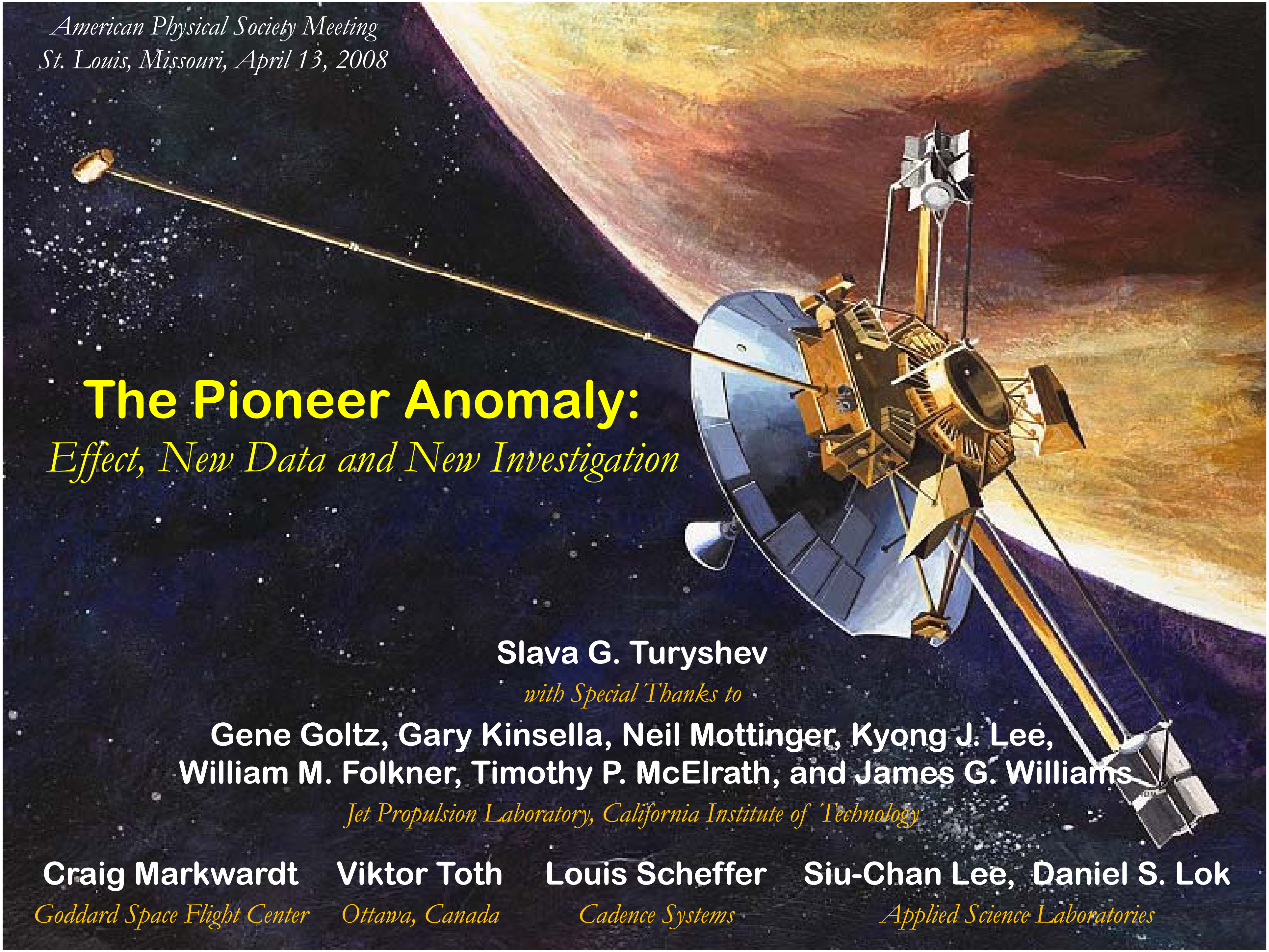
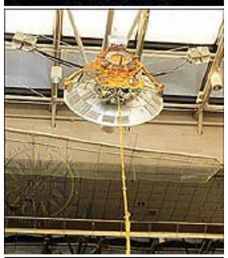
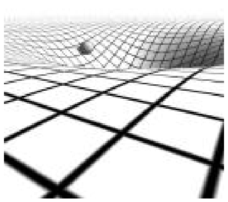
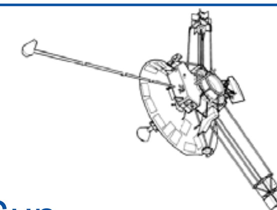

American Physical Society Meeting
St. Louis, Missouri, April 13, 2008
The Pioneer Anomaly:
Effect, New Data and New Investigation
Slava G. Turyshev
with Special Thanks to
Gene Goltz, Gary Kinsella, Neil Mottinger, Kyong J. Lee,
William M. Folkner, Timothy P. McElrath, and James G. Williams
Jet Propulsion Laboratory, California Institute of Technology
Craig Markwardt
Goddard Space Flight Center
Viktor Toth
Ottawa, Canada
Louis Scheffer
Cadence Systems
Siu-Chan Lee, Daniel S. Lok
Applied Science Laboratories

The Pioneer Anomaly: Summary





- Anomalous acceleration of Pioneers 10 and 11:



$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

  - A constant acceleration of both Pioneers *towards* the Sun
  - **No mechanism** or **theory** that unambiguously explains the anomaly
  - Most likely cause is on-board systematics, yet to be demonstrated

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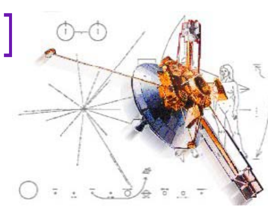
- The Pioneer anomaly, taken at its face value:
  - Pioneers conducted the largest-scale-ever gravitational experiment in the solar system… that failed to confirm Newton's gravity…
  - The Pioneer anomaly constitutes a departure from the Newton's $1/r^2$ gravity law in regions farther than 25 AU from the Sun….

Possible Origin of the "Dark Force"?

- New Physics [many proposals exist, some interesting]
- We focus on Conventional Physics, as the cause:
  - Gas leaks, drag force, **thermal recoil force**, etc…



The Pioneer 10/11 spacecraft

Agency: NASA	Pioneer 10	Pioneer 11
Launch	2 March 1972	5 April 1973
Planetary fly-bys	Jupiter: 4 Dec 1973	Jupiter: 2 Dec 1974 Saturn: 1 Sep 1979
Last data point received	27 Apr 2002 distance ~80.2 AU	1 Oct 1990 distance ~30 AU

Parameters for Pioneer 10 (Pioneer 11 – identical)		
Total spacecraft mass		259 kg
SNAP-19 RTG: mass/distance		13.6 kg / 3 m
High Gain Antenna, diameter		2.74 m
Attitude control: spin-stabilized		~4.28 rpm
Communication system		Data available ($\lambda \simeq 13$ cm)
S-band, up-link	S-band, down-link	
2110 MHz	2292 MHz	Doppler
Spacecraft transmits continuously @ 8 W		

Pioneer 10: pre-launch testing

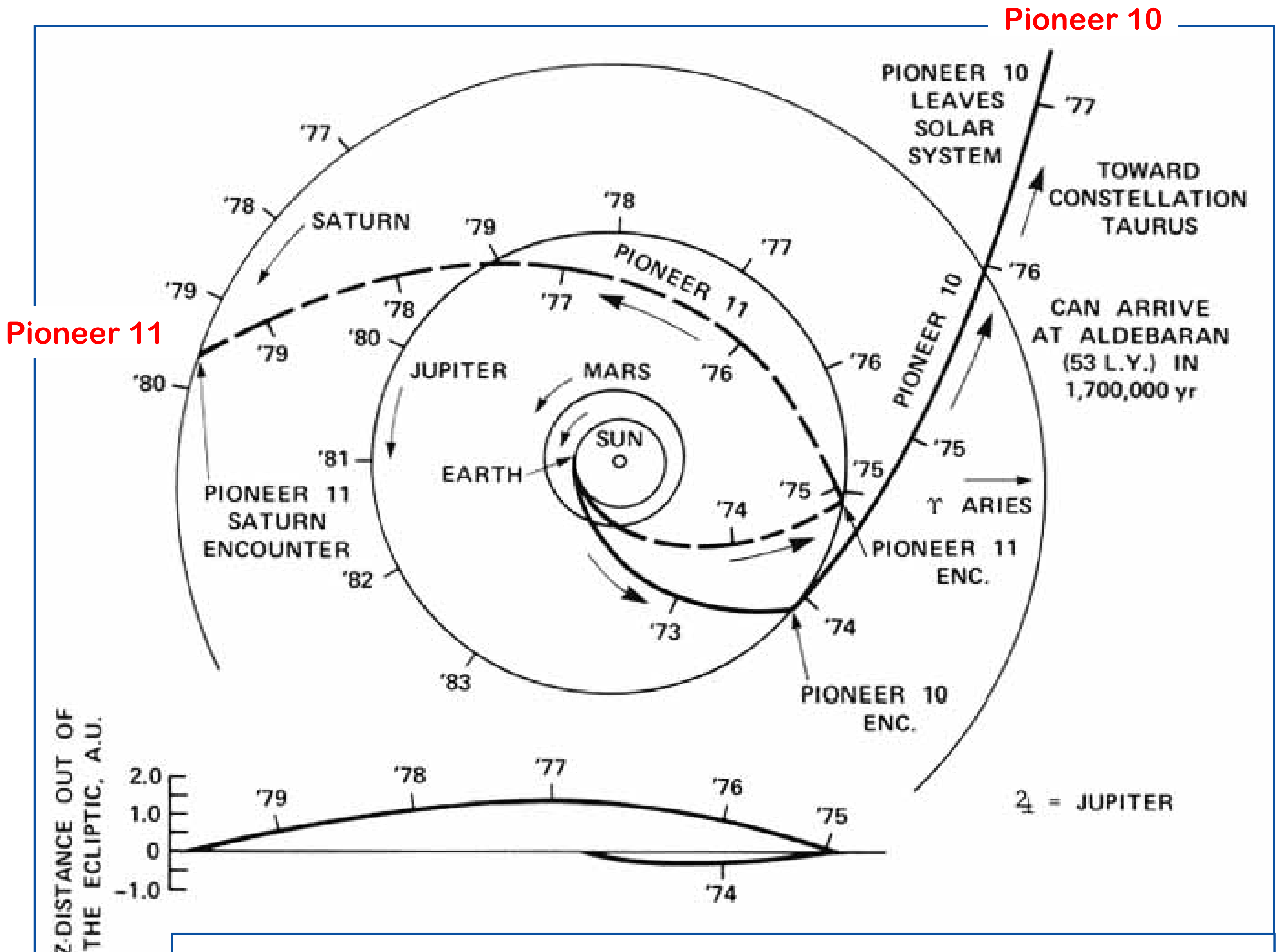
The Pioneers are still the most precisely navigated deep-space vehicles:

- Spin-stabilization and design permitted acceleration sensitivity ~10^{-10} m/s^2, unlike a Voyager-type 3-axis stabilization that were almost 50 times worse;
- Precision celestial mechanics – a primary objective of the Pioneers' extended missions – search for gravitational waves, Planet X, trans-Neptunian objects, etc.

Pioneer 10 Launch: 2 March 1972

Pioneer 10 Launch: 2 March 1972

Pioneers 10 and 11: Main Missions (before 1979)

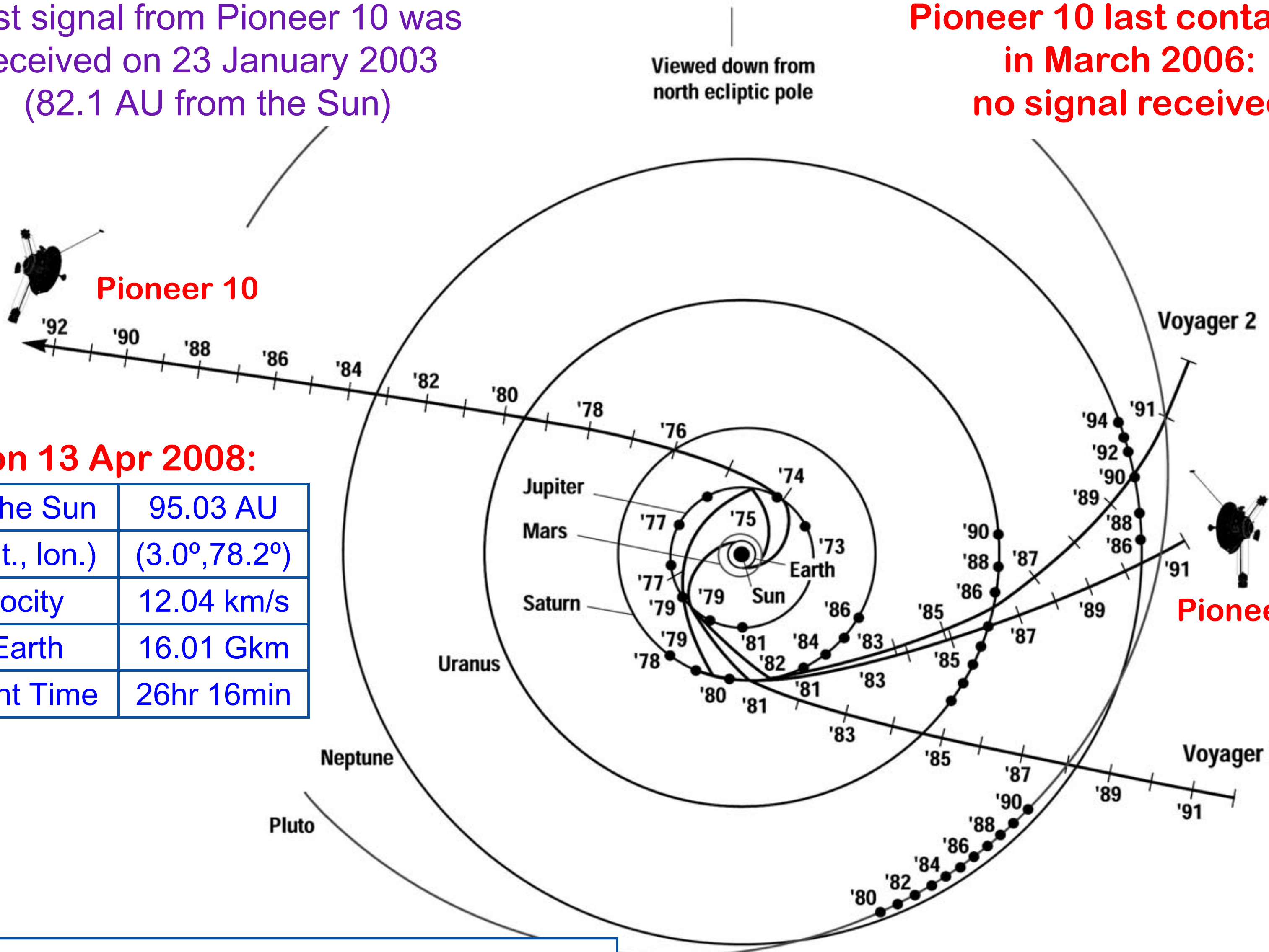


Trajectories of Pioneer 10 & 11 during the main mission phase

Pioneers 10 and 11: Extended Missions (after 1979)

Last signal from Pioneer 10 was received on 23 January 2003 (82.1 AU from the Sun)

Pioneer 10 last contacted in March 2006: no signal received

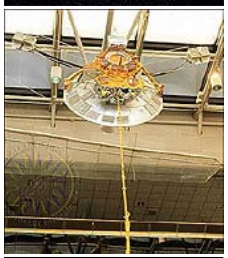


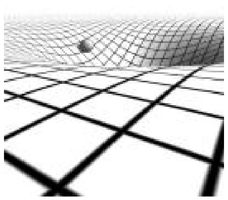
Pioneer 10 on 13 Apr 2008:

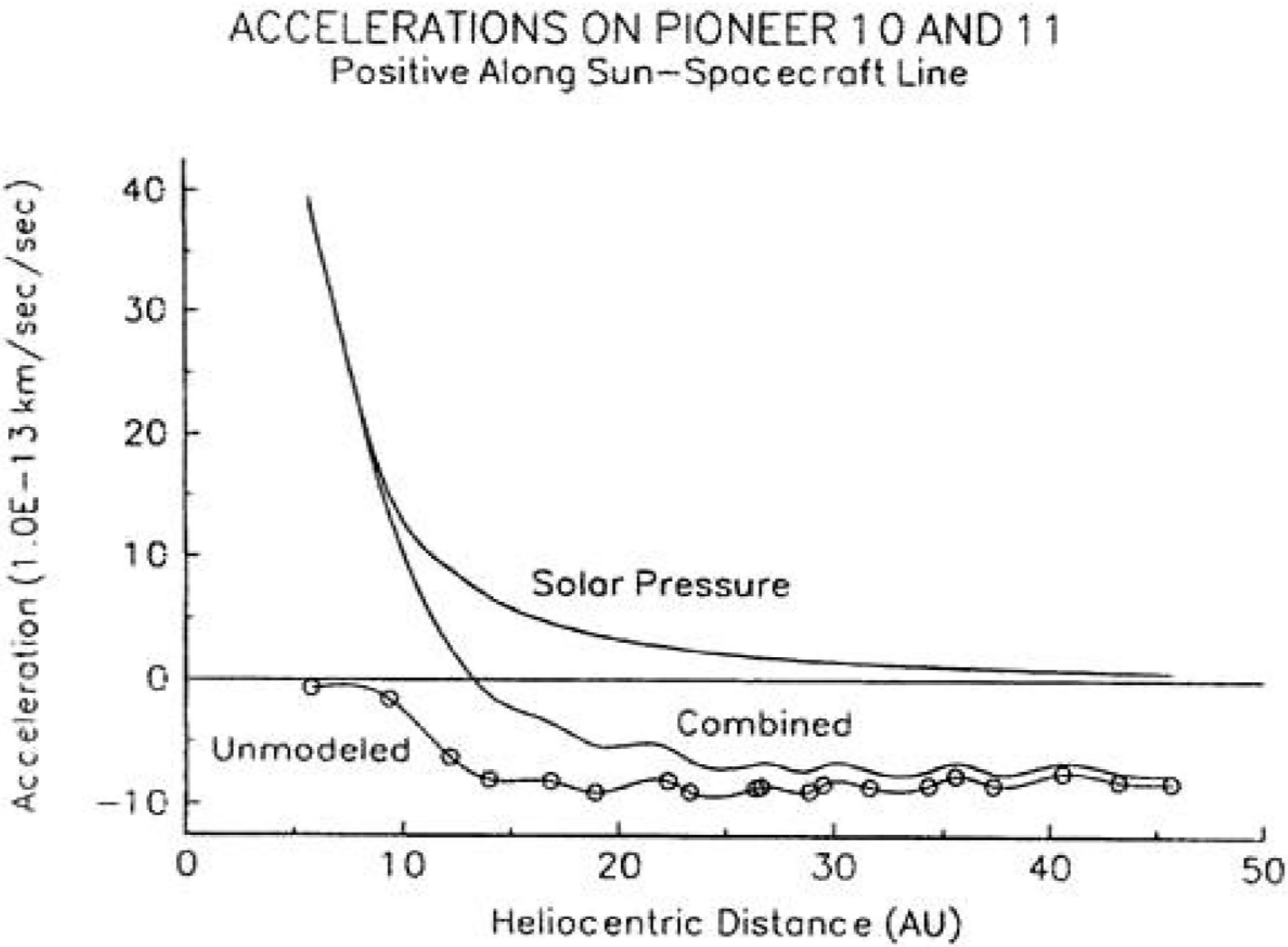
Distance from the Sun	95.03 AU
Position, SE (lat., lon.)	(3.0º,78.2º)
Heliocentric velocity	12.04 km/s
Distance from Earth	16.01 Gkm
Round-Trip Light Time	26hr 16min

Trajectories of Pioneers and Voyagers

History: Detection of the Effect and Earlier Studies



Modeling of Spacecraft Motion

- Relativistic eq.m. for celestial bodies are correct to $(v/c)^4$:
  - Relativistic gravitational accelerations (EIH model) include: Sun, Moon, 9 planets are point masses in isotropic, PPN, N-body metric;
  - Newtonian gravity from large asteroids; terrestrial, lunar figure effects; Earth tides; lunar physical librations.
- Relativistic models for light propagation are correct to $(v/c)^2$

- Model accounts for many sources of non-grav. forces, including:
  - Solar radiation and wind pressure; the interplanetary media;
  - Attitude-control propulsive maneuvers and propellant (gas) leakage from the propulsion system;
  - Torques produced by above mentioned forces;
  - DSN antennae contributions to the spacecraft radio tracking data.
- Orbit determination procedure, includes:
  - Models of precession, nutation, sidereal rotation, polar motion, tidal effects, and tectonic plates drift;
  - Model values of the tidal deceleration, non-uniformity of rotation, polar motion, Love numbers, and Chandler wobble are obtained observationally via LLR, SLR and VLBI (from ICRF).

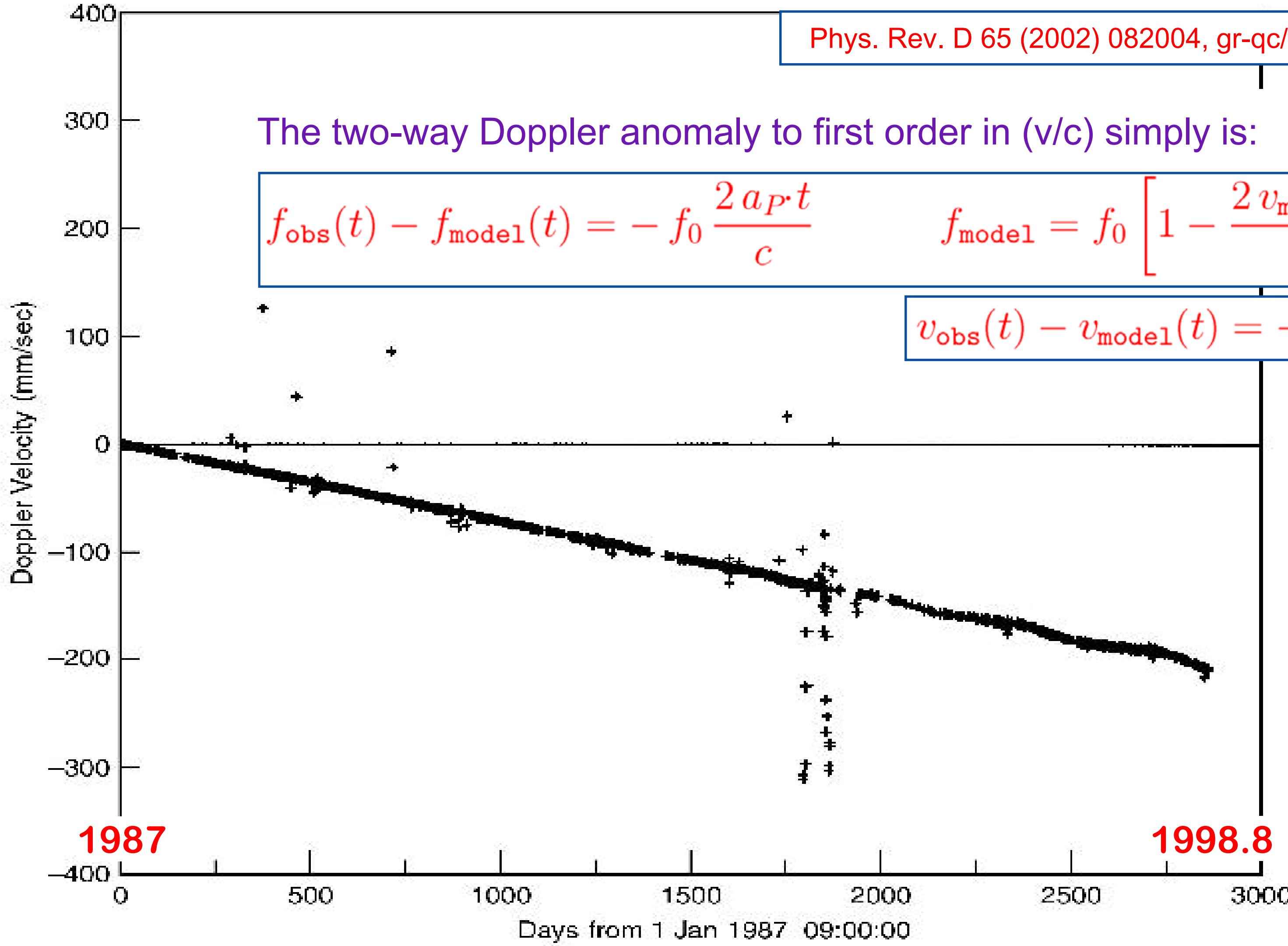
The Observed Anomalous Doppler Drift

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

The two-way Doppler anomaly to first order in (v/c) simply is:

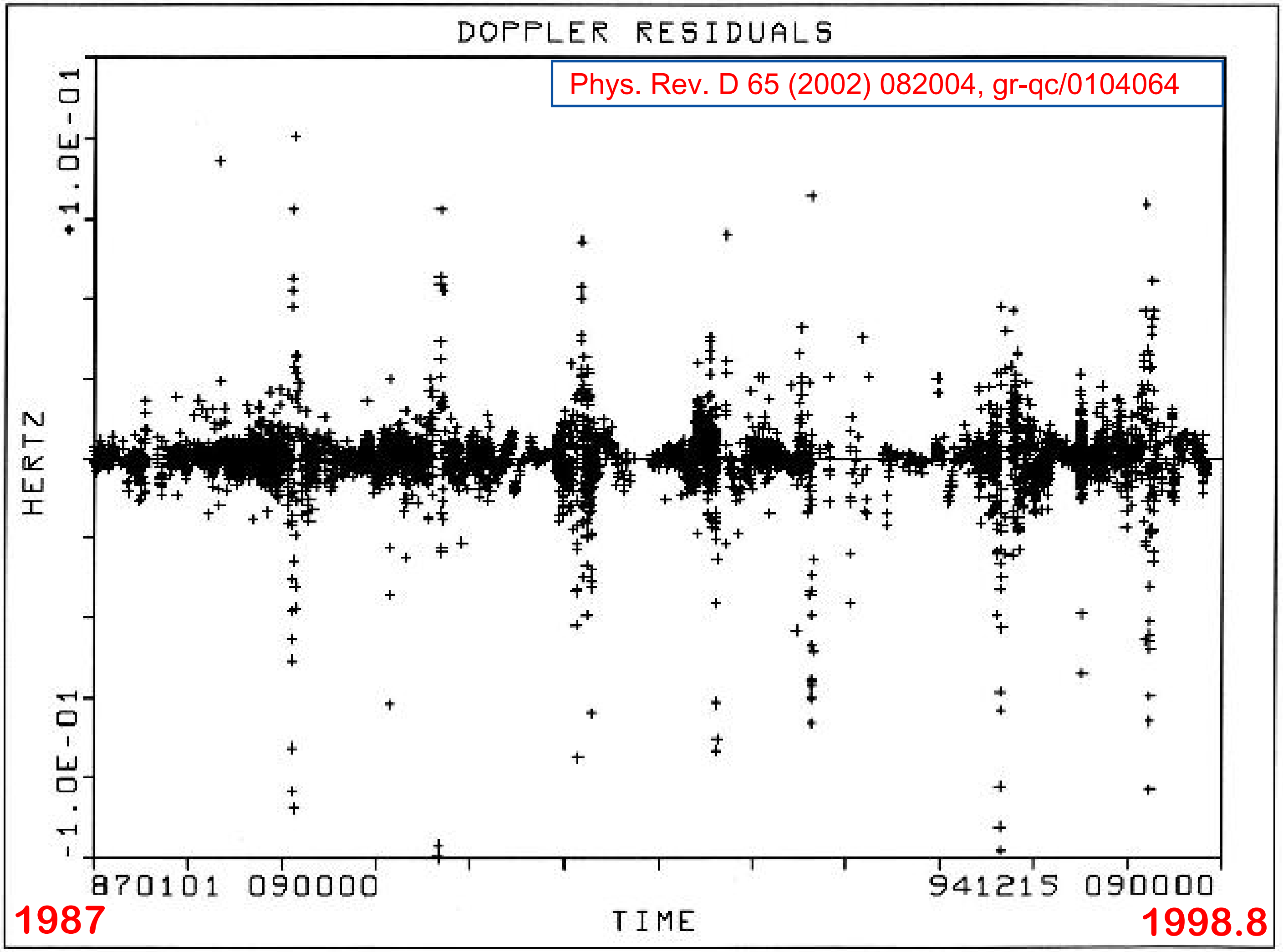
$$f_{\mathrm{obs}}(t) - f_{\mathrm{model}}(t) = -\, f_0 \frac{2\, a_P \cdot t}{c} \qquad f_{\mathrm{model}} = f_0 \left[1 - \frac{2\, v_{\mathrm{model}}(t)}{c}\right]$$

$$v_{\mathrm{obs}}(t) - v_{\mathrm{model}}(t) = -\, 2\, a_P \cdot t$$



The two-way Doppler residuals (observed Doppler velocity minus modeled Doppler velocity) for Pioneer 10 vs time [1 Hz is equivalent to 65 mm/s velocity].

The Pioneer Anomaly: Quality of Data Fit

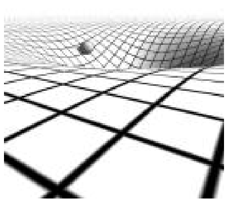


Adding only one more parameter to the model – a constant radial acceleration – led to residuals distribution ~ zero Doppler velocity with a systematic variation ~3.0 mm/s. Quality of the fit is determined by ratio of residuals to the downlink carrier frequency, $\nu_0 \approx 2.29$ GHz.

Sources of Systematic Error: External





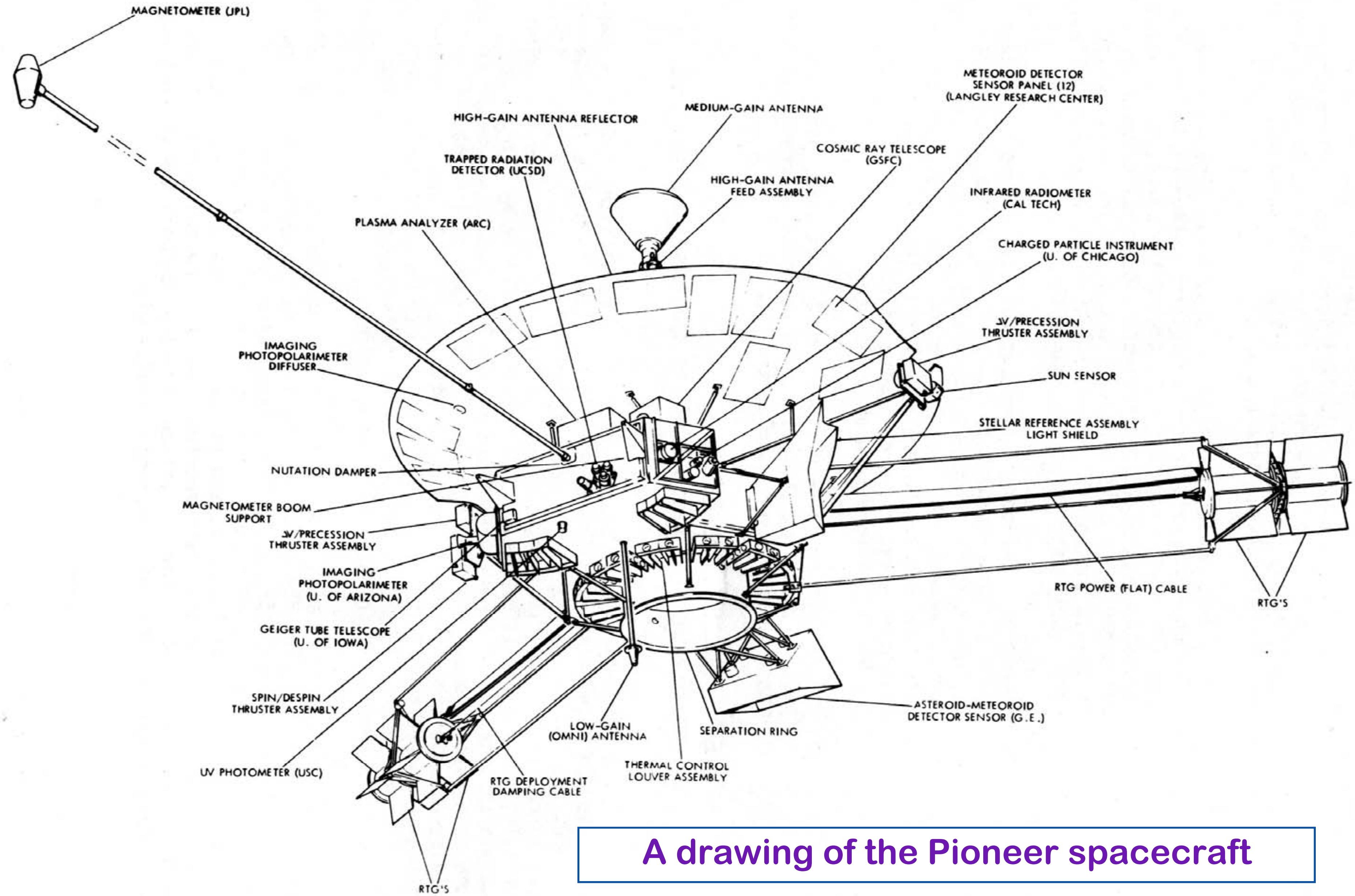


Error budget constituents	Bias 10^{-10} m/s^2	Uncertainty 10^{-10} m/s^2
1 Sources of external systematic error:		
⇛ Solar radiation pressure		$\pm$ 0.001
⇛ ⇛ From the mass uncertainty	+0.03	$\pm$ 0.01
⇛ Solar wind contribution		$\pm < 10^{-5}$
⇛ Effects of the solar corona		$\pm$ 0.02
⇛ Electro-magnetic Lorentz forces		$\pm < 10^{-4}$
⇛ Influence of the Kuiper belt's gravity		$\pm$ 0.03
⇛ Influence of the Earth orientation		$\pm$ 0.001
⇛ DSN Antannae: mechanical/phase stability		$\pm <$ 0.001
⇛ Phase stability and clocks		$\pm <$ 0.001
⇛ DSN station location		$\pm < 10^{-5}$
⇛ Effects of troposphere and ionosphere		$\pm <$ 0.001
2 Computational systematics:		
⇛ Numerical stability of least-squares estimation		$\pm$ 0.02
⇛ Accuracy of consistency/model tests		$\pm$ 0.13
⇛ ⇛ Mismodeling of maneuvers		$\pm$ 0.01
⇛ ⇛ Mismodeling of the solar corona		$\pm$ 0.02
⇛ Annual/diurnal terms		$\pm$ 0.32

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064   IJMP A 17 (2002) 875-885, gr-qc/0107022

An interesting set of error sources, but not of a major concern!

The Pioneer 10/11 Spacecraft

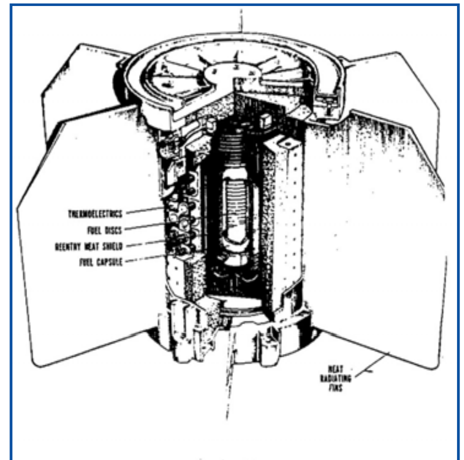


A drawing of the Pioneer spacecraft

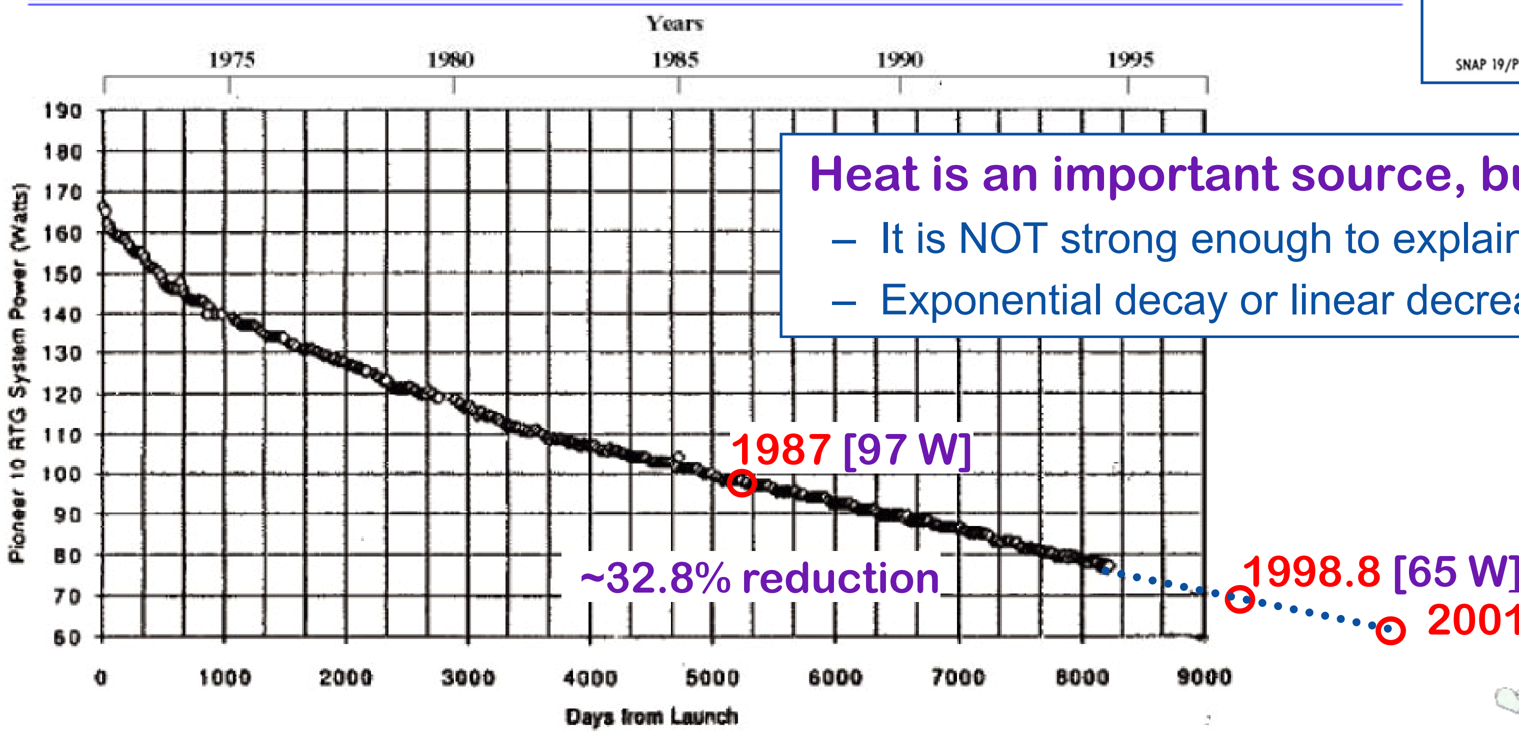
Sources of Systematic Error: On-board

	Error budget constituents	Bias 10^{-10} m/s^2	Uncertainty 10^{-10} m/s^2
3	Sources of external systematic error:		
⇛	Radio beam reaction force	+1.10	± 0.11
⇛	Thermal/propulsion effects from RTGs:		
	⇛ RTG heat reflected off the craft	–0.55	± 0.55
	⇛ Differential emissivity of the RTGs		± 0.85
	⇛ Non-isotropic radiative cooling of s/c		± 0.16
	⇛ Expelled He produced within the RTGs	+0.15	± 0.16
⇛	Propulsive mass expulsion: gas leakage		± 0.56
⇛	Variation between s/c determinations	+0.17	± 0.17

SNAP-19 RTG

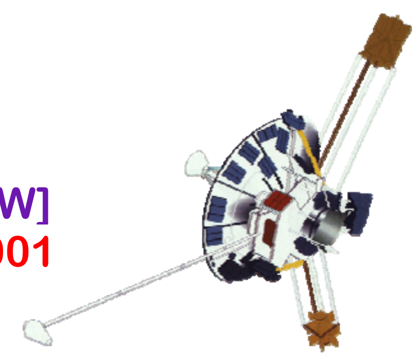


SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR



Heat is an important source, but:

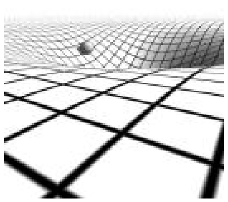
- It is NOT strong enough to explain the anomaly;
- Exponential decay or linear decrease – NOT seen



Focus of the 1995-2002 Analysis







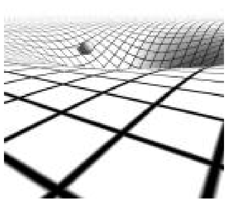
- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated “gas leaks”
  - Nominal thermal radiation due to ^{238}Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations
- Examples of the external effects (used GLL, ULY, and Cassini):
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Viscous drag force due to mass distribution in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth’s Orientation, precession, polar motion, and nutation parameters
- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others
- All the above were rejected as explanations

Most of the systematics are time or/and space dependent!

The Pioneer Anomaly: Summary







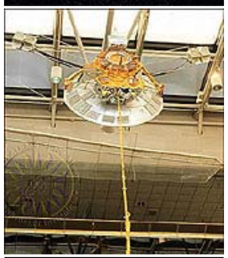
- By 2008 existence of the anomaly is confirmed by 7 codes:
  - JPL's Orbit Determination Program [various versions 1979-2008];
  - The Aerospace Corporation code POEAS [during 1995-2001];
  - Goddard Space Flight Center's study in 2003 [data from NSSDC];
  - Institute for Theoretical Astronomy, Norway, Oslo [2002-2008];
  - Viktor Toth, Canada [2005-2008]; GAP, France [2006-2008], others.
- Observed frequency drift can be interpreted as acceleration of

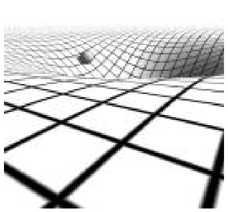
$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

  - **Constant** acceleration of the spacecraft **towards** the Sun…
  - This interpretation has become known as the Pioneer Anomaly.
- Observation $a_P \simeq cH$, stimulated many suggestions….:
  - Kinematical realization of local cosmological frame; momentum-dependent gravitational coupling; modified inertia; non-uniformly-coupled scalar field(s); Brane-worlds; higher-dimensional gravitational models…
- Primary focus of new analysis: **"the heat or not the heat?"**

Existence of the signal is confirmed, its origin is yet unknown

Recent Pioneer Doppler Data Recovery Efforts:

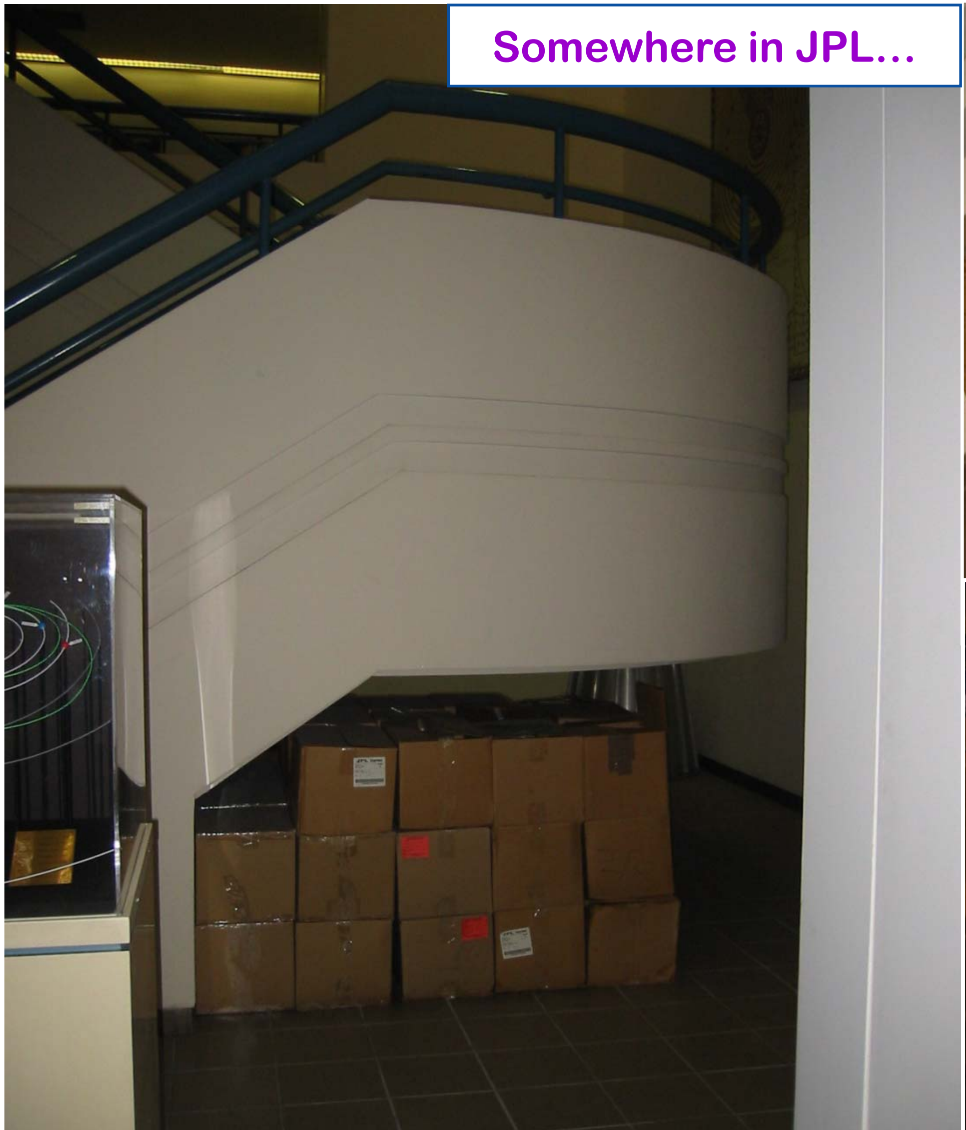



- Pioneer 10 and 11 Doppler data recovery (funded by JPL):
  - Goal: recover all Doppler data from lunch to the last data point
  - Never attempted before: 30+ years is a long time; changed data formats, software, hardware, DSN configuration, people, etc.
  - All data formats, software, hardware are obsolete & not supported
- Results of Data Recovery (as of March 2006):
  - NSSDC: retrieved data for 1978-1995 – all corrupted (changing computer platforms), fixed most of corrupted files – good to use
  - NSSDC: retrieved early data (1972-1976) – corrupted and/or unreadable format (e.g. T66) – still trying to recover some segments
  - JPL: 9-tracks magnetic tapes (1978-1988), read on mini-VAX
  - JPL: found and recovered some early data (1973-1974) from personal data archives of JPLers who workers with Pioneer data
  - Added the data already analyzed 1987-1998, new data 1998-2002
  - The resulted 1972-2002 data has some redundancy, but mostly is a very complete data set assembled for the first time
  - After certification the same set will be available for distribution

The effort on the Pioneer Doppler data recovery almost complete

9-track Magnetic Tapes…

Somewhere in JPL…



Statistics: ~400 tapes… 90 minutes / tape

Recent Pioneer Doppler Data Recovery Effort

Data used for the Analysis (1996-1998):

- Pioneer 10: 11.5 years; distance = 40–70.5 AU $\Rightarrow$ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU $\Rightarrow$ 19,198 data points

Pioneer 10/11 Doppler Data available (since March 2008):

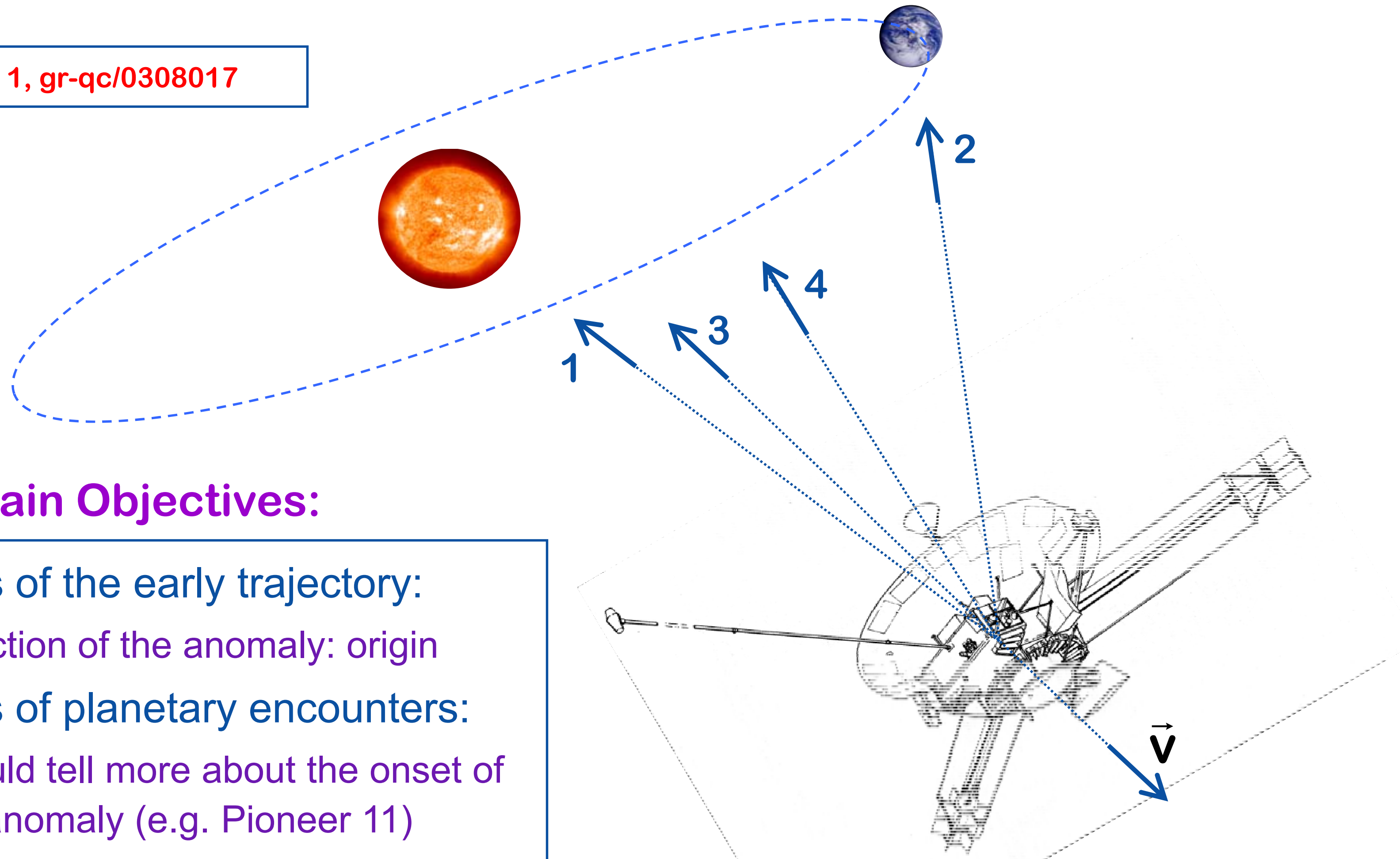
- **Pioneer 10**:
  - 1973-2002: ~30 years
  - Distance range: 4.56–80.2 AU
  - Jupiter encounter
  - ~150,000+ data points
  - Maneuvers, spin, initial cond.
- **Pioneer 11**:
  - 1974-1994: ~ 20 years
  - Distance range: 1.0–41.7 AU
  - Jupiter & Saturn encounters
  - ~120,000+ data points
  - Maneuvers, spin, initial cond.

