# The Pioneer Anomaly: Known and Unknown Unknowns


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# The Pioneer 10/11 missions

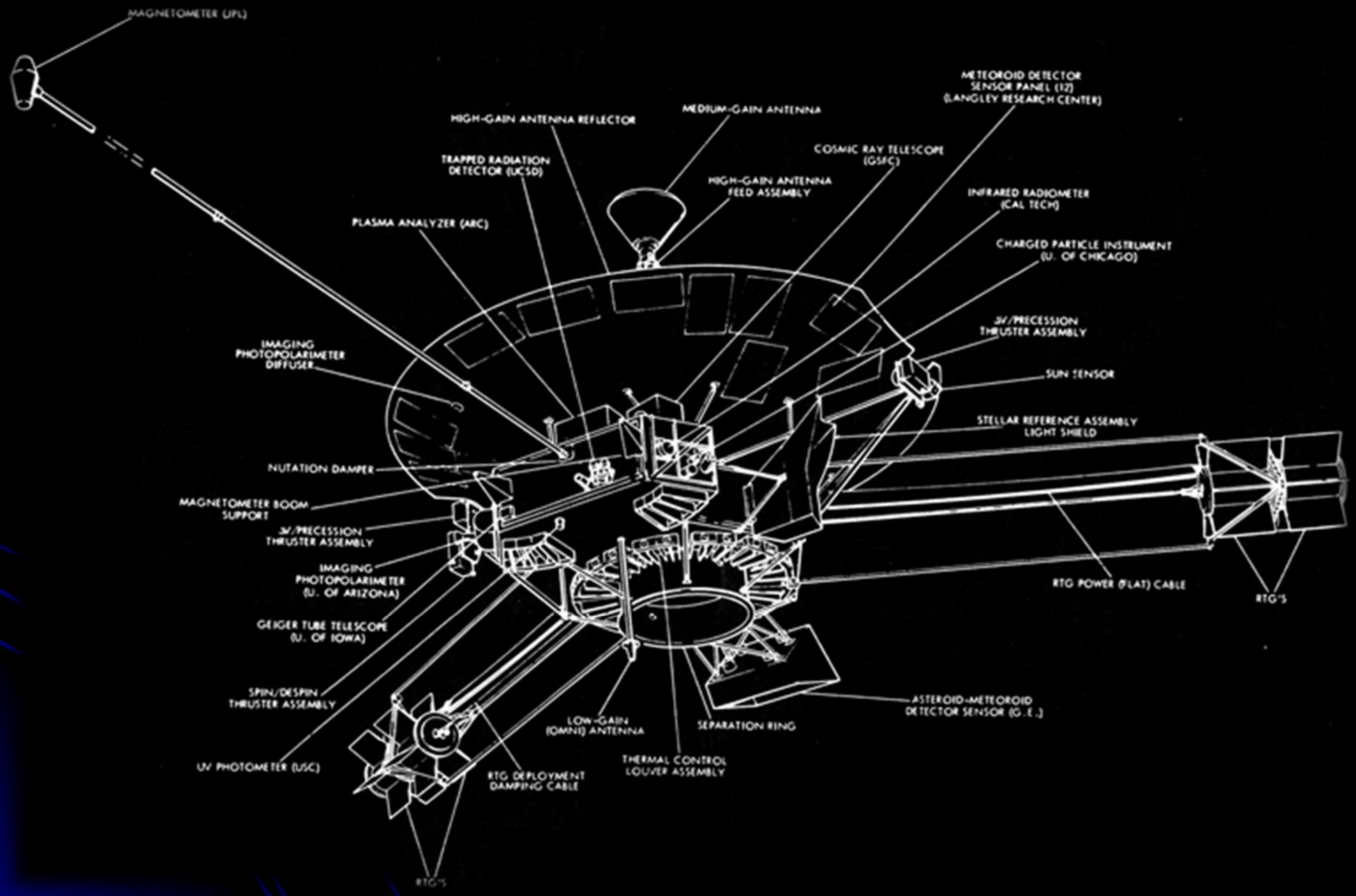
- Launched in 1972 and 1973
- First to explore beyond Mars
- First to visit Jupiter and Saturn
- Planned duration: 600-900 days




