CASSIOPE
e-POP Data User's Guide

Document No: ePOP – 5025

Prepared by:

______________________________ ______________
Andrew Howarth *Date*

Concurred by:

______________________________ ______________
Greg Enno *Date*

Approved by

______________________________ ______________
Andrew Yau *Date*

CHANGE RECORD SHEET

ISSUE	DATE OF RELEASE	REASONS FOR REVISION	INITIALS
A	Jan 23, 2017	Original Version	**AH**

Table of Contents

List of Figures

List of Tables

1. Scope

This document describes the e-POP raw and level 1+ data sets, including data formats, quality indicators, algorithms used for generation of level 1+ products, and a guide for use of the data. e-POP data archival is also discussed.

2. Documentation

2.1 Applicable Documents

AD-1	ePOP-5024 e-POP Instrument Raw and Processed Data Formats REV A.pdf
AD-2	MGF_data_block_v3.pdf
AD-3	OEM4 User Manual Volume 1 Rev 19.pdf
AD-4	OEM4 User Manual Volume 2 Rev 18.pdf
AD-5	rinex302.pdf

Table 1: Applicable documents

2.2 Reference Documents

RD-1	The CERTO Beacon on CASSIOPE/e-POP and Experiments using High-Power HF Ionospheric Heaters, Space Sci. Rev. (2014) DOI: 10.1007/s11214-014-0110-2
RD-2	Fast Auroral Imager (FAI) for the e-POP Mission, Space Sci. Rev. (2014) DOI: 10.1007/s11214-014-0107-x
RD-3	ePOP-4771 FAI_Characterization_Report_Rev_A.pdf
RD-4	The GPS attitude, positioning, and profiling experiment for the enhanced polar outflow probe platform on the Canadian CASSIOPE satellite, Geomatica (2010), 64(2), 233-243
RD-5	Imaging and Rapid-Scanning Ion Mass Spectrometer (IRM) for the CASSIOPE e-POP Mission, Space Sci. Rev. (2015) DOI: 10.1007/s11214-015-0149-8
RD-6	The CASSIOPE/e-POP Magnetic Field Instrument (MGF), Space Sci. Rev. (2014) DOI: 10.1007/s11214-014-0105-z
RD-7	The e-POP Radio Receiver Instrument on CASSIOPE, Space Sci. Rev. (2015) DOI: 10.1007/s11214-014-0130-y
RD-8	The CASSIOPE/e-POP Suprathermal Electron Imager (SEI), Space Sci. Rev. (2015) DOI: 10.1007/s11214-015-0151-1

Table 2: Reference documents

3. Acronyms

A list of the acronyms used in this document are given in Table 3.

CASSIOPE	Cascade Smallsat Ionospheric Polar Explorer
CCD	Charge Coupled Device
CERTO	Coherent Electromagnetic Radio Tomography
e-POP	Enhanced Polar Outflow Probe
eSOC	e-POP Science Operation Center
DHUC	Data Handling Unit Card
FAI	Fast Auroral Imager
GAP	GPS Attitude, Positioning, and Profiling Experiment
GPS	Global Positioning System
HDF5	Hierarchical Data Format version 5
IR	Infrared
IRM	Imaging and Rapid Scanning Ion Mass Spectrometer
lv0	Level 0
lv1,lv2,lv3	Level 1, Level 2, Level 3
MCP	Microchannel Plate
MGF	Magnetic Field Instrument
MOS	Mission Operation System
NMS	Neutral Mass Spectrometer
NRL	United States Naval Research Lab
RINEX	Receiver Independent Exchange Format
RRI	Radio Receiver Instrument
SEI	Suprathermal Electron Imager
UT	Universal Time

Table 3: List of Acronyms

4. Introduction

The e-POP payload consists of eight scientific instruments on the CAScade Smallsat Ionospheric Polar Explorer (CASSIOPE) satellite, seven of which produce data onboard the spacecraft. Data from these instruments are time-tagged and written to a data buffer on the spacecraft, then downlinked to the ground as a single stream to produce the e-POP raw data. The instrument-specific packets are separated from the raw stream and any packets with an invalid CRC are removed, to produce the level 0 data set. Each instrument has its own unique set of processes and algorithms applied to the level 0 data to produce independent level 1+ products.

This document and the associated applicable and reference documents combine to describe the level 0, level 1+, quicklook, and summary products. Software tools for some e-POP instruments that are available through the e-POP Science Operation Center (eSOC) are also described. Finally, the structure of the e-POP data processing and archival system is presented.

5. Data File Formats

The raw, level 0+, and ephemeris data formats and coordinate systems are described in detail in AD-1.

6. Data Product Descriptions

6.1 Ephemeris

The CASSIOPE ephemeris data is produced as a plain text file, one for each day, specifying the position, velocity, and attitude of the spacecraft every 10 seconds in multiple coordinate systems. The contents of the ephemeris data files are described in detail in AD-1.

6.2 CERTO

The e-POP Coherent Electromagnetic Radiation TOmography experiment (CERTO) is for radio transmission from e-POP to ground for radio propagation and ionospheric scintillation measurements. It transmits at three frequencies, namely 150 MHz, 400 MHz, and 1067 MHz, through its three-frequency circular polarized antenna on a 68.6 cm boom. More detail on CERTO may be found in RD-1.

The CERTO science data is captured on the ground at each receiver station. Stations run by the U.S. Naval Research Lab (NRL) transfer data to the University of Calgary for distribution.

6.2.1 CERTO NRL Receiver Science Data Format

6.2.1.1 its Files

The CERTO *.its files contain the raw data output. The naming convention is “YYYYMMDDHHMMS.its”:

```
YYYY = year
MM   = month
DD   = day
HH   = hour
MM   = minute
S    = station name first letter
```

The header contains the following:

Line 1 – date, time, and azimuth of satellite rise, the time, azimuth, and elevation of closest approach, the time and azimuth of satellite setting, the satellite name, and the frequency offset.

Line 2 – the receiving station name, latitude (in degrees), longitude (in degrees), elevation (in meters) and time offset from GMT (in hours).

Line 3 – a line identifying the exact time of the first data point in the file and the data rate

Line 4 – the NASA two-line elements for CASSIOPE used to track the spacecraft

The data following is in counts, with 3277 counts equal to 1 Volt. The data column header identifies the individual data samples.

6.2.1.2 pro Files

File "YYYYMMDDHHMMS.pro" is the main processed data file, containing the Total Electron Count computed for each second (which is a weighted average of 50 data points), the azimuth and elevation of the satellite as viewed from the station, and the geocentric latitude and longitude of the F-layer and E-layer penetration points of the line between the satellite and the station.

Between the TEC and the Azimuth are three data quality flags.

Below that data set is another data set of the UHF S4, VHF S4 and RMS Phase computed over 10 seconds.

File "YYYYMMDDHHMMS.pro" contains a header identical with the associated .its raw data file header.

6.2.1.3 mag Files

File "YYYYMMDDHHMMS.mag" is a diagnostic file. It is only used to evaluate receiver performance. Like the main processed data file, it contains the Total Electron Count computed for each second (which is a weighted average of 50 data points), the azimuth and elevation of the satellite as viewed from the station, and the data quality flags. Instead of the penetration points, the last columns of data contain the signal strengths for VHF and UHF (in counts), and the computed Signal-to-Noise ratio.

Below the main header and above the column headers are five lines of diagnostic data:

Noise Intensity (from the last five seconds of raw data after lock has been lost);

I channel average during the last five seconds;

Q channel average during the last five seconds;

Peak Signal-to-Noise (averaged over 60 seconds);

Peak signal intensity (averaged over 60 seconds).

6.2.1.4 snt Files

File "YYYYMMDDHHMMS.snt" is a plotting file for plotting scintillation data. It is computed for each data point. It contains the detrended intensities of UHF and VHF, and the relative phase between them. If the data quality falls below certain thresholds, the values are set to -999.999.

File "YYYYMMDDHHMMS.snt" contains a header identical with the associated .its raw data file header.

6.3 FAI

The e-POP Fast Auroral Imager (FAI) is a dual-CCD imager capable of producing images in the near infrared (650-1000 nm) and visible (630 nm) regimes. A high-level description of the instrument is available via RD-1. A more in-depth technical description of the instrument, including details on calibration, image corrections, performance, and overall characteristics, is available in RD-2.

6.3.1 FAI Level 0 Data

The FAI level 0 data is completely described in AD-1.

6.3.2 FAI Level 1 Products

FAI has four products that are derived from level 1 data: binary images, png images, a quick look video, and a one-page summary plot. The level 1 image data are derived by applying four corrections to the raw data.

1) **Electronic offset removal**
   A non-zero DC offset is added to the signal as it is captured by the instrument and is adjusted for on the ground. Each raw CCD image has up to 12 columns of 'over-scan' pixels that do not accumulate counts from photons or dark current, which are used to give an estimate of the DC offset for the image. The average of the counts in the over-scan columns is calculated as a correction factor for the whole image.

2) **Optical non-uniformity (vignetting) correction**
   The telecentric FAI lens system suffers from vignetting. Measurements were taken in the lab prior to launch using a uniform integrating sphere to determine coefficients to correct for the vignetting. Each pixel is scaled by a vignetting correction factor.

3) **Dark current removal**
   Each pixel of a CCD accumulates counts even when it has no photons striking it, during both exposure and readout. The rate of accumulation of dark counts is heavily temperature-dependent for the two FAI CCDs. Pre-launch measurements were taken to characterize the dark current for each pixel at a number of temperatures; this library of information is used to correct the counts for each pixel in every image. "Hot" pixels and columns were also included in this correction library. For further details on the dark current subtraction please refer to RD-2.

4) **Pincushion distortion correction**
   Pincushion distortion is apparent on the FAI images. Laboratory images of a checkerboard allowed for coefficients to be determined for a constant correction set to be applied to each camera of the form

$$R_{per}=(aR_{meas}^{3}+bR_{meas}^{2}+cR_{meas}+d)R_{meas}$$

   Where R_{per} is the radius of the pixel in a perfect image, R_{meas} is the measured radius, and a, b, c, and d, are empirical coefficients.

6.3.2.1 FAI Level 1 Binary Images

The detailed description of the level 1 binary data format can be found in RD-2. These files are meant to be read by customized image processing software (e.g. FAItools).

6.3.2.2 FAI Level 1 png Images

FAI level 1 data are available as a png image. A sample image is shown in Figure 1. The printed header data include the following information:

- Camera name (e.g. e-POP FAI IR)
- Date and time in UT of the start of the exposure (e.g. 2014-02-19 07:36:30 UT)
- Exposure time in seconds (e.g. Exp=0.100s)
- Image size in pixels (e.g. 256x256)
- Signal range in image (e.g. DN=0-27791)
- Satellite position in geographic latitude, longitude, and altitude (e.g. SC lat/lon/alt: 49.6º/-79.4º/670 km)
- Satellite attitude yaw, pitch, and roll angles, and attitude accuracy indicator [key: U=Unknown, N=None, L=Low, H=High] (e.g. SC YPR: 0.0º/-0.3º/-0.0º/H). 'Low' accuracy attitude data is derived from the spacecraft coarse sun sensors, and 'High' accuracy data is derived from the star trackers. 'None' indicates that neither the sun sensors nor the star trackers were available, while 'Unknown' indicates a loss of attitude data.
- FAI level 1 software version (e.g. v4)

