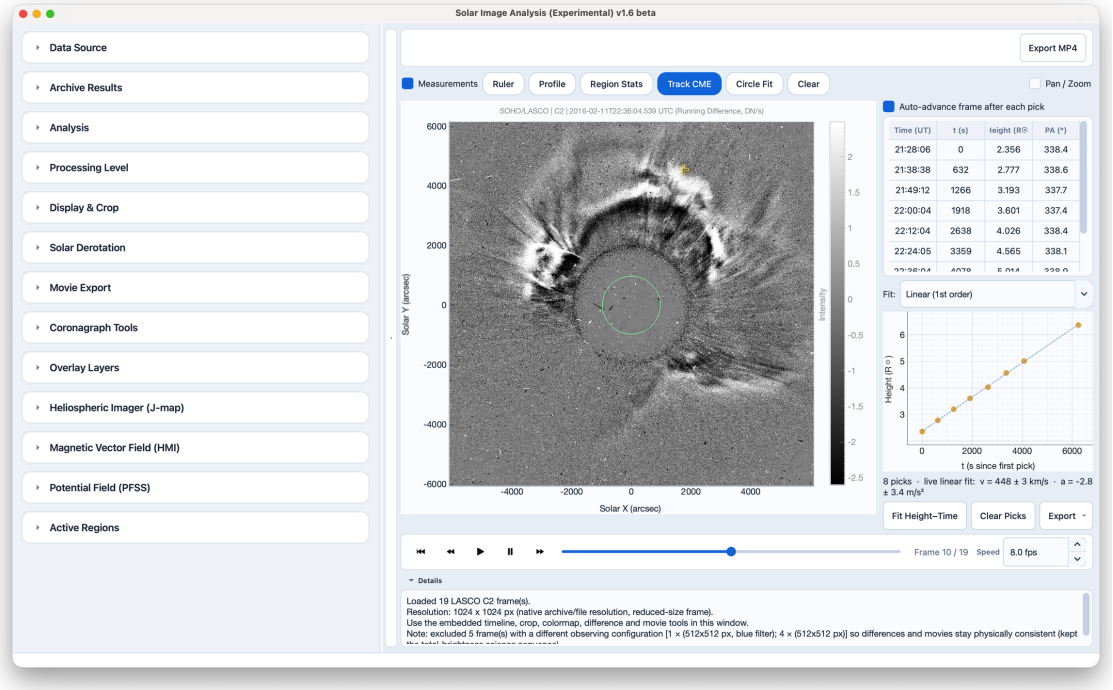


Figure 19.1 CME tracking with the height–time graph in the tracking panel.

19.3 Fitting a circle to a CME front

For eruptions near disk center the front expands as a growing dome rather than moving outwards from the limb, and a single leading-edge click has no well-defined origin. Circle Fit models the CME as a uniformly expanding sphere resting on the solar surface (Figure 19.2).

1. Select Circle Fit and click three or more points along the visible front. The least-squares circle is drawn from the third click and tightens with each further point.
2. Click Commit Circle (Ctrl+Return). The frame's result is added to the table and the next frame is shown.

3 Repeat on each frame, then click Fit Height–Time.

Each row gives the height $h = 1\,R_\odot + 2r$, where r is the fitted radius (the sphere's top is one diameter above the surface), the radius in $R_\odot$, the position angle of the center and the number of points. The fit residual, the center and the leading-edge distance from disk center appear in the row's tooltip. Re-committing a frame replaces its entry.

- Click a wide arc. A short arc is fitted, but it constrains the radius very weakly, and the panel warns when the arc spans less than about 30°.
- Lock centre freezes the center at its current fitted value so that later frames fit the radius alone. Use it once the dome has stopped drifting.

The fit uses Taubin's method (Taubin 1991), which is not biased toward small radii on partial arcs, and works in helioprojective arcseconds so that the front remains a circle when the plate scale differs between the axes.

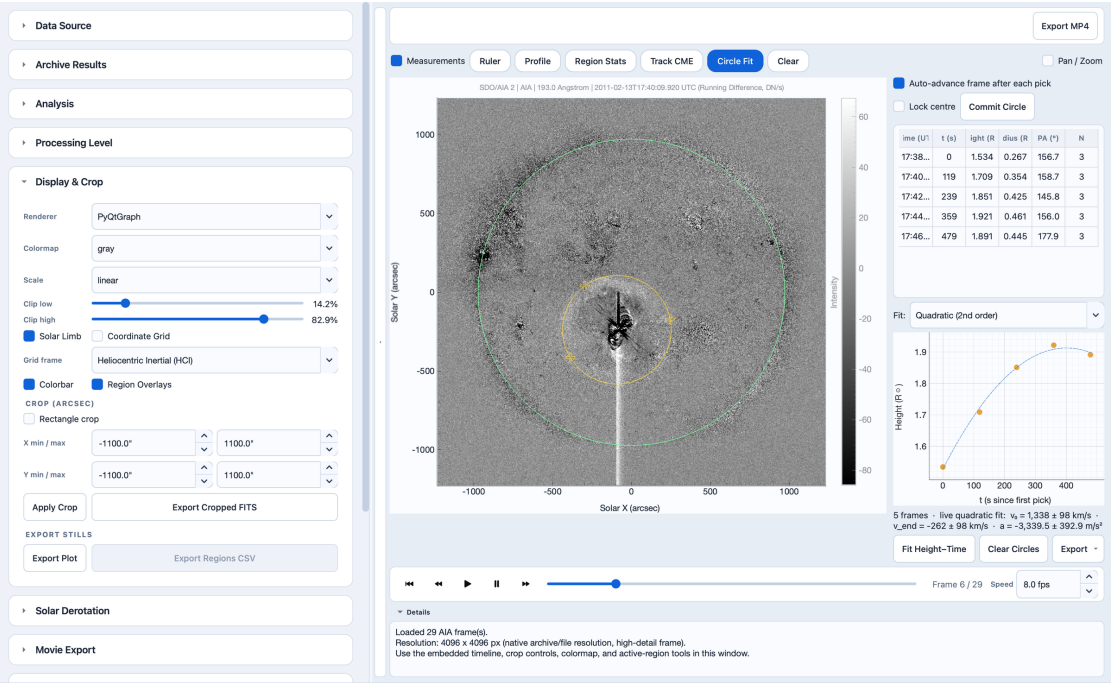


Figure 19.2 Circle fitting of an on-disk CME front.

19.4 The CME tracking panel

The tracking panel shows the measurements of the active tool:

Table for Track CME: Time (UT), t (s) since the first pick, Height (R⊙) and PA (°); for Circle Fit: additionally Radius (R⊙) and the number of points N.

Height–time graph the measured heights against time, with the live fit.

Fit the polynomial order: Linear, Quadratic or Cubic. Changing it refits the points already in the graph.

Fit Height–Time fits the points and reports the speed and acceleration below the graph.

Clear Picks / Clear Circles removes the measurements of the active tool.

Export Table as CSV…, or Graph (PNG, PDF, EPS, SVG, TIFF, JPG)… drawn in light mode and the OriginPro style.

Background: height–time fits

Linear $h = h_0 + vt$: one plane-of-sky speed for the whole track. The acceleration is taken from a companion quadratic fit, as in the CDAW CME catalog.

Quadratic $h = h_0 + v_0 t + \frac{1}{2}at^2$: constant acceleration, with the speed reported at the first and last frame.

Cubic adds a constant jerk, with the speed and acceleration reported at both ends.

Every value carries a 1σ uncertainty propagated from the fit covariance, so the correlations between the polynomial terms are included. A fit of degree n needs $n + 1$ points, and $n + 2$ before an uncertainty can be estimated; with fewer points the value is shown without an error rather than with a misleading zero. Heights from Track CME are plane-of-sky distances, so the derived speeds generally underestimate the true radial speed; Circle Fit heights rely on the assumption of a sphere expanding from the surface.

The measurements — picks, circles, the lock state and the fit order — are saved in the project and matched to the reloaded frames by observation time (Section 17.4). Region Stats is disabled for JP2 quicklook frames, whose pixels are display values (Section 17.3.2).

20

Coronal Magnetic Field Modeling (PFSS)

An EUV image shows where the coronal plasma is, not where the magnetic field is. The Potential Field (PFSS) card of Solar Image Analysis extrapolates the coronal magnetic field from a photospheric magnetogram with the potential-field source-surface model (Altschuler and Newkirk 1969; Schatten et al. 1969) and draws the resulting field lines over the disk (Figure 20.1), so that the modeled loop topology and coronal holes can be compared with the image. The card is shown for disk imagers, magnetographs and synoptic maps.

