The Pioneer Anomaly

Seeking an Explanation in Telemetry Records

The Pioneer Anomaly

- Anomalous acceleration of the Pioneer 10/11 spacecraft was detected in the 1980s, confirmed by several research teams
- May be mechanical in origin, may be "new physics"
- In the past, short stretches of data were studied; new effort under way with complete data set, including on-board telemetry.

Science of the Anomaly

- Astronomy (planetary orbits)
- Relativity theory / fundamental physics
- Radio science
- Thermal physics
- Engineering
- Data processing
- Numerical analysis

The Pioneer 10/11 Missions

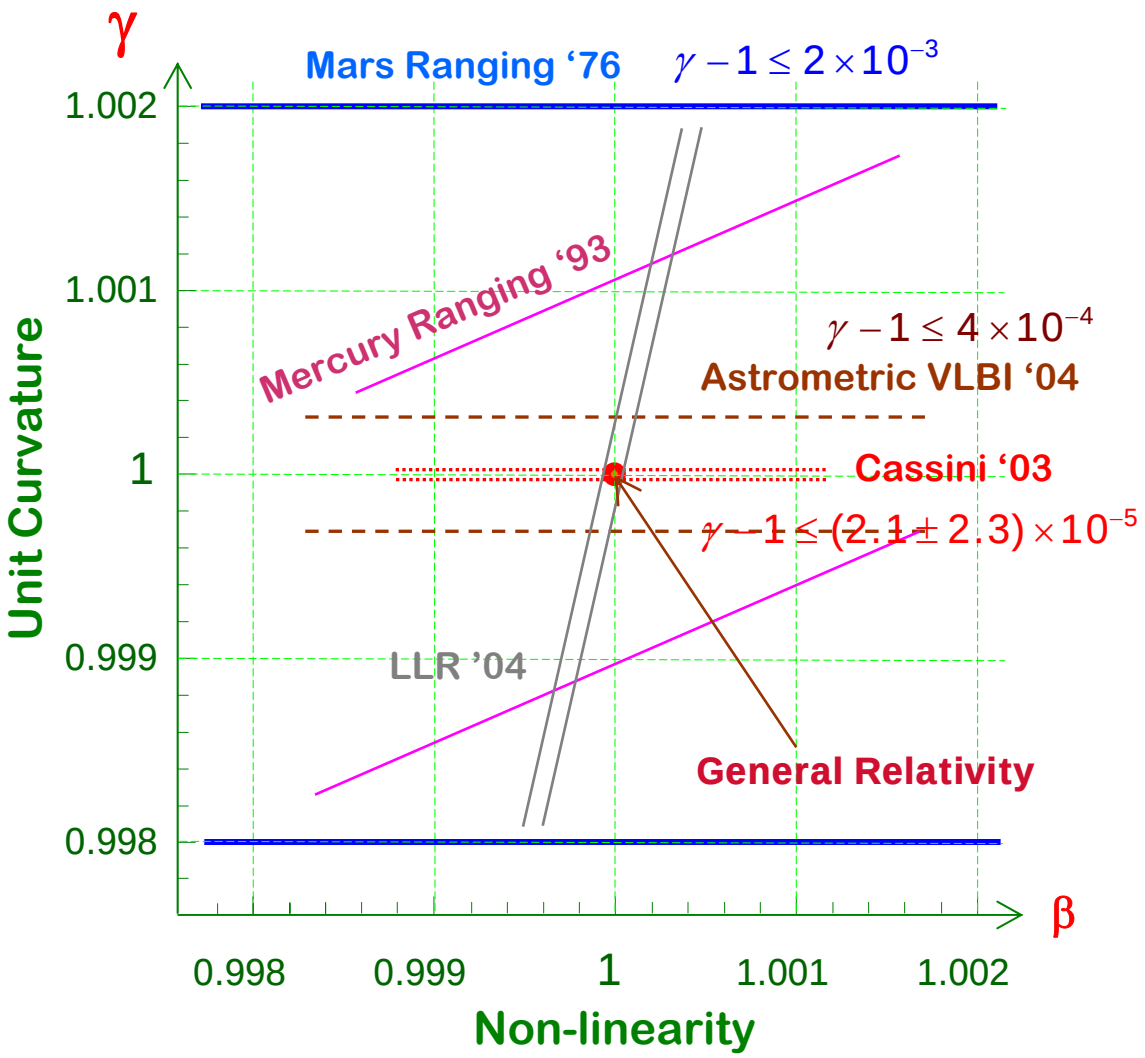
- Launched in 1972 and 1973
- First to explore beyond Mars
- First to visit Jupiter and Saturn
- Planned duration: 600-900 days




Mission Objectives

- Primary Objectives
  - Explore the asteroid belt
  - Explore beyond Mars
  - Explore Jupiter
- Secondary Objectives
  - Explore the outer solar system
  - Search for gravity waves
  - Search for “Planet X”

Experimental General Relativity



$$g_{11} = g_{22} = g_{33} = -\left(1 + \frac{2\gamma}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}}\right)$$

$$g_{pq} = 0 \quad (p,q = 1,2,3;\ p \neq q)$$

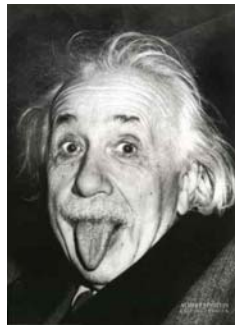
$$g_{14} = g_{41} = \frac{2+2\gamma}{c^3}\sum_{j\neq i}\frac{\mu_j \dot{x}_j}{r_{ij}}$$

$$g_{24} = g_{42} = \frac{2+2\gamma}{c^3}\sum_{j\neq i}\frac{\mu_j \dot{y}_j}{r_{ij}}$$

$$g_{34} = g_{43} = \frac{2+2\gamma}{c^3}\sum_{j\neq i}\frac{\mu_j \dot{z}_j}{r_{ij}}$$

$$g_{44} = 1 - \frac{2}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}} + \frac{2\beta}{c^4}\left(\sum_{j\neq i}\frac{\mu_j}{r_{ij}}\right)^2 - \frac{1+2\gamma}{c^4}\sum_{j\neq i}\frac{\mu_j \dot{s}_j^{\,2}}{r_{ij}}$$

$$+ \frac{2(2\beta-1)}{c^4}\sum_{j\neq i}\frac{\mu_j}{r_{ij}}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} - \frac{1}{c^4}\sum_{j\neq i}\mu_j \frac{\partial^2 r_{ij}}{\partial t^2}$$

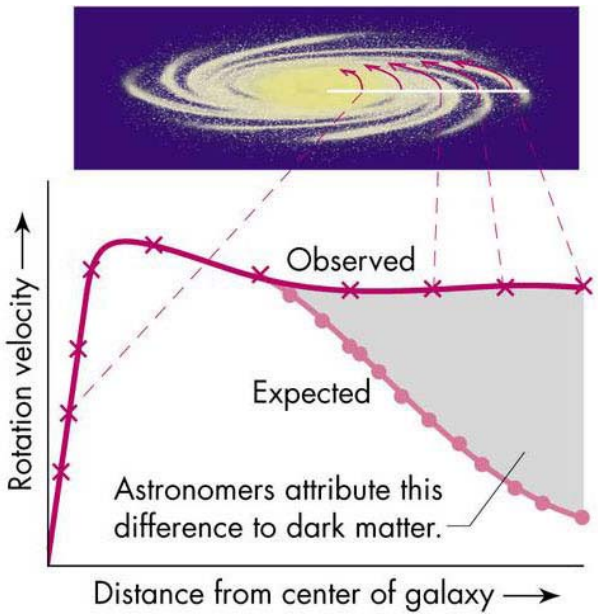


Albert Einstein
(1879-1955)

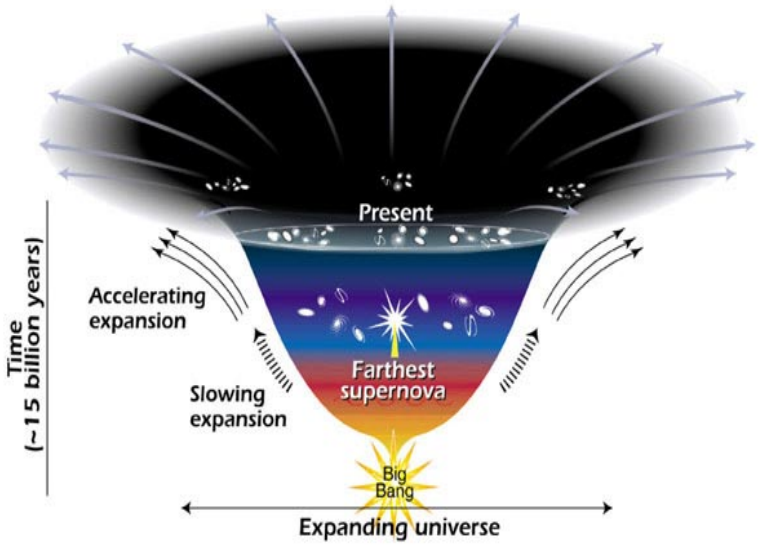
Parameterized Post-Newtonian (PPN) formalism
From Moyer (JPL Publication 00-7)

May not work at large distances

- Galaxies do not rotate as expected
- Supernovae, microwave background show accelerated expansion

