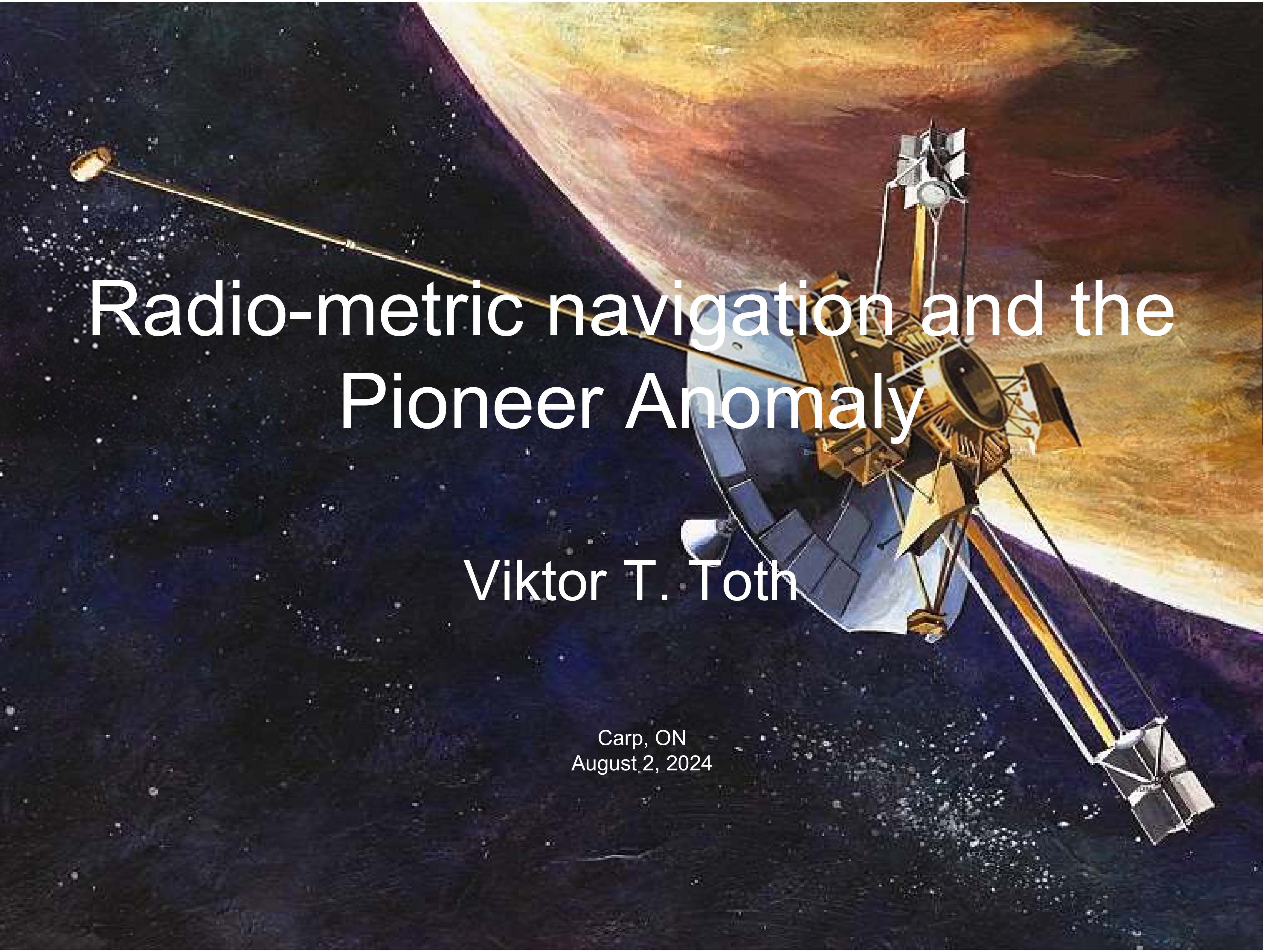


Radio-metric navigation and the Pioneer Anomaly

Viktor T. Toth

Carp, ON
August 2, 2024

Pioneer 10/11

- Launched in 1972 and 1973
- First to fly beyond the orbit of Mars
- First to visit Jupiter and Saturn
- Design lifespan: 600-900 days

Mission

- Primary mission
  - Explore the asteroid belt
  - Research beyond Mars
  - Up close observations of Jupiter
- Secondary mission
  - Explore the outer solar system
  - Look for gravitational waves
  - Look for “planet X”

Discovery of the anomaly

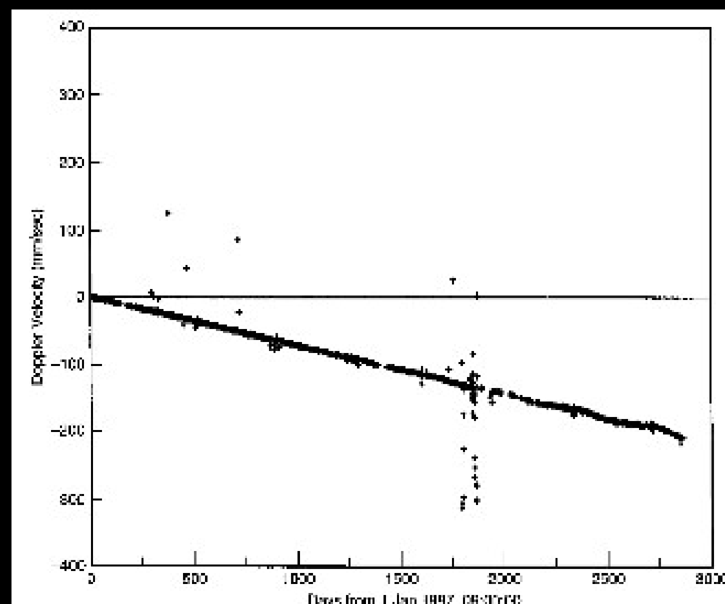
VOLUME 81, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1998

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,¶]

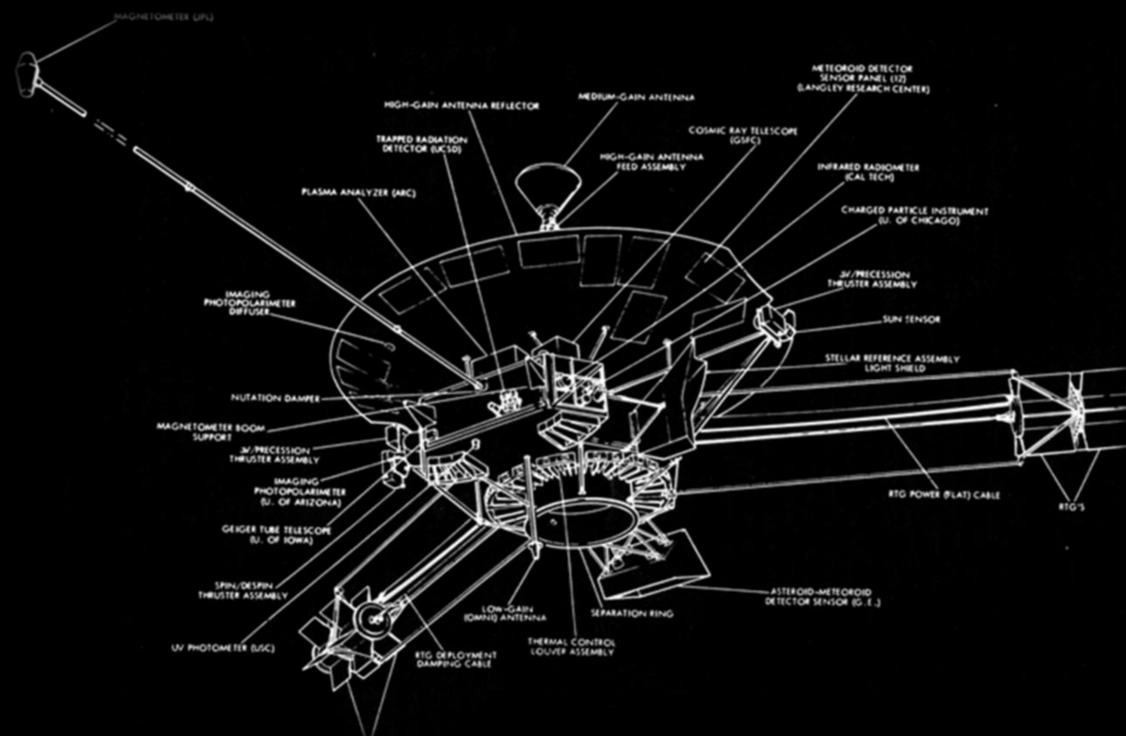
Radio metric data from the Pioneer 10/11, Galileo, and Ulysses spacecraft indicate an apparent anomalous, constant, acceleration acting on the spacecraft with a magnitude $\sim 8.5 \times 10^{-8}$ cm/s^2, directed towards the Sun. Two independent codes and physical strategies have been used to analyze the data. A number of potential causes have been ruled out. We discuss future kinematic tests and possible origins of the signal. [S0031-9007(98)07300-1]

We conclude, from the JPL-ODP analysis, that there is an unmodeled acceleration a_P towards the Sun of $(8.09 \pm 0.20) \times 10^{-8}$ cm/s^2 for Pioneer 10 and of $(8.56 \pm 0.15) \times 10^{-8}$ cm/s^2 for Pioneer 11. The error is determined by use of a five-day batch sequential filter with radial acceleration as a stochastic parameter subject to white Gaussian noise ($\sim$500 independent five-day samples of radial acceleration) [4,5]. *No magnitude variation of a_P with distance was found,* within a sensitivity of 2×10^{-8} cm/s^2 over a range of 40 to 60 AU.