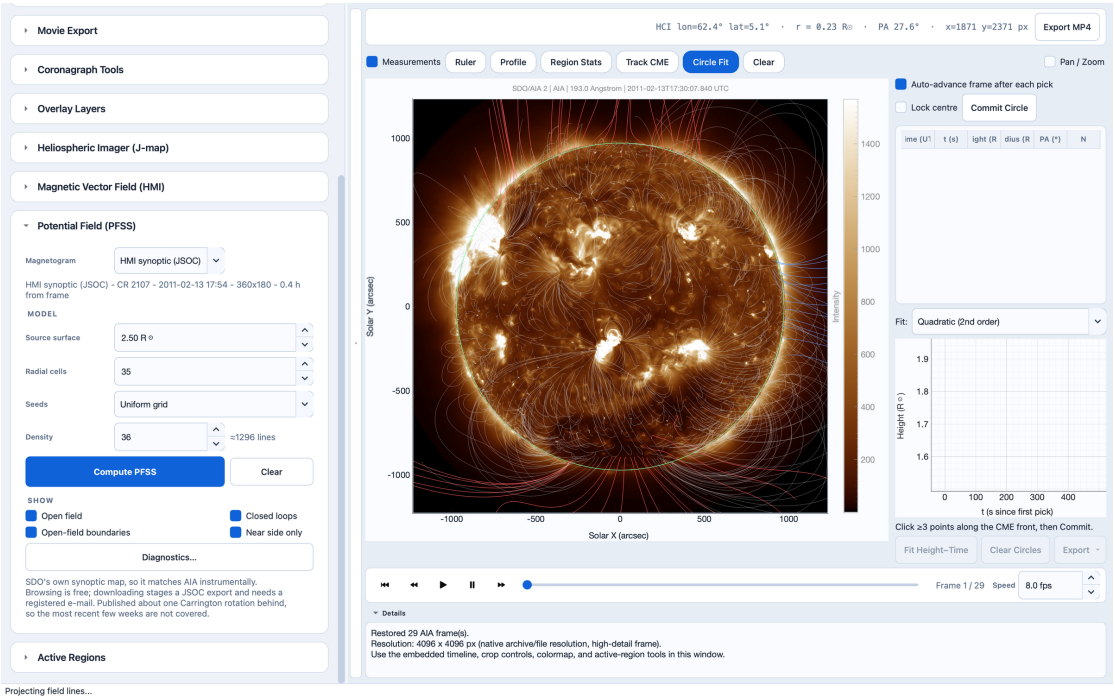


Figure 20.1 PFSS field lines over an AIA image.

Background: the PFSS model

The model assumes a current-free (potential) field between the photosphere and a spherical *source surface* a few solar radii out, where the field is forced to be radial to mimic the solar wind dragging it open. Field lines that reach the source surface are *open* and feed the solar wind; the others are *closed* loops. The open-field footpoint regions are the model's coronal holes, and the polarity-inversion line on the source surface marks where the heliospheric current sheet leaves the model.

Caution. AIA images carry no magnetic-field information, so the boundary condition comes from a *synoptic* magnetogram — a full-Sun map assembled from central-meridian observations over a whole solar rotation. The model therefore describes the global field around your observation, never the instantaneous field, and the far side is always at least two weeks old. The card shows how far the map's date is from the displayed frame; that offset is the number to judge the result by.

20.1 Settings

Table 20.1 Settings of the Potential Field (PFSS) card.

Setting	Description
Magnetogram	The boundary condition (Section 20.1.1). For GONG ADAPT, Realization (0–11) chooses one of the twelve flux-transport realizations; for Local FITS file..., Browse… selects the file. The line below names the loaded map and its time offset from the frame.
Source surface	Height at which the field is forced radial (1.5–10 $R_\odot$; default 2.5 $R_\odot$). Lowering it opens more field.
Radial cells	Radial grid resolution between the photosphere and the source surface (10–150; default 35). More is smoother and slower.
Seeds	Where field lines start (Section 20.1.2).
Density	Seed density (4–64; default 12, about 150 field lines). It controls both speed and legibility; the hint beside it estimates the number of lines.

20.1.1 Magnetograms

GONG synoptic the ground-based GONG synoptic map (Harvey et al. 1996), updated daily and available for any date from 2006 on. No registration is needed; this is the usual choice.

HMI synoptic (JSOC) SDO's own synoptic map, instrumentally consistent with AIA. Searching is free, but downloading stages a JSOC export and needs the registered e-mail set in the Data Source card. The series is published about one Carrington rotation behind, so the most recent weeks are not covered.

GONG ADAPT maps from the ADAPT flux-transport model, which estimates the unobserved far side instead of leaving it weeks old and usually improves open-field predictions. One file holds twelve realizations, which differ mostly on the far side.

Local FITS file... a synoptic map you already have. It must be a full-Sun Carrington map; plate-carrée maps are reprojected to equal-area automatically.

Downloaded magnetograms are cached, so changing a model parameter and solving again does not download the map again. Unmeasured pixels, such as the polar gaps in GONG maps, are filled with zero so that the solution can be computed; their number is reported.

20.1.2 Seeds

Uniform grid an equal-area sample over the visible hemisphere.

Open-field regions a coarse survey is traced first, and then lines are started only where the field is open. This shows coronal-hole connectivity without closed loops dominating the picture.

Current crop concentrates the lines inside the crop rectangle.

Clicked points traces one line from each point clicked on the disk. This needs the PyQtGraph renderer.

Tracing costs about 1.6 ms per field line, so a solution takes a few seconds at most, but beyond about 150 lines the field lines start to hide the image they are compared with. Prefer Open-field regions to a high density when coronal-hole connectivity is what you want.

20.2 Computing and displaying the model

Compute PFSS downloads the magnetogram if needed, solves the potential field and traces the field lines in the background; Clear removes the overlay and the solution. The Show options toggle the layers without recomputing:

Open field lines reaching the source surface, colored by the sign of the radial field at their footpoint: red outward, blue inward.

Closed loops lines returning to the photosphere, drawn in gray.

Open-field boundaries outlines of the open-field footpoint regions, for comparison with the dark coronal holes in 193 or 211 Å images.

Near side only (on by default) hides lines rooted on the far hemisphere. Such lines are not hidden behind the disk once they rise above the limb, so they would otherwise be drawn as arcs outside the disk with no visible footpoint. Clear it for the geometrically complete picture.

Stepping through a sequence re-projects the same solution onto each frame instead of solving again. This is correct, because the synoptic map is valid across the rotation while the observer's view changes from frame to frame.

20.3 Diagnostics

Diagnostics… opens a four-panel window that documents the solution (Figure 20.2):

1. the input magnetogram (B_r) with its provenance;
2. the radial field at the source surface with its neutral line, where the heliospheric current sheet leaves the model — the model's most directly testable prediction;
3. the open (red and blue) and closed (dark) footpoint map in Carrington projection;
4. the solution statistics, including the open flux, the open-area fraction and the number of filled pixels.

Save Figure… saves all four panels as one image (PNG, PDF or SVG).

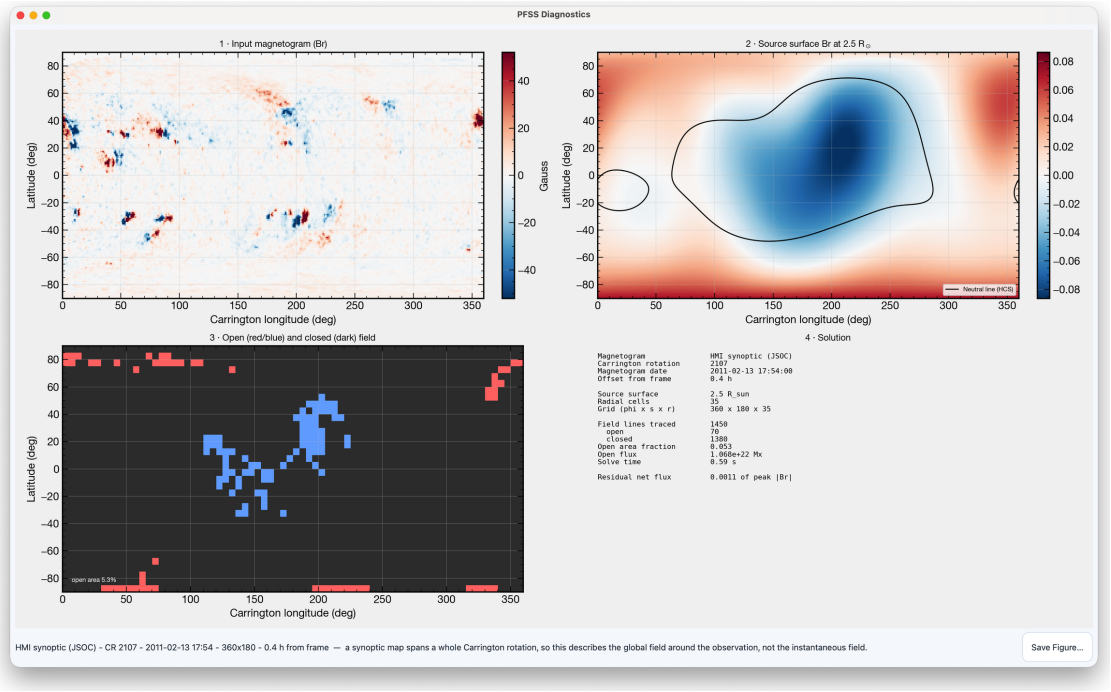


Figure 20.2 The PFSS diagnostics window.

> **Note.** PFSS modeling uses the `sunkit-magex` package (Stansby et al. 2020), which is included in the installers. When the application is run from source without it, the card remains visible but disabled and shows the command to install it. Projects store the PFSS settings, not the solution (Section 17.4).

Part VI

Three-Dimensional CME Reconstruction

Multi-viewpoint reconstruction of coronal mass ejections and their shocks with the Graduated Cylindrical Shell and spheroid/ellipsoid models.