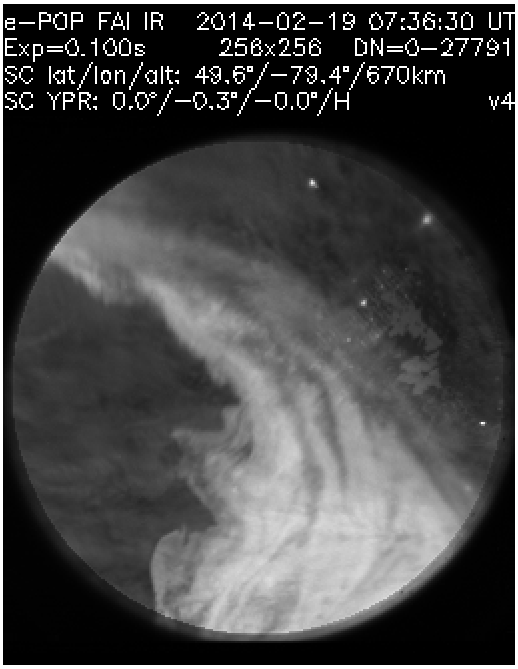
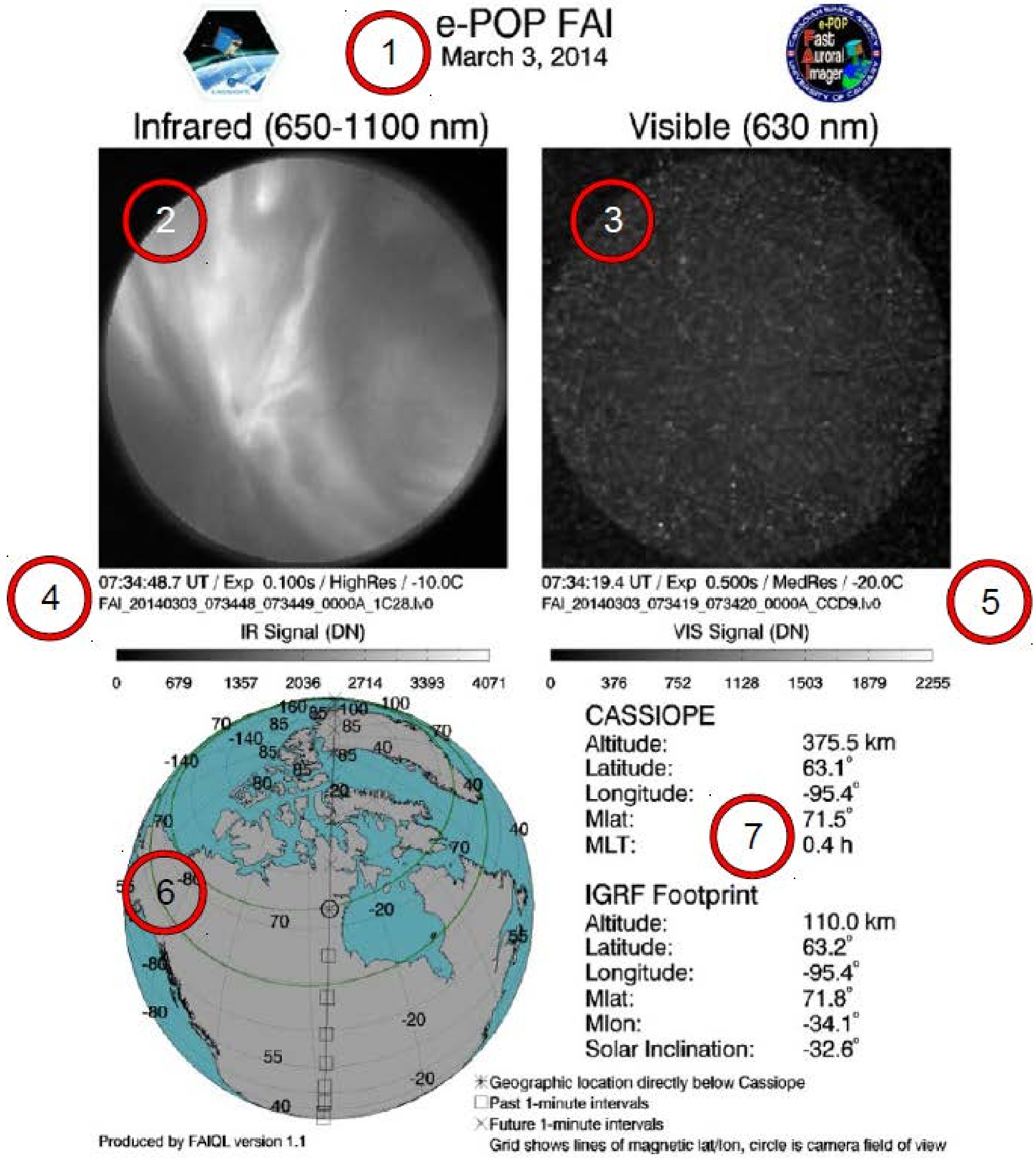


Figure 1: Sample FAI png image

6.3.3 FAI Quicklook

The FAI quicklook videos show images from both FAI CCDs as well as ephemeris and pointing information, and are sped up by a factor of ten for quick perusal. Figure 2 below is a reference for interpreting the FAI quicklook videos.



1 – Date for when images were taken
2 – Latest image from the infrared (650-1100 nm) camera
3 – Latest image from the visible (630 nm) camera
4 – Infrared image information: Time of start of exposure (UT), exposure (s), mode (HighRes=256x256, MedRes=128x128, LowRes=64x64), CCD Temperature (°C), image filename
5 – Visible image information: see #4 above
6 – View of the Earth from the satellite position. Time of view corresponds with the most recent image on the plot. Gridlines are lines of constant magnetic latitude and longitude.
7 – Satellite and IGRF information. Data correspond to the time of the most recent image on the plot.

Figure 2: FAI quicklook video help page

6.3.4 FAI Summary Plots

Figure 3 shows a sample summary plot from October 29, 2016. The top panel is a time series of the center image column taken from successive images from the infrared camera. The second panel is the same but for the visible camera. The third panel is a plot of the mean signal from the 20x20 central area of each camera. Solar inclination is plotted in the fourth panel, imaging mode in the fifth panel (Overscan = 256x320 pixels including an extra 40 over-scan columns, High Res = 256x280 pixels including 24 non-imaging columns, Med Res = 128x140 pixels including 12 non-imaging columns, Low Res = 64x70 pixels including 6 non-imaging columns), and exposure time for each camera is plotted in the bottom panel. Time in UT along with spacecraft ephemeris is plotted on the x-axis. Altitude is in km, geographic latitude and longitude are in degrees, magnetic latitude is in degrees, and MLT is in hours.

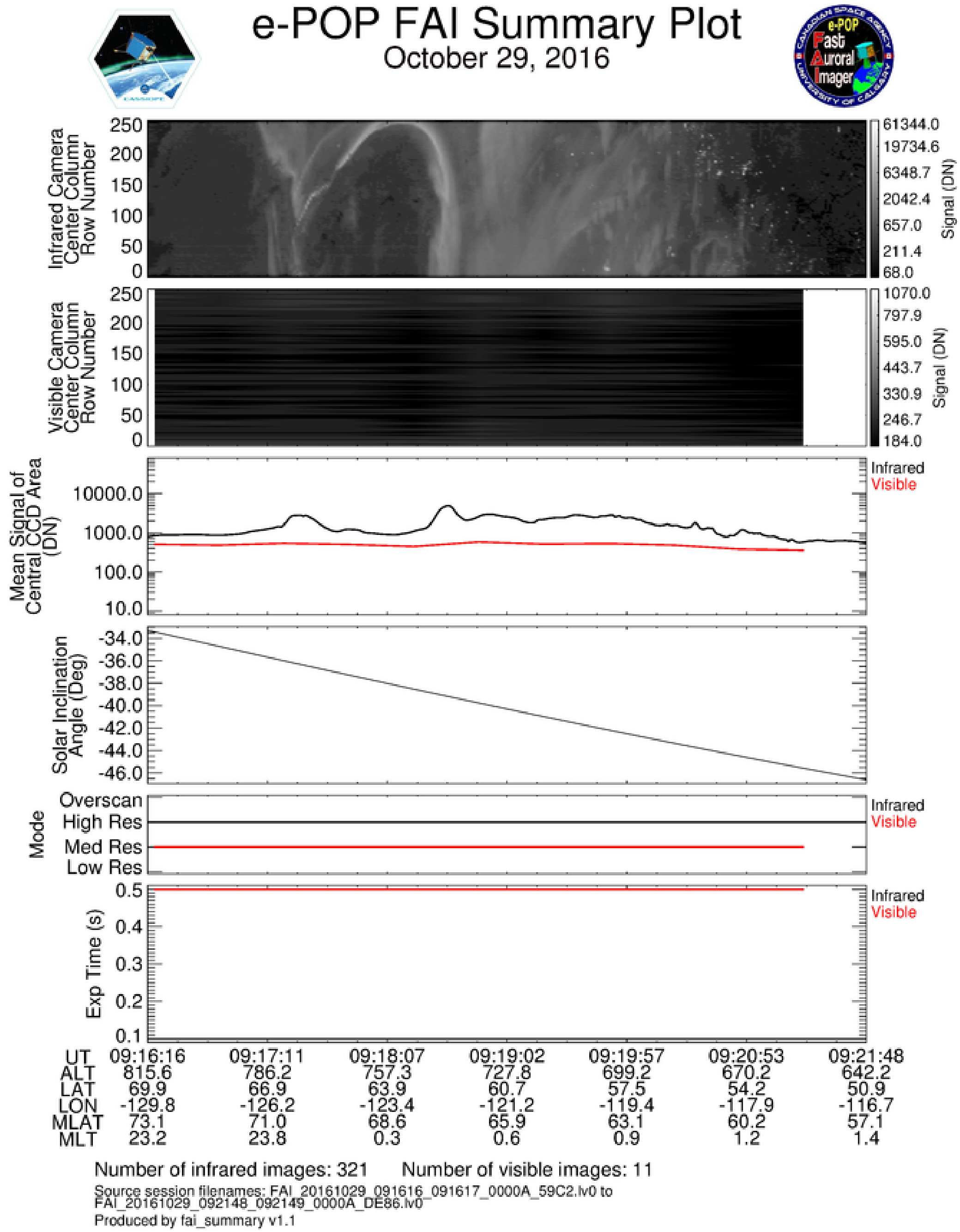


Figure 3: FAI Summary Plot Sample

6.4 GAP

The GPS Attitude, Positioning, and Profiling Experiment (GAP) combines five dual-frequency NovAtel GPS receivers and associated antennas to produce real-time position, attitude, and timing information onboard CASSIOPE. A detailed overview of the GAP instrument and its qualification process can be found in RD-4.

6.4.1 GAP Level 0 Data

The GAP level 0 data is described in detail in AD-1.

6.4.1 GAP Level 1 Products

The GAP level 1 data products are split by GAP GPS receiver number and are binary-type data files consisting of the raw output from the NovAtel GPS receivers. The filename convention is as follows:

`GAP_YYYYMMDD_HHMMSS_hhmmss_RCVR_N.lv1`

Where
`YYYY` = year, `MM` = month, `DD` = day, `HH` = start hour, `MM` = start minute, `SS` = start second, `hh` = end hour, `mm` = end minute, `ss` = end second, `N` = GAP receiver number (0-4). All times are in UT. The GAP GPS antenna locations are shown in Figure 5. The antenna numbers match the receiver numbers. Instructions for decoding the GAP level 1 data can be found in AD-3 and AD-4.

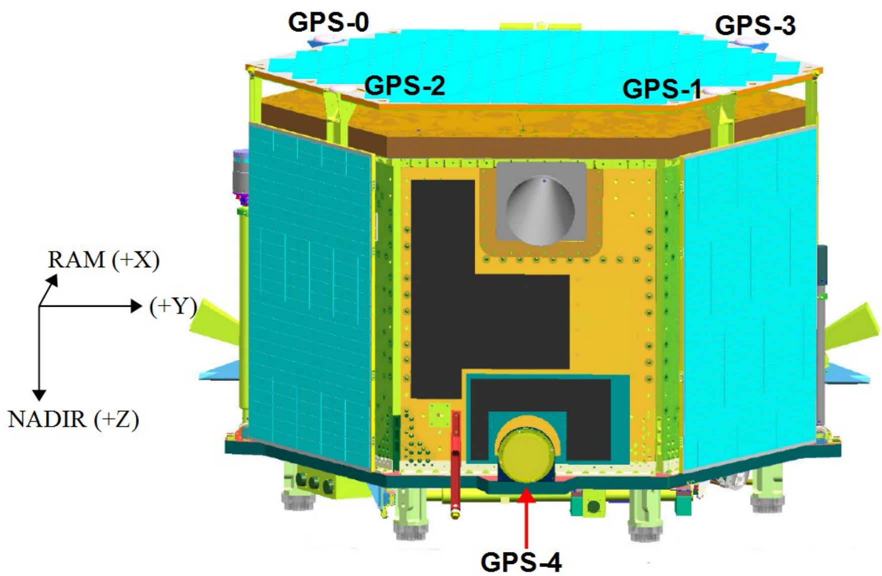


Figure 4: GAP GPS antenna placements

6.4.2 GAP Level 2 Products

The GAP level 2 products are presented in the Receiver INdependent EXchange (RINEX) format, version 3.02. These files are of ASCII type and are produced by the NovAtel-supplied "Convert4" software, operating on the GAP level 1 data files. See AD-5 for a complete description of RINEX files. There are two types of RINEX files produced for GAP; O (observation) and N (navigation), and each share the same name as the lv1 file it was created from, save for the file extension.

6.4.3 GAP Quicklook

The GAP quicklook plot shows when and, if possible, where GPS messages were received on a given day. Figure 4 shows a sample GAP quicklook plot from March 5, 2016. The top panel is a map showing the time and location of all messages where position was calculated. The start and end timestamps are shown adjacent to the start and end of each pass. The points are colour coded to show whether the GPS lock status was unknown (black), coarse steering (blue), or fine steering (green).

The middle panel plots a time series of the number of GPS satellites that GAP was able to lock to, with the colour and shape of the points indicating the type of messages received.

The bottom panel is a complete summary list of all types of GPS messages received and how many messages were received by each GAP receiver. Refer to AD-4 for a detailed description of the GPS message types (e.g. RAWEPHEM, ID41, etc).