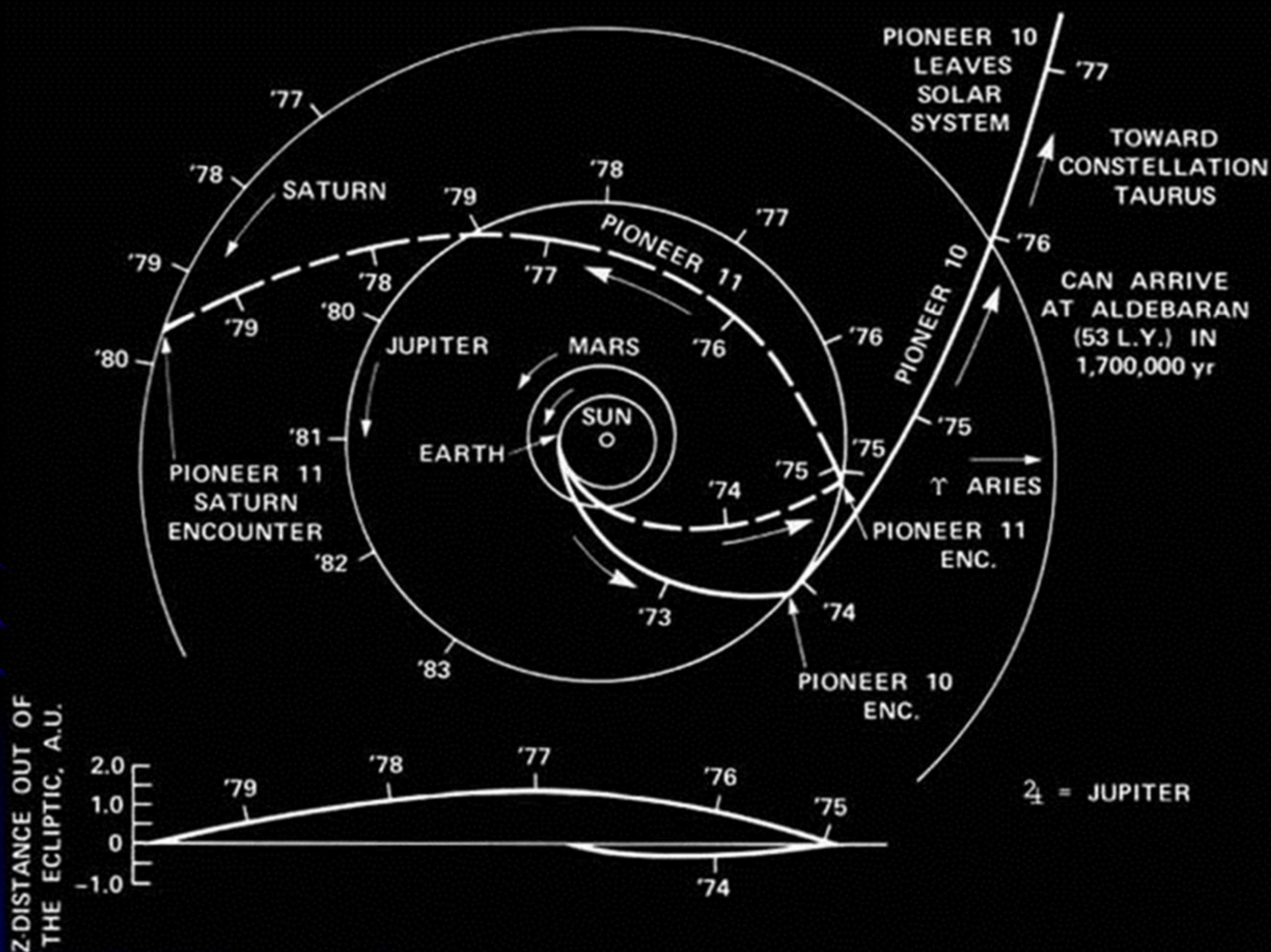


Details about the probes

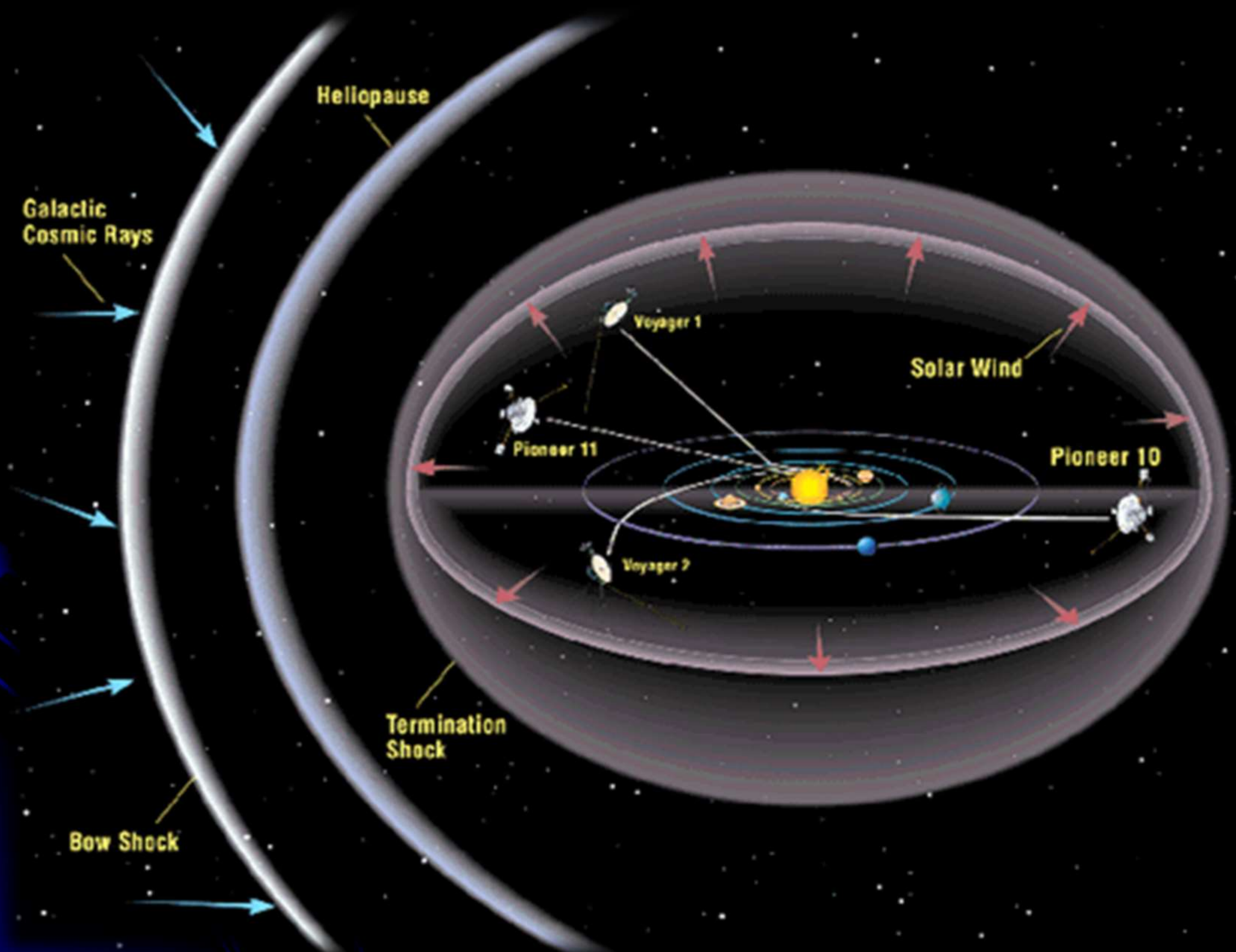
- Mass: ~250 kg
- Spin stabilized (4.8 rpm nominal rate of rotation)
- **Radioisotope thermoelectric generators (RTG)**
- Electric power: ~160 W (at launch)
- 11 scientific instruments
- 2.75 m antenna
- Transmit power: 8 W
- Data rate: 16-2048 bps