- All 600+ ATDFs went through radio-metric data conditioning (2006-2008)
- The entire set of Doppler data should be available by the end if April 2008

Significant volume of the data never analyzed to study the anomaly

Critical Phases of the On-Going Investigation

CQG 21 (2004) 1, gr-qc/0308017

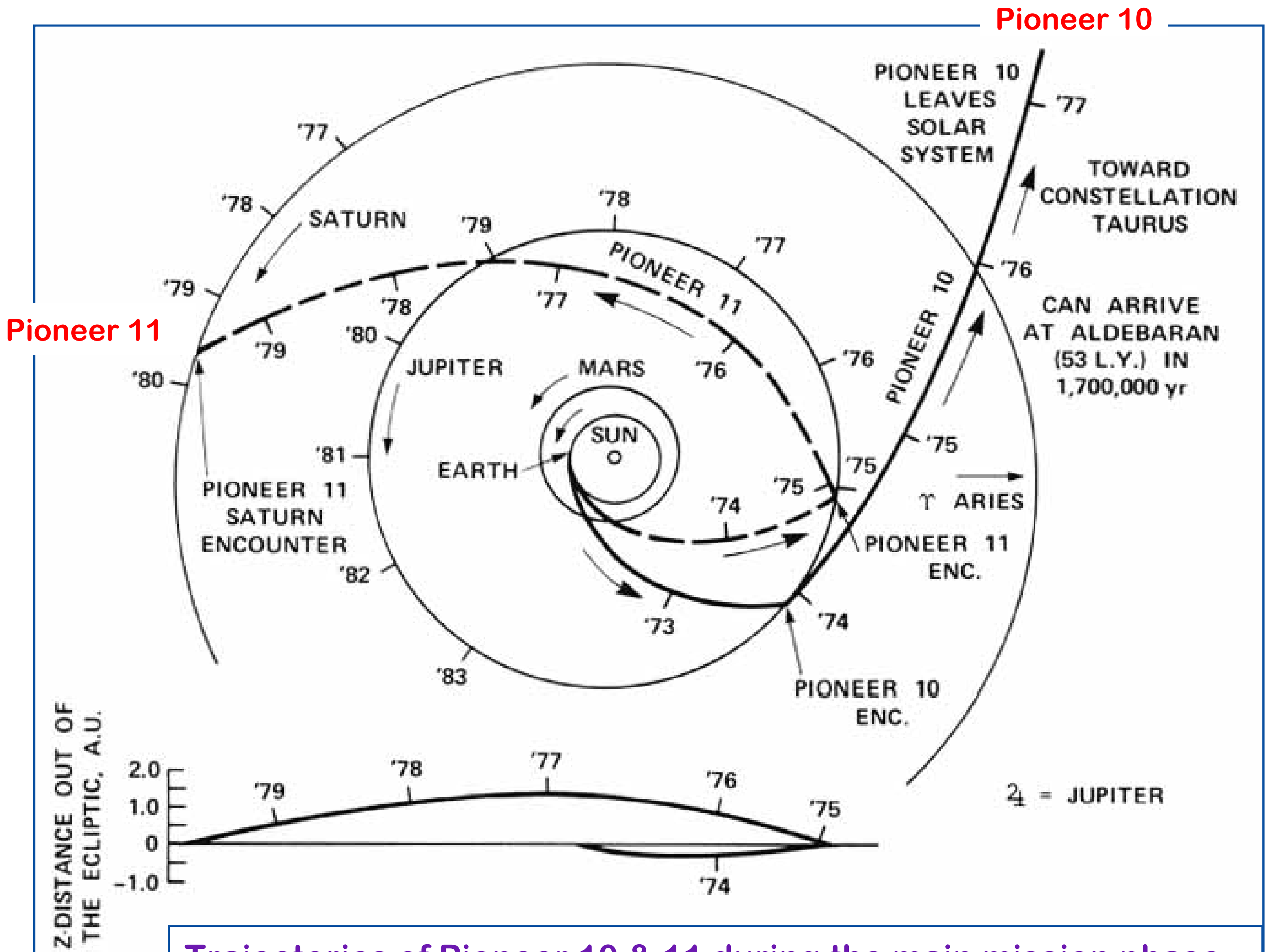


Four Main Objectives:

- Analysis of the early trajectory:
  - Direction of the anomaly: origin
- Analysis of planetary encounters:
  - Should tell more about the onset of the anomaly (e.g. Pioneer 11)
- Analysis of the entire dataset:
  - Temporal evolution of the anomaly
- Focus on on-board systematics:
  - Thermal modeling using telemetry

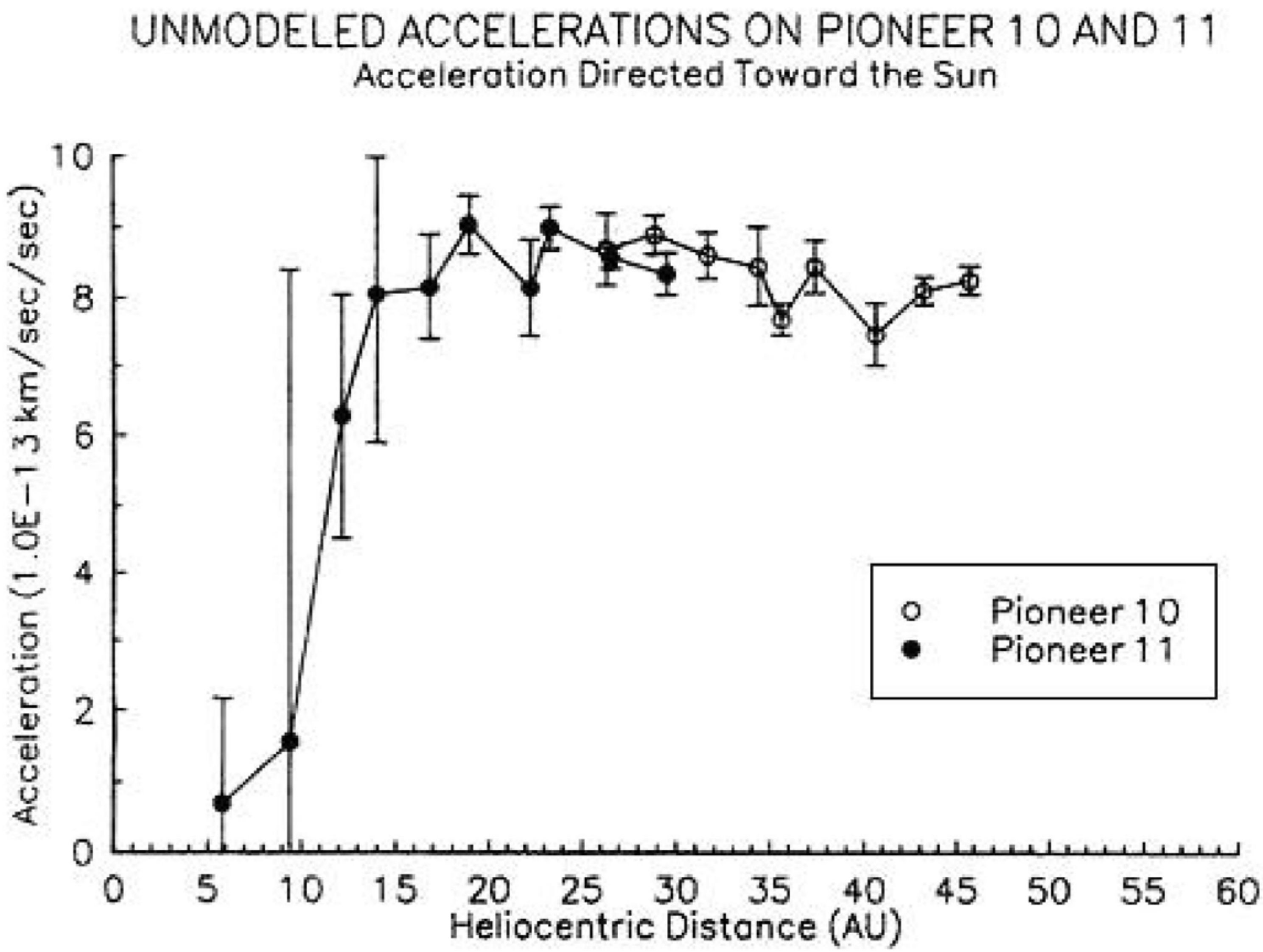
- Towards the Sun: gravitational models?
- Towards the Earth: frequency standards?
- Along the velocity vector: drag or inertia?
- Along the spin axis: internal systematics?

Early Data: Study the Direction of the Anomaly



Trajectories of Pioneer 10 & 11 during the main mission phase

To verify the "onset" of the anomaly…



A plot of early unmodeled accelerations of Pioneer 10 (1981–1989), Pioneer 11 (1977–1989)

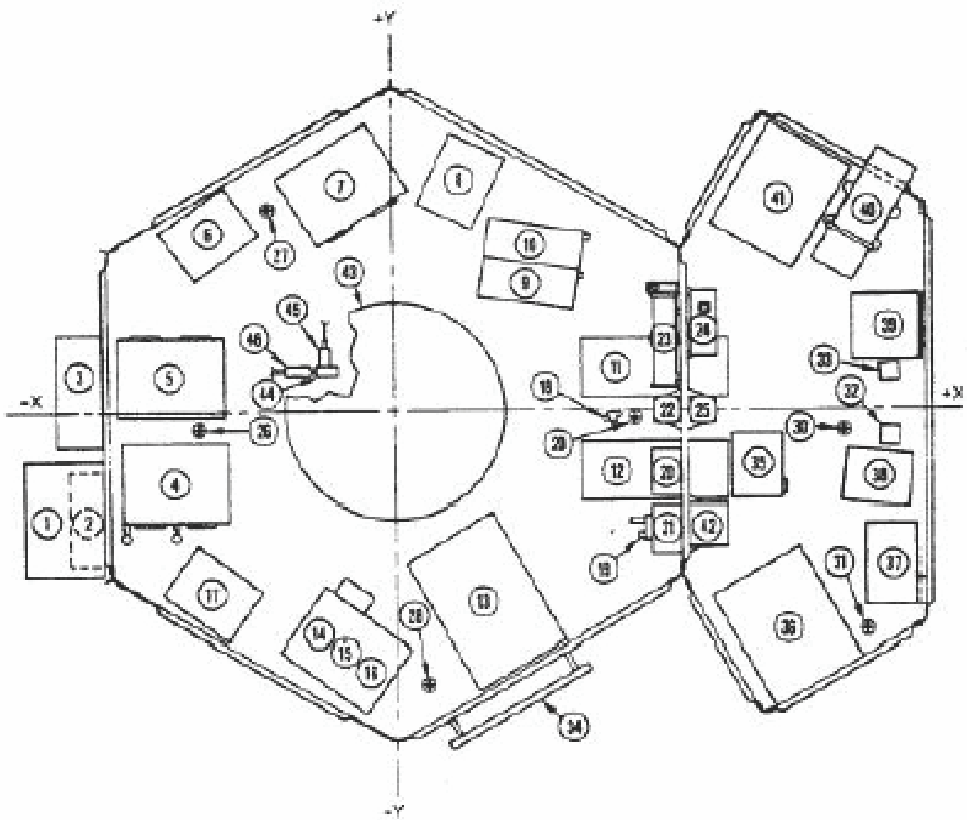
Recovery of the Pioneers' Telemetry Data

- Pioneer Project Documents (1966-2003) @ Ames:
  - All Pioneer 10 and 11 Project documents (design, fabrication, testing, calibrations, quarterly reports, memoranda, etc.)
  - Maneuver records, spin-rate data, significant events of the craft, etc.
  - Lack of funding resulted in improper storage, near destruction
- Master Data Record (MDR): <u>40GB</u> spacecraft telemetry
  - All housekeeping data for both Pioneer 10 & 11 − the only available data on their behavior through the missions
  - Developed a C++ code to read the MDRs and distribute the data
  - MDRs will be used together with the Doppler data to study on-board systematics (e.g. finite-element thermal model, etc.)
- Project documents and data are saved in Ames' Archives!
  - The Pioneer anomaly saved the Pioneer Project archive!
- Late 2006 started development of a finite-element thermal model that uses the recovered telemetry to estimate recoil force

Pioneer design documents & performance data available for analysis

Recovery of the Pioneers' Telemetry Data (MDR)

Each craft: ~114 parameters



INTERNAL EQUIPMENT ARRANGEMENT

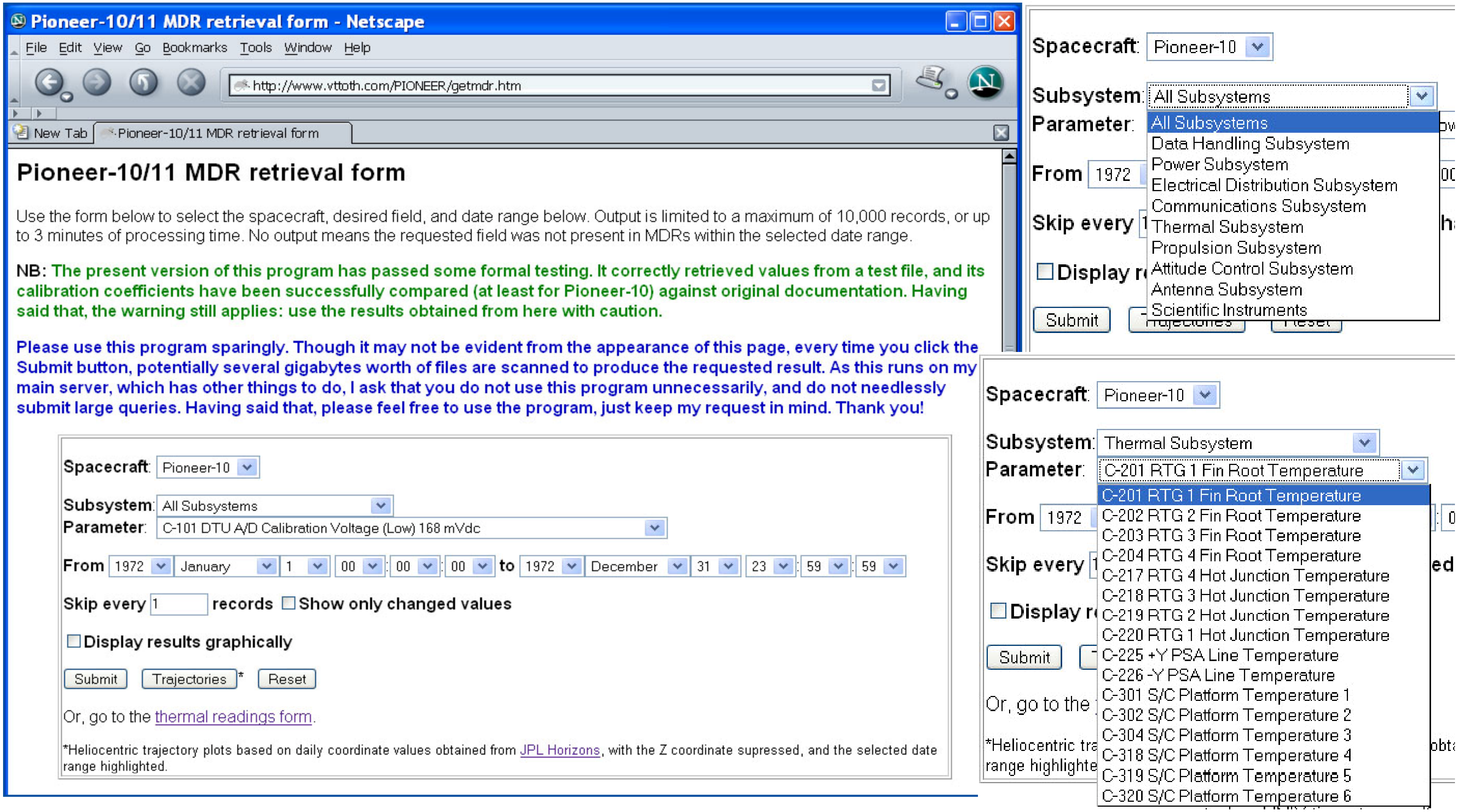
Figure 3.1-1

EQUIPMENT IDENTIFICATION

ITEM NO.	TITLE	REFERENCE SUBSYSTEM	REFERENCE DESIGNATOR*
1	Data Storage Unit (DSU)	Data Handling	0604
2	Asteroid/Meteoroid Detector Electronics (GE/Soberman)	Instruments	0859
3	Battery	Electrical Power	0407
4	Power Control Unit (PCU)	Electrical Power	0402
5	Central TRF Unit	Electrical Power	0414
6	Inverter Assembly No. 2	Electrical Power	0406
7	Command Distribution Unit (CDU)	Electrical Distributor	0301
8	Stellar Reference Assembly (SRA)	Attitude Control	0231
9	Receiver No. 1	Communications	0540
10	Receiver No. 2	Communications	0541
11	TWTA No. 1	Communications	0536
12	TWTA No. 2	Communications	0537
13	Digital Telemetry Unit (DTU)	Data Handling	0603
14	Control Electronics Assembly (CEA)	Attitude Control	0230
15	Conscan Signal Processor	Communications	0533
16	Digital Decoder Unit	Data Handling	0617
17	Inverter Assembly No. 1	Electrical Power	0405
18	Attenuator TWT No. 1	Communications	0536A
19	Attenuator TWT No. 2	Communications	0537A
20	Transmitter Driver No. 1	Communications	0534
21	Transmitter Driver No. 2	Communications	0535
22	Transfer Switch — Receive	Antenna	0590
23	Diplexer No. 2/Coupler	Antenna	0543
24	Diplexer No. 1	Antenna	0542
25	Transfer Switch — Transmit	Antenna	0589
26	Thermistor No. 1	Thermal	0782
27	Thermistor No. 2	Thermal	0783
28	Thermistor No. 3	Thermal	0784
29	Thermistor No. 4	Thermal	0785
30	Thermistor No. 5	Thermal	0786
31	Thermistor No. 6	Thermal	0787
32	Despin Sensor No. 1	Attitude Control	0288
33	Despin Sensor No. 2	Attitude Control	0291
34	Shunt Radiator Assembly	Electrical Power	0408
35	Magnetometer Electronics (JPL/Smith)	Instruments	0850
36	Imaging Photo — Polarimeter (U/Arizona/Gehrels)	Instruments	0857
37	Geiger Tube Telescope (U/Iowa/Van Allen)	Instruments	0853
38	Ultraviolet Photometer (USC/Judge)	Instruments	0856
39	Trapped Radiation Detector (UCSD/Fillius)	Instruments	0855
40	Infrared Radiometer (CIT/Munch)	Instruments	0858
41	Charged Particle Instrument (U/Chicago/Simpson)	Instruments	0852
42	Meteoroid Detector Electronics (LaRC/Kinard)	Instruments	0860
43	Propellant Tank	Propulsion	0929
44	Temperature Transducer	Propulsion	0929
45	Filter - Propellant	Propulsion	0929
46	Pressure Transducer	Propulsion	0929

*The reference designator is used to correlate the unit with telemetry and command "word" assignments.