# 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”

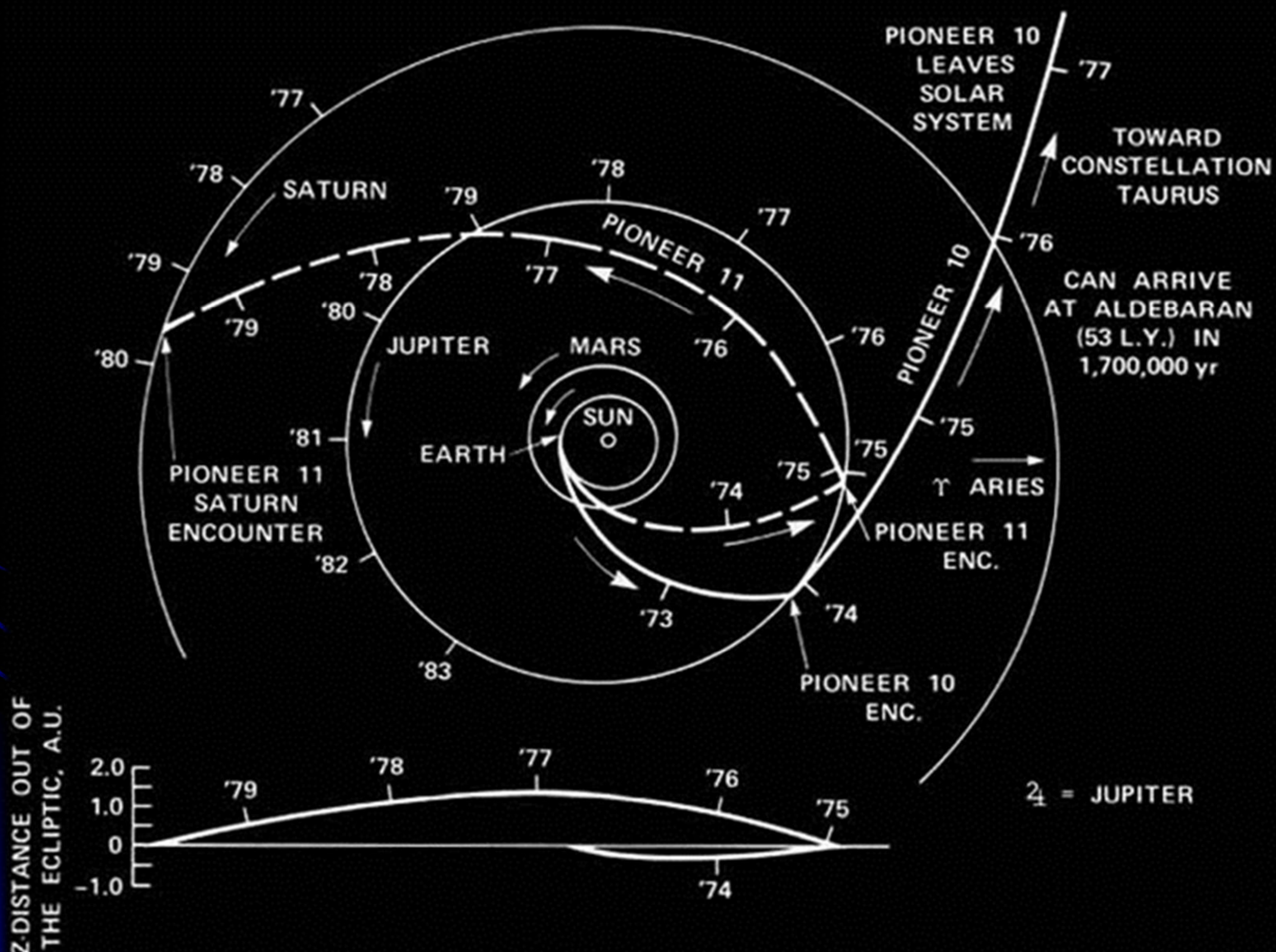
# The Pioneer spacecraft



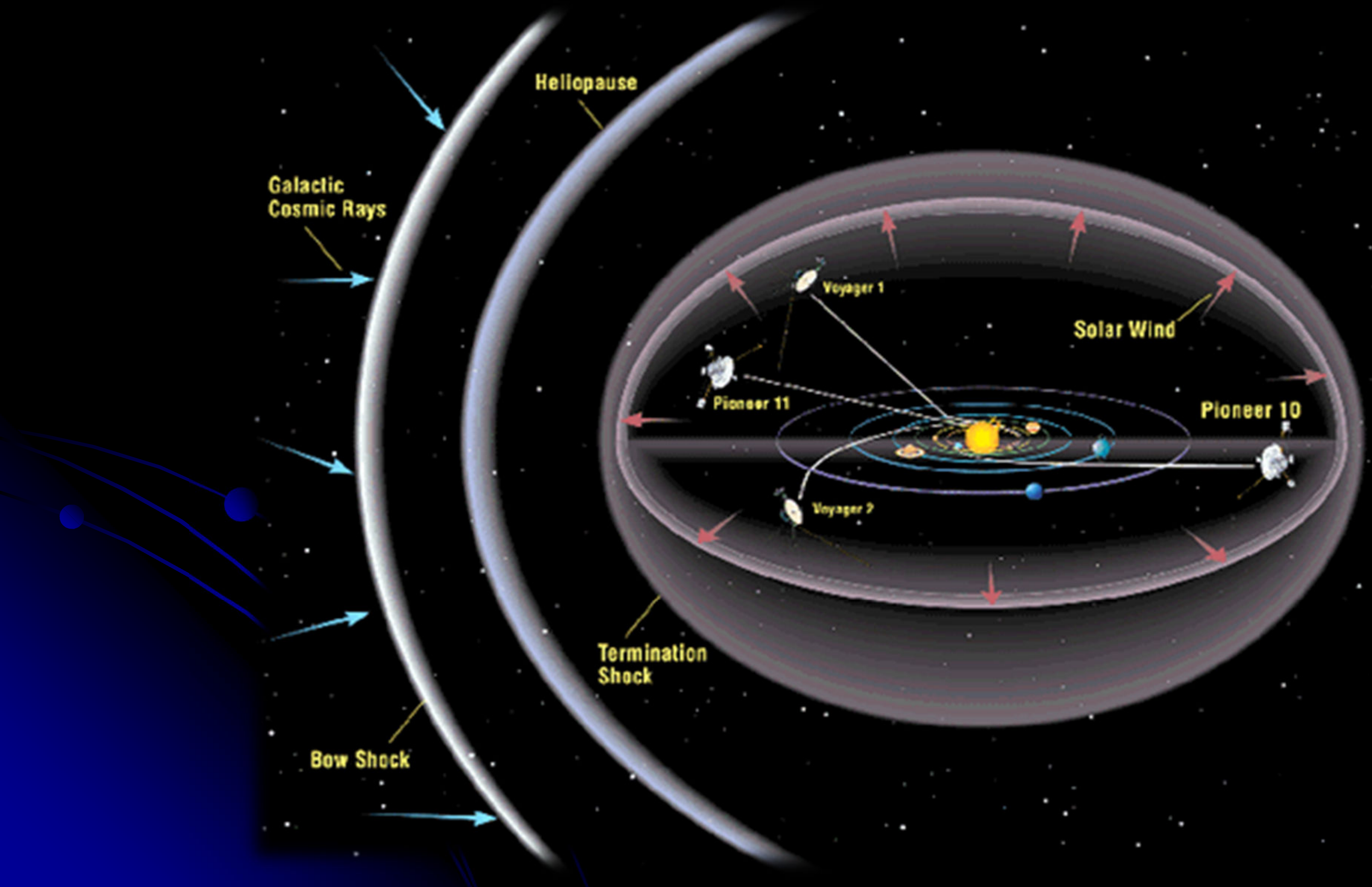
# The Pioneer spacecraft

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

# Pioneer orbits – early years



# Pioneer and Voyager orbits through the outer solar system



# 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 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) was 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 scale" or outside calibrated ranges
- Propellant lines frozen (no maneuvers possible)

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

# 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, limited stretches of data were studied; new effort under way with complete data set, including on-board telemetry.

# 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 independent confirmation by Markwardt (2002)
- Also confirmed independently by Olsen (2005), Toth (2009)

# Interpreting the residual

- Frequency drift: $(5.99 \pm 0.01)\times10^{-9}$ Hz/s (@ ~2 GHz)
- Velocity change: $(8.74 \pm 1.33)\times10^{-10}$ m/s$^2$
- Clock acceleration: $(2.92 \pm 0.44)\times10^{-18}$ s/s$^2$
- Velocity change (acceleration) is the “conventional” interpretation
- Effect small by engineering standards, but huge by the standards of gravity physics

# Consensus as of 2006

- The Pioneer Anomaly is real
- Conventional physics *fails* to explain it
- Alternatives proposed include
  - Gravity modification (MOND, MSTG, Yukawa potential)
  - Dark matter
  - Cosmological origin
- $|a_P| \approx cH_0$: coincidence?

# Background

- First "Pioneer Collaboration" meeting: ISSI, November 2005
- Presentation of newly recovered telemetry: complete thermal, electrical and operational record of the Pioneer 10 and 11 spacecraft
- Discussions with Slava Turyshev: No detailed thermal model for Pioneer!

# Why is it important?

- Total thermal output: 2.5 kW
- Small anisotropy: −2.5% on one side, +2.5% on the other, sufficient to explain acceleration
- Thermal models are approximations
- The anisotropy is a difference that is almost 2 orders of magnitude smaller than the estimated quantities

# ACCURACY IS ESSENTIAL!

# But difficult...

- Spacecraft were built 40 years ago
- Documentation is incomplete, some saved from dumpster

# BUT...

- We recovered the complete telemetry record of both craft
- Telemetry is low resolution but redundant
- Sufficient documentation exists to reconstruct thermal power and material properties

# What we are trying to do...

- It's not a question of either-or, but a question of how much
- Recoil force is conventional physics...

# WE CANNOT IGNORE CONVENTIONAL PHYSICS!

# The case for thermal recoil

- Let me establish the case for the thermal recoil force:

# The case for thermal recoil

# The case for thermal recoil

- Case has been made in 1998
- Case has been made by many others since...
- "Back of the envelope" models are a dime a dozen:
$$P_{1\to 2} = \iint P_1 \cos\chi_1 \cos\chi_2 / \pi r^2 \, dA_1 dA_2$$
- Doing it the right way is hard.

# The ideas are not new...

- They have been around for some time:
  - Murphy (1999): Electrical heat accounts for much of the acceleration
  - Katz (1999): Electrical heat and reflected RTG heat account for the acceleration
  - Scheffer (2003): Combination of conventional forces (including paint degradation) explain acceleration
- Dismissed using “back-of-the-envelope” estimates

# Heat sources

- Heat sources are easily enumerated:
  - RTG waste heat (~2.5 kW)
  - Electrical heat (~100 W)
  - RHUs (~10 W)
  - Propulsion system (transient)