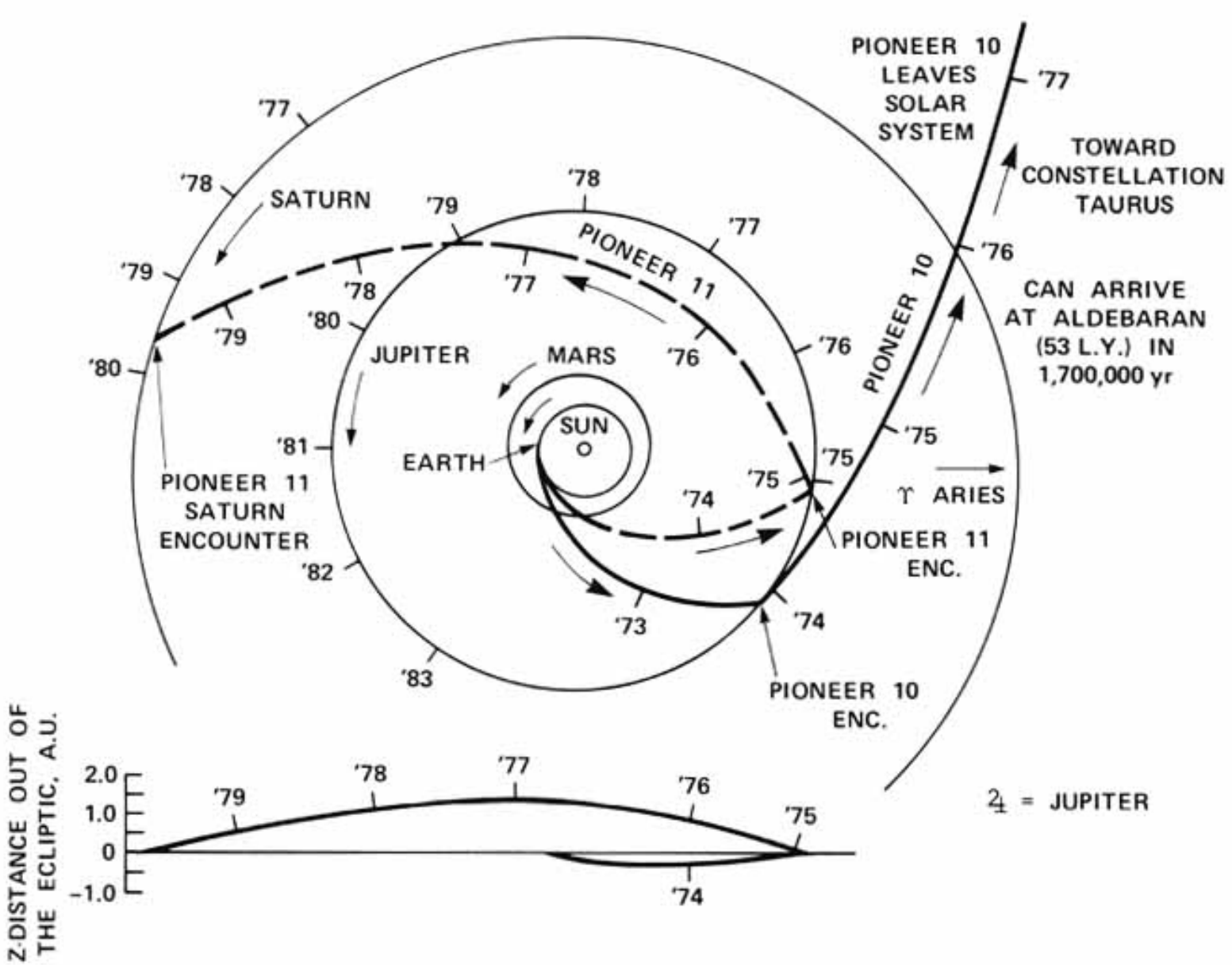


Dark matter?

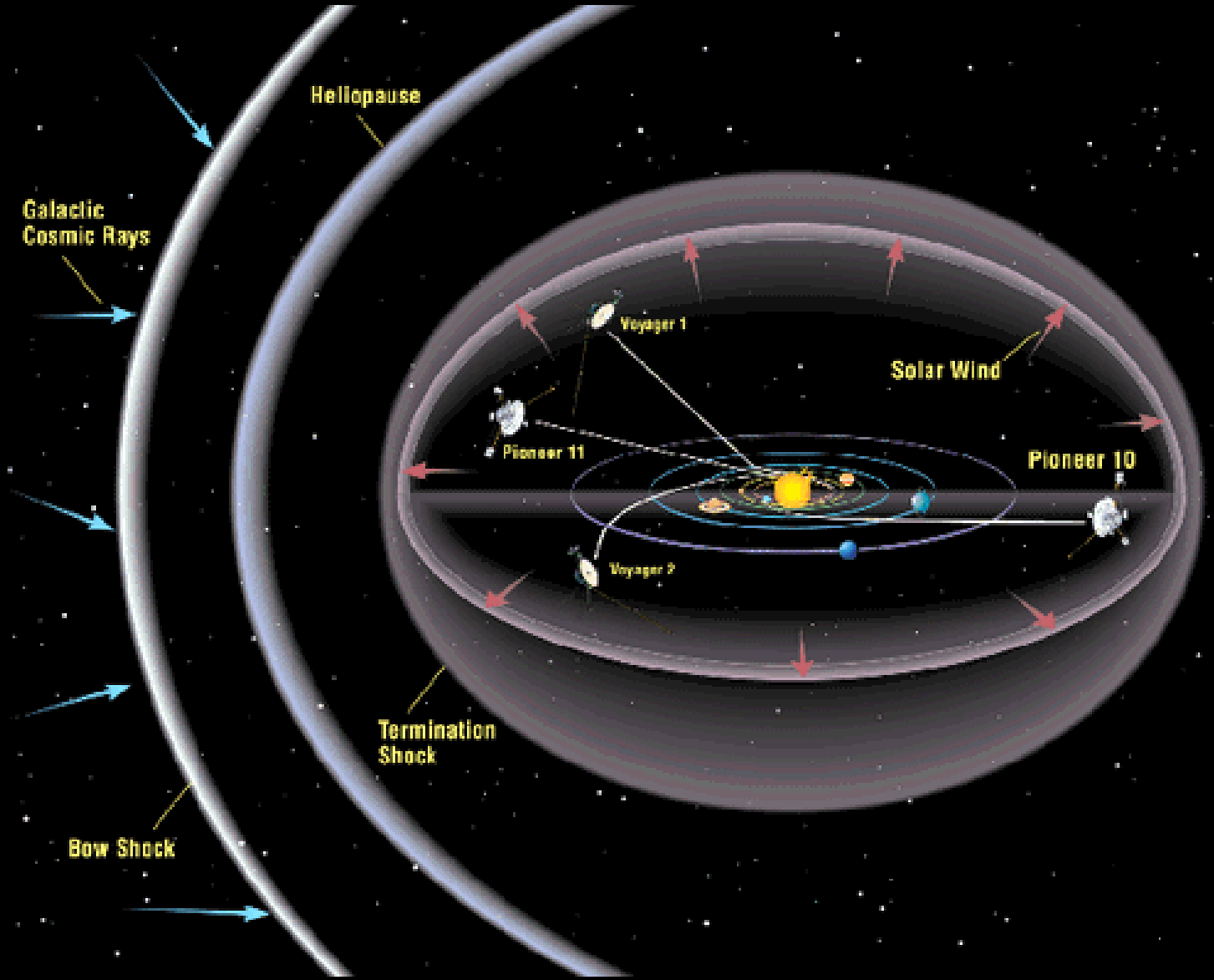


Dark energy?

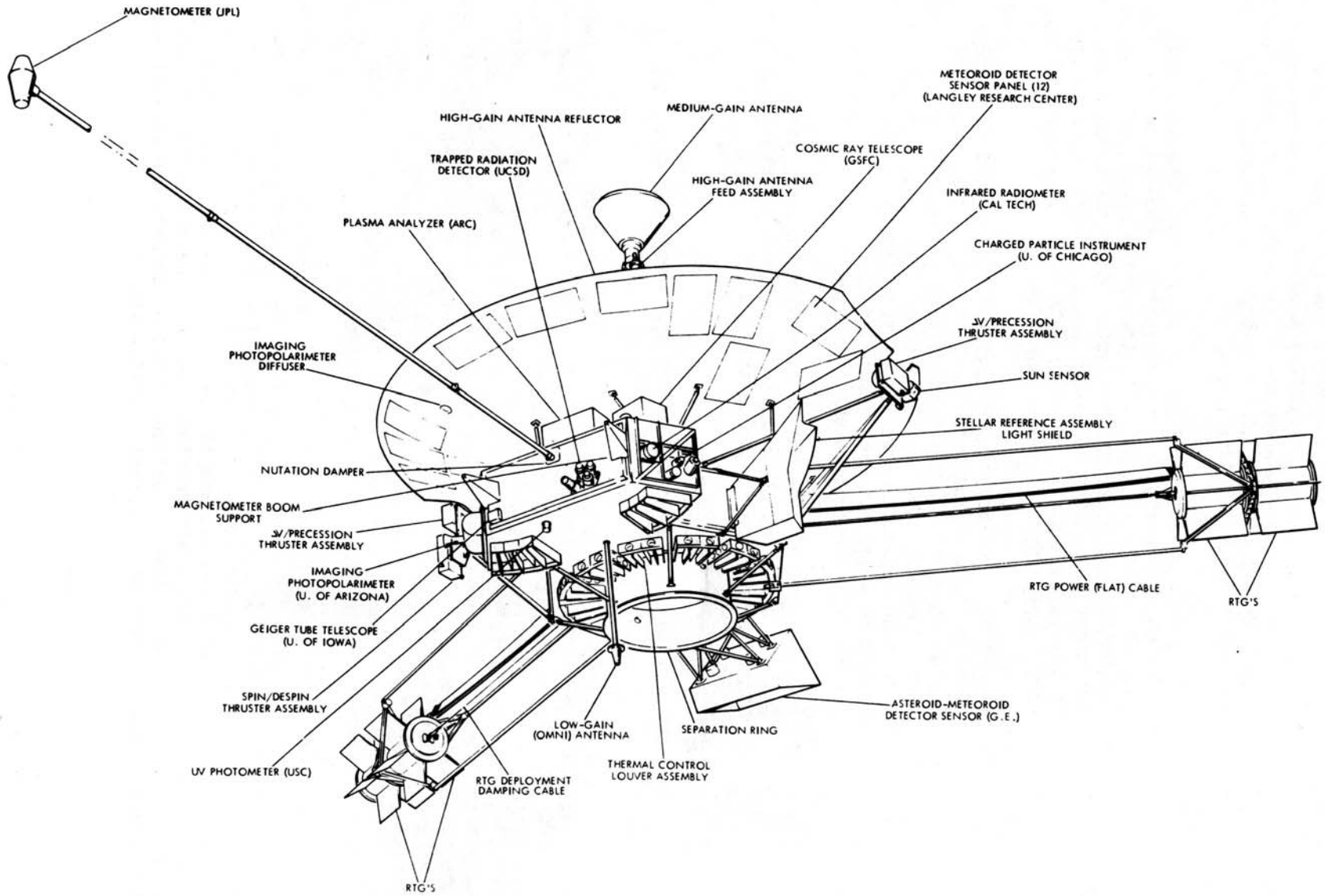
Pioneer Orbits – Early Years



Pioneer and Voyager Orbits through the Outer Solar System



The Pioneer Spacecraft



Science Instruments

1. JPL Helium Vector Magnetometer
2. ARC Plasma Analyzer
3. U/Chicago Charged Particle Experiment
4. U/Iowa Geiger Tube Telescope
5. GSFC Cosmic Ray Telescope
6. UCSD Trapped Radiation Detector
7. UCS Ultraviolet Photometer
8. U/Arizona Imaging Photopolarimeter
9. CIT Jovian Infrared Radiometer
10. GE Asteroid/Meteoroid Detector
11. LaRC Meteoroid Detector
12. Flux-Gate Magnetometer (Pioneer-11 only)