Pioneer trajectories – early years



The Pioneer and Voyager probes in the outer solar system

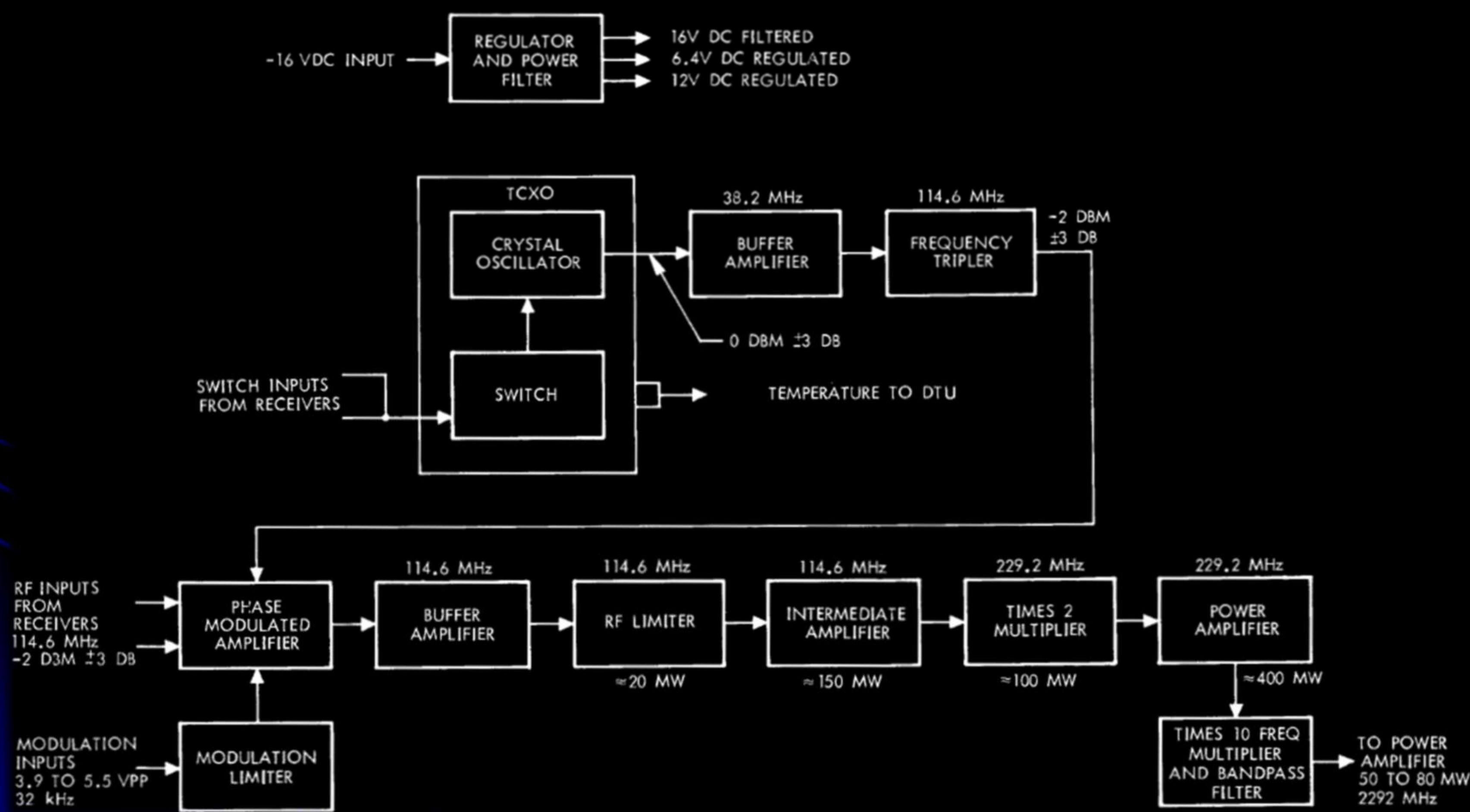


Pioneer 10 after 30 years

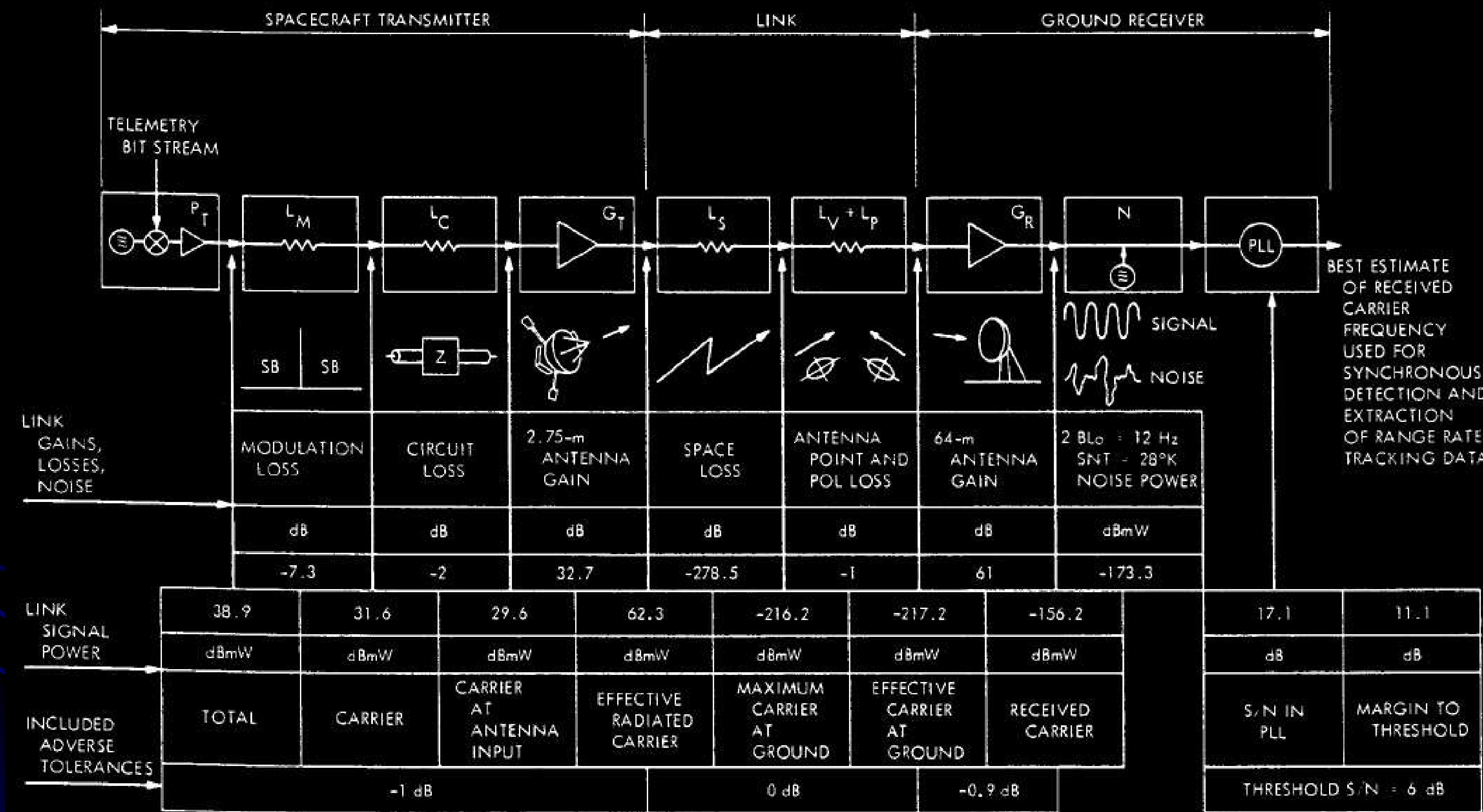
- Heliocentric distance: ~80 AU.
- Light round-trip travel time: ~21 hours
- Heliocentric velocity: ~12 km/s
- One instrument (GTT) still operating (shutdown command sent, confirmation never received)
- Electric subsystem ~ 26VDC instead of nominal 28VDC
- Transmitter crystal oscillator failed (probably temperature-related)
- Transmitter still operating in coherent mode
- Several temperature readings below calibrated minima
- Fuel lines frozen (no maneuvering capability)