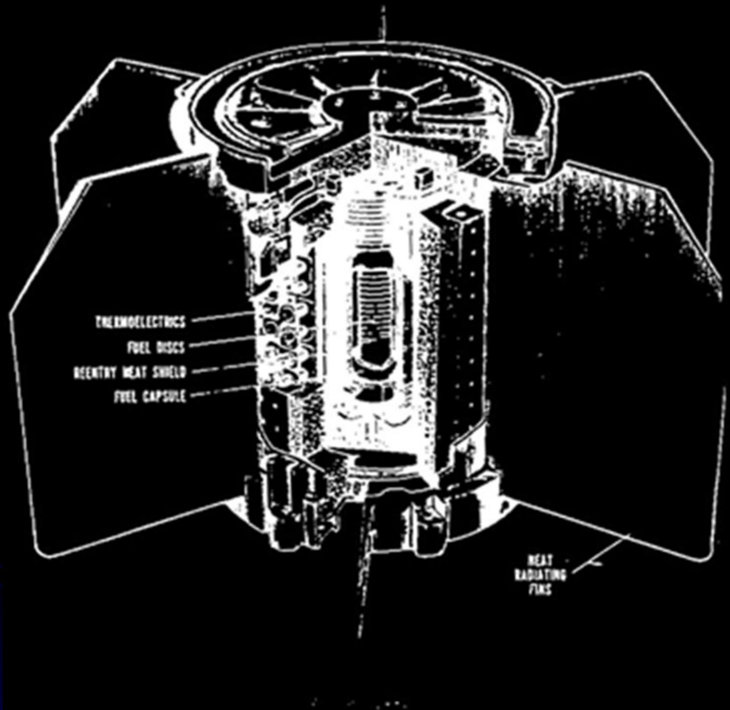
# Pioneer power source

RTG Thermal Power: ~650W

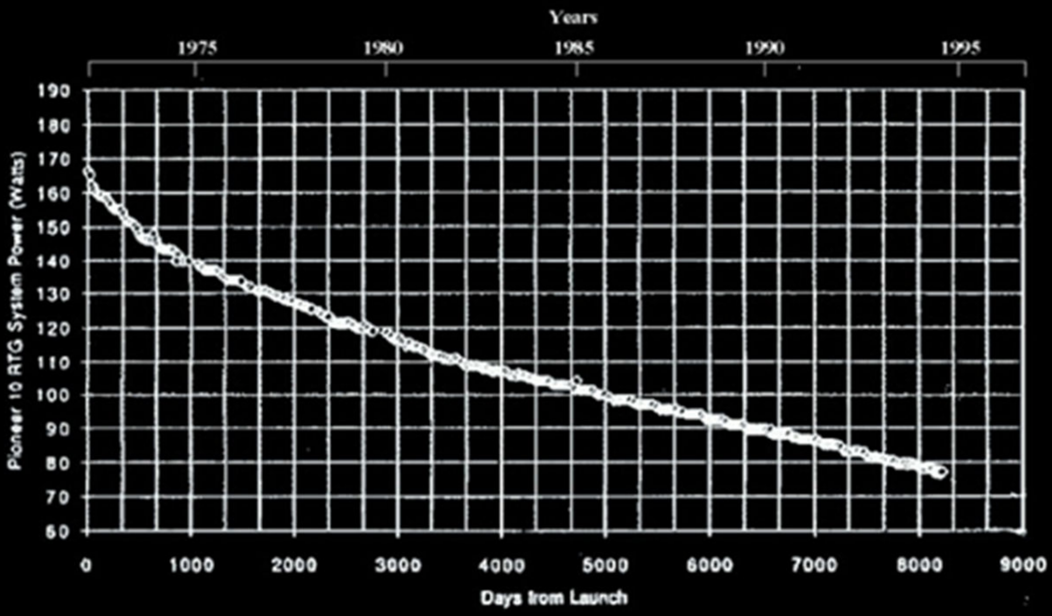
Electrical Power: ~40W

4 RTGs per spacecraft

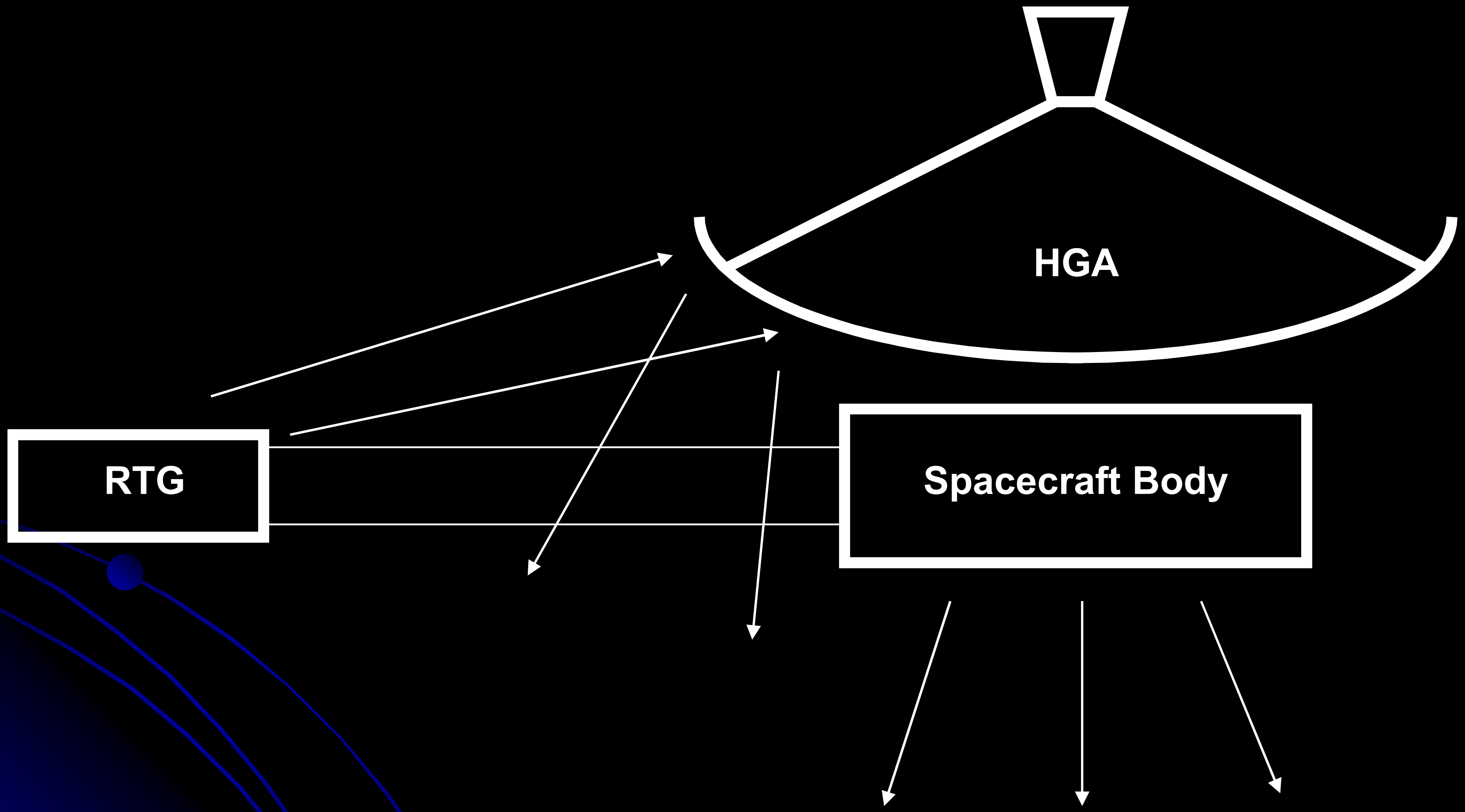
~4.6 kg $^{238}$Pu on board




SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR



# Thermal recoil geometry



# Significance of spin

- Thermal forces are slowly changing. Rate of change much smaller than angular velocity: $\dot{F}/F \ll \omega/\pi$
- To first order, force components perpendicular to spin axis average to zero
- Hence only spin axis component of thermal forces needs to be computed

# Linear behavior

- The two significant non-transient heat sources are electrical and RTG:

$$F \approx c^{-1}\Sigma q_i P_i \qquad (P_i = P_{\rm rtg}, P_{\rm elec})$$

- No significant trapped heat relative to the rate of change in temperatures (no latency)
- No significant variability in the emission/absorption spectrum of materials at spacecraft temperatures
- Physical configuration of spacecraft and mass constant during deep space cruise
- Temperatures are high enough
  - it can be shown that the necessary condition is $T^3 \gg k/\sigma\epsilon l$, where $k$ is the conductance, $\epsilon$ is the emittance, $l$ is the scale or thickness of the material, and $\sigma$ is the Stefan-Boltzmann constant

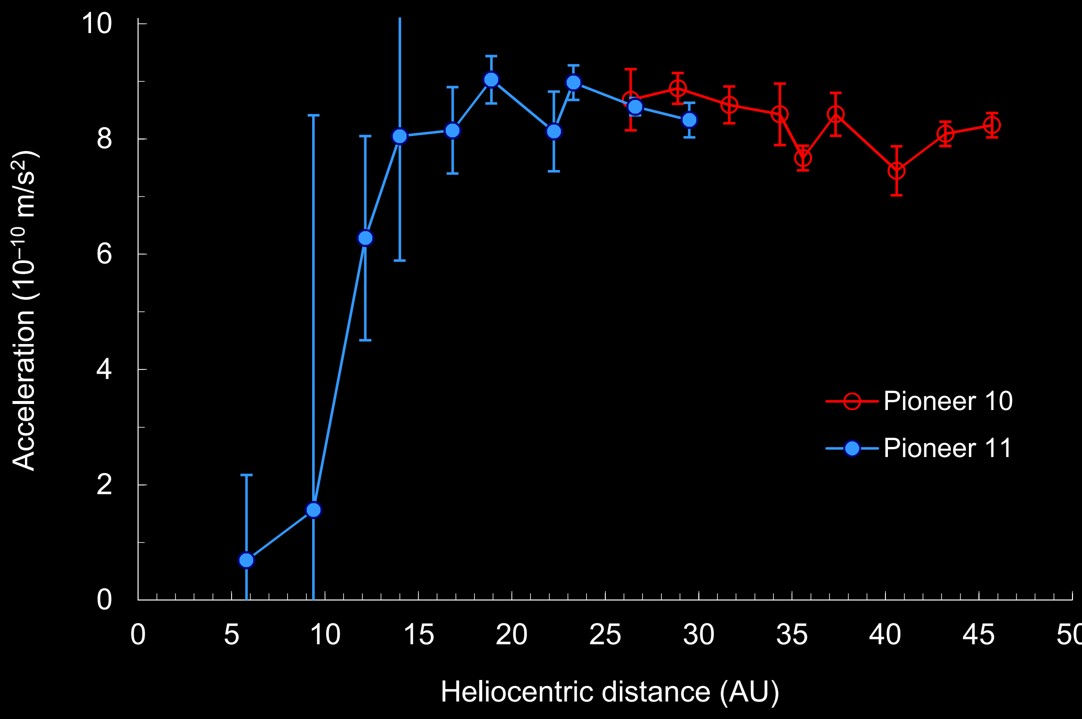
# Constancy and direction

- Isn't the acceleration a) constant, b) sunward?
- Short answer: No
- Long(er) answer: Acceleration is not the observable.
- Long answer: ...