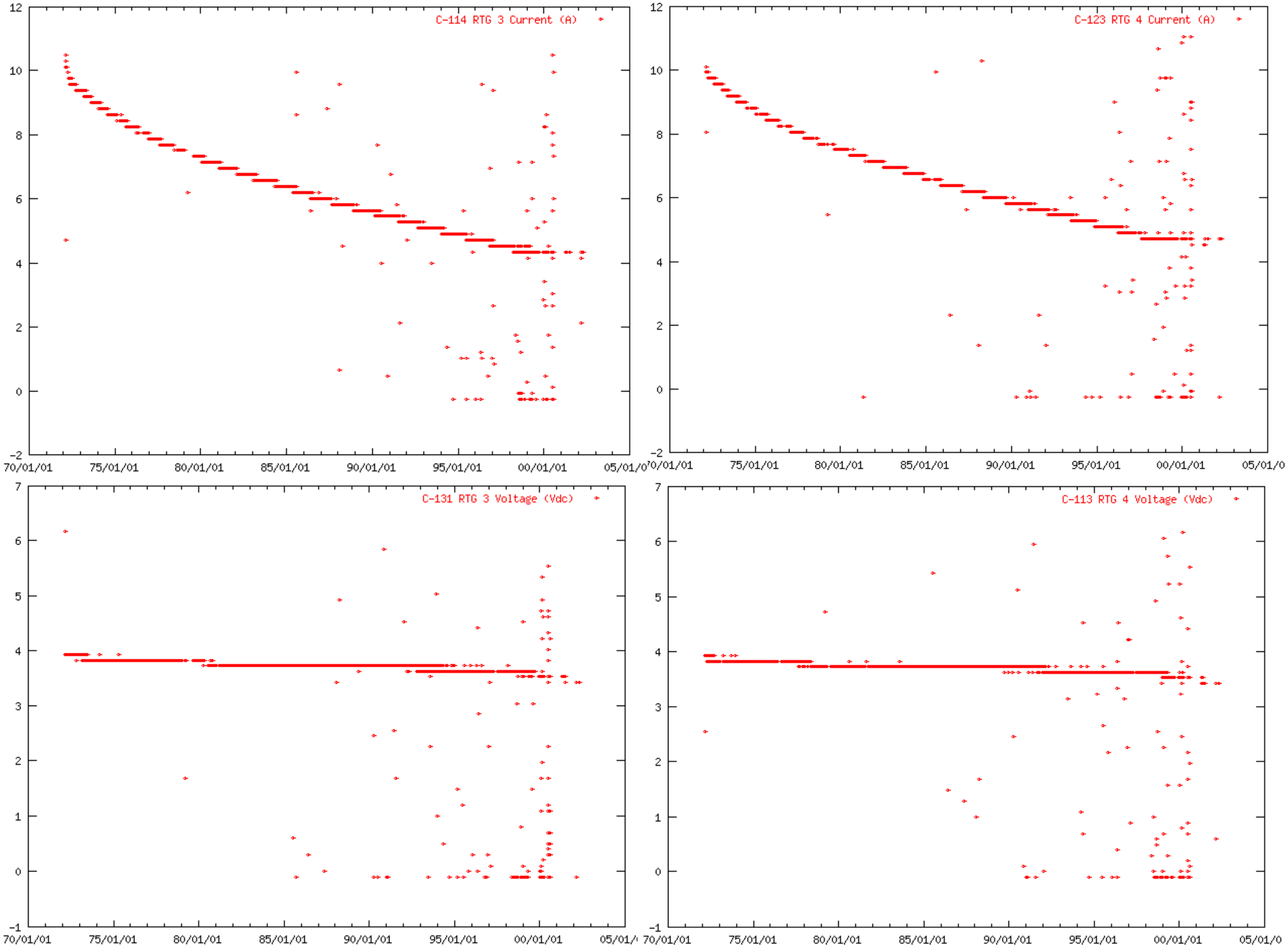
Master Data Records Web-Retrieval Form



Master Data Record will be critical in studying the effect of on-board systematics

THE STUDY OF THE PIONEER ANOMALY

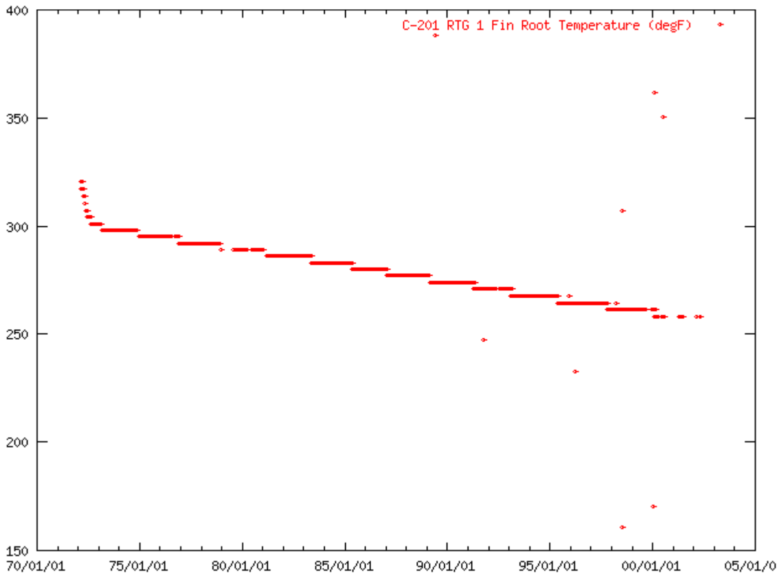
RTGs 3 & 4: Current & Voltage from MDRs

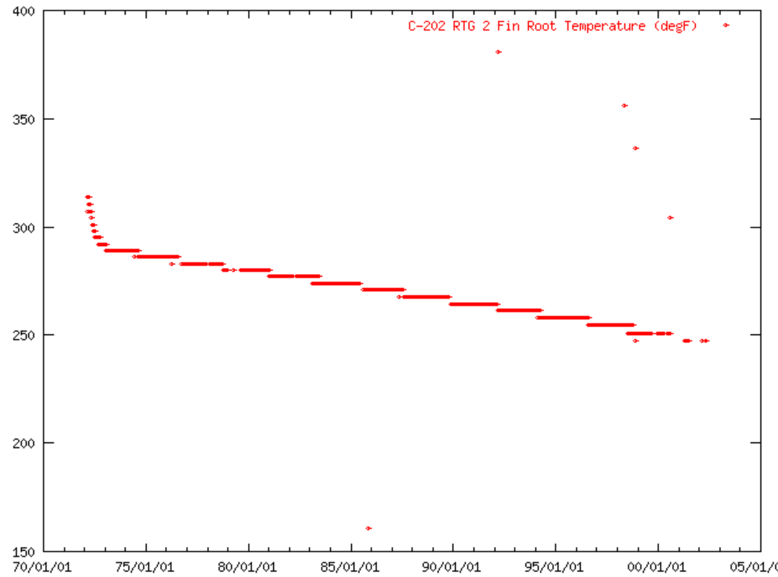


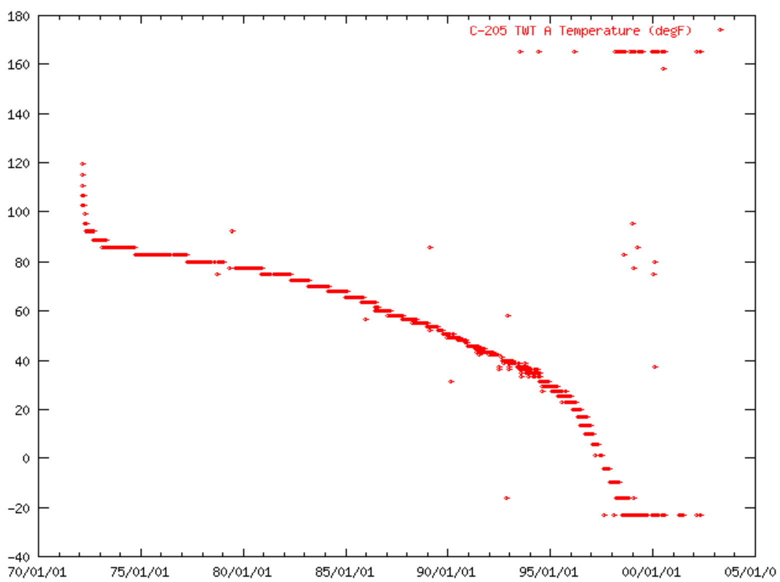
A thermal model may now be aided by the actual flight data

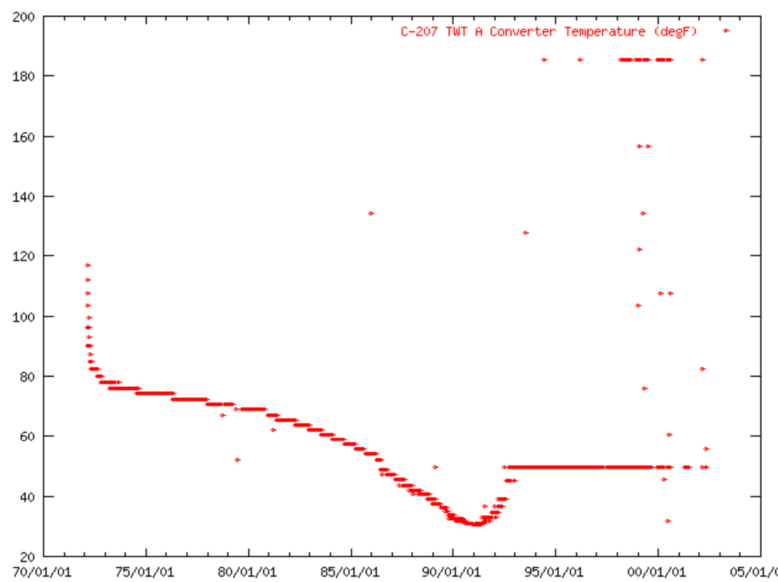
THE STUDY OF THE PIONEER ANOMALY

Thermal History on Pioneer 10









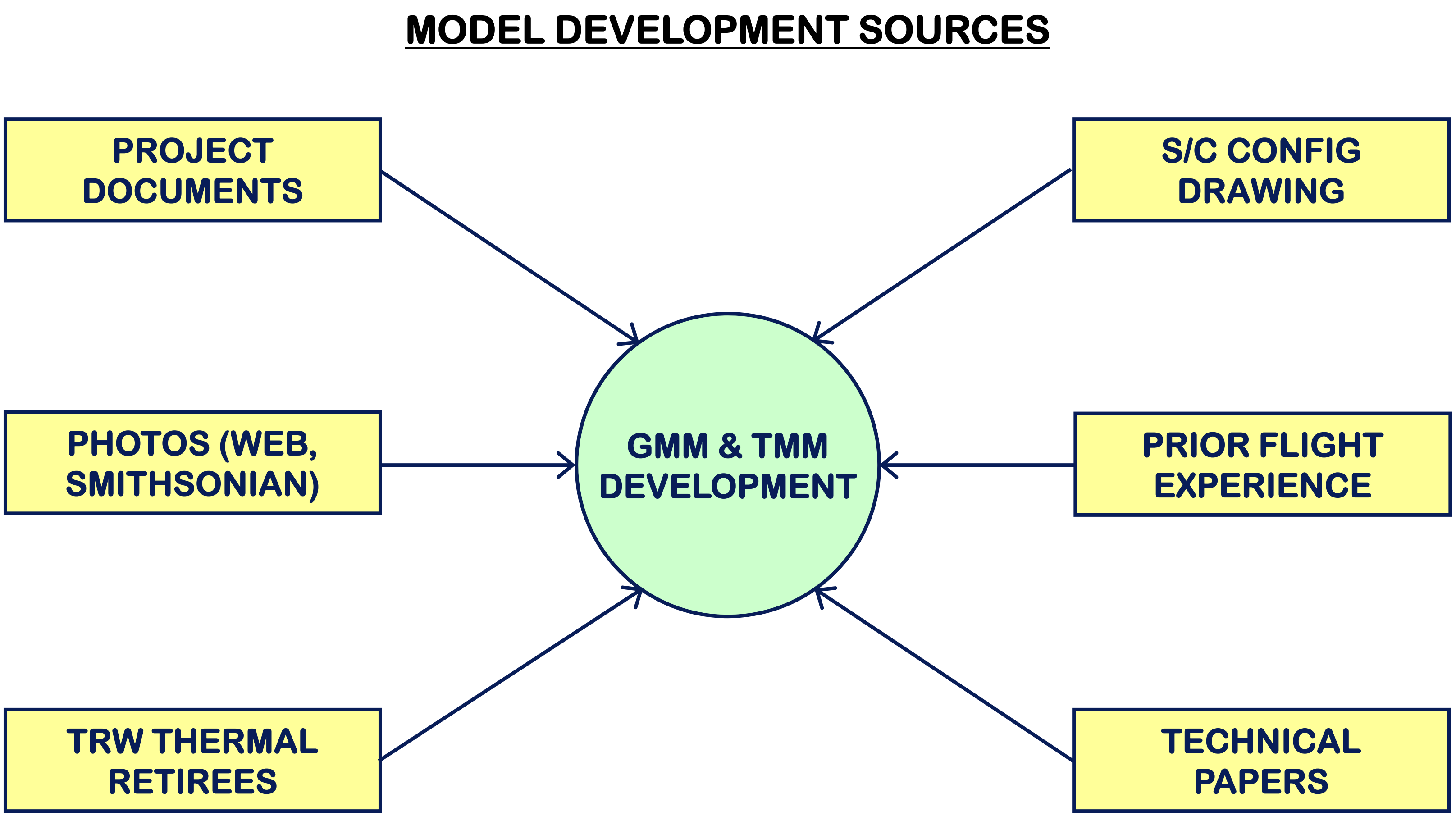
Objectives of Thermal Engineering Study

Evaluate if anisotropic S/C thermal radiosity can explain the anomaly

- Radiosity includes emissive power plus reflected thermal irradiation
- Develop geometric math model (GMM) to:
  - Calculate radiative exchange among all modeled S/C surfaces
  - Calculate absorbed solar loads on S/C (although tiny at 25 AU)
- Develop thermal math model (TMM) to:
  - Calculate predicted temperatures for all modeled S/C surfaces
  - Calculate predicted heat flows for all modeled S/C surfaces
- Develop modeling method to calculate directional components of radiative heat flow
  - Focus on radiative loading parallel to S/C spin axis
- Primary objective:
  - To achieve ample model fidelity needed to either confirm or eliminate thermal emission as an explanation for the Pioneer anomaly

Thermal Modeling Approach for the Pioneers

- Pioneer anomaly work is interesting … and like a treasure hunt
  - Modeling a 35+ year old spacecraft is challenging due to limited info



Pioneer 10 S/C Configuration

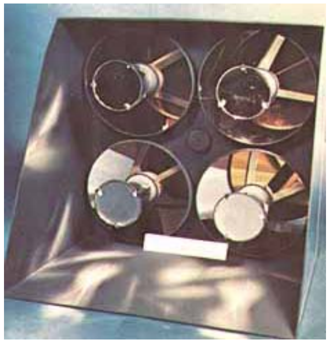
Flight S/C (Courtesy of Jim Moses, TRW Retiree)

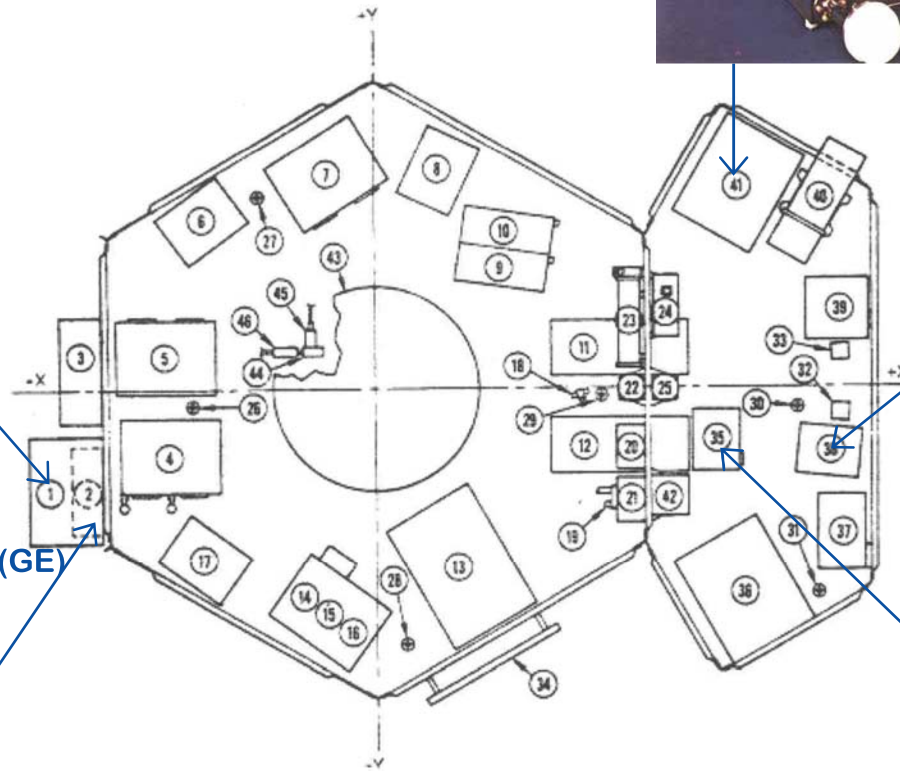
Pioneer in the Smithsonian Air & Space Museum

Science Instrument Locations

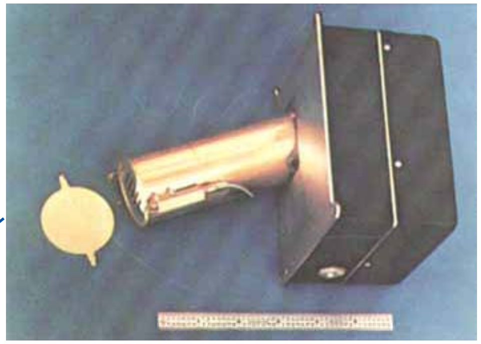
CHARGED PARTICLE DETECTOR (UC)

AMD TELESCOPE (GE)





UV PHOTOMETER (USC)

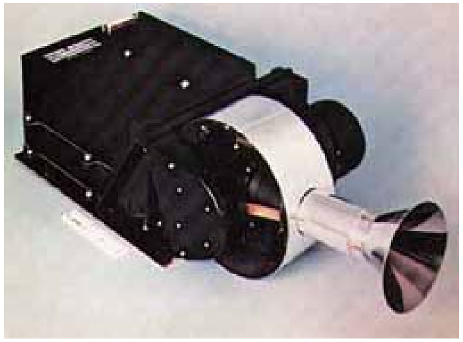


MAGNETOMETER ELECTRONICS (JPL)

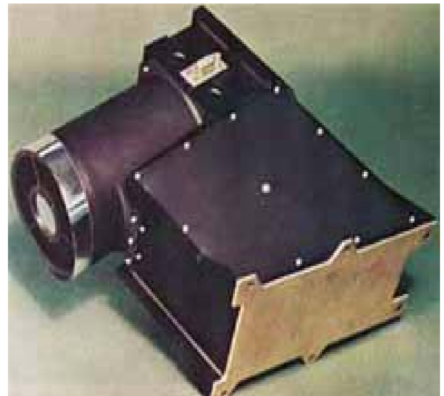
AMD ELECTRONICS (GE)

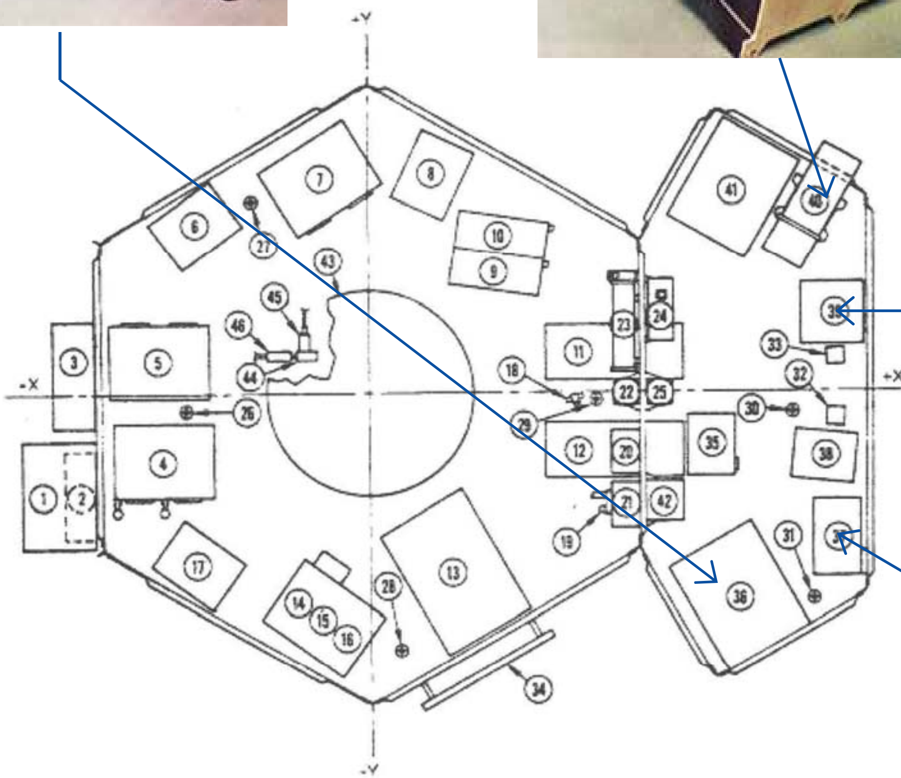
Science Instrument Locations

IMAGING PHOTOPOLARIMETER (UA)

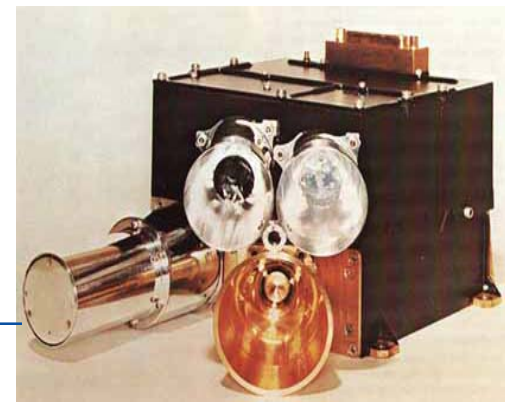


IR RADIOMETER (CIT)





TRAPPED RADIATION DETECTOR (UCSD)



GEIGER TUBE TELESCOPE (UI)

Pioneer Spacecraft Configuration

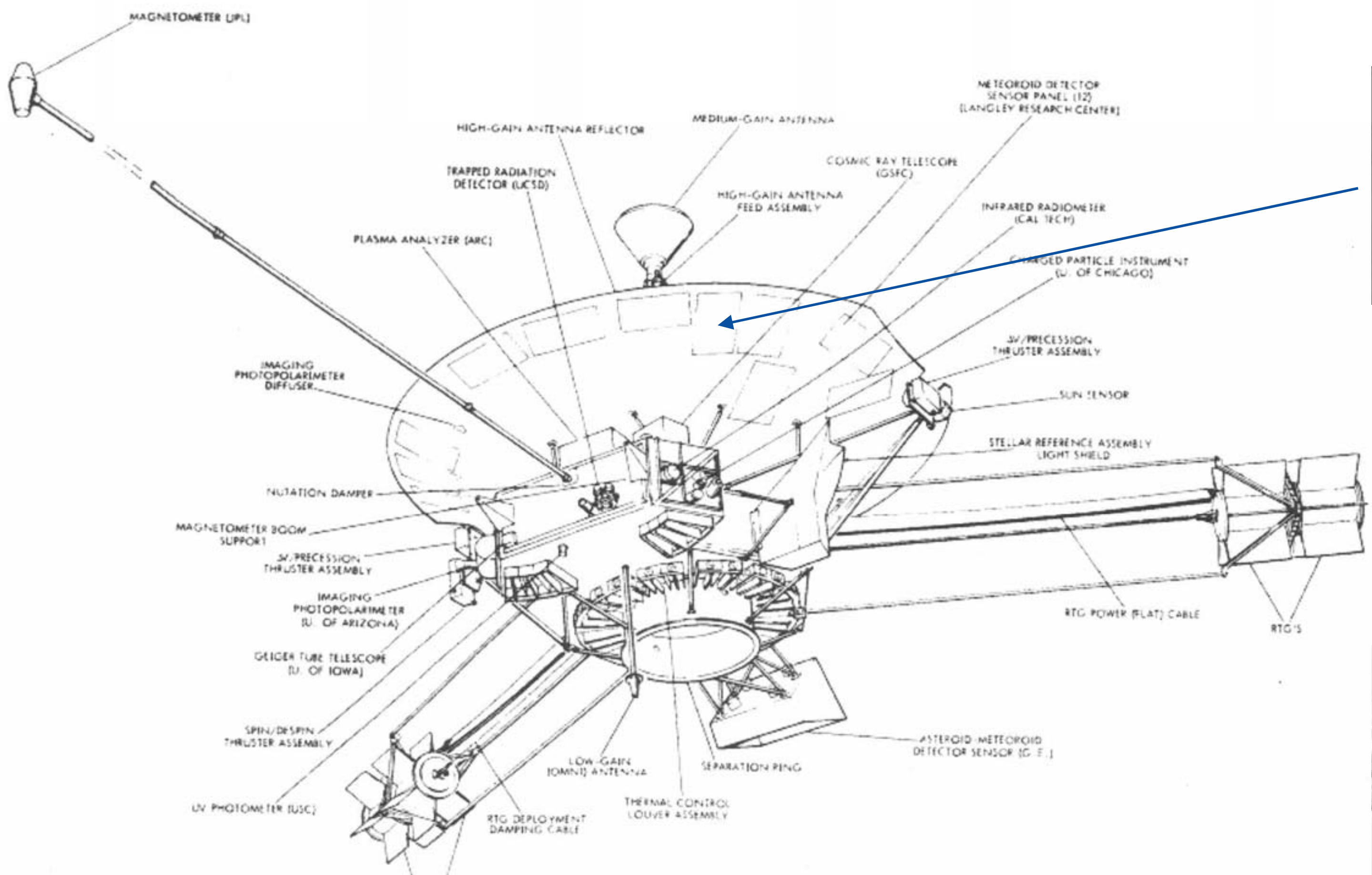
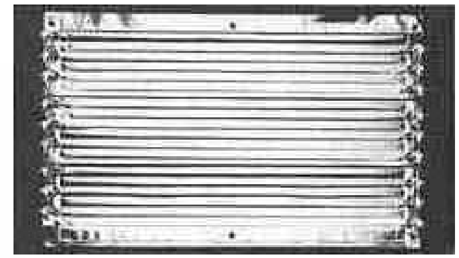
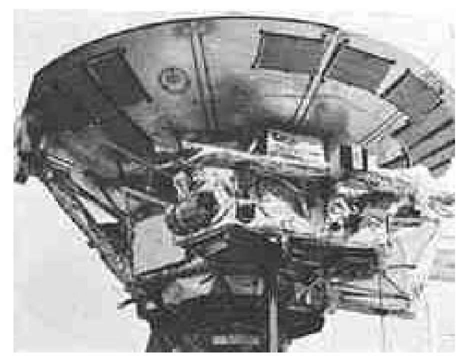


FIGURE 2-2. PIONEER F/G SPACECRAFT

METEOROID DETECTOR
(LeRC)

