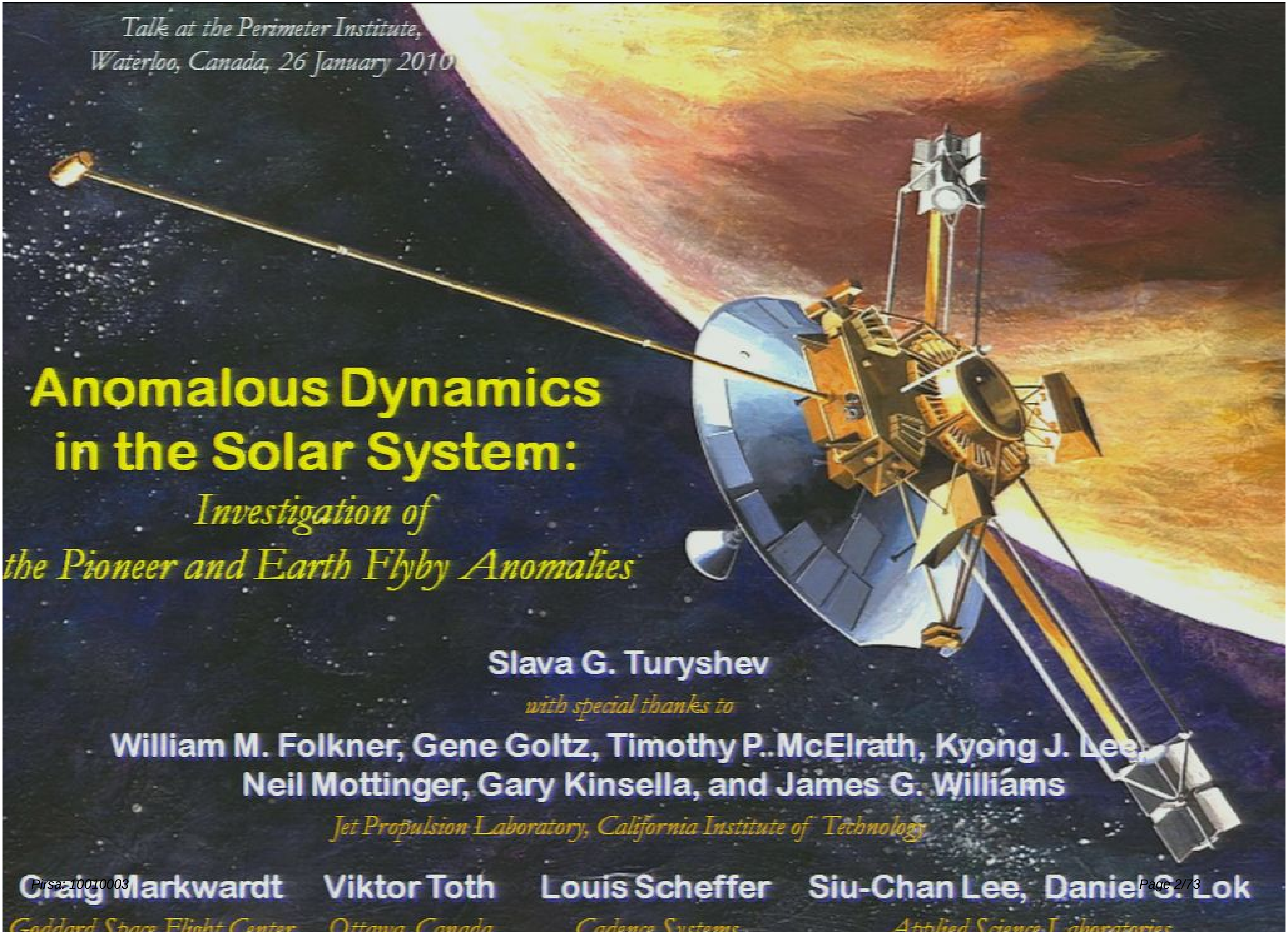
Title: Anomalous Dynamics in the Solar System: Investigation of the Pioneer and Earth Flyby Anomalies

Date: Jan 26, 2010 02:00 PM

URL: http://pirsa.org/10010003

Abstract: The radio-metric tracking data received from the Pioneer 10 and 11 spacecraft from the distances between 20--70 astronomical units from the Sun has consistently indicated the presence of a small, anomalous, blue-shifted Doppler frequency drift that limited the accuracy of the orbit reconstruction for these vehicles. This drift was interpreted as a sunward acceleration of aP = (8.74 ï,±1.33) ï,´ 10ï€-10 m/s2 for each particular spacecraft. This signal has become known as the Pioneer anomaly; the nature of this anomaly is currently being investigated. Recently new Pioneer 10 and 11 radio-metric Doppler and flight telemetry data became available. The newly available Doppler data set is much larger when compared to the data used in previous investigations and is the primary source for new investigation of the anomaly. In addition, the flight telemetry files, original project documentation, and newly developed software tools are now used to reconstruct the engineering history of spacecraft. With the help of this information, a thermal model of the Pioneer vehicles is being developed to study the contribution of thermal recoil force acting on the two spacecraft. The goal of the ongoing efforts is to evaluate the effect of the on-board systems on the spacecrafts' trajectories and possibly identify the nature of this anomaly. The current status of these investigations will be discussed. Besides the Pioneer anomaly, there are other intriguing puzzles in the solar system dynamics still awaiting a proper explanation, notably the, so-called, â€œfly-by anomalyâ€•, that occurred during Earth gravity assists performed by several interplanetary spacecraft. We will discuss the observed effect, the conditions that led to its observation and will elaborate on the potential causes of this anomaly. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.


Talk at the Perimeter Institute,
Waterloo, Canada, 26 January 2010
Anomalous Dynamics
in the Solar System:
Investigation of
the Pioneer and Earth Flyby Anomalies
Slava G. Turyshev
with special thanks to
William M. Folkner, Gene Goltz, Timothy P. McElrath, Kyong J. Lee,
Neil Mottinger, Gary Kinsella, and James G. Williams
Jet Propulsion Laboratory, California Institute of Technology
Craig Markwardt
Viktor Toth
Louis Scheffer
Siu-Chan Lee, Daniel S. Lok
Goddard Space Flight Center
Ottawa, Canada
Cadence Systems
Applied Science Laboratories

THE STUDY OF THE PIONEER ANOMALY

It's all began 11 years ago...

VOLUME 81, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1998

Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration

John D. Anderson,[1,*] Philip A. Laing,[2,†] Eunice L. Lau,[1,‡] Anthony S. Liu,[3,§] Michael Martin Nieto,[4,||] and Slava G. Turyshev[1,¶]
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
[2]The Aerospace Corporation, 2350 E. El Segundo Boulevard, El Segundo, California 90245-4691
[3]Astrodynamic Sciences, 2393 Silver Ridge Avenue, Los Angeles, California 90039
[4]Theoretical Division (MS-B285), Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 10 June 1998)

PHYSICAL REVIEW D, VOLUME 65, 082004

Study of the anomalous acceleration of Pioneer 10 and 11

John D. Anderson,[1,*] Philip A. Laing,[2,†] Eunice L. Lau,[1,‡] Anthony S. Liu,[3,§] Michael Martin Nieto,[4,||] and Slava G. Turyshev[1,¶]
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
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[3]Astrodynamic Sciences, 2393 Silver Ridge Avenue, Los Angeles, California 90039
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(Received 15 May 2001; published 11 April 2002)

Our previous analyses of ra
cated that an apparent anom
$\times 10^{-8}$ cm/s^2, directed towa
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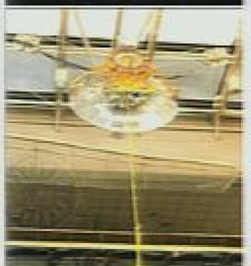
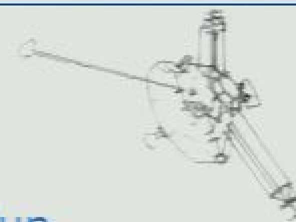
normal to the spacecraft, as w
discuss the methods, theoreti

The Study of the Pioneer Anomaly: New Data and Objectives for New Investigation

The Pioneer Anomaly: Summary

- Anomalous acceleration of Pioneers 10 and 11:



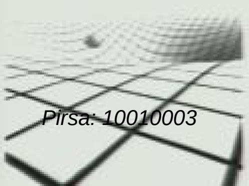
$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

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

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

- 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 STUDY OF THE PIONEER ANOMALY

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

Ames Research Center

TRW

JPL

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
S-band, up-link	S-band, down-link	($\lambda \simeq 13$ cm)
2110 MHz	2292 MHz	Doppler
Spacecraft transmits continuously @ 8 W		

Pioneer 10: pre-launch testing

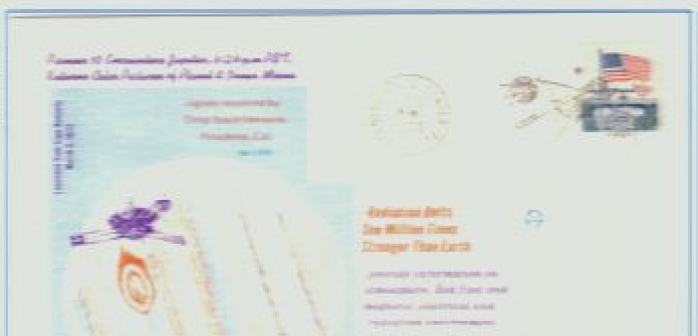
The Pioneers are still the most precisely navigated deep-space vehicles:

- Spin-stabilization and design permitted acceleration sensitivity $\sim 10^{-10}$ 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.

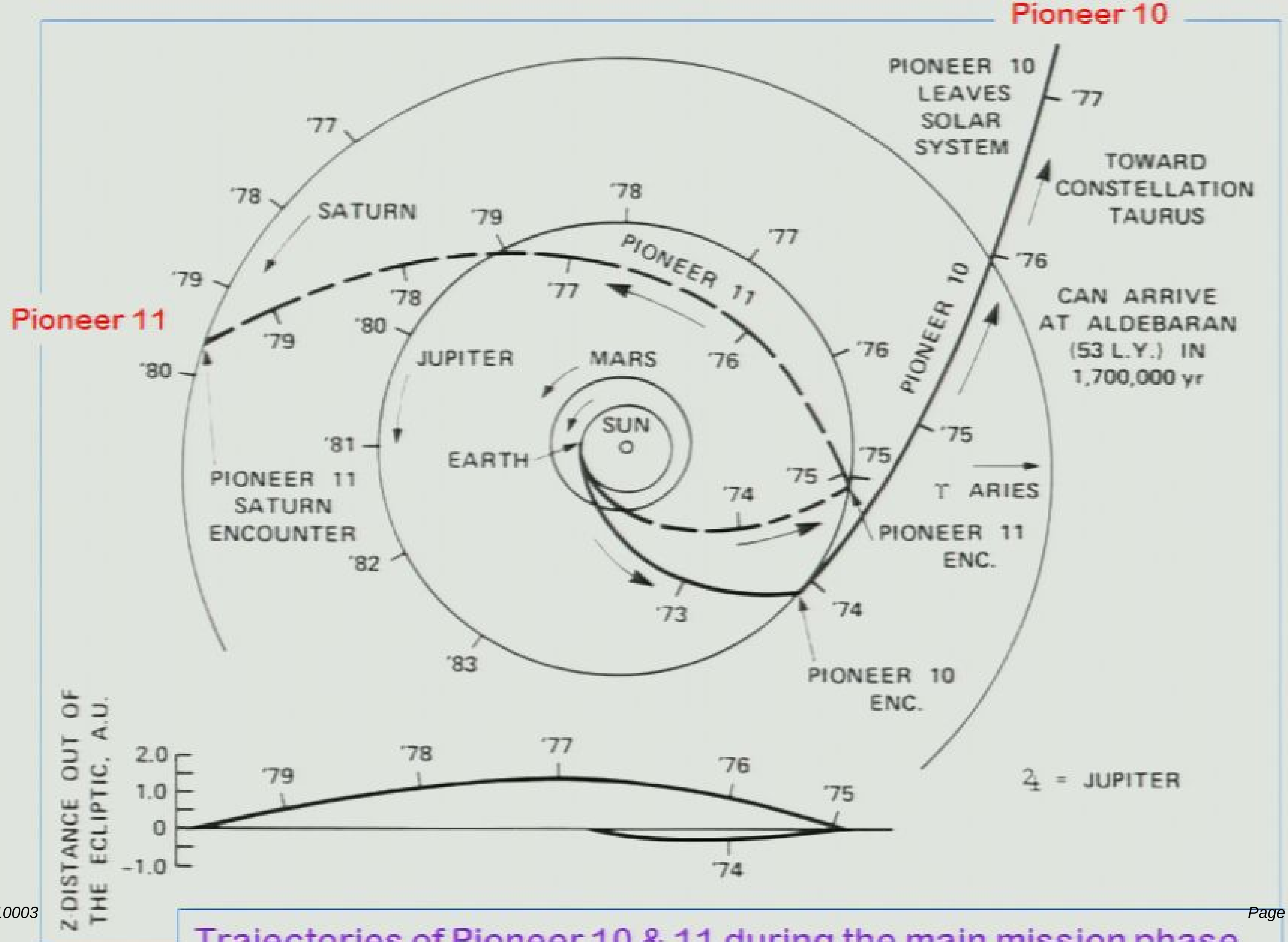
THE STUDY OF THE PIONEER ANOMALY

Pioneer 10 Launch: 2 March 1972

Pioneer 10 Launch: 2 March 1972



Pioneers 10 and 11: Main Missions (before 1979)



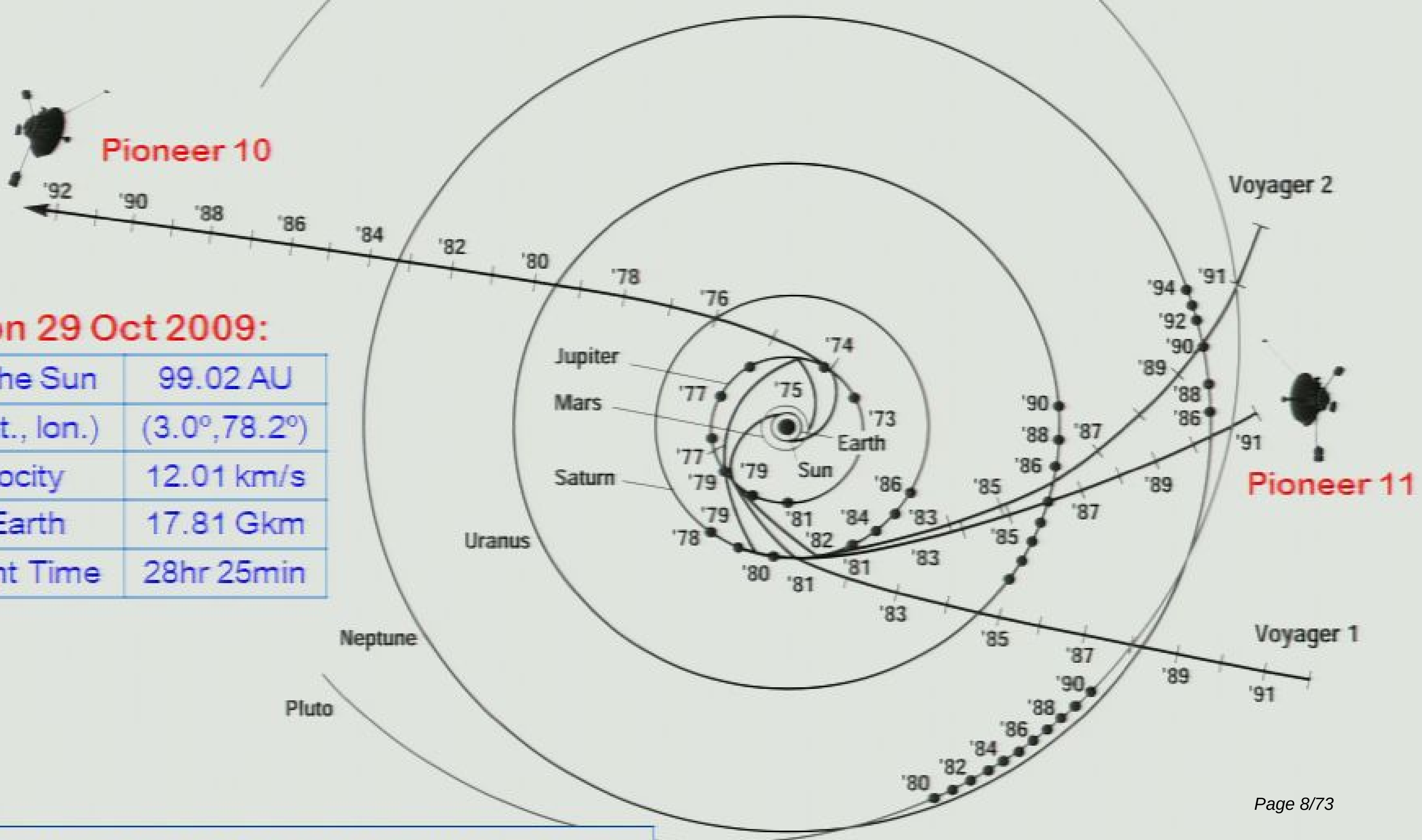
Trajectories of Pioneer 10 & 11 during the main mission phase

THE STUDY OF THE PIONEER ANOMALY

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 29 Oct 2009:

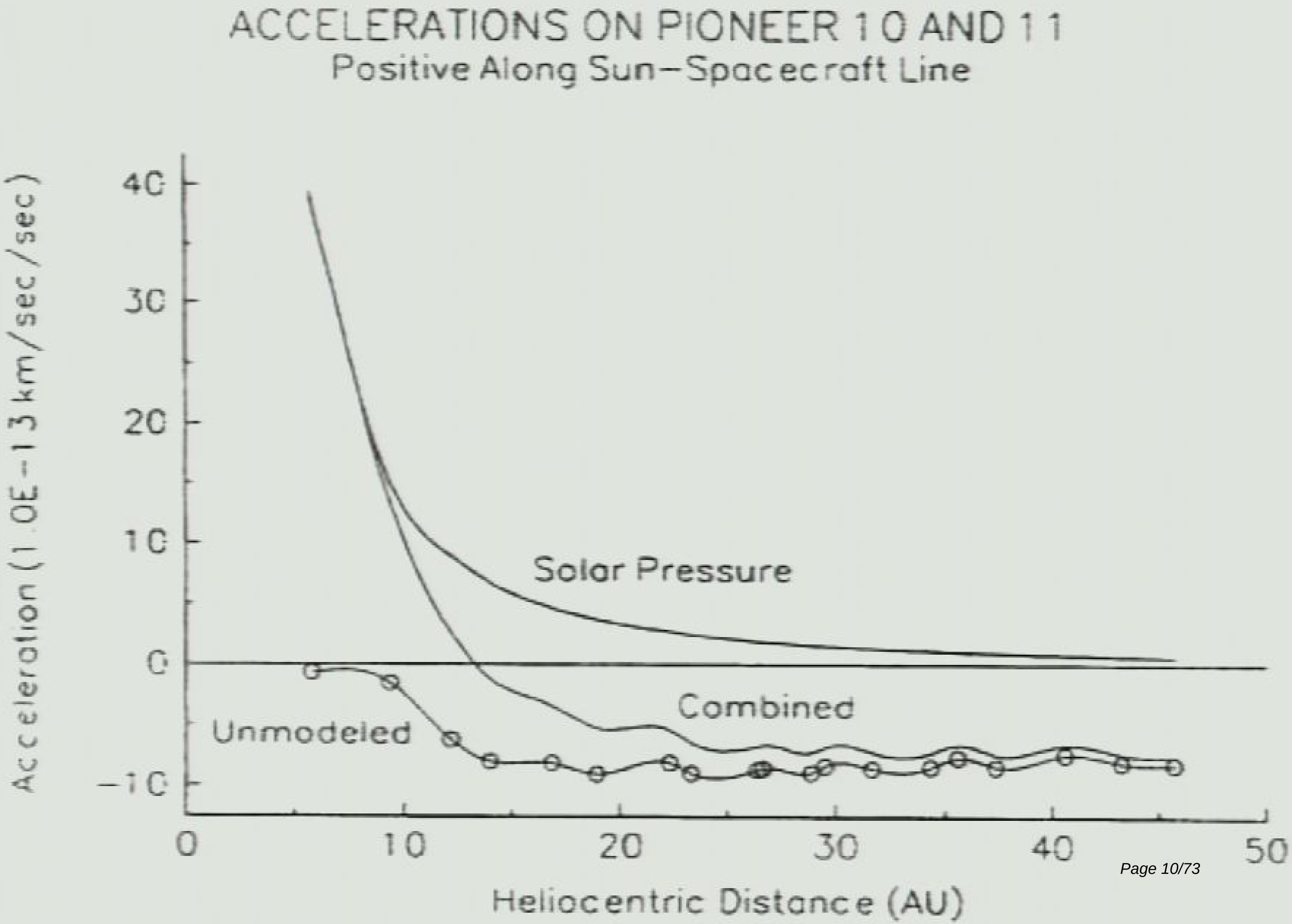
Distance from the Sun	99.02 AU
Position, SE (lat., lon.)	(3.0°,78.2°)
Heliocentric velocity	12.01 km/s
Distance from Earth	17.81 Gkm
Round-Trip Light Time	28hr 25min

Trajectories of Pioneers and Voyagers

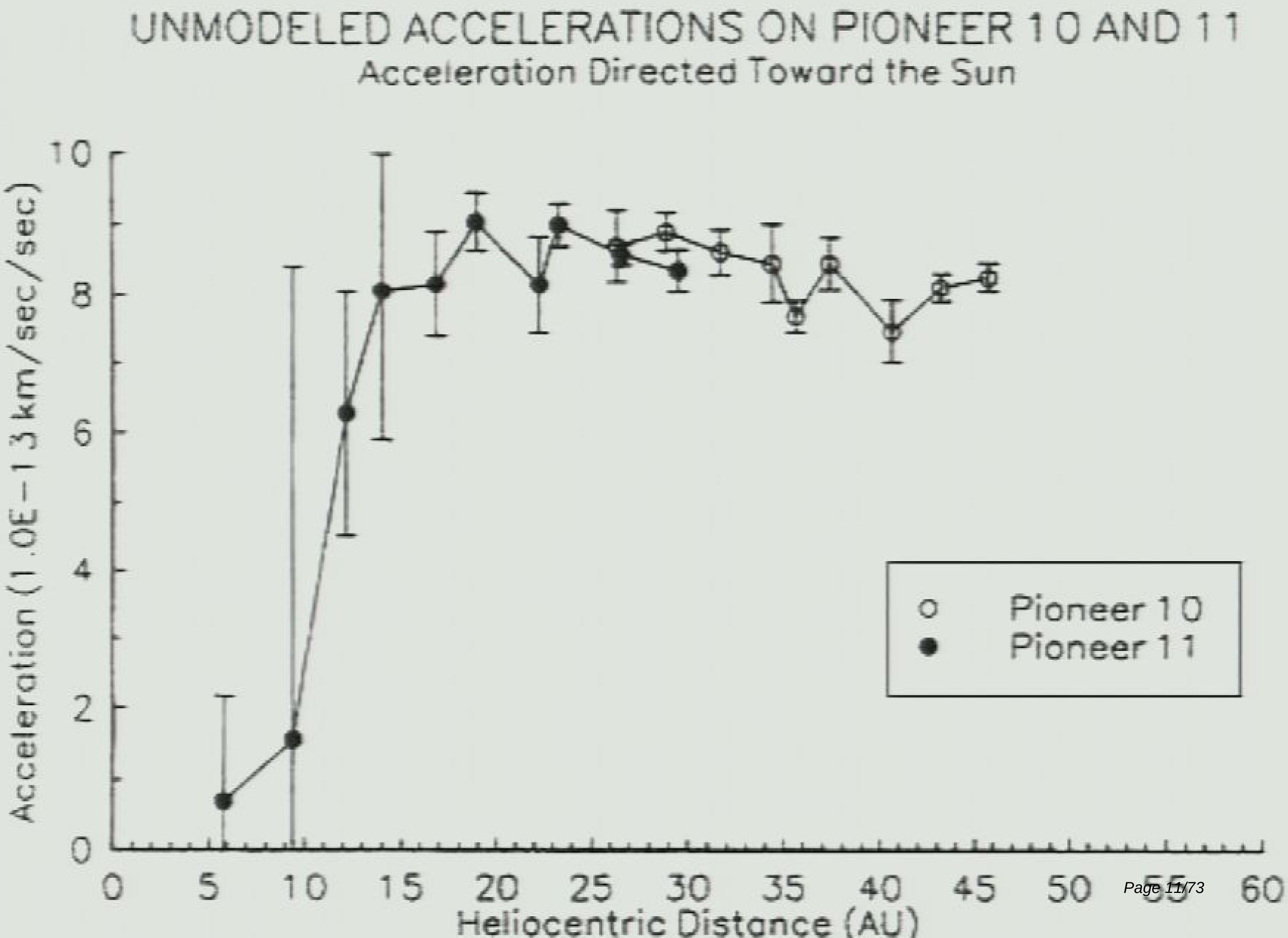
History: Detection of the Effect and Earlier Studies

- 1979: search for unmodeled accelerations w/ Pioneers began:
  - Motivation: Planet X; initiated when Pioneer 10 was at 20 AU;
  - Solar-radiation pressure **away** from the Sun became $< 5 \times 10^{-10}$ m/s^2
- 1980: navigational anomaly first detected at JPL:
  - The biggest systematic error in the acceleration residuals – a constant bias of $(8 \pm 3) \times 10^{-10}$ m/s^2 directed **towards** the Sun

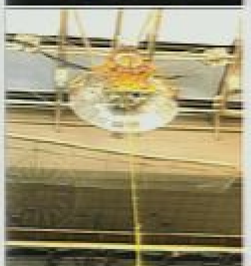
History: Detection of the Effect and Earlier Studies



History: Detection of the Effect and Earlier Studies



History: Detection of the Effect and Earlier Studies

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PRL 81(1998) 2858-2861, gr-qc/9808081

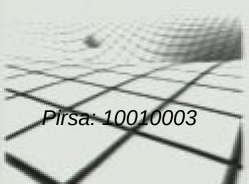
- Initial JPL-ODP analysis in 1990-95:

  $(8.09 \pm 0.20) \times 10^{-10}$ m/s^2 for Pioneer 10

  $(8.56 \pm 0.15) \times 10^{-10}$ m/s^2 for Pioneer 11
  - NO magnitude variation with distance over a range of 40 to 70 AU
  - The error is from a batch-sequential & filter-smoothing algorithm

- **An Error in JPL's ODP?** – Numerous internal checks at JPL
- NASA Grant to The Aerospace Corporation: 1996-1998

