# e-POP Instrument Raw and Processed Data Formats

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## i. References

**R1:** OEM4 User Manual Volume 1 Rev 19.pdf
**R2:** OEM4 User Manual Volume 2 Rev 18.pdf
**R3:** MGF_data_block_v3.xls

# 1. CCSDS Transfer Frames

e-POP instruments collect data into packets with format described in Section 2. When an e-POP science packet is received by the CASSIOPE data handling unit card it has a CCSDS transfer frame header pre-pended to it. The CCSDS transfer frame format is shown below. Of special note is the time information in Bytes 11-16, this is the time that the packet arrived on the data handling unit card. Because the GPS times in the science data packets are often incorrect **this time represents the best estimate of when the data was collected.**

| Byte 01 | Byte 02 | Byte 03 | Byte 04 | Byte 05 | Byte 06 | Byte 07 | Byte 08 |
|---|---|---|---|---|---|---|---|
| AAAB CDDD | DDDD DDDD | EEFF FFFF | FFFF FFFF | GGGG GGGG | GGGG GGGG | HHHH HHHH | HHHH HHHH |

| Byte 09 | Byte 10 | Byte 11 | Byte 12 | Byte 13 | Byte 14 | Byte 15 | Byte 16 |
|---|---|---|---|---|---|---|---|
| IIII IIII | IIII IIII | JJJJ JJJJ | JJJJ JJJJ | JJJJ JJJJ | JJJJ JJJJ | KKKK KKKK | KKKK KKKK |

Each letter in the above diagram represents 1 bit. Described values are true for the e-POP mission only.

### *Field Descriptions*

- A
  - Version – 3 bits
  - Value is always 000 (binary)
- B
  - Type – 1 bit
  - Value is always 0 (binary)
- C
  - Secondary Flag – 1 bit
  - Value is always 1 (binary)
- D
  - Apid – 11 bits
- E
  - Group Flags – 2 bits
  - Value is always 11 (binary)
- F
  - Apid Count – 14 bits
  - Value is a counter, expected to change with each packet.
- G
  - Data Length – 16 bits
  - This is 9 bytes longer than the length of the science data received in this packet.
- H
  - Uncompressed Data Length – 16 bits
  - Since we do not know the data compression algorithm this should be the same as the data length in the last 2 bytes
- I
  - Data CRC – 16 bits

  - This is the CRC calculated over the received science packet. If the science packet was transmitted complete and correct this CRC should be 0x0000. This is an effect of calculating a CRC over itself.
- J
  - Coarse Time – 32 bits
  - This is the spacecraft coarse time of the receipt of the science packet. The value represents the number of seconds since May 24, 1968 at 00:00:00.0 UT (the SMEX epoch).
- K
  - Fine Time – 16 bits
  - This is the spacecraft fine time of the receipt of the science packet. Units are 9e-5 seconds per tick.

For example, a coarse time of 1452284303 and a fine time of 964 corresponds to May 31, 2014 at 20:18:23.0868 UT.

## 2. e-POP Packets

Each e-POP instrument collects science data in discrete packets in the format shown below (as defined in the ePOP-3200 document).

| Byte 1 | 2 | 3 | 4 to 5 | 6 to 7 | 8 | 9 to (n-2) | (n-1) | n |
|---|---|---|---|---|---|---|---|---|
| DLE | STX | PID | Length | Spares | MeasID | Science Data | CRC MSB | CRC LSB |

### *Start of Packet - DLE*

The start of packet identifier for the instrument science data packet is always a <DLE>, which is hexadecimal value 0x10.

### *Start of Packet - STX*

Following the <DLE> is an <STX>, which is hexadecimal value of 0x02.

### *Peripheral Interface Device (PID)*

The PID field contains source and type information. For the science packet, the PID is of the form 0x*5, where * is the assigned PID value of the given instrument which produced the instrument science data packet as shown in Table 2.

| Instrument | PID |
|---|---|
| FAI | 0x65 |
| GAP | 0x35 |
| IRM | 0x95 |
| MGF | 0xA5 |
| NMS | 0xC5 |
| RRI | 0xE5 |
| SEI | 0xF5 |

### Length MSB

The length field is the length of the instrument science data packet in bytes including all packet fields. The length field in a science data packet is an unsigned, 16-bit number. The maximum size of a packet is 32750 bytes. A length of 10 bytes is the minimum value and indicates that no science data is present.

### Length LSB

This byte is least significant byte of the length field.

### Spare

This pair of bytes are reserved for future versions of the protocol. The default values given to the spare bytes are both 0x00.

### Measurement ID

The measurement ID is a counter that increments by one each time a new science measurement is made by the instrument. For instruments that produce data as a time series, the measurement ID increments every time the instrument issues a new science data packet. For instruments that make discrete science measurements, the measurement ID increments every time the instrument issues a new science data packet so long as the measurement fits within a single science data packet (i.e. the science measurement is <= 32750 bytes in length). If the science measurement is too large to fit in a single science data packet, the measurement is split up into $\leq$ 32750 byte segments and the measurement ID remains the same value for all science data packets containing segments of the same science measurement. The measurement ID is an unsigned, 8-bit wrapping counter with a range of 0 to 255.

### Science Data

The science data field contains the data produced by an instrument. This field is dynamic. The size of this field can vary between 0 and 32750 bytes. Some instruments produce 16-bit data while others produce 8-bit data, but in all cases the number of 8-bit bytes present in each science data packet will be even.

### Cyclic Redundancy Check (CRC)

The CRC field is a 16-bit cyclic redundancy check. The 16-bit CRC used is the CRC-CCITT16 format. Every packet contains a CRC that is the CRC of the entire packet including the packet fields and data, but not including the CRC itself. The initial CRC value is 0xFFFF and it employs a truncated polynomial value of 0x1021. The polynomial is as shown in Equation 1.

**Equation 1: CRC-CCITT16**

$$CRC - CCITT16 = X^{16} + X^{12} + X^{5} + 1$$

Note that the CRC-CCITT16 requires 16-bit input in order to calculate the CRC.

# 3. CERTO

CERTO does not save data onboard CASSIOPE.

# 4. FAI

## *Level 0*

Each FAI lv0 image is composed of 10 e-POP packets. The first packet is a header packet containing the camera settings and housekeeping data. Packets 2-9 are the image data (total number of pixels divided into eight equally-sized packets), and the 10$^{th}$ packet is a small trailer packet.