Communications Subsystem

Transmitter Block Diagram

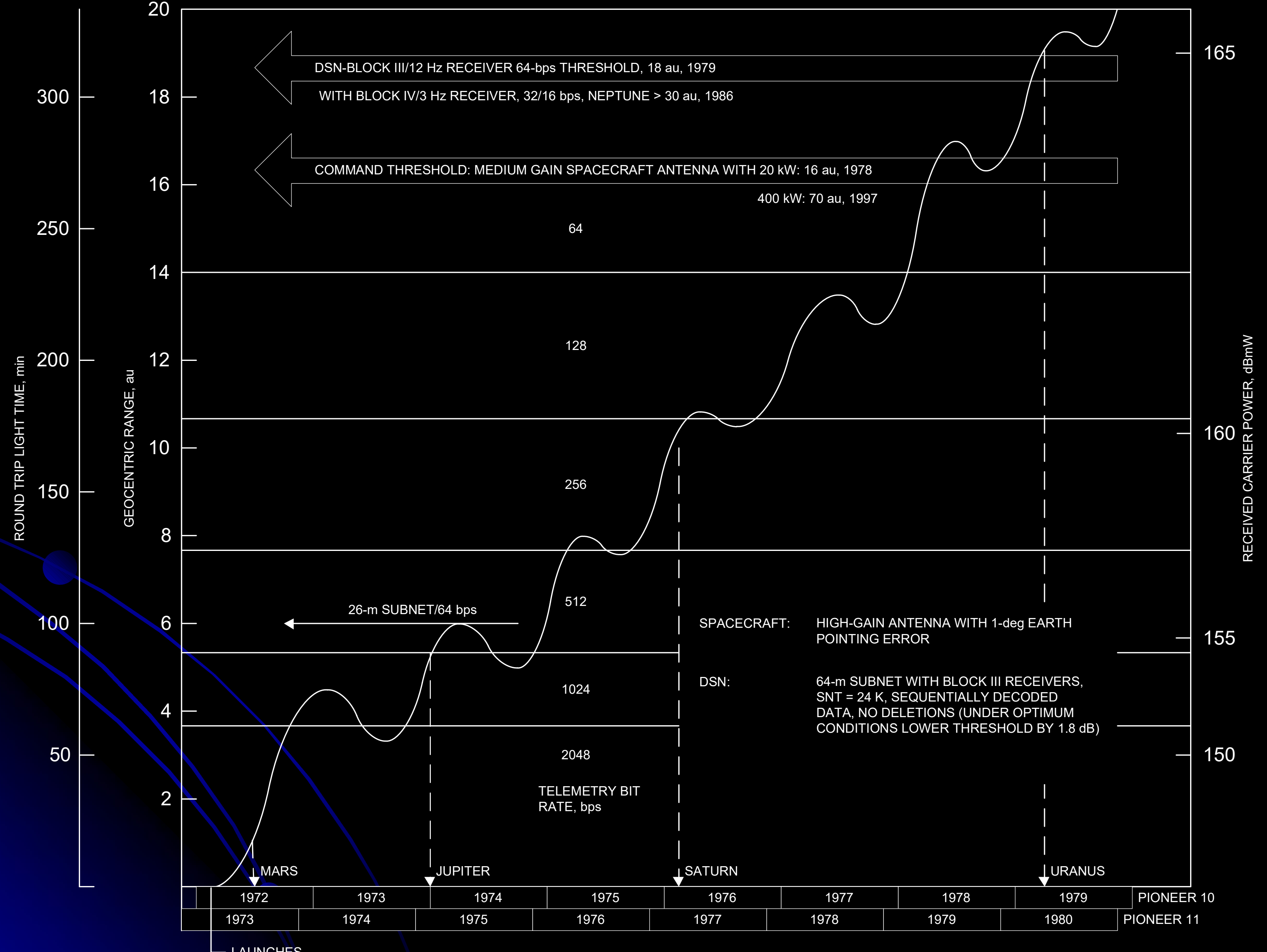


Downlink power budget



Received power was –181 dBm (<10^{-21} W) at EOM

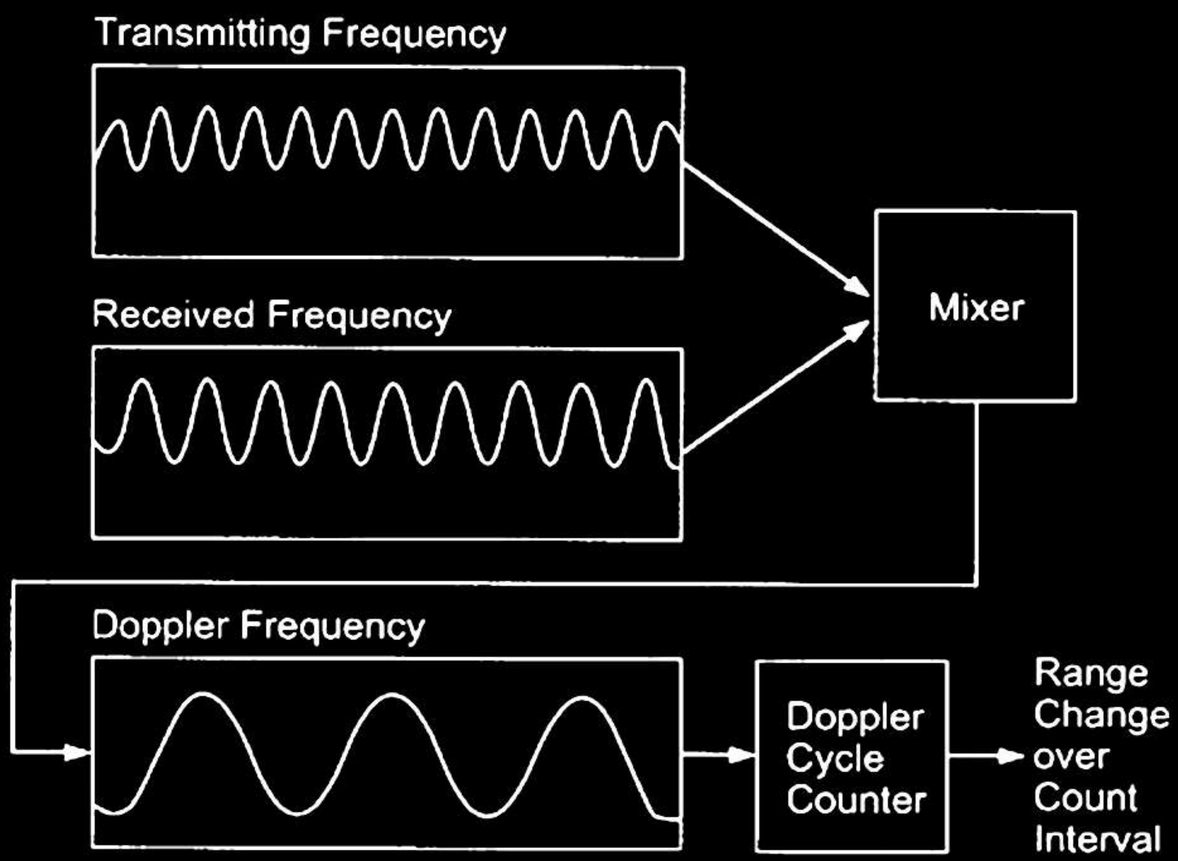
Downlink power budget



Data handling

- Downlink bit rates: 16 - 2048 bps
- 49152 bits on-board storage (ferrite core)
- Digital Telemetry Unit (~800 ICs)
  - 10 science formats (5 used)
  - 4 engineering formats
  - 3 modes (real-time, store, readout)
- Timing and control
- Commanding
- All downlinked data stored in the form of Master Data Records (MDRs)