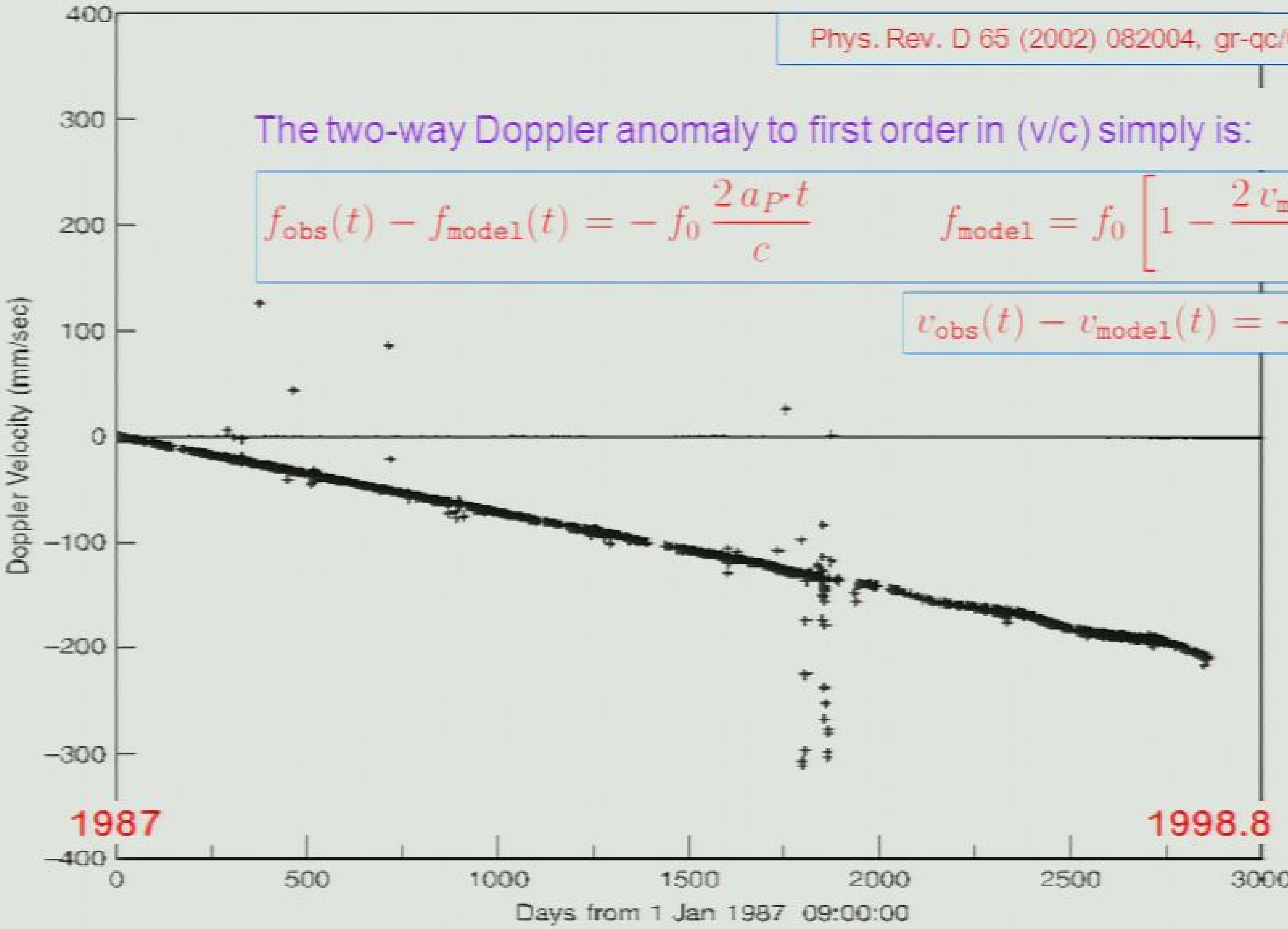
Data used for the analysis conducted during 1996-1998:



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

THE STUDY OF THE PIONEER ANOMALY

The Observed Anomalous Doppler Drift



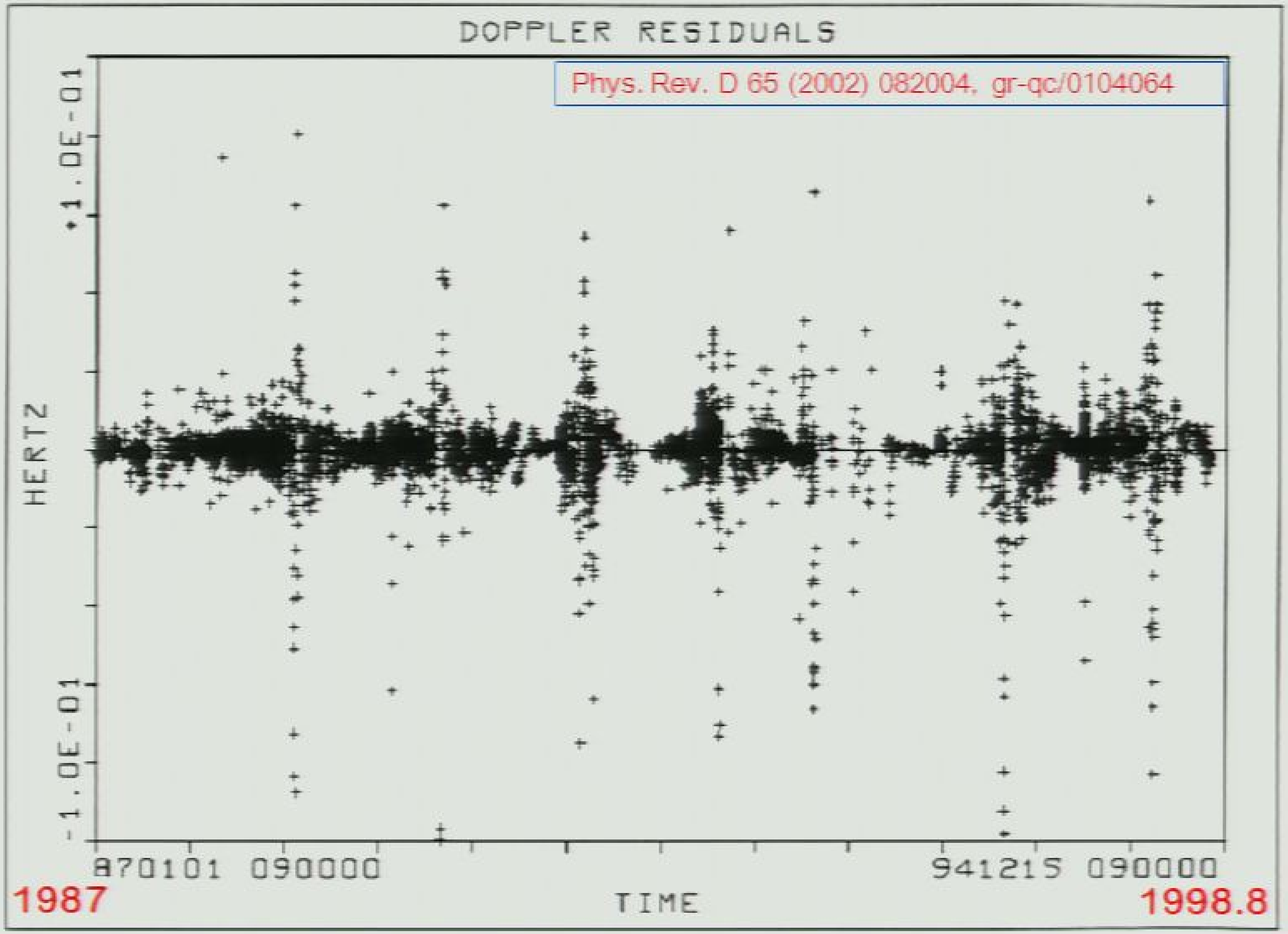
The two-way Doppler anomaly to first order in (v/c) simply is:

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

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

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



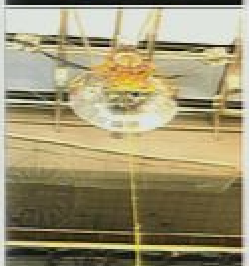
Adding only one more parameter to the model – a constant radial acceleration – led to residuals distribution ~ zero Doppler velocity with a systematic variation ~3.0 mm/s. Quality of the fit is determined by ratio of residuals to the downlink carrier frequency, ν_0 ~ 2.29 GHz

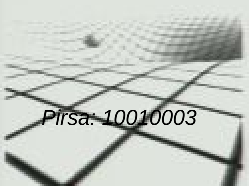
Modeling of Spacecraft Motion

- 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).

Sources of Systematic Error: External

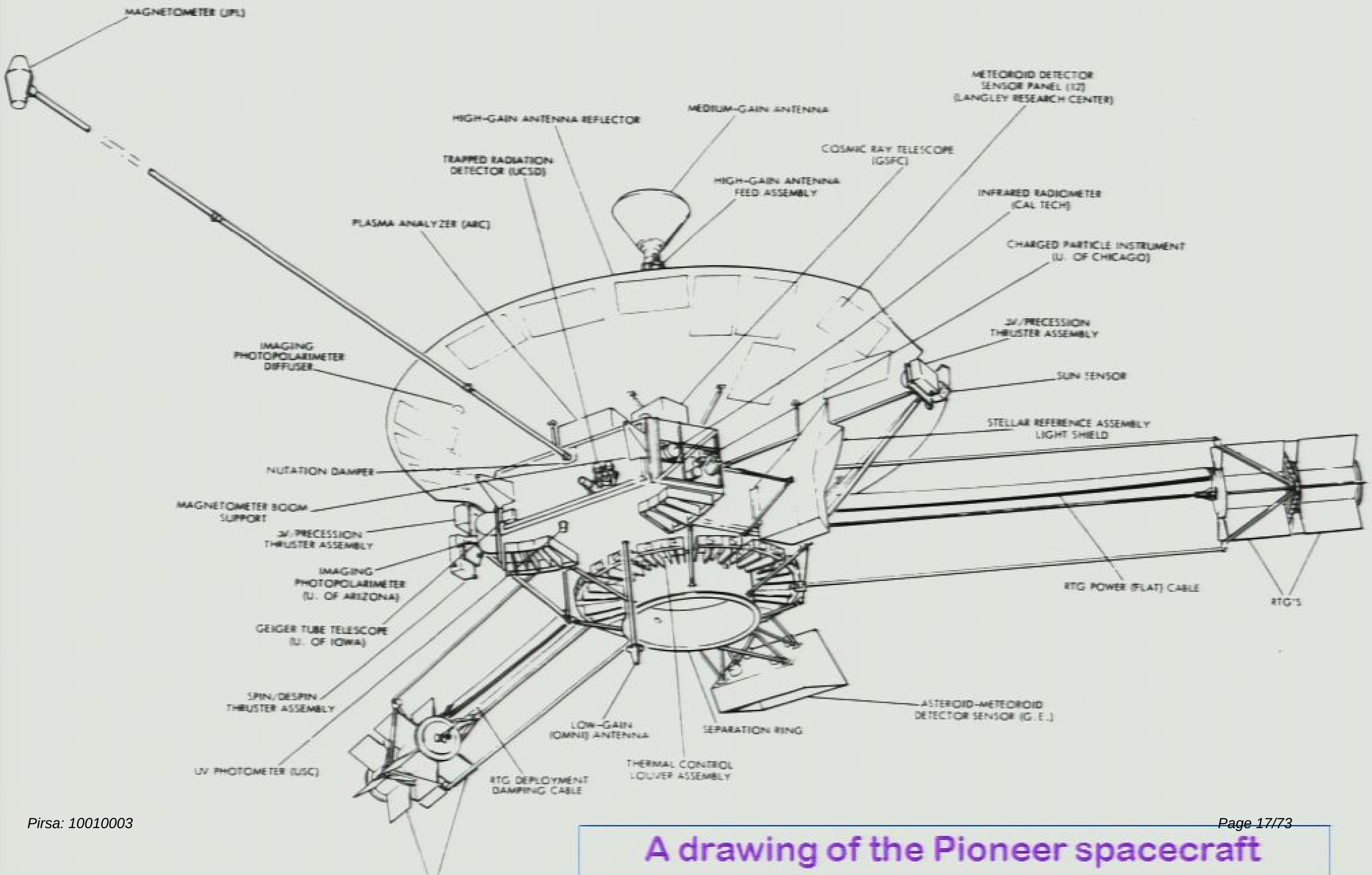
Error budget constituents	Bias 10^{-10} m/s^2	Uncertainty 10^{-10} m/s^2
1 Sources of external systematic error:		
⇛ Solar radiation pressure		$\pm$ 0.001
⇛ From the mass uncertainty	+0.03	$\pm$ 0.01
⇛ Solar wind contribution		$\pm < 10^{-5}$
⇛ Effects of the solar corona		$\pm$ 0.02
⇛ Electro-magnetic 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 STUDY OF THE PIONEER ANOMALY

The Pioneer 10/11 Spacecraft



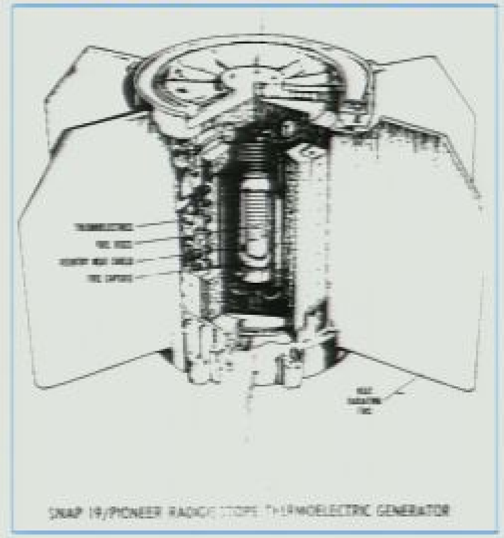
A drawing of the Pioneer spacecraft

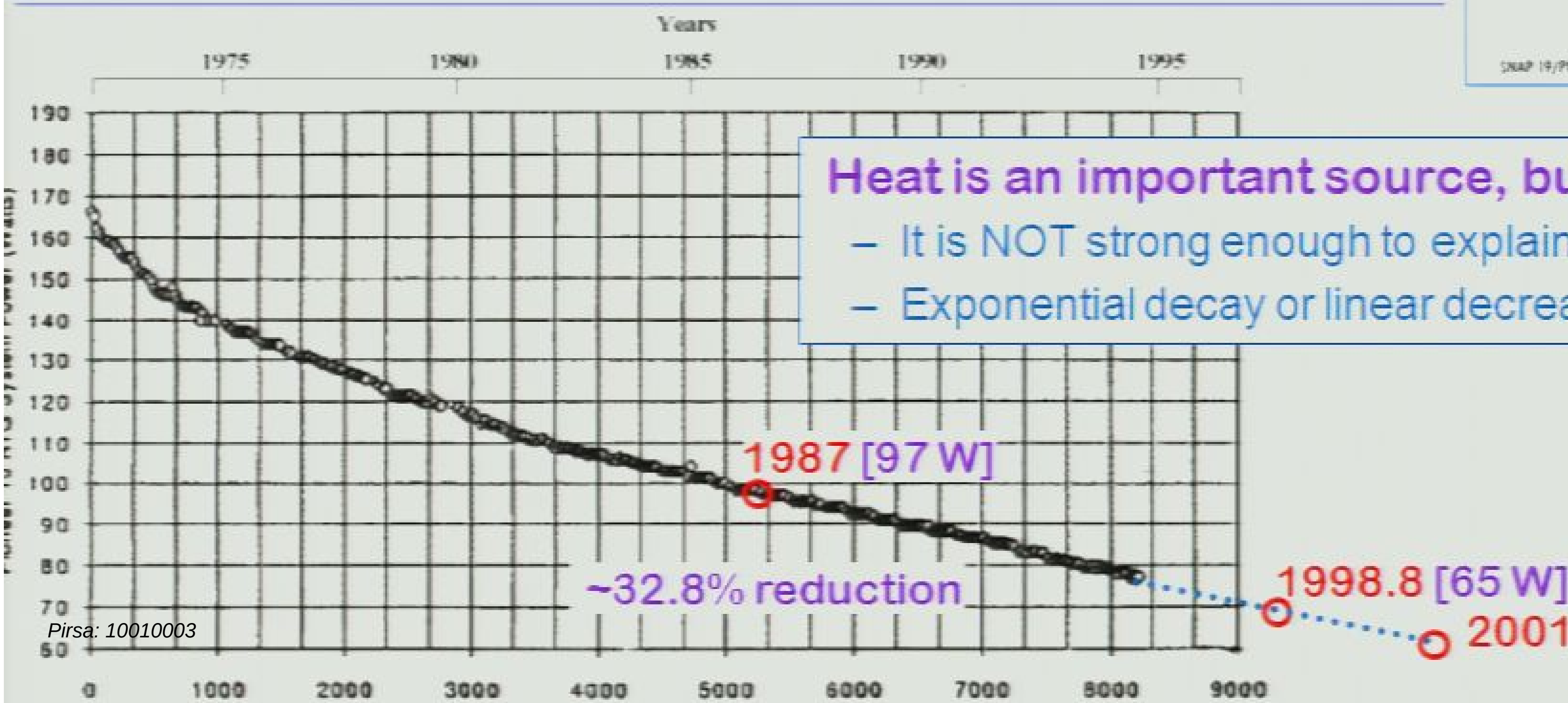
THE STUDY OF THE PIONEER ANOMALY

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





Heat is an important source, but:

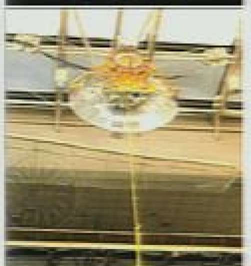
- It is NOT strong enough to explain the anomaly;
- Exponential decay or linear decrease – NOT seen

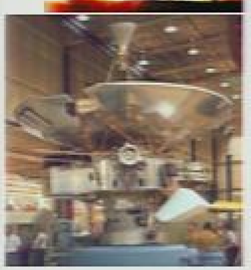
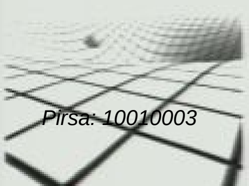
Focus of the 1995-2002 Analysis

- 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 2009 existence of the anomaly is confirmed by 7 codes:
  - JPL's Orbit Determination Program [various versions 1979-2009];
  - 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 [2005-2009]; 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 (>200!):
  - Kinematical realization of local cosmological frame; momentum-dependent gravitational coupling; MONDian mechanism, modified inertia; non-uniformly-coupled scalar field(s); Brane-worlds; higher-dimensional gravitational models, *f*(R) models, etc.
- Primary focus of new analysis: **"the heat or not the heat?"**

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

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 ⇒ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU ⇒ 19,198 data points

Pioneer 10/11 Doppler Data available (since October 2009):

- **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.

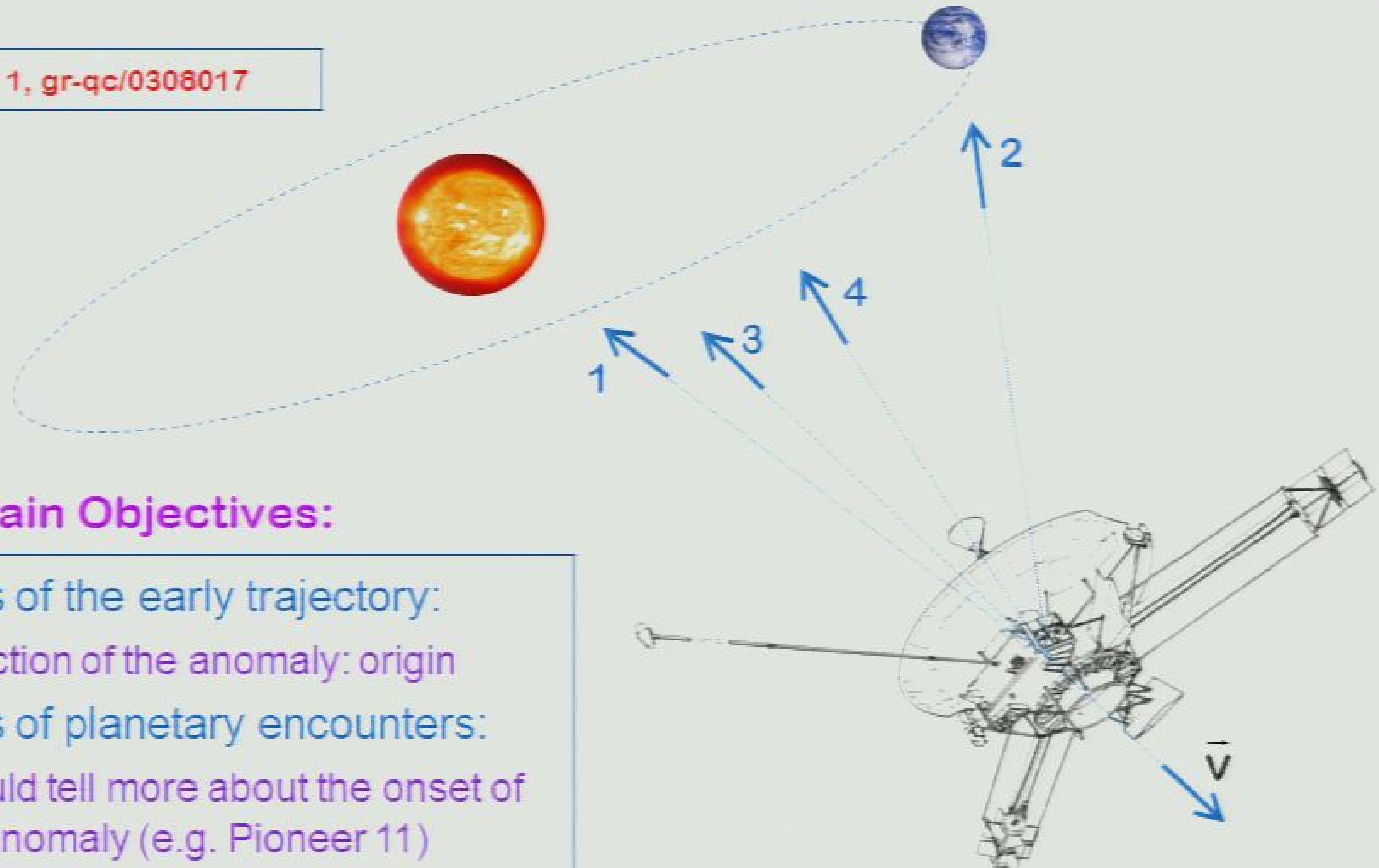
- All 600+ ATDFs went through radio-metric data conditioning (2006-2009)
- The entire set of Doppler data is available since the end of Sept 2009

Significant volume of the data never analyzed to study the anomaly

THE STUDY OF THE PIONEER ANOMALY

Critical Phases of the On-Going Investigation

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

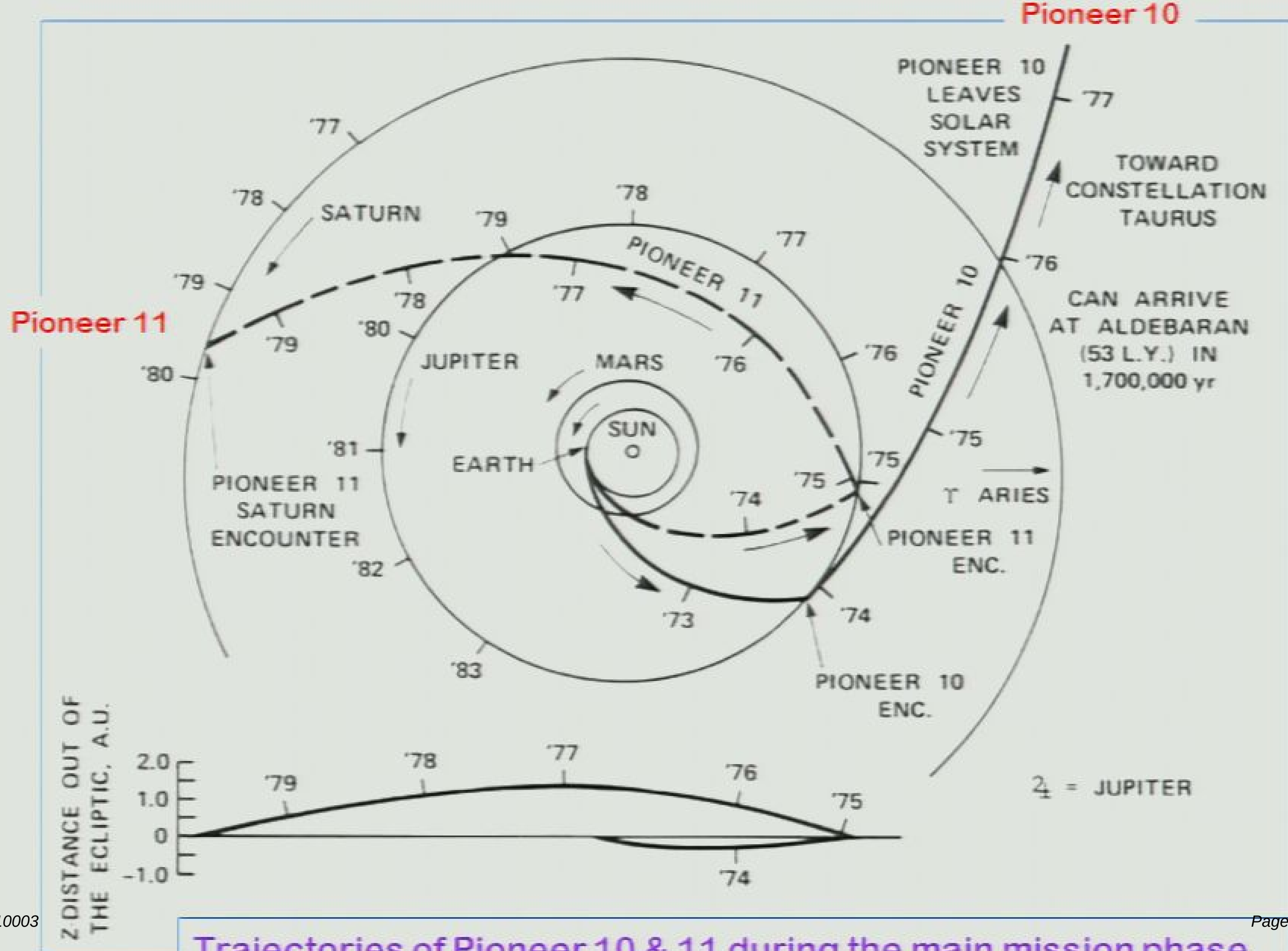


Four Main Objectives:

- 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



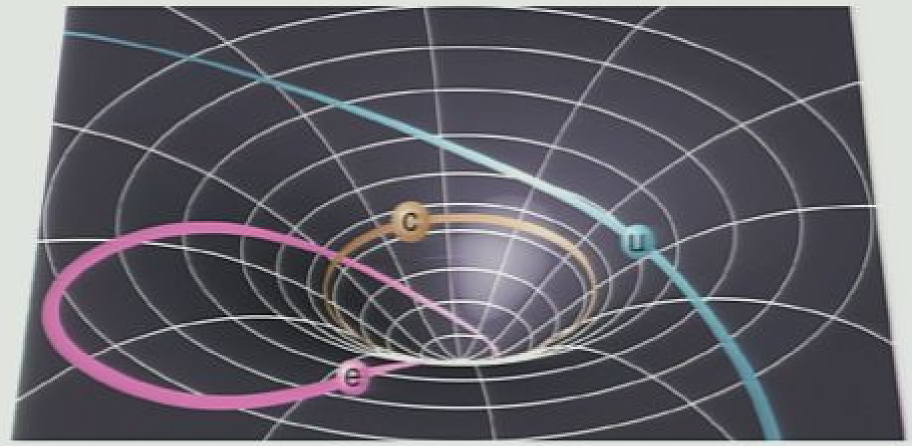
Trajectories of Pioneer 10 & 11 during the main mission phase

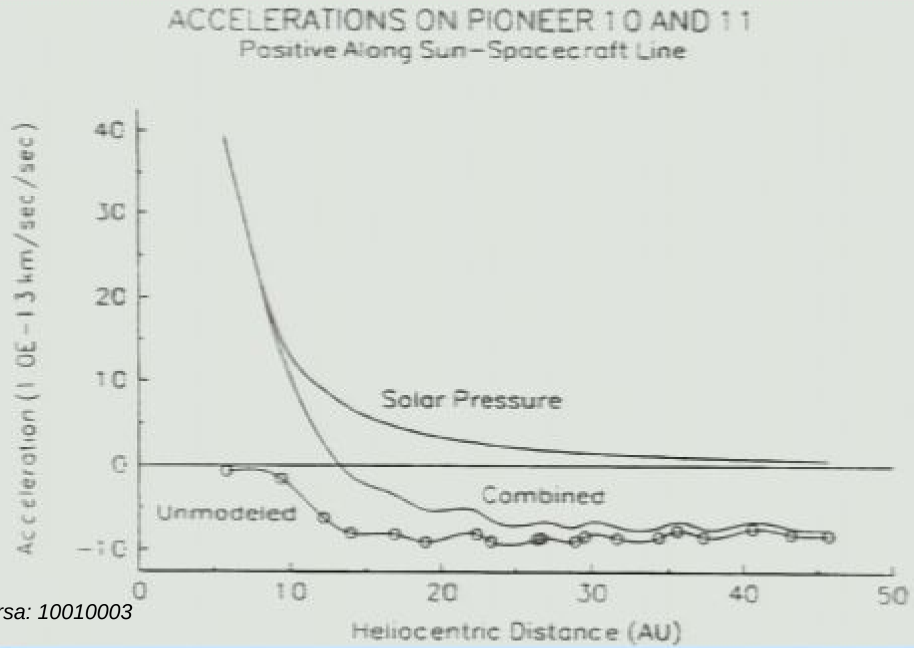
THE STUDY OF THE PIONEER ANOMALY

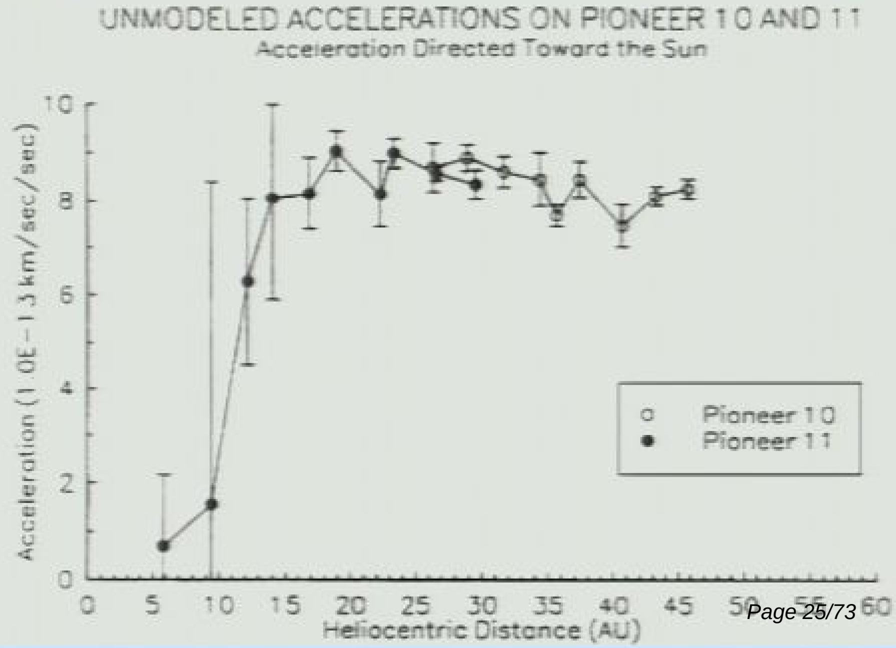
Difference Between Bound & Un-Bound Orbits?

- Navigational Anomalies during Earth fly-byes were observed with multiple spacecraft:
  - Galileo: #1 on 10/8/1990 @ altitude of ~960 km; #2 on 12/8/1992 @ altitude of ~305 km;
  - NEAR: 01/22/1998 @ altitude of ~550 km;
  - Cassini: 08/19/1999 @ altitude of ~1,171 km;
  - Stardust: 01/15/2001 @ altitude of ~6,000 km;
  - Rosetta: 03/04/2005 @ altitude of ~1,900 km.
- Are they relevant to the Pioneer anomaly?

c circular orbit
e elliptical orbit
u unbound orbit







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

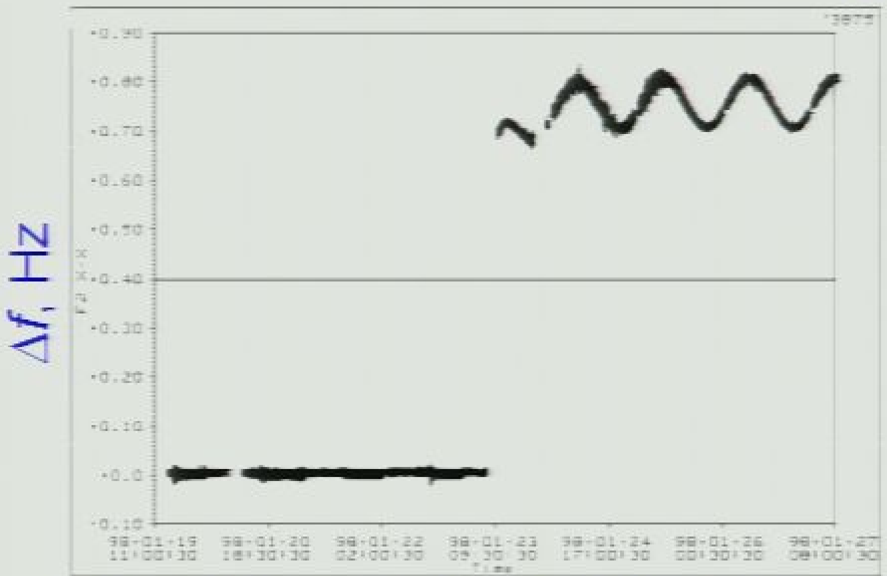
Observed Shifts in Hyperbolic Excess Velocity (V_∞)

- For Earth flybys, the Galileo, NEAR, and Rosetta spacecraft show an anomalous orbital energy increase in the geocentric system.
- Increase in asymptotic velocity v_∞ is 3.92±0.3 mm/s for Galileo, 13.46±0.01 mm/s for NEAR, and 1.80±0.03 mm/s for Rosetta.

Spacecraft (Date)	Nominal V_∞ (km/s)	Shift in V_∞ (mm/s)
Galileo I (1990)	8.95	3.92 ± 0.3
Galileo II (1992)	8.88	-4.6 ± 1.0
NEAR (1998)	6.85	13.46 ± 0.01
Cassini (1999)	16.01	-2.0 ± 1.0
Rosetta (2005)	3.86	1.8 ± 0.03
Messenger (2005)	4.06	0.02 ± 0.01

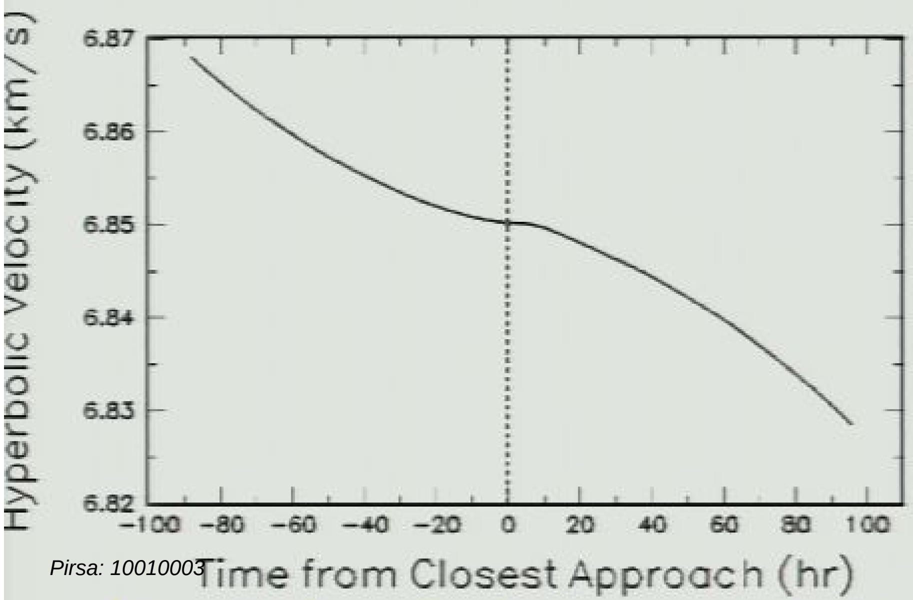
INVESTIGATION OF THE FLYBY ANOMALY

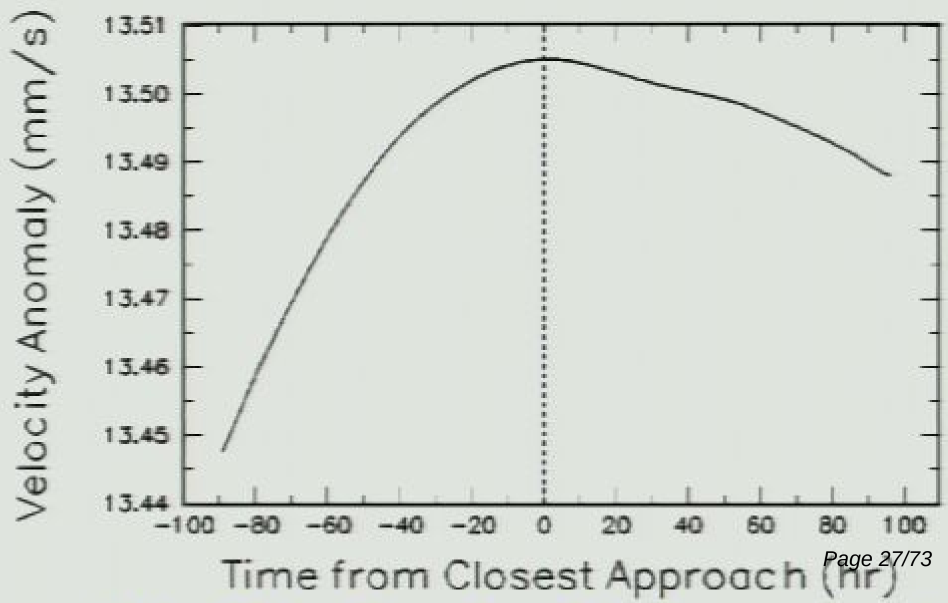
NEAR X-Band Doppler Residuals



Fit to 4 days of data before periapsis

Fit to 4 days of data after periapsis



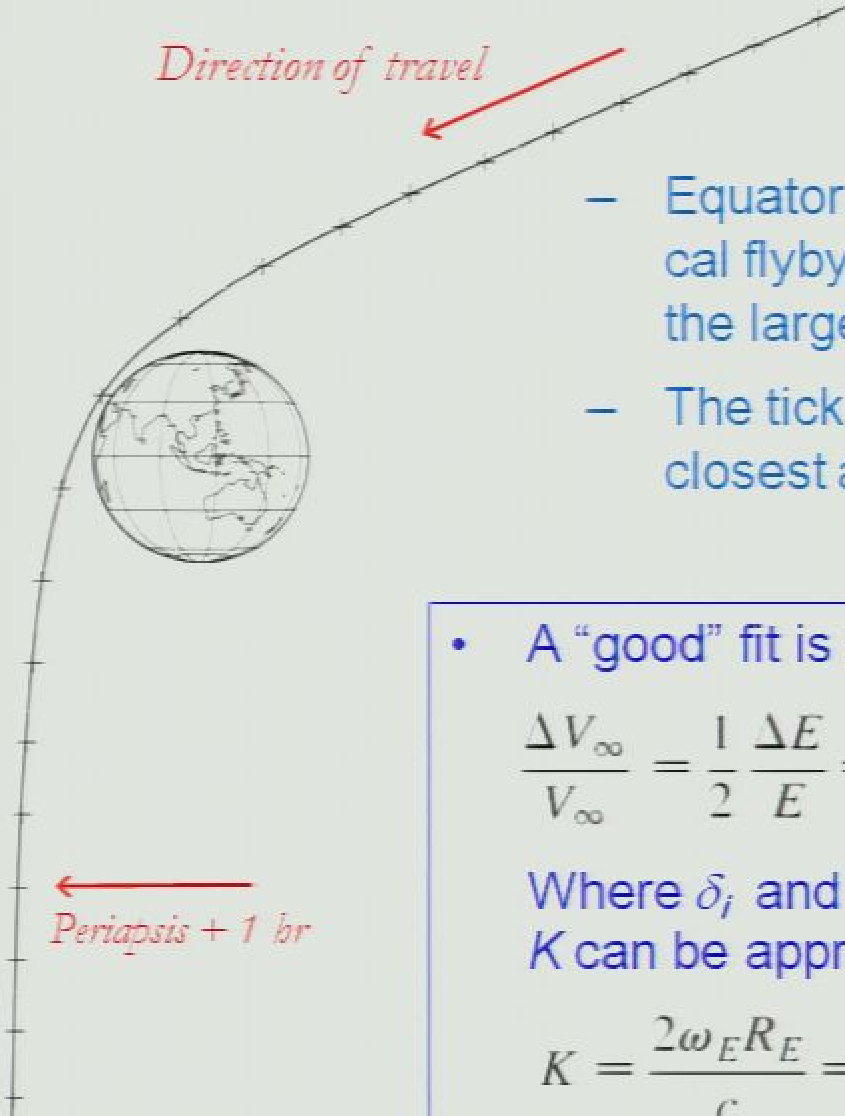


Nominal hyperbolic excess velocity

ΔV_∞: Data fits after & before periapsis

Equatorial Side View of NEAR Earth Flyby (1998)

(Incoming V_∞ Declination -21°, Outgoing V_∞ Declination -72°)



- Equatorial view of the NEAR flyby, the most asymmetrical flyby with respect to the equator and the flyby with the largest energy change.
- The tick marks are at 10-min intervals as measured from closest approach. Other five other flybys are similar.

- A "good" fit is achieved with the following empirical formula:

$$\frac{\Delta V_\infty}{V_\infty} = \frac{1}{2}\frac{\Delta E}{E} = K(\cos\delta_i - \cos\delta_o) \quad \text{where} \quad V_\infty^2 = \mathbf{v}\cdot\mathbf{v} - \frac{2\mu}{r}$$

Where δ_i and δ_o are relative to Earth's equatorial plane.
K can be approximated by

$$K = \frac{2\omega_E R_E}{c} = 3.099 \times 10^{-6}$$

ω_e = Earth's rotation rate (rad/s)
R_e = Earth's radius (km)
c = speed of light (km/s)

Summary of Orbital Parameters

TABLE I. Earth flyby parameters at closest approach for Galileo, NEAR, Cassini, Rosetta, and MESSENGER (M'GER) spacecraft. The altitude H is referenced to an Earth geoid, the geocentric latitude ϕ and longitude λ are listed for the closest approach location. V_f is the inertial spacecraft velocity at closest approach. V_∞ is the osculating hyperbolic excess velocity, the deflection angle (DA) is the angle between the incoming and outgoing asymptotic velocity vectors, the angle I is the inclination of the orbital plane on the Earth's equator, the next four rows represent the right ascension α and declination δ of the incoming (i) and outgoing (o) osculating asymptotic velocity vectors, and M_{SC} is a best estimate of the total mass of the spacecraft during the encounter. The last three rows of the table give the measured change in V_∞, the estimated realistic error in ΔV_∞, and the prediction of ΔV_∞ by Eq. (1). The measured ΔV_∞ for GLL-II is actually —8 mm/s, but it is reduced in magnitude after subtracting out an estimated atmospheric drag of −3.4 mm/s.

Parameter	GLL-I	GLL-II	NEAR	Cassini	Rosetta	M'GER
Date	12/8/90	12/8/92	1/23/98	8/18/99	3/4/05	8/2/05
H (km)	960	303	539	1175	1956	2347
ϕ (deg)	25.2	−33.8	33.0	−23.5	20.20	46.95
λ (deg)	296.5	354.4	47.2	231.4	246.8	107.5
V_f (km/s)	13.740	14.080	12.739	19.026	10.517	10.389
V_∞ (km/s)	8.949	8.877	6.851	16.010	3.863	4.056
DA (deg)	47.7	51.1	66.9	19.7	99.3	94.7
I (deg)	142.9	138.7	108.0	25.4	144.9	133.1
α_i (deg)	266.76	219.35	261.17	334.31	346.12	292.61
δ_i (deg)	−12.52	−34.26	−20.76	−12.92	−2.81	31.44
α_o (deg)	219.97	174.35	183.49	352.54	246.51	227.17
δ_o (deg)	−34.15	−4.87	−71.96	−4.99	−34.29	−31.92
M_{SC} (kg)	2497	2497	730	4612	2895	1086
ΔV_∞ (mm/s)	3.92	−4.6	13.46	−2	1.80	0.02
σ_{V_∞} (mm/s)	0.3	1.0	0.01	1	0.03	0.01
Equation (1) (mm/s)	4.12	−4.67	13.28	−1.07	2.07	0.06

INVESTIGATION OF THE FLYBY ANOMALY

Search for the origin of the anomaly

- Non-Dependences
  - Asymptotic right ascension: incoming or outgoing
  - Direction to sun or moon
  - Close approach distance
  - Orbital deflection
  - Orbital inclination
- Possible Causes?
  - A true force (non-Newtonian) ?
  - Doppler modeling error ?
  - Coordinate frame problem ?
  - Earth-bound dark matter ?
  - Other ?

— The cause is yet unknown

- Possible Cause: Since GLL1 (1990) many models were investigated:
  - Earth's gravity; Earth's geo-magnetic field; Earth's albedo radiation; Earth's atmospheric drag; Earth ocean tides; Earth solid tides
  - Third body effects; solar radiation pressure
  - Spacecraft forces; Spacecraft spin biases
  - General relativity; non-Newtonian (Yukawa potential)
  - Spin-rotation coupling
  - Expansion of the universe

— All Dismissed

Investigation of the fly-by anomaly is still ongoing

Recovery of the Pioneers' Telemetry Data

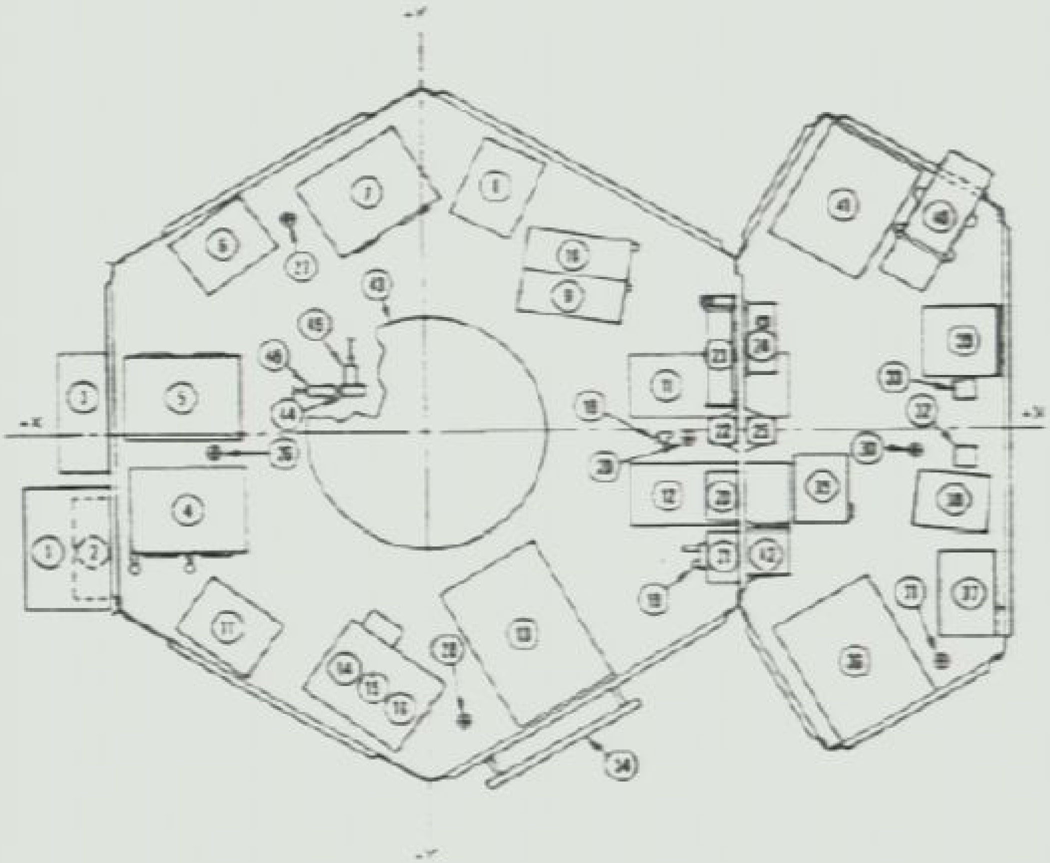
- Pioneer Project Documents (1966-2003) @ Ames:
  - All Pioneer 10 and 11 Project documents (design, fabrication, testing, calibrations, quarterly reports, memoranda, etc.)
  - Maneuver records, spin-rate data, significant events of the craft, etc.
  - Lack of funding resulted in improper storage, near destruction
- Master Data Record (MDR): 40GB 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

THE STUDY OF THE PIONEER ANOMALY

Recovery of the Pioneers' Telemetry Data (MDR)

Each craft: ~114 parameters



INTERNAL EQUIPMENT ARRANGEMENT

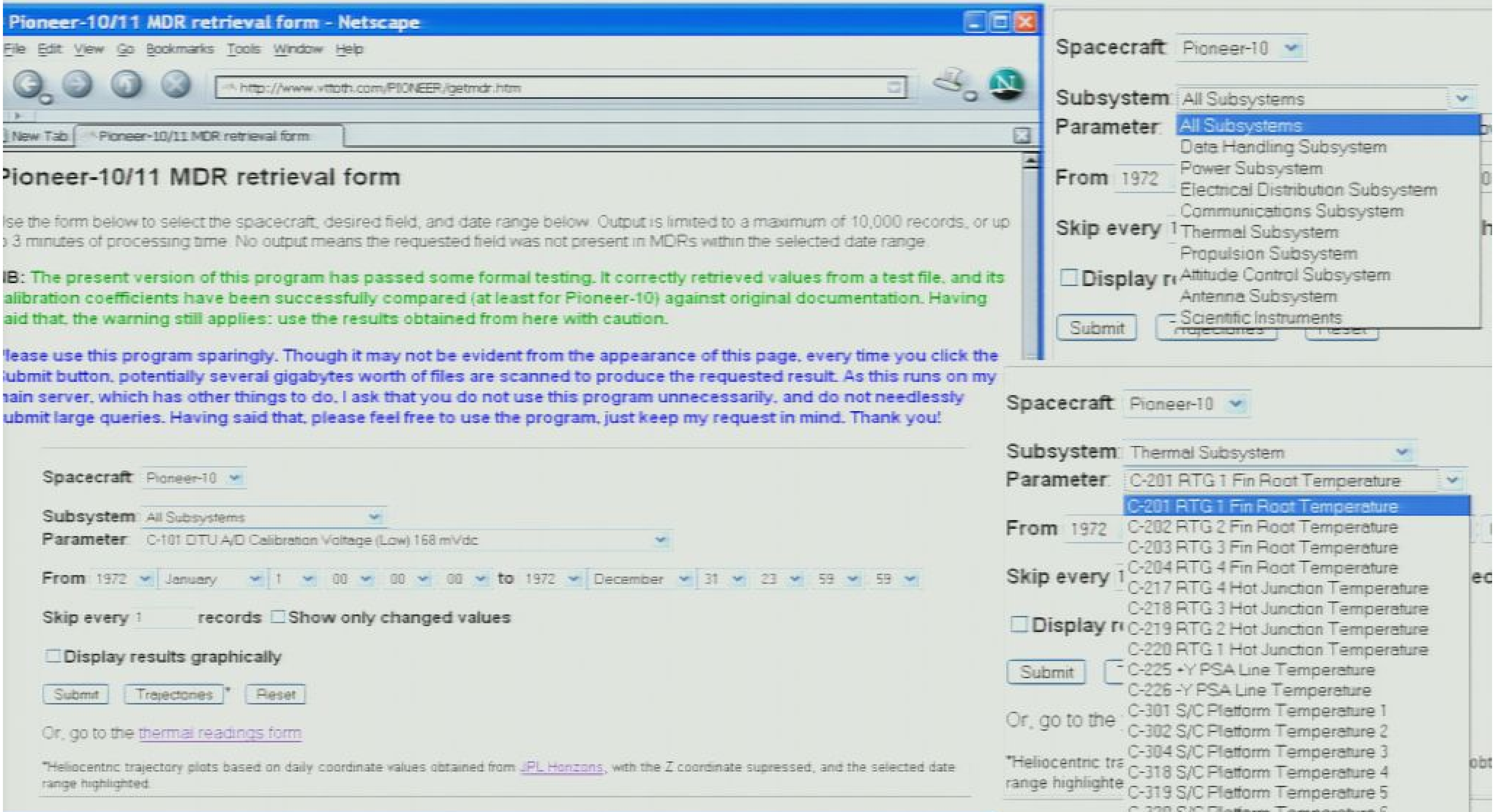
Figure 3.1-1

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	0201
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	0593
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	0298
33	Despin Sensor No. 2	Attitude Control	0271
34	Shunt Radiator Assembly	Electrical Power	0608
35	Magnetometer Electronics (JPL/Smith)	Instruments	0650
36	Imaging Photo — Polarimeter (U/Arizona/Gehrels)	Instruments	0657
37	Geiger Tube Telescope (U/Iowa/Van Allen)	Instruments	0653
38	Ultraviolet Photometer (USC Judge)	Instruments	0656
39	Trapped Radiation Detector (UCSD/Fillius)	Instruments	0655
40	Infrared Radiometer (C.I.T. Munch)	Instruments	0658
41	Charged Particle Instrument (U/Chicago/Simpson)	Instruments	0652
42	Meteoroid Detector Electronics (LaRC Kinard)	Instruments	0660
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

