SPACE RADIATION LABORATORY

Galileo Heavy Ion Counter

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Thomas L. Garrard

Objectives and Overview

The Galileo Heavy Ion Counter (HIC) was added onto the Galileo mission for the purpose of monitoring highly ionizing energetic particles capable of causing "single event upsets" in the memory chips, etc. of the spacecraft in the Jovian magnetosphere. The instrument is optimized to measure the energy spectra and charge composition of oxygen, sulfur, and sodium in the Jovian magnetosphere from ~ 5 MeV/nucleon to ~ 200 MeV/nucleon. We planned to monitor penetrating galactic carbon, nitrogen, and oxygen during the cruise phase and in the outer magnetosphere because these nuclei can also cause "upsets". The capability to cover a charge range up to Fe at low energies is desirable for the cruise phase and for the outer magnetosphere for scientific reasons.

The radial distance range covered by Galileo extends from ~ 4 RJ to more than 100 RJ. The telescope is constrained to function in the flux maxima around 4 RJ and around 7-8 RJ. It should survive radiation damage from fluences calculated for mission lifetimes of more than a year. The instrument also had to be be built within cost, weight, power, volume, time, et cetera limitation imposed by its nature as an add-on to the existing mission.

These constraints were met by using the existing Voyager CRS PTM (Proof-Test Model) instrument. The LET telescopes have demonstrated the ability to resolve O, Na, and S in the Jovian magnetosphere. Eight of these telescopes were exposed to the radiation environment with shielding of only 3 microns Aluminum and only one detector was lost. We adapted the instrument to extend its energy range and to improve its resolution by rerouting LET detector signals into the HET electronics and providing better collimation and a thicker window. To conserve telemetry and emphasize the heavies we raised all thresholds above proton and alpha signals. One of the parallel HET/LET "blocks" of electronics was extracted from the PTM and repackaged to meet volume and shielding constraints.

Relevant flux levels are quite small. The sensitive area of one of the IC's used on Galileo is ~ 3.4×10^{-3} cm^2. AW is ~ 0.01 cm^2 sr. For a circuit to have a 2% chance of seeing an oxygen nucleus, the fluence is 2 Oxygen/cm^2 sr. To observe 10 oxygens we must have a geometry factor of 5 cm^2 sr. Thus one telescope, LET E, has a widened acceptance geometry.

In order to interface signals to the Galileo spacecraft an adapter was added which receives the Voyager data and outputs Galileo data. This adapter also translates Galileo commands for the CRS Voyager interface.

HIC is mounted on top of Bay 2 in the spinning portion of the spacecraft. This location is shown in the JPL Galileo Spacecraft Mechanical Configuration, drawing number 10084461. (See also JPL ICD 10086786.) The telescopes are oriented about 10° "below" the normal to the spin axis, in order to keep the sunshade out of the field of view. In spacecraft coordinates, our boresight is TBD.

Analysis Conditions

Events are generated when particles generate signals satisfying the requirements shown below. Table 1 shows the "physically relevant" conditions for analysis of events of various types.

Table 1 -- Events

Event	condition	geometry factor	energy range (MeV/nucleon)
LETB:	LB1.LB2.LB3.LB4*	0.4293	~ 4.8 to 17.5 for oxygen including L1.L2
DUBL:	LE1.LE2.LE3*	0.435	~ 17 to 18 for oxygen
TRPL:	LE1.LE2.LE3.LE4*	0.435	~18 to 24 nuc for oxygen.
WDSTP:	LE2.LE3.LE4.LE5*	~4.006	~30** to 48 for oxygen.
WDPEN:	LE2.LE3.LE4.LE5	~4.006	~48 to 185 for oxygen. Cutoff at 185 due to LE1 threshold for oxygen but not sulfur.
HGPEN:	LE2.LE3.LE4.LE5.HG	~4.006	Cosmic ray carbon and heavier. Carbon from ~41 MeV/nuc up.

** Energy assignment depends on whether L1 fired.

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The LET B Telescope

The LET-B is a Voyager CRS spare LET with upgrading of the collimator. The cross section of the LET B telescope is illustrated in Figure 1. All detectors are silicon surface barrier devices. Signals from detectors LB1, LB2 and LB3 are analyzed, while LB4 is an anti-coincidence device. The geometry of LB1 and LB2 limits the viewing cone to 50° full angle. Detector areas and thickness are also given in Figure 1.