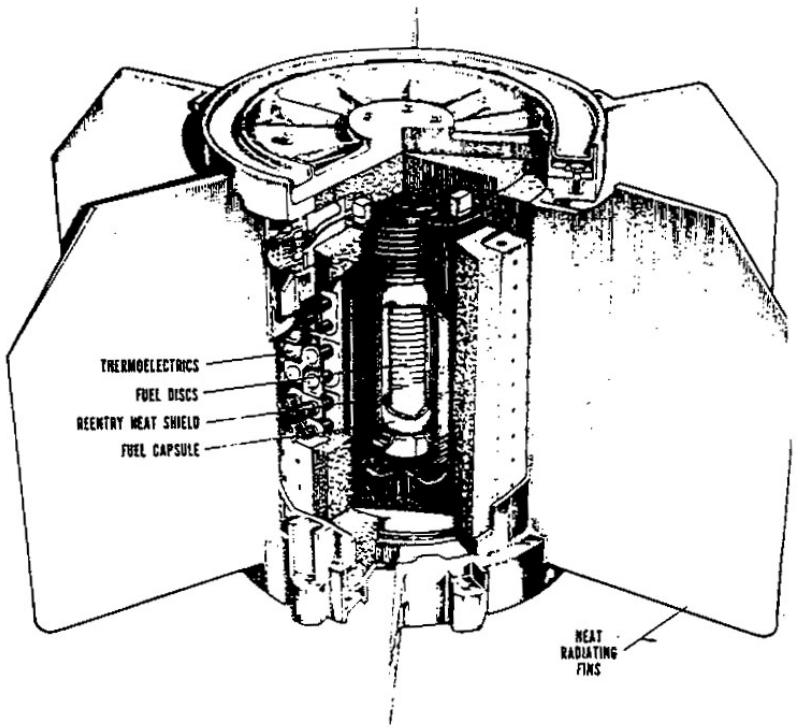
The Pioneer Spacecraft

- Mass: ~250 kg
- Radioisotope Thermoelectric Generators
- Electrical Power: ~160W (at launch)
- 11 Scientific Instruments
- 3m High Gain Antenna
- Transmitter: 8W
- Data rate: 16-2048 bps
- Spin stabilized (4.8 rpm nominal)

Orientation Maneuvers

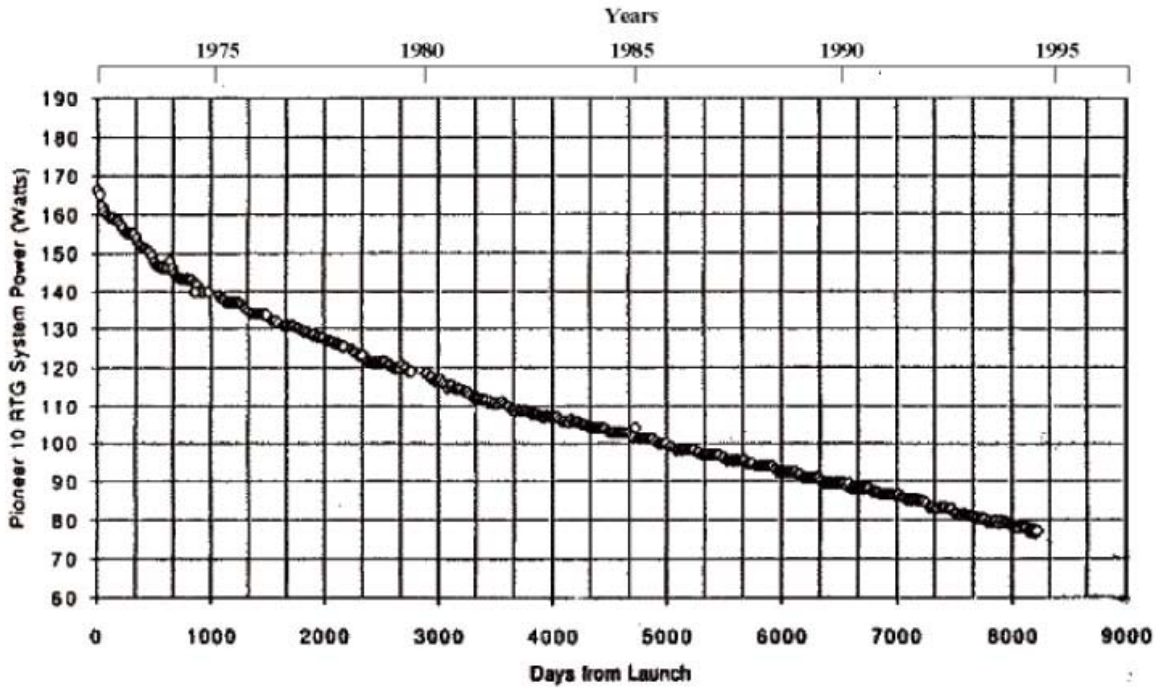
- Few maneuvers needed for spinning spacecraft
- Few maneuvers → clean data
- Ingenious "Closed loop" CONSCAN maneuver lets the spacecraft "home in" on DSN signal
- Late in the mission, ~2 CONSCANs a year were performed

Pioneer Power Source



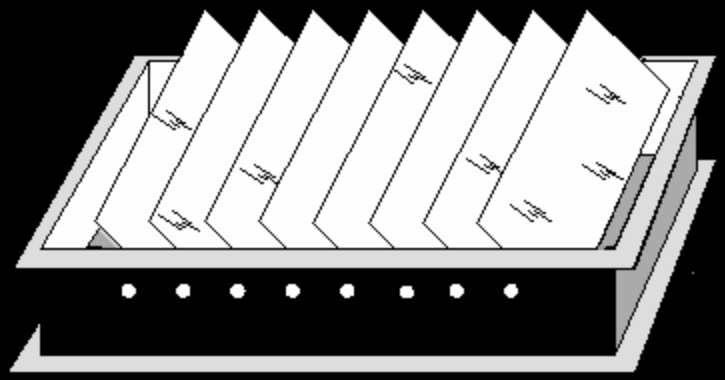
SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

- RTG Thermal Power: ~650W
- Electrical Power: ~40W
- 4 RTGs per spacecraft



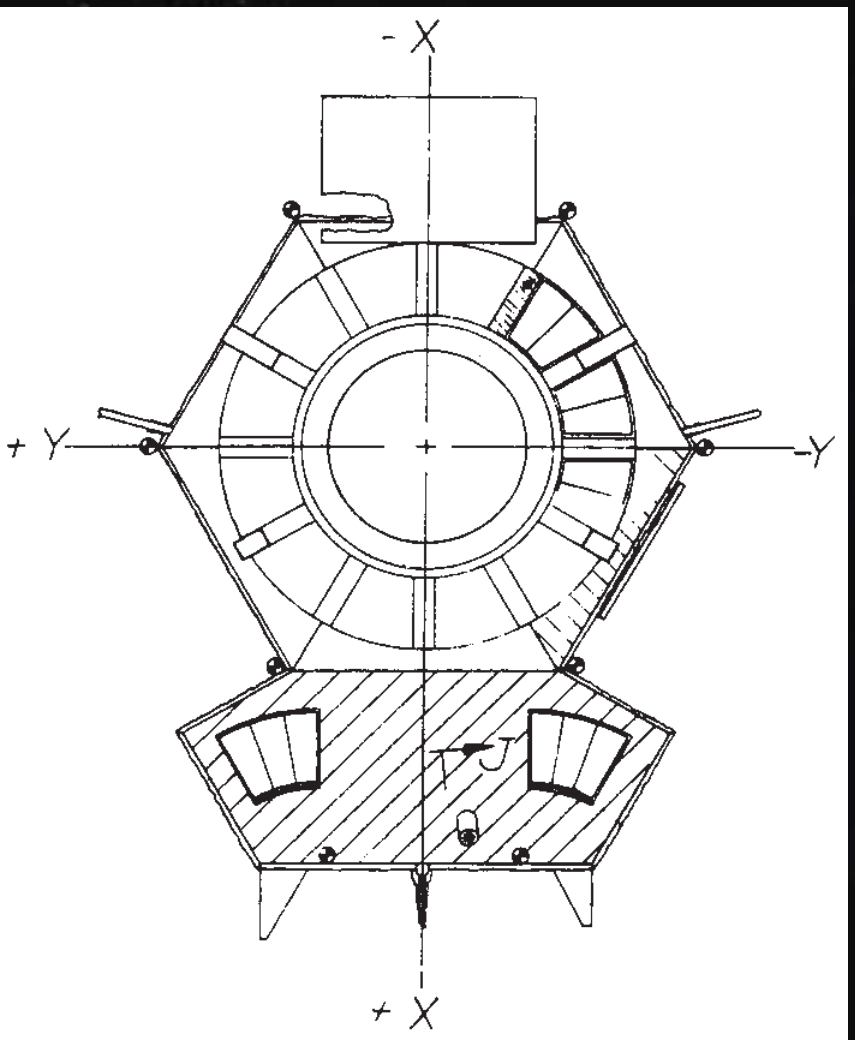
Passive Thermal Control

- Louver system
- Thermally activated bimetallic springs
- Louvers are fully closed <40°F*



*When the Pioneer 10/11 spacecraft were designed, NASA was not yet using the metric system.