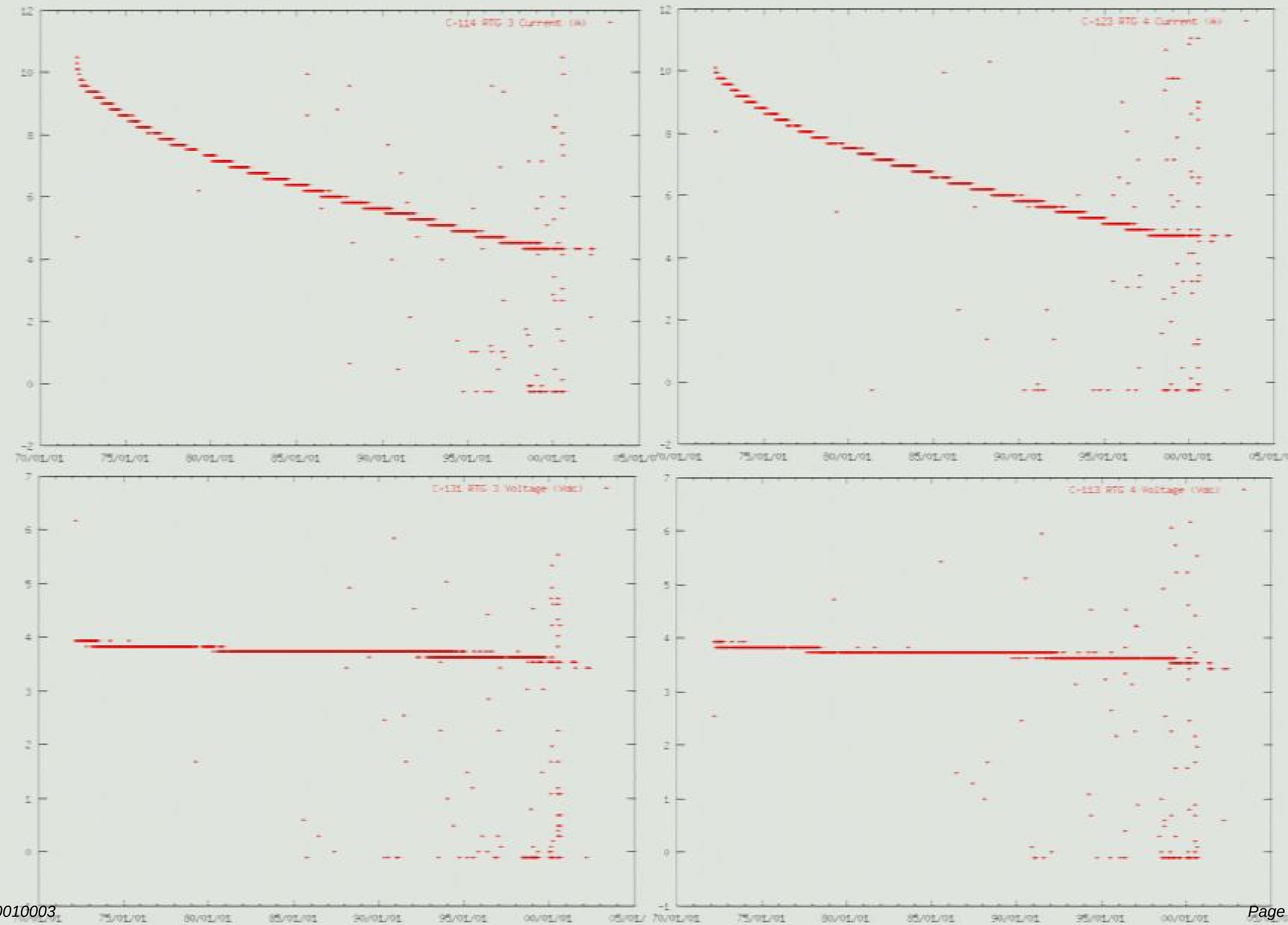
Master Data Records Web-Retrieval Form



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

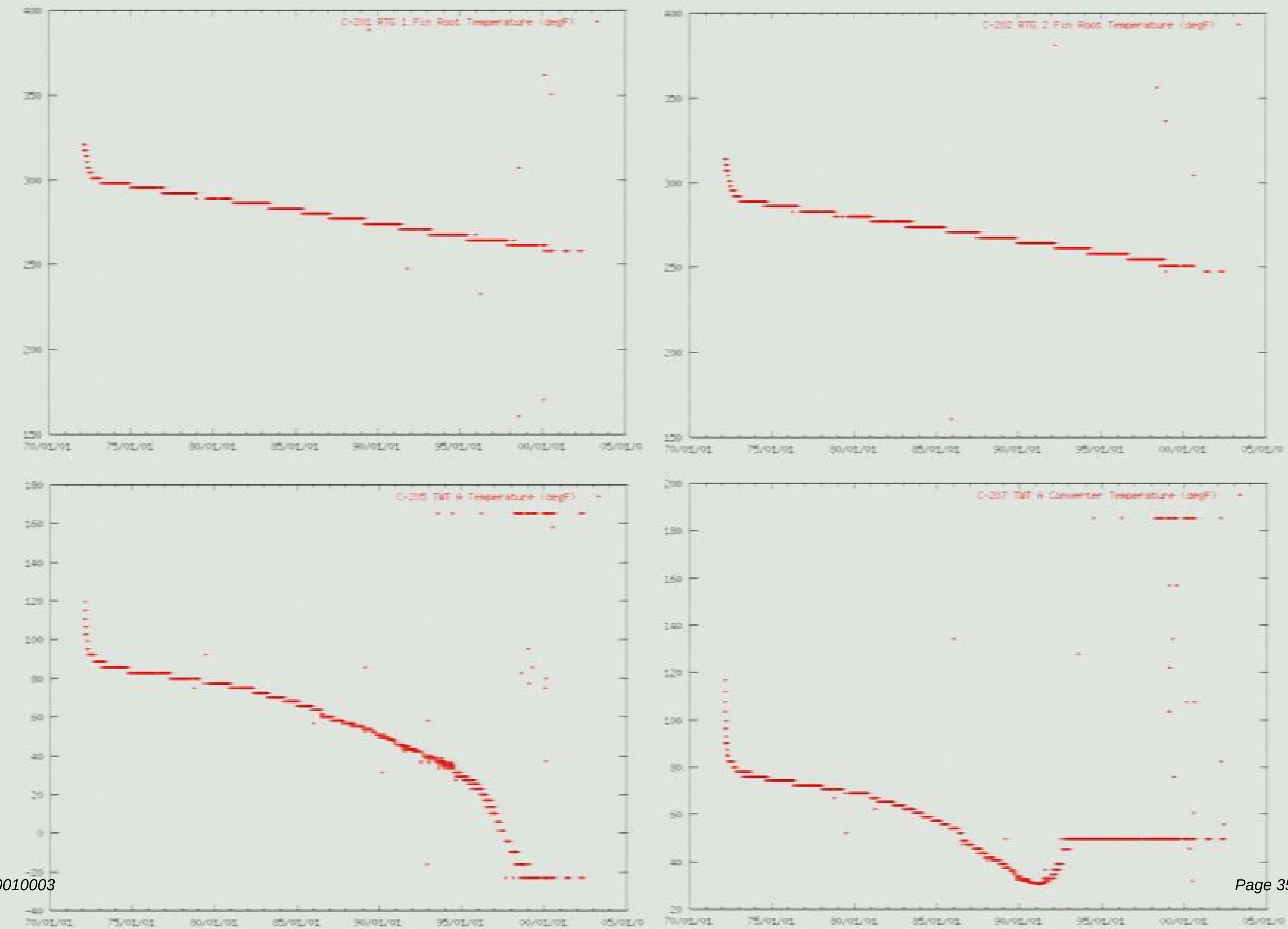
THE STUDY OF THE PIONEER ANOMALY

RTGs 3 & 4: Current & Voltage from MDRs



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

Thermal History on Pioneer 10



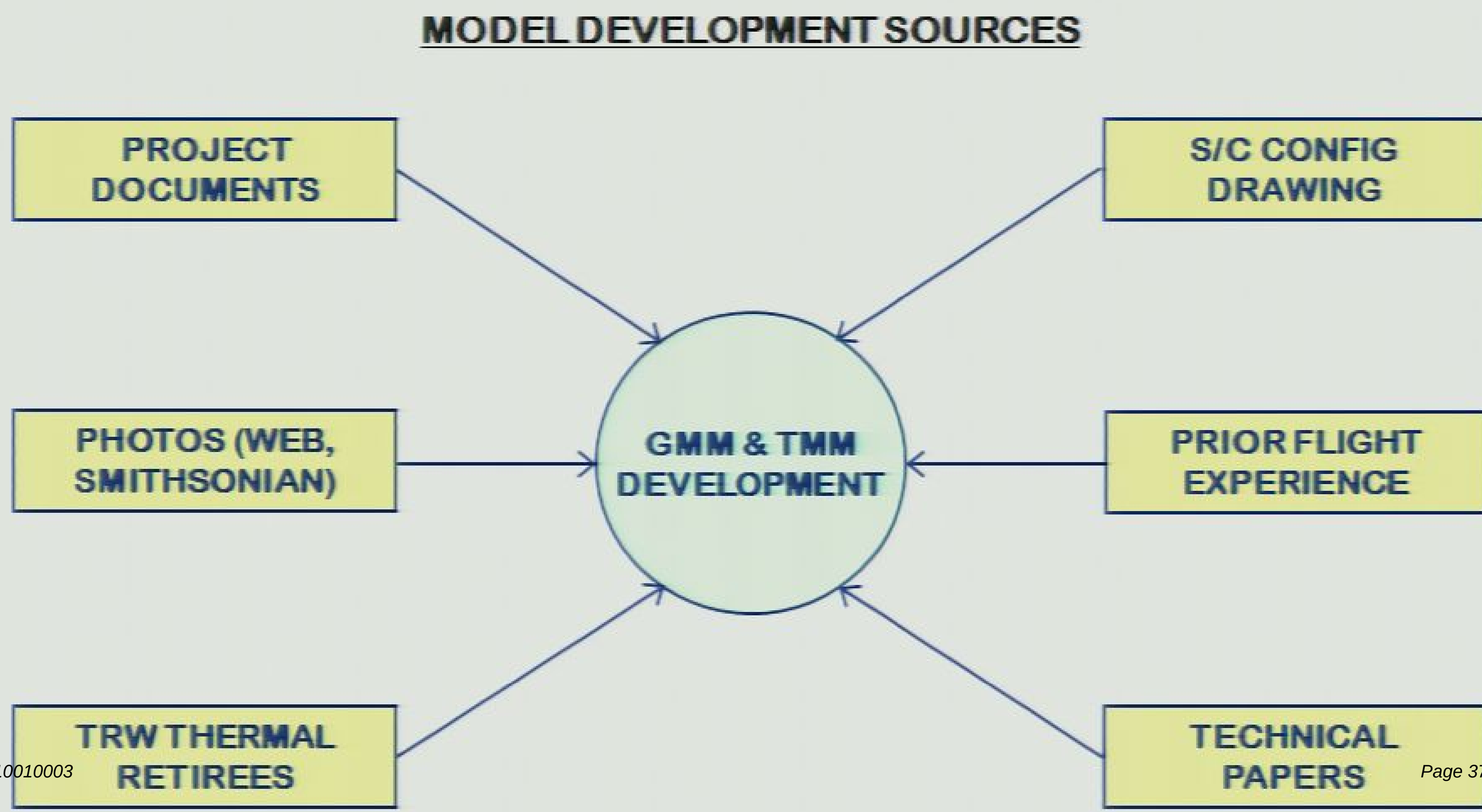
Objectives of Thermal Engineering Study

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 37+ 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

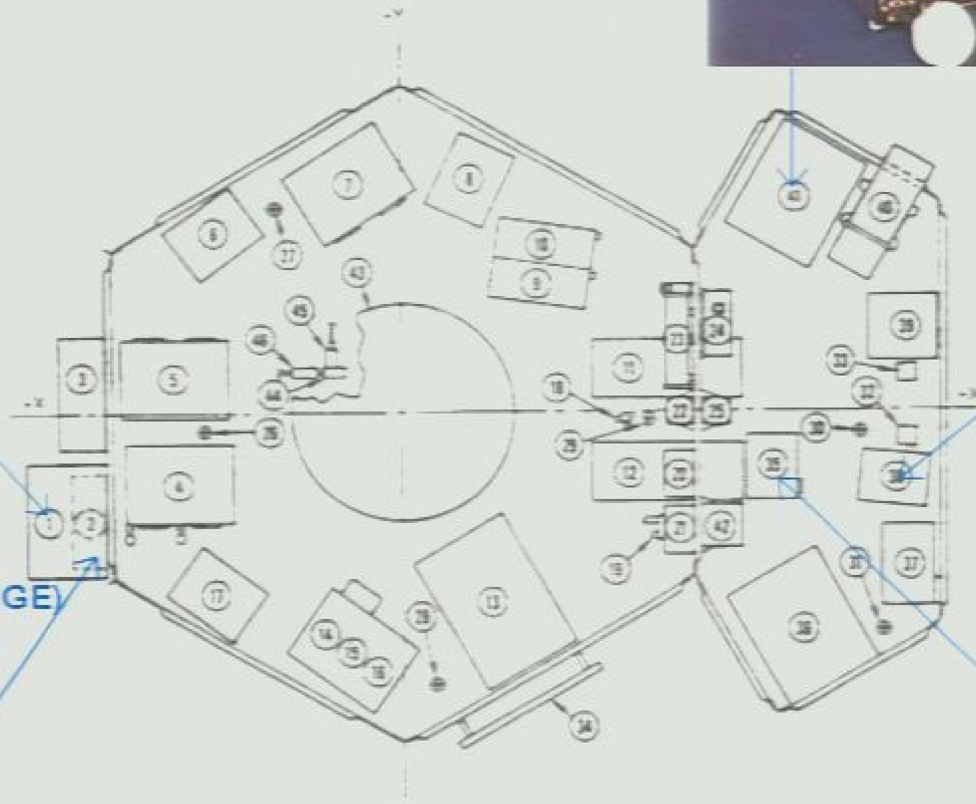
THE STUDY OF THE PIONEER ANOMALY

Science Instrument Locations

CHARGED PARTICLE DETECTOR (UC)

AMD TELESCOPE (GE)

UV PHOTOMETER (USC)



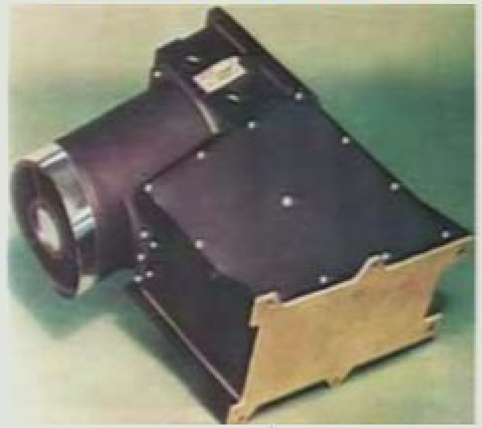
MAGNETOMETER ELECTRONICS (JPL)

AMD ELECTRONICS (GE)

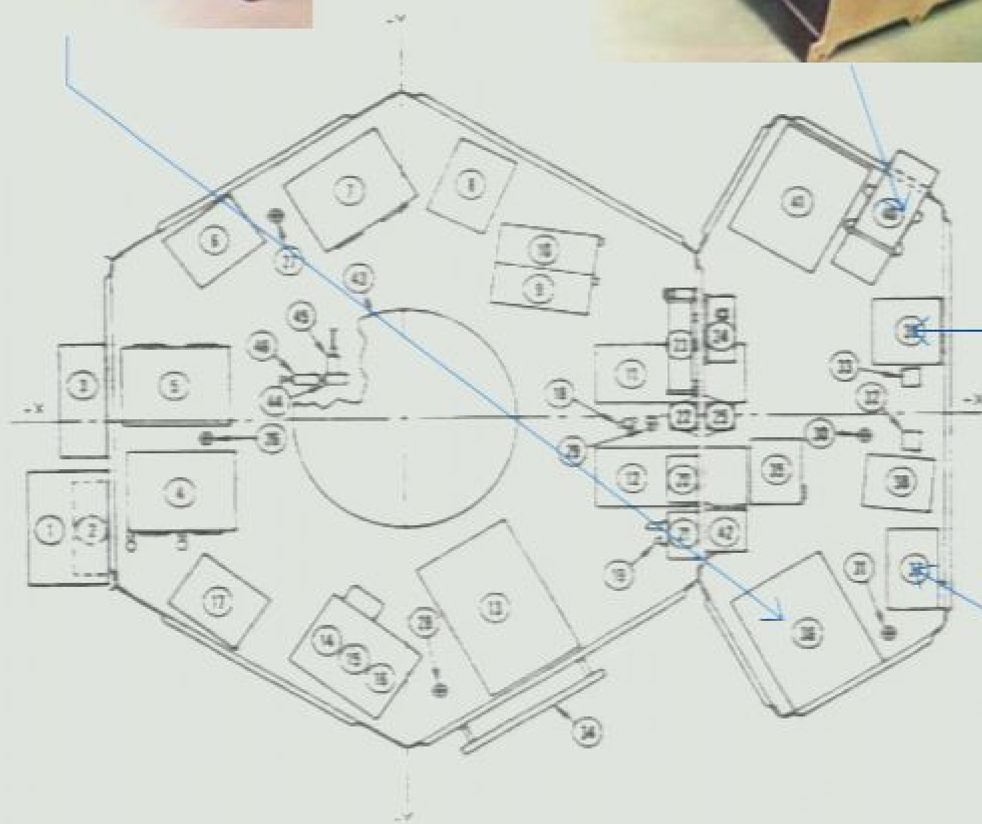
Science Instrument Locations

IMAGING PHOTOPOLARIMETER (UA)

IR RADIOMETER (CIT)



TRAPPED RADIATION DETECTOR (UCSD)



GEIGER TUBE TELESCOPE (UI)

Pioneer Spacecraft Configuration

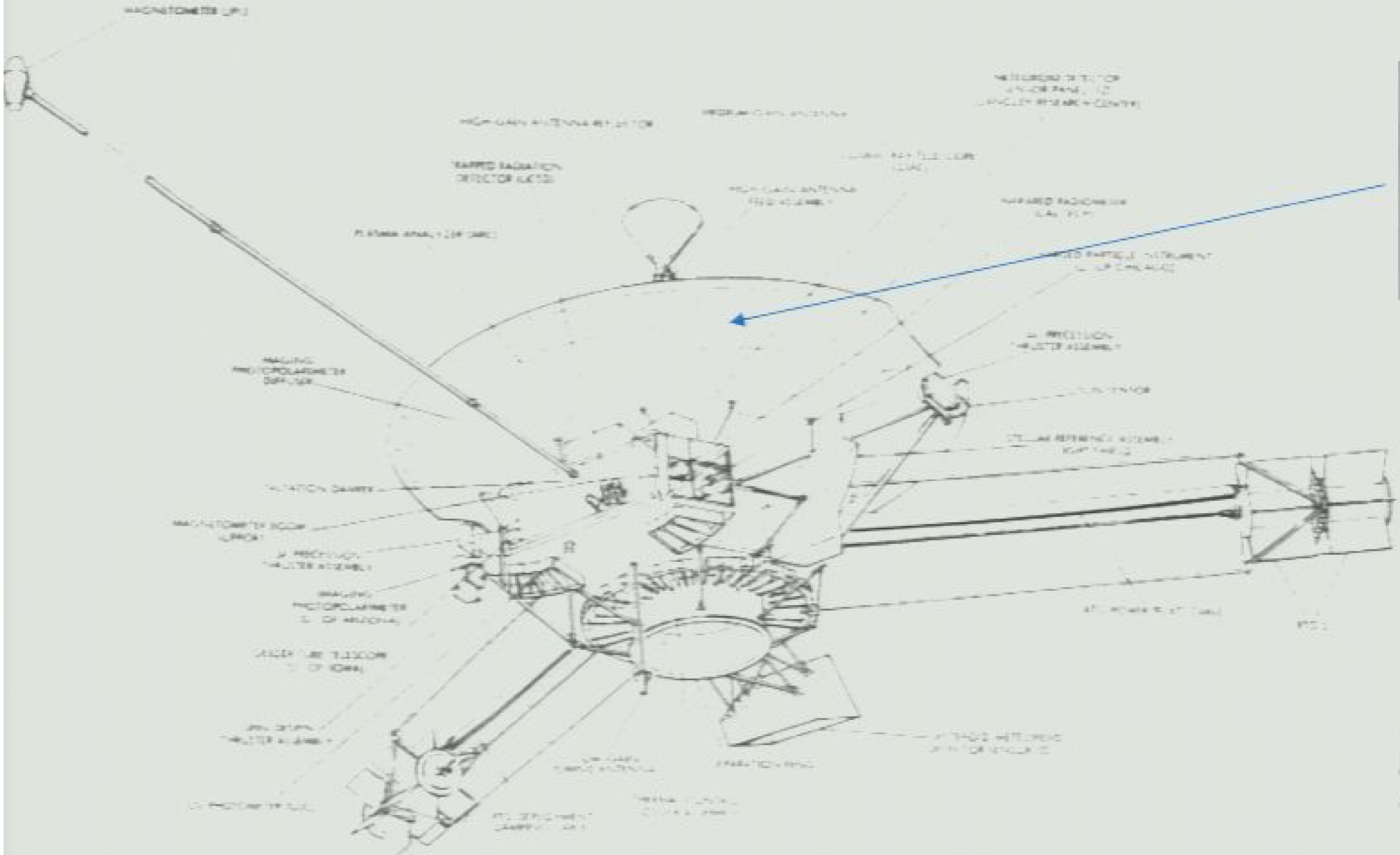
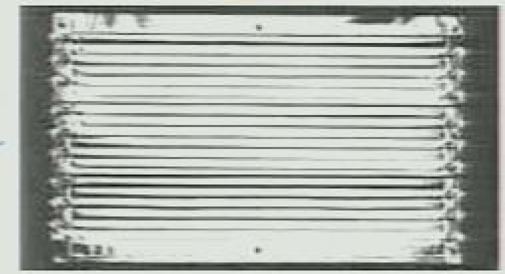
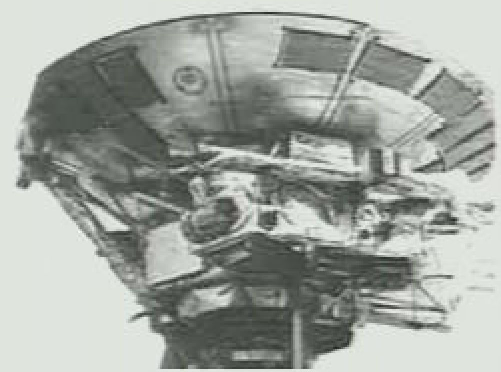


FIGURE 2-1. PIONEER F/G SPACECRAFT

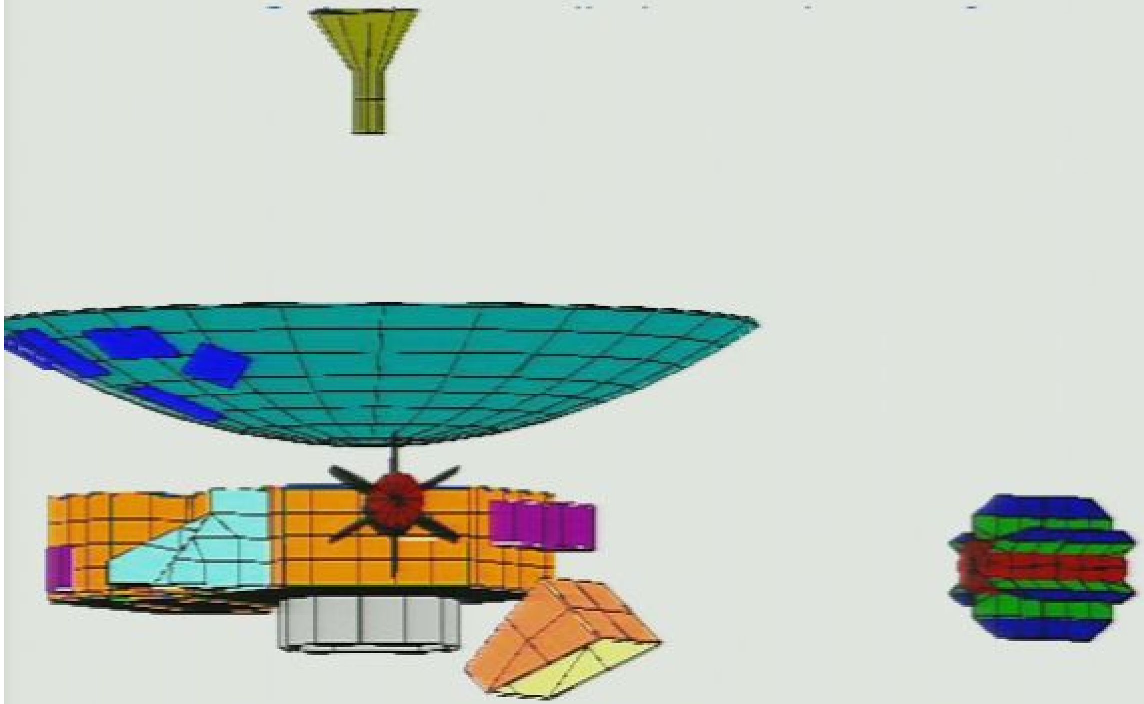
METEOROID DETECTOR
(LeRC)





Geometric Mathematical Model (GMM)