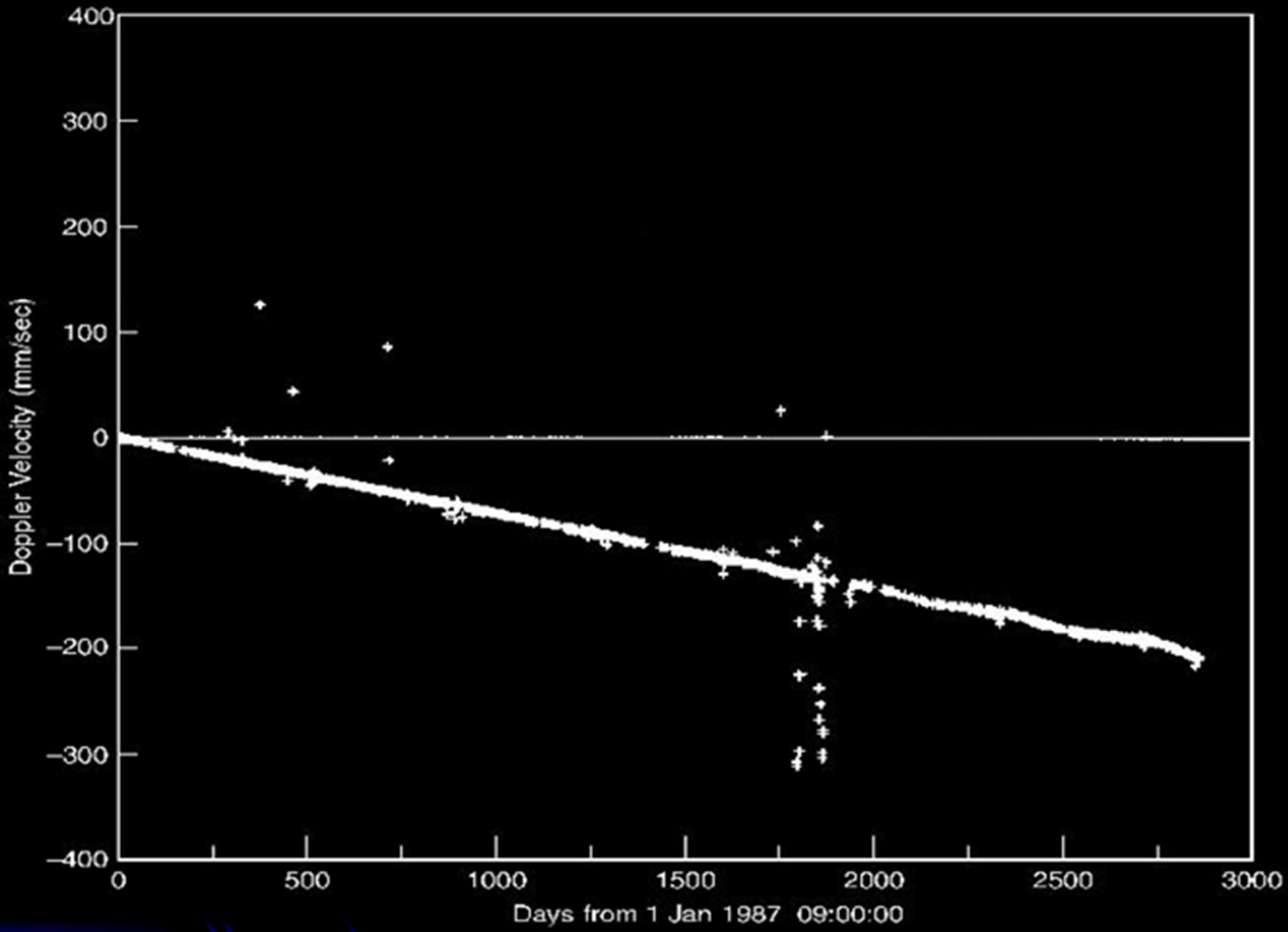
# The Pioneer Anomaly is NOT

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

# The Pioneer Anomaly is NOT



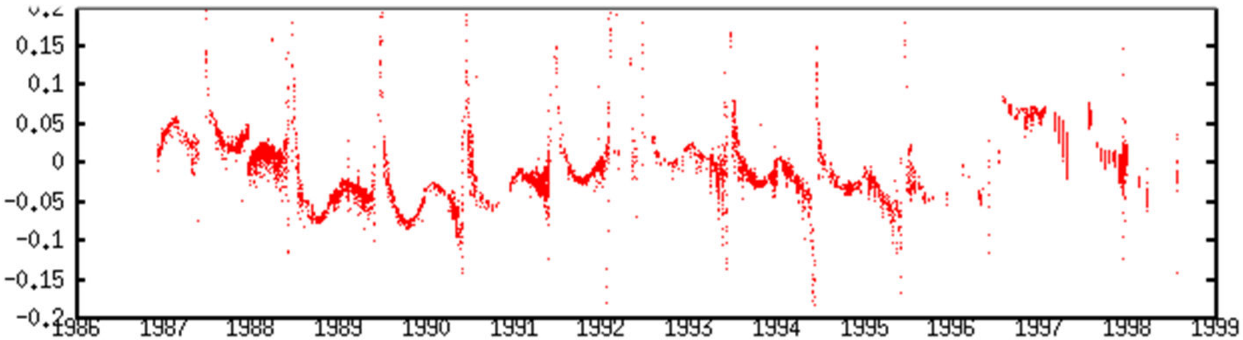
# The Pioneer Anomaly is NOT



# The Pioneer Anomaly IS

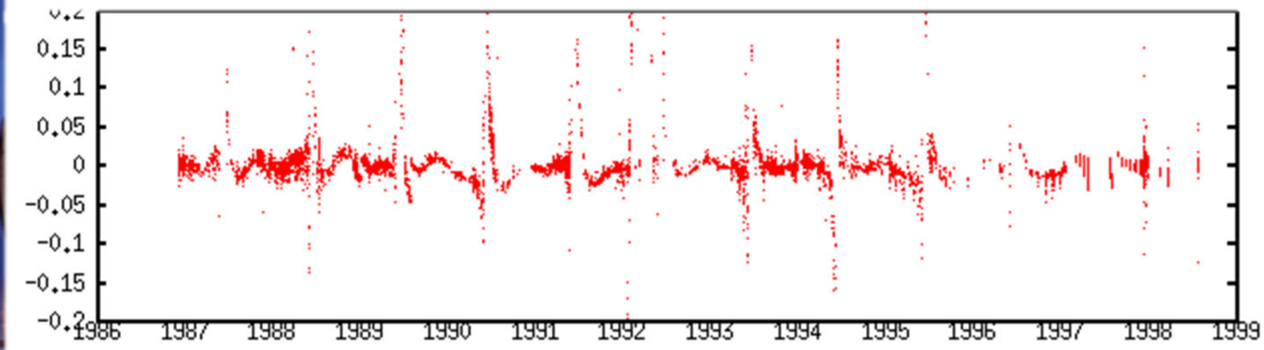
# The Pioneer Anomaly IS

this:



# The Pioneer Anomaly IS

instead of this:



**THE PIONEER ANOMALY IS OUR *INABILITY TO MODEL THE DOPPLER RESIDUAL AT THE EXPECTED LEVEL OF ACCURACY* USING ONLY KNOWN CONVENTIONAL PHYSICS.**

# The solution

- Navigators aren't doing fundamental physics. They fix the *navigational problem* by introducing fictitious forces.

# The canonical solution

- A constant sunward acceleration ($a_P = (8.74 \pm 1.33) \times 10^{-10}$ m/s$^2$) fixes the problem. It does NOT mean that the Pioneer spacecraft necessarily experience a constant sunward acceleration.

# Other solutions

- A temporally decaying acceleration fixes the problem and it is slightly better (no statistically significant difference.)
- Earthward acceleration fixes the problem.
- Earthward, temporally decaying acceleration fixes the problem.
- Other, equally valid solutions also exist.