**FAI header packet data format**

| Field | Size | Comment |
|---|---|---|
| Sync word | 3 bytes | "FAI" = 0x464149 |
| Source | 1 | 0=FAI_SI 1=FAI_SV |
| Instrument Mode | 1 | Instrument operating mode (high-order nibble=VIS camera mode, low nibble=NIR camera mode). Mode values:<br>7 = Ramp data (no image data, 256x256 pixels)<br>5 = High resolution + overscan pixels (264x320 pixels)<br>4 = High resolution (256 x 280 pixels)<br>3 = Medium resolution (128 x 140 pixels)<br>2 = Low resolution (64x70 pixels) |
| GPS Status | 1 | GPS quality code |
| GPS Week | 2 | GPS week data (inaccurate, do not use) |
| GPS Sec | 4 | GPS seconds (inaccurate, do not use) |
| PPS Counter | 4 | PPS counter at start of exposure |
| Exposure start | 4 | Timestamp -- internal 1ms clock at start of exposure |
| Exposure end | 4 | Timestamp -- internal 1ms clock at end of exposure |
| FSW version | 1 | Flight Software version |
| FSW_EPROM | 1 | Software eprom used |
| NROWS | 2 | Number of rows in image |
| NCOLS | 2 | Number of columns |
| VBIN | 1 | Vertical binning |
| HBIN | 1 | Horizontal binning |
| VSKIP | 1 | Vertical preskip |
| HSKIP | 1 | Horizontal preskip |
| EXPTIME | 2 | Exposure time |
| CYCTIME | 4 | Cycle time |
| TEC_SET0 | 2 | Setpoint for IR TEC. 1 DN = 0.1221 K. |
| TEC_SET1 | 2 | Setpoint for VIS TEC. 1 DN = 0.1221 K. |
| TCCD0 | 2 | Temperature for IR CCD. 1 DN = 0.1221 K. |
| TCCD1 | 2 | Temperature for VIS CCD. 1 DN = 0.1221 K. |

| Field | Size | Comment |
|---|---|---|
| ITEC0 | 2 | Current for IR TEC. 1 DN = 1 mA. |
| ITEC1 | 2 | Current for VIS TEC. 1 DN = 1 mA. |
| VM0 | 2 | +3.3V monitor point. 1 DN = 10 mV. |
| VM1 | 2 | -12V monitor point (disabled) |
| VM2 | 2 | +12V monitor point. 1 DN = 10 mV. |
| VM3 | 2 | +24V monitor point. 1 DN = 10 mV. |
| EXP_COUNT | 2 | Exposure counter |
| EDAC | 2 | EDAC error counter |
| | | |
| etc | | Zero-fill to 128 bytes |

**FAI trailer packet data format**

| Field | Size | Comment |
|---|---|---|
| Exposure count | 2 bytes | |
| Spare | 2 | 0x0000 |
| Trailer | 4 | “END” = 0x00454E44 |

FAI image packets are variably-sized depending on the camera mode, contain one 16-bit word per pixel, and are ordered as the CCD is read out: bottom to top, left to right. To see the image in ‘real-world’ coordinates the pixel data needs to be mirrored, then rotated 90 degrees counterclockwise.

### Level 1

FAI lv1 images have the following changes from lv0 images:

- All but the first CCSDS transfer frame have been stripped off
- All e-POP packet headers and CRCs have been removed
- Header data is of the same form up to byte 64, then the following is appended:

| Byte | Description |
|---|---|
| 65 | Level 1 version number |
| 66-69 (float) | S/C XGEI position (m) |
| 70-73 (float) | S/C YGEI position (m) |
| 74-77 (float) | S/C ZGEI position (m) |
| 78-81 (float) | S/C XGEI velocity (m/s) |
| 82-85 (float) | S/C YGEI velocity (m/s) |
| 86-89 (float) | S/C ZGEI velocity (m/s) |
| 90-93 (float) | S/C yaw angle (degrees from Nadir) |
| 94-97 (float) | S/C pitch angle (degrees from Nadir) |
| 98-101 (float) | S/C roll angle (degrees from Nadir) |
| 102 | Attitude solution accuracy (1 = low, 2 = high) |

- Image data is ordered from pixel 0,0 (bottom left of image) to XMAX, YMAX (top right of image), increasing first in X, then in Y. There is no need to rotate or reverse the data array once it is read in. Image data bytes are ordered in an LSB first fashion.
- Image data is corrected for electronic bias offset, dark current, uniformity, and optical distortion
- There is no trailer packet

# 5. GAP

## Level 0

The GAP lv0 science data packet format is shown below.

| Bytes 0-15 | Bytes 16-23 | Byte 24 | Byte 25 | Bytes 26-(N-2) | Bytes N-1 | Byte N |
|---|---|---|---|---|---|---|
| CCSDS header | e-POP packet header | Packet type | Spare | Packet data | CRC MSB | CRC LSB |

### CCSDS header

The CCSDS header is defined in Section 1.

### e-POP packet header

The e-POP packet header is as described in Section 2.

### Packet Type

The GAP packet types are defined below.

| Packet Type Code | Description |
|---|---|
| 0 | GAP FSW image upload failed |
| 1 | GAP message |
| 2 | GPS receiver 0 data |
| 3 | GPS receiver 1 data |
| 4 | GPS receiver 2 data |
| 5 | GPS receiver 3 data |
| 6 | GPS receiver 4 data |
| 7 | GAP memory dump |
| 8 | GAP echo |
| 9 | Attitude solution data |
| 255 | GAP FSW image upload pass |

### Spare

Spare byte with a value of zero.

### Packet Data

For general use, only the GPS receiver data (packet types 2-6) are relevant. This data consists of GPS messages output from the NovAtel GPS receivers. See Reference R1: “OEM4 User Manual Volume 1 Rev

19.pdf” and Reference R2: “OEM4 User Manual Volume 2 Rev 18.pdf” for complete details on the GPS message data.

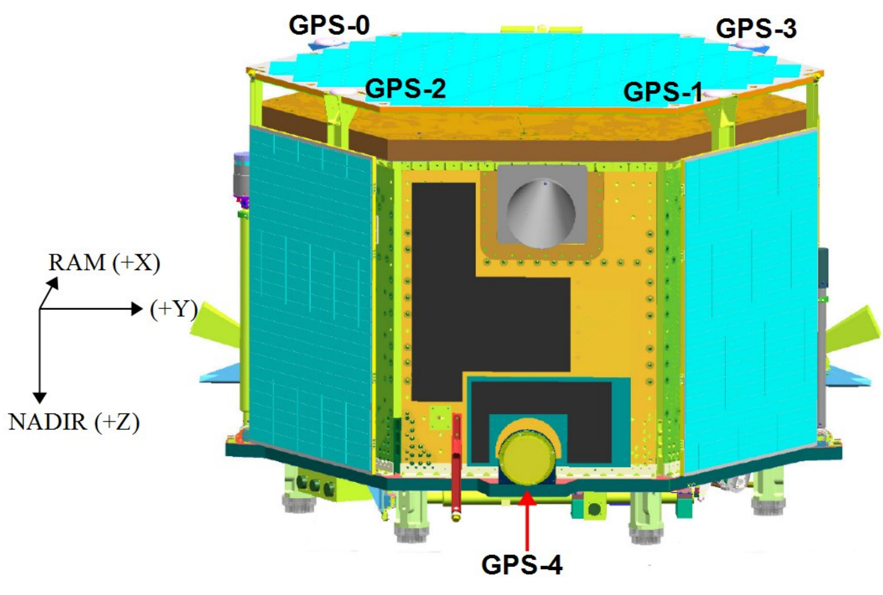
### Level 1

GAP level 1 data files are split by receiver and contain only the NovAtel binary GPS message packets, as defined in Reference R1. 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.

GAP receivers are located on the spacecraft as follows:




s

### Level 2

GAP level 2 files are of ascii type, formatted to the Receiver Independent Exchange Format (RINEX) standard. They are produced by the NovAtel-supplied “Convert4” software. There are two types of RINEX files, 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. IRM

### Level 0

The IRM science data contents are described below.