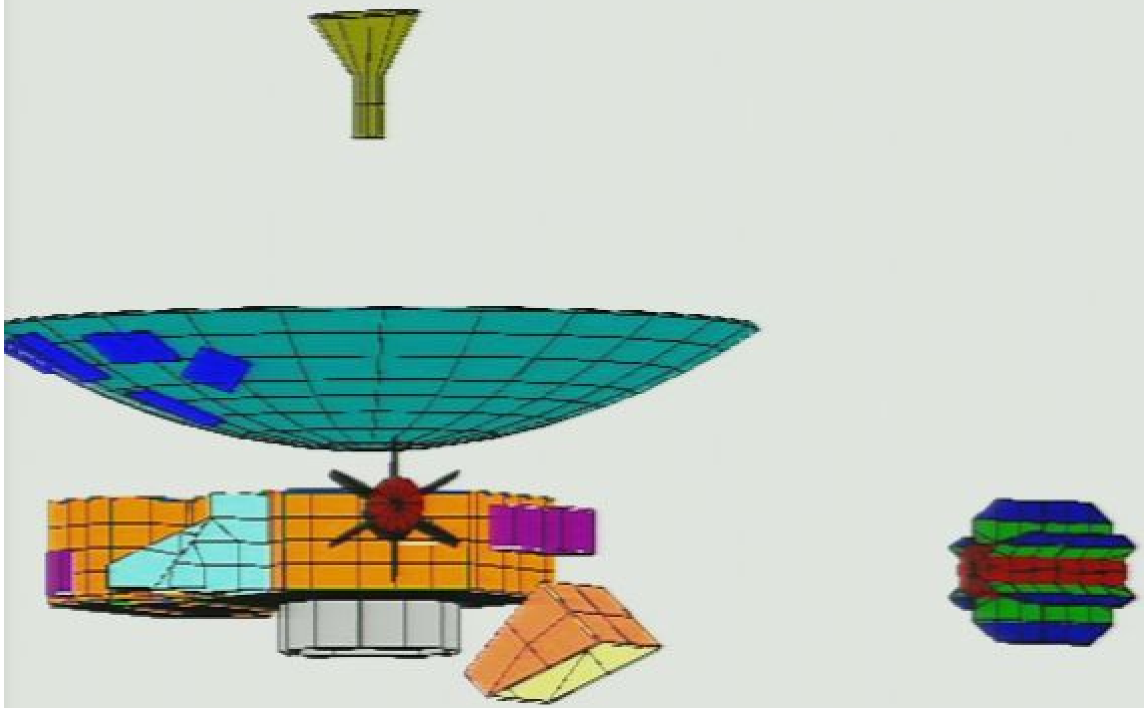
- Used TSS (Thermal Synthesizer System) – one of the standard thermal industry tools



Pioneer 10 GMM

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

Pioneer Vehicle Geometric Math Model

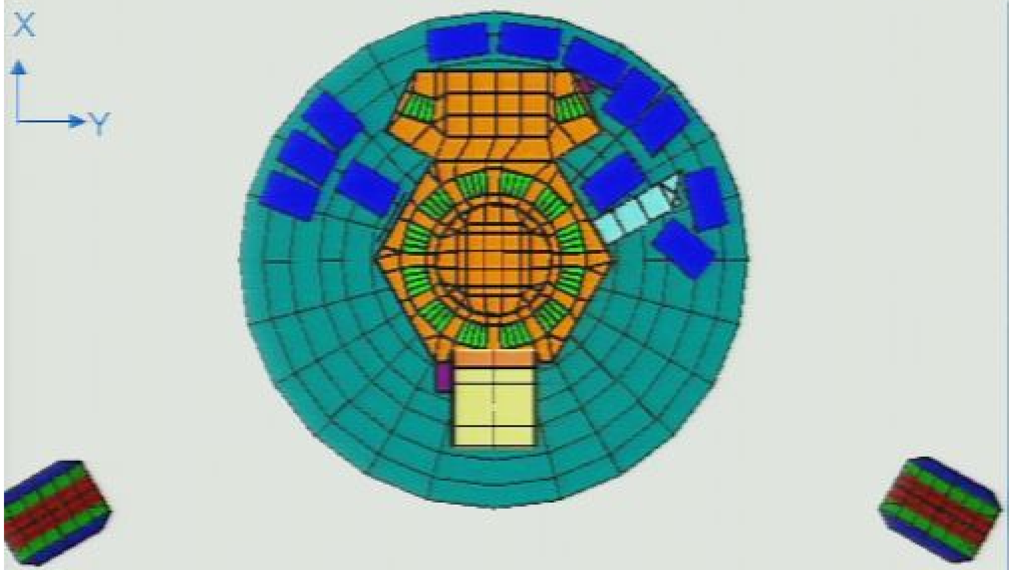


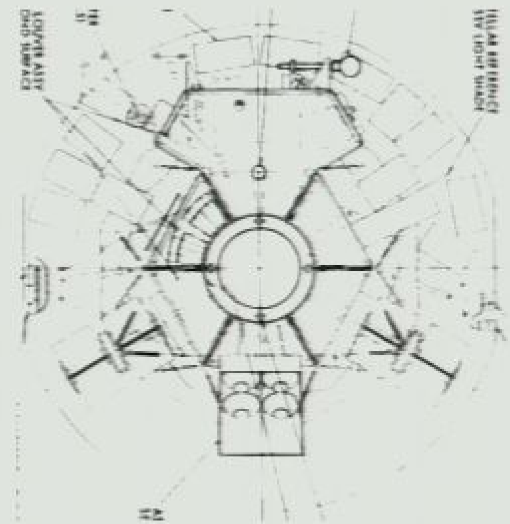
Pioneer 10 GMM

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

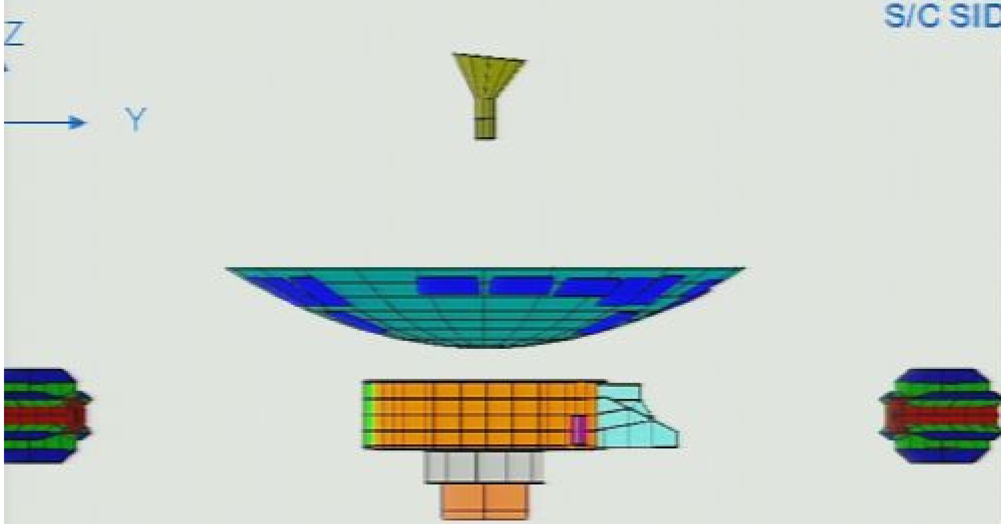
Pioneer Vehicle Geometric Math Model

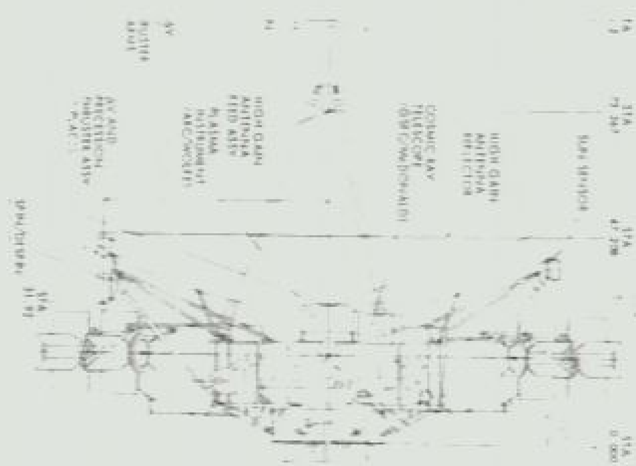
S/C BOTTOM VIEW





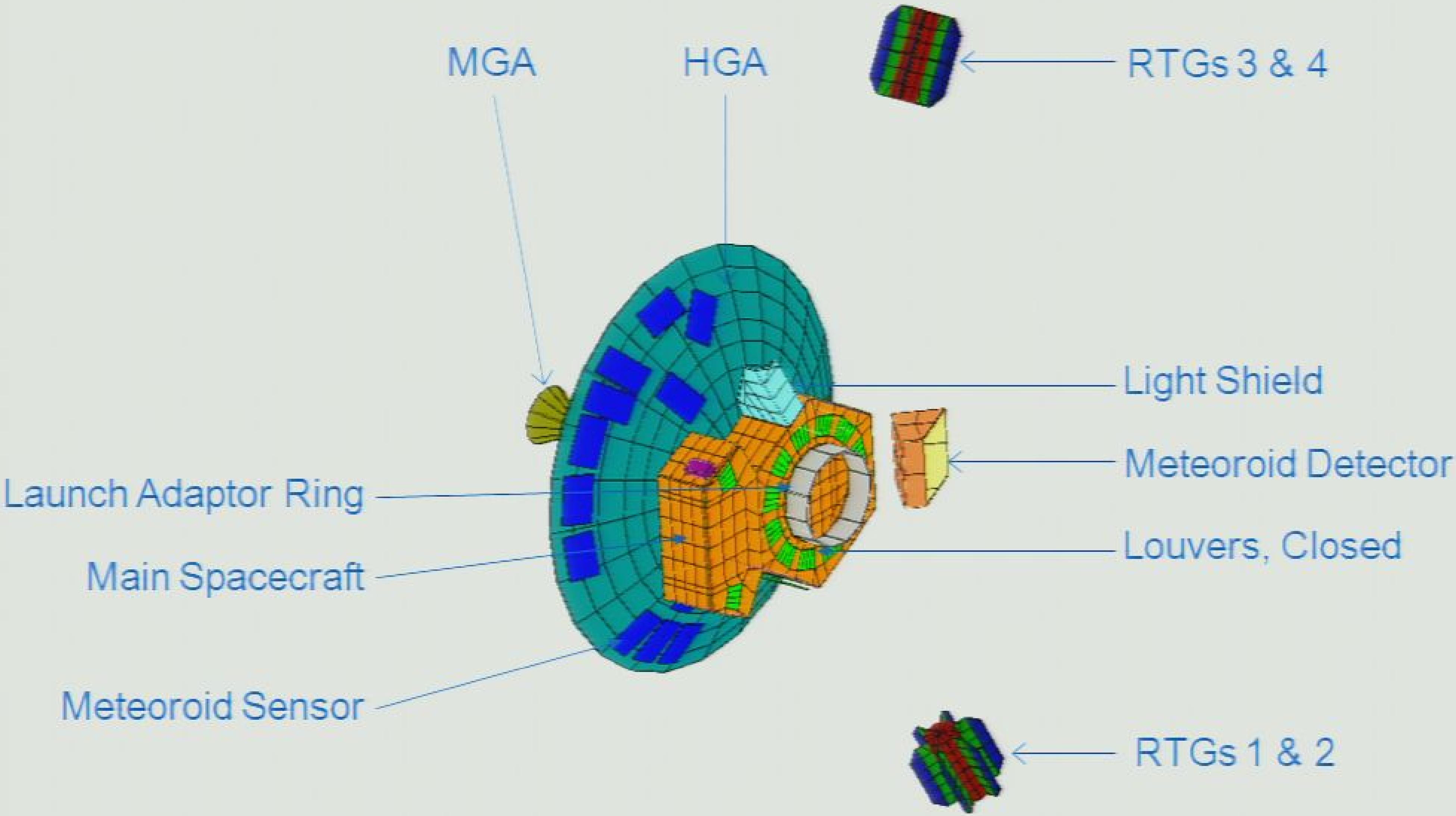
S/C SIDE VIEW





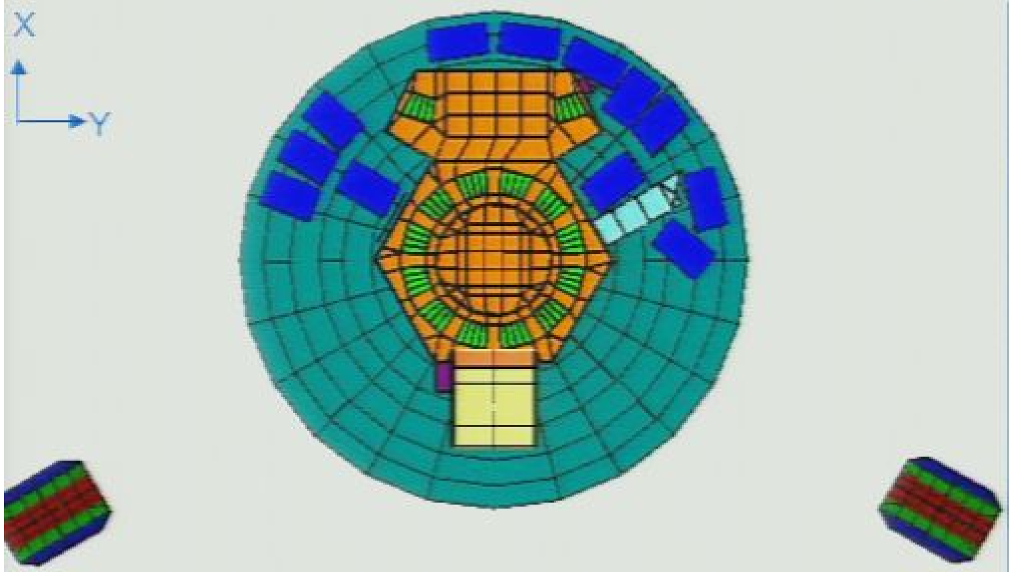
Note: RTGs are Deployed in GMM, but Shown Stowed in S/C Configuration Drawing

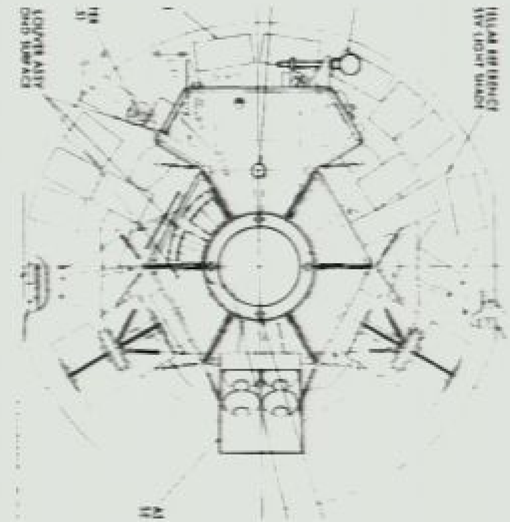
Thermal Geometric Model (Closed Louvers)



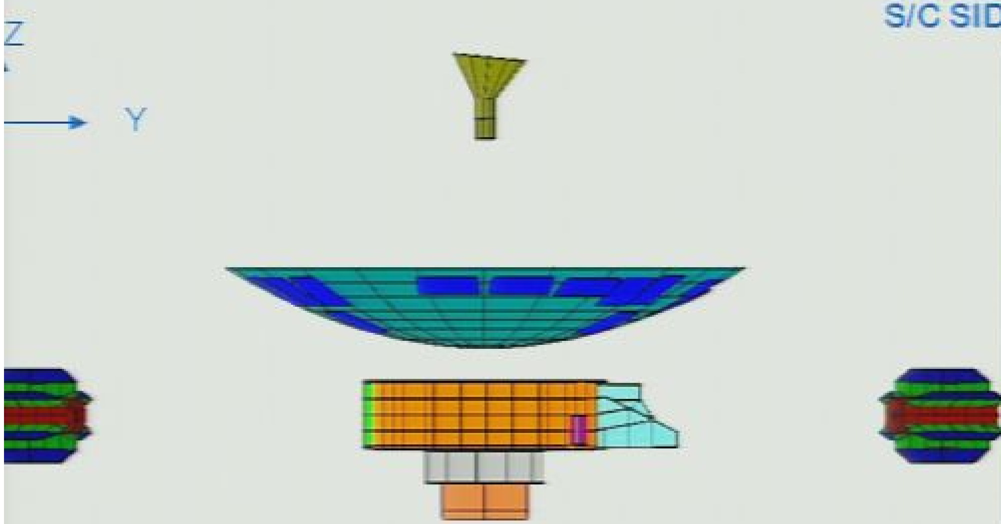
Pioneer Vehicle Geometric Math Model

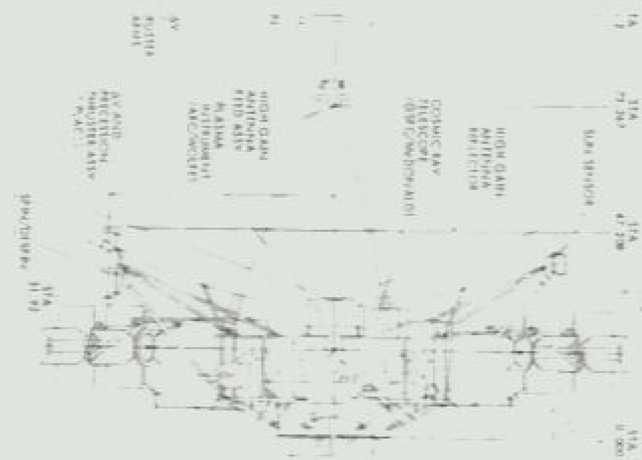
S/C BOTTOM VIEW





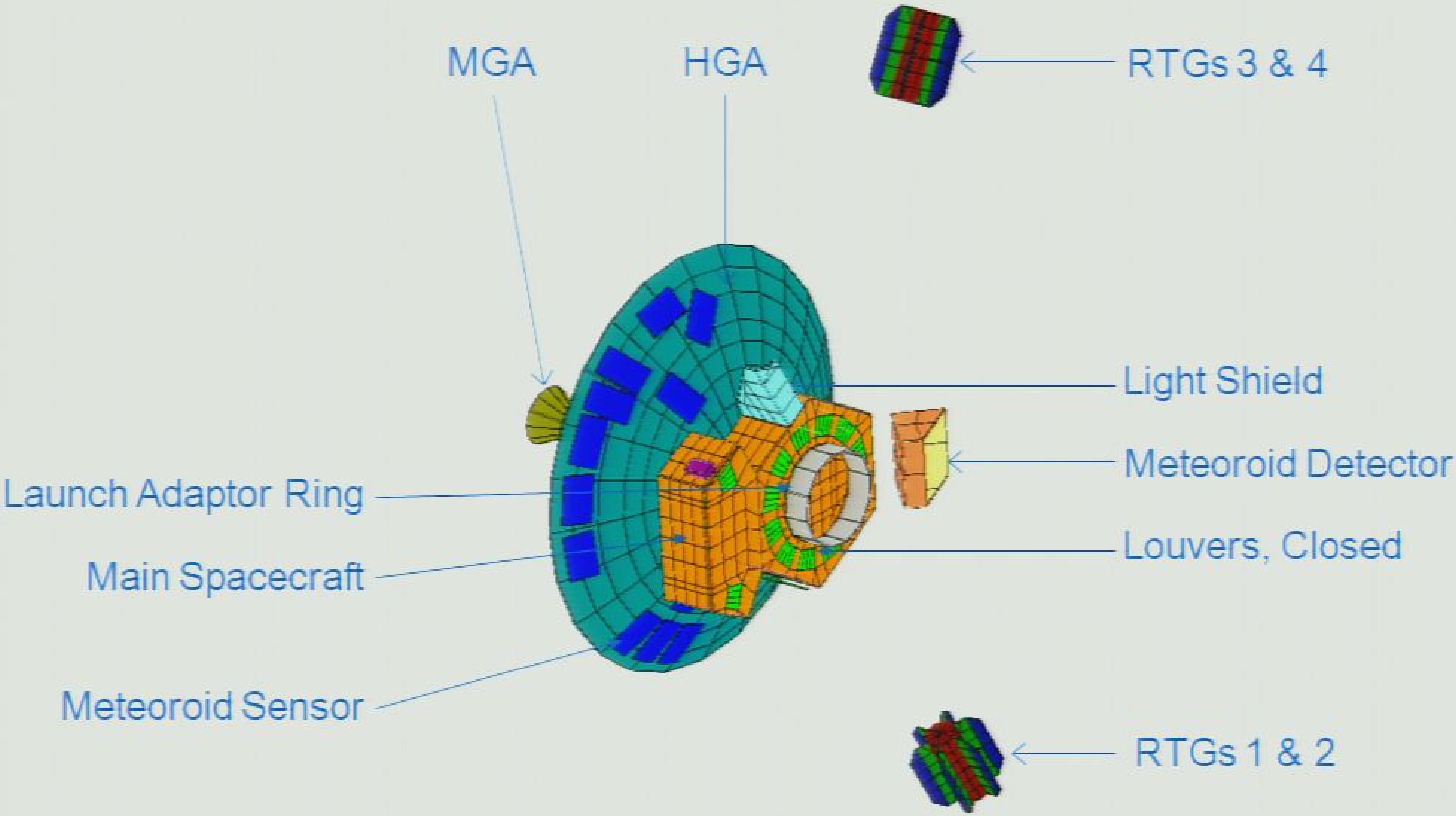
S/C SIDE VIEW



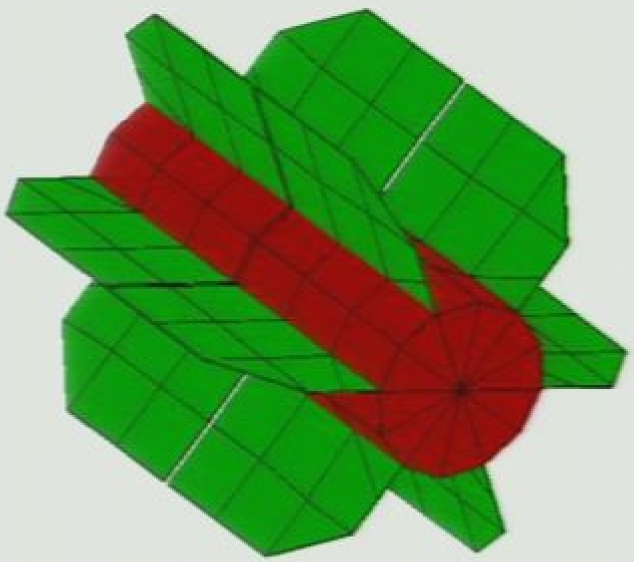


Note: RTGs are Deployed in GMM, but Shown Stowed in S/C Configuration Drawing

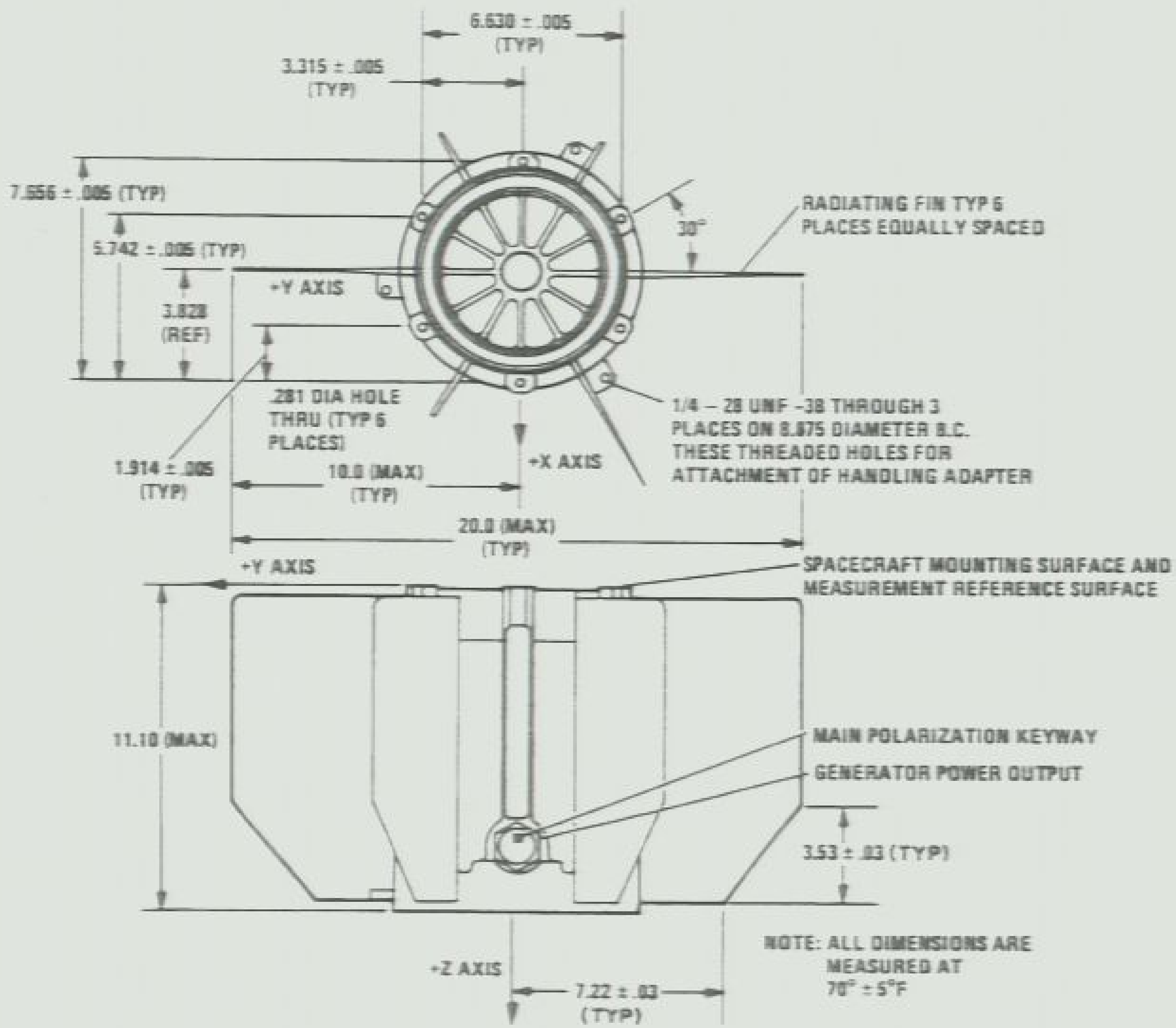
Thermal Geometric Model (Closed Louvers)