# The goodness of fit

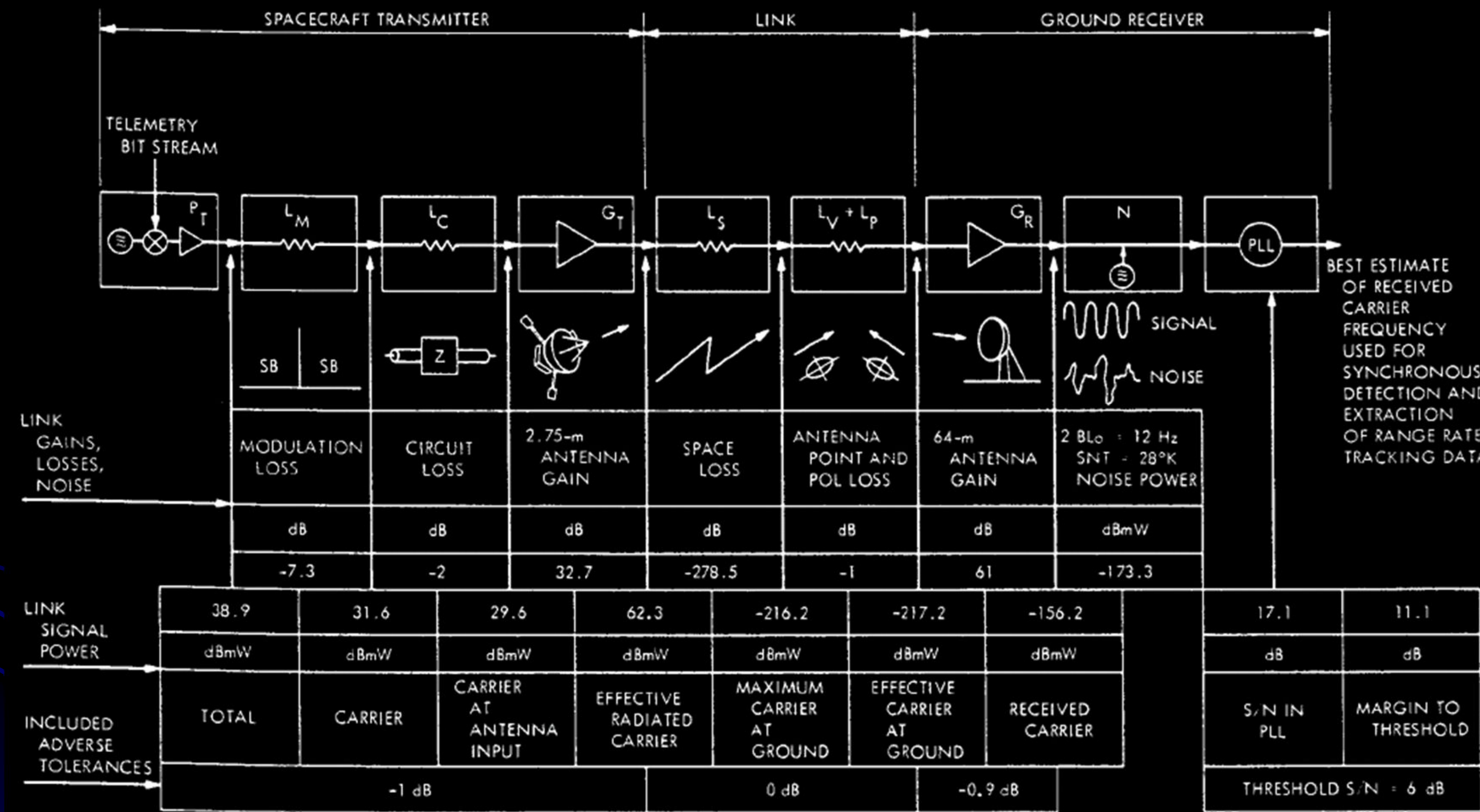
- To compare solutions, we compare residuals
- Even the best residual contains plenty of noise:
  - Mismodeling of the solar system
  - Unknowns: solar plasma, troposphere, other effects
  - Unmodeled forces: small leaks
  - Measurement noise, clock stability, etc.
  - Numerical accuracy

# THE PIONEER SIGNAL IS MODELED WITH AN ERROR AS LOW AS ~2 mHz OVER 20 YEARS IN A 2.29 GHz RADIO SIGNAL!

# Accuracy

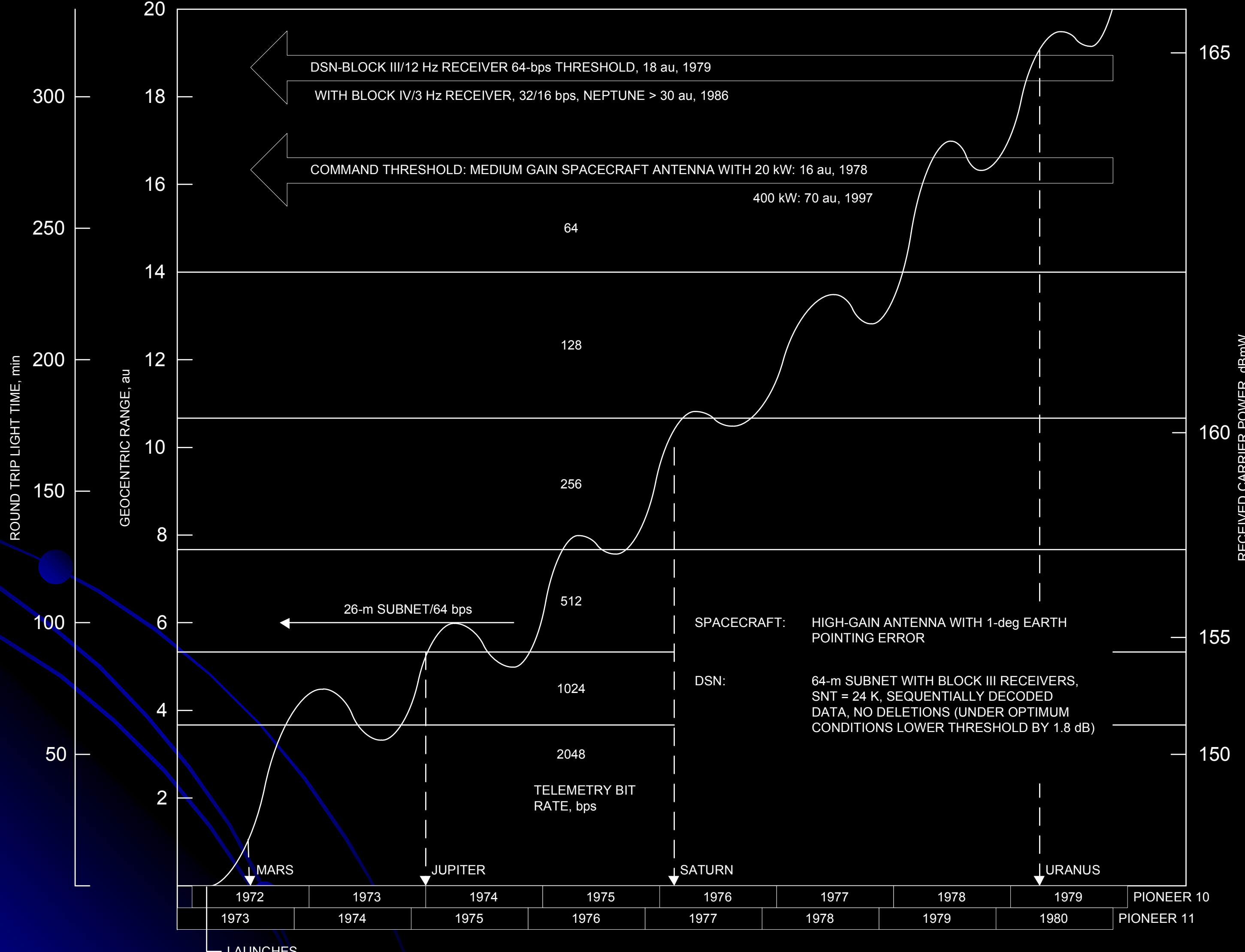
- Measurement and models must be accurate to better than 1 part in $10^{14}$ over 20 years.
- (IEEE 64-bit double precision floating point accuracy: less than 1 part in $10^{16}$.)

# Downlink power budget




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

# Downlink power budget



# Noise is inevitable

- Some of it is random, some not
- Residuals have visible structure
- This explains the difference between unreasonably tight "formal errors" and realistic errors

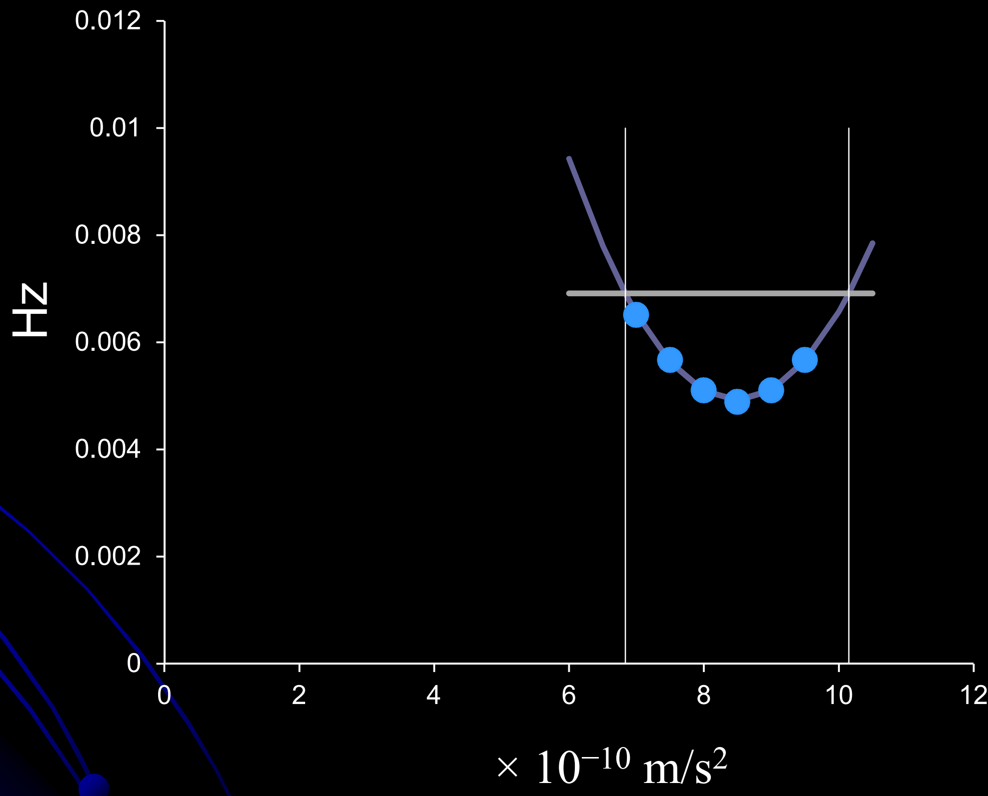
# Autocorrelation

- Statistical methods exist for estimating autocorrelation and the effective degrees of freedom (DOF) in unevenly sampled data
  - Computational difficulties
  - Stability of results
- If we use a crude estimate and assume that DOF = number of model parameters, we get “realistic errors”

# Effect on residuals

- Detuning the model should increase residuals
- If increase is negligible, the error bars on the detuned parameters must be correspondingly large
- What is a negligible increase?