## Common Format

The following science packet contents are common to all IRM instrument modes of operation.
Bytes 9 through 44 represent the science packet housekeeping data, where the elements identified are sampled as unsigned 12-bit quantities and appear as unsigned 16-bit numbers in the header. Bytes 45 through 84 represent the fast analog sampled data, digitized as 12-bit unsigned values contained in unsigned 16-bit packet byte pairs. There are two quantities sampled: the IRM sensor ambient skin current, and the IRM detector total anode current. These quantities are sampled at a fixed real-time rate of 1 KHz, and so the number of samples in each science packet depends upon the rate at which the current instrument mode is producing packets. Finally, bytes 101 through N-2 represent IRM science data. The last two bytes are always the overall CRC.

The science header monitor values are unsigned, 12-bit quantities as output by the analog-to-digital converter, and appear in their natural order of indexing, with MSB first.
Their typical values will be in the mid-range of the 12-bit span. (i.e., 0x800 +/- 20%)

IRM ADC channel list (LVPS)

| ADC Channel | Packet Byte numbers | Designation |
|---|---|---|
| 0 | 9,10 | 3.3 V monitor |
| 1 | 11,12 | 3.3 V current monitor |
| 2 | 13,14 | 5V monitor |
| 3 | 15,16 | 5V current monitor |
| 4 | 17,18 | 2.5 V monitor |
| 5 | 19,20 | 2.5 V current monitor |
| 6 | 21,22 | 12 V monitor |
| 7 | 23,24 | -12 V monitor |

IRM ADC channel list (high voltage power supply)

| Channel | ADC1 | Packet Byte Number | ADC2 | Packet Byte Number |
|---|---|---|---|---|
| 0 | VMCPF_MON | 25,26 | I_VMCPF | 35,36 |
| 1 | VMCPB_MON | 27,28 | I_VMCPB | 37,38 |
| 2 | VSA_MON | 29,30 | VES | 39,40 |
| 3 | VD+ | 31,32 | I_SKIN | 41,42 |
| 4 | VD- | 33,34 | IRM_TEMP_RTN | 43,44 |
| 5 | | | I_ANODE | 45,46 |

Format for IRM AM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 47 | Instrument mode |
| 48 | Instrument sub-mode |
| 49,50 | Number of ToF gate open periods for this measurement |
| 51 | Set_delay parameter current value |
| 52 | HV state flag (0=off,1=on) |
| 53 | Number of cycles the ToF gate is open for this measurement |
| 54 | GPS Time Status |
| 55,56 | GPS week number (u_short) ** DO NOT USE** |
| 57,58,59,60 | GPS milliseconds (u_long) ** DO NOT USE** |
| 61,62 | interpolation clock (u_short) ** DO NOT USE** |
| 63,64 | Number of Iskin/Ianode sample pairs in this packet which precede pixel data |
| 65,66 | Iskin sample 1 |
| 67,68 | Iskin sample 2 |
| 83,84 | Iskin sample 10 |
| N, N+1 | Iskin sample N (determined from bytes 63,64) |
| N+2, N+3 | Ianode sample 1 |
| N+4, N+5 | Ianode sample 2 |
| M, M+1 | Ianode sample M |

Byte 47 (mode byte) takes on the following values:

| Value | Meaning |
|---|---|
| 0x09 | Dump ram, special format |
| 0x0c | calibration mode |
| 0x0f | housekeeping mode, header data only |
| 0x12 | AM mode |
| 0x15 | EM mode |
| 0x18 | REM mode |
| 0x1b | TM mode |
| 0x1e | CTM mode |
| 0x21 | FHM mode |
| 0x24 | FCM mode |
| 0x27 | CMM mode |
| 0x2a | IDLE mode – no science packets |

## Organization of the Science Data

The IRM AM-mode science data will appear as follows:

| Byte Number | Contents |
|---|---|
| M+2 | HIT counter, MSB |
| M+3 | HIT counter, LSB |
| M+4 | Detect Counter, MSB |
| M+5 | Detect Counter, LSB |
| M+6 | first pixel datum, MSB |
| M+7 | first pixel datum, LSB |
| M+8 | second pixel datum, MSB, and so on... |
| ....X-2 | last pixel datum, LSB |

The HIT Counter

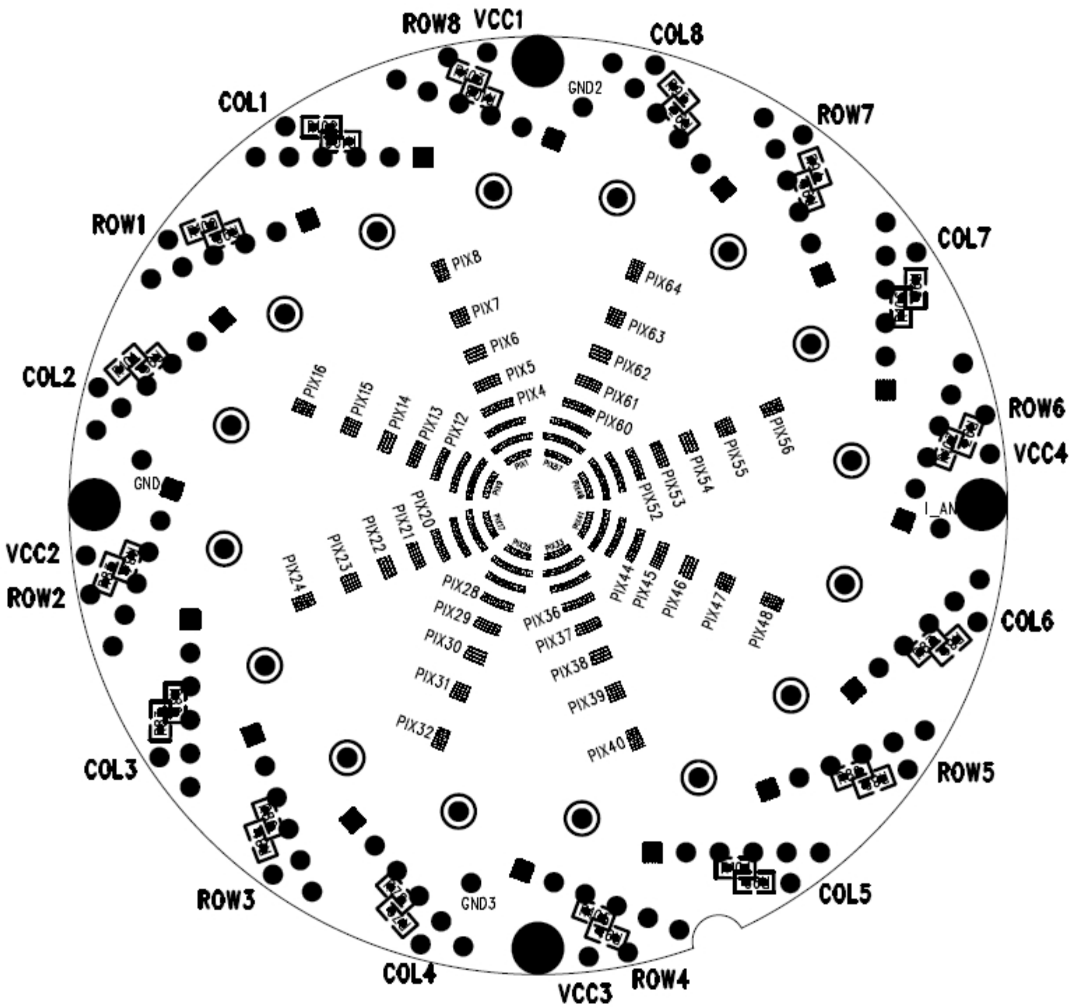
The HIT counter is an unsigned, 16-bit integer, and represents how many pixel data were collected in the last measurement performed, some of whose data are contained in this packet. If this value is zero, then this packet will contain no pixel data after the Detect counter. Thus, the packet will always contain a HIT Counter value, and a Detect Counter value, but will contain zero pixel data if the HIT counter value is equal to zero. NOTE that the number of pixel data in the science packet is NOT necessarily defined by the value of the HIT counter. It usually will correspond, but there are cases where it won't. Therefore, the byte-count values in bytes 4 and 5 of the science packet header must be used to infer the true size of the science packet. This situation arises because the pixel data contained in this science packet may or may not be solely from the measurement whose HIT count is contained in the HIT counter. That is to say, the instrument has a number of modes of operation, each of which places a different interpretation in the pixel data. In the example depicted here, the situation arises when IRM is in the "AM" (Addressed Mode) mode of operation, which is its basic and most commonly-used operating mode. Other modes exist, and their respective data interpretations follow later in this document.