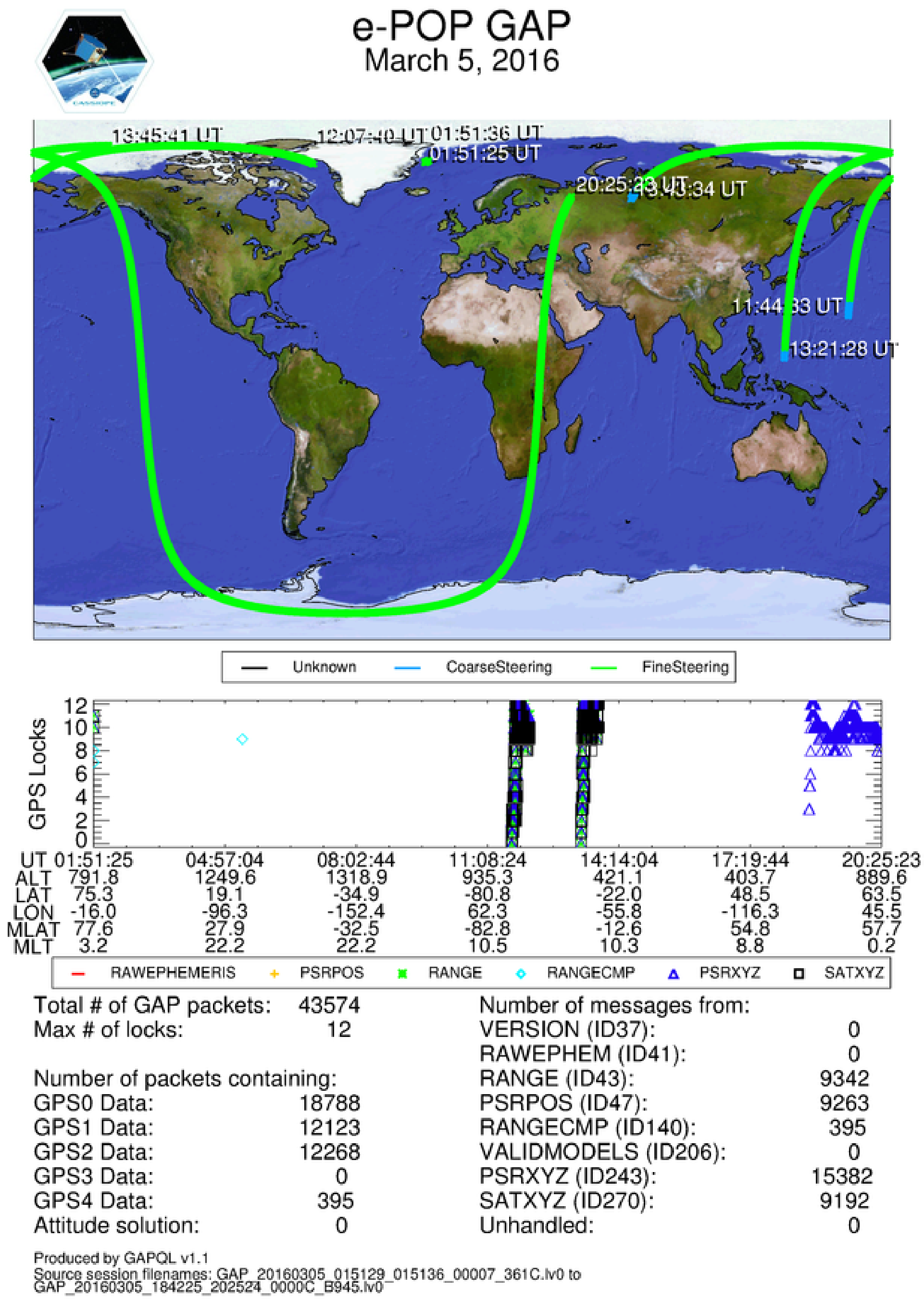


Figure 5: Sample GAP quicklook plot

6.5 IRM

The e-POP Imaging and Rapid-Scanning Ion Mass Spectrometer (IRM) is an ion detector capable of measuring ions in the 0.1-100 eV/q range, and is equipped with a time-of-flight gate to mass resolve ions in the 1-40 amu/q range. A comprehensive overview of IRM can be found in RD-5.

6.5.1 IRM Level 0 Data

Level 0 IRM data files are described in AD-1.

6.5.2 IRM Quicklook

IRM quicklook videos, produced from IRM level 0 data, give an indication of instrument health, settings, and quality of data captured by the instrument. Figure 6 shows a snapshot from an IRM quicklook video.

The top left pane shows the IRM detector pixel layout and associated count rate for each pixel including counts from all inner dome voltage settings for the time period indicated in the title area. The magnetic field and anti-ram directions, projected into the plane of the sensor, are overlaid as red and blue arrows, respectively. The zenith direction is indicated by a black arrow in the middle of the frame, above the legend for the spacecraft X and Z directions.

The bottom pane is a plot of the count rate for each time-of-arrival bin for all inner dome voltage settings combined. The two left panes do not correct for background counts. Background counts are those ions which pass through the time-of-flight gate when it is closed. These ions can be accounted for by estimating their count rate in each pixel/time-of-arrival bin by analyzing the counts in the upper time-of-arrival bins where no ion counts should be detected.

The right upper and lower plots are the same as the left but include counts for a single VSA step only at -260 V, with the estimated background counts removed.

The bottom of the quicklook shows the operating parameters and spacecraft location. Descriptions of the operating parameters can be found in RD-5.

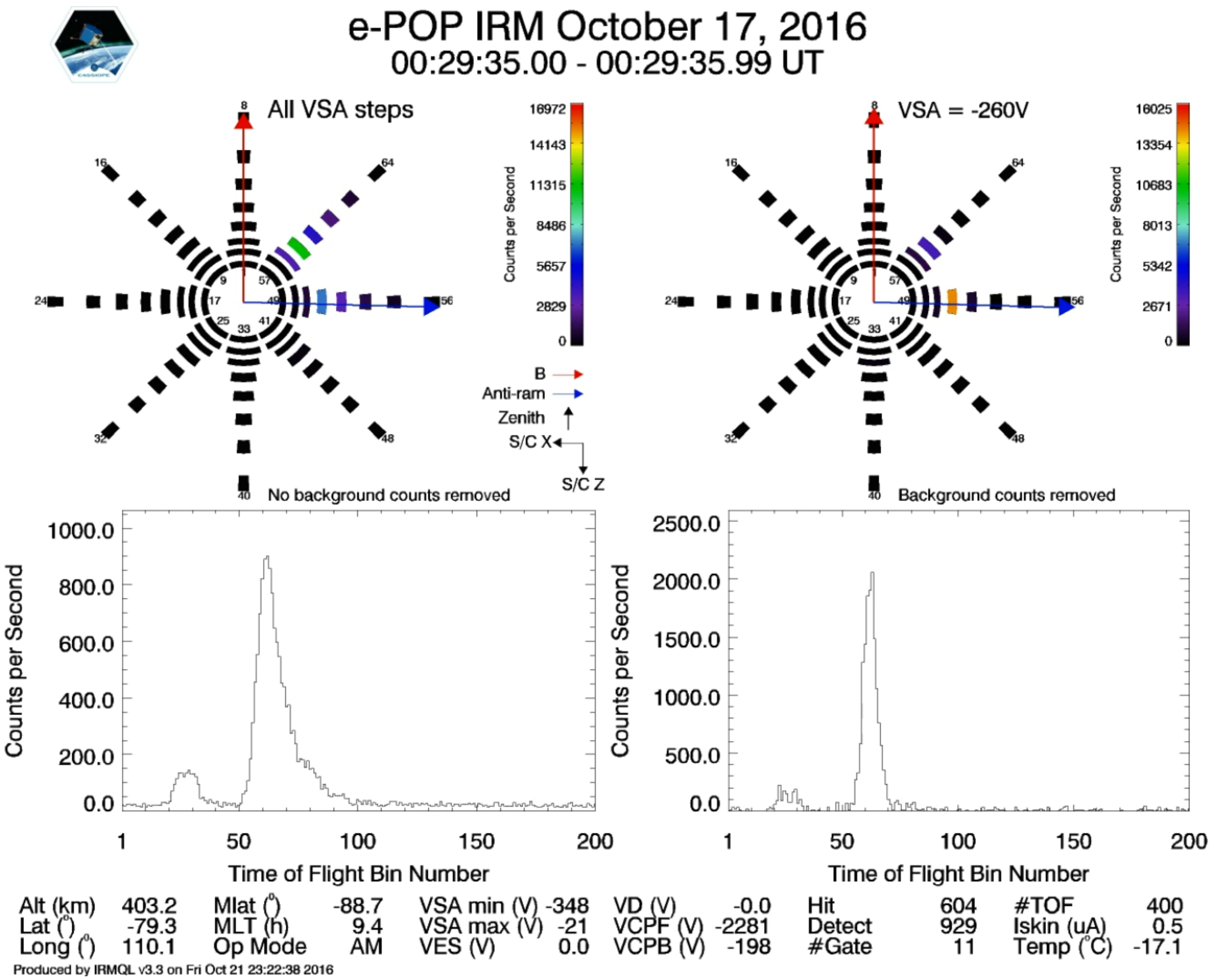


Figure 6: IRM quicklook sample

6.5.3 IRM Summary Plot

IRM summary plots are a one-page time-series plot of pixel counts, time-of-arrival bin, skin current, and total counts per second. A sample is shown in Figure 7. The top panel plots the count rate in each pixel column (see the pixel layout of the IRM detector anode in Figure 6) as a function of time. The y-axis labels indicate which pixel column is represented, and within each column the counts on each pixel row are plotted from bottom to top. For instance, in the –X row the pixel count rates for the inner most pixel (pixel number 49 in Figure 6) is at the bottom of the row, and the count rate for outer most pixel (pixel number 57 in Figure 6) is plotted at the top of the –X row. This is repeated for each row in the top panel. Note that the colour-coded counts are shown in a ‘compressed log scale’ where the top two decades are compressed compared to the bottom three. The attitude of the spacecraft is shown by the solid, dotted, and dash-dot lines overlaid on the plot, representing the direction of the magnetic field, anti-ram, and zenith directions, respectively.

The second plot from the top is a time series of the time-of-arrival bin counts. In this example it is clear that there are at least two species present filling up two distinct time-of-arrival bin ranges. Note that the colours are also plotted in the compressed log scale.

The next plot shows the current on the IRM outer skin in micro amps (positive indicating an abundance of electrons on the skin), and the bottom panel plots the ‘hit counter’ and ‘detect counter’ values. The ‘hit counter’ is incremented when two adjacent amplifiers on the IRM anode register a count whereas the ‘detect counter’ is incremented when only one amplifier records a count. These two values together give an indication of the spread of the electron cloud produced by the microchannel plates that make up part of the IRM ion detection assembly. The pixel counts in the top panel are made up of ‘hit counter’ counts.

The spacecraft ephemeris data is shown on the x-axis. IRM operating voltages and settings are shown in the table below the plots. Refer to RD-5 for a description of the voltages and operating modes of IRM.

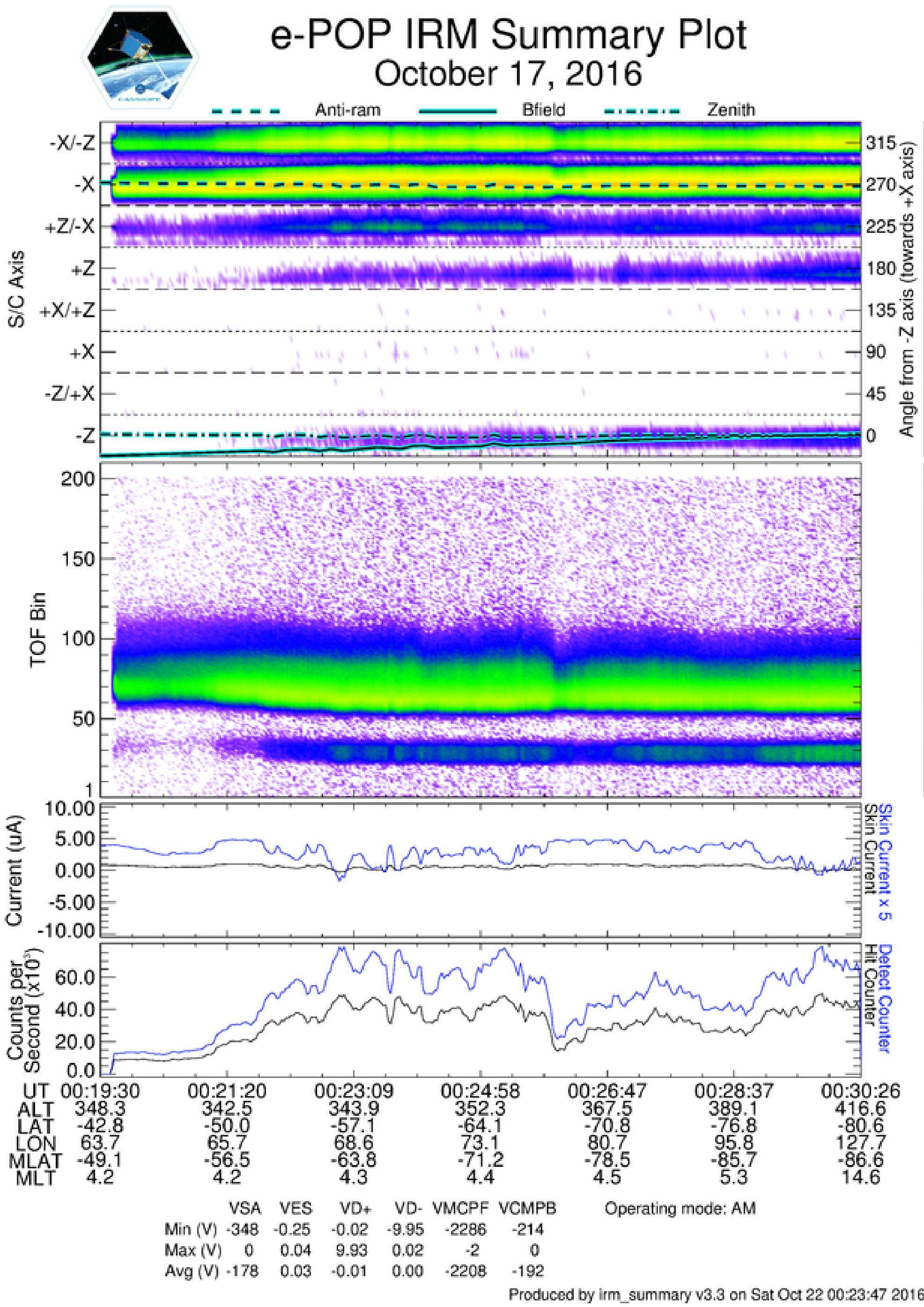


Figure 7: Sample IRM summary plot

6.6 MGF

The e-POP MaGnetic Field instrument (MGF) consists of dual, tri-axial fluxgate magnetometers mounted on an 80-cm carbon fibre boom for measurements of magnetic field perturbations. Further details on all aspects of the MGF instrument may be found in RD-6.