Pioneer Louver Arrangement



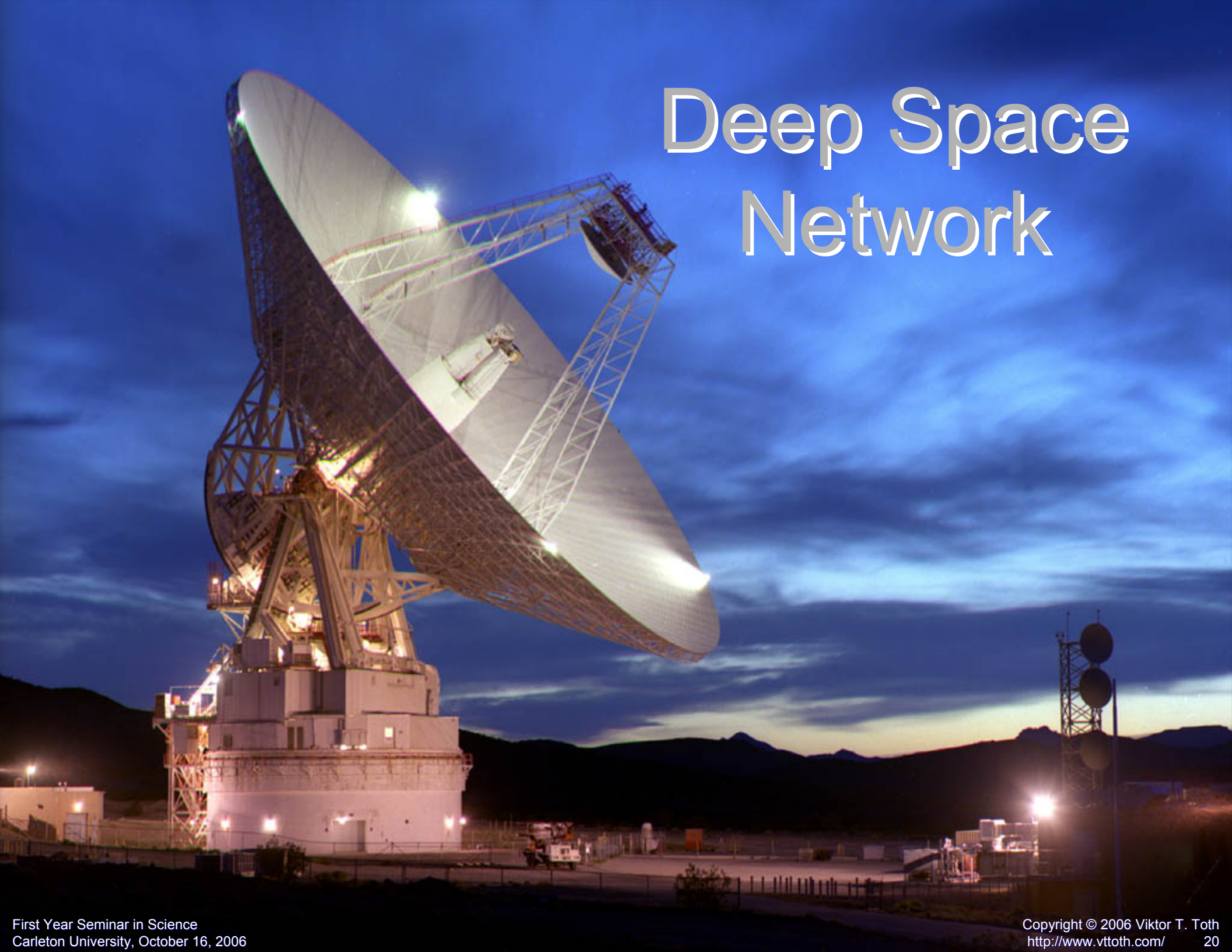
Pioneer 10 After 30 Years

- Distance from Sun: ~80 AU
- Round-trip light time: ~21 hours
- Speed relative to the Sun: ~12 km/s

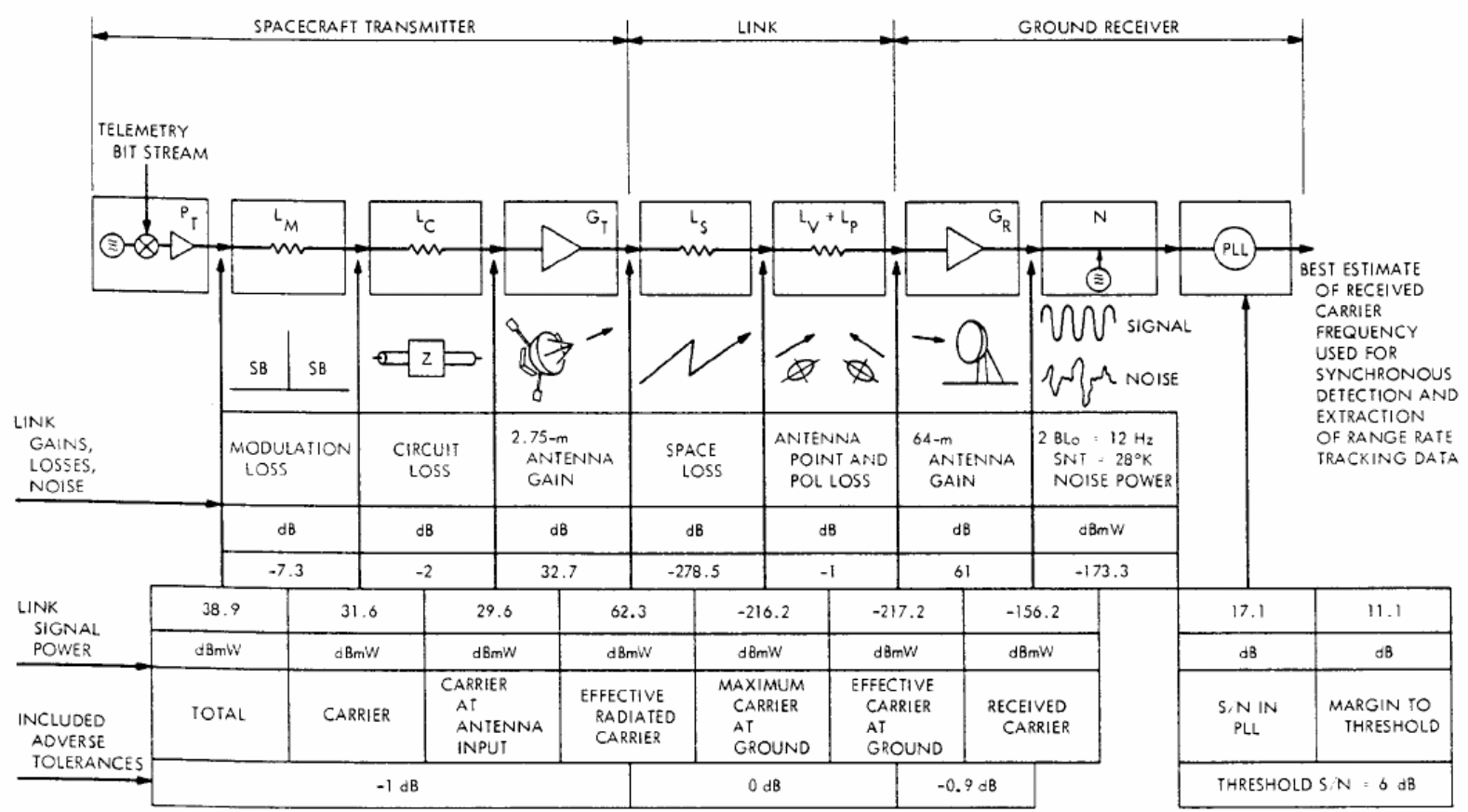
Pioneer 10 After 30 Years

- One instrument (GTT) still operating (power-down command sent last track, but never confirmed)
- Bus voltage ~ 26VDC instead of nominal 28VDC
- Transmitter XCO failed (probably due to cold)
- Transmitter still operating in coherent mode
- Many temperature readings “off the scale” or outside calibrated ranges
- Propellant lines frozen (no maneuvers possible)

Pioneer 10/11 are the most precisely navigated deep space craft to date.