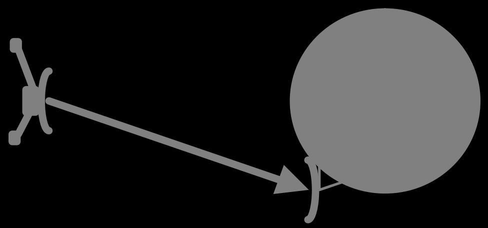
Doppler Measurements



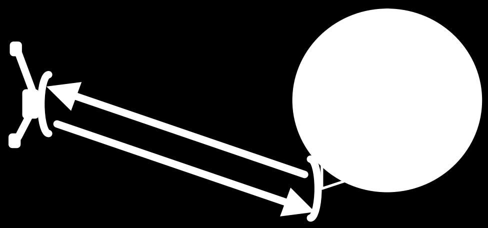
Analysis of Doppler data

- Observations are two-way or three-way Doppler

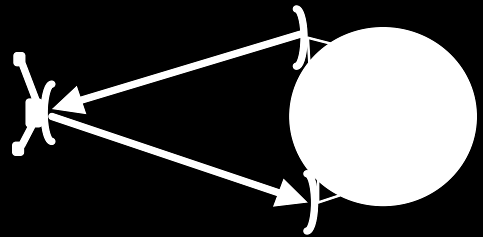
- One-way Doppler



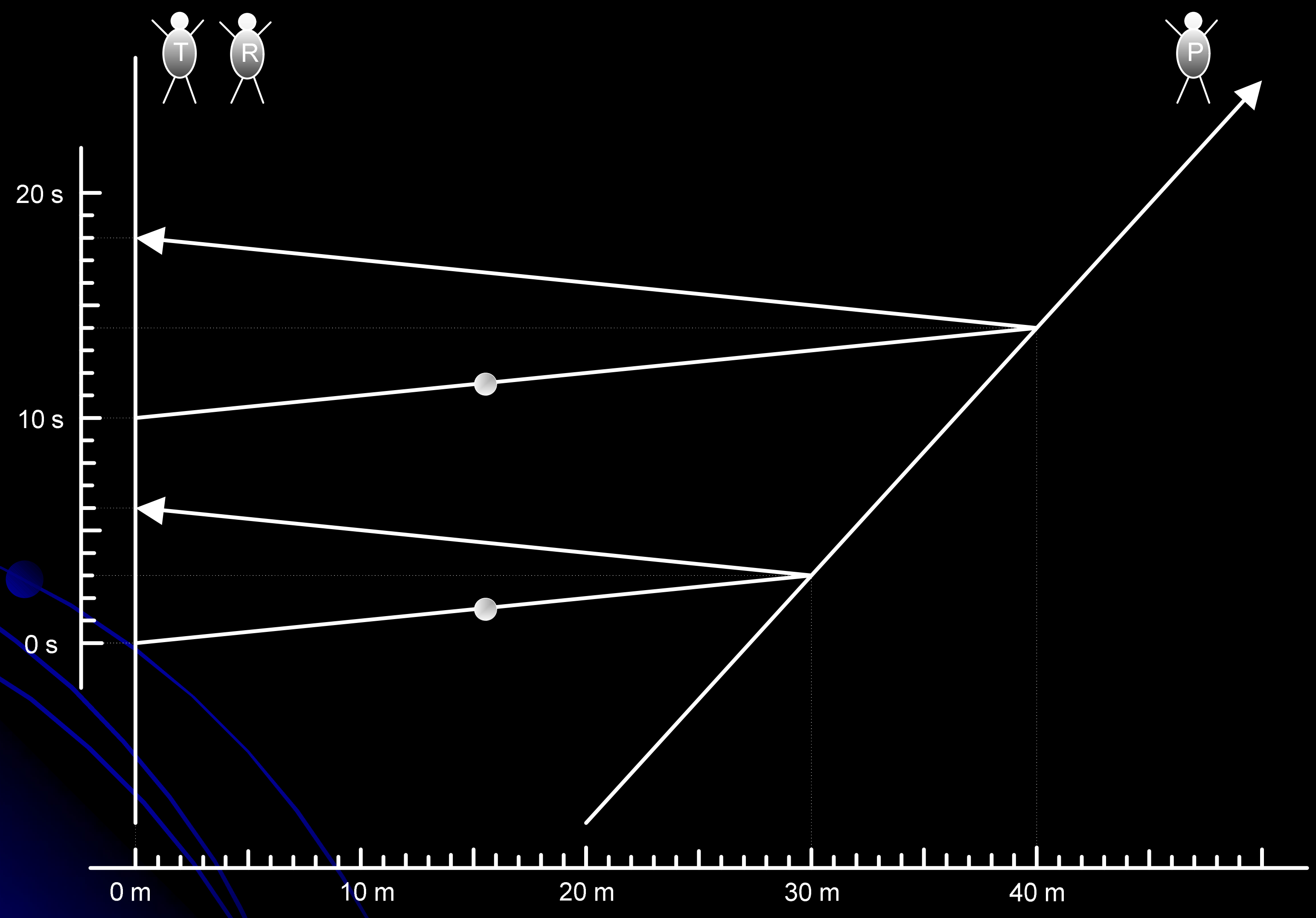
- Two-way Doppler



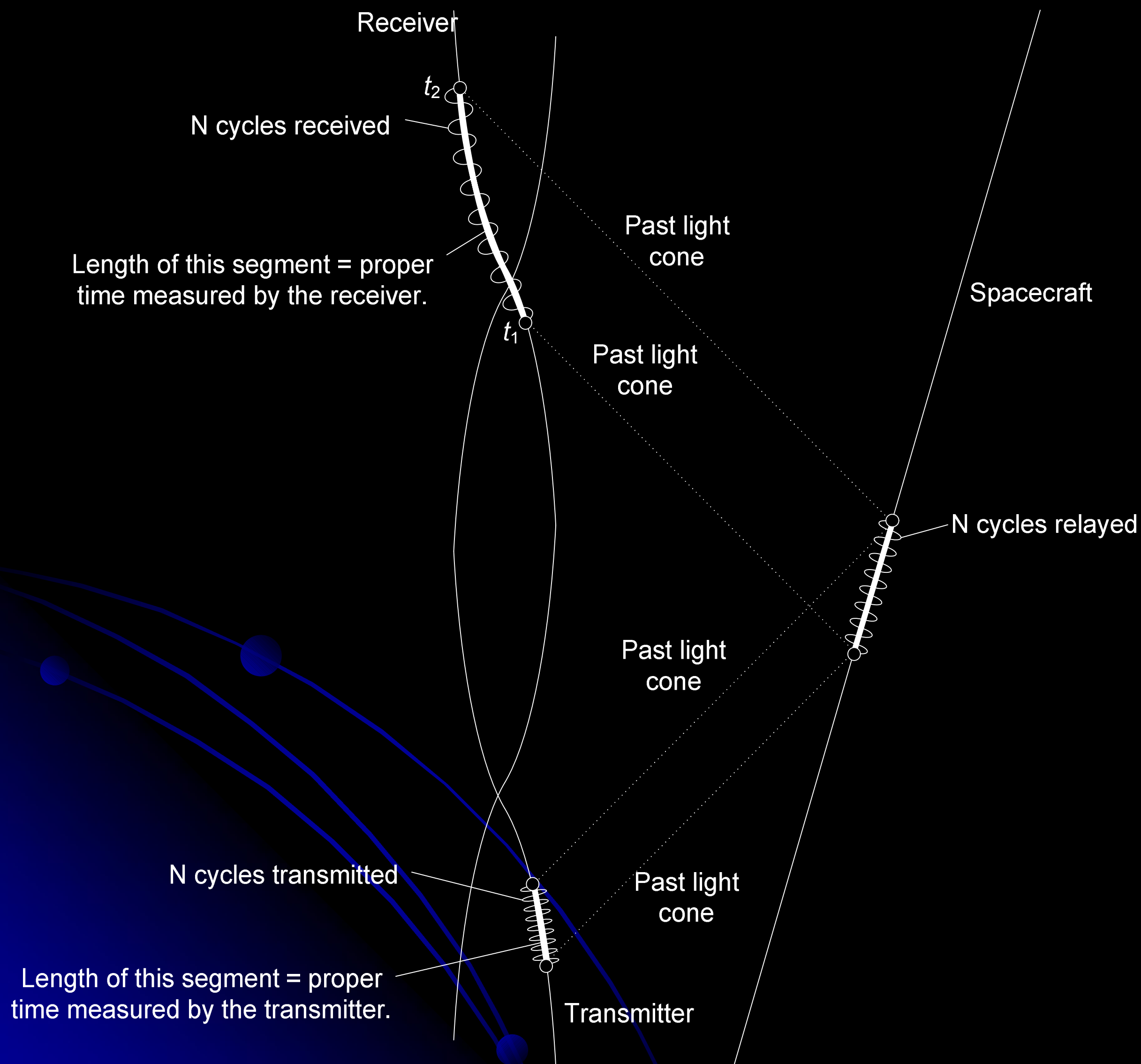
- Three-way Doppler



Two-way (or three-way) Doppler

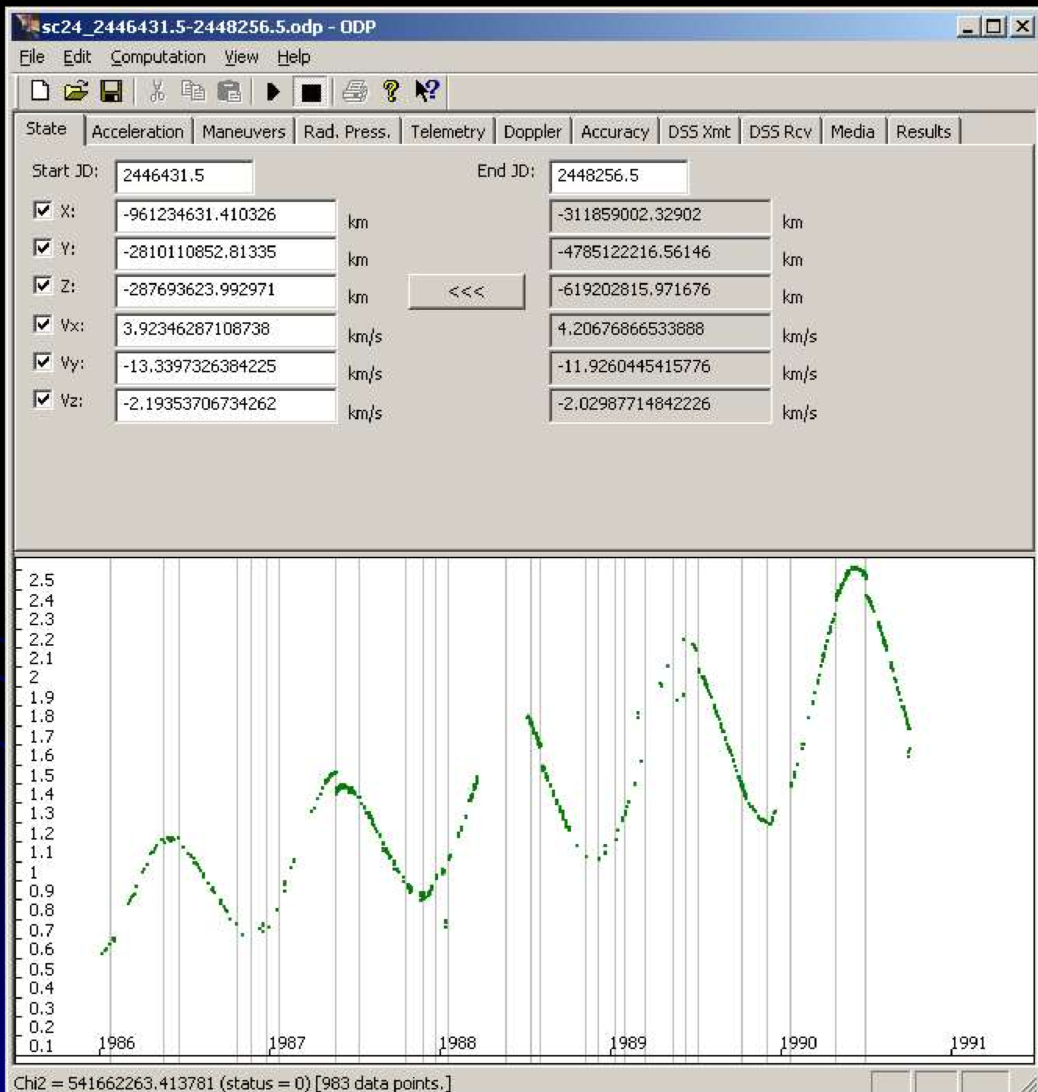


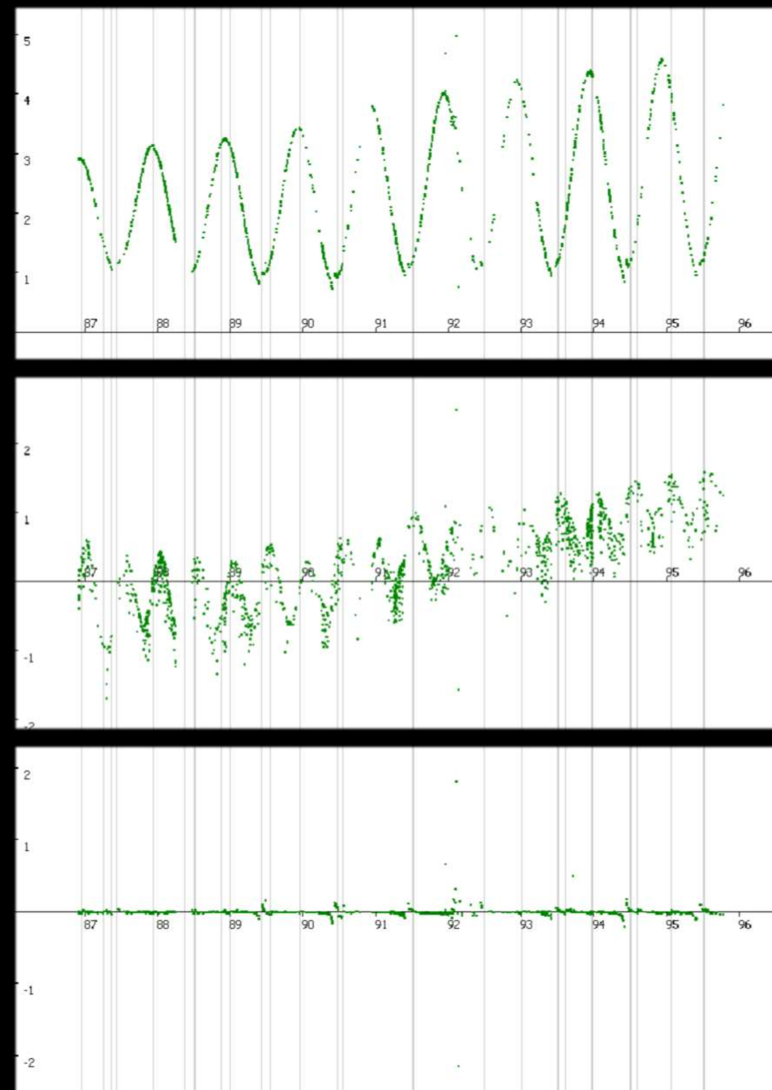
Doppler measurements



- Receiver counts cycles between moments of time t_1 és t_2
- These moments are projected back onto the worldline of the probe and the transmitter. The computation takes into account the following:
  - PPN-gravity of larger solar system bodies
  - Maneuvers
  - Small nongravitational forces (e.g., fuel leaks)
  - Shapiro-delay
  - Impact of interplanetary medium (solar wind plasma)
  - Atmospheric effects
  - Location of ground station (tides, continental drift)
- The number of cycles can be estimated from the transmitter frequency
- This is compared to the number of cycles counted by the receiver
- Iterating the model, we can minimize the residual difference