The Detect Counter

The Detect counter is another unsigned 16-bit number. Its value is equal to or greater than that of the HIT counter, but never less. This value has no significance to the GSE software, other than to have its value displayed on the user terminal as data packets are processed.

## *IRM Anode Pixel arrangement and encoding*

The pixels on the IRM anode are arranged as per the following diagram. The notch or arrow indicates the vertical, Earth-facing direction when the S/C is in its ‘nadir’ orientation (+Z downwards, +X into ram).




| Pixel | Column | Row |
|---|---|---|
| 1 | 1 | 1 |
| 2 | 1 | 2 |
| 3 | 1 | 3 |
| 4 | 1 | 4 |
| 5 | 1 | 5 |
| 6 | 1 | 6 |
| 7 | 1 | 7 |
| 8 | 1 | 8 |
| 9 | 2 | 1 |
| 10 | 2 | 2 |
| 11 | 2 | 3 |
| 12 | 2 | 4 |
| 13 | 2 | 5 |
| 14 | 2 | 6 |
| 15 | 2 | 7 |
| 16 | 2 | 8 |

| Pixel | Column | Row |
|---|---|---|
| 17 | 3 | 1 |
| 18 | 3 | 2 |
| 19 | 3 | 3 |
| 20 | 3 | 4 |
| 21 | 3 | 5 |
| 22 | 3 | 6 |
| 23 | 3 | 7 |
| 24 | 3 | 8 |
| 25 | 4 | 1 |
| 26 | 4 | 2 |
| 27 | 4 | 3 |
| 28 | 4 | 4 |
| 29 | 4 | 5 |
| 30 | 4 | 6 |
| 31 | 4 | 7 |
| 32 | 4 | 8 |
| 33 | 5 | 1 |
| 34 | 5 | 2 |
| 35 | 5 | 3 |
| 36 | 5 | 4 |
| 37 | 5 | 5 |
| 38 | 5 | 6 |
| 39 | 5 | 7 |
| 40 | 5 | 8 |
| 41 | 6 | 1 |
| 42 | 6 | 2 |
| 43 | 6 | 3 |
| 44 | 6 | 4 |
| 45 | 6 | 5 |
| 46 | 6 | 6 |
| 47 | 6 | 7 |
| 48 | 6 | 8 |
| 49 | 7 | 1 |
| 50 | 7 | 2 |
| 51 | 7 | 3 |
| 52 | 7 | 4 |
| 53 | 7 | 5 |
| 54 | 7 | 6 |
| 55 | 7 | 7 |
| 56 | 7 | 8 |
| 57 | 8 | 1 |
| 58 | 8 | 2 |
| 59 | 8 | 3 |
| 60 | 8 | 4 |

| Pixel | Column | Row |
|---|---|---|
| 61 | 8 | 5 |
| 62 | 8 | 6 |
| 63 | 8 | 7 |
| 64 | 8 | 8 |

## The Pixel Data

The IRM anode pixels are arranged as an eight-spoked wheel, with 8 concentric rings intersecting the 8 spokes. Row 1, encoded as row 0, is nearest the center, and column 1, encoded as column 0, is opposite the Nadir-facing notch on the anode board.

Each point of intersection represents a pixel, for a total of 64 pixels. When an ion strikes a pixel intersection, the location and the instant of arrival are recorded. The pixel data are encoded as a 6-bit number, with 3 bits each for row and column (one minus the row and column numbers in the table above).

The pixel data are encoded as follows in each 16-bit pixel datum:

| 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| r | r | r | c | c | c | ToF9 | ToF8 | ToF7 | ToF6 | ToF5 | ToF4 | ToF3 | ToF2 | ToF1 | ToF0 |

Where bits 15-13 represent the row number of the detected pixel, and bits 12-10 represent the column number of the detected pixel. The pixel number can be interpreted as a 6-bit positive binary number represented by bits 15 through 10.

The time of the detection is also measured, with a 10-bit counter, whose value is contained in the fields ToF9 thru ToF0, in straight positive binary form. The range of this parameter is [0:1023], representing bins number 1 through 1024. This represents the number of time-of-flight counting intervals of 40 nano-seconds it took the detected ion to travel from the ion entry gate to the detector apparatus.

## EM Mode

Science data format for IRM EM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1, M+2 | Counts in pixel number 1 |
| M+3, M+4, ... | Counts in pixel number 2, and so on... |
| … | Up to counts in pixel 64 |

The counts in each pixel represent a histogram of detections, counted per pixel. The number of cycles used to collect the sample set is represented in the header quantity NumToF. Looking at the anode board from the outboard side, column #1 is 180° from the nadir notch and the columns are numbered sequentially in the counter clockwise direction.  Row #1 is the innermost (closest to the centre of the board) and the rows are numbered sequentially outward.

### *REM Mode*

Science data format for IRM REM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1, M+2 | Sum of counts in row number 1 |
| M+3, M+4... | Sum of counts in row number 2, and so on... |
| … | Up to sum counts in row 8 |

The counts represent a histogram of detections, counted per row number. The number of cycles used to collect the sample set is represented in the header quantity NumToF. Looking at the anode board from the outboard side, column #1 is 180° from the nadir notch and the columns are numbered sequentially in the counter clockwise direction.  Row #1 is the innermost (closest to the centre of the board) and the rows are numbered sequentially outward. The rows are encoded in bits [15:13] of the IRM data word. FSW sums all counts for pixels by their respective row number, producing the desired reduced histogram. The summations are represented as unsigned, 16-bit quantities.

### *TM Mode*

Science data format for IRM TM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1,M+2 | Counts in ToF bin 1 |
| M+3,M+4, … | Counts in ToF bin 2, and so on... |
| … | Up to counts in ToF bin 1024 |

In this mode, the data represent a histogram of counts in each ToF bin. The number of cycles used to collect the sample set is represented in the header quantity NumToF.