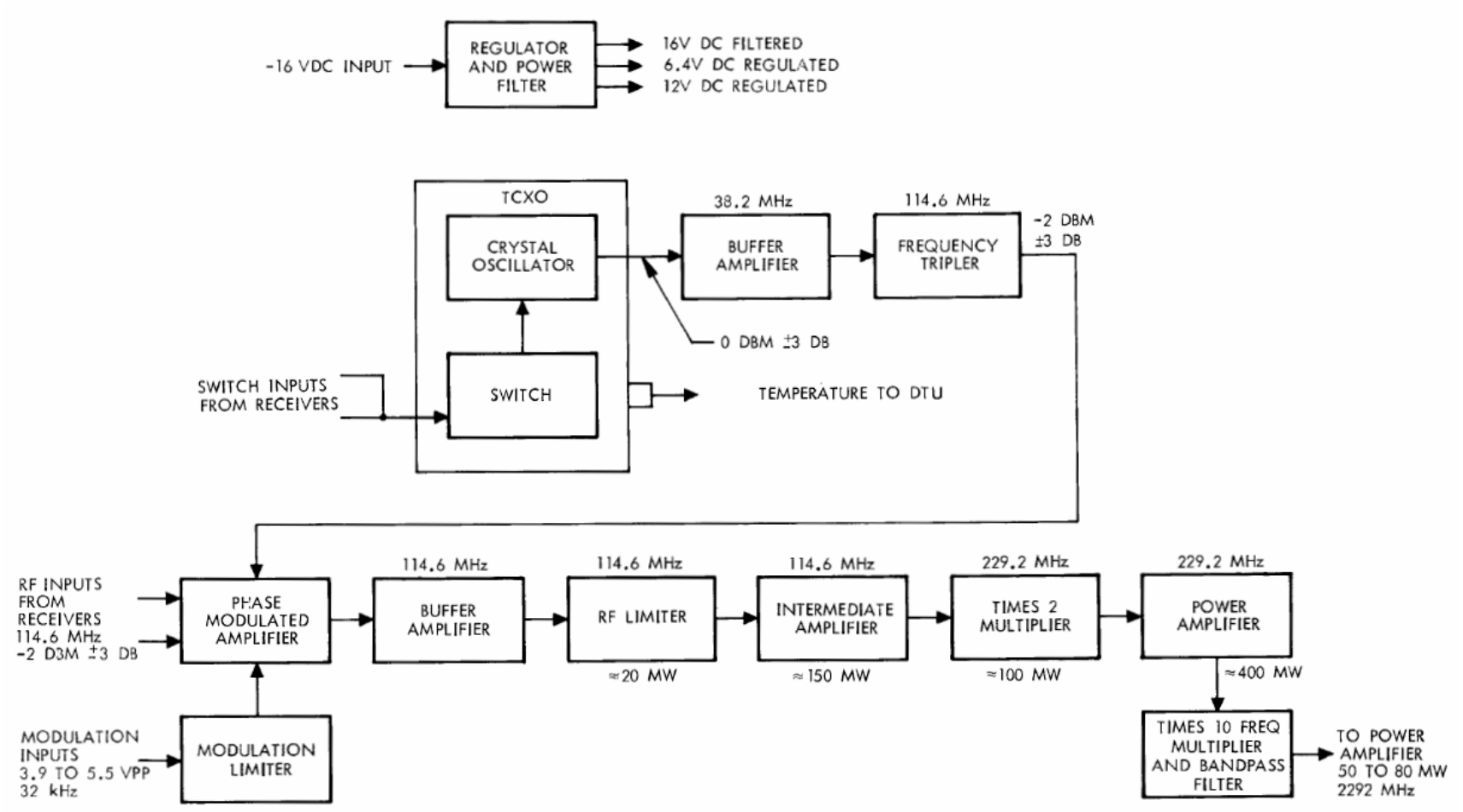
Downlink Power Budget



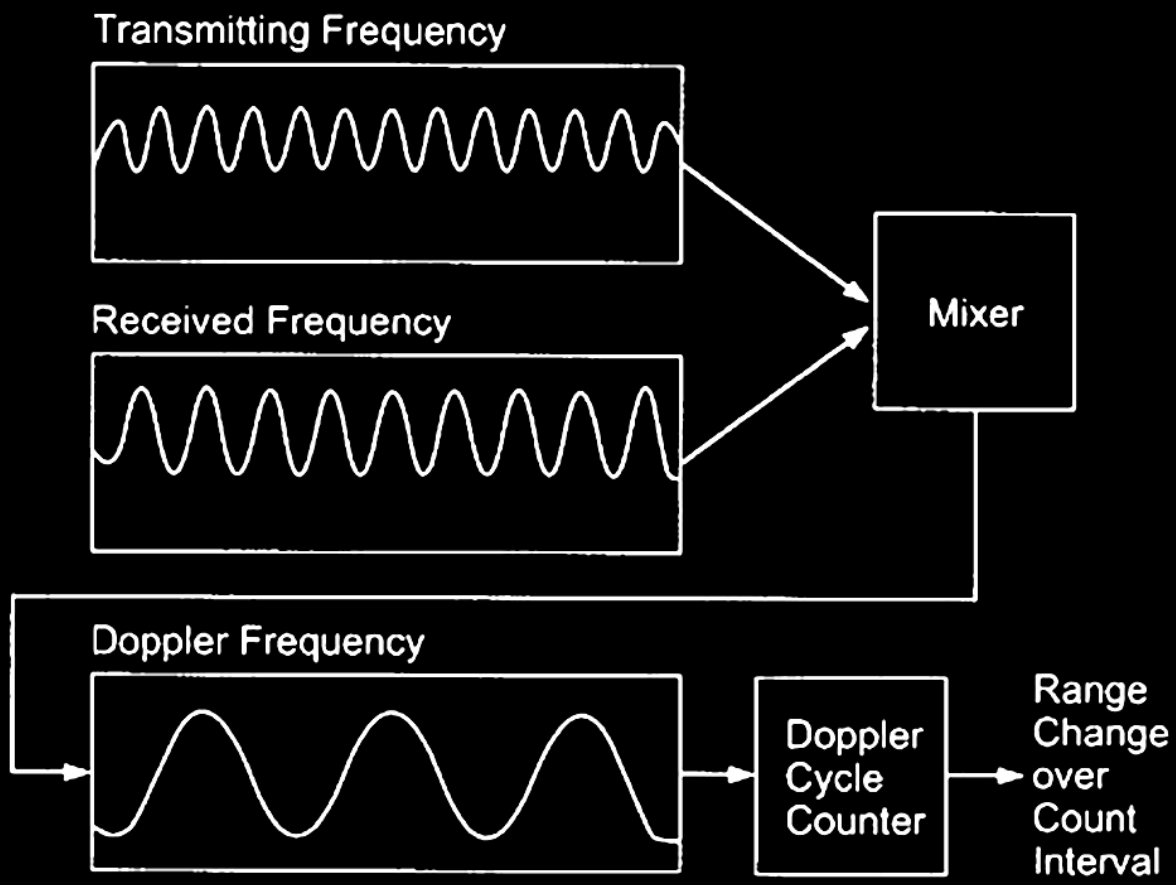
- Received power was –181 dBm at EOM!
- That is <0.000000000000000000001 W!