# Effect on residuals



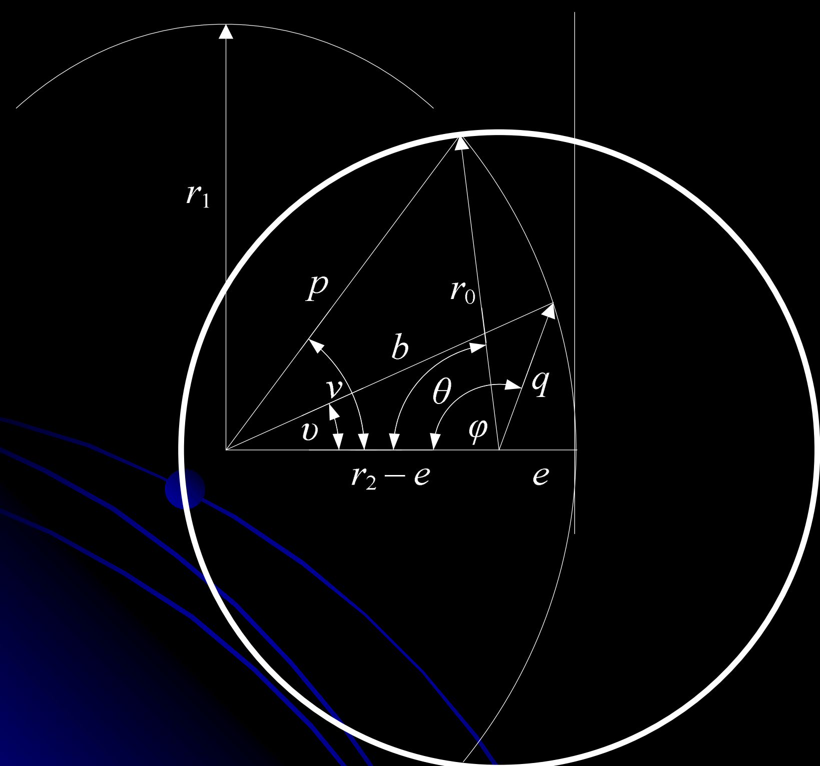
# The “right way”

- Build a comprehensive thermal model
- Use all available data: Validate the model using redundant telemetry
- Incorporate the model into the orbit determination code to model the actual observable (Doppler)

# Or the highway?

- Recovered the telemetry
- Constructed a “crude” geometric model
- Constructed a refined ray-traced model using simple isothermal surfaces but real material properties and power
- Built independent orbit determination code that incorporated the thermal recoil

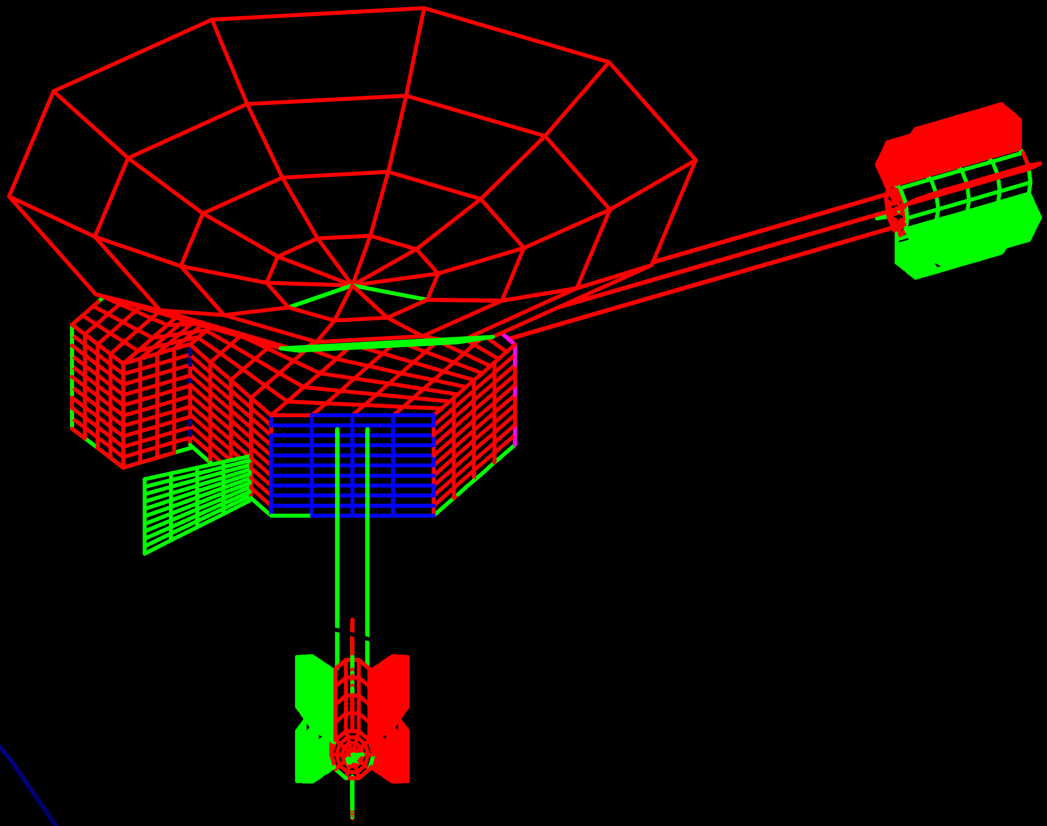
# A simple model




```
with(student);
alpha=0.04;
r0:=54;
h:=17;
d:=11;
R:=evalf((r0^2+h^2)/2/h);
ls[1]:=97.3;
ls[2]:=102.85;
ls[3]:=114.95;
zetas[1]:=0.097/4.*cos('delta');
zetas[2]:=0.596/4.*sin('delta');
zetas[3]:=0.596/4.*sin('delta');
for k from 1 to 3 do
l:=ls[k];zeta:=zetas[k];
r1:=R*sqrt((R+d)^2+l^2-R^2)/sqrt((R+d)^2+l^2);
e:=r1*sqrt((R+d)^2+l^2)/(R+d)-l*R/(R+d);
r2:=r1*(R+d)/sqrt((R+d)^2+l^2);
m:=sqrt((R+d)^2+l^2);
s:=R-sqrt(R^2-r^2);
n:=sqrt(l^2+r^2-2*l*r*cos(alpha));
u:=sqrt(n^2+(d+s)^2);
coschi:=-(u^2+R^2-m^2)/(2*R*u);
EQ1:=P*(r1^2*(1-S)+r2^2*S)=r1^2*r2^2;
EQ2:=P=(r2-e)^2+r0^2-2*(r2-e)*r0*C;
EQ3:=S/r0^2=(1-C^2)/P;
use RealDomain in res1:=solve({EQ1,EQ2,EQ3,-1<=C,C<=1},{P,C,S}) end;
theta:=arccos(eval([C],res1)[1]);
EQ4:=b^2*(r1^2*cos(mu)^2+r2^2*sin(mu)^2)=r1^2*r2^2;
EQ5:=b^2=(r2-e)^2+q^2-2*(r2-e)*q*cos(alpha);
EQ6:=sin(mu)/q=sin(alpha)/b;
use RealDomain in res1:=solve({EQ4,EQ5,EQ6},{b,mu,q}) end:
res2:=solve(op(1,simplify(evalf(eval([q],res1)[1]))),_Z):
res3:=`if`(evalf(eval(res2[1],alpha=Pi/2))>0,res2[1],res2[2]):
q:=unapply(factor(simplify(evalf(res3))),alpha);
beta:=arctan((d+s)/n);
delta:=arccos((u^2+l^2-r^2-(d+s)^2)/(2*u*l));
I1:=evalf(coschi*zeta*R*r/sqrt(R^2-r^2)*sin(beta)/u^2/Pi):
res1:=evalf(simpson(simpson(I1,r=0..r0,100),alpha=-theta..theta,100));
res2:=evalf(simpson(simpson(I1,r=0..q(alpha),100),alpha=theta..2*Pi-theta,100));
Pincident[k]:=Re(res1+res2);
I2:=evalf(coschi*zeta*R*r/sqrt(R^2-r^2)/u^2/Pi):
res1:=evalf(simpson(simpson(I2,r=0..r0,100),alpha=-theta..theta,100));
res2:=evalf(simpson(simpson(I2,r=0..q(alpha),100),alpha=theta..2*Pi-theta,100));
Preemitted[k]:=0.17*2/3*(-0.81)/0.89*Re(res1+res2);
I3:=evalf(sqrt(1-r^2/R^2)*coschi*zeta*R*r/sqrt(R^2-r^2)/u^2/Pi):
res1:=evalf(simpson(simpson(I3,r=0..r0,100),alpha=-theta..theta,100));
res2:=evalf(simpson(simpson(I3,r=0..q(alpha),100),alpha=theta..2*Pi-theta,100));
Pdiffuse[k]:=0.83*(1-sigma)*2/3*Re(res1+res2);
uz:=d+s-2*u*coschi/R*(R-s);
I4:=evalf(-uz/u*coschi*zeta*R*r/sqrt(R^2-r^2)/u^2/Pi):
res1:=evalf(simpson(simpson(I4,r=0..r0,100),alpha=-theta..theta,100));
res2:=evalf(simpson(simpson(I4,r=0..q(alpha),100),alpha=theta..2*Pi-theta,100));
Pspecular[k]:=0.83*sigma*Re(res1+res2);
Ptotal[k]:=Pincident[k]+Preemitted[k]+0.83*(Pspecular[k]+Pdiffuse[k]);
end do;
Ptotal[1]+Ptotal[2]+Ptotal[3];
eval(Ptotal[1]+Ptotal[2]+Ptotal[3],sigma=.7428);
```