## CTM Mode

Science data format for IRM FHM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1, M+2 | Counts in ToF bin 1 |
| M+3, M+4,… | Counts in ToF bin 2, and so on... |
| M+255,M+256 | Counts in ToF bin 128 |
| M+257,M+258 | Sum of ToF bins 129 and 130 |
| M+259,M+260,... | Sum of ToF bins 131 and 132, and so on... |
| M+511,M+512 | Sum of ToF bins 383 and 384 |
| M+513,M+514… | Sum of ToF bins 385 thru 388 |
| M+831,M+832 | Sum of ToF bins 1021 thru 1024 |

In CTM mode, "Compressed Time-of-Flight" mode, the amount of ToF data are reduced through a simple binning technique. The ToF bins 1 through 128 are represented as-is, the next 256 ToF bins are reduced summed) by 2, and the remaining 640 bins are reduced (summed) by 4.

## FHM Mode

Science data format for IRM FHM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1,M+2 | Counts in pixel number 1 |
| M+3,M+4... | Counts in pixel number 2, and so on... |
| M+129,M+130 | Counts in pixel 64 |
| M+131,M+132 | Counts in ToF bin 1 |
| M+133,M+134... | Counts in ToF bin 2, and so on... |
| M+2177,M+2178 | Counts in ToF bin 1024 |

In this mode, the data represent a histogram of counts in both pixels and ToF bins. This is simply a combination of the foregoing EM and TM modes. The number of cycles used to collect the sample set is represented in the header quantity NumToF.

### FCM Mode

Science data format for IRM FCM Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 9-M | As per "AM" mode |
| M+1,M+2 | Counts in pixel number 1 |
| M+3,M+4... | Counts in pixel number 2, and so on... |
| M+127,M+128 | Counts in pixel 64 |
| M+129, M+130 | Counts in ToF bin 1 |
| M+131, M+132… | Counts in ToF bin 2, and so on... |
| M+383, M+384 | Counts in ToF bin 128 |
| M+385, M+386 | Sum ToF bins 129 and 130 |
| M+387, M+388… | Sum ToF bins 131 and 132, and so on... |
| M+639, M+640 | Sum of ToF bins 383 and 384 |
| M+641, M+642… | Sum of ToF bins 385 thru 388… |
| M+959, M+960 | Sum of ToF bins 1021 thru 1024 |

This mode is a simple concatenation of the atomic modes EM and CTM. Data display can be as per those modes.

### Level 1

IRM lv1 data consists of a text file containing self-described data in a column-separated format. Data includes the date and time in UT, the current on the outer IRM sensor surface (skin current) in micro amps, the number of ions detected in the period, and the voltage on the inner hemispheric dome (VSA) in volts used to select the energy range of the measured particles. Positive skin current values indicate a net positive charge flux on the IRM sensor surface.

## 7. MGF

### Level 0

MGF lv0 data is described in reference document R3: MGF_data_block_v3.xls.

### Level 1

MGF lv1 data is an intermediary data format and is not meant for general consumption.

### Level 2

MGF lv2 data is contained in a self-describing, column-separated ascii file.

### Level 3

MGF lv3 data is contained in a self-describing, column-separated ascii file. There are four level 3 data products.

| MGF Product | Description |
|---|---|
| *.1sps.GEI.lv3 | 1 sample per second, corrected magnetic data in GEI coordinates |
| *.1sps.SC.lv3 | 1 sample per second, corrected magnetic data in SC coordinates |
| *.10sps.SC.lv3 | 10 sample per second, corrected magnetic data in GEI coordinates |
| *.10sps.SC.lv3 | 10 sample per second, corrected magnetic data in SC coordinates |

# 8. NMS

NMS lv0 data packets will be described in a later version of this document.

# 9. RRI

## *Level 0*

There are 3 formats of packets that are received as part of the RRI science packet stream.

- **Test Mode Packets –** These are produced when the instrument is in test mode.
- **Custom Mode Packets –** These are the routine science packets produced by RRI.
- **Sync Packets –** These packets are introduced into the custom mode packet stream to provide feedback regarding the state of the instrument.

### *Test Mode Packets*

| DLE | STX | PID | LENGTH | SPARES | MEASUREMENT ID | COUNTER |
|---|---|---|---|---|---|---|
| 10 | 02 | E5 | 0100 | 0000 | FSW Version XX | XXXXXX |

| GPS STATUS | GPS WEEK | GPS SECOND | MICROSECOND COUNTER | DATA (116 WORDS) | CRC | CRC |
|---|---|---|---|---|---|---|
| XX | XXXX | XXXXXXXX | XXXXXXXX | XX | CRC | CRC |

The PID for each of the science packet formats is E5.
The length of each science packet is 0x0100 bytes (256 bytes).
The counter is a 4-byte internal counter that numbers the packets from the RRI instrument.
GPS Status and GPS Week are values from the time packets sent to RRI. The GPS second is internally incremented between time packets using the pulse per second signal given to the instrument. The reported value is in milliseconds. **** The GPS millisecond value sent to RRI is not accurate, and should not be used****. The microsecond counter is a count of the number of clock ticks of the 80 MHz clock since the counter was last reset. Each time the counter is read it is reset, and each time the pps tick is valid, the counter is reset. The counter is read once every 4 packets. The following formula converts from microsecond counter to nanoseconds. The counter counts up from 200 million below 0xFFFF FFFF.

$$((CounterValue) - (0xFFFFFFFF - 200000000)) * 12.5ns$$

The data in the test mode packets is of the format: 1, 1, 1, 1, 2, 2, 2, 2, 3, 3, 3, 3, 4, 4, 4, 4, 5, 5, 5, 5, ….. 29, 29, 29, 29; Each of the four output channels is a ramp from 1 to 29. Each number is stored as 2 bytes.

### *Custom Mode Packets*

| DLE | STX | PID | LENGTH | SPARES | MEASUREMENT ID | COUNTER |
|---|---|---|---|---|---|---|
| 10 | 02 | E5 | 0100 | 0000 | FSW Version XX | XXXXXX |

| GPS STATUS | GPS WEEK | GPS SECOND | MICROSECOND COUNTER | DATA (116 WORDS) | CRC | CRC |
|---|---|---|---|---|---|---|
| XX | XXXX | XXXXXXXX | XXXXXXXX | XX | CRC | CRC |

The PID for each of the science packet formats is E5.
The length of each science packet is 0x0100 bytes (256 bytes).
The counter is a 4-byte internal counter that numbers the packets from the RRI instrument.
GPS Status and GPS Week are values from the time packets sent to RRI.
The GPS second is internally incremented between time packets using the pulse per second signal given to the instrument. The reported value is in milliseconds. **** The GPS millisecond value sent to RRI is not accurate, and should not be used****. The microsecond counter is a count of the number of clock ticks of the 80 MHz clock since the counter was last reset. Each time the counter is read it is reset, and each time the pps tick is valid, the counter is reset. The counter is read once every 4 packets. The following formula converts from microsecond counter to nanoseconds. The counter counts up from 200 million below 0xFFFF FFFF.

$$((CounterValue) - (0xFFFFFFFF - 200000000)) * 12.5ns$$

The data in the science packet is 29 measurements of each of the four output streams.
If the data format selected was I1-Q1-I3-I4, the data in the science packets is organized I1-Q1-I3-I4 repeated 29 times. Each data measurement is 32 bits (1 word).