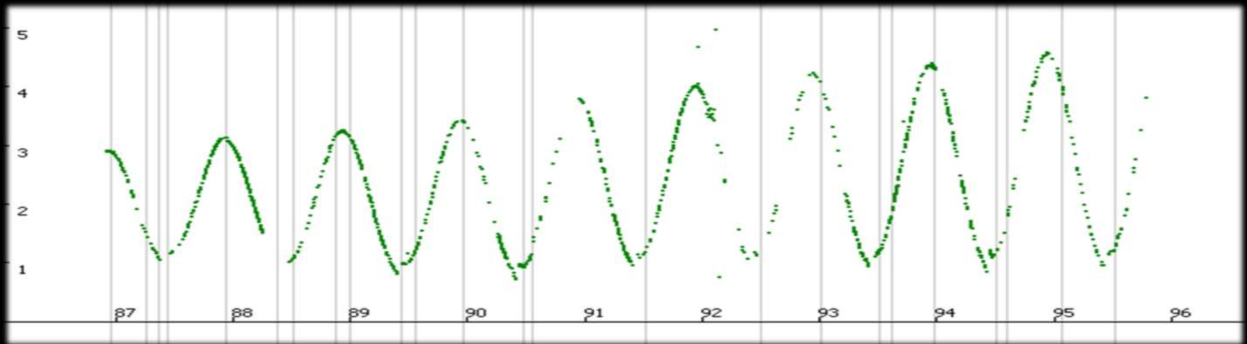
Orbit estimation



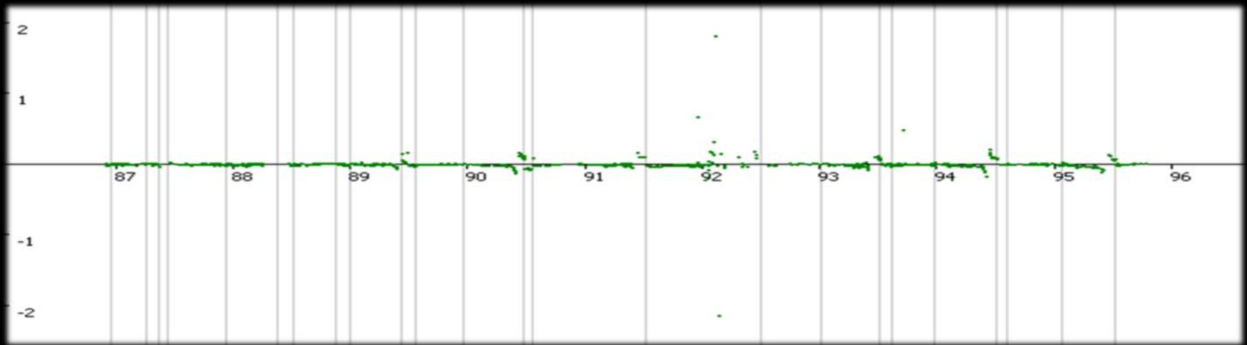


Doppler fitting

- Model predicts the motion of the probe and Doppler
- Antenna measures actual Doppler
- Difference is the „Doppler residual"
- "Bad" fit:



- "Good" fit:



- Accuracy is measured in mHz!

Accuracy

- 2.29 GHz radio signal is modeled with an accuracy of ~2 mHz over a 20 year span
- Measurement and models must be accurate to better than 1 part in 10^{14}
- (IEEE 64-bit double precision floating point accuracy: about 1 part in 10^{16})

Results and confirmations

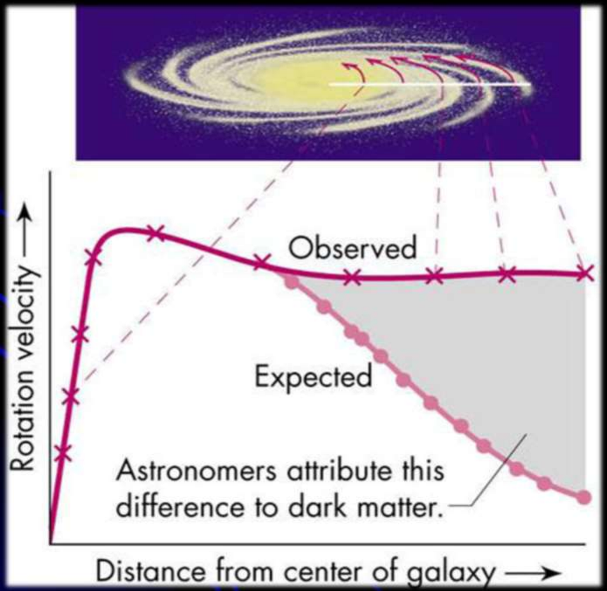
- Research began in 1979 (for “planet X”)
- First signs of anomaly in 1980
- Initial JPL ODP analysis in 1990-95
- Aerospace Corporation confirms: 1996-98
- Independent confirmation:
  Markwardt (2002), Olsen (2005), Toth (2009)
- Limited data available:
  no telemetry, no thermal model.

Interpreting the residual

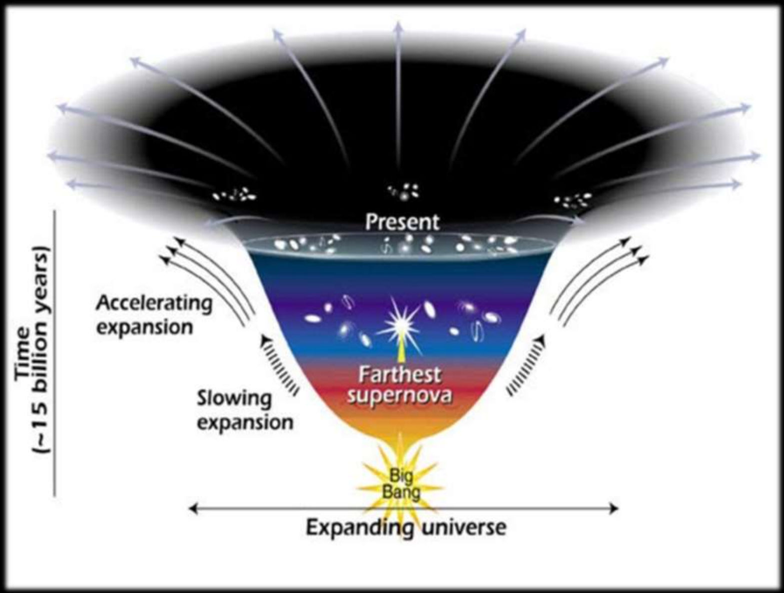
- Frequency shift: $(5.99 \pm 0.01)\times 10^{-9}$ Hz/s
- Velocity change: $(8.74 \pm 1.33)\times 10^{-10}$ m/s^2
- Time dilation: $(2.92 \pm 0.44)\times 10^{-18}$ s/s^2
- Change in velocity (acceleration) is the “generally accepted” interpretation
- The effect is small in engineering terms but large from the perspective of gravitational physics

Misbehavior of gravity on cosmic scales

- Galaxies do not rotate as expected
- Supernovas, cosmic background radiation suggest accelerating expansion

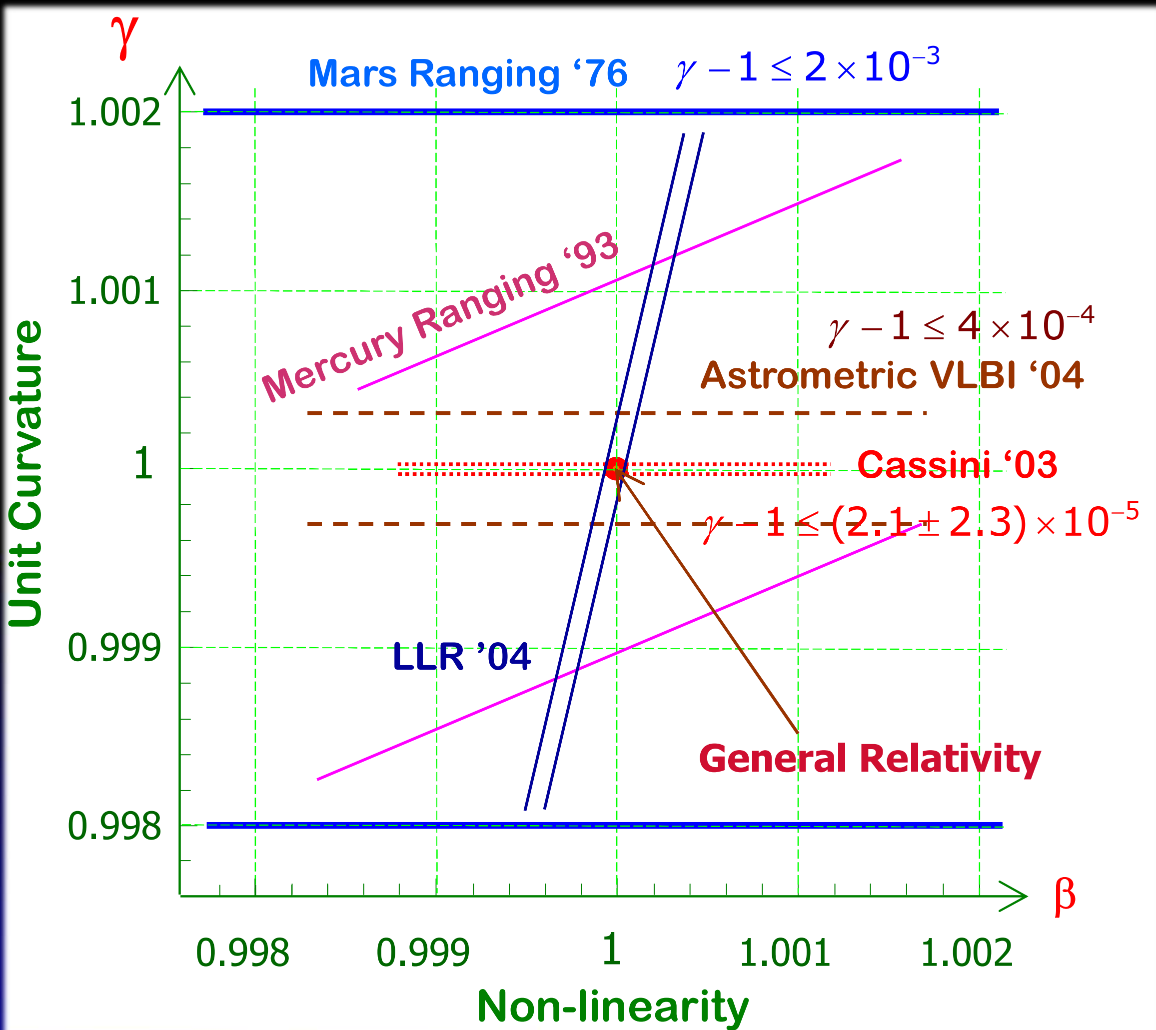


Dark matter?