LET B Detector Positions and Sizes

Item	height (cm)	radius (cm)	thickness (µm)	pathlength (L1L2)	material	thickness (µm equiv Si)	area (cm^2)
WA	3.55	2.60	25	25.6	Kapton	20.0	21.237
LB1	0	0.9456	32.06	32.84	Si		2.8092
LB2	-4.08	0.9458	29.607	30.34	Si		2.8104
LB3	-4.3	1.144	421.24	432.21	Si		4.1151
LB4	-4.47	1.137	439.92	451.09	Si	450	4.0621

Height refers to bottom of item.

Figure 1

The LET E Telescope

The LET-E is modified from the Voyager LET by substitution of two thick surface barrier detector (LE4 and LE5) for the existing L4 and by much heavier collimation and shielding.

The cross section of the telescope is shown in Figure 2. Detectors LE1, LE2 and LE3 are surface barrier devices; LE4 and LE5 are lithium drifted. Signals from all detectors are analyzed. LE1 and LE2 define a 50° viewing cone, while LE2 and LE5 define a 92° viewing cone in the wide angle mode. Detector areas and thicknesses are also given in Figure 2.

LET E Detector Positions and Sizes

Item	height (cm)	radius (cm)	thickness (µm)	pathlength (L1L2)	material	thickness (µm equiv Si)	area (cm^2)
WA	7.00	6.37	76	77.9	Kapton	60.0	127.48
WB	5.54	5.30	256.54	262.95	Al	289.5	88.247
LE1	4.08	0.9489	30.41	31.16	Si		2.8288
LE2	0	0.9491	33.41	34.24	Si		2.8302
LE3	-0.22	1.138	463.12	474.95	Si		4.0678
LE4	-0.65	2.19	2000	2050	Si		15.

Figure 2

dead			53.2	54.5	Si		
LE5	-1.08	2.19	2000	2050	Si		15.
dead			54.9	56.3	Si		

Height refers to bottom of item.

Geometry Calculations

Table 2 -- Geometrical Factors		
Items	**Geom**	**half-angle**
LB1,W	3.02	45°
LB1,LB2	0.4293	24.87°
LE1,WA	7.34	68°
LE2,WA	4.006	46.27°
LE1,LE2	0.435	24.95°
LE2,LE3,LE4,WA	4.006	46.27°
LE2,LE3,LE4,LE5,WA	4.006	46.27°

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Logic and Data Format

The existing Voyager electronics was modified by rerouting preamp inputs and outputs so that LET E talks to the HET electronics and by making minor changes to some of the logic. In addition to this, the GEM (Galileo Element Monitor) adapter board (GAB) which interfaces the CRS-HIC to the Galileo spacecraft imposes some structure on the data.

Figure 3 shows the structure of the electronics and the following sections document separately the changes and the new status of the electronics.

Event Format

Events consist of four 12-bit words: the tag word, PHA3, PHA2, and PHA1 (words 4 through 7 of the spacecraft minor frame, see Packets). All zero's are telemetered if no event is available. The format of the tag word is shown in Table 5 and contents of the PHA's is shown in Table 6 and in Figure 4. Separate buffers are used for each of the five event modes, and readout of events progresses cyclically through the five buffers. The polling of buffers is done in the sequence LET B, WDPEN, DUBL, TRPL, LET B, WDPEN, WDSTP. Thus LET B and WDPEN events get more emphasis if all buffers are filling more rapidly than they can be readout.

Table 5 -- Tag Word Format

HIC bit number	Contents of TAG word (word 4 of minor frame)	
	LET E	LET B
4-1	LE4	slant(SLB)
4-2	LE1	LB3
4-3	LE5	LB2
4-4	LE3	LB1
4-5	slant(SB)	0 (DLA2)
4-6	LE2	DLB3 (cmd 8-5)
4-7	0	DLB2 (cmd 8-6)

4-8	HG	0 (DLA3)
4-9	buffer ind.	1
4-10		0
4-11	1 (LET E)	0 (LET B)
4-12	caution flag	caution flag

The caution flag indicates PHA overflow and/or gain switching in progress. The LET E buffer indicator (bits 9 and 10) has the following states:

```
4-9     4-10             4-9     4-10
  0        0    DUBL       1        1    WDSTP
  0        1    TRPL       1        0    WDPEN
```

Most events will have a tag bit pattern from the following list:

```
LB Triple
    &      LET B
cmd state Double DUBL TRPL WDPEN WDPEN wL1 WDSTP
   F48      B48   4C2  5C6  BCA      FCA      9CE
   F08      B68
   F68
```