21

The GCS CME Fitting Window

A single coronagraph view cannot separate a CME's direction from its size: a wide CME aimed at the observer and a narrow one crossing the sky can look alike. Two well-separated views break that ambiguity, and a third over-constrains it. The GCS CME Fitting window reconstructs a CME in three dimensions by fitting one Graduated Cylindrical Shell (GCS) model (Thernisien 2011; Thernisien et al. 2006) to up to three coronagraph viewpoints at once, and optionally a spheroid or ellipsoid to the shock the CME drives (Kouloumvakos et al. 2019; Kwon et al. 2014). The parameters follow the conventions of PyThea (Kouloumvakos et al. 2022), so results can be compared directly.

This chapter describes the window and how images are loaded and viewed. Fitting, recording and exporting are described in Chapter 22.

21.1 Opening the window

Open the window with Analysis → GCS CME Fitting… in the main window or in Solar Image Analysis. The window downloads its own images, so nothing needs to be loaded first:

- from the main window, the visible time range of the spectrum becomes the event range;
- from Solar Image Analysis, the event range is centered on the displayed frame, one hour either side.

Choosing the menu item again reuses the open window and passes it the new time.

The fitting is part of the main window's project (Section 10.1): its channels, display settings, front points and recorded fits are saved with the radio and Solar Image Analysis work, and a reopened project restores the window. With Embed data the JPEG2000 images are stored in the project too, so the fit reopens offline.

21.2 Window layout

The window is divided into the regions numbered in Figure 21.1 and described in Table 21.1.

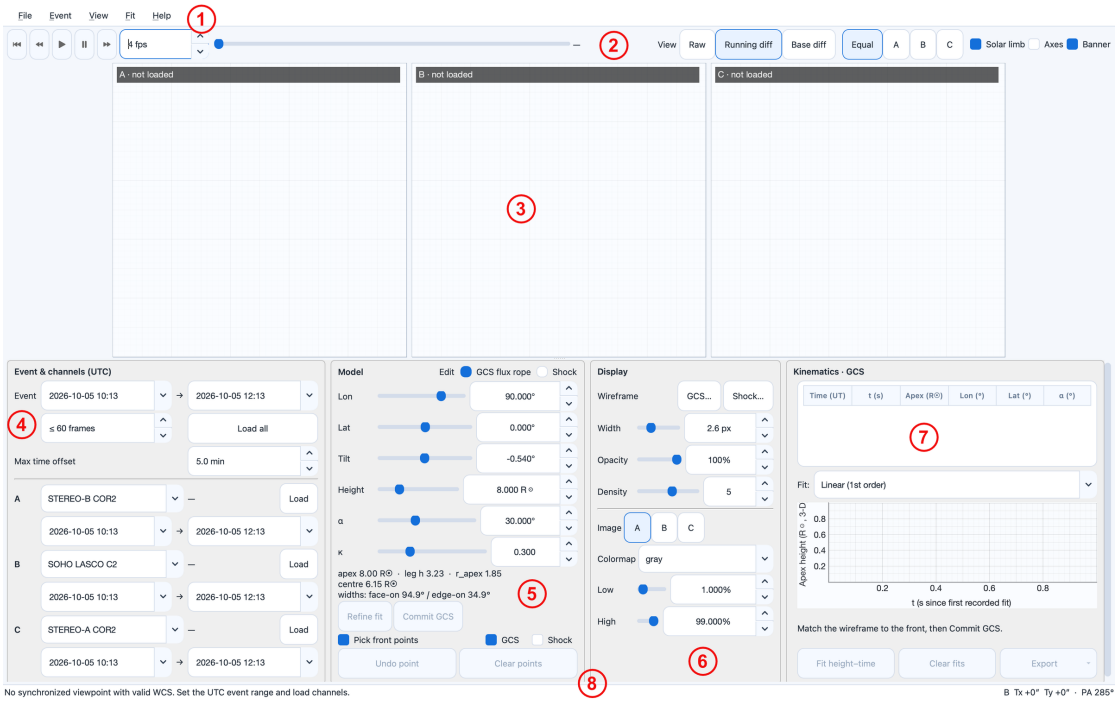


Figure 21.1 The GCS CME Fitting window in the equal layout.

Table 21.1 Regions of the GCS CME Fitting window.

No.	Region	Description
1	Menu bar	File, Event, View, Fit and Help (Section 21.7).
2	Toolbar	Playback, the shared time, image mode, layout and overlay toggles (Section 21.3).
3	Viewpoint panels	Panels A, B and C, each showing one channel's image nearest the shared time, with the models drawn on it.
4	Event & channels card	Event range, frame cap, time-offset limit and the three channels (Section 21.4).
5	Model card	The edited model, its parameters, front-point controls, Refine fit and Commit (Chapter 22).
6	Display card	Wireframe colors and style, and each image's color map and contrast (Section 21.6).
7	Kinematics card	Recorded fits, height–time graph and fit (Section 22.6).
8	Status bar	Messages, including the views taking part in a fit and their separations, and the helioprojective position under the cursor.

21.3 Toolbar

Playback first frame (Home), previous (←), play and pause (Space), next (→), and the playback speed (1–30 fps; default 4 fps). With fits recorded, the model follows them during playback.

Time slider and time label step through the event. Every panel shows its own image nearest the selected UTC time, which is displayed beside the slider.

View Raw (the images as downloaded), Running diff (each image minus the previous one; selected whenever images load) or Base diff (each image minus the first of the sequence).

Layout Equal shows three equal images with the cards beneath (0); A, B or C enlarges that panel, stacks the other two beside it and moves the cards to the right (1–3).

Solar limb, Axes, Banner outline the photosphere in every image (on by default; the reference against which a CME's height is judged), show arcsecond axes around each image, and show the information banner across the top of each image (B).

The keys apply while an image has keyboard focus.

21.4 Loading the viewpoints

The Event & channels (UTC) card (Figure 21.2) defines what is loaded.

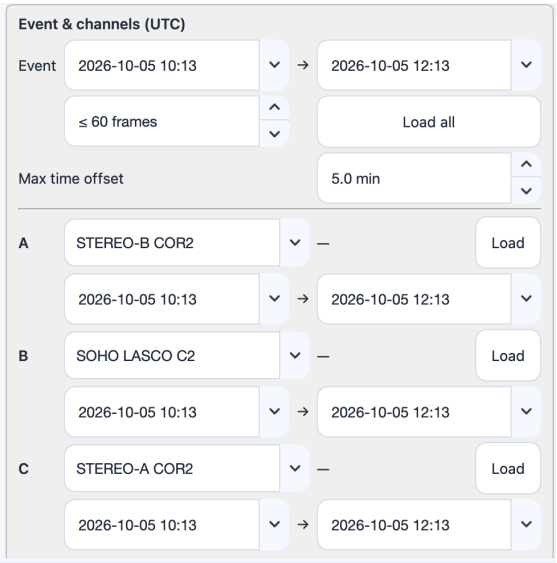


Figure 21.2 The Event & channels card.

Event the UTC start and end of the event, up to three days. Changing them sets every channel's range; each channel's range can then be adjusted on its own.

≤ frames the maximum number of images per channel (2–200; default 60). A longer sequence is thinned evenly across the event rather than cut short.

Load all (Ctrl+L) loads every channel. Each channel also has its own Load button and a frame count. Event → Cancel downloads stops a slow load.

Max time offset the largest difference between an image's time and the shared time for the image to take part in a fit (0–60 min; default 5 min). Models are still drawn on the other panels for comparison. Use a smaller value for a fast-evolving CME; the default is a workflow choice, not an accuracy guarantee.

A, B, C the channel of each panel and its time range.

The available channels are listed in Table 21.2. By default panels A, B and C show STEREO-B COR2, SOHO LASCO C2 and STEREO-A COR2, left to right. Channels without data for the event date are grayed out. The STEREO-B archive ends on 27 September 2014, so for later events panel A reports that it has no data; only SOHO and STEREO-A then remain as vantage points, and another channel in panel A (LASCO C3 or COR1-A) adds an image but not a new viewing direction.

Table 21.2 Coronagraph channels available for GCS fitting.

Channel	Available
SOHO LASCO C2	from 21 February 1997
SOHO LASCO C3	from 20 February 1997
STEREO-A COR1	from 4 December 2006
STEREO-A COR2	from 29 December 2006
STEREO-B COR1	12 December 2006 to 27 September 2014
STEREO-B COR2	10 January 2007 to 27 September 2014

The images are Helioviewer JPEG2000 files, so loading needs network access; downloaded images are cached and reused. Changing a channel's source or range discards its loaded images and any pending results. A 15-minute e-CALLISTO file spans only one or two coronagraph images (about one every 15 minutes for COR2 and every 12 minutes for LASCO C2), so widen the range to follow a CME.

21.5 Reading the images

The banner across each image gives the instrument, the actual observation time, its offset from the shared time and the difference reference. In running difference the first image of each channel is differenced against the archive image just before the range, and is shown raw only when no earlier image exists. Clicked front points belong to the image on which they were clicked and return when that image is shown again.

21.6 The Display card

Wireframe GCS… and Shock… choose the colors of the two models (orange and sky blue by default); Width (0.5–8 px), Opacity (10–100%) and Density (mesh density, 1–8) set the

wireframe style.

Image A, B, C select a panel, then set its Colormap and contrast sliders. Every load resets the color map to gray.

21.7 Menus

Table 21.3 Menus of the GCS CME Fitting window.