### Sync Packets

| DLE | STX | PID | LENGTH | SPARES | MEASUREMENT ID | COUNTER |
|---|---|---|---|---|---|---|
| 10 | 02 | E5 | 0100 | 0000 | FSW Version XX | XXXXXX |

| GPS STATUS | GPS WEEK | GPS SECOND | MICROSECOND COUNTER | DATA (116 WORDS) | CRC | CRC |
|---|---|---|---|---|---|---|
| XX | XXXX | XXXXXXXX | XXXXXXXX | XX | CRC | CRC |

The PID for each of the science packet formats is E5.
The length of each science packet is 0x0100 bytes (256 bytes).
The counter is a 4-byte internal counter that numbers the packets from the RRI instrument.
GPS Status and GPS Week are values from the time packets sent to RRI.
The GPS second is internally incremented between time packets using the pulse per second signal given to the instrument. The reported value is in milliseconds. **** The GPS millisecond value sent to RRI is not accurate, and should not be used****. The microsecond counter is a count of the number of clock ticks of the 80 MHz clock since the counter was last reset. Each time the counter is read it is reset, and each time the pps tick is valid, the counter is reset. The counter is read once every 4 packets. The following formula converts from microsecond counter to nanoseconds. The counter counts up from 200 million below 0xFFFF FFFF.

$$((CounterValue) - (0xFFFFFFFF - 200000000)) * 12.5ns$$

The data contains information from the custom mode command relating to the setup of the instrument.

| byte | Contents | Explanation |
|---|---|---|
| 23 | 0x52 | **'R'** |
| 24 | 0x52 | **'R'** |
| 25 | 0x49 | **'I'** |
| 26 | 0x53 | **'S'** |
| 27 | 0x59 | **'Y'** |
| 28 | 0x4E | **'N'** |
| 29 | 0x43 | **'C'** |
| 30 | 0x0X | X = 1-8; Science Packet number. |
| 31,32 | 0xXXXX | GAIN 1 |
| 33,34 | 0xXXXX | GAIN 2 |
| 35,36 | 0xXXXX | GAIN 3 |
| 37,38 | 0xXXXX | GAIN 4 |
| 39 | 0x00 | SPARE |
| 40 | 0x0X | SWITCH K1 |
| 41 | 0x0X | SWEEP A |
| 42 | 0x0X | BANDWIDTH A |
| 43,44,45,46 | 0xXXXXXXXX | F1 A |
| 47,48,49,50 | 0xXXXXXXXX | F2 A |
| 51,52,53,54 | 0xXXXXXXXX | ΔF A |
| 55,56 | 0xXXXX | DWELL A |
| 57 | 0x0X | SWEEP B |
| 58 | 0x0X | BANDWIDTH B |
| 59,60,61,62 | 0xXXXXXXXX | F1 B |
| 63,64,65,66 | 0xXXXXXXXX | F2 B |
| 67,68,69,70 | 0xXXXXXXXX | ΔF B |
| 71,72 | 0xXXXX | DWELL B |
| 73,74 | 0xXXXX | DATA FORMAT |
| 75-254 | 0x00 | Zero Filled |

In fixed frequency mode there are 4 sync packets at the start of the science stream.
In sweep frequency mode 4 sync packets are issued each time the sweep is reset to F1.

## *Level 1*

RRI lv1 data is in the HDF5 data format. The table below lists the variables available in each file.

| Field Name | Description |
|---|---|
| RRI Settings/Antenna 1 Gain | Monopole 1 gain setting (Low, Medium, or High) |

| | |
|---|---|
| RRI Settings/Antenna 2 Gain | Monopole 2 gain setting (Low, Medium, or High) |
| RRI Settings/Antenna 3 Gain | Monopole 3 gain setting (Low, Medium, or High) |
| RRI Settings/Antenna 4 Gain | Monopole 4 gain setting (Low, Medium, or High) |
| RRI Settings/Antenna Configuration | Antenna configuration, Monopole or Dipole |
| RRI Settings/Sweep Mode A | Sweep mode of Channel A. Fixed Frequency, Linear Sweep, or Logarithmic Sweep. |
| RRI Settings/Sweep Mode B | Sweep mode of Channel B. Fixed Frequency, Linear Sweep, or Logarithmic Sweep. |
| RRI Settings/Bandwidth A (kHz) | Bandwidth for Channel A, 5 kHz or 30 kHz |
| RRI Settings/Bandwidth B (kHz) | Bandwidth for Channel B, 5 kHz or 30 kHz |
| RRI Settings/Start Frequency A (Hz) | Start Frequency for Channel A |
| RRI Settings/End Frequency A (Hz) | End frequency of a sweep, Channel A |
| RRI Settings/Dwell Time A (s) | Number of seconds to dwell on each frequency of a sweep, Channel A |
| RRI Settings/Start Frequency B (Hz) | Start Frequency for Channel B |
| RRI Settings/End Frequency B (Hz) | End frequency of a sweep, Channel B |
| RRI Settings/Dwell Time B (s) | Number of seconds to dwell on each frequency of a sweep, Channel B |
| RRI Settings/Delta Frequency A (Hz) | For a linear sweep this is the step size in Hz of each frequency step. For a logarithmic sweep this is the starting step size, with each step size being twice the one before it. This has no meaning for fixed frequency. Applies to Channel A. |
| RRI Settings/Delta Frequency B (Hz) | For a linear sweep this is the step size in Hz of each frequency step. For a logarithmic sweep this is the starting step size, with each step size being twice the one before it. This has no meaning for fixed frequency. Applies to Channel B. |
| RRI Settings/Data Format | List of the four data streams output by RRI.<br>IX = In-phase signal from monopole X, X=1, 2, 3, or 4<br>QX = Quadrature output from monopole 1, X=1, 2, 3, or 4<br>e.g. I1Q1I3Q3 means In-phase and Quadrature data output from Channels A and B. In dipole mode this is I and Q from each dipole. |
| RRI Data/Channel A Frequencies (Hz) | Frequency of Channel A at the specified time. |
| RRI Data/Channel B Frequencies (Hz) | Frequency of Channel B at the specified time. |
| CASSIOPE Ephemeris/Ephemeris MET (seconds since May 24, 1968) | Time, measured in seconds since May 24, 1968 00:00:00 UT. |
| CASSIOPE Ephemeris/GEI Position (km) | Spacecraft position in GEI 2000 coordinates |
| CASSIOPE Ephemeris/GEI Velocity (km per s) | Spacecraft velocity in GEI 2000 coordinates |
| CASSIOPE Ephemeris/GSM Position (km) | Spacecraft position in GSM coordinates |
| CASSIOPE Ephemeris/Geographic Latitude (deg) | Spacecraft geographic latitude |
| CASSIOPE Ephemeris/Geographic Longitude (deg) | Spacecraft geographic longitude |
| CASSIOPE Ephemeris/Altitude (km) | Spacecraft altitude (WGS84) |