Table 6 -- PHA Contents				
mode	**PHA3**	**PHA2**	**PHA1**	**logic condition**
DUBL	-	LE1	LE2	LE1.LE2.LE3
TRPL	LE3	LE1	LE2	LE1.LE2.LE3.LE4
WDSTP	LE3	LE4	LE2	LE2.LE3.LE4.LE5
WDPEN	LE3	LE4+LE5	LE2	LE2.LE3.LE4.LE5
LET B	LB3	LB2	LB1	LB1.LB2.LB3.LB4

Rate Scalers

Eight rate accumulators (numbered A through H) are used. In two of the accumulators (F and H), the input signals are subcommutated sixteen times. (The same subcom sequence controls status readout.) Table 7 shows rate readout as a function of accumulator letter and subcom state.

Table 7 -- Rate Readout									
	Rate Letter								
N = accum. subcom state	**A**	**B**	**C**	**D**	**E**	**G**	**F**	**H**	**readout subcom state**
0	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	2
1	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	3
2	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	4
3	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	LBTRP	5

4	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	6
5	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	7
6	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	8
7	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	9
8	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	LE5	LB1	10 (A)
9	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	LE3	LB2	11 (B)
10 (A)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	LE4	LB3	12 (C)
11 (B)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	LE2	LB4	13 (D)
12 (C)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	14 (E)
13 (D)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	15 (F)
14 (E)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	0
15 (F)	DUBL	TRPL	WDSTP	WDPEN	LETB	LE1	SB	SLB	1

The first five rates are rates of "events" (an event is a triggering of the HIC by an energetic particle or the PHA and TAG data generated by such a triggering) as defined below, the remainder are singles rates from the detectors (LE1 - LE5, LB1 - LB4) or slant discriminators (SLB in LET B, SB in LET E). LBTRP is the rate of LB1.LB2.LB3.LB4* coincidences. The requirements for the various types of events are discussed in the event section.

The spin of the spacecraft at 3 rpm nominal will allow calculation of anisotropies from the rate scalers after the fact. Note that the eight rate scalers are read every 2 seconds; ten times per spin. It will be necessary to understand the buffering delay to get the phase right (or perhaps vice-versa).

Rate Compression

Rate counts are accumulated in a 24-bit accumulator which is reset to the all-one's state. The first count (if any) increments the accumulator into the all-zero's state; the next increments to a single one; and so forth. At the end of the appropriate time interval (3 minor frames = 2 sec on Galileo) the contents of the accumulator are up-shifted until the most significant one bit is in position 24 (the MSB of the accumulator) or until 31 shifts have been done. The instrument then transmits five bits which specify the number of shifts and 7 bits which specify the 7 less significant bits of the 8 most significant bits in the up-shifted accumulator. The single MSB is known to be a 1.

For example, zero counts leaves the accumulator at all-one's. Zero shifts are required to up-shift a 1 into position 24. All 8 MSB's are 1's. The transmitted number has 5 leading 0 bits and 7 trailing 1 bits (octal 0177). One count leaves the accumulator at all-zero's. Thirty-one up-shifts are done searching for a 1 but none is found. This case is the exception to the MSB = 1 rule. The transmitted number has 5 leading 1's and 7 trailing 0's (octal 7600). Two counts leave the accumulator at 1. Twenty-three shifts are required. The transmitted number is octal 5600. For 7200 counts (the internal calibrator) the accumulator state will be binary 1*1100000*11111 ; eleven shifts will be required and the italicized bits will form the mantissa. The result is 010111100000 in binary, 5E0 in hex, 2740 in octal.

To decompress rates, the 7-bit mantissa is picked up and put in position 17 through 23 of a computer word with at least 24 bits (numbered 1 to 24). Bit number 24 is set to 1. The word is then down-shifted the number of times indicated by the 5-bit exponent. The word is then incremented to compensate for the all-one's reset state of the accumulator. In pseudo-FORTRAN notation,

```
rate = (128+mantissa)*(2**16)
rate = rate/2**exponent
rate = rate + 1
```

Two exceptions must be checked for -- if rate = 0 or 1 (very common on the ground) then the algorithm fails. These cases are recognized and handled as indicated in the examples above.

If the resulting rate is greater than 256, a better estimate for many data processing applications is obtained by using 128.5 ± 0.5 instead of 128 in the formula above. For example, hex 5E0 decodes as 7185±16.

Table 8 specifies examples for the smaller numbers likely to be encounted in flight.