Command	Function	Shortcut
File → Open Project…	Open a project in the main window.	
File → Save Project	Save the main window's project, including this fit.	Ctrl+S
File → Save Project As…	Save the project to a new file.	Ctrl+Shift+S
File → Export analysis JSON…	Parameters, points and provenance of both models.	
File → Export recorded fits CSV…	Recorded series of the edited model.	
File → Export height–time graph…	Height–time graph with the chosen fit.	
File → Save viewpoint snapshot…	The three views as shown.	
File → Export movie (GIF/MP4)…	Movie of the event with recorded shells.	
File → Export fitting report (PDF)…	Complete fitting report.	
File → Close window	Close the window.	Ctrl+W
Event → Load all channels	Load every channel.	Ctrl+L
Event → Cancel downloads	Stop running loads.	
Event → Apply event range to all channels	Reset every channel to the event range.	
Event → Go to UTC time…	Jump to the image nearest a typed time.	Ctrl+G
Event → First / Previous / Next / Last frame, Play / pause	Navigation and playback.	Space
View → Raw / Running difference / Base difference	Image mode.	
View → Equal viewpoints / Focus A / Focus B / Focus C	Layout.	0–3
View → GCS wireframe / Shock wireframe / Solar limb / Arcsecond axes / Image banners	Overlay toggles.	B

Command	Function	Shortcut
View → Reset image zoom, Fit layout to window	Restore the zoom and the panel sizes.	
Fit → Edit GCS flux rope / Edit shock	Choose the model to edit.	
Fit → Pick front points	Toggle point picking.	
Fit → Undo last front point	Remove the last point clicked in any panel.	Ctrl+Z
Fit → Clear current front points	Remove the edited model's points.	
Fit → Refine current model	Least-squares refinement.	Ctrl+R
Fit → Record fit at current time	Commit the fit.	Ctrl+Return
Fit → Restore / Delete recorded fit at current time	Revisit or remove a recorded fit.	
Fit → Reset model parameters	Reset the edited model.	
Fit → Fit recorded heights over time	Kinematic fit.	
Help → Fitting workflow and scientific limits…	Summary of the procedure and its limits.	F1

22

Fitting the Flux Rope and the Shock

This chapter describes the models of the GCS CME Fitting window, how they are aligned and refined against the observed fronts, how fits are recorded over time to build kinematics, and how results are exported.

22.1 The Model card

The Model card (Figure 22.1) shows the parameters of one model at a time. Choose the model with Edit on the card's title row:

GCS flux rope the Graduated Cylindrical Shell, fitted to the CME ejecta.

Shock a spheroid or ellipsoid, fitted to the shock the CME drives — its faint outer envelope (Section 22.7).

Both models are drawn in every panel (the shell in orange and the shock in sky blue by default); the edited model is the one that the handles, clicks, Refine fit, Commit and the Kinematics card act on.

22.2 GCS parameters

Six sliders, each with a numeric entry, control the shell (Table 22.1).

Table 22.1 Parameters of the GCS flux-rope model.

Slider	Range	Meaning
Lon	−180° to 180°	Stonyhurst longitude of the direction of propagation.
Lat	−89° to 89°	Stonyhurst latitude of the direction of propagation.
Tilt	−90° to 90°	Rotation of the shell about the propagation direction.
Height	1.05–30 $R_\odot$	Distance of the leading edge (apex) from Sun center — not the altitude above the surface.
α	1°–80°	Half-angle between the legs of the shell.
κ	0.05–0.95	Aspect ratio, controlling the thickness of the shell.

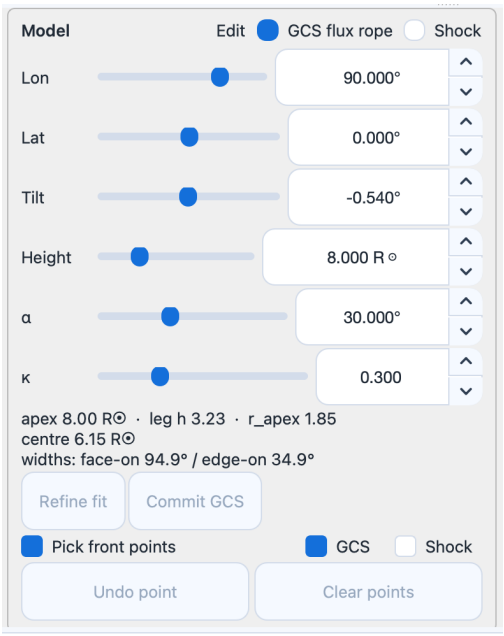


Figure 22.1 The Model card with the GCS parameters.

Set the direction, tilt, α and κ before fine-tuning the height. The apex can also be dragged in any panel: moving it around the Sun turns the direction, and moving it outwards or inwards changes the height. The readout below the sliders gives the derived leg height, apex cross-section radius, center distance, and the intrinsic face-on and edge-on widths.

> **Background: GCS geometry**
>
> The GCS is a hollow croissant: two conical legs joined by a curved front with a circular cross-section that grows with distance from the Sun (Thernisien 2011; Thernisien et al. 2006). The face-on width is $2[\alpha + \arcsin\kappa]$ and the edge-on width $2\arcsin\kappa$; both include the shell thickness and differ from the apparent width in a coronagraph image. Because the height is the leading edge, it feeds the height–time fit directly. GCS is a flux-rope model, not a shock model.

22.3 Clicking the front

With Pick front points ticked, left-click points along the same front in two or more views. Points are drawn in each panel and are used by Refine fit:

- a right-click removes that panel's last point;
- Undo point (Ctrl+Z) removes the point clicked last in any panel;
- Clear points removes all of the edited model's points on the displayed images;
- untick Pick front points to navigate without adding points.

The GCS wireframe and Shock wireframe options hide a model temporarily so that the observed front can be inspected. Each model keeps its own front points.

22.4 Refining the fit

Refine fit (Ctrl+R) makes a local least-squares adjustment of the edited model through the clicked points. It refines a fit; it cannot find one from scratch, because longitude, α and κ are poorly conditioned in GCS, so first align the shell roughly with the CME by eye. The refinement fits as many parameters as the points support (Table 22.2); the status bar names the parameters fitted and how many more points would free the next one.

Table 22.2 Staged refinement of the GCS model.

Front points	Parameters fitted
2	Height
4, in two separated views	Height, longitude, latitude
5	…and tilt
6	…and α
7	All six parameters (adding κ)

The status bar also reports the views taking part, their angular separations and the number of points. Only images within the Max time offset of the shared time take part. With a single view, or with no pair of views between 20° and 160° apart, the direction cannot be constrained and is held fixed; empty, nearly coincident and nearly opposite viewpoints do not constrain the direction independently. Formal errors are shown when the local solution is reliable, are withheld otherwise, and become invalid when the model or the observations change.

22.5 Recording fits

Commit GCS (Ctrl+Return) records the current fit at the shared time, together with the images it was made from and their observation details. Step to later times and repeat to build a height–time series. One combination of images cannot be recorded at two different times, so repeated images never count as independent height measurements.

When stepping, dragging the time slider or playing, the recorded shells are drawn: each fit on its own images, interpolated between recorded times (a display, not a fit) and held before the first and after the last record. A model with nothing recorded keeps its slider values, so commit before stepping away. Fit → Restore recorded model at current time and Delete recorded fit at current time revisit or remove a record; Fit → Reset model parameters resets the edited model.

Moving the event range to a different event sets the recorded fits aside. They return when you come back to that event, and the JSON export includes them.

22.6 Kinematics

The Kinematics card (Figure 22.2) lists the recorded fits of the edited model beside a height–time graph. For the GCS model the table shows Time (UT), t (s), Apex (R⊙), Lon (°), Lat (°) and α (°);

for the shock, κ replaces α.

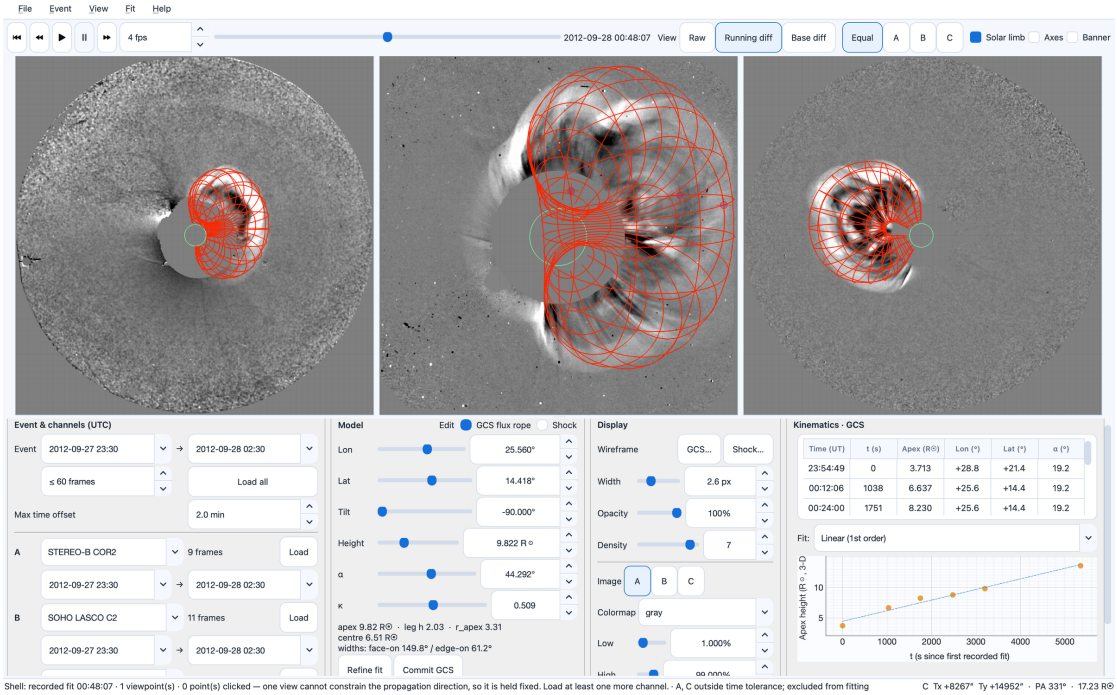


Figure 22.2 A GCS fit with three recorded times; the Kinematics card (right) lists the recorded fits beside their height–time graph and linear fit.