| | |
|---|---|
| CASSIOPE Ephemeris/Magnetic Latitude (deg) | Spacecraft magnetic latitude |
| CASSIOPE Ephemeris/Magnetic Longitude (deg) | Spacecraft magnetic longitude |
| CASSIOPE Ephemeris/MLT (hr) | Spacecraft magnetic local time |
| CASSIOPE Ephemeris/Yaw (deg) | Spacecraft attitude yaw angle. See appendix A for definition of yaw. |
| CASSIOPE Ephemeris/Pitch (deg) | Spacecraft attitude pitch angle. See appendix A for definition of pitch. |
| CASSIOPE Ephemeris/Roll (deg) | Spacecraft attitude roll angle. See appendix A for definition of roll. |
| RRI Data/Radio Data Monopole 1 (mV) | Voltage of output 1 (Data Format determines what output 1 represents) |
| RRI Data/Radio Data Monopole 2 (mV) | Voltage of output 2 (Data Format determines what output 2 represents) |
| RRI Data/Radio Data Monopole 3 (mV) | Voltage of output 3 (Data Format determines what output 3 represents) |
| RRI Data/Radio Data Monopole 4 (mV) | Voltage of output 4 (Data Format determines what output 4 represents) |

# 10. SEI

## *Level 0*

### *Common Format*

The following science packet contents are common to all SEI modes of operation. The number of bytes in a science data packet is determined by the mode of operation, and varies from 866 in Housekeeping mode, to 3136 in Hi-res mode.

Bytes 9 through 44 represent the science packet housekeeping data, where the elements identified are sampled as unsigned 12-bit quantities and appear as unsigned 16-bit numbers in the header. Bytes 65 through 80 represent the fast analog sampled data, digitized as 12-bit unsigned values contained in unsigned 16-bit packet byte pairs. There are two quantities sampled: the SEI sensor ambient skin current, and the SEI detector total phosphor current. These quantities are sampled at a fixed real-time rate of 400 Hz, and so the number of samples in each science packet depends upon the rate at which the current instrument mode is producing packets. Finally, after the housekeeping data to the end of the packet – 2 bytes represent SEI image data. The last two bytes are always the overall CRC.

The science header monitor values are unsigned, 12-bit quantities as output by the analog-to-digital converter, and appear in their natural order of indexing, with MSB first.
Their typical values will be in the mid-range of the 12-bit span. (i.e., 0x800 +/- 20%)

SEI ADC channel list (LVPS)

| ADC Channel | Packet Byte numbers | Designation |
|---|---|---|
| 0 | 9,10 | 3.3 V monitor |
| 1 | 11,12 | 3.3 V current monitor |
| 2 | 13,14 | 5 V monitor |
| 3 | 15,16 | 5V current monitor |
| 4 | 17,18 | spares |
| 5 | 19,20 | spares |
| 6 | 21,22 | 12 V monitor |
| 7 | 23,24 | -12 V monitor |

SEI ADC channel list (HVPS) (for reference only)

| Channel | ADC1 | Packet Byte Number | ADC2 | Packet Byte Number |
|---|---|---|---|---|
| 0 | Vskin_MON | 25,26 | Iskin_mon | 35,36 |
| 1 | Vinner_MON | 27,28 | SEI_temp_mon | 37,38 |
| 2 | VCPF_MON | 29,30 | Imcpf_mon | 39,40 |
| 3 | VCPB_mon | 31,32 | Imcpb_mon | 41,42 |
| 4 | Vphos_mon | 33,34 | Iphos_mon | 43,44 |
| 5 | | | spares | 45,46 |

Format for SEI Normal Mode, 100-Hz Sampling Rate

| Packet Byte Number | Contents |
|---|---|
| 47 | Instrument mode (see list below) |
| 48 | SEI FSW Version |
| 49 | Instrument Detection Mode (0=SEI, 1=SII) |
| 50 | Summation factor (for integration mode) |
| 51 | Set_delay parameter current value |
| 52 | HV state flag (0=off,1=on) |
| 53 | Spare |
| 54 | GPS Time Status* |
| 55,56 | GPS week number (u_short) ** Do not use ** |
| 57,58,59,60 | GPS milliseconds (u_long) ** Do not use ** |
| 61,62 | interpolation clock (u_short) ** Do not use ** |
| 63,64 | Number of Iskin/Iphos sample pairs in this packet which precede pixel data |
| 65,66 | Iskin sample 1 |
| 67,68 | Iskin sample 2 |
| 69,70 | Iskin sample 3 |
| 71,72,… | Iskin sample 4 and so on… |
| N, N+1 | Iskin last sample |
| N+2, N+3 | Iphos sample 1 |
| N+4, N+5,… | Iphos sample 2 and so on… |
| M, M+1 | Iphos final sample |
| | |
| M+2,M+3,M+4,M+5 | CCD corner pixels |
| M+6-M+31 | spares |

Byte 47 (mode byte) takes on the following values:

| Value | Meaning |
|---|---|
| 0x09 | Dumpram, special format |
| 0x0c | calibration mode |
| 0x0f | housekeeping mode |
| 0x12 | Normal mode |
| 0x15 | Hires mode |
| 0x18 | Integration mode |
| 0x1b | Analog mode |

## *Organization of the Science Data*

The SEI is a CCD imager, and produces data which represent optical images of the phosphor screen in the detector. The CCD imager device has a native resolution of 256 x 256 elements. This device is read out at high speed employing a 4x4 binning method where four rows are summed into one before reading out a row, and four individual pixels are summed into the output prior to digitization. Therefore, the dimensions of the images coming from the CCD system are 64 x 64, and the total number of pixels is 4096. The pixel signals are digitized to 8 bits of precision, so the incoming CCD image buffer is 4096 bytes in size.

The image size is further reduced by using a lookup table which cuts off the four corners of the image. The result of this circular cropping is an array of 8-bit pixels totaling 3024 bytes. This data forms the bulk of the science payload of the SEI hi-res science packet. The cropped 64x64 pixel image is further binned 2x2 to yield a lower-resolution version of the image. These data are produced when SEI is in the Normal and Integration modes of operation.

Prior to cutting off the corners of the 64x64 pixel image, a small area of each corner is summed into an average value. Each of the averaged corner pixels is included in the housekeeping portion of the science packet. These data are used for dark-current and temperature compensation on the ground.

The SEI Hires-mode science data will appear as follows (H=number of bytes in the SEI header):

| Byte Number | Contents |
|---|---|
| H+1 | First pixel |
| H+2 | Second pixel |
| H+3024 (N-2) | Last pixel |

In Normal mode, the 64x64-pixel image is binned a further factor of 2x2, and the then circularly-cropped. The image data come out to 756 pixels per image. These data appear in the science packet in place of the 3024 pixels appearing in hi-res mode:

| Byte Number | Contents |
|---|---|
| H+1 | First pixel |
| H+2 | Second pixel |
| H+757 | Last pixel |
| H+758 | pad |

While in Integration mode, the SEI bins and crops the image to 756 pixels, just like Normal mode, but sums up a number of images as determined by the parameter N which is passed in with the command to set the mode. Thus, the effective imaging rate is 100Hz/N. Note that to support the summation, the pixel data become 16-bits per pixel, so the science payload is 756 x 2 = 1512 bytes:

| Byte Number | Contents |
|---|---|
| H+2, H+2 | First pixel |
| H+3, H+4 | Second pixel |
| H+1513,H+1514 (N-2) | Last pixel |

## *SEI Non-imaging modes*

**Dumpram**

The dumpram is not an operational mode, but a means to downlink blocks of DSP operating memory.