6.6.1 MGF Level 0 Data

The MGF level 0 data is described in AD-1.

6.6.2 MGF Level 1 Data

The MGF level 1 processor uses the packet timestamps and sequence numbers to align the MGF packets from the two magnetometers, tag in timestamps as they occur, and unpack the binary packets into an ASCII file in unprocessed instrumental units. The level 1 MGF data is an internal product and is not recommended for routine use.

6.6.3 MGF Level 2 Data

The MGF level 2 processor applies the preflight ground calibration to the magnetic data and metadata to convert to physical units, removes transients generated by instrumental range changes, and interpolates the timestamps to create a best-estimate for the sampling time of each data point. The level 2 MGF data is an internal product and is not recommended for routine use.

6.6.4 MGF Level 3 Data

The MGF level 3 processor applies the pre-flight calibrations and removes the interaction between the two MGF sensors. Eventually, the two instrument data streams will be merged to estimate and remove the spacecraft field. Currently, the level 3 data is derived from a single instrument. The spacecraft attitude solution is used to generate a second data product by rotating the measured magnetic field into a geophysical geocentric equatorial inertial (GEI) frame. Finally, the data is filtered and down-sampled to 10 and 1 samples per second (sps) time series aligned to the GPS-derived second boundaries.

The Level 3 data is provided as ASCII files using the format defined in Table 4.

Column Name	Example Value	Description
LV3_DESCRPT	LV3_MAGDATA	This is magnetic data
Time (s)	1508041541.000000	Seconds since the SMEX epoch (May 24 1968 00:00:00 UTC)
B_SCY (nT)	13643.928	B (nT) – Spacecraft X Coordinate (Ram aligned in nominal spacecraft orientation)
B_SCZ (nT)	23858.315	B (nT) – Spacecraft Y Coordinate (Cross-track aligned in nominal spacecraft orientation)
B_SCZ (nT)	23858.315	B (nT) – Spacecraft Z Coordinate (Nadir aligned in nominal spacecraft orientation)
B_SCY (nT)	13643.928	B (nT) – GEI X Coordinate
B_SCZ (nT)	23858.315	B (nT) – GEI Y Coordinate
B_SCZ (nT)	23858.315	B (nT) – GEI Z Coordinate
Loc X (GEI)	-5.1343278192E+06	Location – GEI X Component

Column Name	Example Value	Description
Loc Y (GEI)	4.0842133664E+06	Location – GEI Y Component
Loc Z (GEI)	3.6760843014E+06	Location – GEI Z Component

Table 4: MGF level 3 data format description

6.6.5 MGF Quicklook Plot

The MGF quicklook plot is generated for each MGF turn-on session. Figure 8 shows a sample plot. The top two panels show the Fourier power as a function of time and frequency for the outboard (top) and inboard (bottom) sensors. Below those, in panel three, is a plot of the total magnetic field for each magnetometer. The bottom two panels plot the temperature of the sensors and the electronics cards for each magnetometer (top panel), as well as the voltage monitor deltas (bottom panel), which is the difference between the measured voltage and the expected voltage of the monitor circuit.

The data along the x-axis are, from top to bottom, UT time, altitude in km, geographic latitude and longitude in degrees, magnetic latitude in degrees, and magnetic local time in hours.

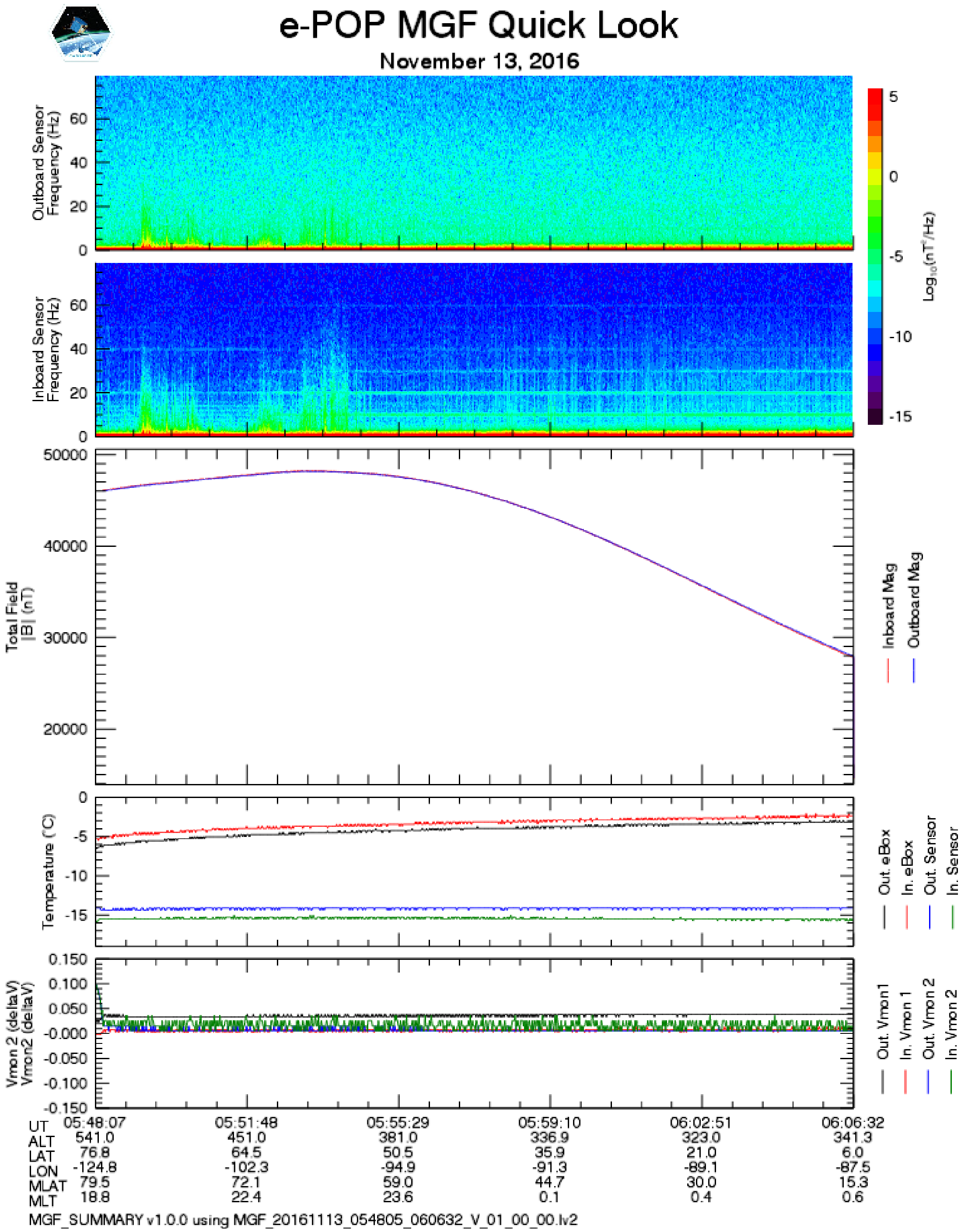


Figure 8: MGF quicklook sample

6.6.6 MGF Summary Plot

Figure 9 shows a sample MGF summary plot. The panels show the inboard magnetometer, outboard magnetometer, and IGRF reference field for the x, y, z, and total field components (top to bottom). The x-axis parameters are the same as those in the MGF quick look plots.

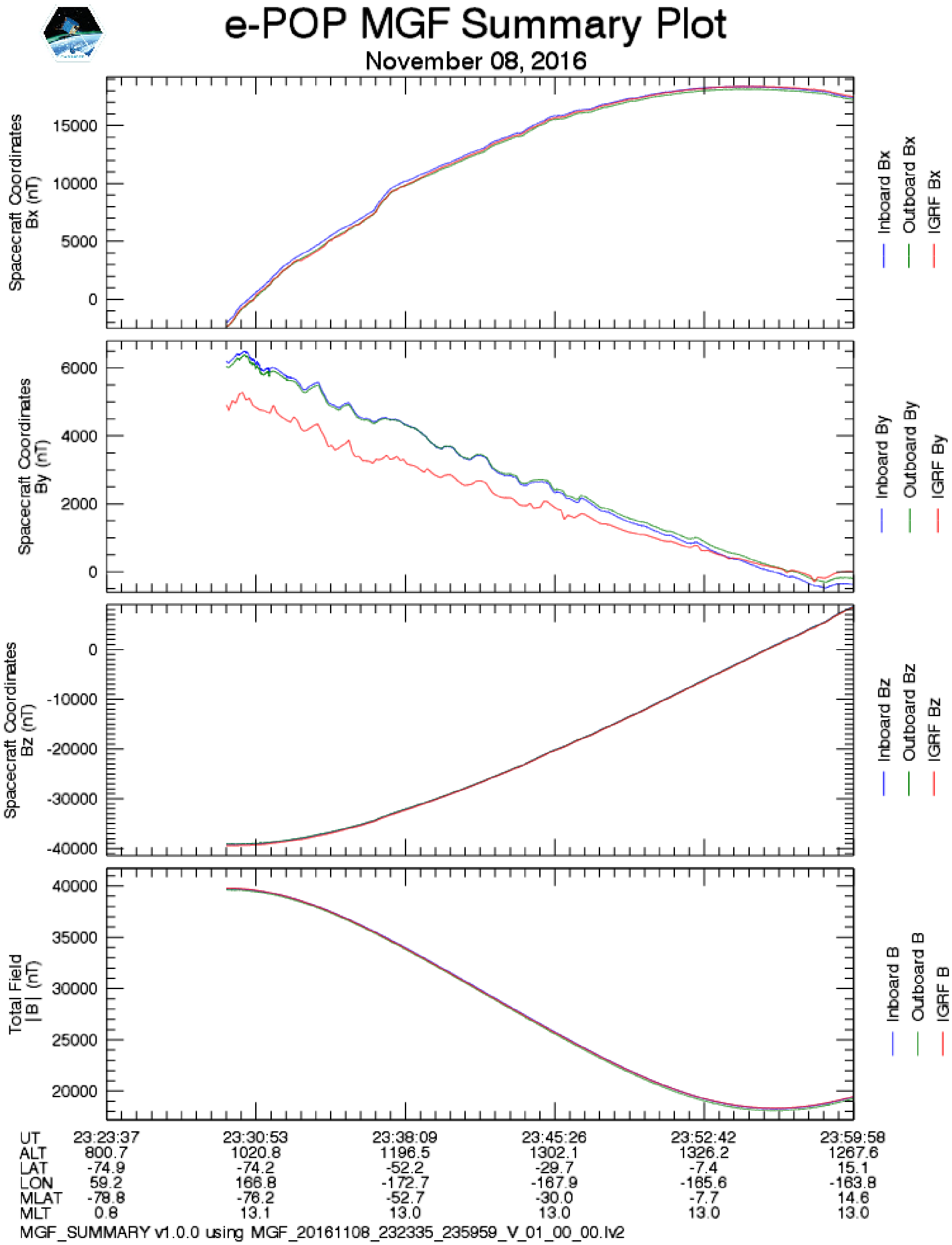


Figure 9: MGF summary plot sample

6.7 NMS

The e-POP Neutral Mass and velocity Spectrometer (NMS) measures the mass composition and velocity of neutral atmospheric species in the 1-40 amu mass and 0.1-2 km/s velocity range.

Content will be added in a future release of this document.

6.7.1 NMS Quicklook Plot

Content will be added in a future release of this document.

6.8 RRI

The Radio Receiver Instrument (RRI) measures wave electric fields in the 10Hz - 18MHz range, at magnitudes from 1 µV/m to 1 V/m. It has two input channels, each of which connect to two, 3-m monopole antennas. A complete description of the RRI instrument can be found in RD-7.

6.8.1 RRI Level 0 Data

RRI level 0 data is described in AD-1.

6.8.2 RRI Level 1 Data

RRI level 1 data utilizes the HDF5 file format and is described in detail in AD-1.

6.8.3 RRI Quicklook

The RRI quicklook is composed of spectrograms (measured antenna voltage as a function of time and frequency) for both RRI input channels. Figure 8 shows a sample RRI quicklook plot. The RRI settings are listed above the main panels, including settings for the channel selectors (I1, Q1, I2, Q2, I3, Q3, I4, or Q4 for each monopole), linear or dipole antenna mode, and the gain settings (low, medium, or high). The spacecraft ephemeris is shown on the x-axis below the Universal Time.

Linear and logarithmic sweeps over frequency are possible with RRI. The Fast Fourier Transform is computed over 5208 samples by default but will vary if required by a shorter dwell time of a frequency sweep.