- Double-click a row to go back to its time and restore its model.
- Choose a Linear, Quadratic or Cubic fit and click Fit height–time. A fit of degree n needs $n + 1$ recorded times, and $n + 2$ before errors can be estimated (Section 19.4).
- Clear fits removes the recorded fits of the edited model.
- Export saves the table as CSV or the graph as a figure.

The heights are de-projected under the model assumptions, so the speeds are model-dependent radial speeds rather than plane-of-sky speeds.

22.7 Fitting the shock

Choose Edit: Shock to fit the shock with a Spheroid or an Ellipsoid (Figure 22.3). The parameters follow PyThea's conventions exactly (Table 22.3).

The derived readout gives the center distance and the semi-axes, under PyThea's names. Click the shock front and use Refine fit: the model's exactly computed projected outline is pulled through the points in every view, with its own sequence of height, direction and shape parameters. Record shock fits with Commit Shock. The shock keeps its own front points, recorded fits, kinematics and CSV file. With fewer than three views, ε and the tilt are weakly constrained and an ellipsoid's shape parameters trade off against each other, so prefer a spheroid.

Table 22.3 Parameters of the shock model.

Slider	Range	Meaning
Lon, Lat	as for GCS	Stonyhurst direction of the shock center and apex.
Height	1.05–30 $R_\odot$	Heliocentric distance of the apex (center distance plus the radial semi-axis a).
κ	0.05–2.0	Self-similar constant $\kappa = b/(h - 1\,R_\odot)$: the lateral size for a given apex height.
ε	−0.99 to 0.99	Signed eccentricity: positive stretches the shock radially ($a > b$), negative flattens it ($a < b$).
Tilt	−90° to 90°	Ellipsoid only: rotation about the radial axis; at 0 the b axis is parallel to the solar equator.
α (b/c)	0.5–1.5	Ellipsoid only: ratio of the two lateral semi-axes.

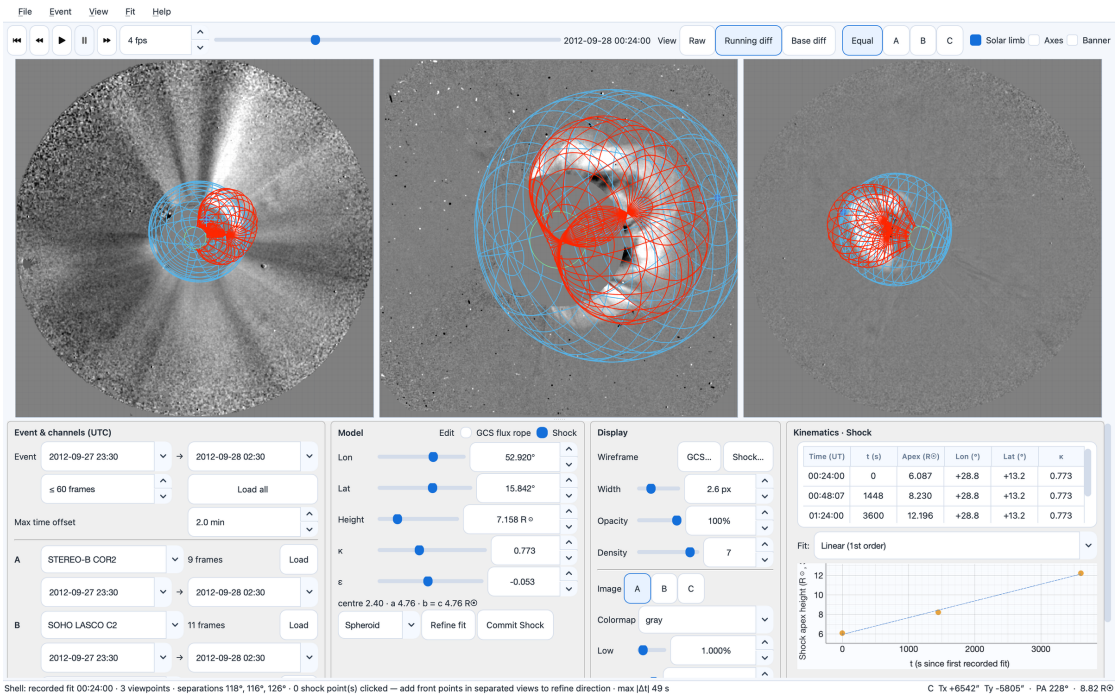


Figure 22.3 Shock and flux-rope models in three viewpoints.

22.8 Exporting results

Images and graphs are drawn again from the data rather than copied from the screen, always on a white page whatever the application theme; graphs follow the OriginPro style. Figures can be saved as PNG, PDF, EPS, SVG, TIFF or JPG.

Save Project (Ctrl+S) saves the fitting with the rest of the main window's project (Section 10.1).

Export analysis JSON... the current, recorded and set-aside parameters of both models, with the clicked points, image times, offsets and observer geometry. The file (schema version 2) has a shock section beside the GCS keys. It is an analysis export, not a PyThea session file.

Export recorded fits CSV… the recorded series of the edited model (`cme_gcs_fit.csv` or `cme_shock_fit.csv`).

Export height–time graph… the recorded apex heights with error bars and the chosen fit, titled with the model and fit, with the speed and acceleration in the legend.

Save viewpoint snapshot… the three views as shown, with arcsecond axes, the wireframes, the solar limb, the front points and a note of where each drawn shell comes from. With the banners hidden, only each panel's name is printed above it.

Export movie (GIF/MP4)… every time step as playback shows it, recorded shells included, at the playback speed. MP4 needs the bundled FFmpeg; a GIF is offered when it is unavailable.

Export fitting report (PDF)… the viewpoints and their separations, the model at the current time, every recorded fit drawn on the images it was made from with its parameters and observation details, each model's linear, quadratic and cubic height–time fits (each with a titled graph and all its parameters, then compared), and the method, its limits and references (Figure 22.4).

Stepping through time for a movie or a report leaves the window as it was: the time shown, the working models, their formal errors and the front points are restored afterwards.

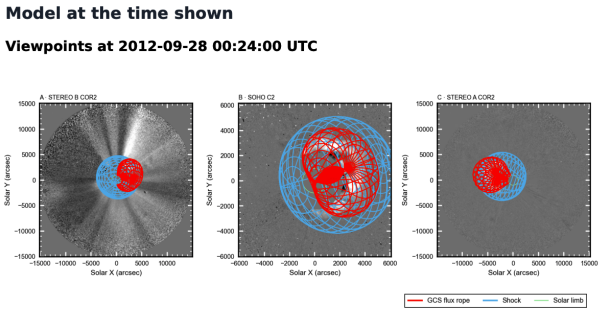


Figure 22.4 A page of the GCS fitting report.

Scientific limits. GCS models the flux rope, not the shock. Formal fit errors leave out the uncertainty from identifying the front, non-simultaneous images, image preparation and the assumed geometry, and a small residual does not make a fit unique or accurate (Verbeke et al. 2023). Helioviewer JPEG2000 images are display products: suitable for fitting shapes, not for calibrated intensity measurements. Help → Fitting workflow and scientific limits… (F1) summarizes the procedure and these limits.

Appendices

A

Keyboard Shortcuts

On macOS, Ctrl in the shortcuts below corresponds to the Command key.

Table A.1 Shortcuts of the main window.

Shortcut	Action
Ctrl+O	Open FITS files
Ctrl+Shift+O	Open a project
Ctrl+S	Save the project
Ctrl+Shift+S	Save the project as a new file
Ctrl+E	Export the figure
Ctrl+F	Export the spectrum as FITS
Ctrl+Z	Undo
Ctrl+Shift+Z	Redo
Ctrl+Shift+Left	Add the previous observation to the timeline
Ctrl+Shift+Right	Add the next observation to the timeline
F1	Open the built-in user guide
Right-click or double-click	Finish drift-rate picking; close a polygon annotation

Table A.2 Shortcuts of Solar Image Analysis.

Shortcut	Action
Ctrl+S	Save the project
Ctrl+Shift+S	Save the project as a new file
Ctrl+Return	Commit the fitted circle (Circle Fit)
Esc or right-click	Cancel the measurement pick in progress

Table A.3 Shortcuts of the GCS CME Fitting window. The single-key shortcuts apply while an image has focus.