**Calibration mode**

The calibration mode is for internal e-POP science operation use only.

**Housekeeping Mode**

The Housekeeping mode collects Iskin samples at 400 Hz, and prepares a science packet at a 100 Hz rate. Thus, the packet structure is:

| Packet Byte Number | Contents |
|---|---|
| Bytes 9-62 | As per Normal mode |
| 63,64 | Number of Iskin samples in this packet |
| 65,66 | Iskin sample 1 |
| 67,68 | Iskin sample 2 |
| 863,864 | Iskin sample 400 (maximum) |

**Analog mode**

In Analog mode, SEI functions the same as in housekeeping mode, producing a packet at 1Hz. In this mode, both Iskin and Iphos samples are included. The structure is identical to that of housekeeping mode except that there are 400 pairs of each of Iskin and Iphos:

| Packet Byte Number | Contents |
|---|---|
| Bytes 9-62 | As per Normal mode |
| 63,64 | Number of Iskin/Iphos samples in this packet |
| 65,66 | Iskin sample 1 |
| 67,68 | Iskin sample 2 |
| 863,864 | Iskin sample 400 (maximum) |
| 865,866 | Iphos sample 1 |
| 867,868 | Iphos sample 2 |
| 1663,1664 | Iphos sample 400 (maximum) |

## *SEI Lookup Tables*

Below is IDL code for creating the SEI pixel lookup tables.

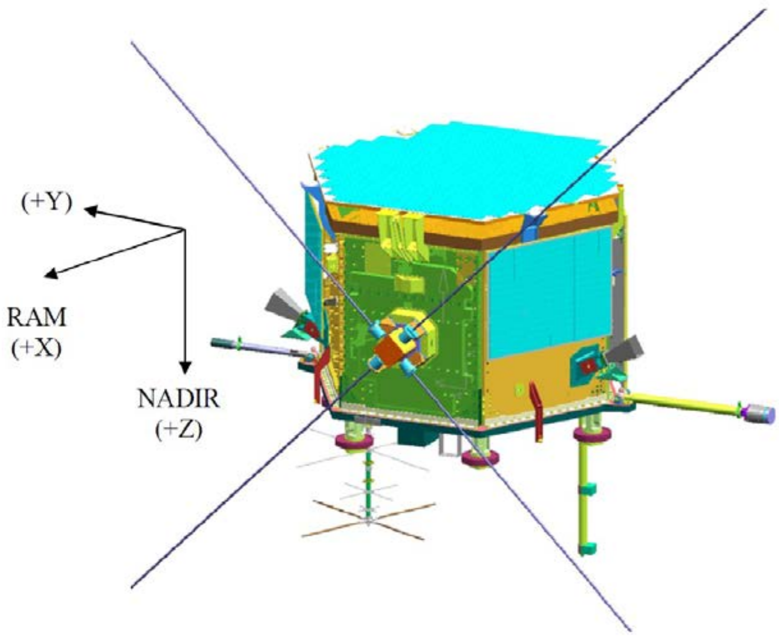
```
;; HIRES mode
 croptableHiRes = intarr(3024)
 npix = 0
 for i = 0 , 63 do begin
   for j = 0 , 63 do begin
     itmp =  i - 31
     itmp *= itmp
     jtmp =  j - 31
     jtmp *= jtmp
     if ((itmp + jtmp) lt 965 and npix lt 3024) then croptableHiRes[npix++] = i*64 + j
   endfor
 endfor

 ;; LOWRES (Normal) mode
 croptableLowRes = intarr(756)
 npix = 0
 for i = 0 , 31 do begin
   for j = 0 , 31 do begin
     itmp =  i*2 - 31
     itmp *= itmp
     jtmp =  j*2 - 31
```

```
    jtmp *= jtmp
    if (itmp + jtmp lt 965) then croptableLowRes[npix++] = i*32 + j
  endfor
endfor
```

# Appendix A – Coordinate Systems

## *Spacecraft coordinates*

CASSIOPE axes are defined as follows:
+X points through RRI
+Y points in the direction of the SEI boom
+Z points out the bottom of the spacecraft



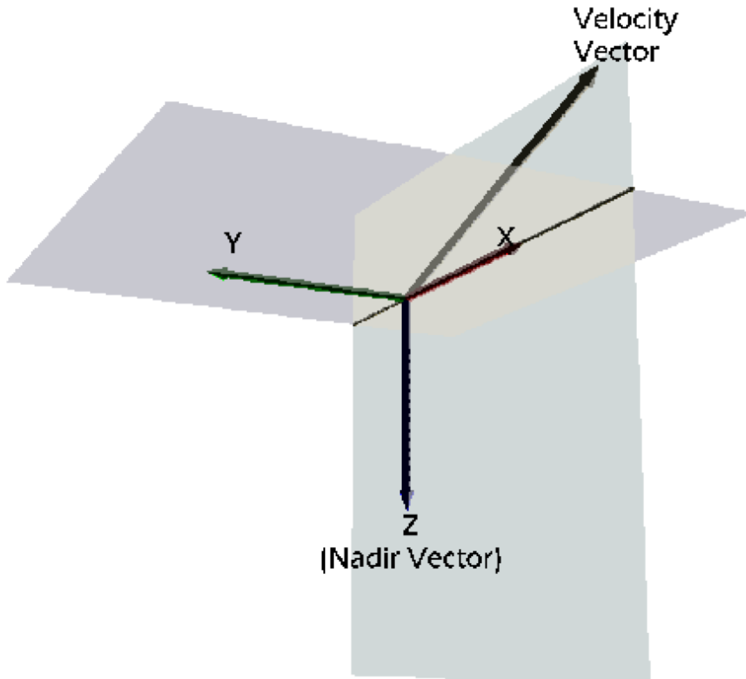

## *GEI coordinates*

Geocentric Equatorial Inertial (GEI) coordinates are often used for spacecraft position and velocity descriptions and are defined as follows:
+X points towards the First Point of Aries (the direction in space defined by the intersection between the Earth's equatorial plane and the plane of its orbit around the Sun)
+Z is parallel to the Earth's rotation axis (positive to the north)
+Y completes the right-handed orthogonal triad

The epoch for the GEI coordinate system is 12:00 UT on January 1, 2000 (i.e. J2000 GEI coordinates).

## *Yaw, Pitch, and Roll*

Spacecraft attitude is defined by the angles of yaw, pitch, and roll relative to the "Nadir" pointing direction. Nadir is defined as:
S/C +**Z** along the negative position vector, **R**
S/C +**Y** is along the negative orbit normal (-**R** x **V** = **Z** x **V**)
S/C +**X** is toward velocity (**X** = **Y** x **Z**)




Roll is the rotation of the S/C about the X axis (positive is from +Y towards +Z).
Pitch is the rotation of the S/C about the Y axis (positive is from +Z towards +X).
Yaw is the rotation of the S/C about the Z axis (positive is from +X towards +Y).
The attitude of the satellite is determined by rotating from the "Nadir" attitude in the order roll, pitch, yaw.