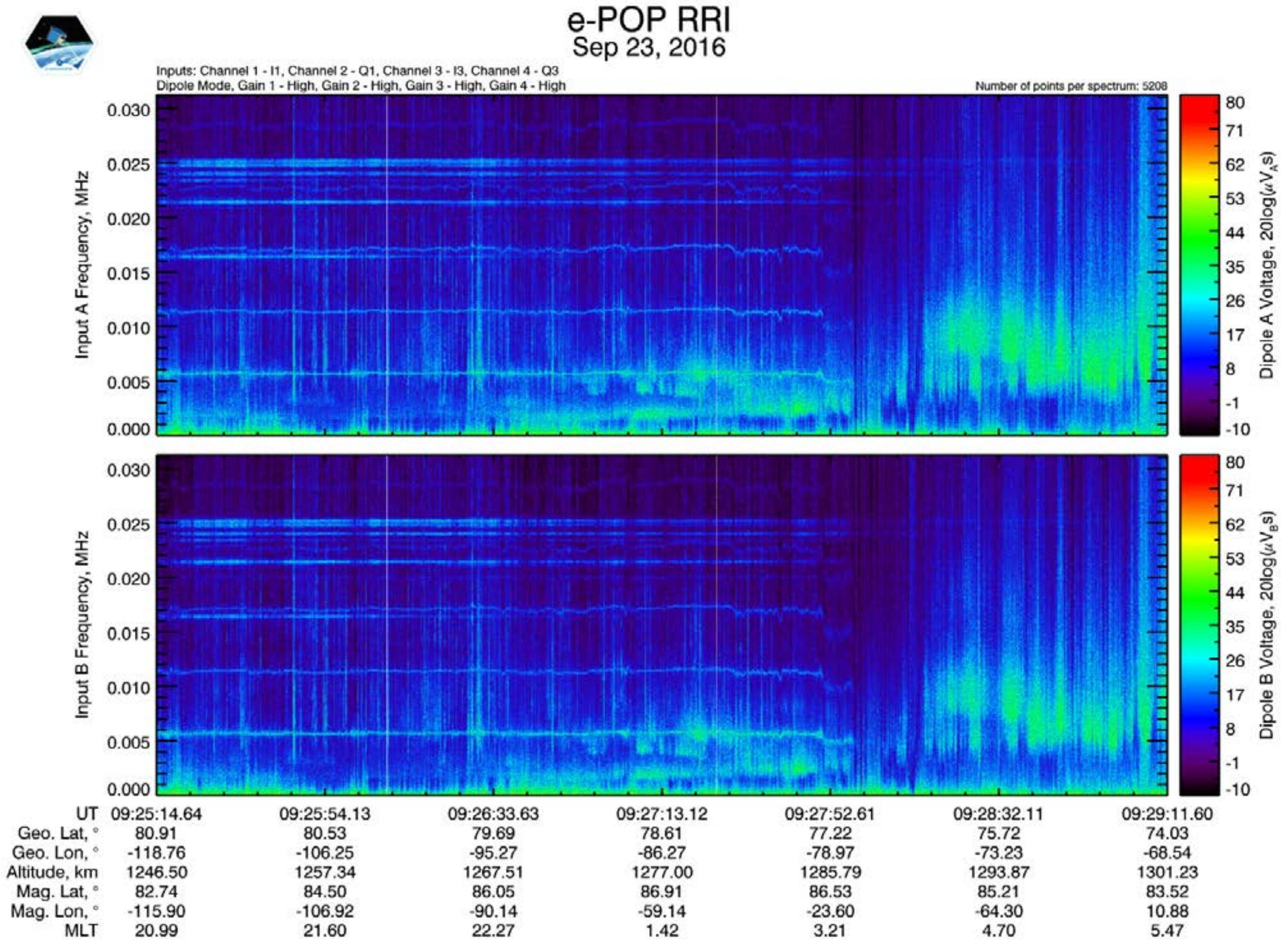


Figure 10: Sample RRI quicklook

6.9 SEI

The e-POP Suprathermal Electron Imager (SEI) measures the electron energy and pitch angle distribution over the energy range of 1 to 200 eV, with particular emphasis on photoelectrons in the 1 to 50 eV range. It is also capable of measuring ions. A complete description of the instrument is contained in RD-8.

6.9.1 SEI Level 0 Data

The SEI level 0 data is described in AD-1.

6.9.2 SEI Quicklook

Like IRM, the SEI quicklook is a video product used to assess instrument health, performance, and high-level data quality. An example frame is shown in Figure 9. The main panel is a snapshot of the SEI CCD, cropped to the specified number of pixels based on the instrument mode setting. CCD counts are displayed in a log scale and each image is the average a number of images, typically 100. When available, the attitude information is overlaid in the form of red and blue arrows, red for the magnetic field direction projected into the plane of the sensor, and blue for the anti-ram direction, also projected into the plane of the sensor. The bottom portion of the plot shows the time, instrument settings, and spacecraft position.

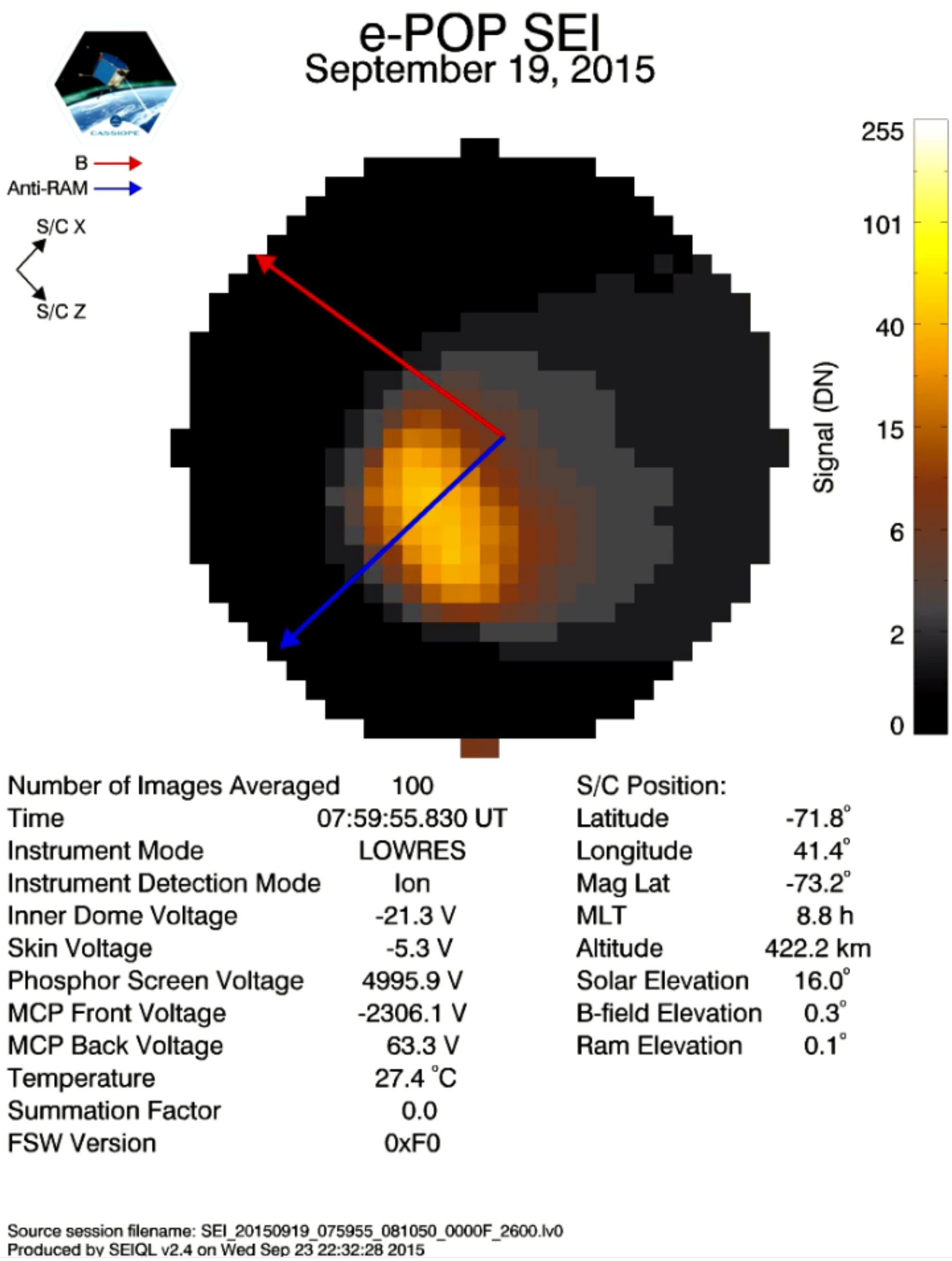


Figure 11: SEI Quicklook Sample

The SEI quicklook table data are described below.

Item	Description
Instrument Mode	SEI CCD operating mode. Modes include HIRES (64x64 pixels), LOWRES (32x32 pixels), and INTEGRATION (32x32 pixels integrated over a time indicated by the Summation Factor)
Instrument Detection Mode	Particle detection mode, either Electron or Ion.
Inner Dome Voltage	Voltage on the inner dome of the hemispherical analyzer. This controls the energy range of the detected particles.
Skin Voltage	Voltage applied to the outer SEI skin
Phosphor Screen Voltage	Voltage applied to the phosphor screen that sits between the CCD and the microchannel plates.
MCP Front Voltage	Voltage applied to the top of the microchannel plates (MCP)
MCP Back Voltage	Voltage applied to the bottom of the microchannel plates
Temperature	Temperature of the SEI sensor head. The temperature sensor reports **incorrect temperature values**.
Summation Factor	Number of images added together to get the final image
FSW version	Version number of the onboard flight software
Latitude	Spacecraft latitude
Longitude	Spacecraft longitude
Altitude	Spacecraft altitude
Solar Elevation	Angle between the spacecraft position vector and the sun-earth line
B-field Elevation	Angle between the magnetic field and the SEI CCD plane
Ram Elevation	Angle between the spacecraft ram direction and the SEI CCD plane

Table 5: SEI operating parameters

6.9.3 SEI Summary Plot

Figure 10 shows an example SEI summary plot. The top panel is a plot of instrument counts as a function of time and angle around the SEI CCD for the ring of pixels at a radius of npix/2, where npix is the number of pixels in one dimension of the image. Note that the counts are log scaled by colour.

The second panel plots counts as a function of time and energy. The energy of the particles is determined from the pixel position and voltage on the SEI inner dome via the following formula

$$E = 0.61141(r/32.0)^{1.18667} * |vInner|$$

where r is the radius of the illuminated pixel with respect to the image center (image center is [34.5568, 33.1462] in hires mode), and vInner is the voltage on the inner dome.

The first moment of the image is plotted in the second panel. The x and y first moments are computed as follows:

$$x_m = \frac{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} x_{ij} \, C_{ij}}{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} C_{ij}}$$
$$y_m = \frac{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} y_{ij} \, C_{ij}}{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} C_{ij}}$$

where C_{ij} are the counts at the [i,j] pixel, x_{ij}, y_{ij} are the x and y position of the [i,j] pixel, and N is the number of pixels in one dimension of the CCD.

The solar zenith angle is the angle between the sun and the local zenith direction, and is plotted in the fourth panel.

The bottom panel shows the SEI mode as a function of time.

Other operating parameters are indicated above the top panel. See Table 5 for a description of these values.

The spacecraft position is indicated on the x-axis. ALT is altitude in km, LAT is the geographic latitude in degrees, LON is the geographic longitude in degrees, MLAT is the magnetic latitude in degrees, and MLT is the magnetic local time in hours.

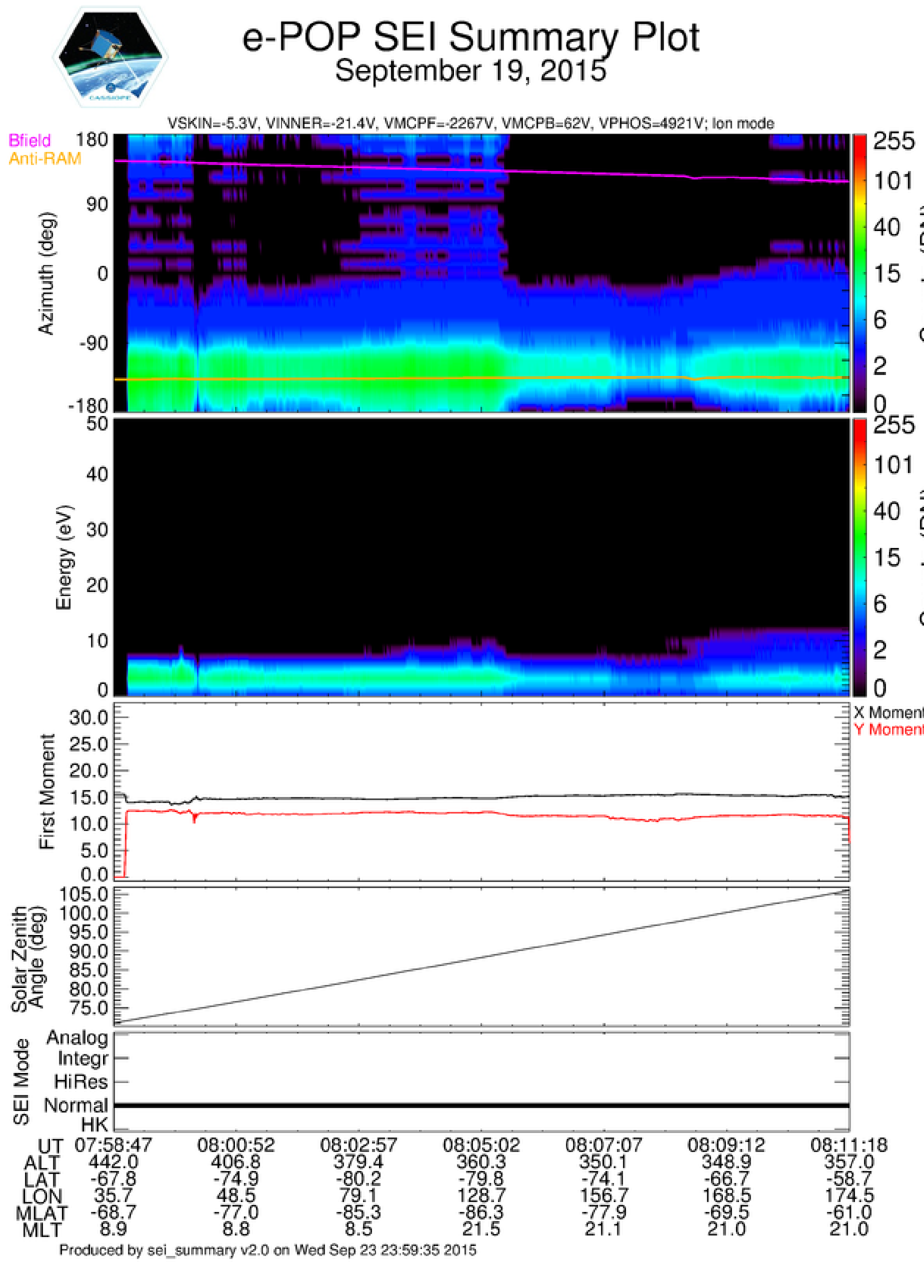


Figure 12: Sample SEI summary plot

7. e-POP Software Tools

e-POP software tools are available for general use and can be obtained by visiting http://epop.phys.ucalgary.ca/data. All tools are written in the IDL language. IDL must be installed on a local computer for use, however an IDL license is not required for most functions. As of the writing of this document, the software suite can be used to read in and display data from the FAI, IRM, RRI, and SEI data sets. At present, no publically available software are available to display the data from CER, GAP, MGF, or NMS. Tools to manipulate these remaining data sets will hopefully be available soon.