Communications Subsystem

Transmitter Block Diagram

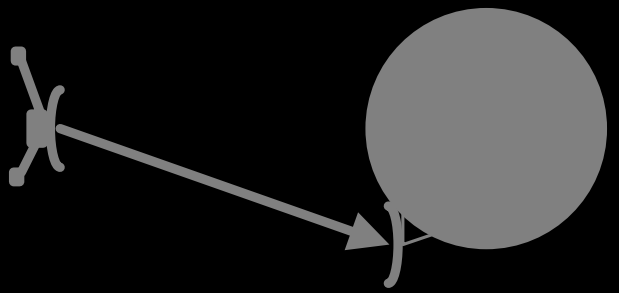


Doppler Measurements

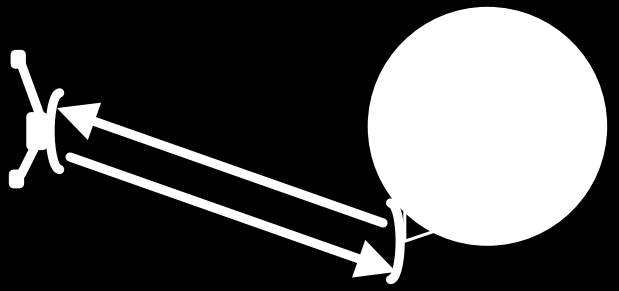


Doppler Measurements

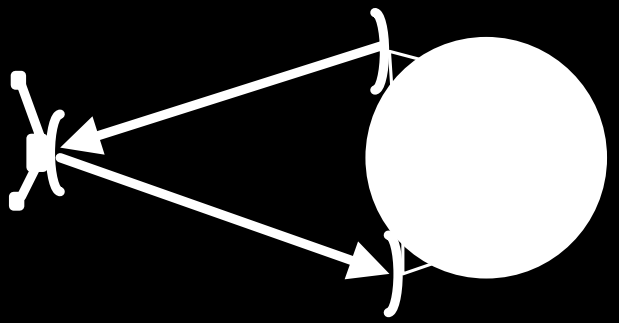
- One-way Doppler



- Two-way Doppler

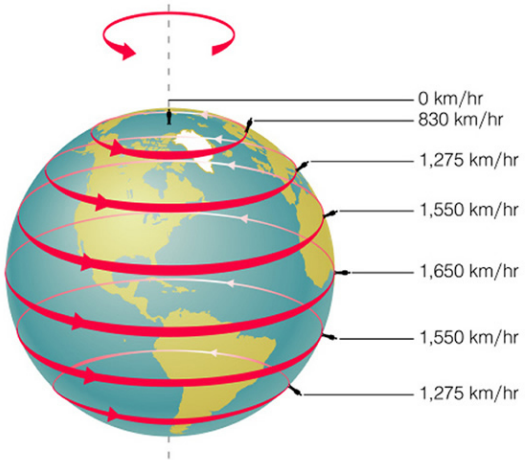


- Three-way Doppler

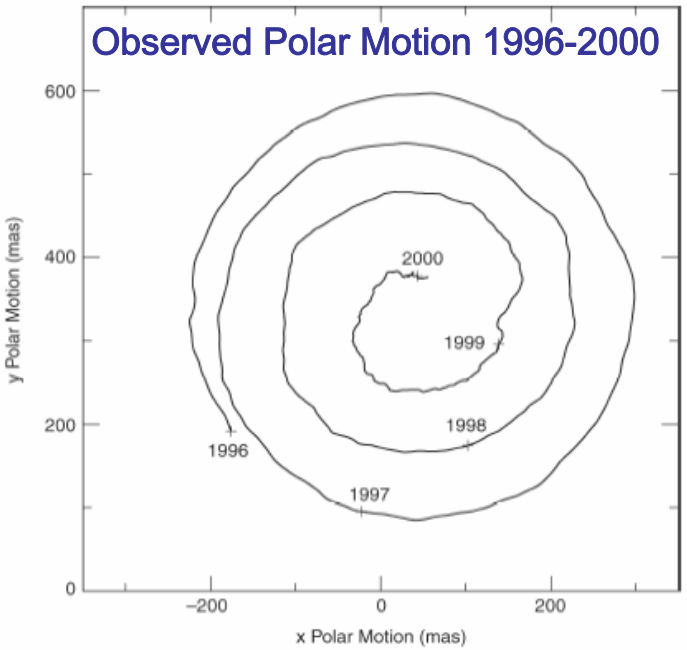


Terrestrial Effects

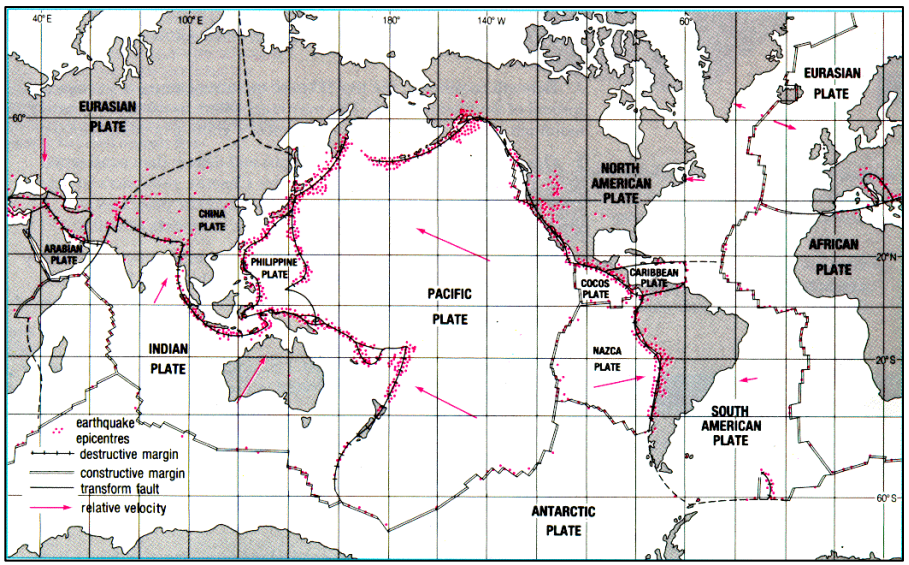
Earth Rotation



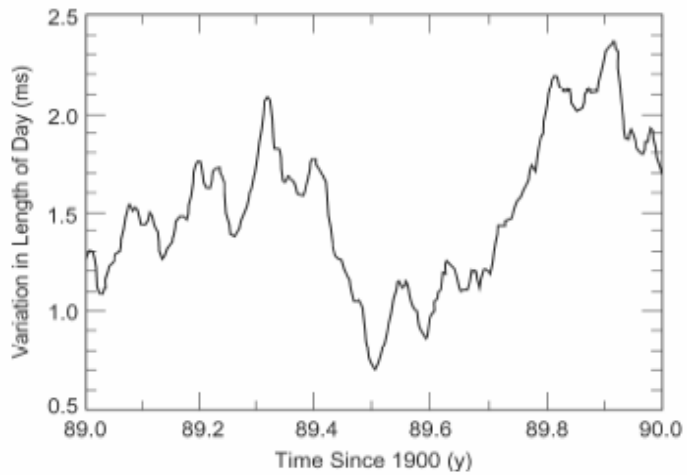
Observed Polar Motion 1996-2000



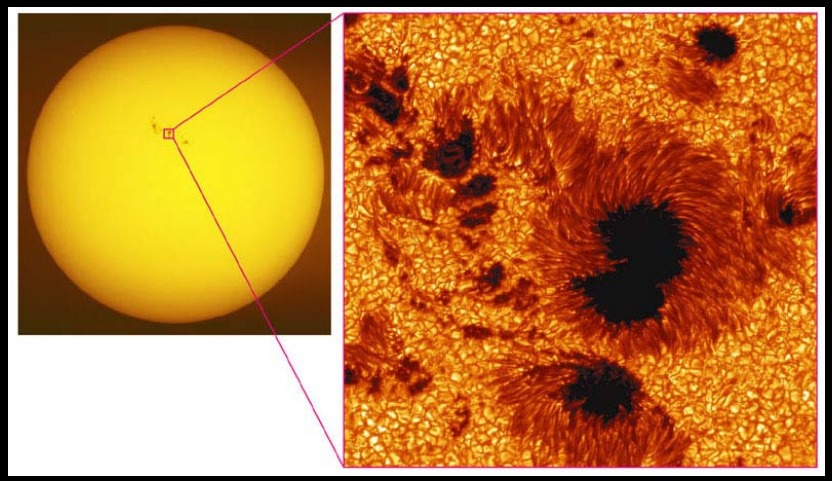
Tectonic Plate Motion

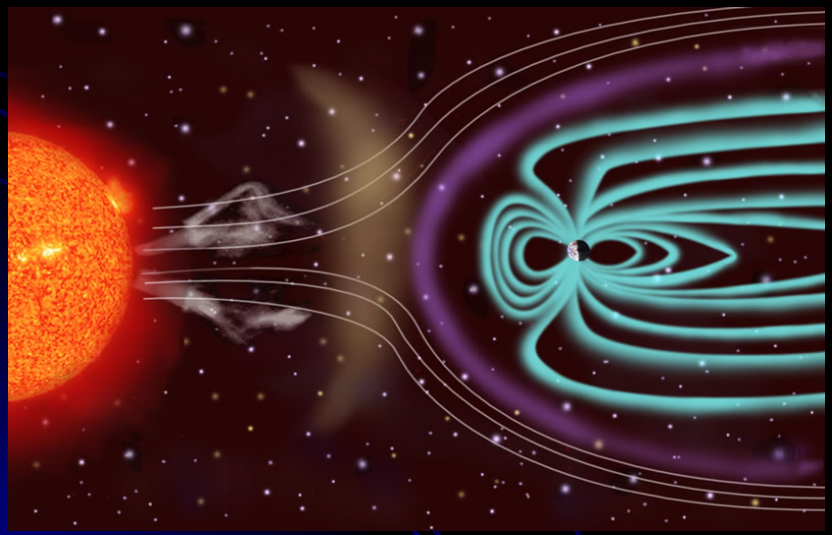


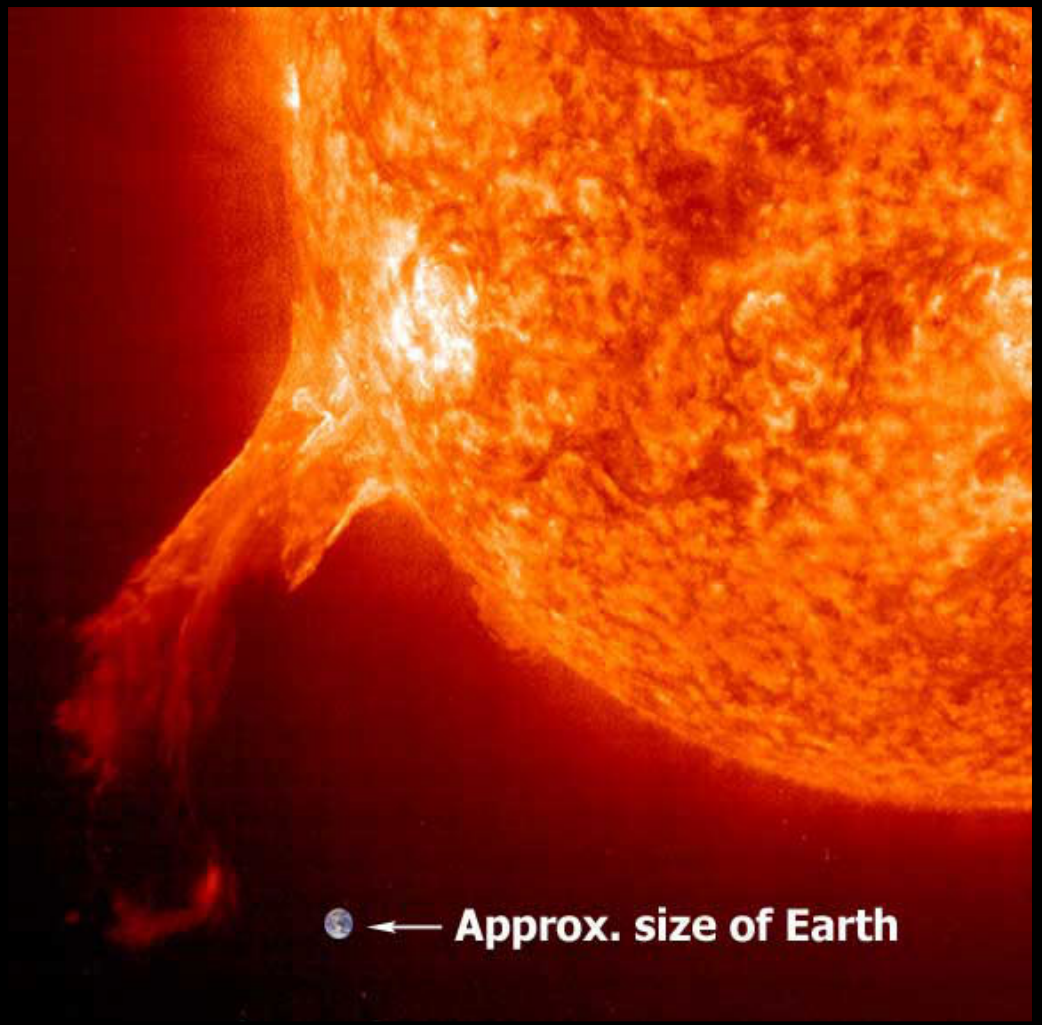
Variation in Length of Day since 1990



Solar Effects

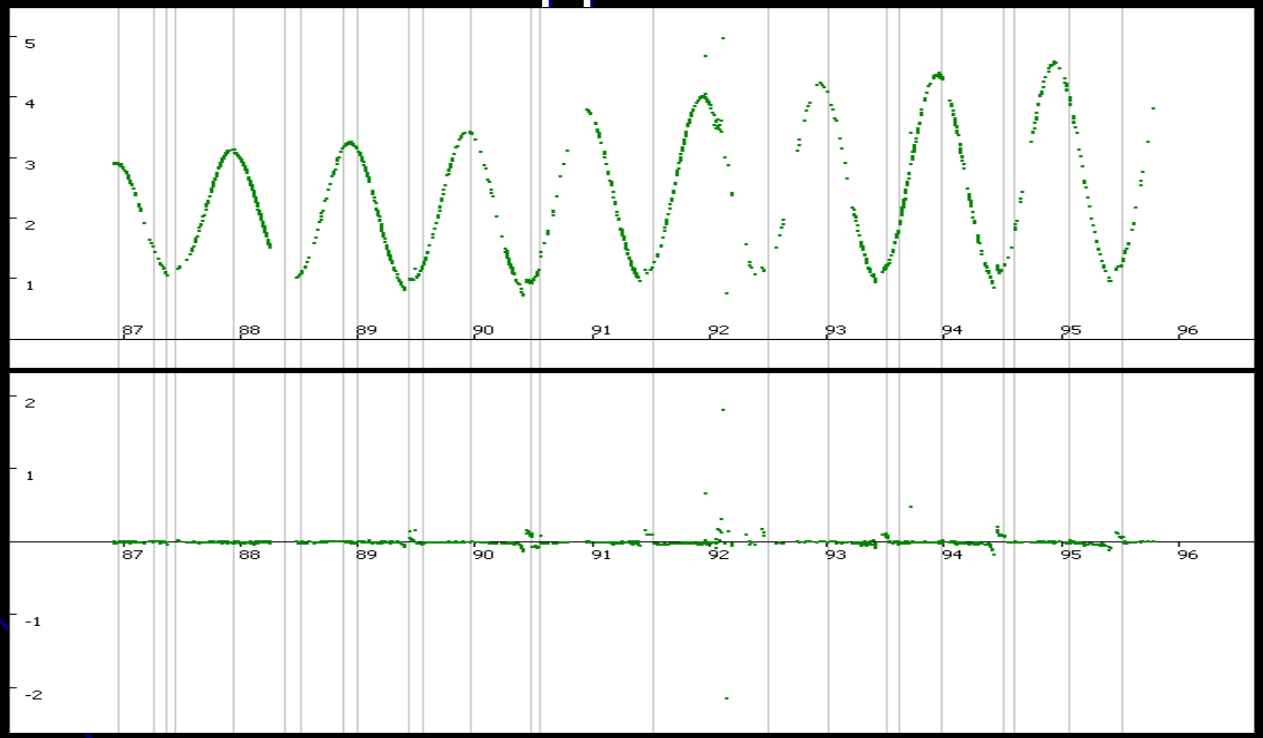






Doppler Fits

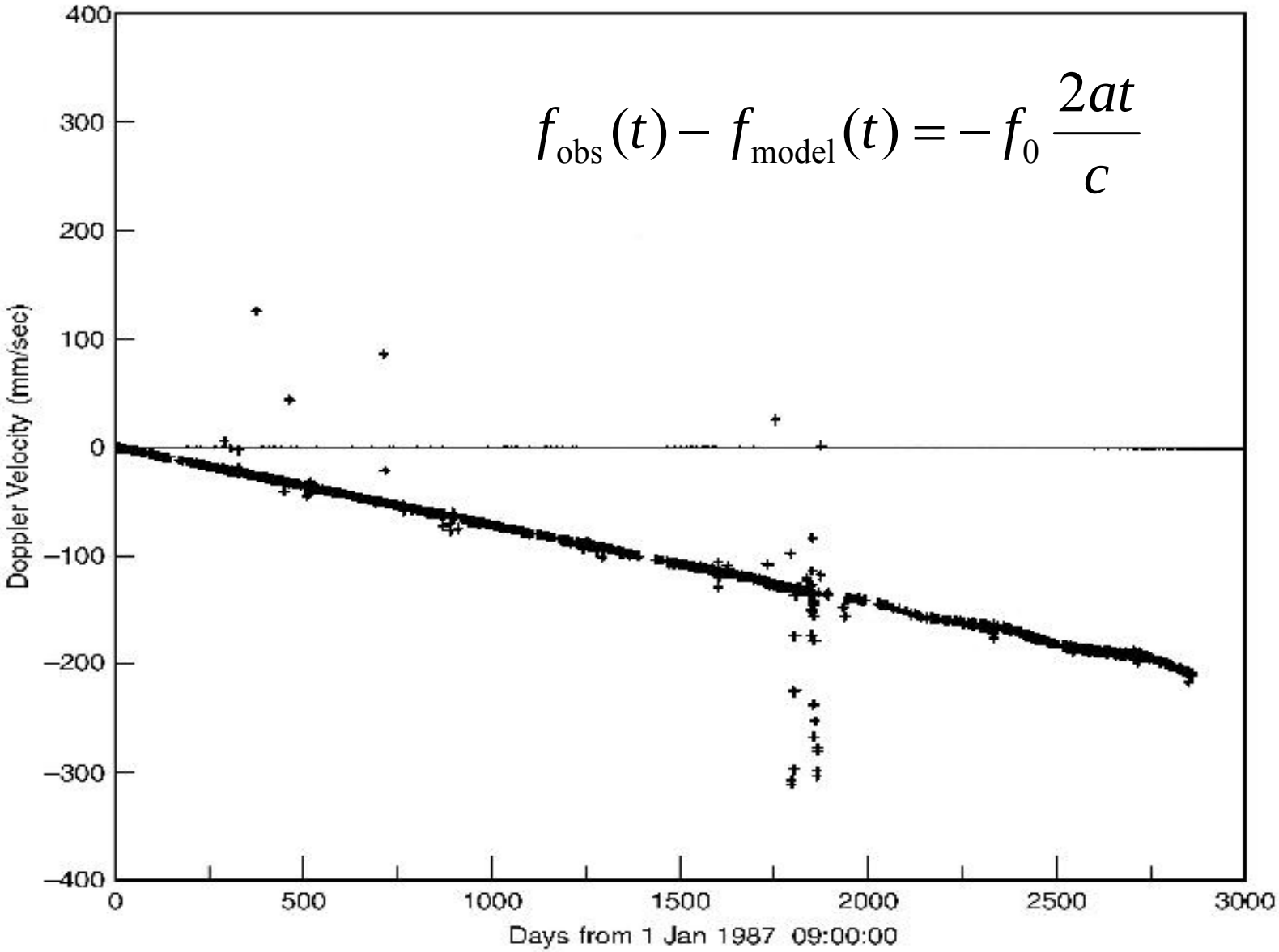
- Model predicts spacecraft motion and Doppler
- Antenna measures actual Doppler
- Difference is called the “Doppler Residual”
- “Bad” fit:



- “Good” fit:
- Accuracy is measured in mHz!

Doppler Residuals

$$f_{\text{obs}}(t) - f_{\text{model}}(t) = -f_0 \frac{2at}{c}$$



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

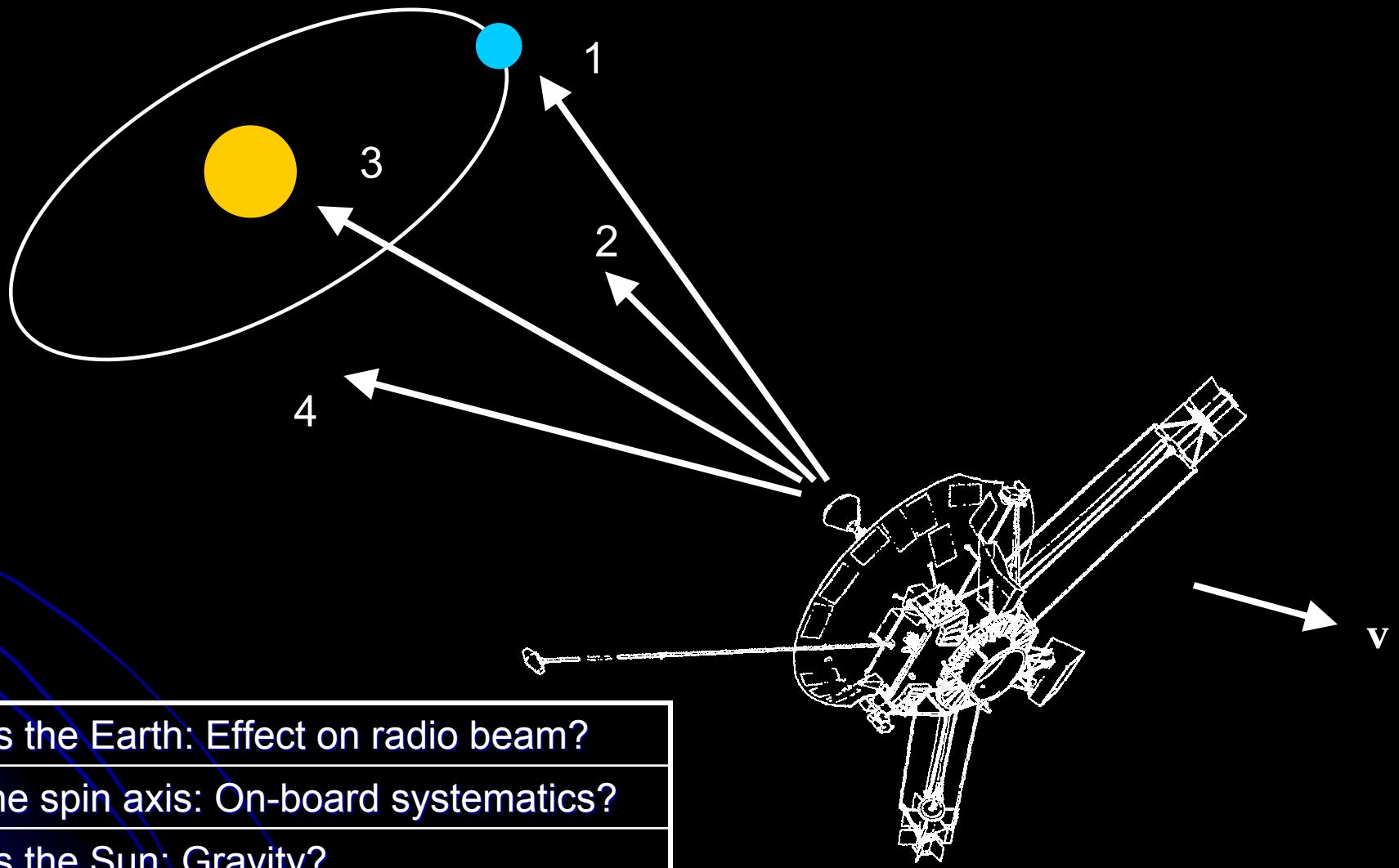
Discovery of the Anomaly

- Search began in 1979 (for “Planet X”)
- Anomaly first detected in 1980
- Initial JPL ODP analysis in 1990-95
- Aerospace Corporation confirms: 1996-98
- Another confirmation by Markwardt (2002)
- Also confirmed by Olsen (2005)

Interpreting the Residual

- Frequency shift: $(5.99 \pm 0.01) \times 10^{-9}$ Hz/s
- Velocity change: $(8.74 \pm 1.33) \times 10^{-10}$ m/s^2