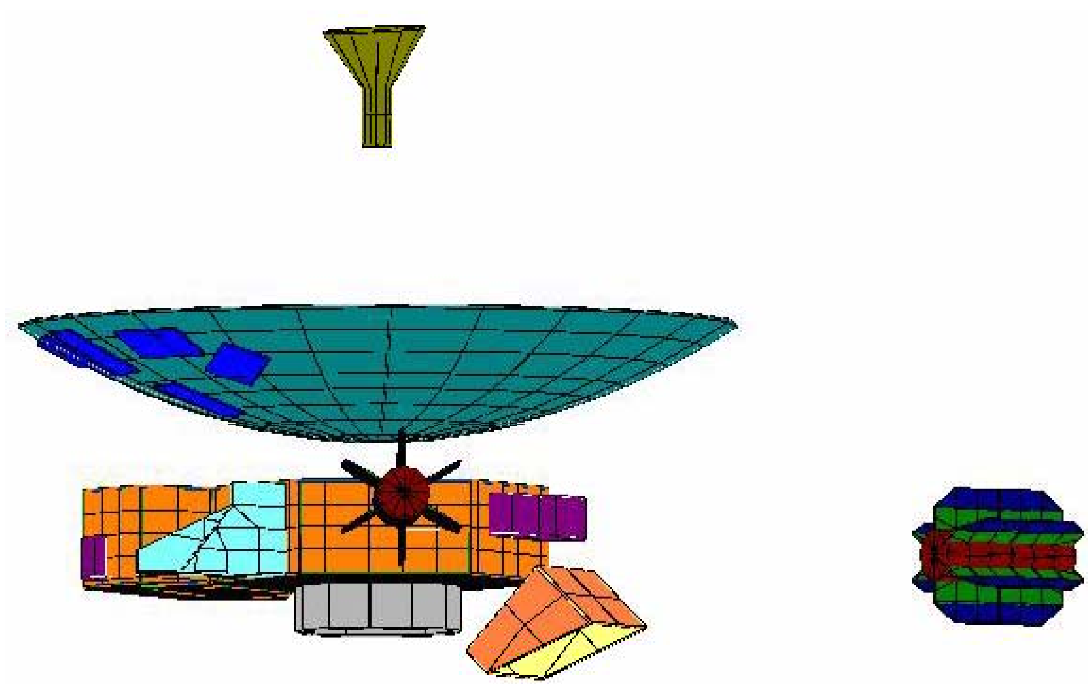




Geometric Mathematical Model (GMM)

- Used TSS (Thermal Synthesizer System) – one of the standard thermal industry tools
  - Calculates radiative exchange factors and environmental heat loads for all modeled surfaces.
  - Used on many JPL flight projects since the mid 1990s.
- Model S/C geometry, thermo-optical properties, sun position in TSS
  - S/C geometry simulated by utilizing geometric primitives (rectangle, cylinder, disk).
- S/W uses Monte-Carlo ray tracing
  - 2M rays per surface for calculation of radiation interchange factors.
  - 4M rays per surface for solar loading calculation.
- Pioneer 10/11 GMM runs two days to calculate radiation network and solar loads

Pioneer Vehicle Geometric Math Model

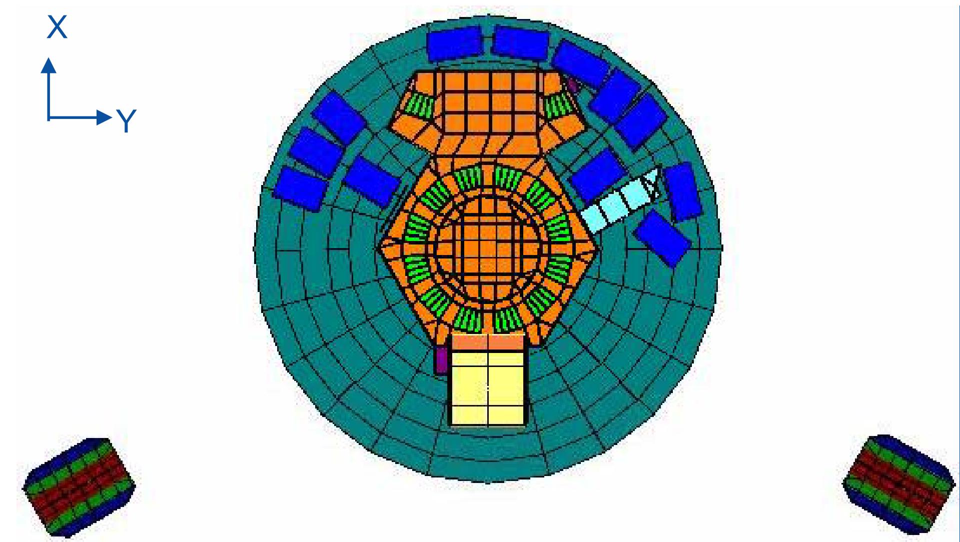


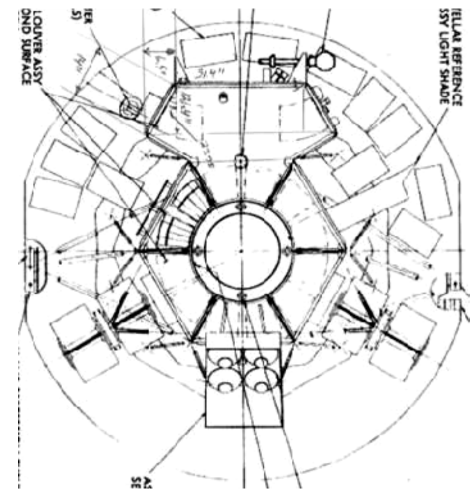
Pioneer 10 GMM

Test Article in Thermal Model Test
(Mix of Flight and Non-flight H/W)

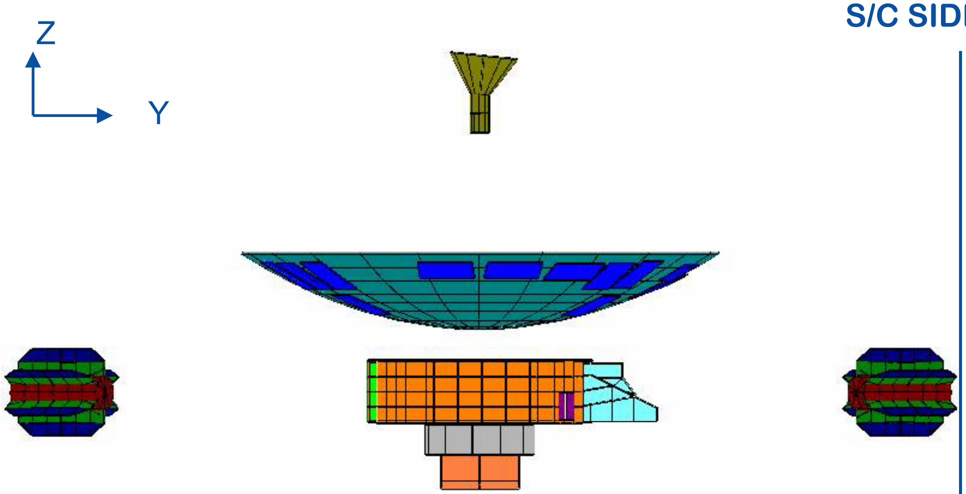
Pioneer Vehicle Geometric Math Model

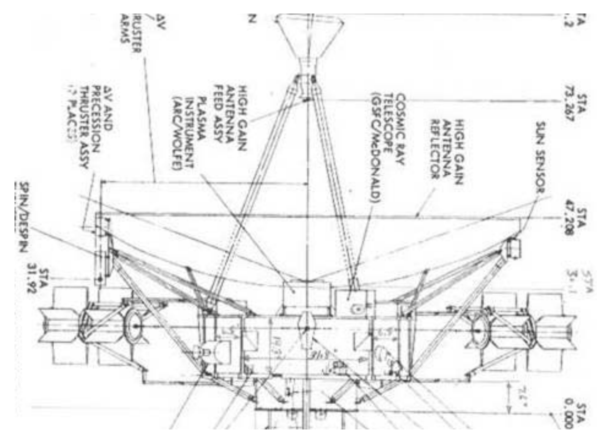
S/C BOTTOM VIEW





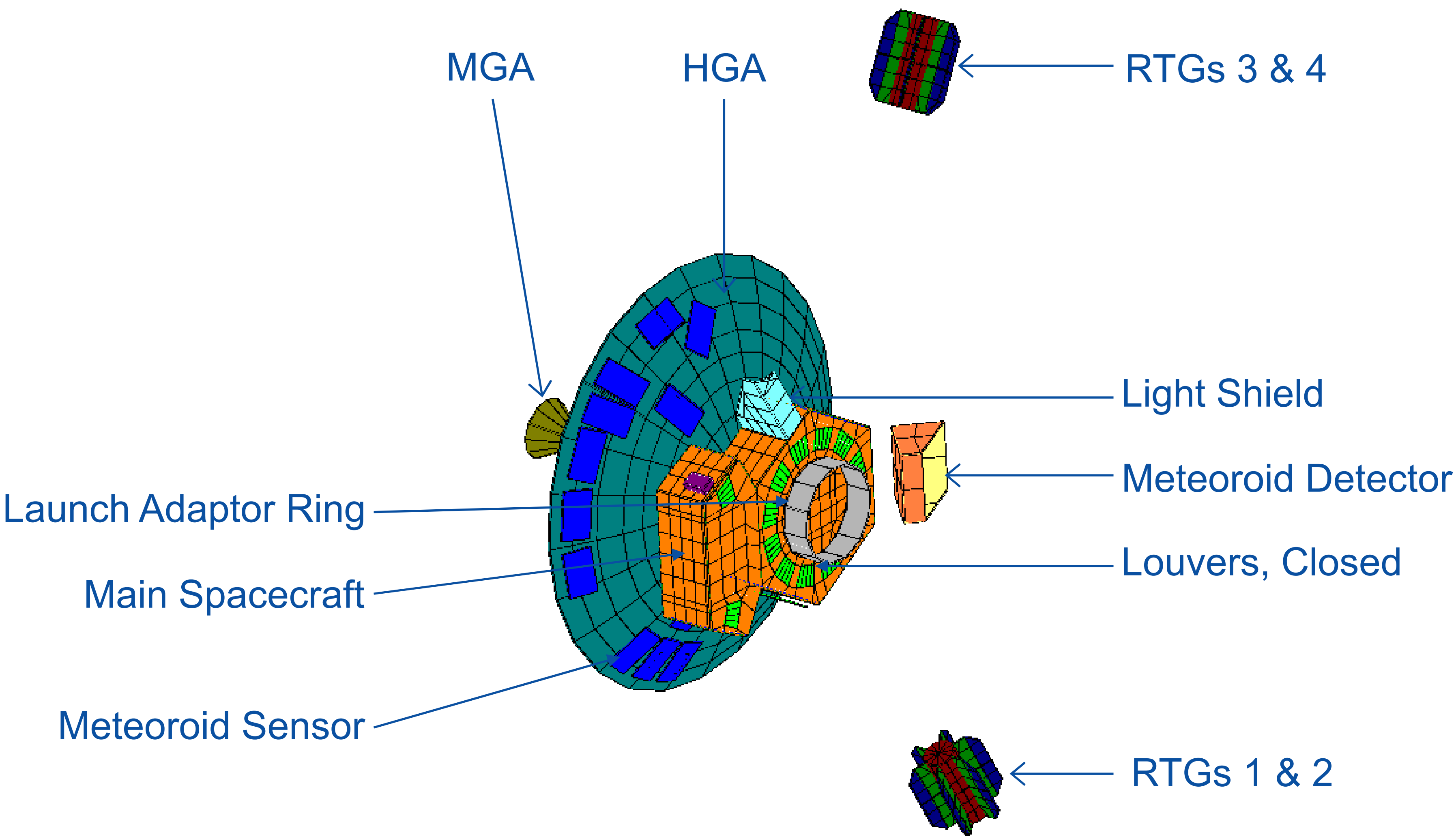
S/C SIDE VIEW



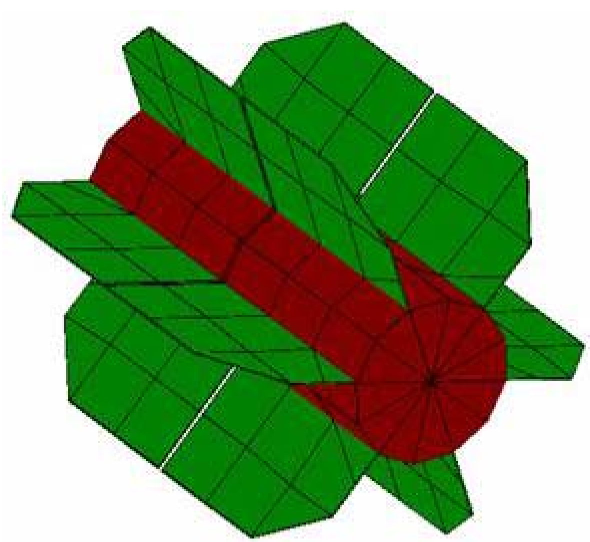


Note: RTGs are Deployed in GMM, but Shown Stowed in S/C Configuration Drawing

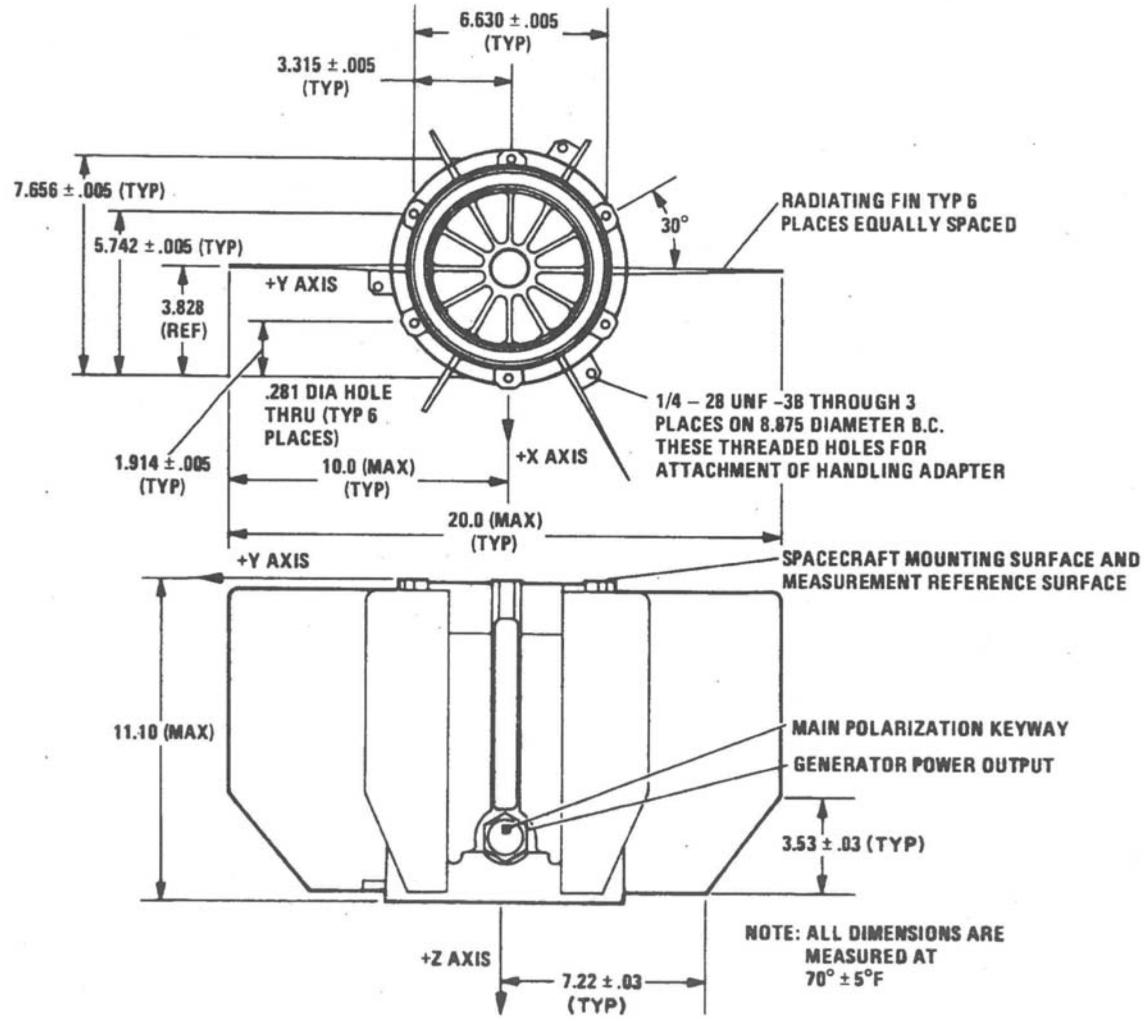
Thermal Geometric Model (Closed Louvers)



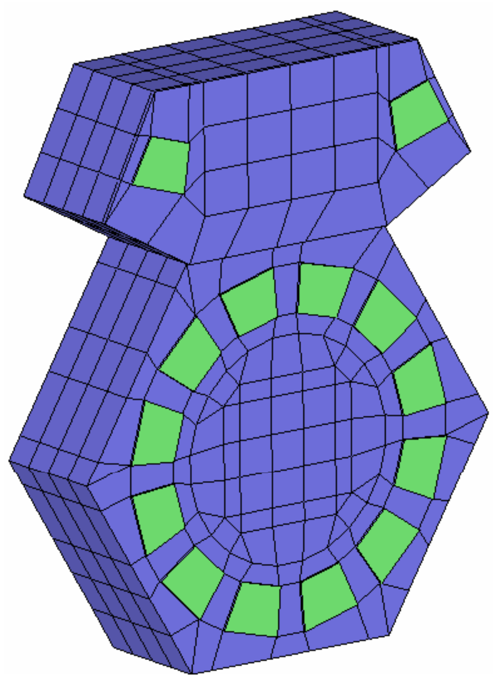
SNAP-19 RTG Modeling



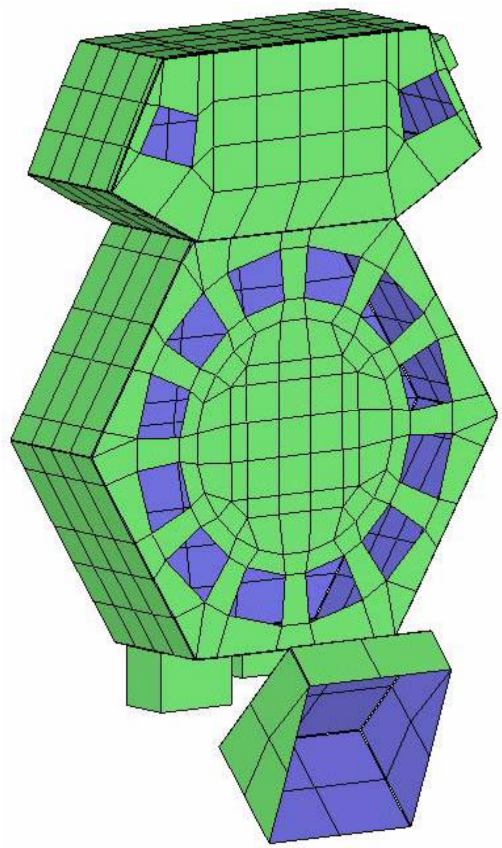
Pioneer 10/11 GMM



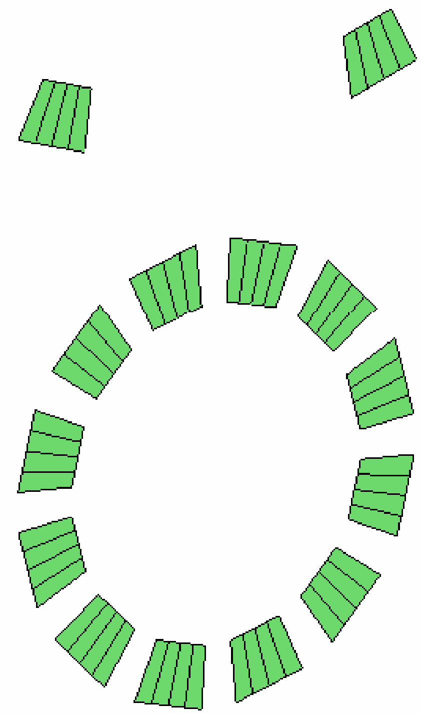
GMM S/C Surfaces, MLI and Closed Louvers



Active Spacecraft Surfaces



Spacecraft MLI



Closed Louvers

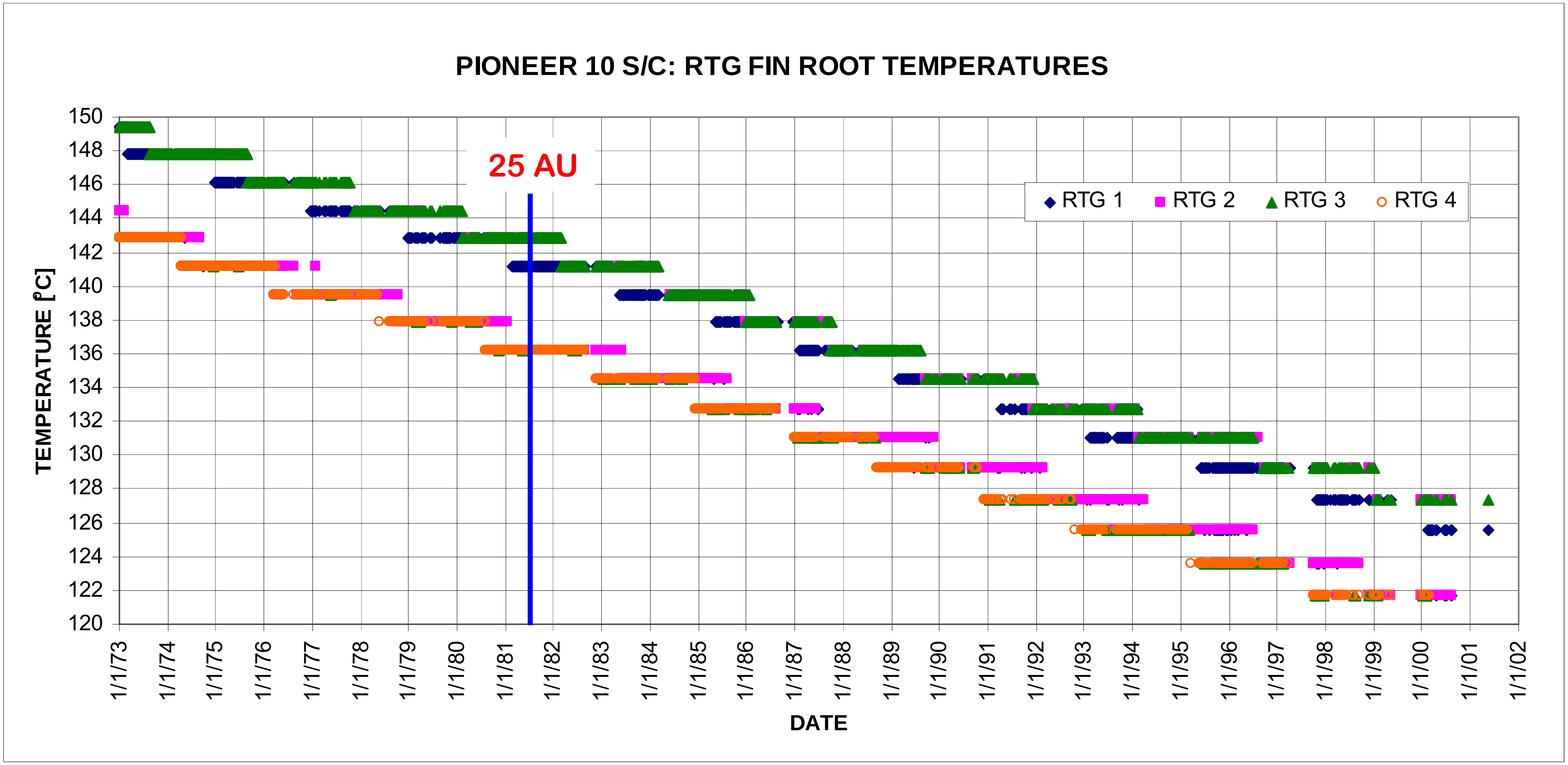
Green refers to active radiating surfaces; blue refers to inactive radiating surfaces

Thermal Mathematical Model (TMM)

- Used SINDA/3D (S3D): One of the standard thermal industry tools
  - S3D is a FEM thermal analyzer consists of a GUI & the SINDA-G solver
  - Used on many JPL flight projects the past ten years
- Pioneer spacecraft thermal mathematical model (TMM)
  - Models material property values and thicknesses, power, thermal boundary conditions.
  - ~3000 nodes and 2600 plate elements.
  - 3.4 million radiation conductors, ~7000 linear conductors
- TMM checkout process includes multiple distances and solar load cases, and RTG temperatures
- TMM boundary conditions include space + S/C surfaces using flight telemetry
  - Used telemetry for **4 RTG fin roots**, **6 panels** (equipment/science compartments), & **various science instruments**.