SNAP-19 RTG Modeling



Pioneer 10/11 GMM

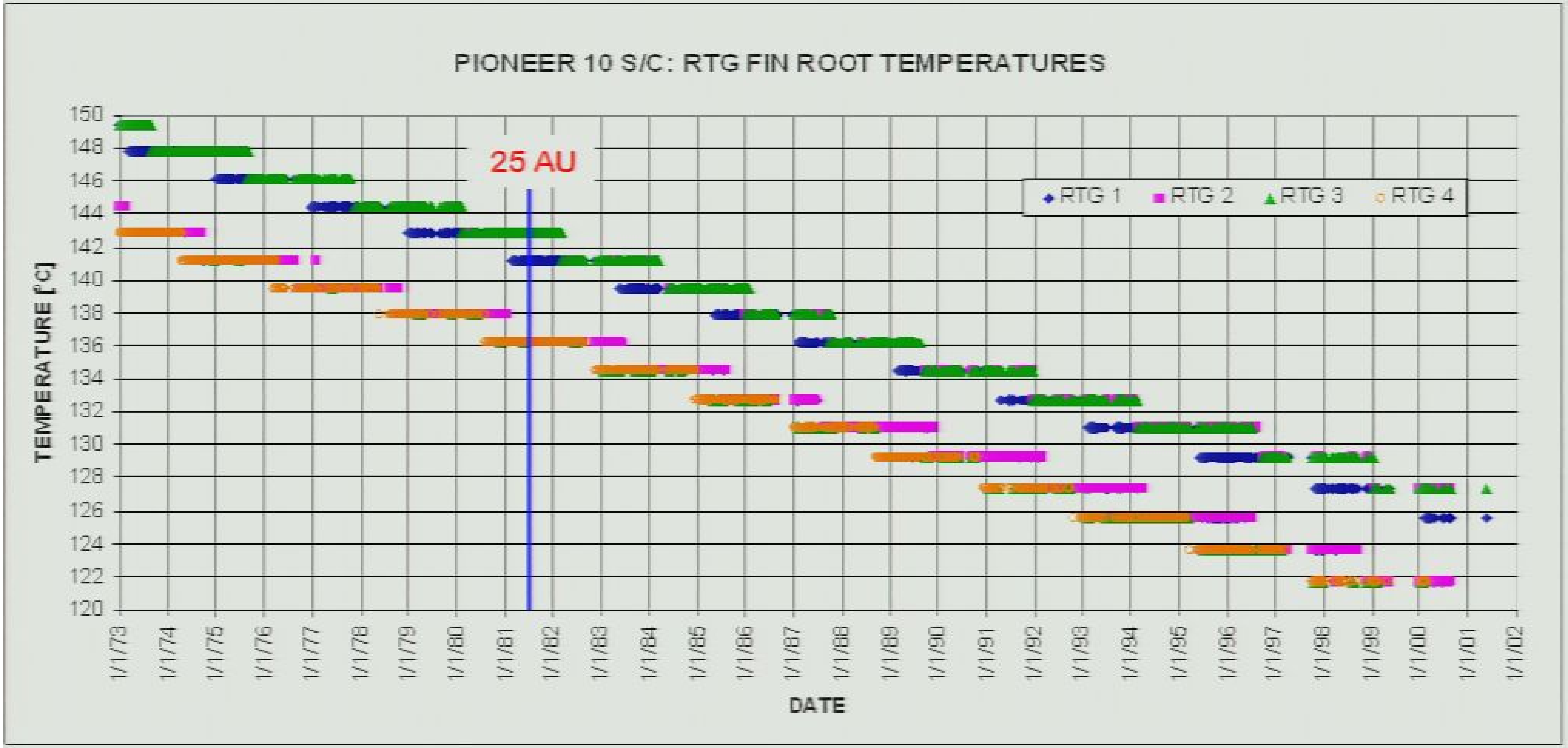


Thermal Mathematical Model (TMM)

- 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

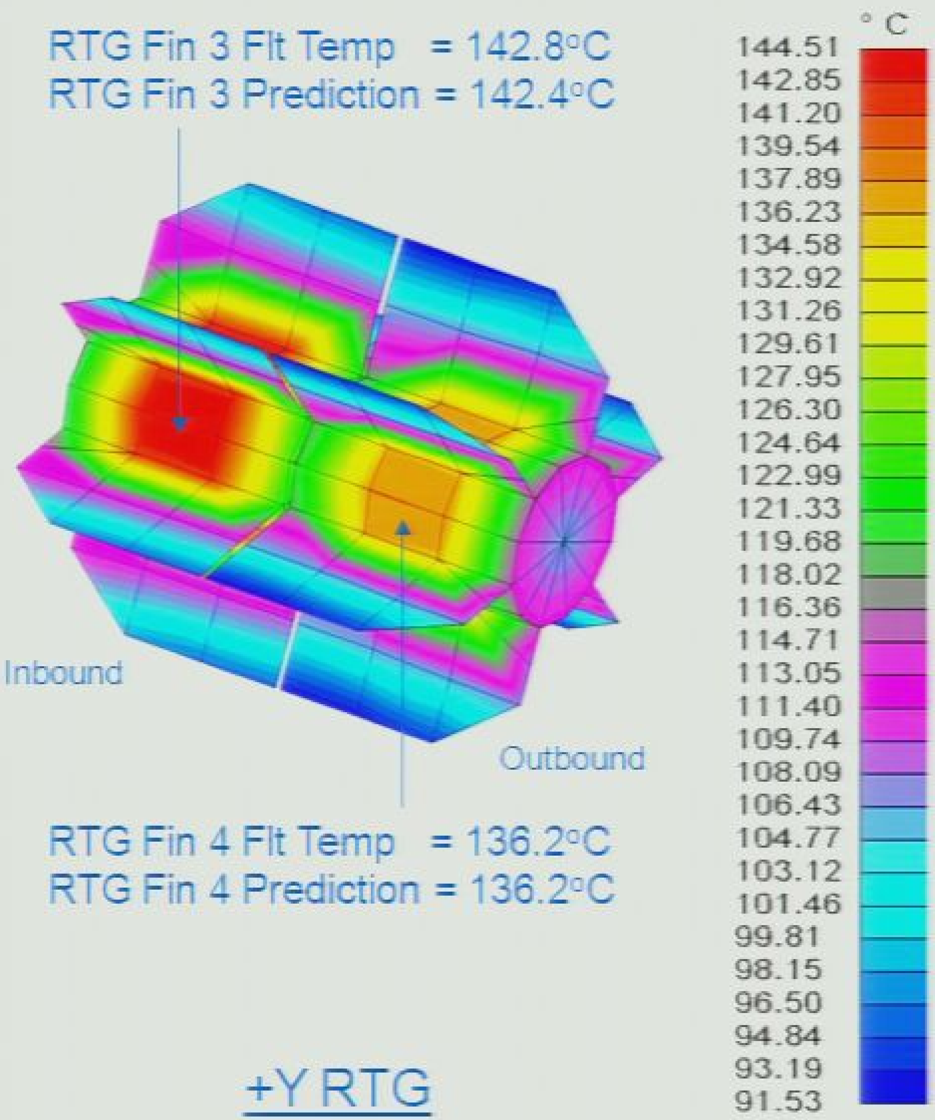
Pioneer 10 S/C Temperature Telemetry



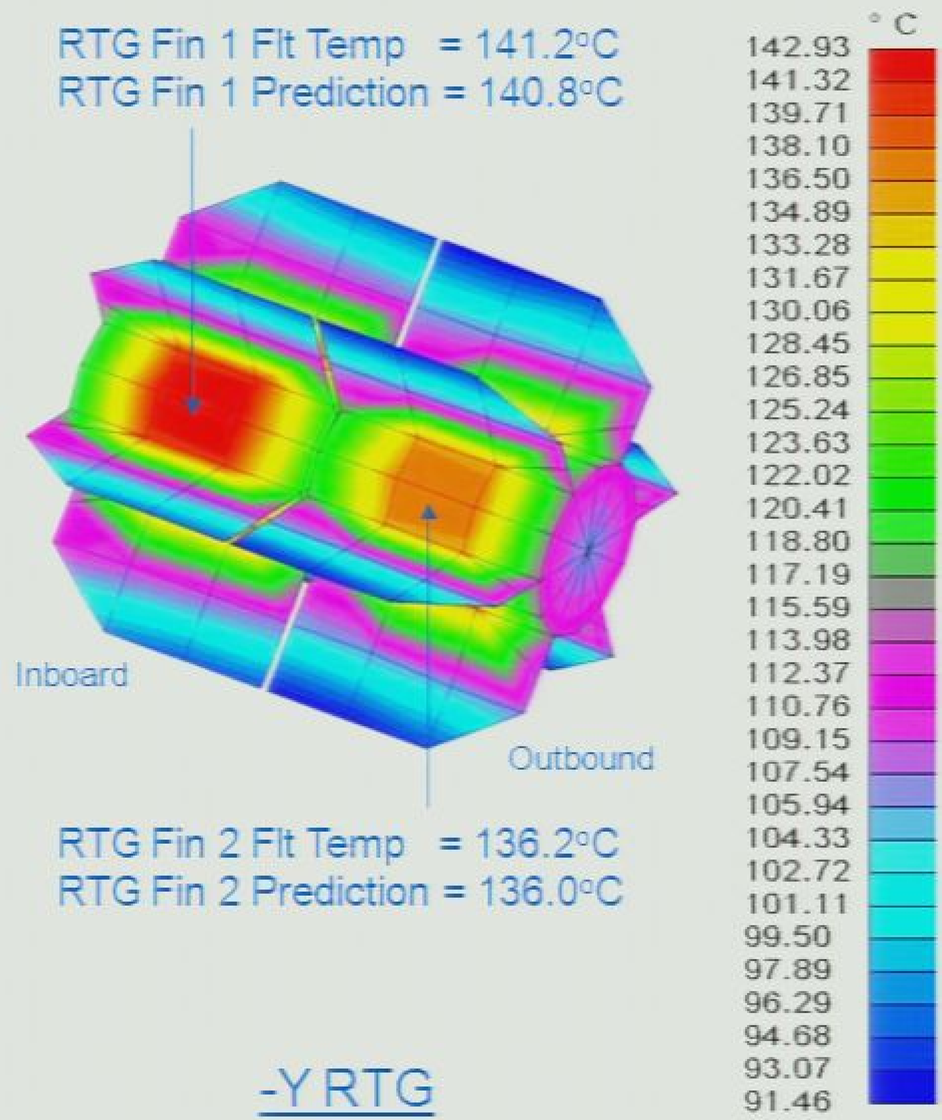
RTG fin root temperature telemetry is used as boundary condition nodes in the TMM (RTGs 1 & 3 are inboard, RTGs 2 & 4 are outboard RTGs

THE STUDY OF THE PIONEER ANOMALY

Measured Versus Predicted RTG Temps



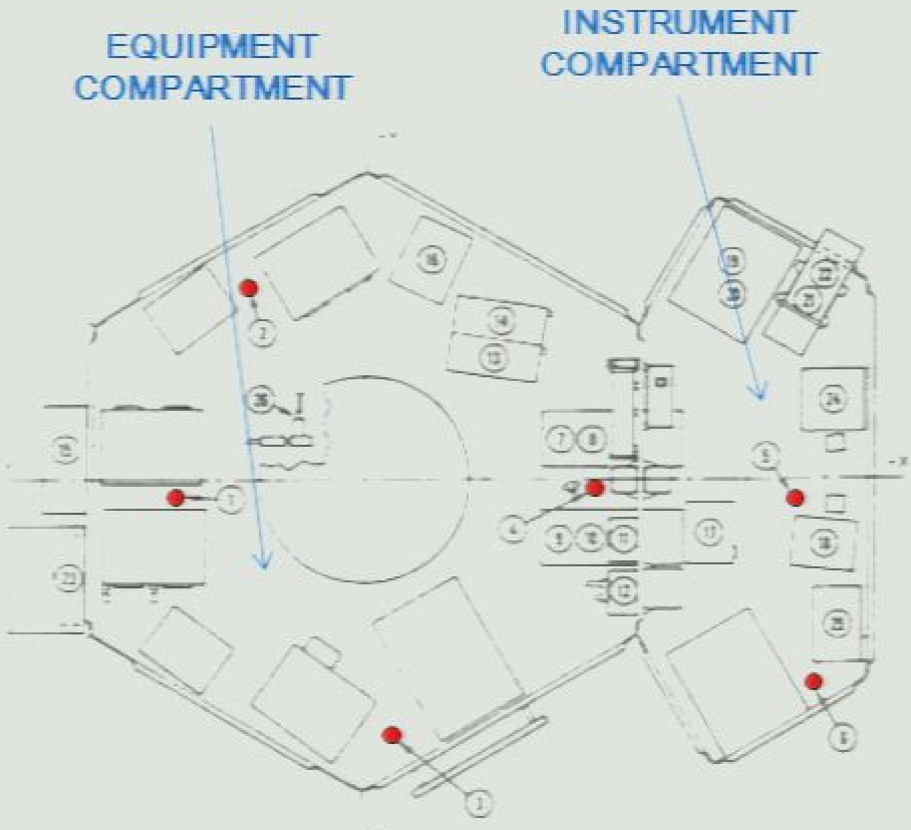
+Y RTG



-Y RTG

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

Panel Temperature Telemetry Locations

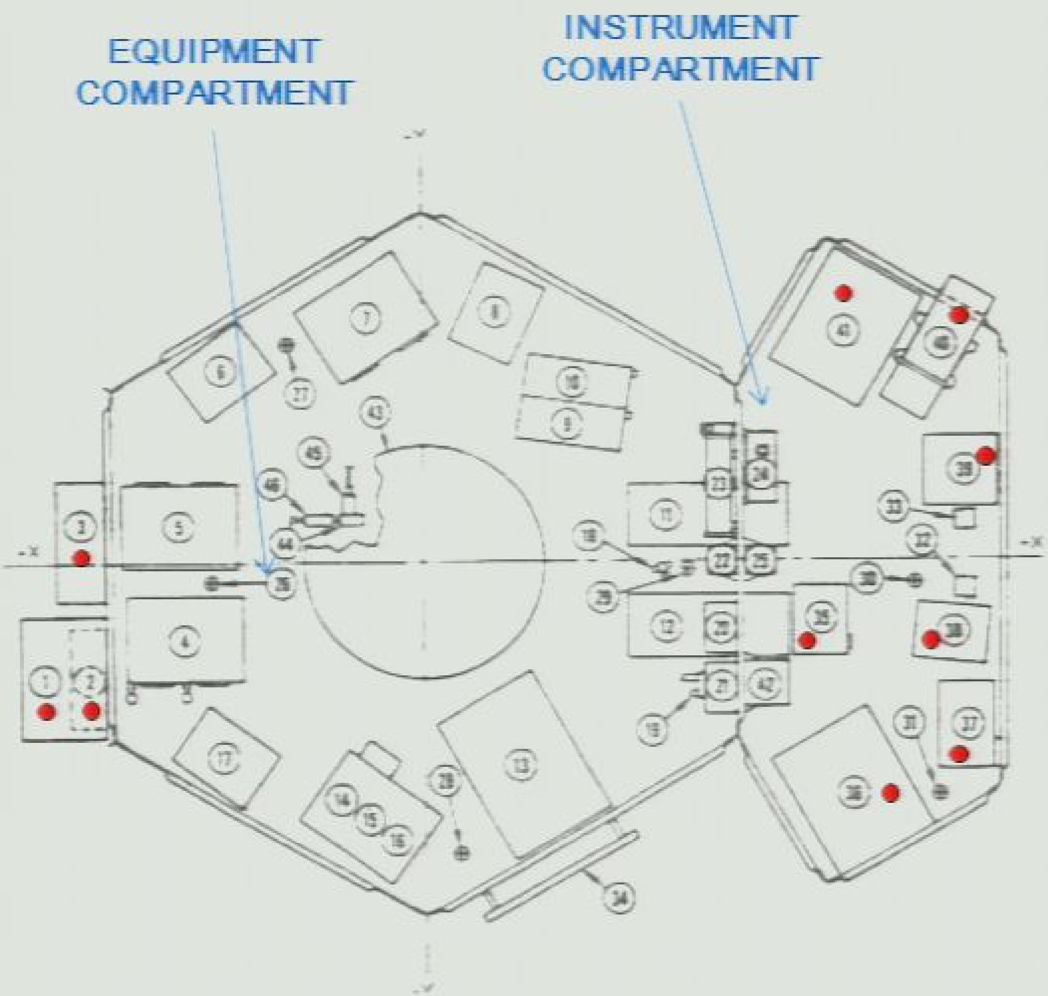


S/C Bottom View, -Z Side

TEMPERATURE SENSOR LOCATION

IDENTIFICATION NO.	TLM Word	DESCRIPTION	LOCATION
		Thermal	
[illegible]	C-301	Equipment Platform	On platform
[illegible]	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	
[illegible]	C-205	TWTA-A	Collector, TWTA-A
8	C-207	Converter, TWTA-A	Power Supply, TWTA-A
9	C-208	TWTA-B	Collector, TWTA-B
10	C-221	Converter, TWTA-B	Power Supply, TWTA-B
[illegible]	C-206	Driver-A, Auxiliary Oscillator	TCXO Subassembly
12	C-223	Driver-B, Auxiliary Oscillator	TCXO Subassembly
[illegible]	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-112	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 1.1-2)
	E-128	Cosmic Ray Detector(GSFC/McDonald)	Internal to unit
	E-107	Arc Plasma Detector(Arc/White)	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-328	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-128	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

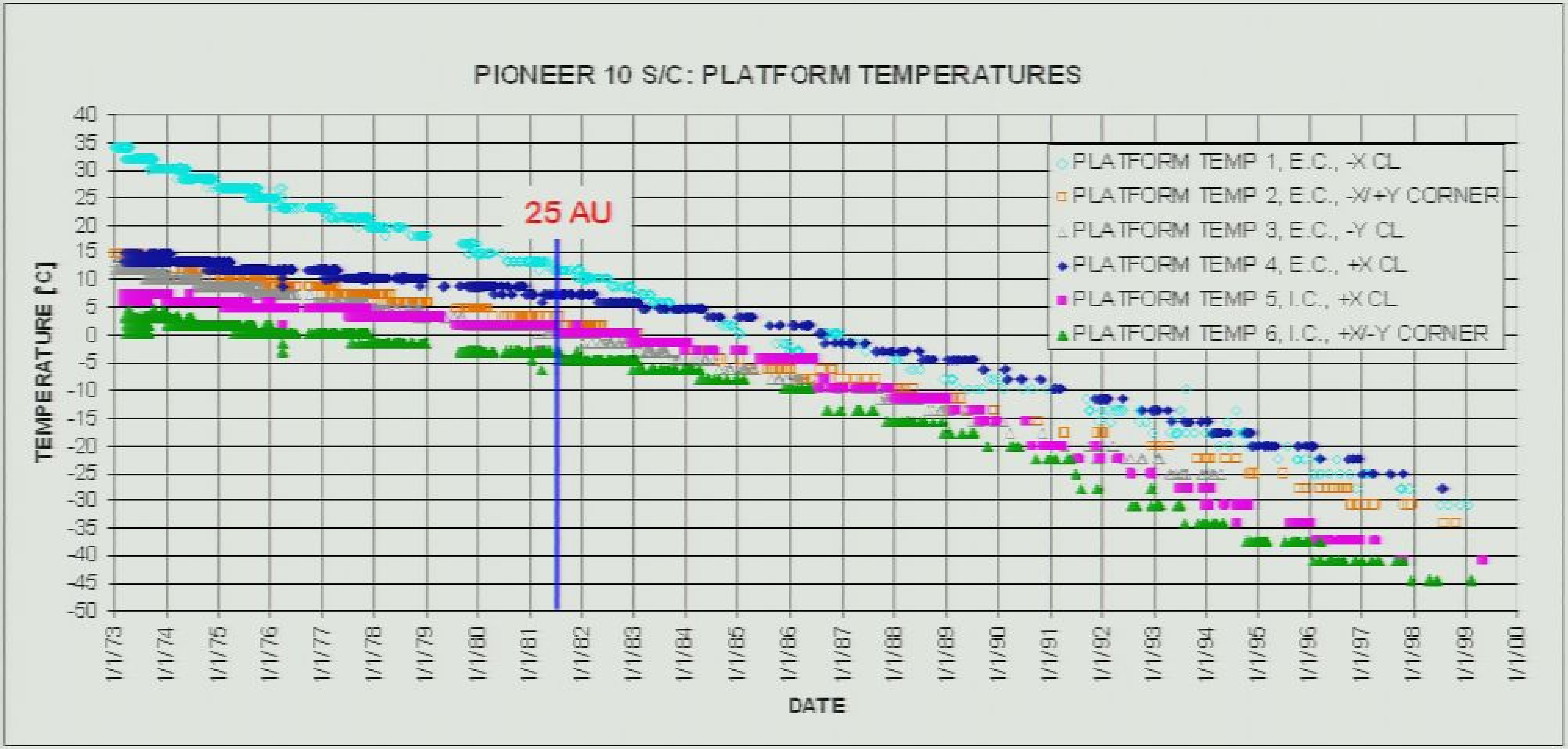
EQUIPMENT IDENTIFICATION

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	0539
23	Diplexer No. 2 Coupler	Antenna	0543
24	Diplexer No. 1	Antenna	0542
25	Transfer Switch — Transmit	Antenna	[illegible]
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	[illegible]
31	Thermistor No. 6	Thermal	[illegible]
32	Despin Sensor No. 1	Attitude Control	[illegible]
33	Despin Sensor No. 2	Attitude Control	[illegible]
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	0854
39	Trapped Radiation Detector (UCSD, [illegible])	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	[illegible]
44	Temperature Transducer	Propulsion	0929
45	[illegible]	Propulsion	0929
46	Pressure Transducer	Propulsion	[illegible]

*The reference designator is used to correlate this unit with telemetry and command word [illegible]

THE STUDY OF THE PIONEER ANOMALY

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

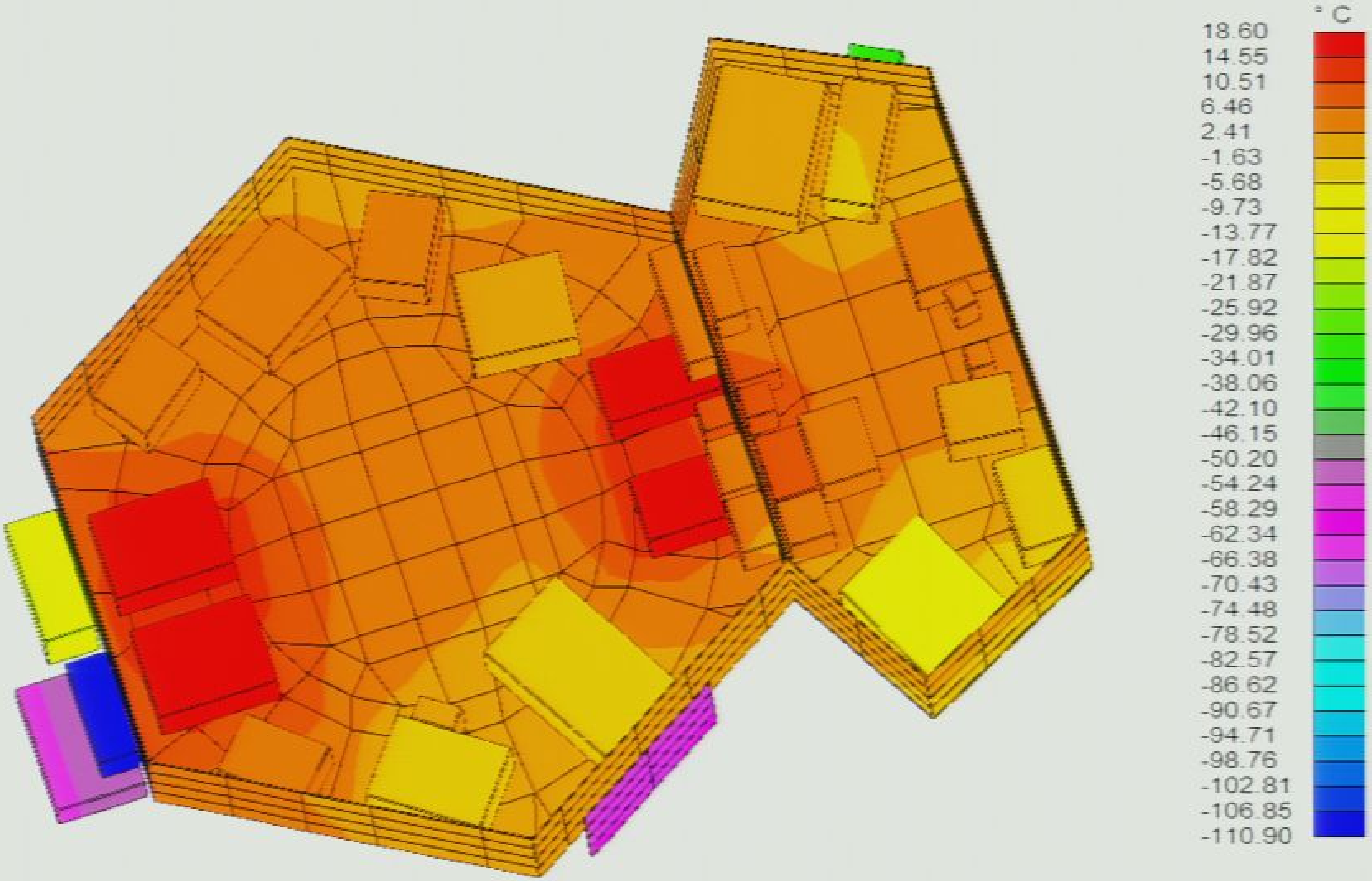
Modeled Surface Properties

Component	Surface Coating	Material	Thickness [Inch]	K [W/m-K]	Density [kg/m^3]	Cp [J/kg-K]	ε*	EOL α	EOL ε
Electronics Boxes	black paint	Al 6061	0.1	169	2770	961.2	--		0.86
ε* 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
ε* 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
ε* 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)