0.008897107518

# A more complicated model



# More results

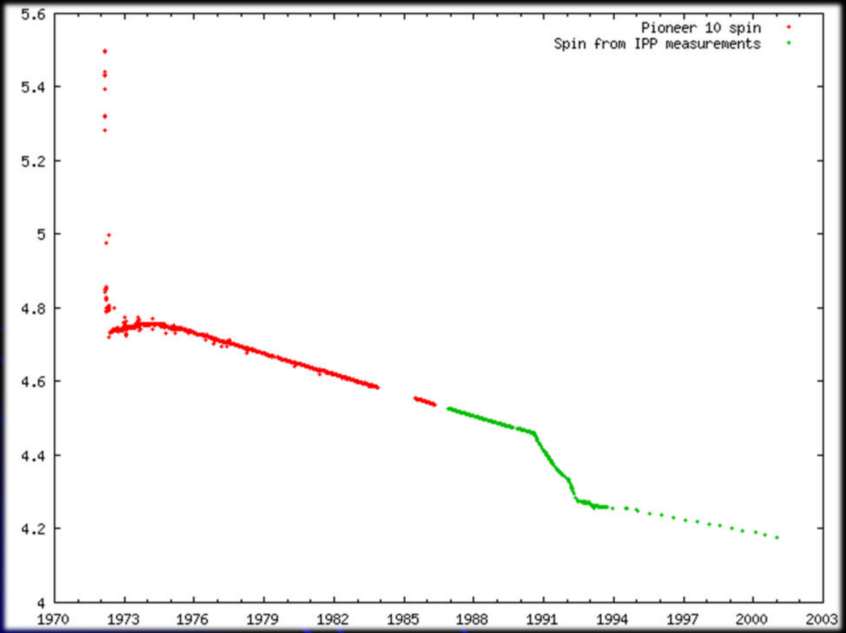
- Thrust and spin rate change

```
fe_elec
Iteration 1: Thrust = -36.436 / 94.8192
Iteration 2: Thrust = -37.2946 / 99.5209
Iteration 3: Thrust = -37.3916 / 100.052
Iteration 4: Thrust = -37.403 / 100.114
Iteration 5: Thrust = -37.4044 / 100.122
Iteration 6: Thrust = -37.4045 / 100.122
Iteration 7: Thrust = -37.4045 / 100.123
Iteration 8: Thrust = -37.4045 / 100.123
Iteration 9: Thrust = -37.4045 / 100.123
Iteration 10: Thrust = -37.4045 / 100.123
DONE.
```

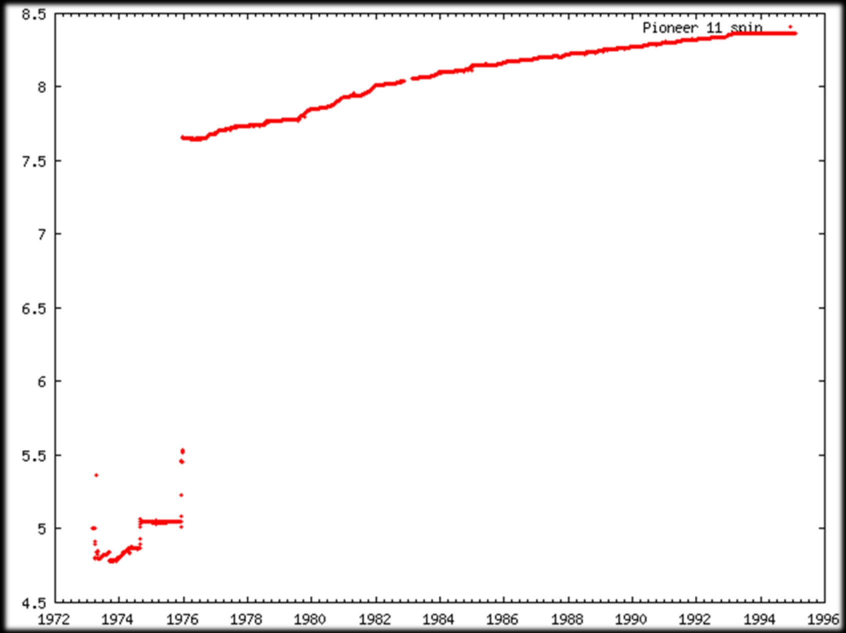
```
fe_rtg
Iteration 1: Thrust = -0.0130118 / 0.869754, Torque(0.00721829,0.494318,0.00466599)
Iteration 2: Thrust = -0.0107575 / 0.986882, Torque(0.00146408,0.335283,0.01585)
Iteration 3: Thrust = -0.0104659 / 0.999871, Torque(-0.000599535,0.311347,0.0123182)
Iteration 4: Thrust = -0.0104445 / 1.00114, Torque(-0.000857704,0.309028,0.0117846)
Iteration 5: Thrust = -0.0104432 / 1.00125, Torque(-0.000883748,0.30882,0.0117335)
Iteration 6: Thrust = -0.0104431 / 1.00126, Torque(-0.000886127,0.308802,0.0117291)
Iteration 7: Thrust = -0.010443 / 1.00126, Torque(-0.000886442,0.3088,0.0117287)
Iteration 8: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
Iteration 9: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
DONE.
```