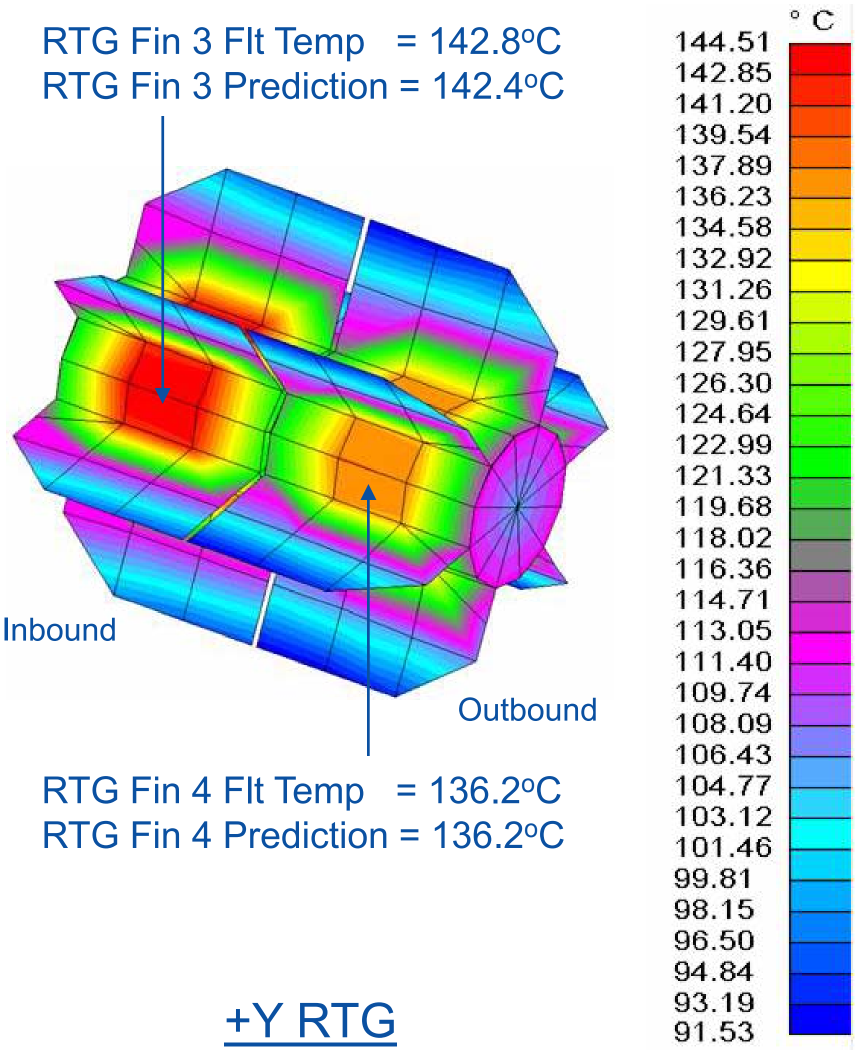
THE STUDY OF THE PIONEER ANOMALY

Pioneer 10 S/C Temperature Telemetry

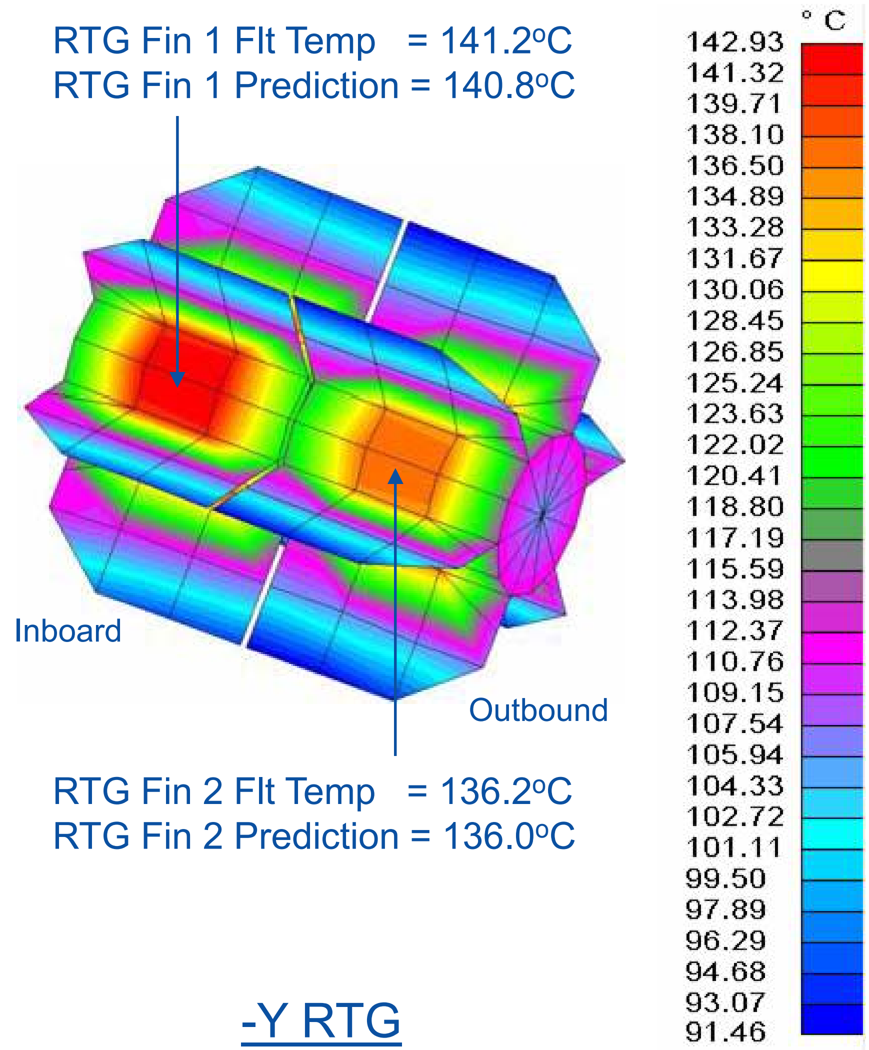


RTG fin root temperature telemetry is used as boundary condition nodes in the TMM (RTGs 1 & 3 are inboard, RTGs 2 & 4 are outboard RTGs

Measured Versus Predicted RTG Temps



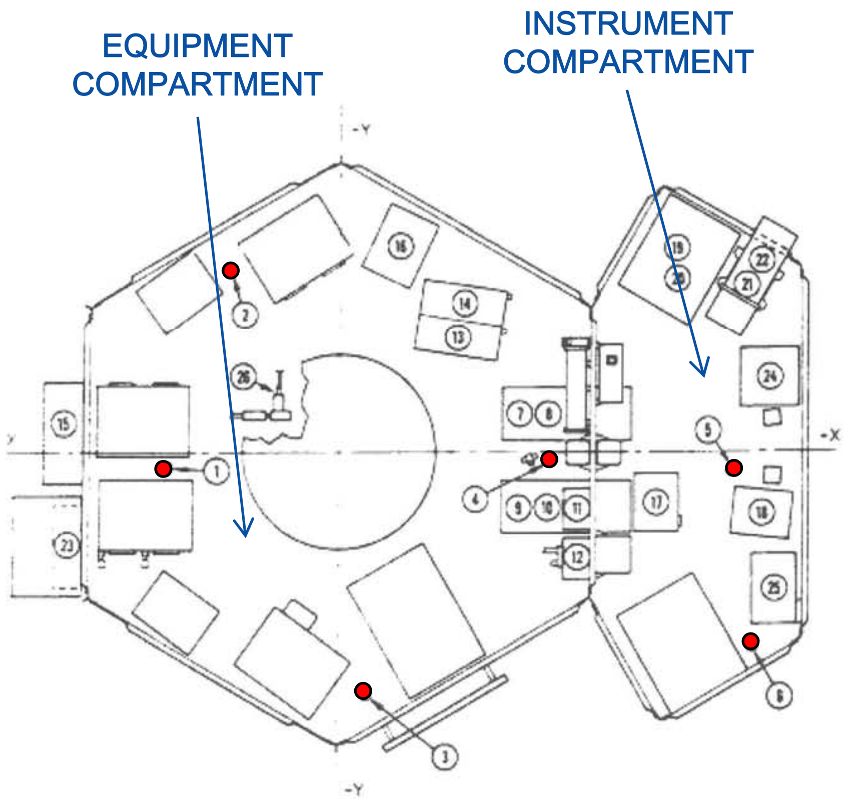
+Y RTG



-Y RTG

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

Panel Temperature Telemetry Locations

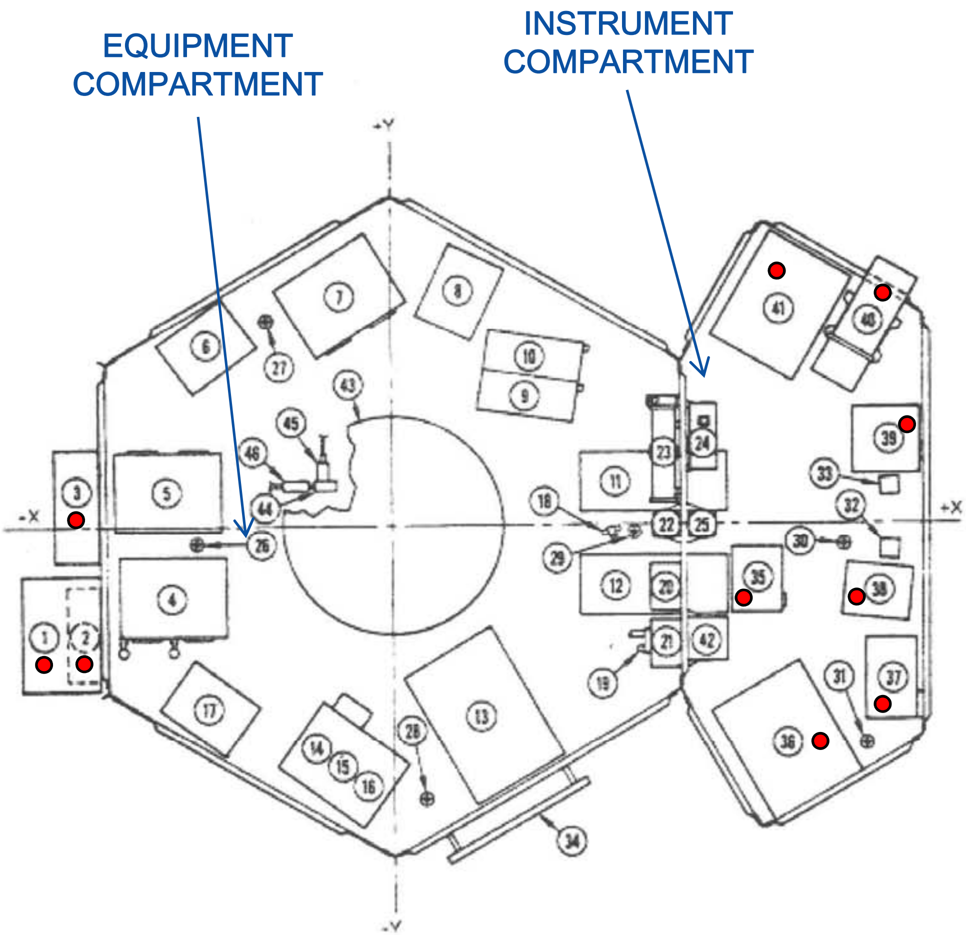


S/C Bottom View, -Z Side

TEMPERATURE SENSOR LOCATIONS

IDENTIFICATION NO.	TLM "Word"	DESCRIPTION	LOCATION
		Thermal	
1	C-301	Equipment Platform	On platform
2	C-302	Equipment Platform	On platform
3	C-304	Equipment Platform	On platform
4	C-318	Equipment Platform	On platform
5	C-319	Equipment Platform	On platform
6	C-320	Equipment Platform	On platform
		Communications	
7	C-205	TWTA-A	Collector, TWTA-A
8	C-207	Converter, TWTA-A	Power Supply, TWTA-A
9	C-228	TWTA-B	Collector, TWTA-B
10	C-221	Converter, TWTA-B	Power Supply, TWTA-B
11	C-206	Driver-A, Auxiliary Oscillator	TCXO Subassembly
12	C-223	Driver-B, Auxiliary Oscillator	TCXO Subassembly
13	C-222	Receiver-A	VCO Subassembly
14	C-227	Receiver-B	VCO Subassembly
		Power	
15	C-115	Battery	On housing near connector
		Attitude Control	
16	C-303	Stellar Reference Assembly(SRA)	On amplifier board
	C-317	Sun Sensor Assembly(SSA)	Between circuit boards in SSA
		Instruments	
17	E-102	Magnetometer Electronics(JPL/Smith)	Internal to unit
18	E-109	Ultraviolet Photometer(USC/Judge)	Internal to unit
19	E-110	Charged Particle(U/Chicago/Simpson)	Internal to unit
20	E-213	Charged Particle(U/Chicago/Simpson)	Internal to unit
21	E-117	Infrared Radiometer, Low Range(CIT/Munch)	Internal to unit
22	E-201	Infrared Radiometer, High Range(CIT/Munch)	Internal to unit
23	E-118	Asteroid/Meteoroid Detector Electronics, Preamplifier(GE/Soberman)	Internal to unit
24	E-209	Trapped Radiation Detector(UCSD/Fillius)	Internal to unit
25	E-221	Geiger Tube Telescope(U/Iowa/Van Allen)	Internal to unit
	E-125	Cosmic Ray Electronics(GSFC/McDonald)	Internal to unit } Mounted on top of instruments compartment (see Figure 3.1-2)
	E-128	Cosmic Ray Detector(GSFC/McDonald)	Internal to unit
	E-101	Arc Plasma Detector(Arc/Wolfe)	Internal to unit
		Propulsion	
26	C-327	Propellant Supply	Propellant liquid at filter
	C-309	VPT Propellant Inlet Manifold	VPT Assembly No. 1, -Y axis
	C-326	VPT Propellant Inlet Manifold	VPT Assembly No. 2, +Y axis
	C-310	SCT Propellant Inlet Manifold	SCT Assembly, -Y axis
	C-311	VPT No. 1, TCA No. 2	Catalyst bed, +Y axis (Top)
	C-312	VPT No. 2, TCA No. 2	Catalyst bed, +Y axis (Bottom)
	C-328	VPT No. 3, TCA No. 1	Catalyst bed, -Y axis (Top)
	C-325	VPT No. 4, TCA No. 1	Catalyst bed, -Y axis (Bottom)
		RTG's	
	C-201	RTG No. 1 Fin Root	Cylindrical Case, Inboard RTG, -Y axis
	C-202	RTG No. 2 Fin Root	Cylindrical Case, Outboard RTG, -Y axis
	C-203	RTG No. 3 Fin Root	Cylindrical Case, Inboard RTG, +Y axis
	C-204	RTG No. 4 Fin Root	Cylindrical Case, Outboard RTG, +Y axis
	C-217	RTG No. 4 Hot Junction	Hot junction thermocouple, Outboard RTG, +Y axis
	C-218	RTG No. 3 Hot Junction	Hot junction thermocouple, Inboard RTG, -Y axis
	C-219	RTG No. 2 Hot Junction	Hot junction thermocouple, Outboard RTG, -Y axis
	C-220	RTG No. 1 Hot Junction	Hot junction thermocouple, Inboard RTG, -Y axis

Science Instrument Temperature Telemetry Sites



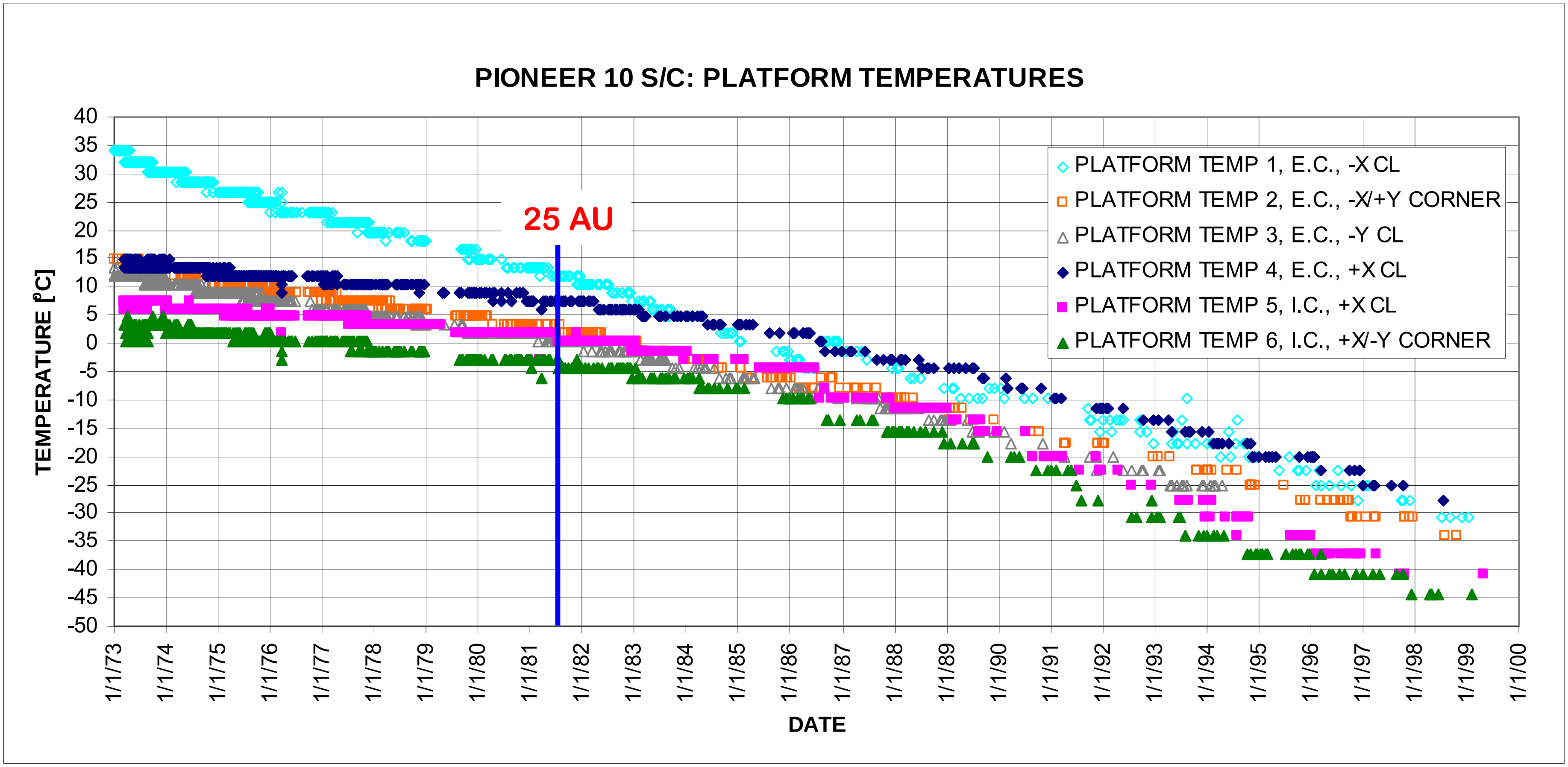
S/C Bottom View, -Z Side

EQUIPMENT IDENTIFICATION

ITEM NO.	TITLE	REFERENCE SUBSYSTEM	REFERENCE DESIGNATOR*
1	Data Storage Unit (DSU)	Data Handling	0604
2	Asteroid/Meteoroid Detector Electronics (GE/Soberman)	Instruments	0859
3	Battery	Electrical Power	0407
4	Power Control Unit (PCU)	Electrical Power	0402
5	Central TRF Unit	Electrical Power	0414
6	Inverter Assembly No. 2	Electrical Power	0406
7	Command Distribution Unit (CDU)	Electrical Distributor	0301
8	Stellar Reference Assembly (SRA)	Attitude Control	0231
9	Receiver No. 1	Communications	0540
10	Receiver No. 2	Communications	0541
11	TWTA No. 1	Communications	0536
12	TWTA No. 2	Communications	0537
13	Digital Telemetry Unit (DTU)	Data Handling	0603
14	Control Electronics Assembly (CEA)	Attitude Control	0230
15	Conscan Signal Processor	Communications	0533
16	Digital Decoder Unit	Data Handling	0617
17	Inverter Assembly No. 1	Electrical Power	0405
18	Attenuator TWT No. 1	Communications	0536A
19	Attenuator TWT No. 2	Communications	0537A
20	Transmitter Driver No. 1	Communications	0534
21	Transmitter Driver No. 2	Communications	0535
22	Transfer Switch — Receive	Antenna	0590
23	Diplexer No. 2/Coupler	Antenna	0543
24	Diplexer No. 1	Antenna	0542
25	Transfer Switch — Transmit	Antenna	0589
26	Thermistor No. 1	Thermal	0782
27	Thermistor No. 2	Thermal	0783
28	Thermistor No. 3	Thermal	0784
29	Thermistor No. 4	Thermal	0785
30	Thermistor No. 5	Thermal	0786
31	Thermistor No. 6	Thermal	0787
32	Despin Sensor No. 1	Attitude Control	0288
33	Despin Sensor No. 2	Attitude Control	0291
34	Shunt Radiator Assembly	Electrical Power	0408
35	Magnetometer Electronics (JPL/Smith)	Instruments	0850
36	Imaging Photo — Polarimeter (U/Arizona/Gehrels)	Instruments	0857
37	Geiger Tube Telescope (U/Iowa/Van Allen)	Instruments	0853
38	Ultraviolet Photometer (USC/Judge)	Instruments	0856
39	Trapped Radiation Detector (UCSD/Fillius)	Instruments	0855
40	Infrared Radiometer (CIT/Munch)	Instruments	0858
41	Charged Particle Instrument (U/Chicago/Simpson)	Instruments	0852
42	Meteoroid Detector Electronics (LaRC/Kinard)	Instruments	0860
43	Propellant Tank	Propulsion	0929
44	Temperature Transducer	Propulsion	0929
45	Filter - Propellant	Propulsion	0929
46	Pressure Transducer	Propulsion	0929

*The reference designator is used to correlate the unit with telemetry and command "word" assignments.