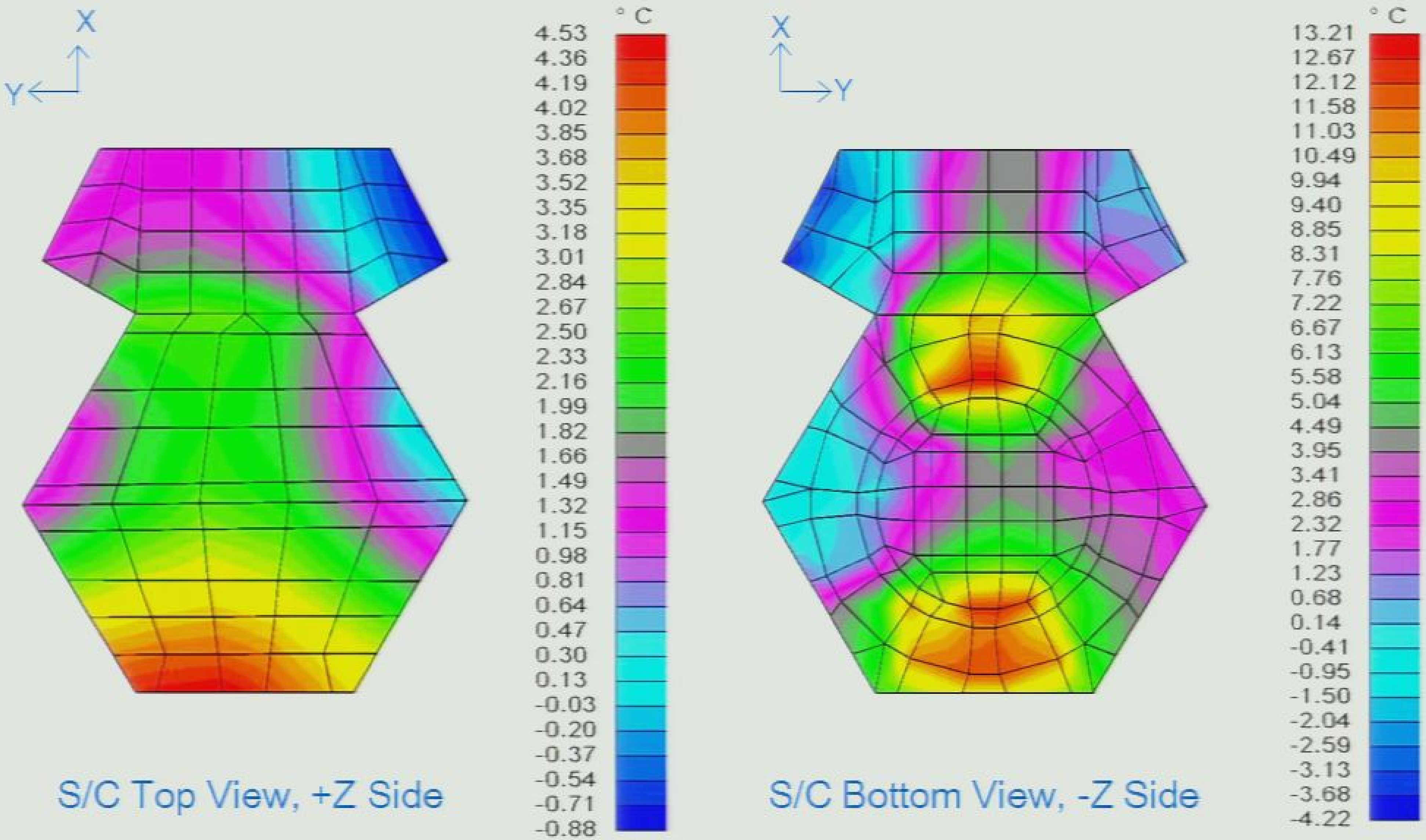
Component	Surface Coating	Material	Thickness [Inch]	K [W/m-K]	Density [kg/m^3]	Cp [J/kg-K]	e*	EOL a	EOL e
Launch Support Ring (Exterior)	bare	Al 6061	0.1	169.0	2770	961.2	--	0.24	0.10
Launch Support Ring (Interior)	black paint	Al 6061	0.1	169.0	2770	961.2	--	0.95	0.84
Meteoroid Detector (Inside Facing)	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)

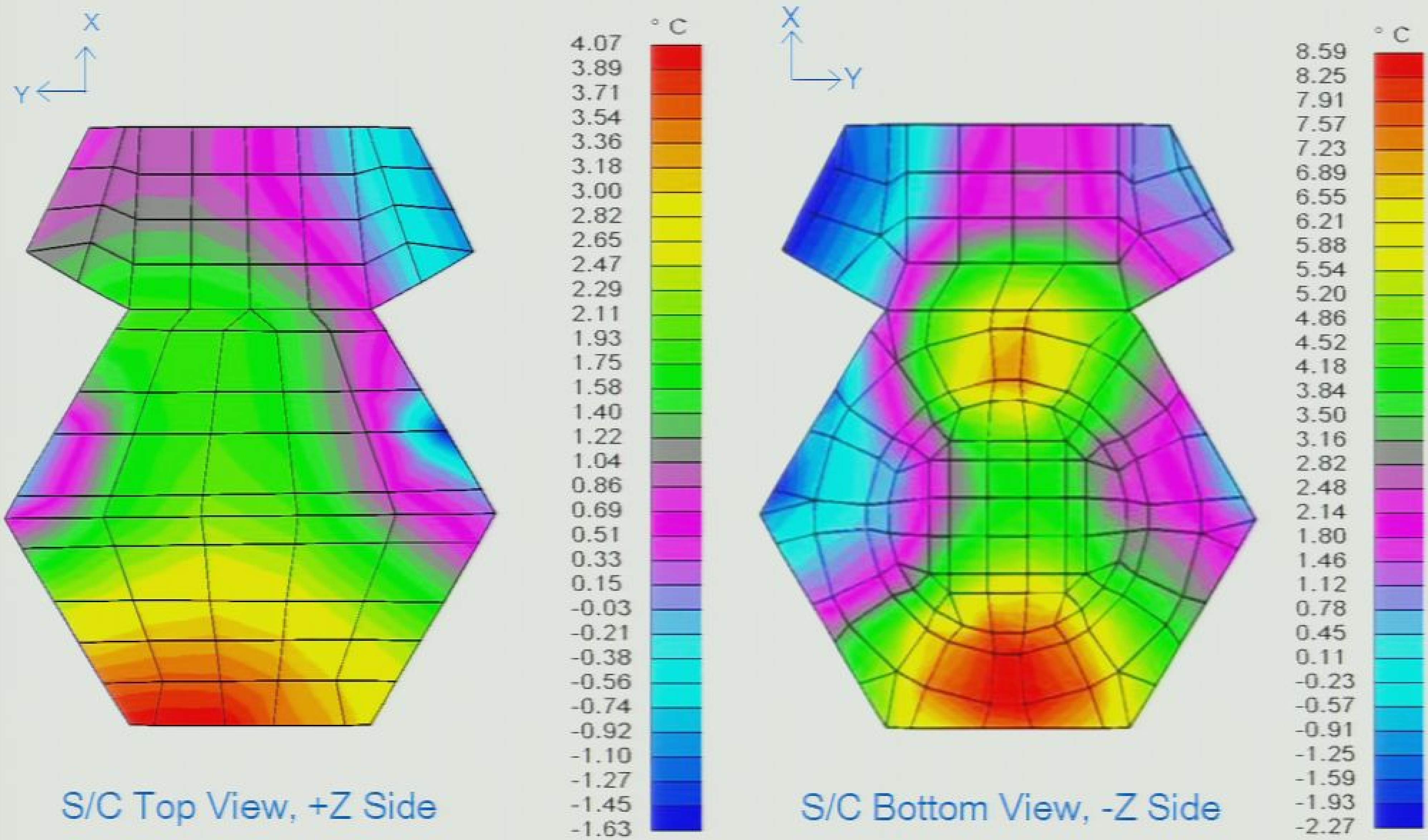
Predicted Temps - Interior Compartment Surfaces



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

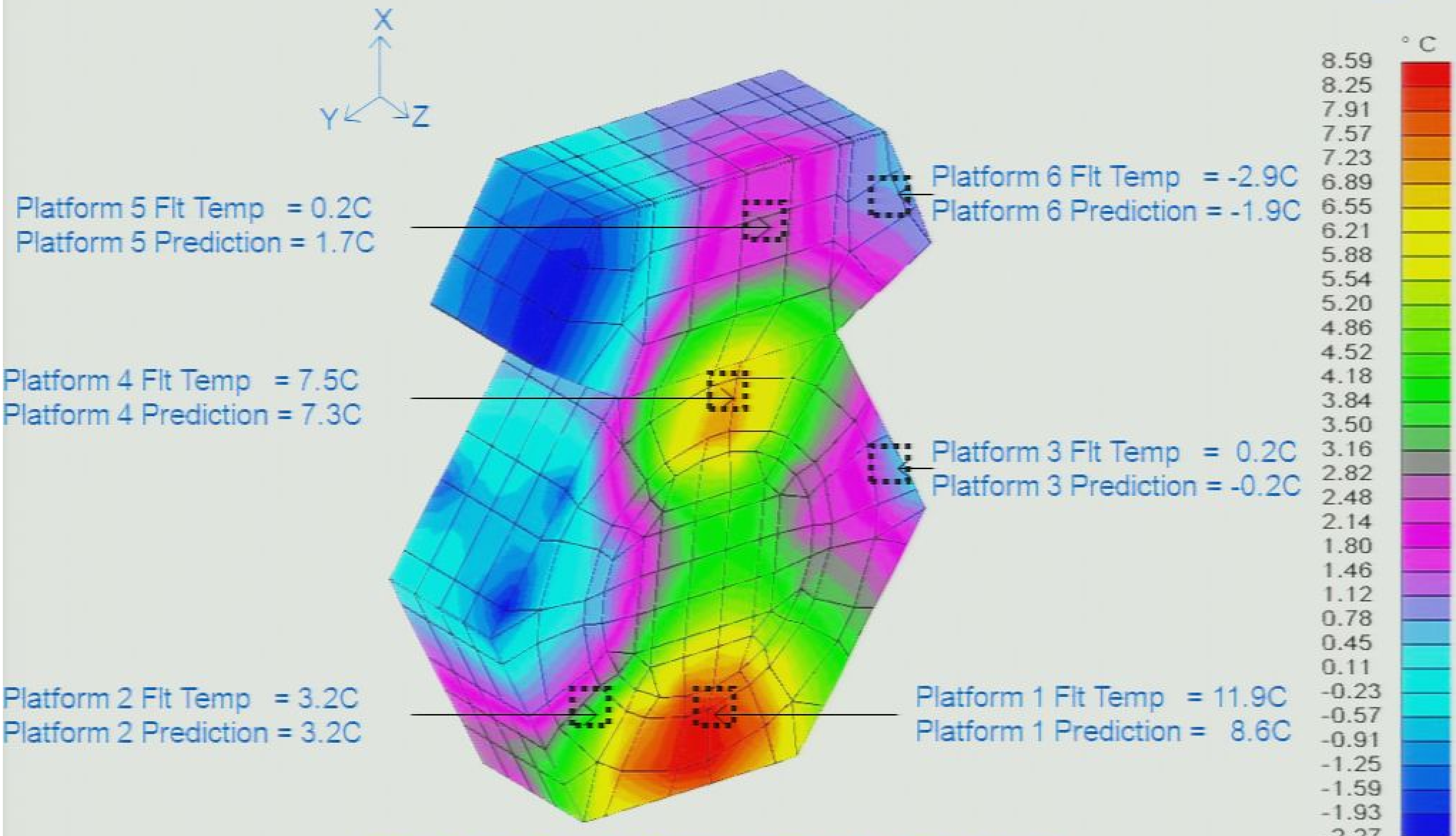
THE STUDY OF THE PIONEER ANOMALY

Predicted Temps - Exterior Compartment Surfaces



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

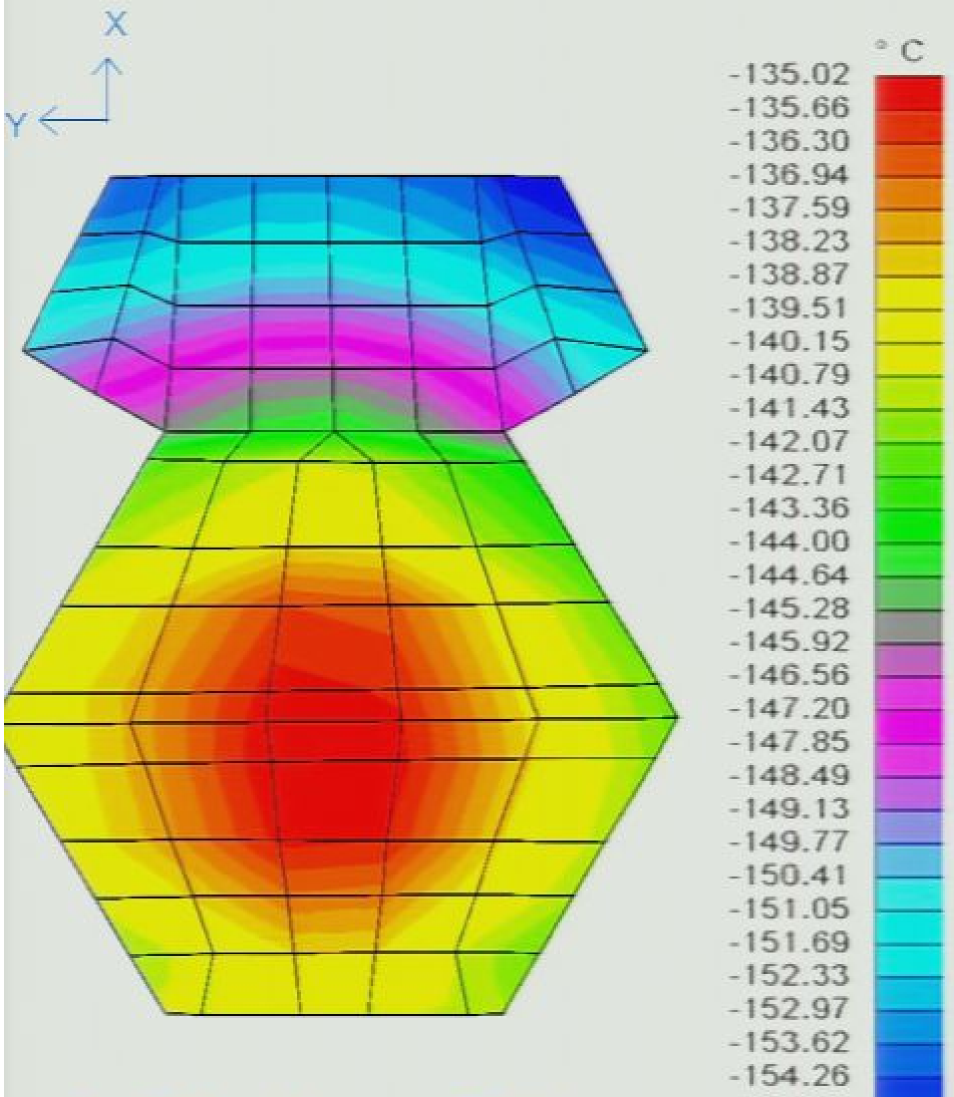
Measured Versus Predicted Compartment Temps



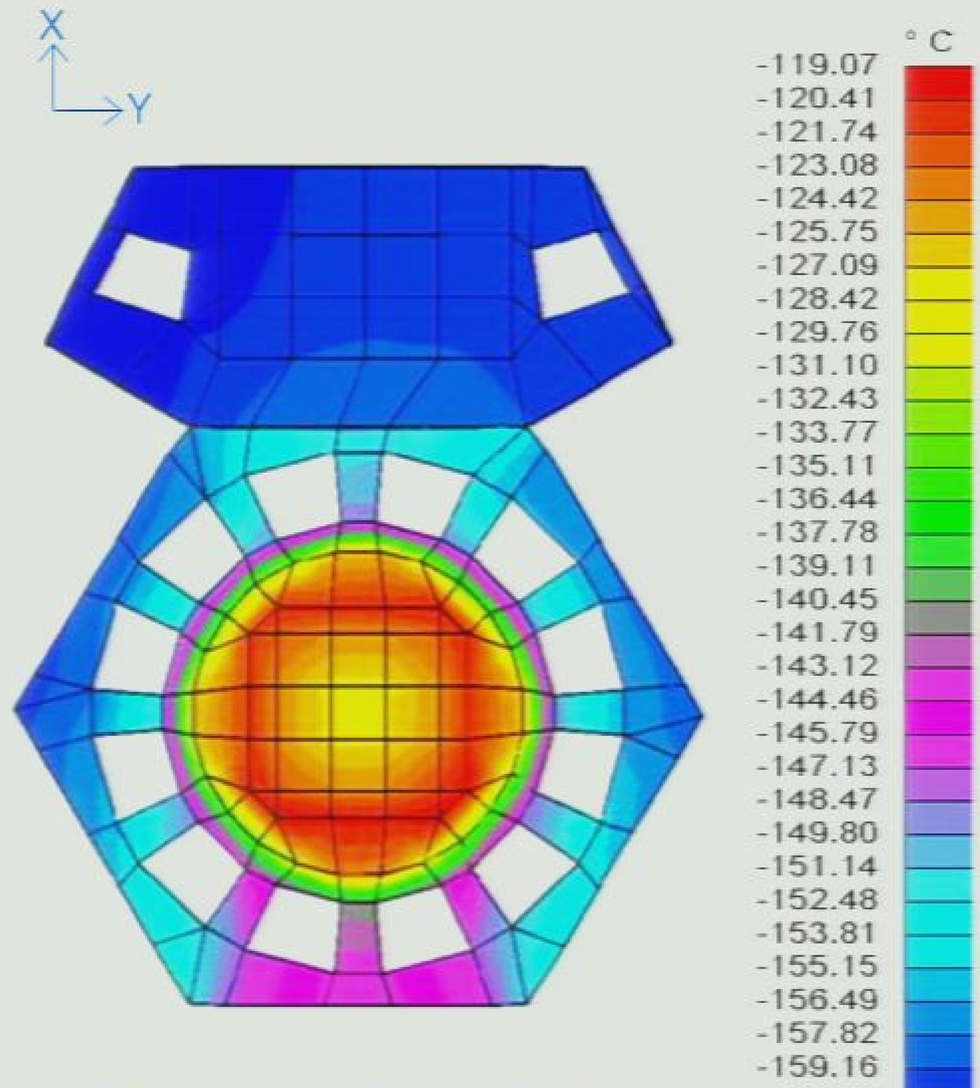
EQUIPMENT AND INSTRUMENT COMPARTMENTS

THE STUDY OF THE PIONEER ANOMALY

Predicted Temps - Spacecraft MLI



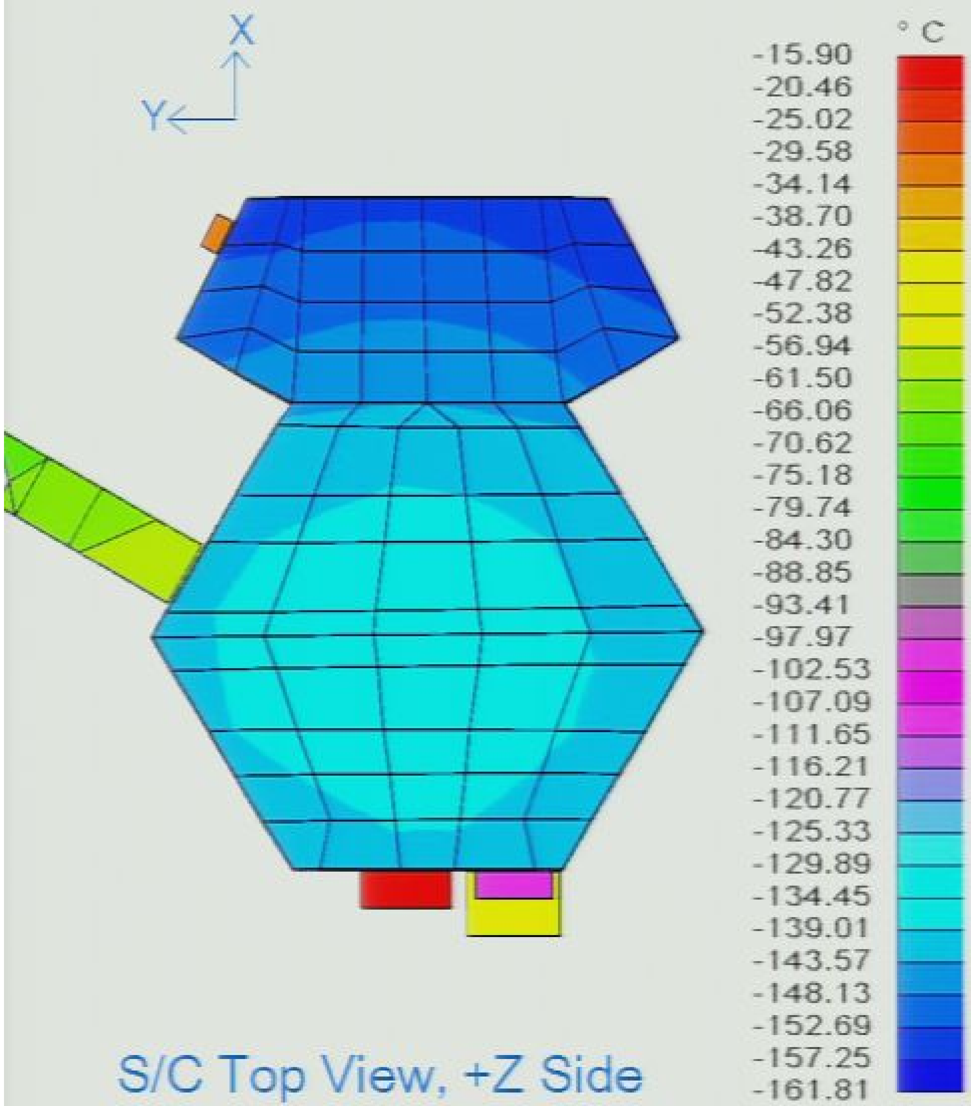
S/C Top View, +Z Side

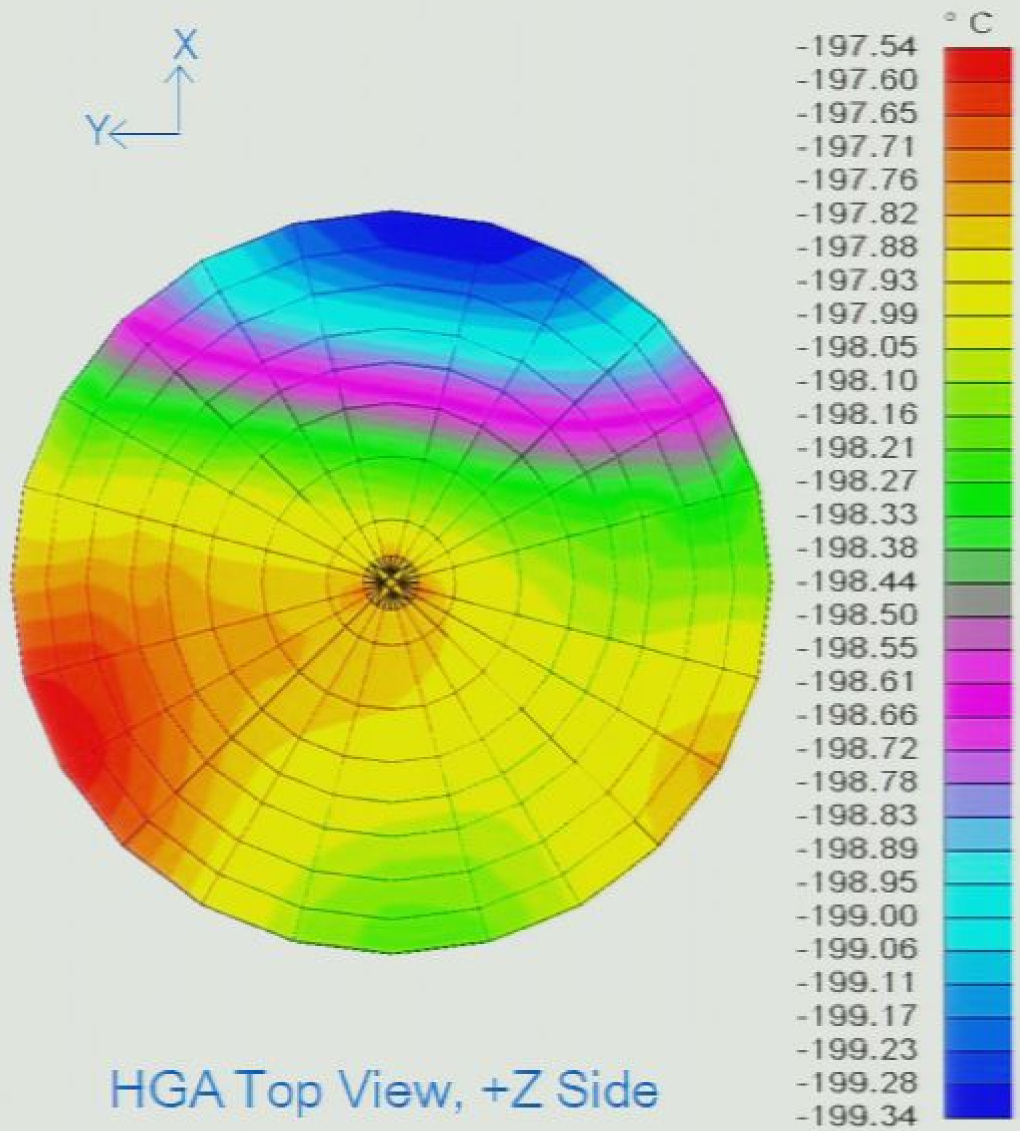


S/C Bottom View, -Z Side

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

Predicted Temps - HGA Temperatures

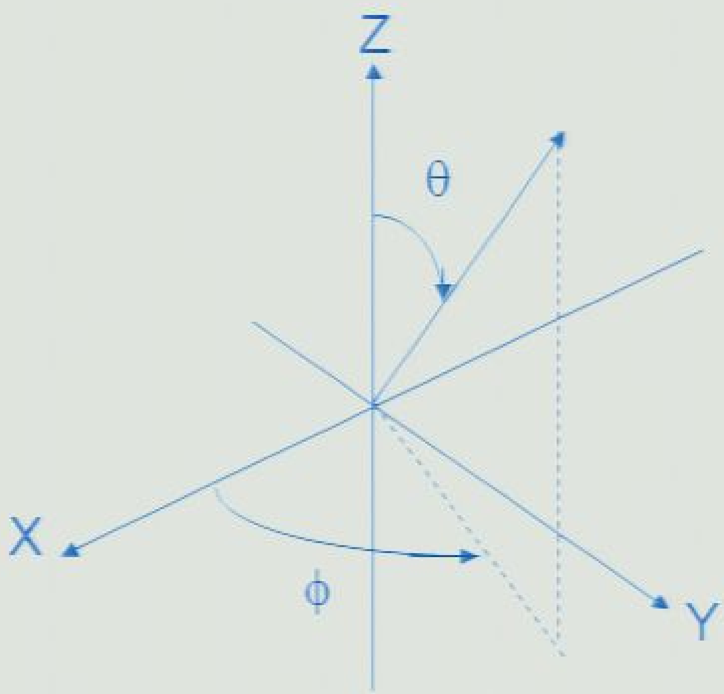


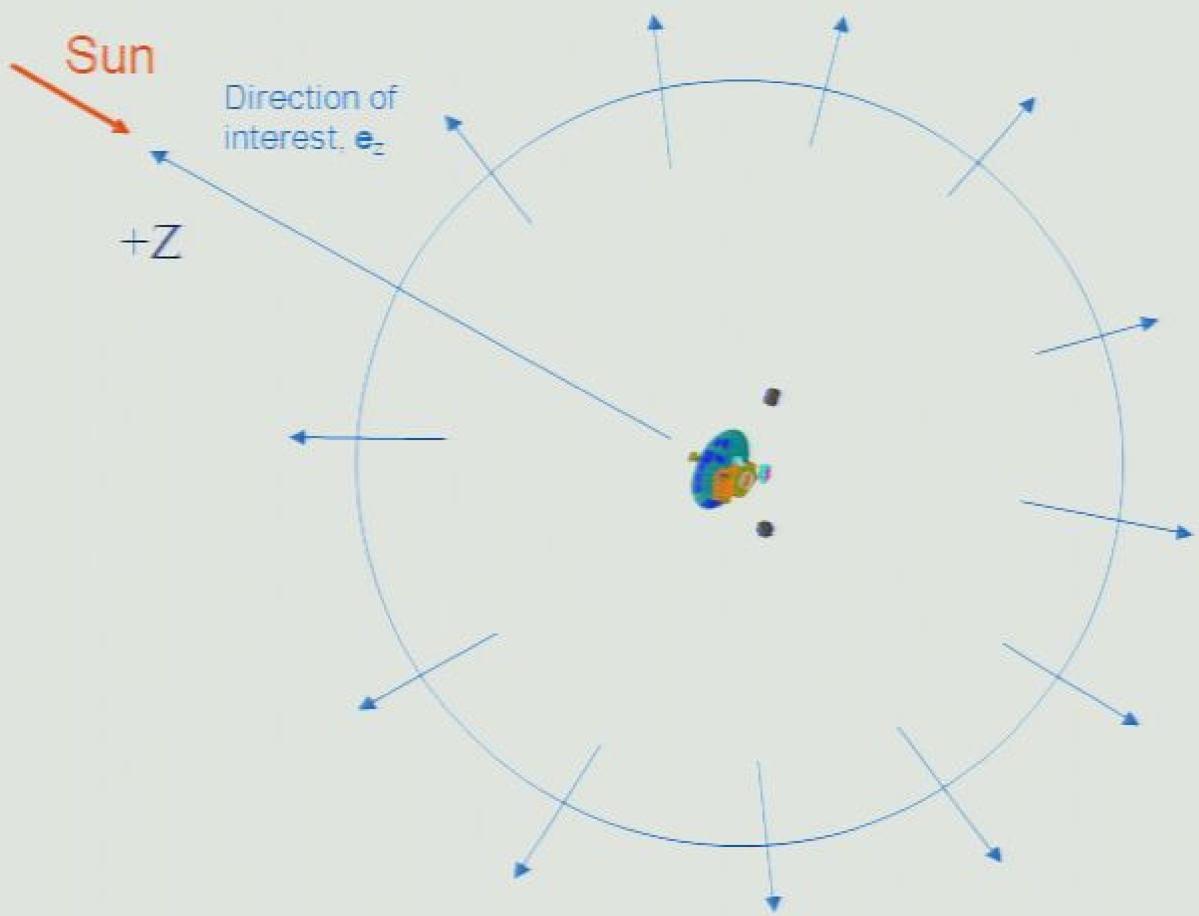


Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)