Shortcut	Action
Space	Play or pause
← / →	Previous or next frame
Home	First frame
B	Show or hide the image banners
0	Equal layout
1, 2, 3	Enlarge panel A, B or C
Ctrl+L	Load all channels
Ctrl+G	Go to a UTC time
Ctrl+Z	Undo the last front point
Ctrl+R	Refine the edited model
Ctrl+Return	Record the fit at the current time
Ctrl+S	Save the project
Ctrl+Shift+S	Save the project as a new file
Ctrl+W	Close the window
F1	Fitting workflow and scientific limits
Right-click	Remove the panel's last front point

B

File Formats and Outputs

B.1 Files read and written by the application

Table B.1 File types of the e-CALLISTO FITS Analyzer.

Extension	Meaning
`.fit`, `.fits`, `.fit.gz`, `.fits.gz`	Radio spectra in the main window, and solar images in Solar Image Analysis. Upper-case suffixes are accepted.
`.efaproj`	The one project file: radio analysis, Solar Image Analysis, GCS fitting and event context, with the solar and GCS images linked or embedded (Section 10.1). Projects saved by version 3.2 cannot be opened by version 3.1.
`.efaview.json`	Portable view configuration: display range, units, thresholds, color map and graph styling (Section 7.2.2).
`.ecsolar`	Solar Image Analysis session from version 3.1 and earlier. Opening one imports it as a new project; it is no longer written (Section 17.4).
`.srs`	Learmonth spectrograph daily archive file (Section 13.1).

B.2 Exported FITS files

A FITS file written with File → Export As → Export to FIT has the structure of a standard CALLISTO file:

Primary HDU the two-dimensional spectrum (frequency × time) with the chosen `BITPIX`, and the original header updated with the keywords in Table B.2.

`AXIS` extension a binary table with one row and the columns `FREQUENCY` (MHz) and `TIME` (s).

B.3 Summary of outputs

Table B.2 Header keywords added or updated on FITS export.

Keyword	Content
`HISTORY`	"Exported by e-CALLISTO FITS Analyzer", the plot type, the units shown, and the source file (or the first and last source of a combined dataset).
`COMBINED`	`T` for a combined dataset, `F` otherwise.
`COMBMETH`	Combination method: `time`, `frequency` or `time_frequency`.
`NFILES`	Number of source files of a combined dataset.
`BUNIT`	Intensity unit of the data.
`DATAMIN`, `DATAMAX`	Minimum and maximum data values.
`BSCALE`, `BZERO`	Scaling for integer data.

Table B.3 Outputs produced by the application.

Output	Format	Produced by
Spectrum figure	PNG, PDF, EPS, SVG, TIFF, JPG	File → Export As → Export Figure
Processed spectrum	FITS	File → Export As → Export to FIT
Provenance report	Markdown and JSON	File → Export As → Export Provenance Report…
Analysis log	CSV and TXT	File → Export As → Export Analysis Log…
Project report	PDF	File → Generate Project Report…
Batch images	PNG (300 dpi)	Batch processor
Maximum-intensity points	CSV (time channel, time, frequency)	Maximum Intensities, File → Save As
Analyzer results	Excel `.xlsx` (Table 8.6)	Burst Analyzer, Save Data
Analysis graphs	PNG, PDF, EPS, SVG, TIFF, JPG	Maximum Intensities, Analyzer, band-splitting
Spectral overview	PNG, PDF, EPS, SVG, TIFF	Downloader, Spectral Overview
Station comparison	PNG, PDF, EPS, SVG, TIFF	Multi-Station Comparison
Learmonth conversion	FIT	Learmonth browser
GOES, SEP, Dst, Kp data	PNG and CSV	Solar-event viewers
SunPy plots and statistics	PNG, PDF, SVG, TIFF, JPG; CSV	SunPy Explorer
Solar images	PNG; cropped FITS; MP4, GIF (labelled, north up)	Solar Image Analysis
Active regions	CSV	Solar Image Analysis

Output	Format	Produced by
CME tracking	CSV; PNG, PDF, EPS, SVG, TIFF, JPG	Solar Image Analysis tracking panel
PFSS diagnostics	PNG, PDF, SVG	PFSS diagnostics window
GCS analysis	JSON; CSV; figures; GIF, MP4; PDF report	GCS CME Fitting
Geomagnetic response	PNG, PDF, EPS, SVG, TIFF, JPG; CSV with provenance	Geomagnetic Response window
Event figure	PNG, PDF, EPS, SVG, TIFF, JPG	File → Export As → Event Figure…
Diagnostics bundle	ZIP	About → Report a Bug...

C

Data Sources

Table C.1 lists the archives from which the application retrieves data. Access requires a network connection; most archives are public and need no registration, the exception being JSOC exports, which need a registered e-mail address. When you publish results based on these data, acknowledge the providers as their data policies request.

Table C.1 Archives used by the e-CALLISTO FITS Analyzer.

Data	Provider and address	Used by
e-CALLISTO FITS spectra	e-CALLISTO archive, FHNW, https://soleil.i4ds.ch/solarradio/data/2002-20yy_Callisto/	Downloader, Timeline, Multi-Station Comparison
e-CALLISTO burst lists	Monstein catalog, https://soleil.i4ds.ch/solarradio/data/BurstLists/2010-yyyy_Monstein/	Downloader, Burst List
Learmonth spectrograph	Australian Bureau of Meteorology, Space Weather Services, https://downloads.sws.bom.gov.au/wdc/wdc_spec/data/learmonth/raw/	Learmonth browser
STEREO/SWAVES level-2	NASA Space Physics Data Facility, https://spdf.gsfc.nasa.gov/pub/data/stereo/combined/swaves/level2_cdf/	SWAVES loader
GOES XRS and SGPS	NOAA National Centers for Environmental Information, https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/	GOES viewers, GOES overlay
Dst index	World Data Center for Geomagnetism, Kyoto (final, provisional or real-time), https://wdc.kugi.kyoto-u.ac.jp	Dst viewer, Geomagnetic Response
Kp index	GFZ German Research Centre for Geosciences, https://kp.gfz.de	Kp viewer, Geomagnetic Response
Solar wind, IMF, SYM-H and AE (OMNI 5-min)	NASA Space Physics Data Facility, https://spdf.gsfc.nasa.gov/pub/data/omni/omni_cdaweb/hro_5min/	Geomagnetic Response

Data	Provider and address	Used by
Recent solar wind and IMF at L1	NOAA NCEI DSCOVR archive; NOAA SWPC real-time solar wind, https://services.swpc.noaa.gov/json/rtsw/	Geomagnetic Response (stand-in where OMNI is not yet published)
CMEs, flares, shocks, storms, SEP events	NASA CCMC DONKI, https://ccmc.gsfc.nasa.gov/DONKI/	Event Context Strip, Geomagnetic Response markers, Event Story
GOES flare list	NOAA SWPC, through the Heliophysics Event Knowledgebase (HEK)	Event Context Strip, Event Story
SOHO/LASCO CME catalog	CDAW Data Center, NASA GSFC, https://cdaw.gsfc.nasa.gov	CME catalog, Event Context Strip, Event Story
SDO/AIA and SDO/HMI	Joint Science Operations Center, https://jsoc.stanford.edu; Virtual Solar Observatory	Solar Image Analysis, SunPy Explorer, PFSS (HMI synoptic)
AIA synoptic 1024^2 FITS	JSOC AIA synoptic archive, https://jsoc1.stanford.edu/data/aia/synoptic/	Solar Image Analysis (FITS · reduced size)
SOHO/EIT, SOHO/LASCO, STEREO/SECCHI, GOES/SUVI, PROBA2/SWAP	Virtual Solar Observatory and mission archives, through SunPy	Solar Image Analysis, SunPy Explorer, overlay layers
Helioviewer JPEG2000 images	Helioviewer Project, https://api.helioviewer.org	JP2 quicklooks, Live Preview, AIA Sun in the occulter, GCS CME Fitting, Event Figure thumbnails
GONG synoptic and ADAPT maps	National Solar Observatory, through SunPy	PFSS
NOAA active-region labels	Heliophysics Event Knowledgebase (HEK), through SunPy	Active-region labels
Software updates	GitHub releases, https://github.com/SaanDev/e-Callisto_FITS_Analyzer	Update check
Website and online guide	https://ecallistoanalyzer.org	Help → Official Website

Note. Archive availability changes over time. The calibrated SOHO/LASCO and SOHO/EIT archives lag real time by many months, the HMI synoptic series is published about one Carrington rotation behind, OMNI solar-wind data appear a few weeks after observation, the definitive AIA synoptic set about a week after, and STEREO-B data end in 2014. Downloaded files are cached locally and can be reused without network access.

D

Models and Formulas

This appendix collects the relations used to compute the quantities reported by the application. Heights r are heliocentric distances in solar radii ($R_\odot = 696\,340$ km), electron densities n_e are in cm^{-3} and frequencies f in MHz.

D.1 Intensity scales

CALLISTO digits to dB the CALLISTO receiver's logarithmic detector maps 2500 mV onto 256 digits with a slope of 25.4 mV/dB, so that $\Delta I_{\mathrm{dB}} = \Delta I_{\mathrm{digits}} \times 2500/(256 \times 25.4) \approx 0.384$ dB per digit. The Plotutil median-dB recipe used by Median (dB) and the batch processor uses $2500/(255 \times 25.4)$.