Pioneer 10 Temperature Telemetry



TMM predicted panel temperatures compared to this thermal telemetry at 25 AU
E.C. is Equipment Compartment, I.C. is Instrument Compartment

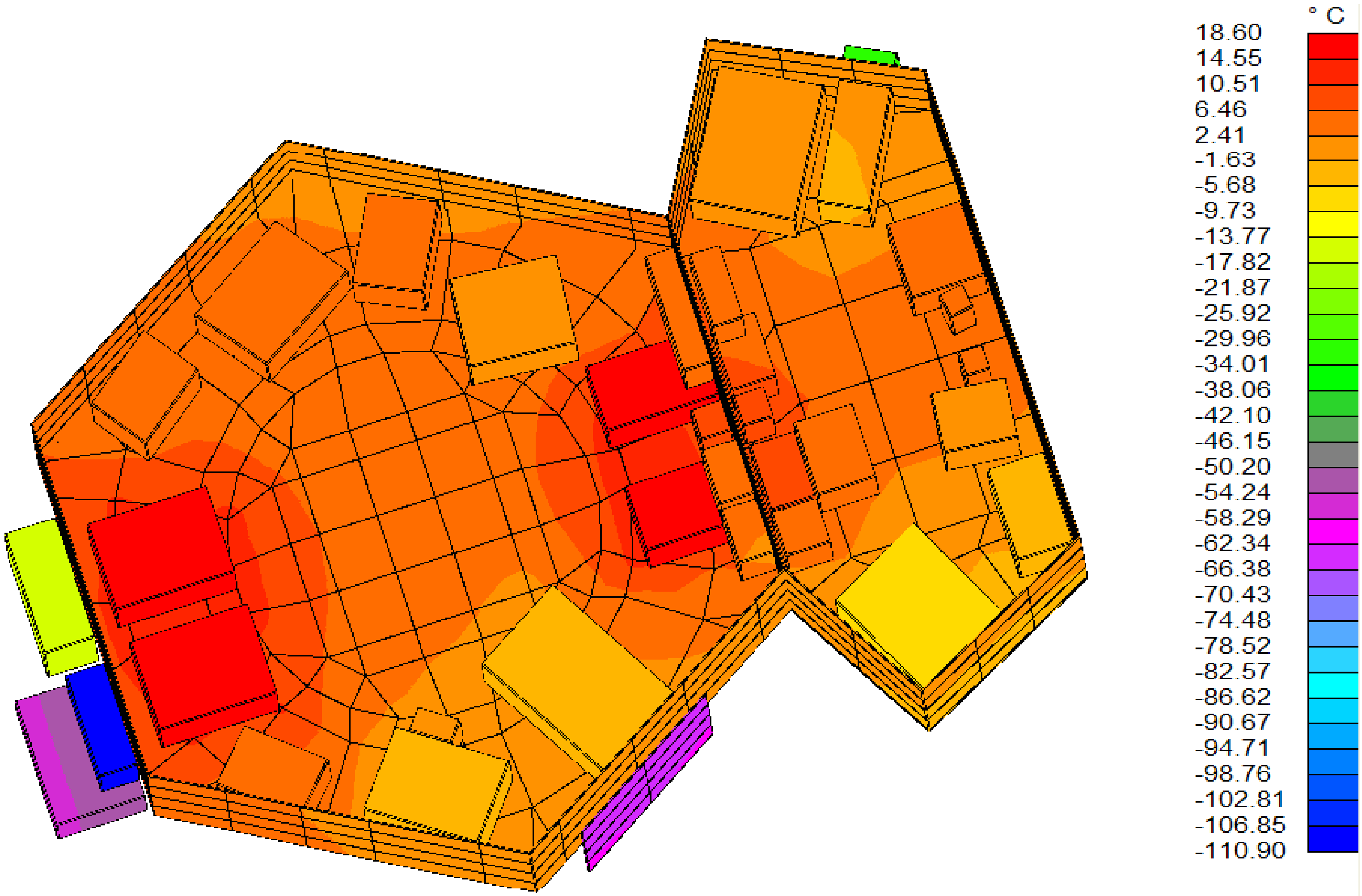
Modeled Surface Properties

Component	Surface Coating	Material	Thickness [Inch]	K [W/m-K]	Density [kg/m^3]	Cp [J/kg-K]	e*	EOL a	EOL e
Electronics Boxes	black paint	Al 6061	0.1	169	2770	961.2	--		0.86
e* of MLI on Electronics Box	--	--	--	--	--	--	0.03		
MLI on Electronics Box	--	--	--	--	--	--	--	0.17	0.70
Exterior Electronic Box (Battery and DSU)	silver backed Teflon	Al 6061	0.1	169	2770	961.2	--	0.17	0.65
Equipment Compartment, Interior	black paint	Al 6061	0.1	169	2770	961.2	--		0.86
Science Compartment, Interior	black paint	Al 6061	0.1	169	2770	961.2	--		0.86
S/C panel (h=0.0183 W/in^2-K)	--	Al honeycomb	0.25	--	--	--	--		
S/C surface below louvers	second surface mirrors (5 MIL AgFEP?)	Al 6061	0.1	169	2770	961.2	--	0.09	0.81
Outer SC Body (panel that divides the two hexagonal S/C Bodies)	black paint	Al 6061	0.1	169	2770	961.2	--		0.86
e* of MLI on SC	--	--	--	--	--	--	0.02		
MLI (+Y -X , -Y -X Side Panel, & Side Facing Aft) on S/C	2 mil alum Kapton	--	--	--	--	--	--	0.46	0.69
MLI (+X,-X, +Y +X , -Y +X & +Z Side Panels) on S/C	2 mil alum Mylar	--	--	--	--	--	--	0.20	0.69
Louvers (facing both sides)	bare	Al 6061	0.1	169	2770	961.2	--	0.17	0.04
Shunt Radiator	white paint	Al 6061	0.1	169	2770	961.2	--	0.24	0.84
e* of MLI behind Shunt Radiator	--	--	--	--	--	--	0.03		
Light Shield (Exterior)	bare	Al 6061	0.1	169	2770	961.2	--	0.17	0.04
Light Shield (Interior)	black paint	Al 6061	0.1	169	2770	961.2	--	0.95	0.84

Modeled Surface Properties (Cont'd)

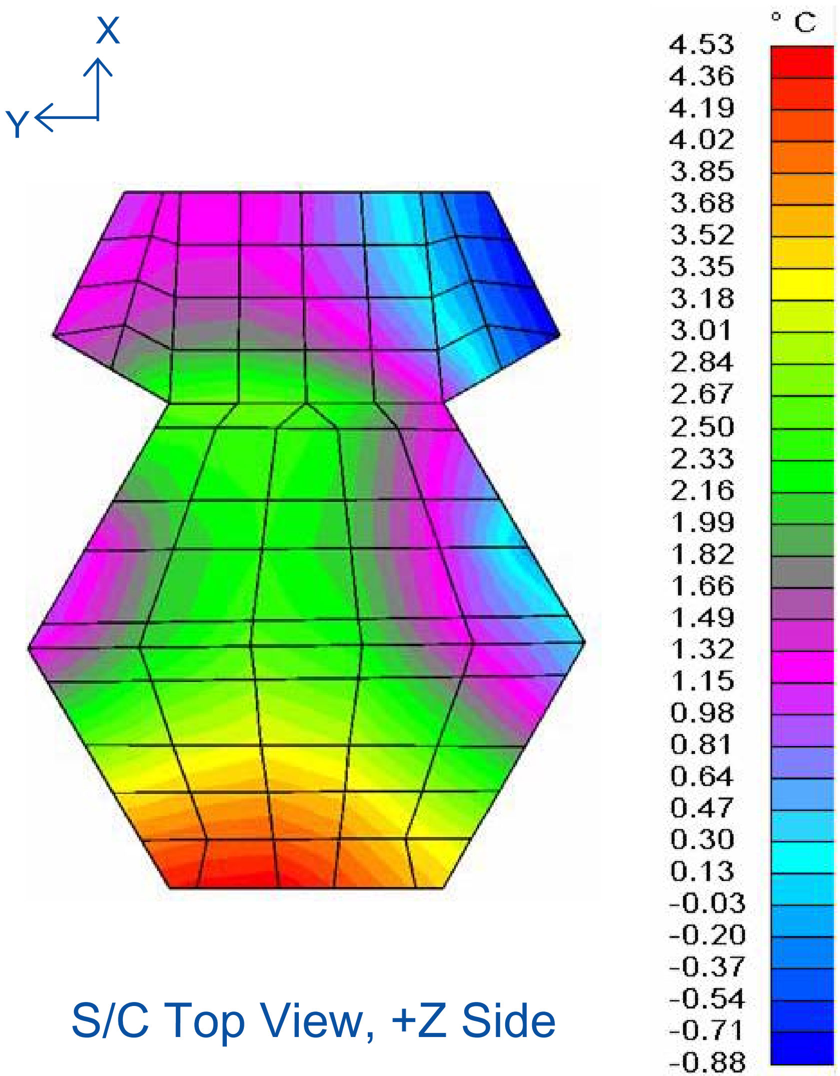
Component	Surface Coating	Material	Thickness [Inch]	K [W/m-K]	Density [kg/m^3]	Cp [J/kg-K]	e*	EOL a	EOL e
Launch Support Ring (Exterior)	bare	Al 6061	0.1	169.0	2770	961.2	--	0.24	0.10
Launch Support Ring (Interior)	black paint	Al 6061	0.1	169.0	2770	961.2	--	0.95	0.84
Meteoroid Detector (Inside Facing)	black paint	Al 6061	0.1	169.0	2770	961.2	--	0.95	0.84
e* of MLI on Meteoroid Detector	--	--	--	--	--	--	0.03		
MLI on Meteoroid Detector	2 mil Alum Mylar	--	--	--	--	--	--	0.17	0.70
Meteoroid Sensors (facing space)		Al 6061	0.1	169.0	2770	961.2	--	0.36	0.09
Meteoroid Sensors (facing HGA)	black paint	Al 6061	0.1	169.0	2770	961.2	--	0.98	0.90
HGA (facing Earth)	DC92-007 white paint, 1% specularity	Al 6061	0.1	169.0	2770	961.2	--	0.50	0.84
HGA Honeycomb (h=0.0183 W/in^2-K)	--	Al honeycomb	0.25"	--	--	--	--		
HGA (facing S/C)	bare	Al 6061	0.1	169.0	2770	961.2	--	0.17	0.04
MGA (Exterior)	white paint	Al 6061	0.1	169.0	2770	961.2	--	0.50	0.84
MGA (Interior)	black paint	Al 6061	0.1	169.0	2770	961.2	--	0.95	0.84
RTG Body	white paint	HM31A-F Mg Alloy	0.16	104.6	1800	1047.6	--	0.50	0.82
RTG Fin (from root fin to mid fin)	white paint	HM21A-T8 Mg Alloy	0.1	136.6	1800	1047.6	--	0.50	0.82
RTG Fin (from mid fin to fin tip)	white paint	HM21A-T8 Mg Alloy	0.1	136.6	1800	1047.6	--	0.50	0.82

Dual Compartments and Electronic Boxes

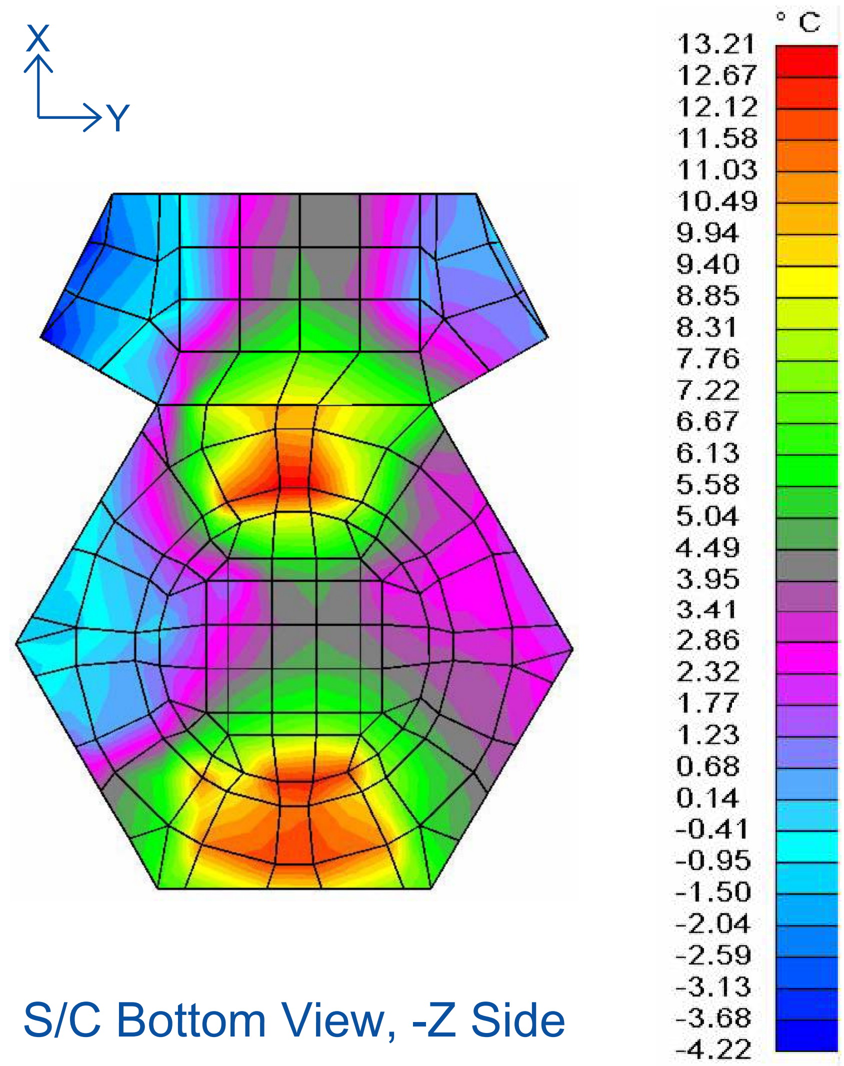


Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

Predicted Temps - Interior Compartment Surfaces



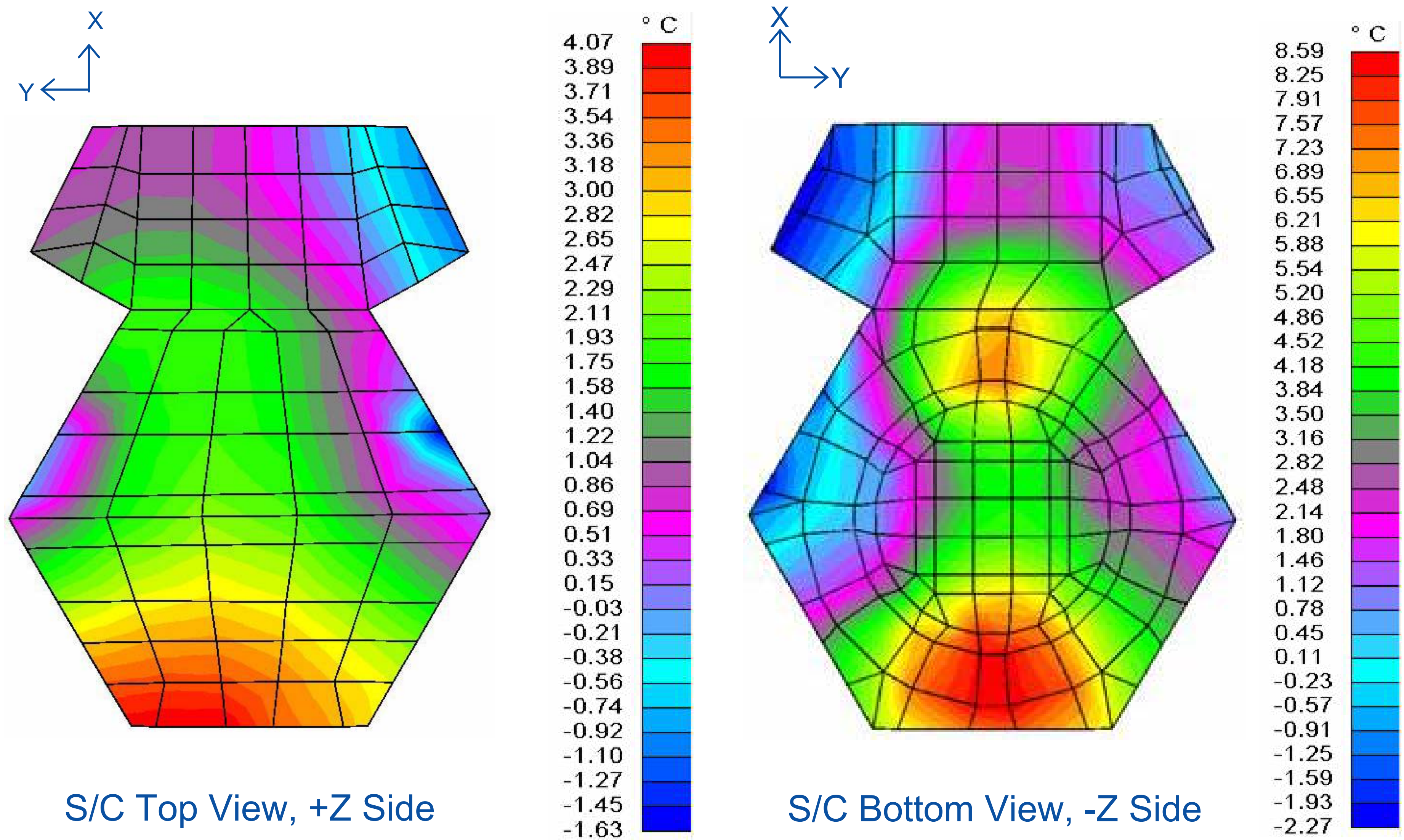
S/C Top View, +Z Side



S/C Bottom View, -Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

Predicted Temps - Exterior Compartment Surfaces

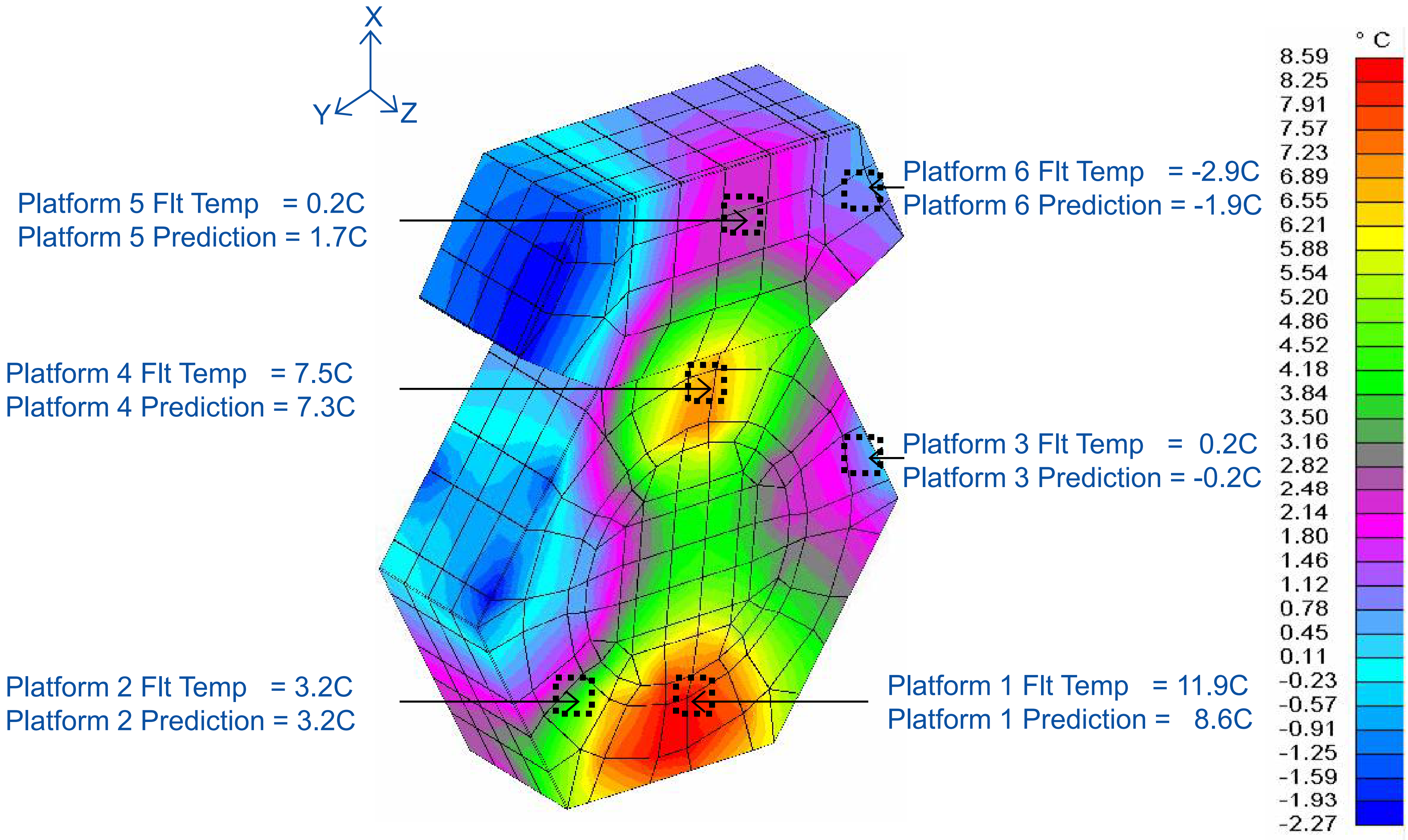


S/C Top View, +Z Side

S/C Bottom View, -Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

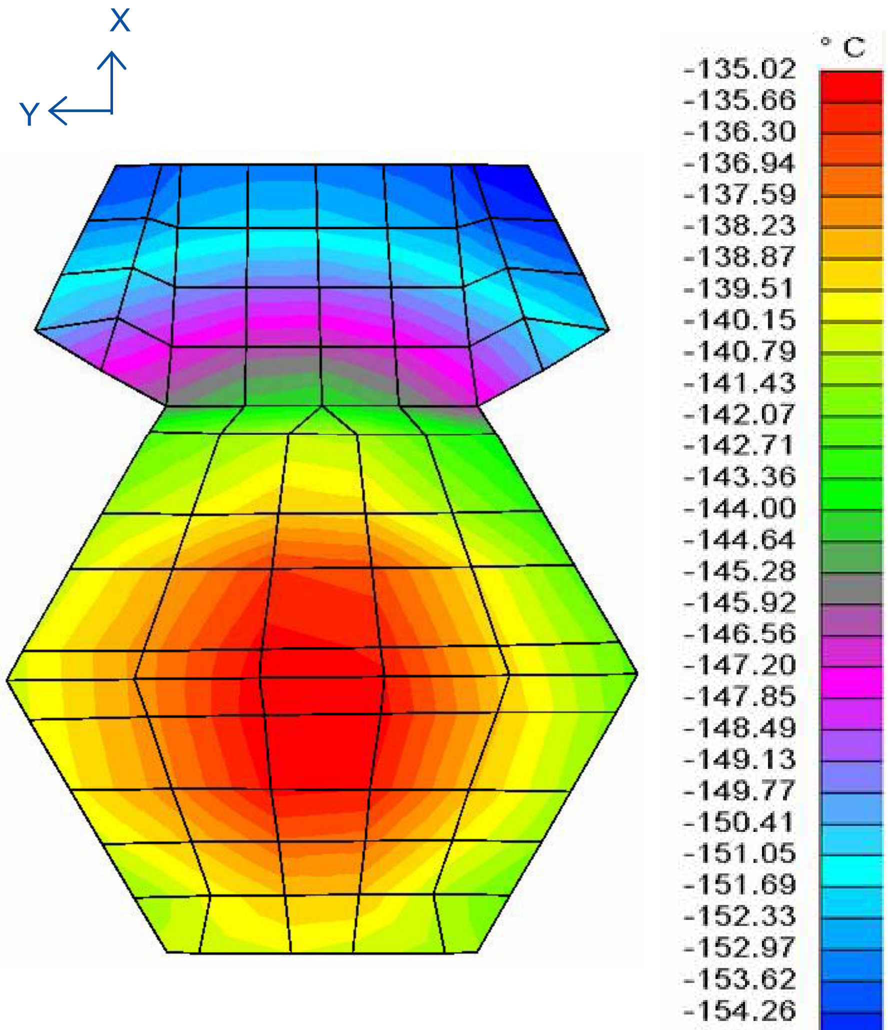
Measured Versus Predicted Compartment Temps



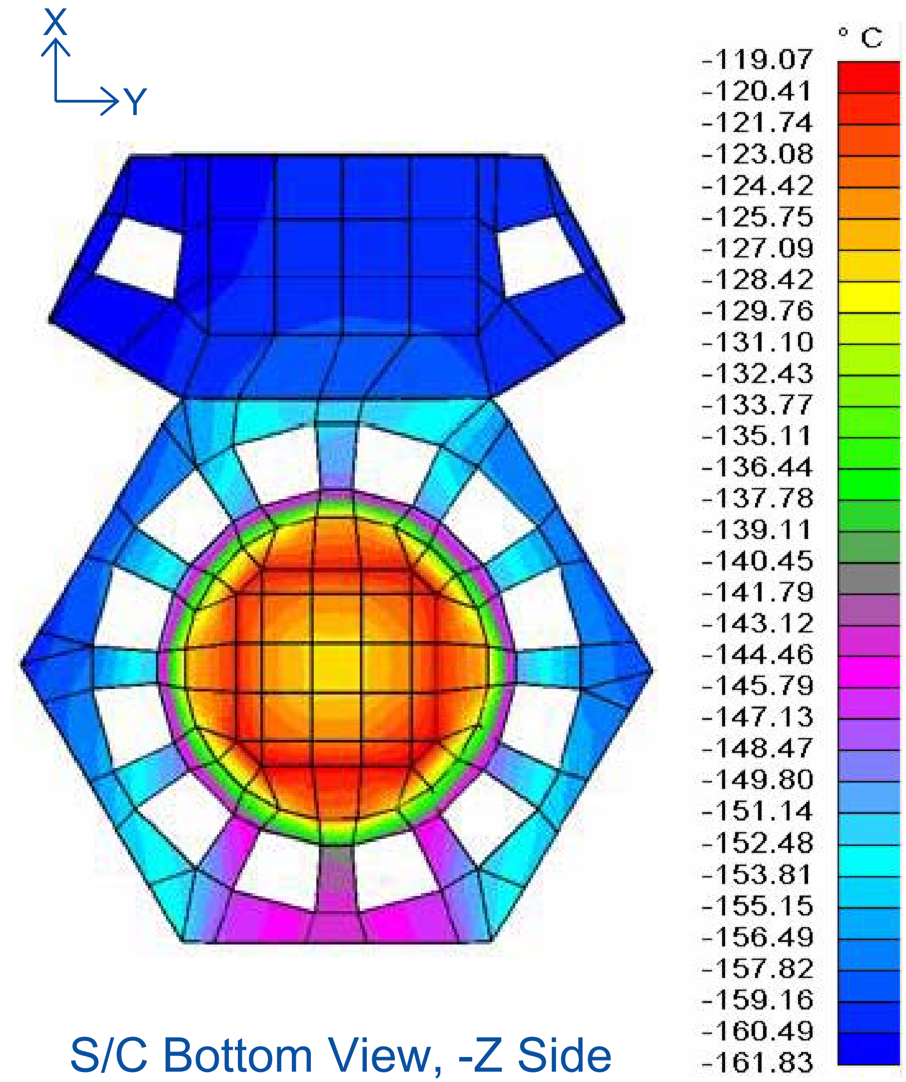
EQUIPMENT AND INSTRUMENT COMPARTMENTS

Note: Ignore Temp Scale 2nd Sig Digit (S/W Artifact)