Dark energy?

Experimental general relativity



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

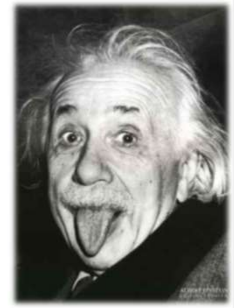
$$g_{pq}=0\quad(p,q=1,2,3;\ p\neq q)$$

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

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

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

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



Albert Einstein
(1879-1955)

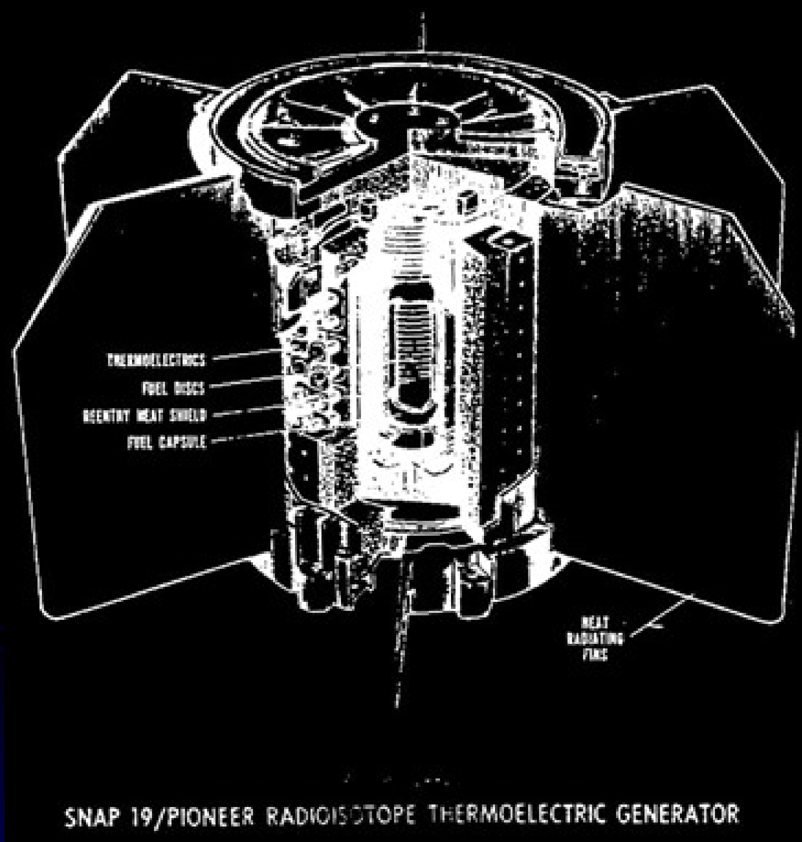
Parameterized post-Newtonian (PPN) formalism following Moyer (JPL Publication 00-7)

Analysis of the anomaly

- Glitch, or “new physics”?
- Suggested explanations:
  - Modified gravity (MOND, STVG, Yukawa potential)
  - Dark matter
  - Cosmological origin ($|a_P| \approx cH_0$: coincidence?)
- Recoil force due to heat generated on board and radiated was not properly investigated.
- Let me explain why this is important:

Heat generated on board

Pioneer power source

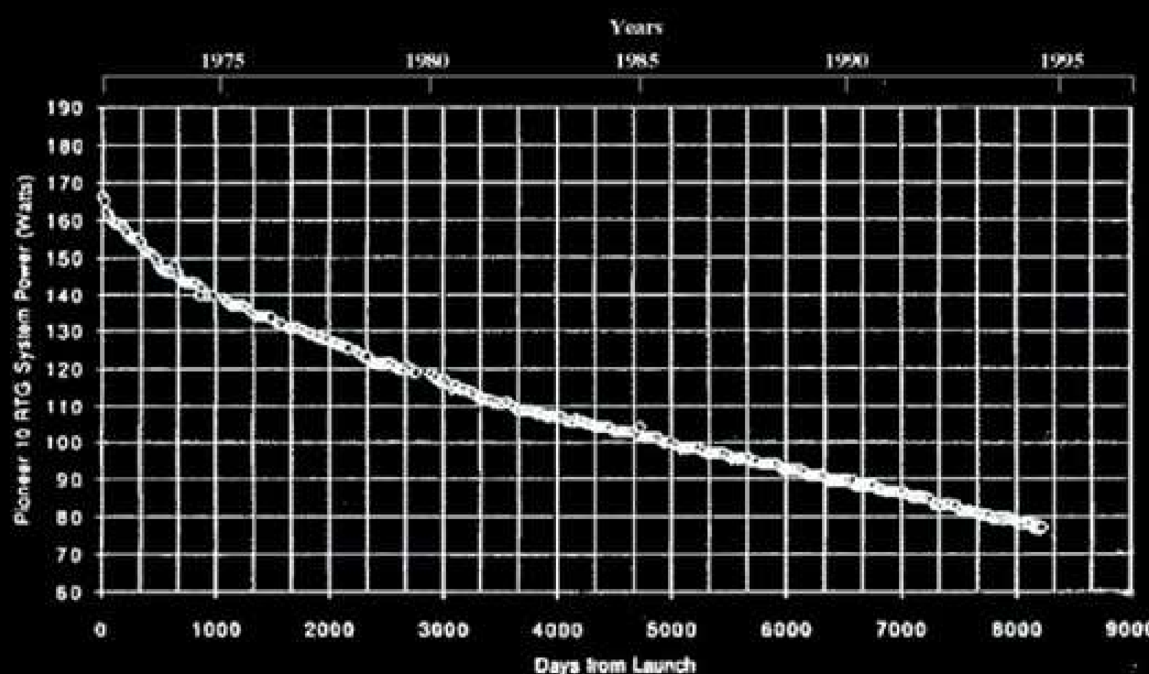


RTG Thermal Power: ~650W

Electrical Power: ~40W

4 RTGs per spacecraft

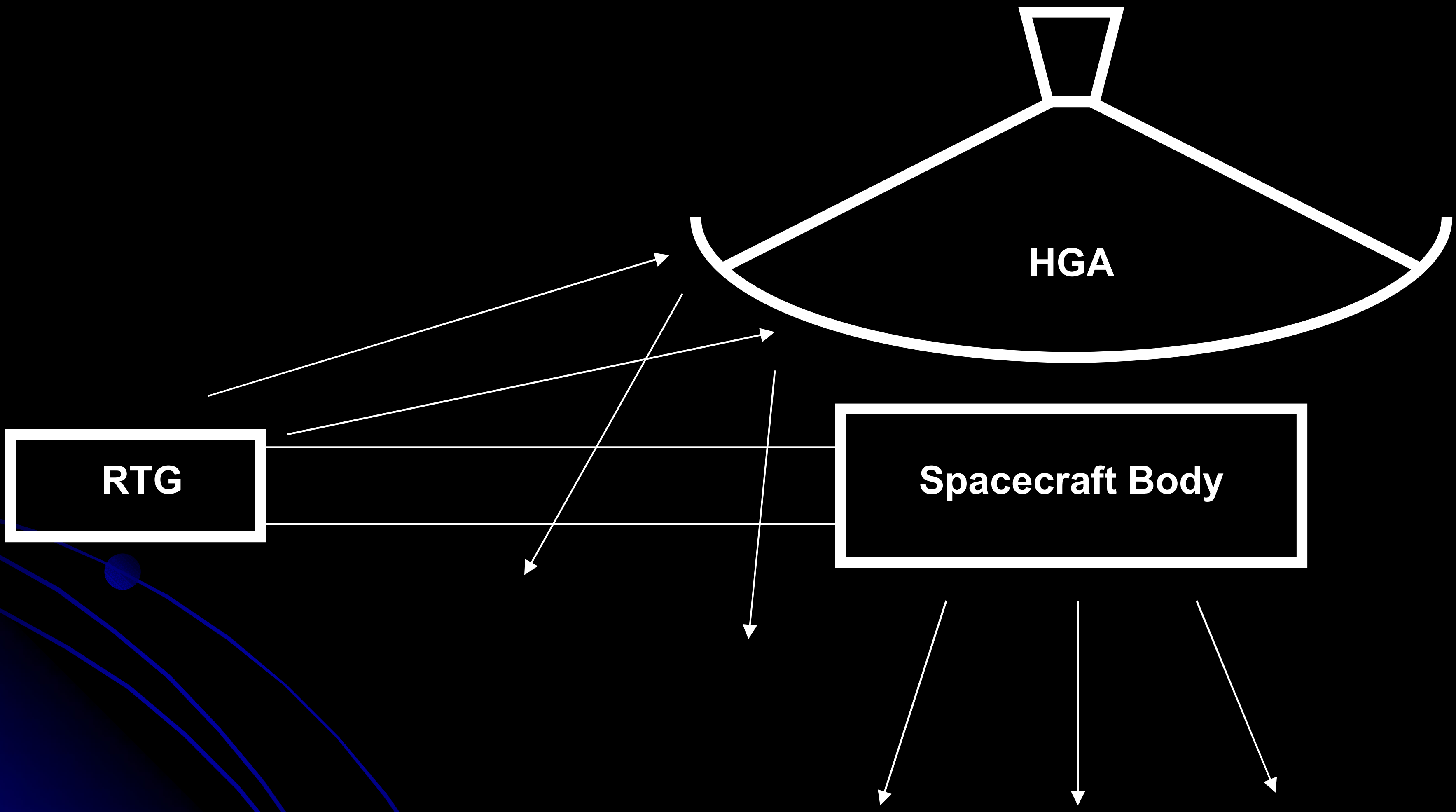
~4.6 kg ^{238}Pu on board



Thermal analysis

- Question: How much force is due to on-board generated heat?
- Heat sources are known:
  - RTG waste heat (~2.5 kW)
  - Electric heat (~100 W)
  - Radioisotope heater units (~10 W)
  - Propulsion (transients)