ARTEMIS-IV 4096 ADC counts over a 70 dB range: 58.51 counts per dB.

GOES flare class from the peak 0.1–0.8 nm flux F: A for $F < 10^{-7}$, B for $10^{-7} \le F < 10^{-6}$, C for $10^{-6} \le F < 10^{-5}$, M for $10^{-5} \le F < 10^{-4}$ and X for $F \ge 10^{-4}$ W m^{-2}; the number is F divided by the lower limit of the class (10^{-8} for A up to 10^{-4} for X), for example M2.5 for $F = 2.5 \times 10^{-5}$ W m^{-2}.

D.2 Radio burst analysis

Plasma frequency. The fundamental emission frequency is the local plasma frequency

$$f_p = 8.98 \times 10^{-3} \sqrt{n_e} \quad \text{MHz}, \tag{D.1}$$

so $n_e = (f/8.98 \times 10^{-3})^2$. For harmonic emission $f = 2 f_p$; the application divides the observed frequencies and drift rates by two before computing heights and speeds.

Coronal density models. Each model is multiplied by the fold number N ($n_e \to N\, n_e$).

For the Newkirk model the emission height has the closed form

$$r = \frac{4.32\ \ln 10}{\ln[n_e/(N \times 4.2 \times 10^4)]}. \tag{D.2}$$

For the other models the height is found numerically between 1 $R_\odot$ and 215 $R_\odot$ (1 AU); frequencies outside this range have no height.

Table D.1 Coronal electron-density models.

Model	$n_e(r)$ in cm^{-3}
Newkirk	$4.2\times10^4\times10^{4.32/r}$
Saito	$1.36\times10^6\,r^{-2.14}+1.68\times10^8\,r^{-6.13}$
Leblanc	$3.3\times10^5\,r^{-2}+4.1\times10^6\,r^{-4}+8.0\times10^7\,r^{-6}$
Baumbach–Allen	$10^8\left(2.99\,r^{-16}+1.55\,r^{-6}+0.036\,r^{-1.5}\right)$
Mann	$5.14\times10^9\exp[13.83\,(1/r-1)]$

Power-law backbone and drift rate.

$$f(t)=a\,(t-t_0)^{-b},\qquad \frac{\mathrm{d}f}{\mathrm{d}t}=-a\,b\,(t-t_0)^{-b-1}. \tag{D.3}$$

The goodness of fit is reported as $R^2=1-\sum(f_i-\hat f_i)^2/\sum(f_i-\bar f)^2$ and RMSE $=\sqrt{\overline{(f_i-\hat f_i)^2}}$.

Shock speed.

$$v=R_\odot\left|\frac{\mathrm{d}f}{\mathrm{d}t}\right|\left|\frac{\mathrm{d}r}{\mathrm{d}f}\right|,\qquad \frac{\mathrm{d}r}{\mathrm{d}f}=\frac{2\,n_e}{f\;|\mathrm{d}n_e/\mathrm{d}r|}. \tag{D.4}$$

The *initial* values are evaluated at the starting frequency, the 90th percentile of the fitted frequencies; the *average* values are means along the backbone with their standard errors.

Band splitting (Vršnak et al. 2002).

$$X=\left(\frac{f_u}{f_l}\right)^2,\qquad M_A=\sqrt{\frac{X\,(X+5)}{2\,(4-X)}},\qquad V_A=\frac{V_s}{M_A}, \tag{D.5}$$

$$B=V_A\sqrt{\mu_0\,m_p\,n_e}\quad\text{(SI units; reported in gauss).} \tag{D.6}$$

D.3 Image measurements

Circle fit. For a sphere of fitted radius r resting on the solar surface, the height of its top is $h=1\,R_\odot+2r$.

Height–time fits.

$$\text{linear:}\quad h=h_0+v\,t, \tag{D.7}$$

$$\text{quadratic:}\quad h=h_0+v_0\,t+\tfrac{1}{2}a\,t^2, \tag{D.8}$$

$$\text{cubic:}\quad h=h_0+v_0\,t+\tfrac{1}{2}a_0\,t^2+\tfrac{1}{6}j\,t^3. \tag{D.9}$$

Uncertainties are propagated from the covariance of the fitted coefficients.

D.4 Geomagnetic response

Derived solar-wind parameters. Where OMNI data are not yet published, the derived quantities are computed from the L1 measurements with OMNI's own formulas (King and Papitashvili 2005), with V in km s^{-1}, N_p in cm^{-3}, T in K and B, B_z (GSM) in nT:

$$P_{\mathrm{dyn}} = 2 \times 10^{-6}\, N_p V^2 \quad \text{nPa} \quad \text{(the factor 2 allows for about 4\% alpha particles)}, \tag{D.10}$$

$$E_y = -V B_z \times 10^{-3} \quad \text{mV m}^{-1}, \tag{D.11}$$

$$\beta = \frac{\left(4.16 \times 10^{-5}\, T + 5.34\right) N_p}{B^2}, \tag{D.12}$$

$$M_A = \frac{V\sqrt{N_p}}{20\, B}. \tag{D.13}$$

Storm class and G level. The storm class follows Gonzalez et al. (1994) from the Dst minimum: weak (≤ -30 nT), moderate (≤ -50 nT), intense (≤ -100 nT) and super (≤ -250 nT). The NOAA G level follows from the Kp maximum as $G = \lfloor \mathrm{Kp} \rfloor - 4$ for Kp ≥ 5 (G1 at Kp 5 to G5 at Kp 9) (NOAA Space Weather Prediction Center n.d.).

D.5 Three-dimensional CME models

GCS (Thernisien 2011; Thernisien et al. 2006). Parameters: Stonyhurst longitude and latitude of the propagation direction, tilt, leading-edge height h, half-angle α and aspect ratio κ. Intrinsic widths:

$$w_{\text{face-on}} = 2\left[\alpha + \arcsin\kappa\right], \qquad w_{\text{edge-on}} = 2\arcsin\kappa. \tag{D.14}$$

Shock spheroid and ellipsoid (Kouloumvakos et al. 2022). With the radial semi-axis a and lateral semi-axes b and c:

$$h = r_{\text{center}} + a, \qquad \kappa = \frac{b}{h - 1\,R_\odot}, \qquad \varepsilon = \begin{cases} +\sqrt{1-(b/a)^2} & a > b, \\ -\sqrt{1-(a/b)^2} & a < b, \end{cases} \qquad \alpha = \frac{b}{c}. \tag{D.15}$$

A spheroid has $c = b$ ($\alpha = 1$, no tilt).

E

Troubleshooting

E.1 Main window

Buttons and menu items are grayed out.

Most analysis controls, and the Graph Properties panel, are enabled only after a file is loaded. Isolate Burst additionally requires background subtraction.

Rectangle zoom does nothing.

Click Lock zooming and panning first, then Rectangular Zooming, and drag a rectangle. Each activation allows one rectangle.

Drift-rate picking does not stop.

Right-click or double-click to finish the series of points.

Selected files cannot be combined.

The message names the reason — for example non-consecutive timestamps, mixed stations or an incomplete time × focus-code grid. Check the rules in Table 5.1.

The UT time axis is unavailable.

UT display, UT display ranges and UT alignment in the Multi-Station Comparison need the `TIME-OBS` keyword in the FITS header. Use seconds instead.

The thresholds were reset after background subtraction.

Limits chosen on raw data would saturate the background-subtracted scale and are therefore reset. Set them again, or apply a preset.

The application closed unexpectedly.

Restart it and accept the offer to recover the autosave snapshot, or use File → Recover Last Session....

A save fails on Windows.

The proposed folder may not be writable (for example inside `C:\\ProgramFiles`); choose another folder when asked.

A project cannot be opened in version 3.1.

Projects saved by version 3.2 cannot be opened by version 3.1. Open them in version 3.2 or later, and keep a copy saved by version 3.1 if you still need it there.

A linked project downloads its images again.

A project saved with Link data refers to image files on this computer. If they were moved, or the download cache was cleared, the frames are fetched again from the archive. Save with Embed data to take a project to another computer or to work offline.

Part of a project did not open.

A part that cannot be read is skipped and named in a message; the rest of the project opens. Check that the linked images are still available, or reopen an embedded copy.

E.2 Event context and geomagnetic response

The Geomagnetic Response card asks to press Refresh.

Solar Events → Fetch Event Context Automatically is off. Press Refresh, or turn the option on.

Some geomagnetic panels are empty or say "not yet published".

OMNI data appear a few weeks after observation. For recent days the solar wind and IMF come from DSCOVR or SWPC real-time L1 data, labelled *L1, not time-shifted to the bow shock*; SYM-H and AE have no stand-in and appear once OMNI publishes them. GOES proton data may also be missing for the last few weeks.

An event-strip lane is marked (!).

The catalog could not answer for part of the range yet, for example a CDAW month that has not been published or a DONKI request that failed. The reason is shown in the status bar, and the day is asked for again next time.

The Event Figure shows GOES data of another event.

Fetched GOES and proton series belong to the event and range they were fetched for. After loading another file, press Fetch missing data again.

E.3 Downloads and archives

The station list is empty or a station is missing.

Station lists contain only stations with data on the selected UTC days. Check the date and the network connection.

A listed burst has no FITS files.

Catalog detections do not guarantee that matching files are archived. Increase Extra time, or search another station.