Predicted Temps - Spacecraft MLI



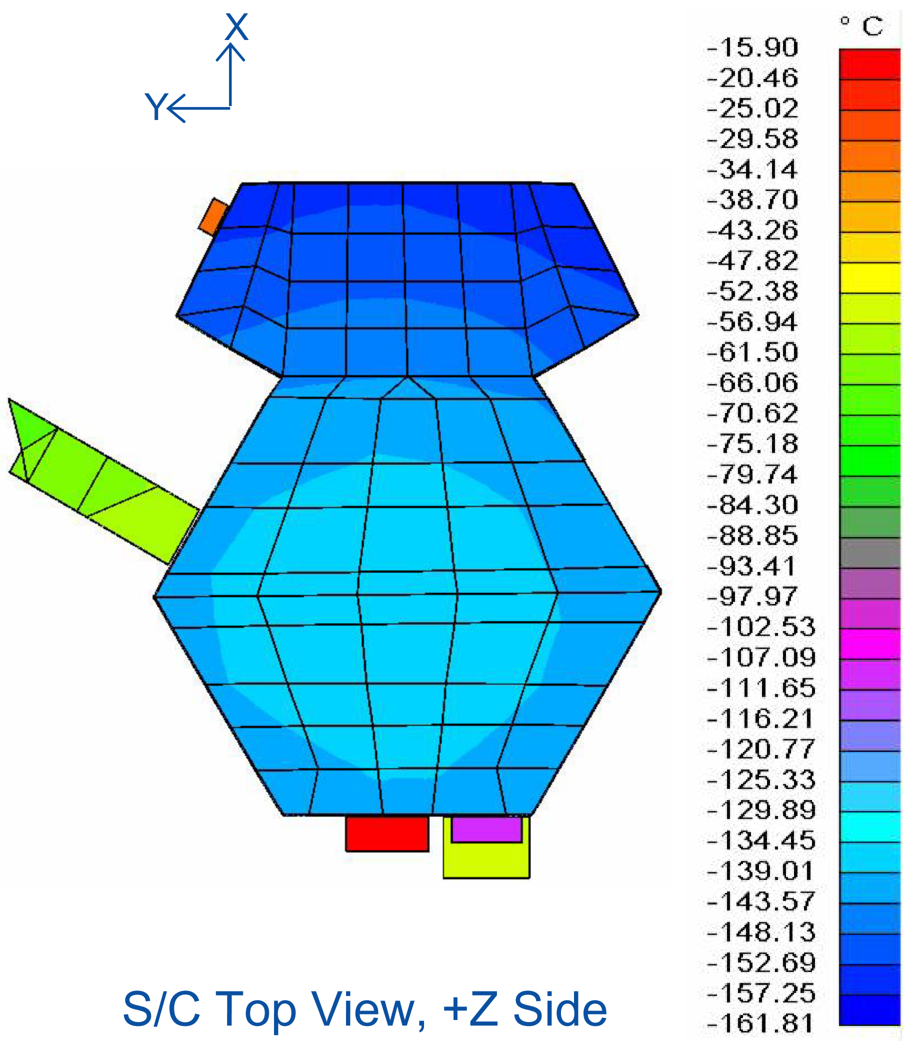
S/C Top View, +Z Side



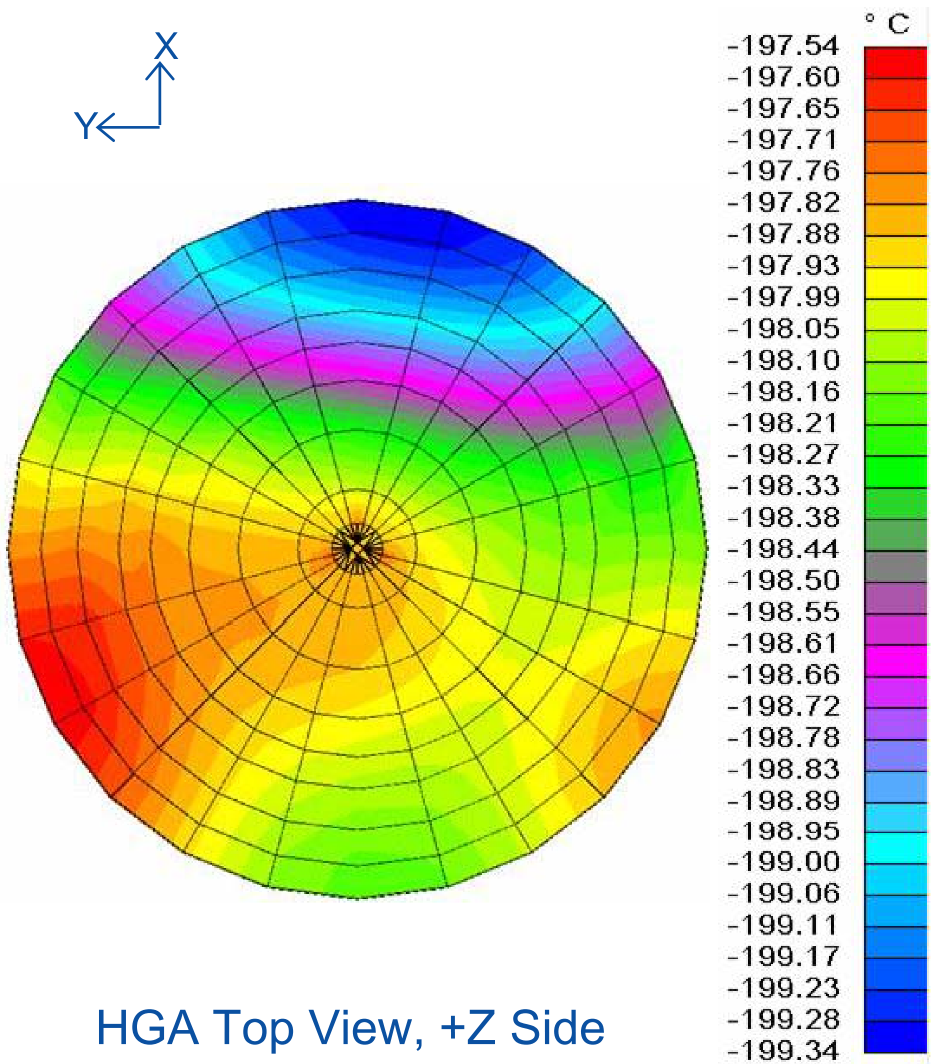
S/C Bottom View, -Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

Predicted Temps - HGA Temperatures



S/C Top View, +Z Side

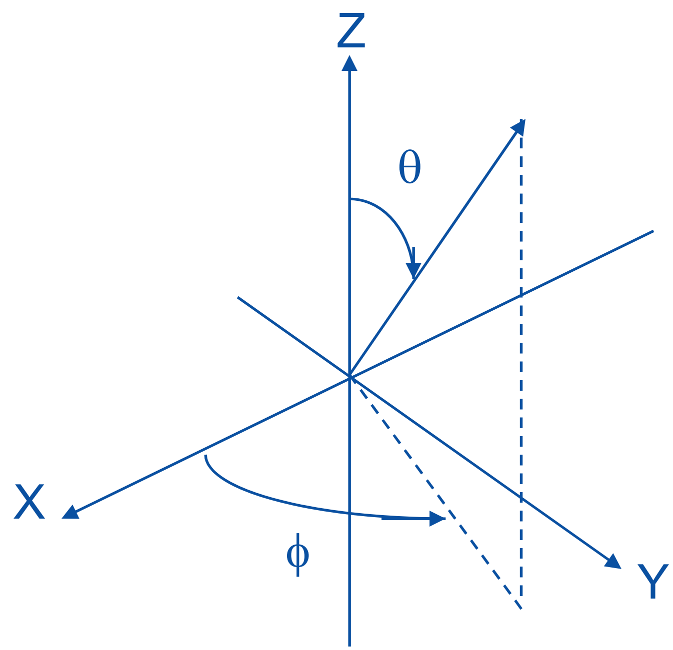


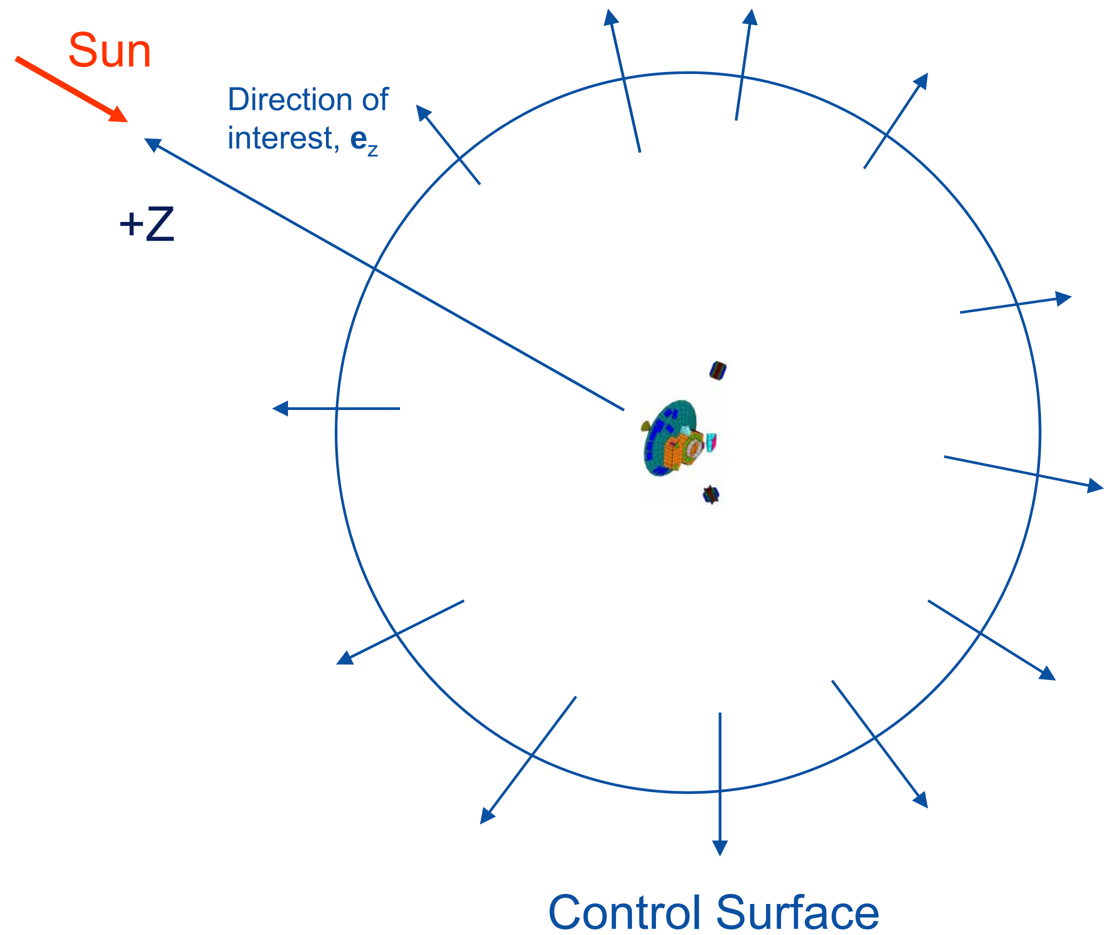
HGA Top View, +Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

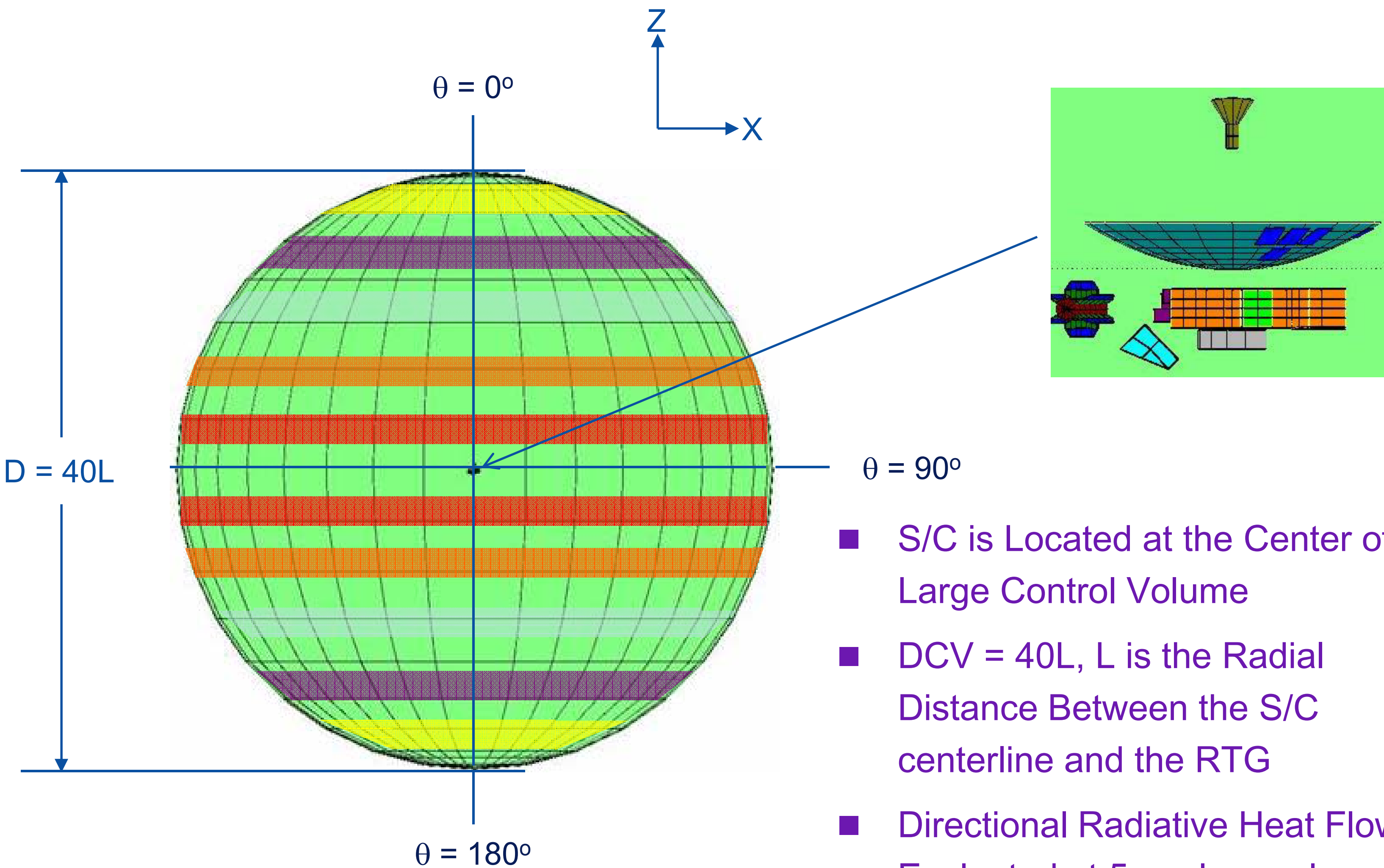
Calculation of Directional Thermal Emission

- Spacecraft emits in all directions, but only the component parallel to the spin axis is relevant





Control Volume in Geometric Math Model



- S/C is Located at the Center of a Large Control Volume
- DCV = 40L, L is the Radial Distance Between the S/C centerline and the RTG
- Directional Radiative Heat Flow is Evaluated at 5o polar angle intervals (5° Wide Latitude Bands)

Calculation of Net Directional Thermal Emission

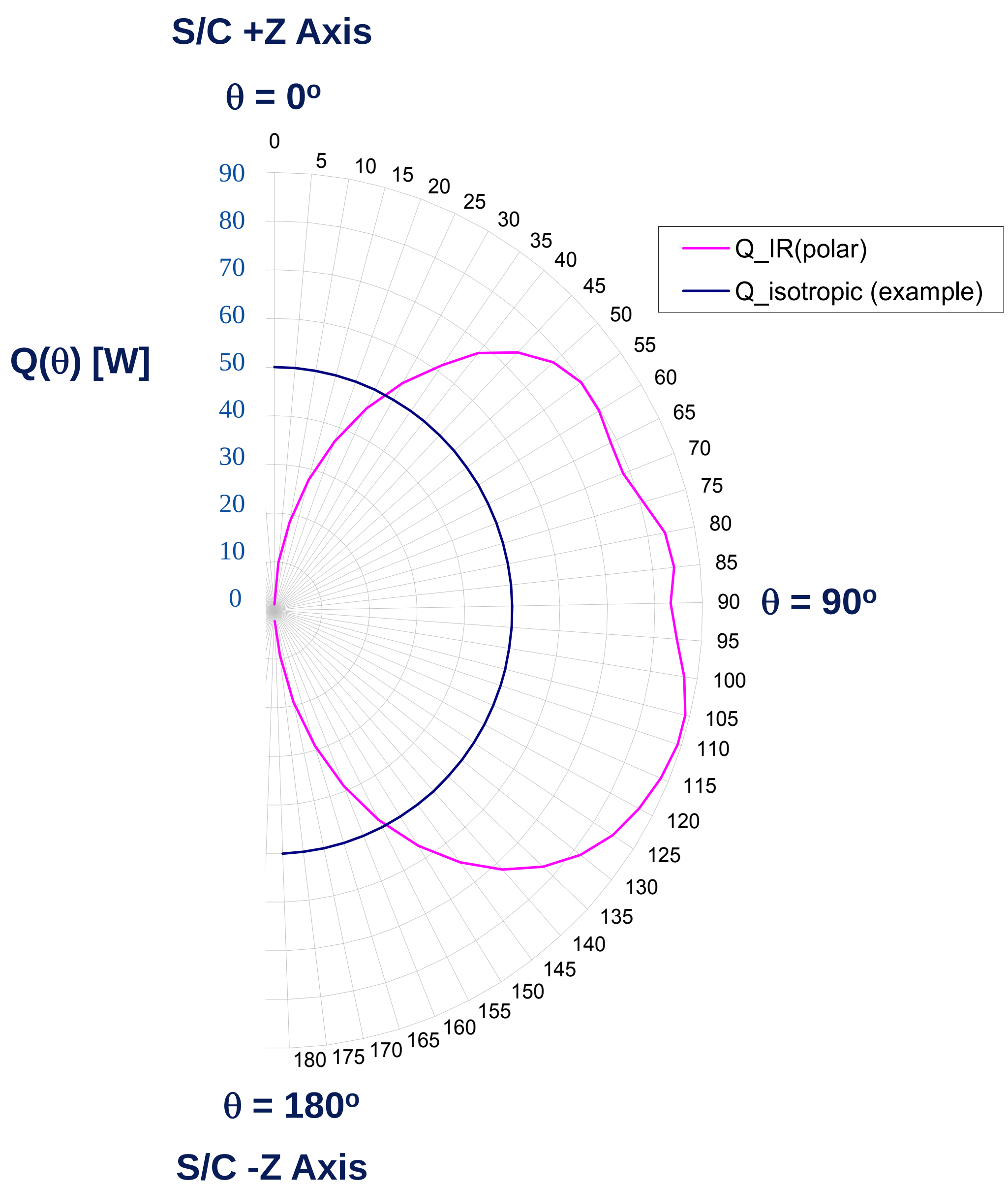
- Net thermal emission in the direction of the Z-axis:

$$Q_z = \int_A \vec{q} \cdot d\vec{A}_z + \vec{S} \cdot \vec{e}_z$$

$$= \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \varepsilon_i A_i \sigma T_i^{\,4} B_{i,jk} \cos\theta_j + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (1-\alpha_i) A_i B_{i,jk} \frac{S_{1AU}}{R_{AU}^2} \cos\theta_j$$

  - S_{1AU} is the solar constant at 1 AU
  - R_{AU} is the distance in AU of the spacecraft from the sun
  - Subscripts j,k refer to the element located at (θ_j, ϕ_k) on the spherical control volume
- Net directional emission = 0 for an isothermal, isotropic emitter when external sources are absent (i.e., uniform S/C temp & e)

Anisotropic Thermal Emission from Pioneer 10 s/c



Examples of Parametric Thermal Cases

- Various modeled properties
  - Calculate P10 anisotropic thermal emission at 25 AU

CASE	DESCRIPTION	LOUVER BLADES	NOMINAL DEGRADED α/ε PROP	EXTREME DEGRADED α/ε PROP	ESH EFFECT
BASELINE	BEST LOUVER ε_{EFF}, NOMINAL DEGRADED WHITE PAINT	X	X		NO
4B	REALISTIC LOUVER ε_{EFF}, ESH EFFECT	ε_{EFF} = 0.13		X	YES
4C	DUST-COVERED RTGs, $\alpha = \varepsilon = 1$	ε_{EFF} = 0.13	X		NO
4D	OPEN FAULT ALL LOUVERS, ESH EFFECT	ε_{EFF} = 0.74		X	YES
ESH EFFECT = EQUIVALENT SUN HOUR EFFECT WHICH MEANS DIFFERENT α/ε PROPERTIES ARE USED FOR SUNLIT AND SHADED SURFACES					

MODELED SPACECRAFT ASSEMBLY	BASELINE CASE NOMINAL DEGRADED α/ε PROP	CASE 4B & 4D EXTREME DEGRADED α/ε PROP	CASE 4C DUSTY RTGs α/ε PROP
HGA, SUNLIT SIDE	0.50/0.84	0.65/0.84	0.50/0.84
RTG FRAME, SUNLIT SIDE	0.50/0.82	0.65/0.84	1.0/1.0
RTG FRAME, SHADED SIDE	0.50/0.82	0.21/0.85	1.0/1.0
RTG FIN, SUNLIT SIDE	0.50/0.82	0.65/0.84	1.0/1.0
RTG FIN, SHADED SIDE	0.50/0.82	0.21/0.85	1.0/1.0
MGA EXTERNAL	0.50/0.84	0.65/0.84	0.50/0.84
SHUNT RADIATOR	0.24/0.84	0.21/0.85	0.24/0.84

  - Temperature telemetry data are used as boundary conditions.
  - Louvers are modeled with effective emittance between e_{eff} = 0.13 (closed) and 0.74 (open)

Planned Thermal Model Development

- More analysis to quantify anisotropic contributions from individual sources
  - Calculate percentage of 23 W that RTGs, louvers and HGA contribute
- Calculate anisotropic emission at other AU distances and off-sun angles
- Thermal sensitivity analysis
  - Vary a_S and e_{IR} properties for key surfaces (HGA backside, RTGs, louver OSR)
    - Apply extreme property values to bound degradation
    - Evaluate impacts on temperature, heat flow and force
  - Apply distinct e_{IR} properties to sunlit & shaded RTG surfs (degradation differs)
    - Thermo-optical property degradation differs
  - Evaluate HGA backside specularity impact
  - Vary spherical control volume diameter to ensure results convergence
    - Increase angular mesh of spherical control volume
- Investigate TRW/NGST archivist lead (P10 Thermal PDR/CDR info there?)
  - Provide design and configuration details not supplied in high-level project docs
    - Materials, thicknesses, geometric details, surface finishes
  - Show this TMM to retired TRW thermal engrs (spark memories, more details?)

Conclusions and Next Steps

- May 2008 the new Doppler data will be available, thus
  - Primary effort – certification & analysis of the extended Doppler data
  - To determine true direction of the anomaly and its behavior as a function of distance from the Sun
- High fidelity Thermal Model of the Pioneers is available and evolving
  - Ideal tool for future analysis
  - Capable of examining all heliocentric distances and off-sun angles
  - Capable of identifying anisotropic thermal contributions from individual spacecraft subsystems
- Next Steps: focus on the Anomaly using all available data:
  - Analysis of Pioneer 11 Doppler data (proceed with early data, then entire mission)
  - The proceed with Pioneer 10….
  - Combined analysis of Doppler and telemetry data
- Stay tuned… the fun part of the analysis has just began!

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