Table 8 -- Rate Compression Examples

raw counts	compressed octal	compressed hex	decompressed counts	resolution
0	177	07F	0	1
1	7600	F80	1	1
2	5600	B80	2	1
3	5400	B00	3	1
4	5500	B40	4	1
5	5200	A80	5	1
6	5240	AA0	6	1
7	5300	AC0	7	1
8	5340	AE0	8	1
9	5000	A00	9	1
10	5020	A10	10	1
11	5040	A20	11	1
12	5060	A30	12	1
16	5160	A70	16	1
17	4600	980	17	1
32	4770	9F8	32	1
33	4400	900	33	1
34	4404	904	34	1
64	4574	97C	64	1
65	4200	880	65	1
128	4376	8FE	128	1
129	4000	800	129	1
130	4001	801	130	1
256	4177	87F	256	1
257	3600	780	257	2
258	3600	780	257	2

Command/Status Data

A Galileo command consists of two 8-bit bytes sent to the GAB as documented in the JPL IRD 512335. These 16 bits are decoded by the GAB. The first bit is spare, the second indicates "cal start" (BC28CAL), the third indicates "high voltage on" (BC28HVON), and the fourth indicates that the following 12 are a serial command. These 12 bits are sent on to the CRS electronic as was done on Voyager. As before, these 12 bits are interpreted as a four-bit column number or register address and eight bits of data for that column. Table 10 shows the interpretation of each bit. Recall that commandable functions are also shown in the rate definitions in Table 6 by brackets.

The JPL nomenclature indicated in parentheses above and in Table 9 must be used when speaking with them. The prefix BC is bus command; GEM/HIC is experiment number 28. When printing status data JPL/MTS uses hex. When specifying commands to be sent, they usually use binary for the eight bits of "data".

Table 9 -- Command/Status Data

column-> number	**0 status only, no command**	**2 BC28E**	**6 BC28PHA**	**8 BC28ANAL**	**12 (C) BC28BP**	**13 (D) BC28MISC**
bit number						
5 (MSB)	redundant polling	LE1 preamp power off		Delete LB3 terms		High Voltage redundant enable
6		LE2 preamp power off		Delete LB2 terms		Cal Stim Disable
7	High Voltage enable	LE3 preamp power off	Disable WDSTP mode			redundant polling
8	HET 2 gain	LE4 preamp power off	Disable TRPL mode	Delete LE3 terms		
9				Delete LE4 terms	LB4 preamp power off	
10	Cal Status Q3 (MSB)	LE5 preamp power off	Disable DUBL mode	Delete LE1 terms (RB)	LB3 preamp power off	
11	Cal Status Q2		Disable LET B	Delete LE2 terms	LB2 preamp power off	auto gain
12 (LSB)	Cal Status Q1 (LSB)		Disable WDPEN	Delete LE1 terms (RA)	LB1 preamp power off	high gain

Analog Data

Analog data is readout by the spacecraft via a multiplexed line. In the telemetry we receive an eight-bit "data number" (dn). The multiplexor is stepped by the adapter board once each 7 minor frames, but this sequence is not synched to the spacecraft major frame (rim) structure. Note that two step signals are required to step the multiplexer; it may well take 14 minor frames to switch states. The reset signal cannot be sent. Synchronism must be achieved by inspecting the data. The data consists of power supply voltages and temperatures as listed in Table 11.

Table 11 -- Analog Signals

number	**name**	**nominal value**	**description**
1	V+10	234	+ 10 volt power supply voltage
2	ZERO	0	unused and grounded
3	V+6	251	+ 6 volt power supply voltage
4	V+3	250	+ 3 volt power supply voltage
5	V-3	52	- 3 volt power supply voltage
6	V-6	59	- 6 volt power supply voltage
7	V-12	91	- 12 volt power supply voltage

8	ZERO	0	unused and grounded
9	ZERO	0	unused and grounded
10	LOW	16	unused and held at about 0.2 volts
11	LOW	16	unused and held at about 0.2 volts
12	LOW	16	unused and held at about 0.2 volts
13	LOW	16	unused and held at about 0.2 volts
14	TLB	61	LET B temperature
15	TLE	60	LET E temperature
16	TPC	56	power converter temperature
17	ZERO	0	unused and grounded
18	TBP	58	baseplate temperature
19	TPHA	57	PHA electronics temperature
20	TTP	61	top plate temperature
21	ZERO	0	unused and grounded
22	ZERO	0	unused and grounded
23	ZERO	0	unused and grounded
24	ZERO	0	unused and grounded

The temperature calibrations for the multiplexed analog data are roughly given by