- Clock acceleration: $(2.92 \pm 0.44) \times 10^{-18}$ s/s^2
- Velocity change (acceleration) is the "conventional" interpretation
- Effect small by engineering standards, but huge by the standards of gravity physics

Unknown direction



1.	Towards the Earth: Effect on radio beam?
2.	Along the spin axis: On-board systematics?
3.	Towards the Sun: Gravity?
4.	Opposite the direction of motion: Drag force?

Consensus as of 2006

- The Pioneer Anomaly is real
- Conventional physics *fails* to explain it
- Alternatives proposed include
  - Modified Newtonian Dynamics (MOND)
  - Nonsymmetric gravitational theory
  - Dark matter
  - Yukawa potential ($V_{\text{grav}} = -Ge^{-mr}/r$)
- $a_P \approx cH_0$ – coincidence?

Thermal Radiation

- Only ~65W of directed heat needed
- ~2500W heat available on board
- Heat sources include
  - Radioisotope thermoelectric generators (RTGs)
  - Electrically generated heat
  - Small radioisotope heater units (RHUs)
- Previous estimates: insufficient directed heat to explain the anomaly
- Conclusions based on rough estimates

Telemetry

- Precise and detailed information on
  - Electrical power
  - Temperatures
- All information from spacecraft was packaged in Master Data Records (MDRs)
- Once science data was extracted and spacecraft operations no longer needed the data, MDRs were thought to be expendable

BUT…

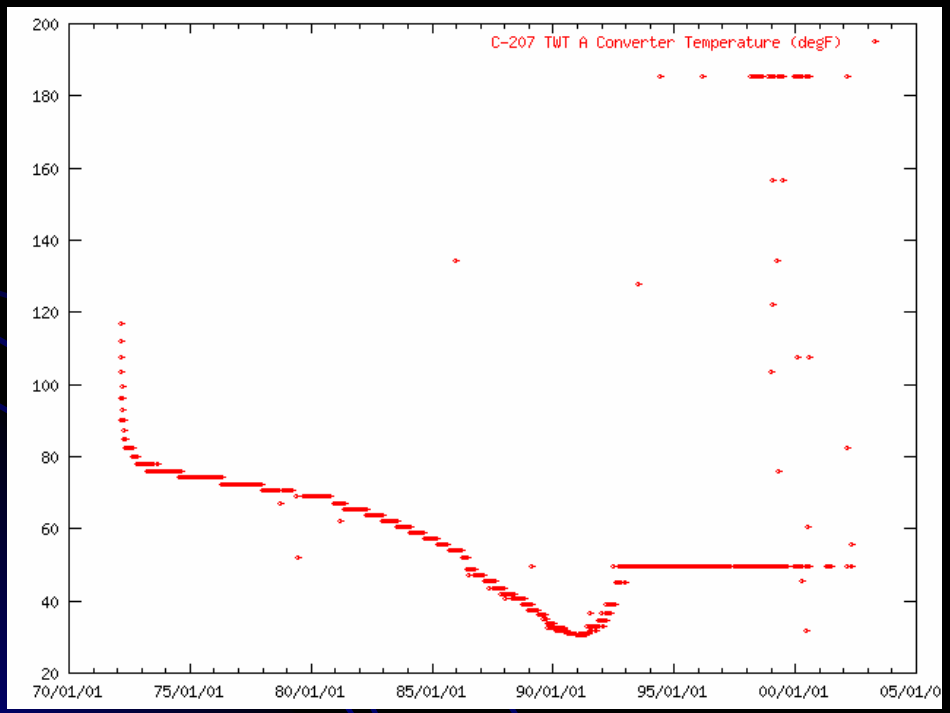
- The Pioneer 10/11 MDRs were saved!
- First, on tape
- Later, ‘floptical’ disks
- Total amount of data: 40 gigabytes

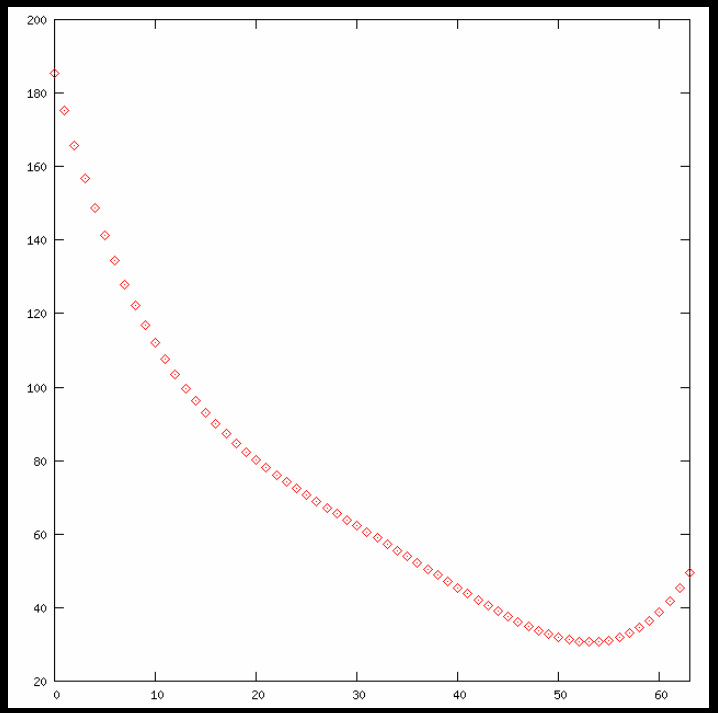
What's in the Telemetry?