7.1 FAI

FAItools is a software package for viewing and geolocating FAI images.

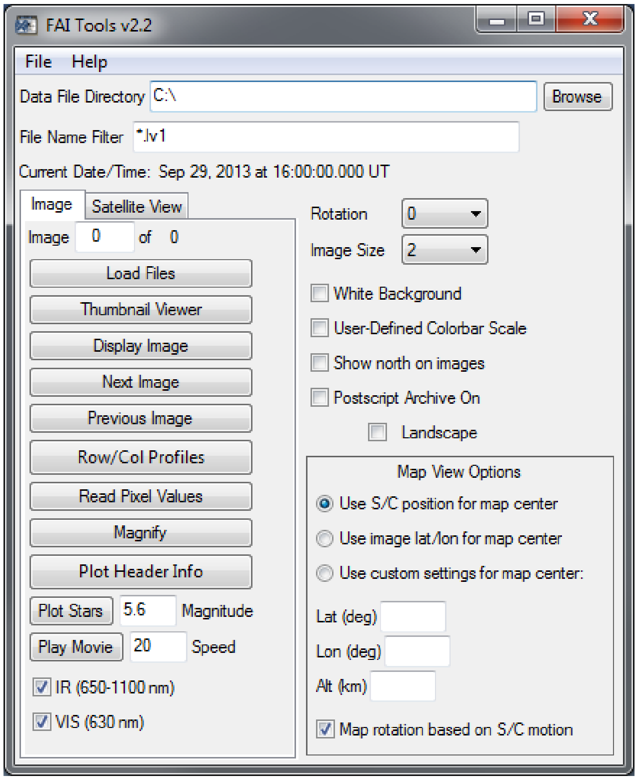


Figure 13: FAItools main GUI

To start FAItools, double-click the FAItools.sav file and the main GUI should appear (Figure 13). To load images into the tool, enter in a path where your FAI level 1 images (*.lv1) reside into the "Data File Directory" box, or click the "Browse" button and locate the folder. Image names may be filtered before being loaded by utilizing the "File Name Filter" box. Once these parameters are correctly entered, click the "Load Files" button.

Images can now be viewed as a bunch of thumbnails ("Thumbnail Viewer" button, Figure 14), one-by-one ("Display Image", "Next Image", and "Previous Image" buttons, Figure 15), or as a movie ("Play Movie" button).

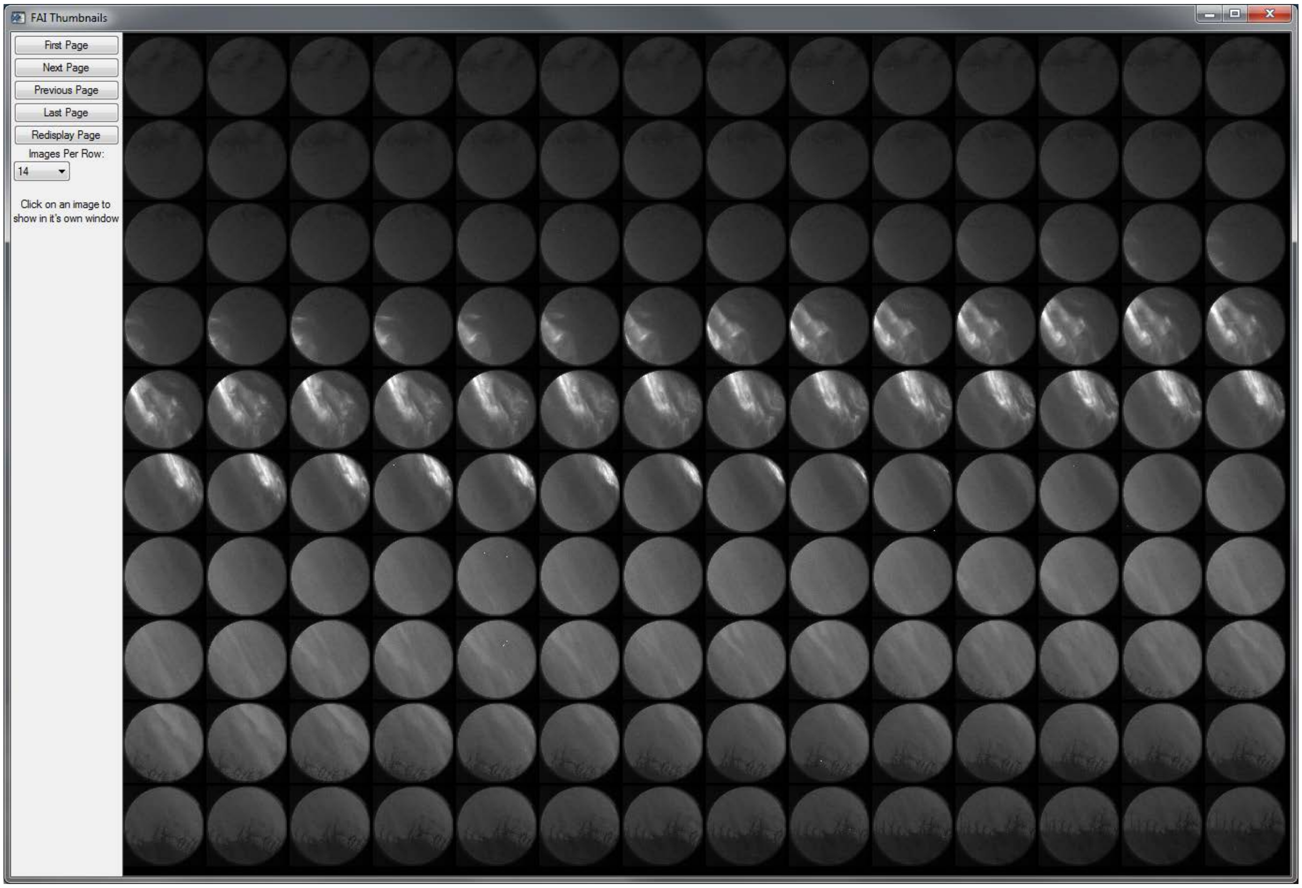


Figure 14: FAItools thumbnail viewer

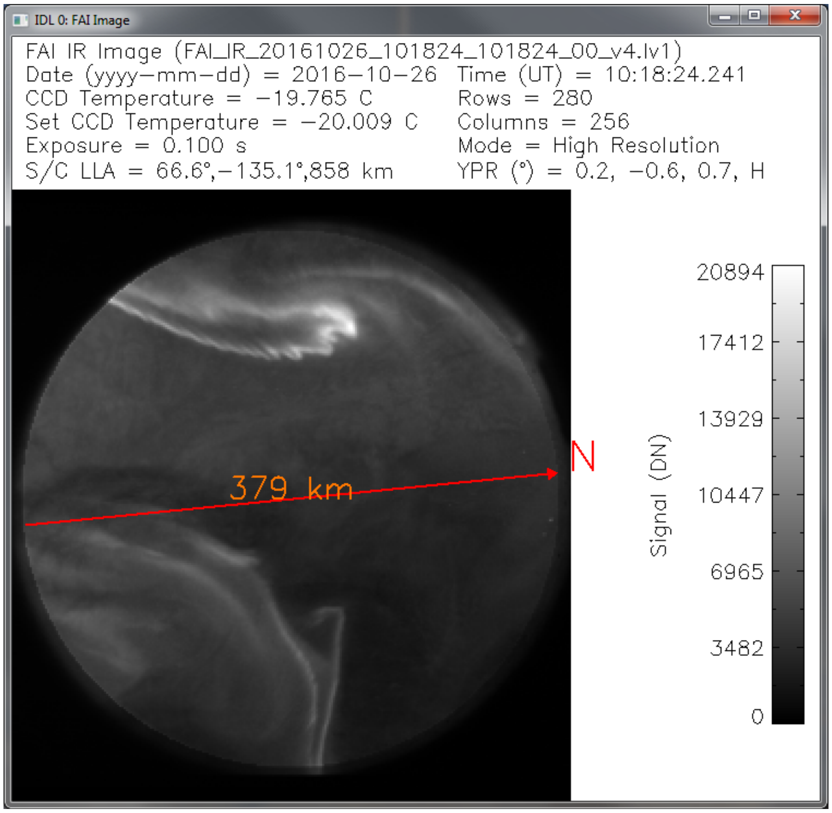


Figure 15: FAItools image display with overlay

Geolocating images is done using the "Satellite View" tab on the main GUI. Select either "Satellite View", "Stereographic View", or "Mercator View" first to set the map projection, then add selected items to the output with the remaining buttons, e.g. "Project Image Onto Map", "Add Magnetic Grid", and "Add Oval → Quiet Time → Unfilled" to get the view shown in Figure 16 for November 26, 2016 at 10:18:24. The map view can be adjusted by editing the fields in the "Map View Options" area as well.

Output from FAItools can be created in two ways. For postscript output check the "Postscript Archive On" button. This causes all subsequent displays to be directed to the postscript file. Uncheck the archive button to close the file. Alternatively you may use the "File" menu to select other outputs such as capturing the currently active window to a jpg file, or to create specialized mp4 videos of images or map projections (e.g. see Figure 17).

General options include changing the default colour table ("File→Load Color Table"), setting a custom colour bar scale (checking the "User-Defined Colorbar Scale"), and selecting output from only the IR or VIS camera ("IR (650-1100nm)" and "VIS (630nm)" checkboxes on the "Image" tab).