$°C = A_0 + A_1*(dn) + A_2*(dn)^2 + A_3*(dn)^3$

where

$A_0 \sim 67.$
$A_1 \sim -1.$
$A_2 \sim 5. * ^{-3}$
$A_3 \sim -11. * 10^{-6}$

There is also a separate temperature transducer on the telescope housing which is not multiplexed and which is readout by the spacecraft. The JPL acronym is TTEMP. Its calibration is given by

$A_0 \sim -102.45$
$A_1 \sim +0.674666$
$A_2 \sim 90.524 * 10^{-6}$
$A_3 \sim 0.0$

Packets

Do not confuse HIC instrument packets, described here, with CDS 02 telemetry packets, described in Galileo Project Doc. 625-205: 3-280, Phase 2 (available from JPL).
The GAB issues a fixed sequence of word gates to CRS to create a particular mixture of rates, status, and PHA's which are then sent on to the Galileo spacecraft by GAB or HIC. A HIC instrument packet consists of three minor frames. Each minor frame consists of eight 12-bit words. The third minor frame of the three in a packet contains subcommutated rate and status data, with a subcom depth of 16. Thus an instrument cycle consists of 16 packets, numbered 0 through 15 by the four MSB's in the status word. Figure 6 illustrates the packet format.

Error Protection Encoding

The CRC word consists of 8 bits of actual CRC (the CRC character) and four trailing bits of zero's. The CRC character is generated in a 8-bit shift register which applies the encoding polynomial x**8 + x**7 + x**6 + 1. On the ground, where the error rate is negligible, the CRC should be checked but no data correction is necessary.

The encoding circuit is illustrated in Figure 7. The following "subroutine" will perform the same encoding.

```
initialize 84-element array x() to zero
loop for n = 1 to 84
        input =  nth bit of 84-bit data stream
        x(0)  =  x(8) XOR input
        x(8)  =  x(7) XOR x(0)
        x(7)  =  x(6) XOR x(0)
        x(6)  =  x(5)
        x(5)  =  x(4)
        x(4)  =  x(3)
        x(3)  =  x(2)
        x(2)  =  x(1)
        x(1)  =  x(0)
end of loop
CRC = 128*x(8) + 64*x(7) + 32*x(6) + 16*x(5) + 8*x(4)
      + 4*x(3) + 2*x(2) + x(1)
```

Synchronism

There are some values which the 12-bit log compressed rate words never have (including F00 and 020) and others which are impossible in the Galileo application because the rapid readout (every 3 minor frames or every 2 seconds) means that we cannot accumulate more than about 100,000 counts in the accumulator. Thus if the first four bits of an rs word have value 1, 2, 3, 12, 13, or 14 the rs word is a status word and the index SCN must be 2 (possible values are 0, 1, 2) and mux state N is the value found. The following "subroutine" will determine all the HIC pointers after less than 30 minor frames. N is the value of the first four bits, and MUXN is the mux state,

```
if ([N<1] or [N>14]) return
if ([N>3] and [N<12]) return
if (LCN==3*N+2) return
SCN = 2
MUXN = N
LCN = 3*N + SCN
return
```

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PHA Gain and Discrimination Levels

The nominal gain and discriminator values are given below. Actual values should be requested from Thomas L. Garrard.

Table 12 -- Gain and Discriminator Values		
detector name	**normal full scale (MEV)**	**normal discriminator (MEV)**
LE1	307	9.6
LE2	307	2.0
LE3	2048	26.
LE4	6144	120.
LE5	6144	120.
LB1	307	0.5
LB2	307	0.4
LB3	2048	4.0
LB4	50*	2.0
* Pre-amp full scale; not connected to an analyzer.		
LET E -- Slant SB:		
	low gain -> LE1 + LE2/2 + LE3/10 + (LE4+LE5)/25 = 9.6 MeV	
LET B -- Slant SLB:		
	LB1 + 0.42*L2 + 0.20*L3 = 9.6 MeV	

Buffering

Both events and rates go though one stage of buffering in the instrument and another in the GAB. Study the cal stim printouts to see the 2 minor frame delay in the readout here. More buffering must be done in the CDS (spacecraft); this is almost certainly one minor frame. This must be understood so that correlation or rate readout and angle from the AACS can be done.

Figure 9 shows accumulation time and readout time of rate data. It also shows two extreme possibilities for event time and event readout; one event readout with minimal buffering delay and one with a maximum delay due to all six event polling buffers being full. The AACS is readout with no delay as shown in the figure.