- MDRs contain
  - Reception characteristics
  - Science data
  - ***Engineering telemetry***
- Types of readings
  - Thermal
  - Electrical (voltages, currents)
  - Propellant pressure
  - Switches and sensors
  - Command and logic states
  - Counters

Analog Readings

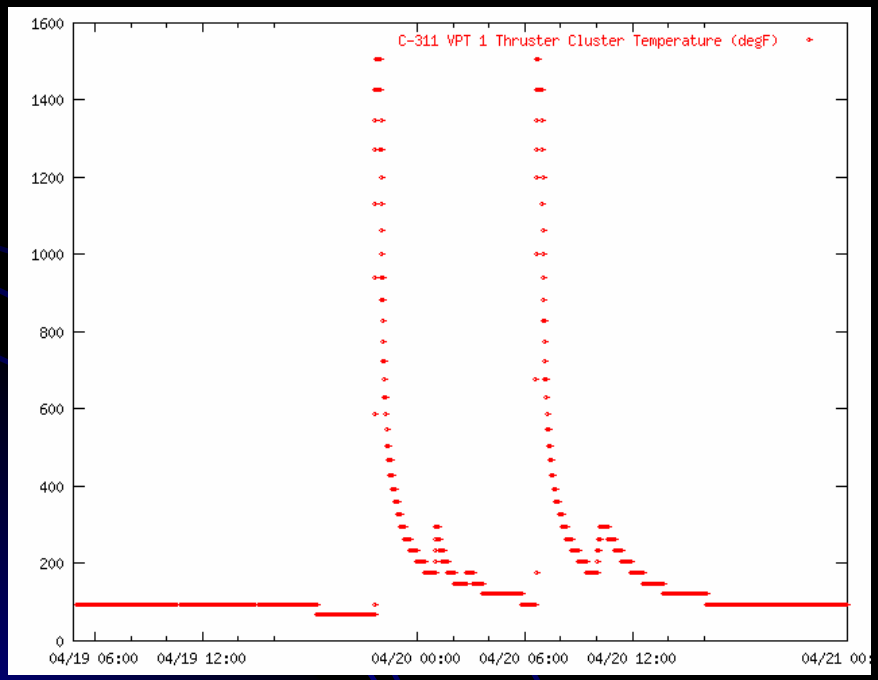
- Analog data is low-resolution (6 bits, 64 levels)
- Calibration is important



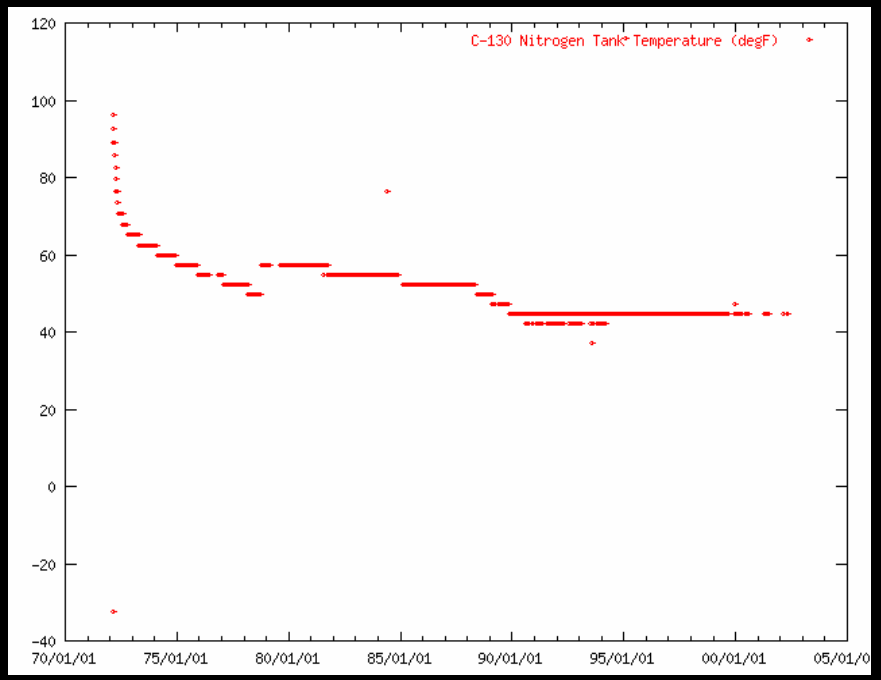


What do we see?

- Individual events (e.g., thruster firings)
- Long term trends (e.g., propellant temp.)

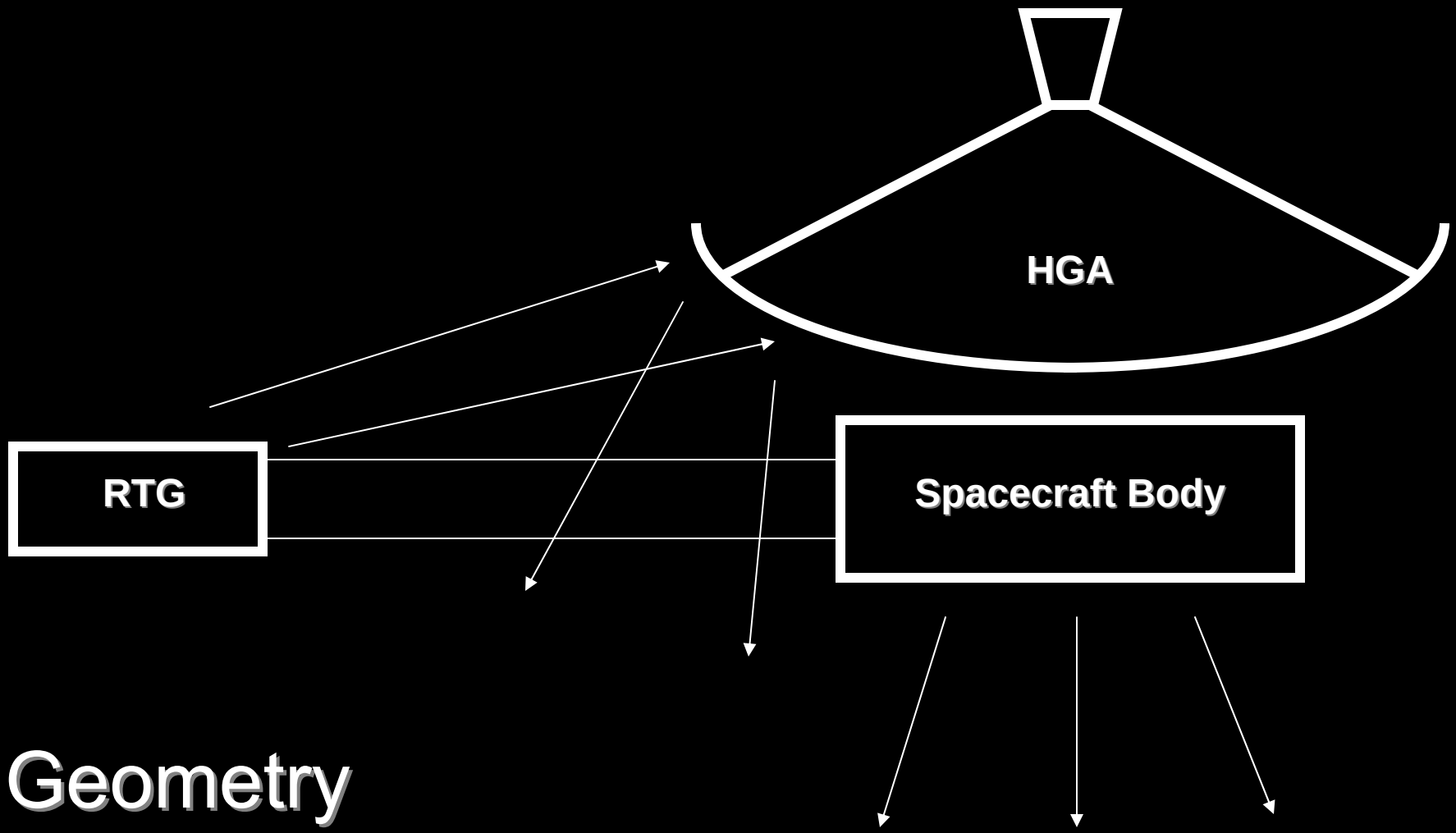


VPT1 temperature on board Pioneer 11 on April 19-20, 1974 (major course correction maneuver)



Nitrogen tank temperature on board Pioneer 10, entire mission.

Design Information



- Geometry
- Infrared Reflectivity

New Analysis

- Design details +

  Telemetry record =

  New estimates on acceleration and its temporal profile!

- Better yet: Incorporate thermal model into orbit estimation

Focus

- RTG heat: Radiation reflected off the back of the HGA, which is highly reflective
- Electrical heat: most heat generated inside main spacecraft body, emitted preferentially through the back

New Analysis

- Complete Doppler data set has been collected and assembled
- Telemetry is available
- It is possible to “refly” both missions, analyzing any anomalous behavior
- Using telemetry in orbital analysis is new technique; never done before
- We hope to find an unambiguous answer

Conclusions

- Wikipedia lists the Pioneer Anomaly as one of the great 'unresolved problems' in physics
- New Scientist calls it one of "13 things that do not make sense"
- But, the explanation may be mundane
- Either way, it's win-win: new physics is great, but improved spacecraft navigation is also a valuable result

Questions?