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 10th 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: 7 = Ramp data (no image data, 256x256 pixels) 5 = High resolution + overscan pixels (264x320 pixels) 4 = High resolution (256 x 280 pixels) 3 = Medium resolution (128 x 140 pixels) 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_vX-Z.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), X = major revision number, Z = minor revision number. 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

Pixel	Column	Row
16	2	8
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

Pixel	Column	Row
60	8	4
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. IX = In-phase signal from monopole X, X=1, 2, 3, or 4 QX = Quadrature output from monopole 1, X=1, 2, 3, or 4 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

Field Name	Description
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.