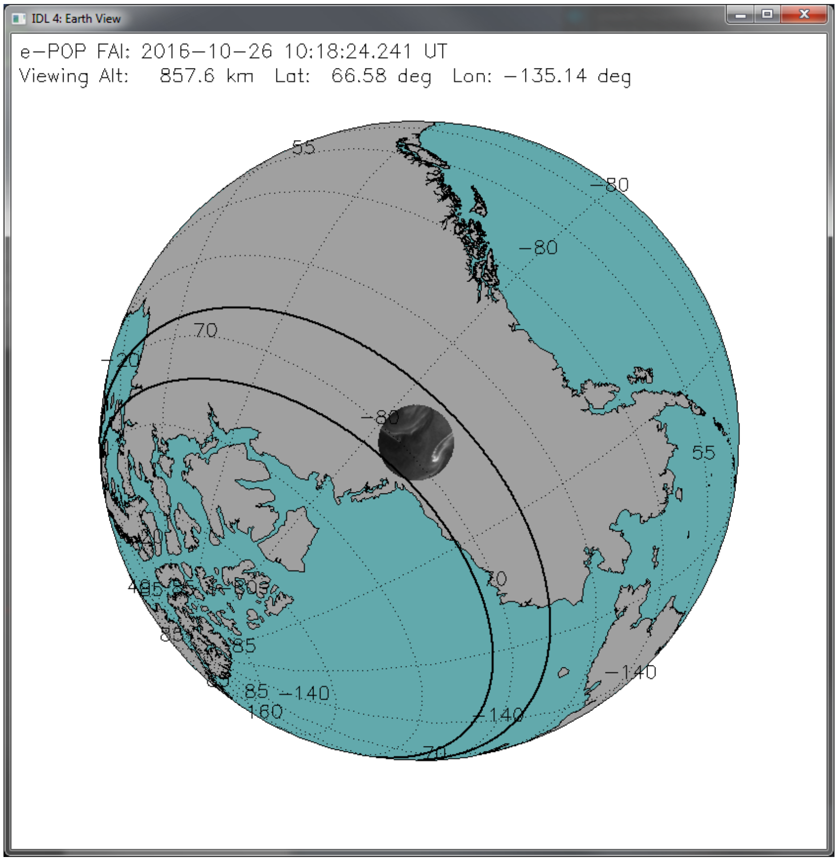


Figure 16: FAI satellite view

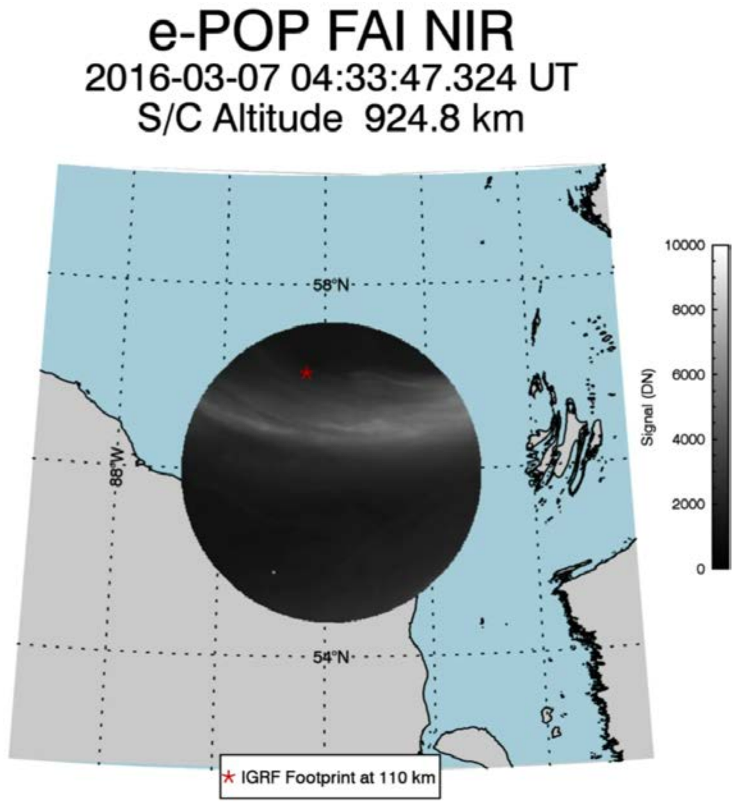


Figure 17: FAItools video map projection

7.2 IRM

The IRMtools software is designed to view the raw IRM lv0 data. It shows a graphical display of ion counts on the IRM anode, can plot time-of-arrival bin histograms, as well as plot IRM engineering housekeeping data. The IRM pixel anode is oriented such that pixel column 3 (pixels 17-24) are aligned with the spacecraft X-axis, and pixel column 5 (pixels 33-40) are aligned with the spacecraft Z-axis.

Figure 18 shows the main IRMtools GUI. IRM lv0 files are loaded by clicking the “Open…” button and selecting a file. IRM packet data is displayed one at a time or in movie form, with each packet’s data displayed in the left text area. Plots are created using the lower boxed section, use the drop-down button to select a plot type, then click the “Plot” button to display the plot. Plot options are also available below the “Plot” button. To save output to a file select either “File → Capture Current Window…” or “File → Start Postscript File Log…”. To close the postscript file click “File → End Postscript Log”. While the postscript file log is open all output will be sent to file and not to the screen.

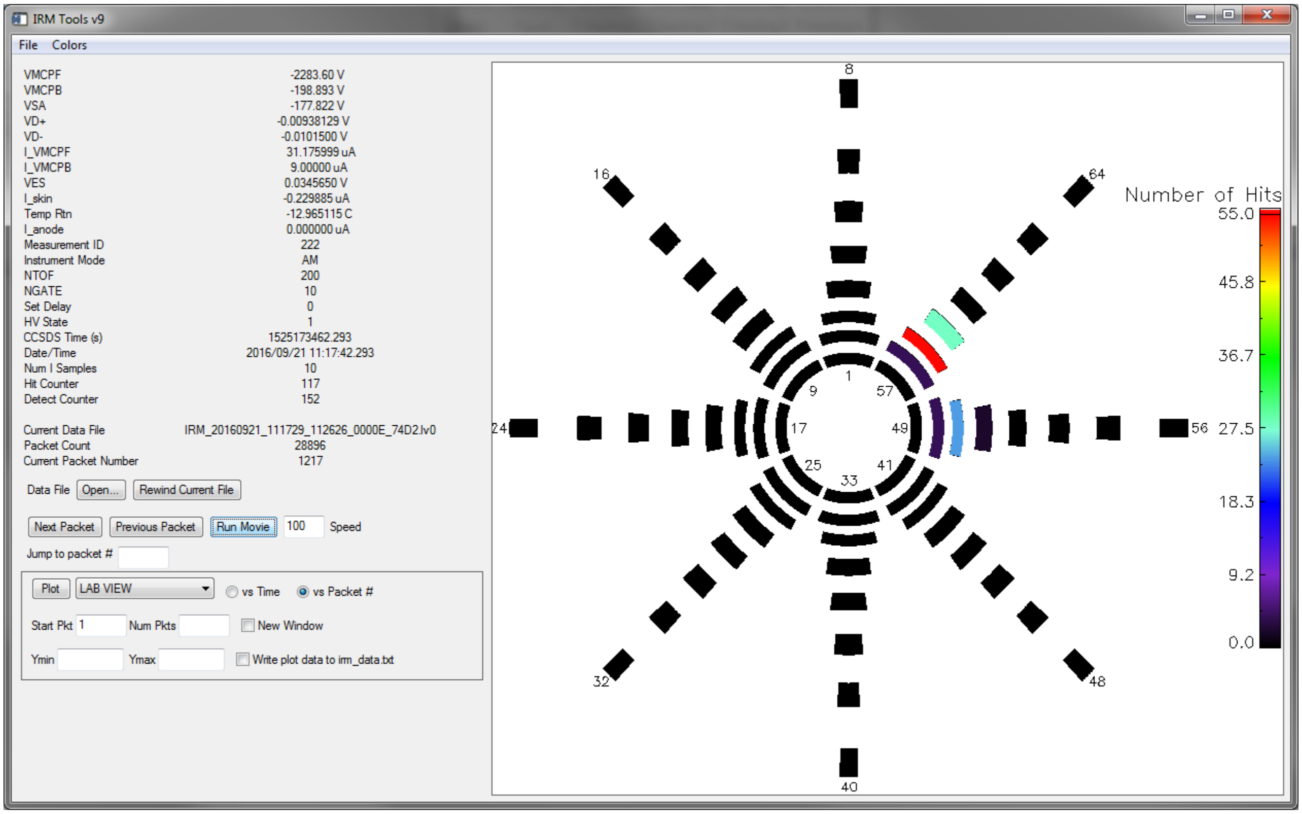


Figure 18: IRMtools main GUI

7.3 RRI

An IDL routine is provided to read the RRI lv1 HDF5 files, titled "read_rri_lv1.pro". Its usage is as follows:

```
.compile read_rri_lv1
rri_data = read_rri_lv1([inputFileName], [sec_in=sec_in], $
    [total_sec=total_sec], [decm=decm], [/geographic_interp], $
     [/geomag_interp], [/gei_gsm_interp], [/attitude_interp])
```

Optional Inputs	Description
inputFileName	Specifies the path to an rri hdf5 file
sec_in	Number of seconds into the file to start reading data from. Default is the start of the file.
total_sec	Number of seconds of data to read from the file. Default is to read the entire file.
decm	Decimation keyword to specify how to decimate the data - program reads in one out of every decm data points.
geographic_interp	Interpolate the geographic ephemeris data to each radio_data point. Default is 1 sample per second.
geomag_interp	Interpolate the geomagnetic ephemeris data to each radio_data point. Default is 1 sample per second.

Optional Inputs	Description
`gei_gsm_interp`	Interpolate the gei and gsm ephemeris data to each radio_data point. Default is 1 sample per second.
`attitude_interp`	Interpolate the attitude ephemeris data to each radio_data point. Default is 1 sample per second.

Table 6: read_rri_lv1 input parameters

Returned is a structure containing the following attributes:

Instrument Setting	Description
gain1	gain on antenna 1 (low, medium, or high)
gain2	gain on antenna 2 (low, medium, or high)
gain3	gain on antenna 3 (low, medium, or high)
gain4	gain on antenna 4 (low, medium, or high)
switch_k1	'Monopole' or 'Dipole' antenna configuration
sweep_mode_A	Sweep mode for input A. 'Fixed Frequency', 'Linear Sweep', or 'Logarithmic Sweep'
sweep_mode_B	Sweep mode for input B. 'Fixed Frequency', 'Linear Sweep', or 'Logarithmic Sweep'
bandwidth_A	Bandwidth of input A, 5 or 30 kHz
bandwidth_B	Bandwidth of input B, 5 or 30 kHz
F1_A	Frequency start for input A (MHz)
F2_A	Frequency end for input A (MHz)
DF_A	Delta frequency for input A (MHz)
DWELL_A	Time spent at each frequency on channel A (s)
F1_B	Frequency start for input B (MHz)
F2_B	Frequency end for input B (MHz)
DF_B	Delta frequency for input B (MHz)
DWELL_B	Time spent at each frequency on channel B (s)
chan_A_freq	Array of values for each data point indicating the center frequency (MHz) at that time for channel A
chan_B_freq	Array of values for each data point indicating the center frequency (MHz) at that time for channel B
data_format	Indicates data streams provided. Format is four of 'I1' 'Q1' 'I2' 'Q2' 'I3' 'Q3' 'I4' 'Q4', e.g. "I1Q1I3Q3". In dipole mode, "I1Q1I3Q3" means that the in-phase and quadrature streams from dipole 1 and 2 are in the data. In monopole mode, "I1I2I3I4" means that the in-phase voltages from all four monopoles are presented in the data stream.
gei	Interpolated S/C position in GEI coordinates for each antenna voltage (km)
vgei	Interpolated S/C velocity in GEI coordinates for each antenna voltage (km/s)
gsm	Interpolated S/C position in GSM coordinates for each antenna voltage (km)

Instrument Setting	Description
lat	Interpolated geographic latitude for each antenna voltage data point (deg)
lon	Interpolated geographic longitude for each antenna voltage data point (deg)
alt	Interpolated geographic altitude for each antenna voltage data point (km)
mlat	Interpolated magnetic latitude for each antenna voltage data point (deg)
mlon	Interpolated magnetic longitude for each antenna voltage data point (deg)
mlt	Interpolated magnetic local time for each antenna voltage data point (h)
yaw	Interpolated S/C attitude yaw value each antenna voltage data point (deg)
pitch	Interpolated S/C attitude pitch value each antenna voltage data point (deg)
roll	Interpolated S/C attitude roll value each antenna voltage data point (deg)
radio_data1	Antenna voltage data from data_format identifier #1, e.g. from I1, in mV
radio_data2	Antenna voltage data from data_format identifier #2, e.g. from Q1, in mV
radio_data3	Antenna voltage data from data_format identifier #3, e.g. from I3, in mV
radio_data4	Antenna voltage data from data_format identifier #4, e.g. from Q3, in mV
time	Time, in seconds, since May 24, 1968 at 00:00:00 UT, of each radio_data set (data comes in sets of 4)
no_interp_ephemeris_time	Time, in seconds since May 24, 1968 at 00:00:00 UT, of each non-interpolated ephemeris data point

Table 7: read_rri_lv1 structure output

Example use:

```
IDL> .r read_rri_lv1
IDL> rri_data = read_rri_lv1('RRI_20140419_044348_044917_lv1_v2.h5',
sec_in=10, total_sec=20, decm=1)
IDL> dummy = label_date('%H:%M:%S',OFFSET=JULDAY(05,24,1968,0,0,0.0d))
IDL> plot, rri_data.time/86400.0d, rri_data.radio_data1,
xtickformat='LABEL_DATE', title='e-POP RRI April 19, 2014', xtitle='Time
(UT)', ytitle = 'Antenna 1 Voltage (mV)'
```

Sample output:

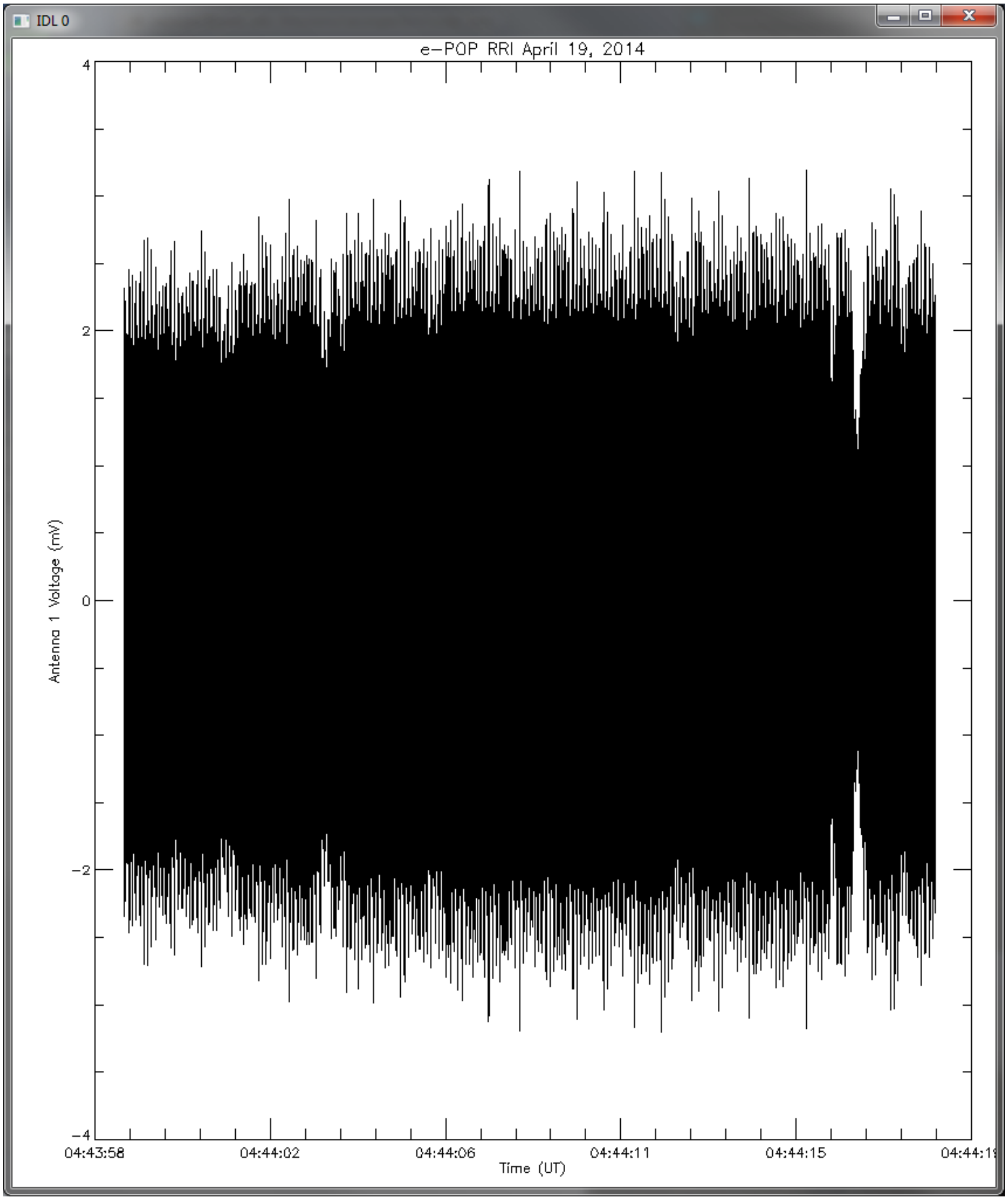


Figure 19: Sample RRI data plot

7.4 SEI

The SEI Tools software is for visualizing the SEI level 0 data. Load an SEI lv0 file by clicking "Open..." and selecting a file. Images can be viewed as a movie by clicking the "Run Movie" button. For most SEI passes it is best to view the data using the LOG scaling option. There is also a thumbnail viewer available.

Plots of intensity, moments, and engineering housekeeping data can be created using the "Plot" button along with the dropdown box to its right. By default plots appear in the GUI, but selecting the "New Window" checkbox allows plots to be created in a new, larger window.

Options for outputting plots to file are located in the "File" menu. For postscript output, open a file using "File→Start Postscript File Log", create a plot using the "Plot" button, then close the postscript file via "File→End Postscript File Log".

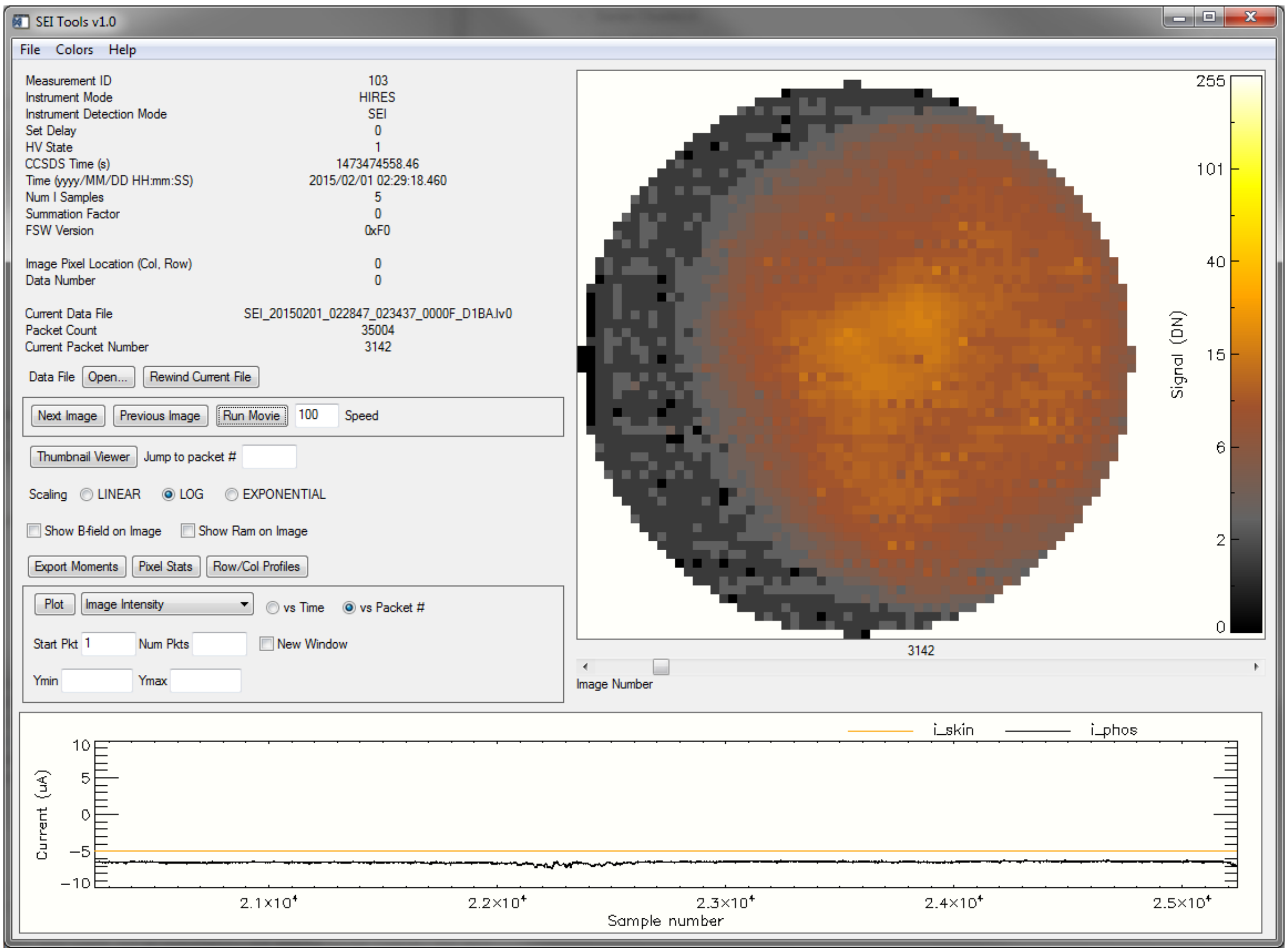


Figure 20: SEI Tools GUI

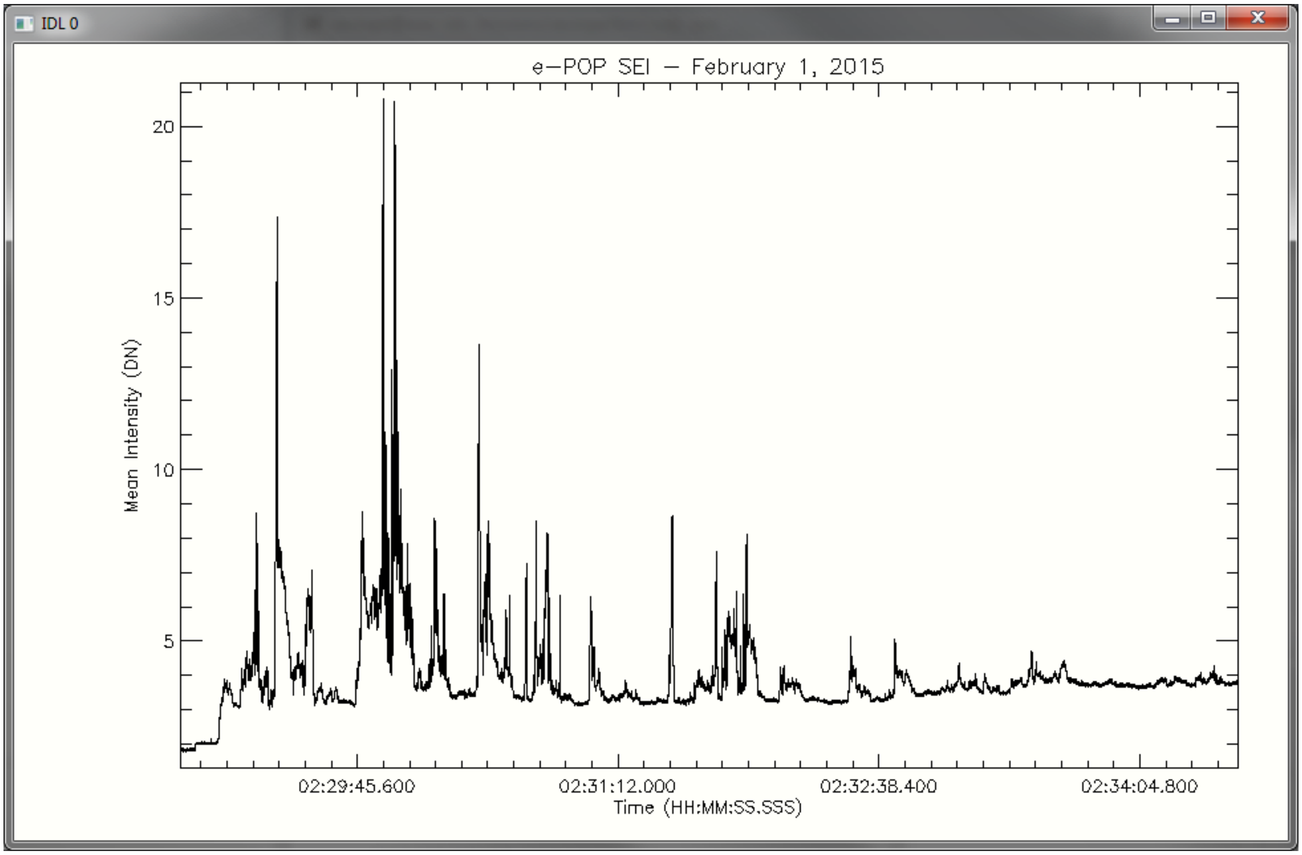


Figure 21: Sample SEI Tools plot

8. e-POP Data Archival

The e-POP science data is archived at many stages during processing. Figure 22 shows how the e-POP science data is received, stored, archived, and shared.

Copy 1 is the raw, compressed data files that are received by the University of Calgary from the ground station provider and are saved exactly as they are received.

Copy 2 is the unpacked science and spacecraft bus data that is parsed and evaluated by the CASSIOPE Mission Operation System (MOS). Spacecraft health and safety is evaluated using this data, and spacecraft ephemeris products are generated at this level.

Copy 3 is a compressed copy of Copy 2 along with the MOS evaluation products (plots, reports, etc.) This copy is stored at a separate, secure, off-site location on a different operating system than Copy 2.

Copy 4 is an exact copy of Copy 2 but on a separate machine.

Copy 5 is comprised of the level 0 data as well as the level 1+ data products that are generated on the e-POP science data server. The level 1+ data products are versioned and reproducible from the level 0 data.

Copy 6 is an exact copy of Copy 5 but on a separate machine.

Copy 7 is an exact copy of Copy 5 but on a publically-accessible data server. This server is accessed by cssdp.ca as well as epop-data.phys.ucalgary.ca.

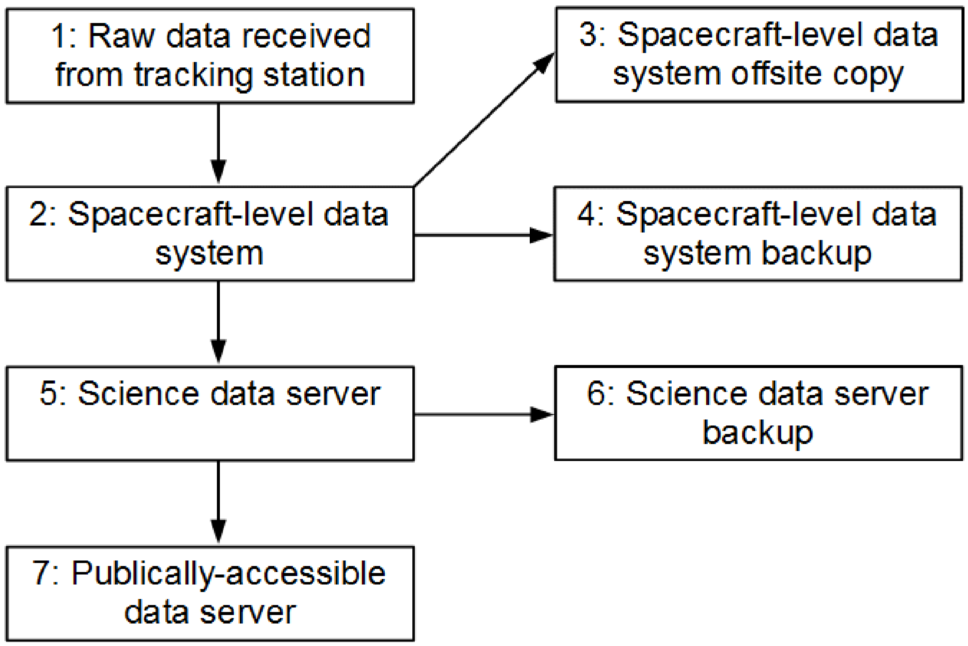


Figure 22: e-POP data tree

The e-POP Science Operation Center (eSOC) and MOS systems are protected by a firewall as well as an intrusion prevention and detection system that monitors for and blocks unauthorized system access. Multiple operating systems are utilized to protect against data loss and corruption from O/S-dependant virus and/or malware attacks.