Geometry of thermal radiation



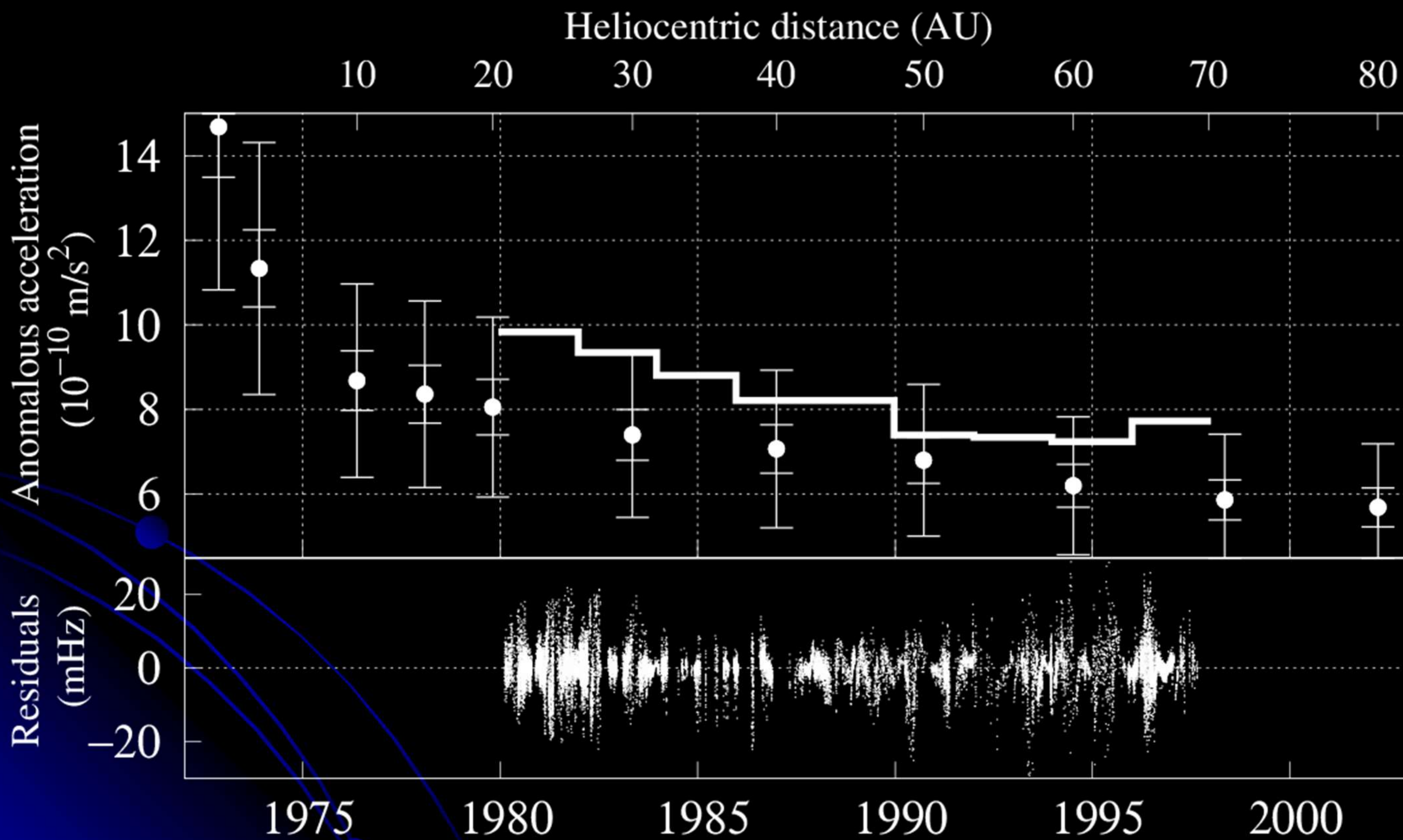
The thermal hypothesis

- Thermal power: 2.5 kW
- Small anisotropy: −2.5% in one direction, +2.5% in the other is sufficient
- Thermal models are approximate
- Anisotropy is almost 2 orders of magnitude smaller than the underlying effect

The Role of Telemetry

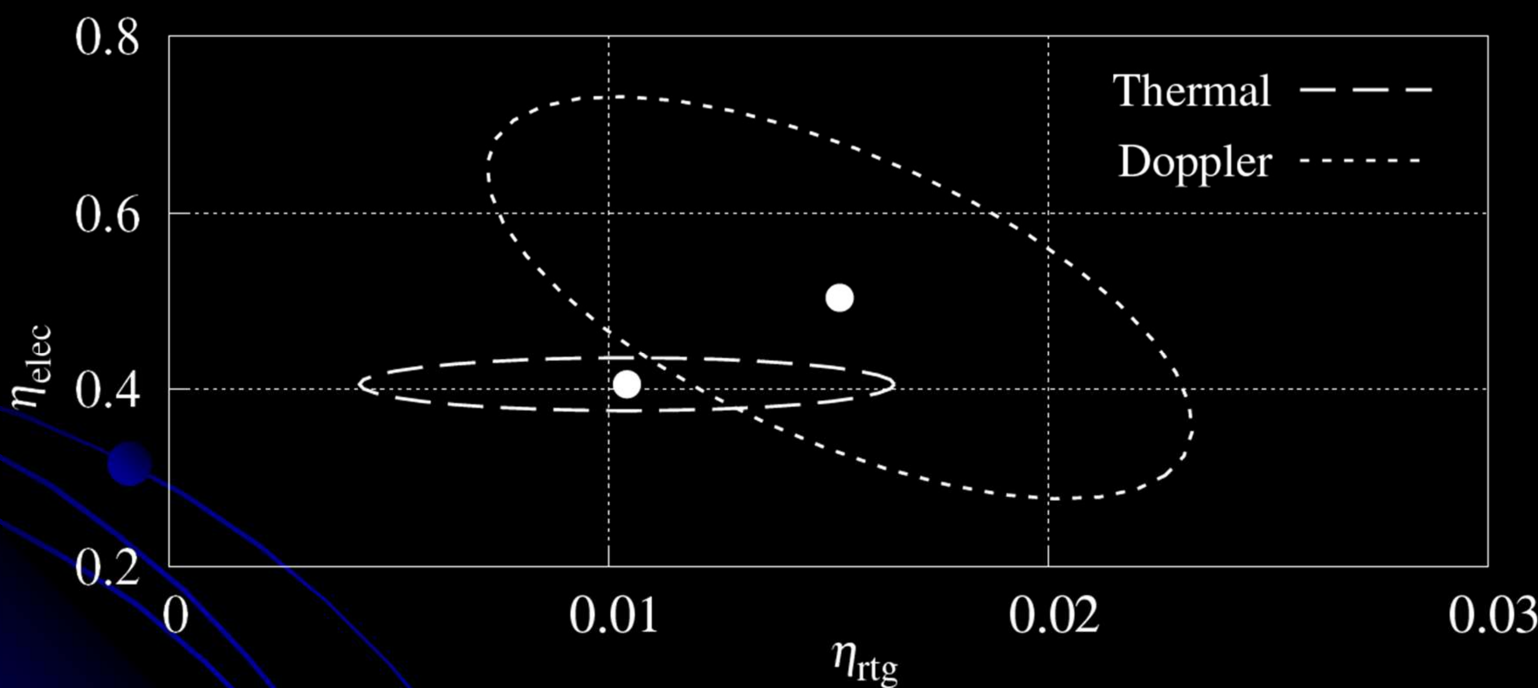
- Available telemetry for the entire mission durations tells us (almost) everything we need to know about on-board forces

Thermal results



Comparison

- The η can be estimated independently based on Doppler and thermal analysis



- No statistically significant anomaly remains

Some open questions

- Pioneer 11 behavior (no surprises expected)
- Spin rate change
- Initial behavior of anomaly
- Outgassing by surface materials
- RTG surface materials
- Statistical behavior
- DSN signal strength analysis

Other probes

- New Horizons: no funding for Doppler monitoring; opportunity lost
- Voyager-probes: non-spinners
- Other probes: wrong orbits, large RTGs, frequent maneuvers, etc.
- Pioneer 10 and 11 remain the most precisely navigated deep space probe in the foreseeable future

Summary

- In the foreseeable future, Pioneer 10/11 remain the most precise, largest-scale gravitational experiment
- It would have been great to observe deviations from Einstein's gravity in the solar system
- The anomaly was apparent
- Lessons:
  - Limits of navigational precision
  - Importance of preserving raw data, original project documentation
  - "Back of the envelope" calculations are insufficient to estimate very small effects

Thank you