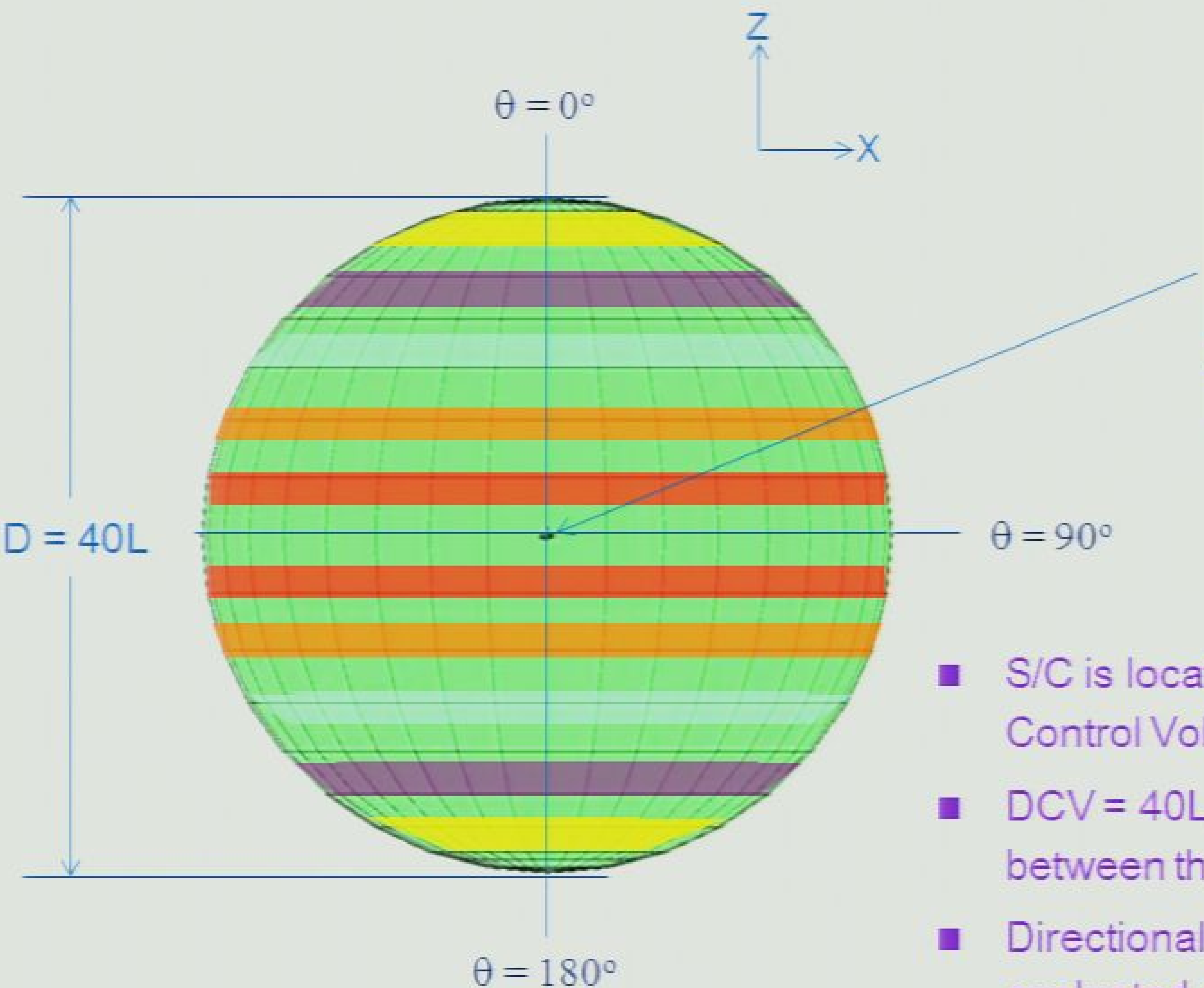
Calculation of Directional Thermal Emission

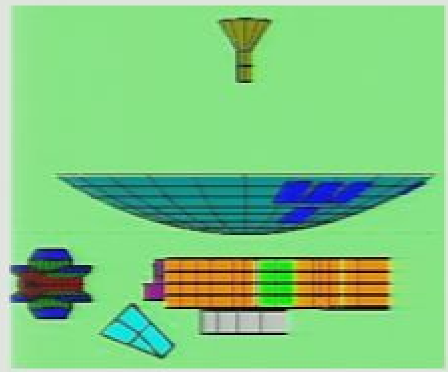
- Spacecraft emits in all directions, but only the component parallel to the spin axis is relevant





Control Volume in Geometric Math Model

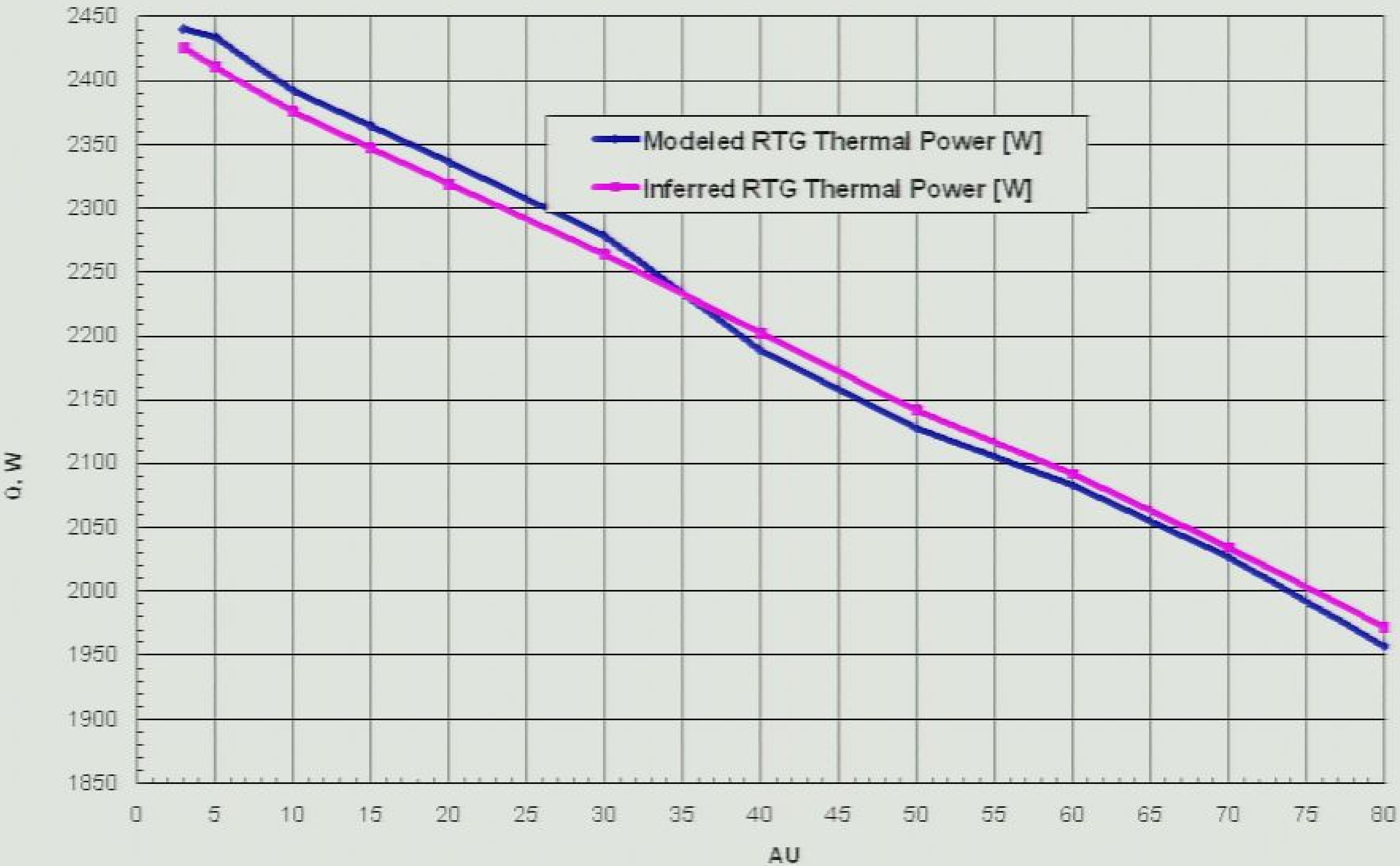




- S/C is located at the center of a Large Control Volume
- DCV = 40L, L is the radial distance between the S/C centerline and the RTG
- Directional radiative heat flow is evaluated at 5° polar angle intervals (5° wide latitude bands)

THE STUDY OF THE PIONEER ANOMALY

RTG Thermal Power: Modeled vs. Inferred



Calculation of Net Directional Thermal Emission

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

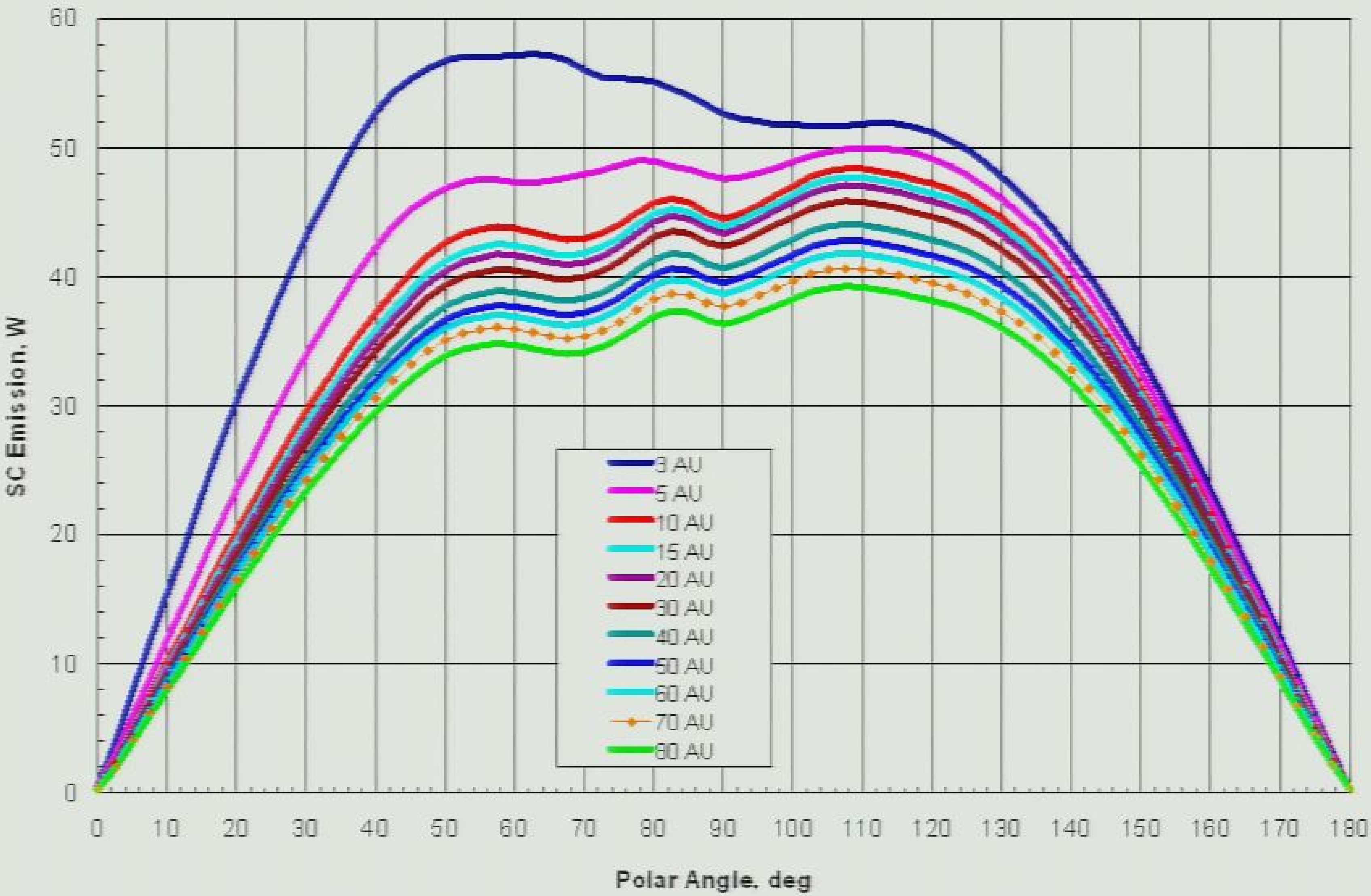
$$Q_z = \int_A \vec{q} \cdot d\vec{A}_z + \vec{S} \cdot \vec{e}_z$$

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

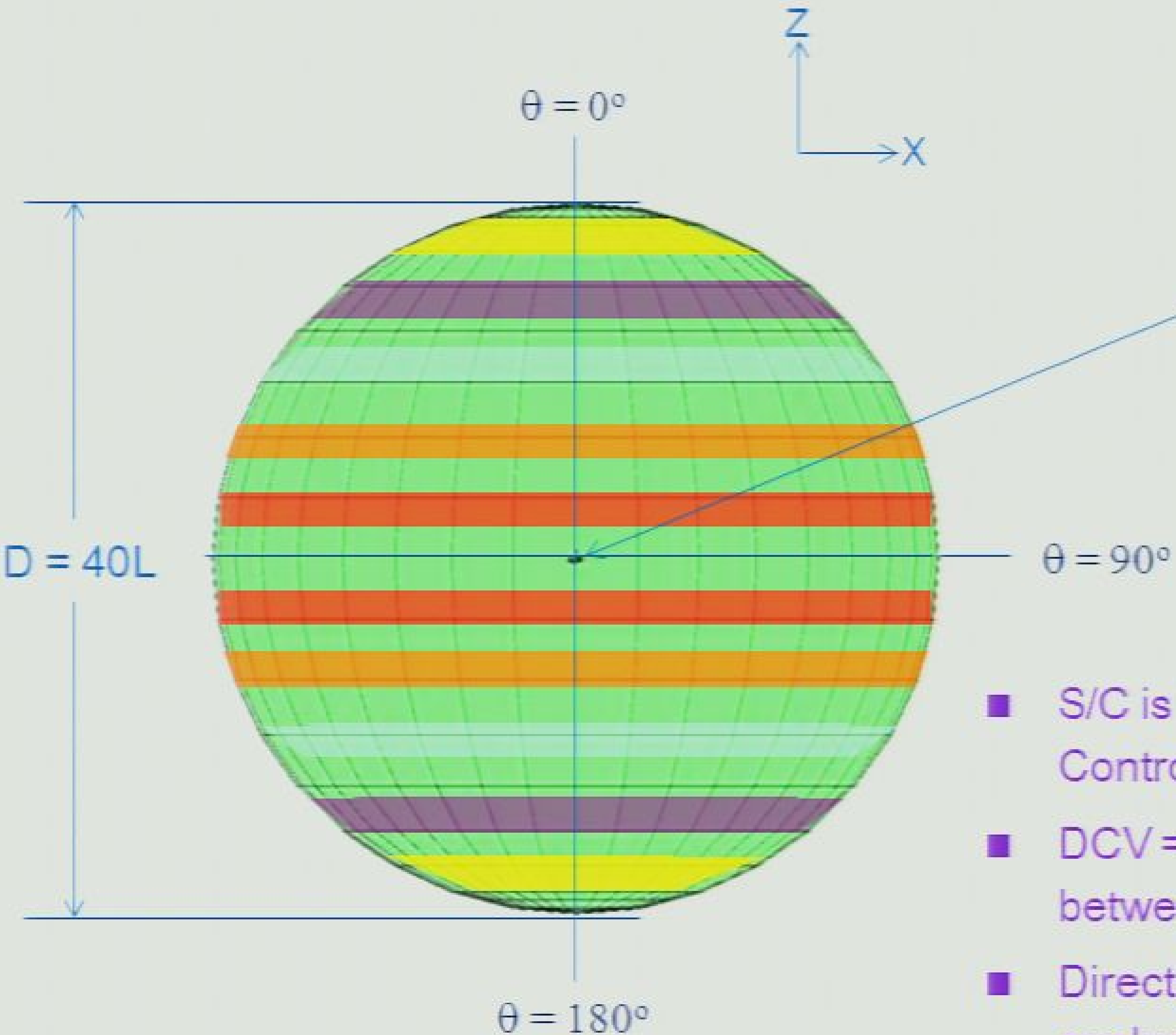
  - S_{1AU} is the solar constant at 1 AU
  - R_{AU} is the distance in AU of the spacecraft from the sun
  - Subscripts j,k refer to the element located at (θ_j, ϕ_k) on the spherical control volume
- Net directional emission = 0 for an isothermal, isotropic emitter when external sources are absent (i.e.,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

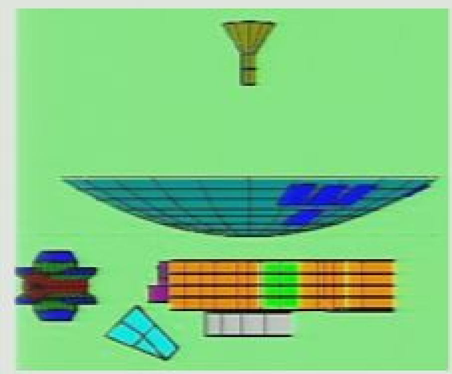
THE STUDY OF THE PIONEER ANOMALY

P-10 S/C Total IR Emission vs. Polar Angle



Control Volume in Geometric Math Model





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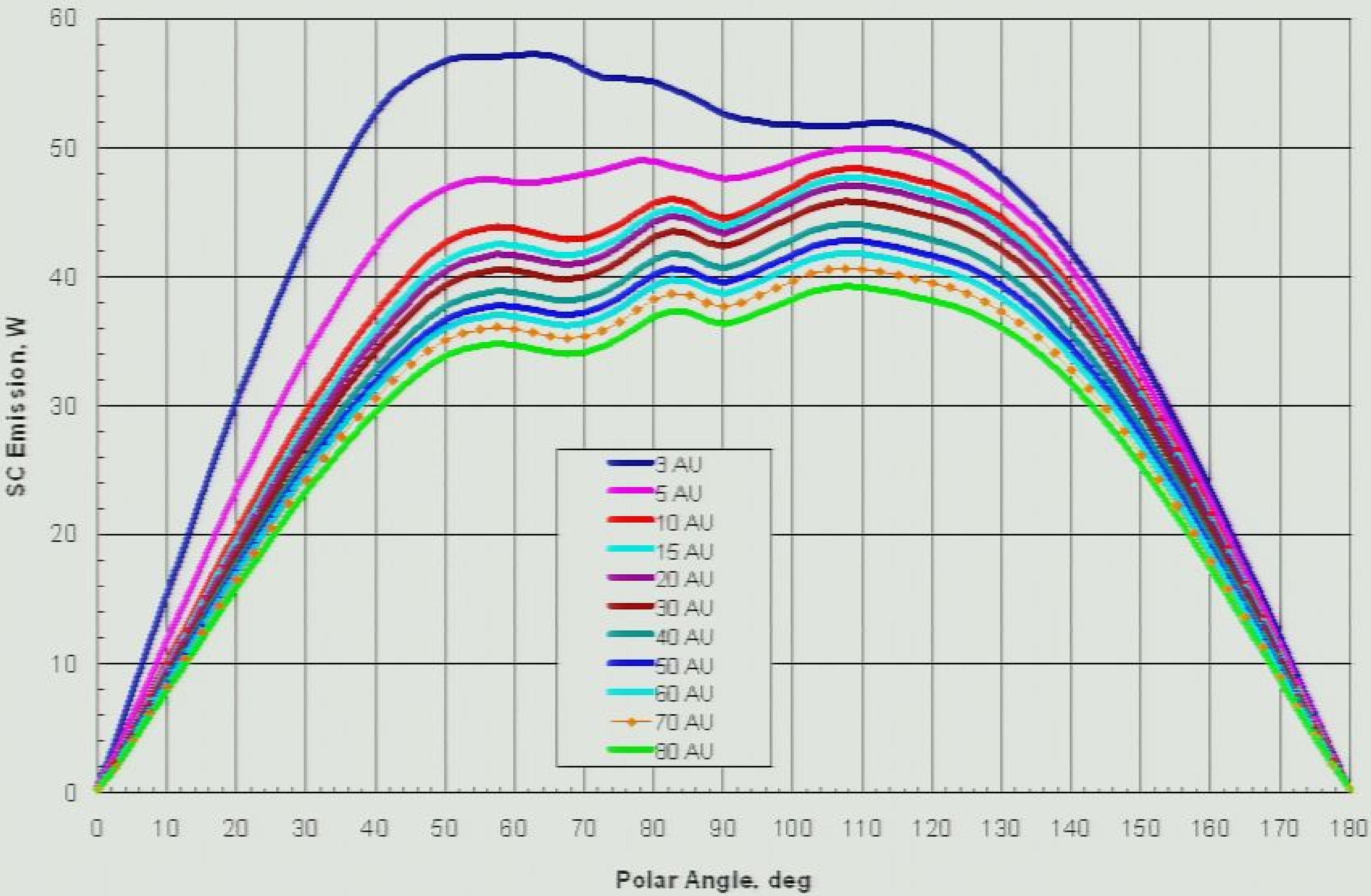
THE STUDY OF THE PIONEER ANOMALY

P-10 S/C Total IR Emission vs. Polar Angle



Predicted P-10 Q(-Z) from 3-80 AU

AU DISTANCE	Modeled S/C IR Emission [W]	Q(-Z) Excludes Reflected Solar [W]	HGA Reflected Solar in +Z [W]	HGA Reflected Solar in -Z [W]	Q(-Z) Includes HGA Reflected Solar [W]	HGA Absorbed Solar [W]	S/C + HGA Absorbed Solar [W]
3	2943.7	-149.2	293.0	-293.0	-442.2	427.3	503.5
5	2616.2	-11.5	105.5	-105.5	-117.0	159.0	182.4
10	2437.7	40.5	26.4	-26.4	14.1	40.5	46.1
15	2384.5	51.8	11.7	-11.7	40.1	18.0	20.5
20	2347.5	54.3	6.6	-6.6	47.7	10.1	11.5
30	2282.9	52.8	2.9	-2.9	49.9	4.5	5.1
40	2191.1	51.5	1.6	-1.6	49.9	2.5	2.9
50	2129.4	50.0	1.1	-1.1	48.9	1.6	1.8
60	2084.1	45.8	0.6	-0.6	45.1	1.1	1.3
70	2027.6	43.5	0.5	-0.5	43.0	0.8	0.9
80	1957.4	42.3	0.4	-0.4	41.9	0.6	0.7

Sign Convention: 293 W in +Z Direction ≡ -293 W in -Z Direction so Column F = Column C - Column D = Column C + Column E
Propellant Tank Treated as a Diffusion Node, Not a Boundary Node
Absorbed Solar Load Calculations Account for the Larger Off-Sun Angles at Smaller AU Distances

Conclusions and Next Steps

- 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
- As of October 2009 the new Doppler data is available, thus
  - Certification of the extended Pioneer 10 and 11 Doppler data set
  - Focus on the determination of the true direction of the anomaly and its behavior as a function of distance from the Sun
- Next Steps: focus on the Anomaly using all available data:
  - Analysis of Pioneer 11 Doppler data (proceed with early data, then entire mission)
  - Then proceed with Pioneer 10….
  - Combined analysis of Doppler and telemetry data
- Stay tuned… the fun part of the analysis has just began!

The Pioneer Collaboration

S.G. Turyshev, J.D. Anderson, S.W. Asmar *(JPL, Caltech, Pasadena CA),*
M.M. Nieto *(LANL, Los Alamos, NM),* **B. Mashhoon** *(U of Missouri, Columbia, MO)*
H.J. Dittus, C. Laemmerzahl, S. Theil *(ZARM, U of Bremen),*
B. Dachwald, W. Seboldt *(DLR, Köln),* **W. Ertmer, E. Rasel** *(IQO, Hannover),*
R. Förstner, U. Johann *(Astrium, Friedrichshafen),* **K. Scherer** *(U of Bonn),*
T.J. Sumner *(Imperial College, London),* **R. Bingham, B. Kent** *(RAL, Didcot),*
O. Bertolami *(IST, Lisboa),* **H.-J. Blome** *(FH Aachen),* **F. Hehl, C. Kiefer** *(U of Cologne),*
S. Reynaud *(ENS/LKB, Paris),* **A. Brillet, F. Bondu, E. Samain** *(OCA, Nice),*
P. Touboul, B. Foulon *(ONERA, Châtillon),* **P. Bouyer** *(IOTA, Paris),*
D. Giulini *(U of Freiburg, Breisgau),* **J.L. Rosales** *(QIG, RSFE, Madrid),*
C. de Matos *(ESA-HQ, Paris),* **A. Rathke, C. Erd, J. C. Grenouilleau, D. Izzo** *(ESA/ESTEC),*

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