Recent SOHO/LASCO or SOHO/EIT data cannot be found.

The calibrated archives lag real time by many months. Use Find Latest to locate the newest archived data, or Live Preview (Helioviewer) for recent quicklook images.

JSOC downloads, binned frames or cutouts are refused.

Enter a JSOC notify e-mail registered at https://jsoc.stanford.edu/ajax/register_email.html in the Data Source card. Binned and cutout frame sizes require the JSOC source.

The disk is filling up.

Empty the caches with the Clear Cache buttons of the e-CALLISTO Downloader and the SunPy Explorer, or with Data → Reset All (clear cache & defaults) in Solar Image Analysis.

E.4 Solar Image Analysis and GCS fitting

Light Curve, Region Stats or processing levels are disabled.

JP2 quicklook frames are display images, not calibrated data, so the photometric tools are disabled for them. Load the same frames as a FITS product.

A JSOC binned or cutout download seems stuck.

JSOC builds binned and cutout frames on request, which can take minutes; the progress bar shows a busy indicator with the reason meanwhile. Stop cancels the wait.

The PFSS card is disabled.

When running from source, install the `sunkit-magex` package; the card shows the command.

Clicked PFSS seeds or the crop rectangle do not respond.

These interactions need the PyQtGraph renderer (Display & Crop card).

A GCS panel reports that it has no data.

The STEREO-B archive ends on 27 September 2014. Switch that panel to another channel.

GCS refinement does not change the direction.

The direction is constrained only by at least four points in two views separated by 20°–160°. Add points in a second, well-separated view.

MP4 export is not offered.

MP4 export needs FFmpeg, which is bundled with the installers. If it is unavailable, save a GIF instead.

E.5 Installation

macOS reports that the application cannot be verified.

Open System Settings → Privacy & Security and click Open Anyway, or Control-click the application and choose Open.

The application does not start on Linux.

Install the package with `apt`, which also installs the required Qt/OpenGL libraries (`libgl1`, `libegl1`, `libxkbcommon-x11-0`, `libxcb-cursor0`).

Qt reports “DLL load failed” when running from source on Windows.

Rebuild the virtual environment with `packaging/windows/repair_windows_venv.ps1`.

If a problem persists, report it with About → Report a Bug... (Section 4.4).

Glossary

ADAPT
Air Force Data Assimilative Photospheric Flux Transport model; synoptic magnetograms that estimate the unobserved far side of the Sun.

AE, AL, AU
Auroral electrojet indices, measuring the strength of the auroral currents.

AIA
Atmospheric Imaging Assembly on SDO; full-disk EUV and UV imager.

Alfvén Mach number (M_A)
Ratio of the shock speed to the Alfvén speed.

Alfvén speed (V_A)
Speed of Alfvén waves, $B/\sqrt{\mu_0 \rho}$; depends on the magnetic field and plasma density.

ARTEMIS-IV
Solar radio spectrograph at Thermopylae, Greece.

Background subtraction
Removal of each frequency channel's steady receiver and sky level from a dynamic spectrum.

Band splitting
Division of a Type II emission lane into two parallel bands emitted upstream and downstream of the shock.

Base difference
Each image minus the first image of the sequence.

`BITPIX`
FITS keyword giving the data type of the stored values.

Bow shock
The standing shock where the solar wind first meets Earth's magnetosphere; OMNI data are time-shifted to its nose.

Bz
The north–south component of the interplanetary magnetic field; strongly southward (negative) Bz drives geomagnetic storms.

Carrington coordinates
Heliographic coordinates that rotate with the Sun at the Carrington rate; used for synoptic maps.

CDAW
Coordinated Data Analysis Workshop data center at NASA GSFC, host of the SOHO/LASCO CME catalog.

CME
Coronal mass ejection: an eruption of magnetized plasma from the corona.

Compression ratio (X)
Ratio of the downstream to the upstream plasma density at a shock.

Coronagraph
Telescope that blocks the solar disk with an occulter to observe the faint corona.

Density model
Function $n_e(r)$ giving the coronal electron density at a heliocentric distance.

Derotation
Compensation for solar differential rotation over an image sequence.

Digit
Raw CALLISTO intensity value (analog-to-digital converter unit, ADU), about 0.384 dB per digit.

DONKI
NASA's Space Weather Database Of Notifications, Knowledge, Information, run by the CCMC.

Drift rate
Rate of change of the emission frequency of a burst, $\mathrm{d}f/\mathrm{d}t$.

DSCOVR
Deep Space Climate Observatory, a NOAA solar-wind monitor at L1.

Dst index
Disturbance storm-time index; measure of the ring current and geomagnetic storm strength.

Dynamic spectrum
Radio intensity as a function of frequency and time.

e-CALLISTO
World-wide network of CALLISTO solar radio spectrometers.

EIT
Extreme-ultraviolet Imaging Telescope on SOHO.

Embedded project
A project that stores its solar and GCS images inside the file, so it opens anywhere, even offline.

EUV
Extreme ultraviolet.

EUVI
Extreme Ultraviolet Imager of STEREO/SECCHI.

Event Story
The opening section of a project report, which tells the event from the Sun to the Earth.

Event time
The time the Geomagnetic Response and the event-context tools are centered on: the loaded data's start, a burst-list row or a downloader selection.

FITS
Flexible Image Transport System, the standard astronomical data format.

Focus code
Two-digit identifier of a CALLISTO receiver or frequency band at a station.

Fold number
Factor multiplying a coronal density model to represent denser structures.

Fundamental, harmonic
Plasma emission at the local plasma frequency, or at twice it.

G level
NOAA geomagnetic storm level, from G1 (Kp 5) to G5 (Kp 9).

GCS
Graduated Cylindrical Shell, a geometric flux-rope model of CMEs.

GOES
Geostationary Operational Environmental Satellites of NOAA, carrying the XRS, SGPS and SUVI instruments.

GONG
Global Oscillation Network Group, a ground-based network providing synoptic magnetograms.

HEK
Heliophysics Event Knowledgebase.

Helioprojective coordinates
Observer-centered angular coordinates on the sky, in arcseconds from Sun center.

Helioviewer
Service providing JPEG2000 solar images for browsing.

HI Heliospheric Imagers (HI1, HI2) of STEREO/SECCHI.

HMI
Helioseismic and Magnetic Imager on SDO.

IMF
Interplanetary magnetic field, carried by the solar wind.

J-map
Time–elongation map built from a slit through a sequence of images.

JP2 quicklook
A Helioviewer JPEG2000 image: fast to download, with display values rather than calibrated data.

JSOC
Joint Science Operations Center, the SDO data archive.

Kp index
Planetary three-hourly index of geomagnetic activity, from 0 to 9.

L1
The Sun–Earth Lagrange point about 1.5 million km upstream of Earth, where solar-wind

monitors such as DSCOVR operate.

LASCO
Large Angle and Spectrometric Coronagraph (C2, C3) on SOHO.

Level 1, 1.5, 1b, 2
Processing levels of solar image data, from archive products to registered or composite images.

Linked project
A project that refers to solar and GCS image files on this computer instead of storing them.

NRGF
Normalizing-radial-graded filter, which flattens the radial brightness gradient of coronagraph images.

Occulter
Disk in a coronagraph that blocks the bright inner field of view.

OMNI
NASA's combined, quality-checked solar-wind and IMF data set, time-shifted to the bow shock.

Open and closed field
Magnetic field lines that reach the source surface, or return to the photosphere.

OriginPro style
The publication graph style used for exported figures: closed frame, inward ticks and a white background.

PFSS
Potential-field source-surface model of the coronal magnetic field.

Plasma β
Ratio of plasma pressure to magnetic pressure.

Plasma frequency
Natural oscillation frequency of electrons in a plasma, $f_p \approx 8.98\,\sqrt{n_e}$ kHz.

Position angle (PA)
Angle on the sky measured from solar north toward east.

Power law
Function of the form $a\,t^{-b}$.

$R_\odot$
Solar radius, 696 340 km.

RFI
Radio-frequency interference from terrestrial transmitters.

Ridge
The line of peak intensity of a burst in a dynamic spectrum.

Running difference
Each image minus the previous image.

SDO
Solar Dynamics Observatory.

SECCHI
Sun Earth Connection Coronal and Heliospheric Investigation on STEREO (EUVI, COR1, COR2, HI1, HI2).

SEP
Solar energetic particles.

SGPS
Solar and Galactic Proton Sensor on GOES-R series satellites.

SOHO
Solar and Heliospheric Observatory.

Source surface
Sphere in the PFSS model beyond which the field is radial.

STEREO
Solar Terrestrial Relations Observatory (Ahead and Behind spacecraft).

Stonyhurst coordinates
Heliographic coordinates with longitude zero facing the Earth.

SUVI
Solar Ultraviolet Imager on GOES.

SWAVES
Radio and plasma wave instrument on STEREO.

SWPC
NOAA Space Weather Prediction Center.

SYM-H
A 1-minute geomagnetic index of the ring current, comparable to Dst.

Synoptic map
Full-Sun map assembled over a solar rotation.

Type II burst
Slowly drifting radio burst produced by a shock wave.

Type III burst
Fast-drifting radio burst produced by electron beams.

UT
Universal Time.

VSO
Virtual Solar Observatory.

XRS
X-Ray Sensor on GOES, with short (0.05–0.4 nm) and long (0.1–0.8 nm) channels.

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