# Spin history

## Pioneer 10 spin

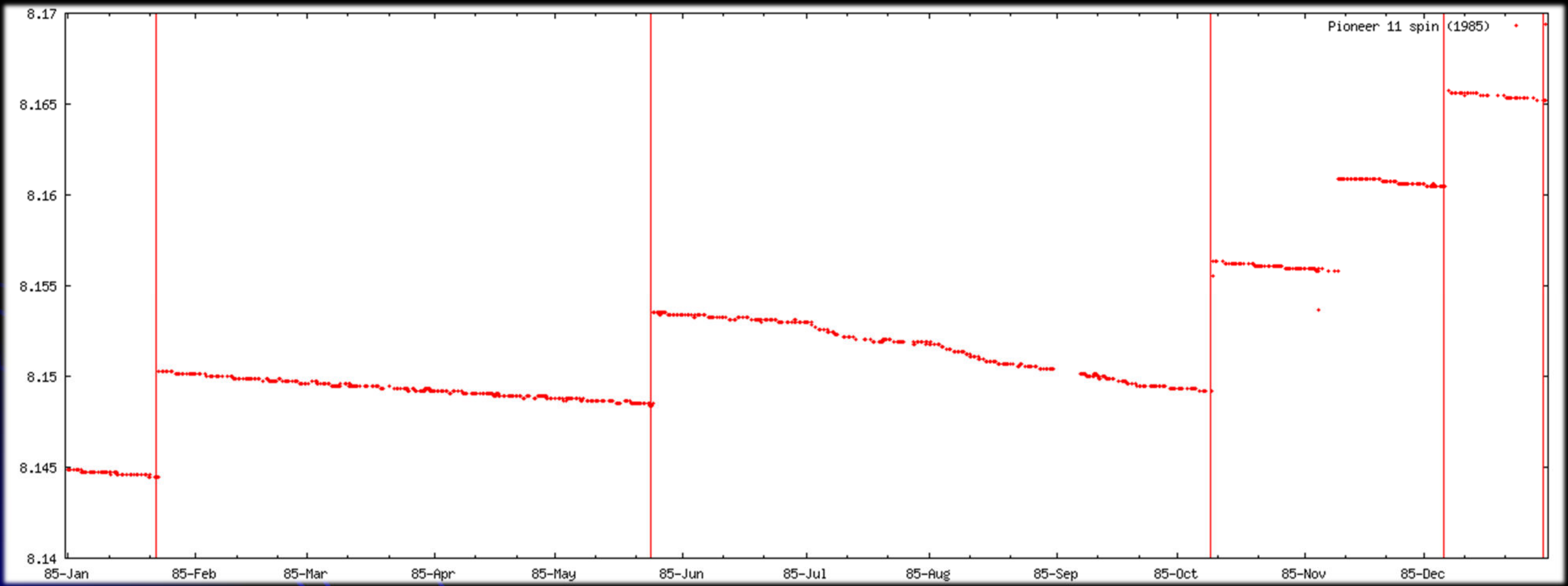



## Pioneer 11 spin

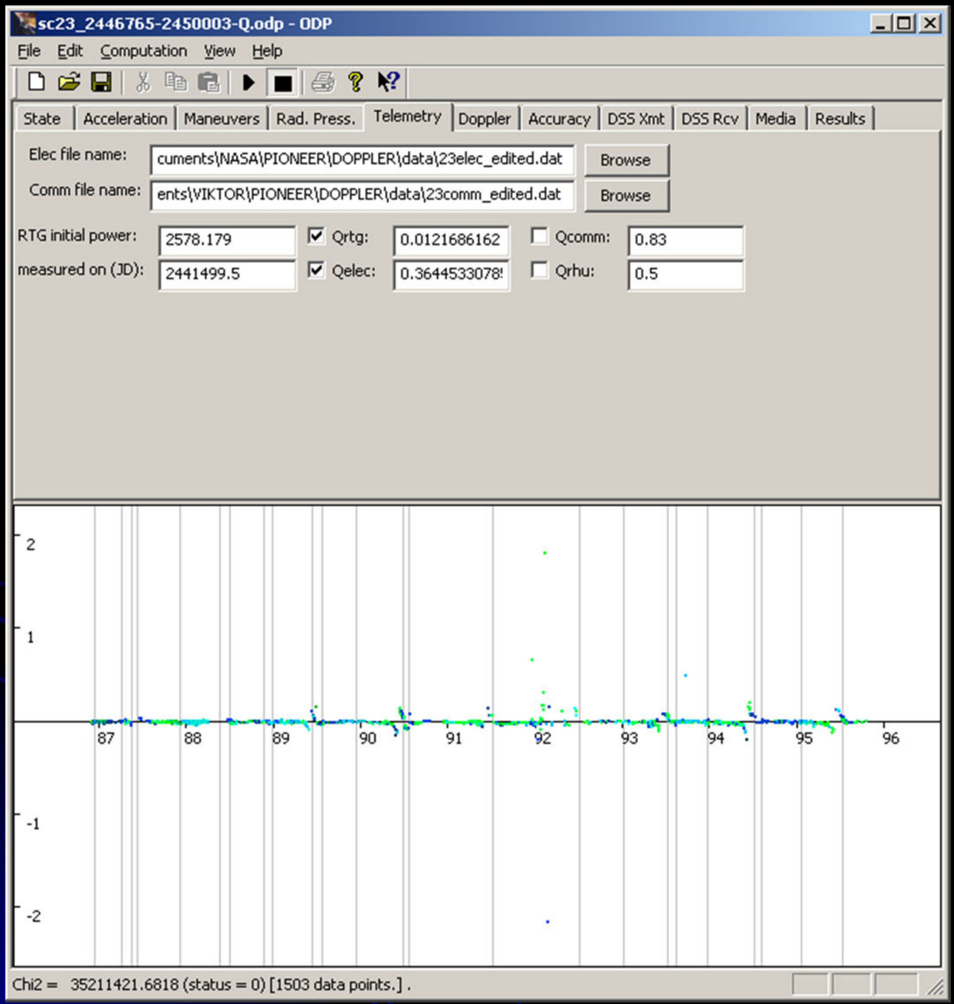


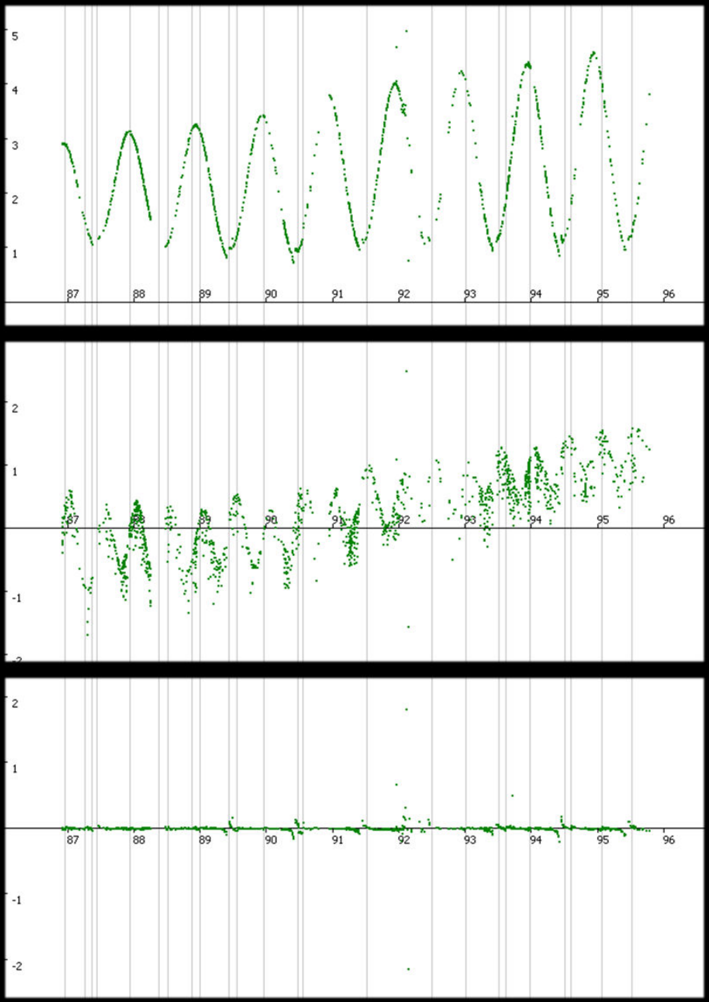
# Spin history

## Pioneer 11 spin detail (1985)



# Orbit determination with on-board forces



# Some results

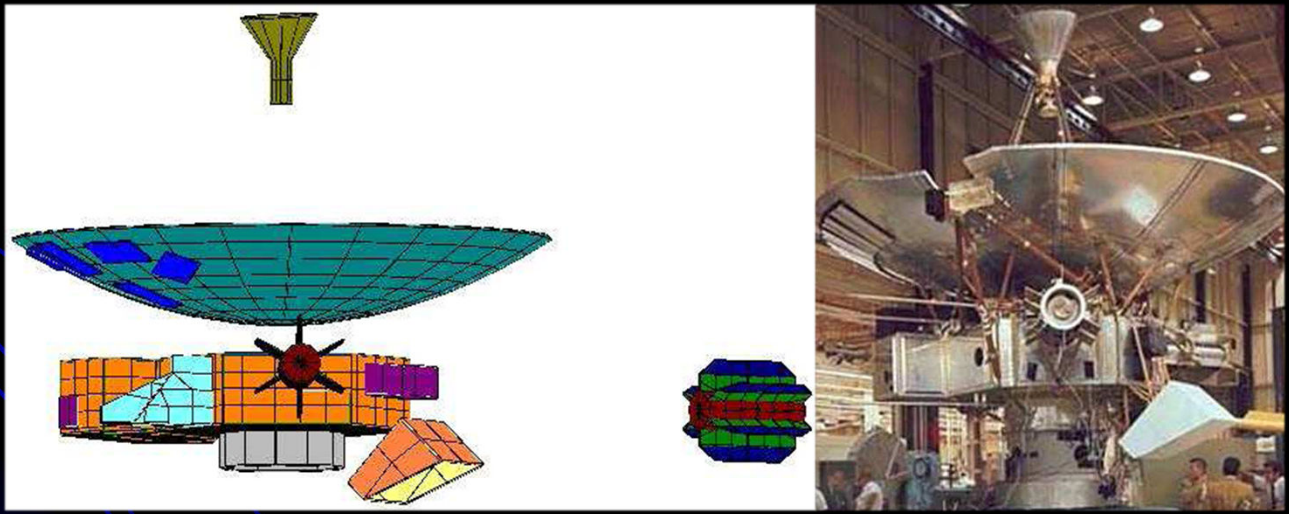
- Confirmed the presence of the Doppler anomaly
- Verified that the recoil force is indeed a linear function of RTG and electrical heat
- Recoil force yields good Doppler fit
  or conversely
- Doppler data can be used to estimate the recoil force coefficients

# Still not good enough

- Insufficiently detailed model (isothermal surfaces, no heat conduction, no individual instruments)
- Untested methodology
- Untested software

# The real McCoy

- Report on the “definitive” model is on its way.





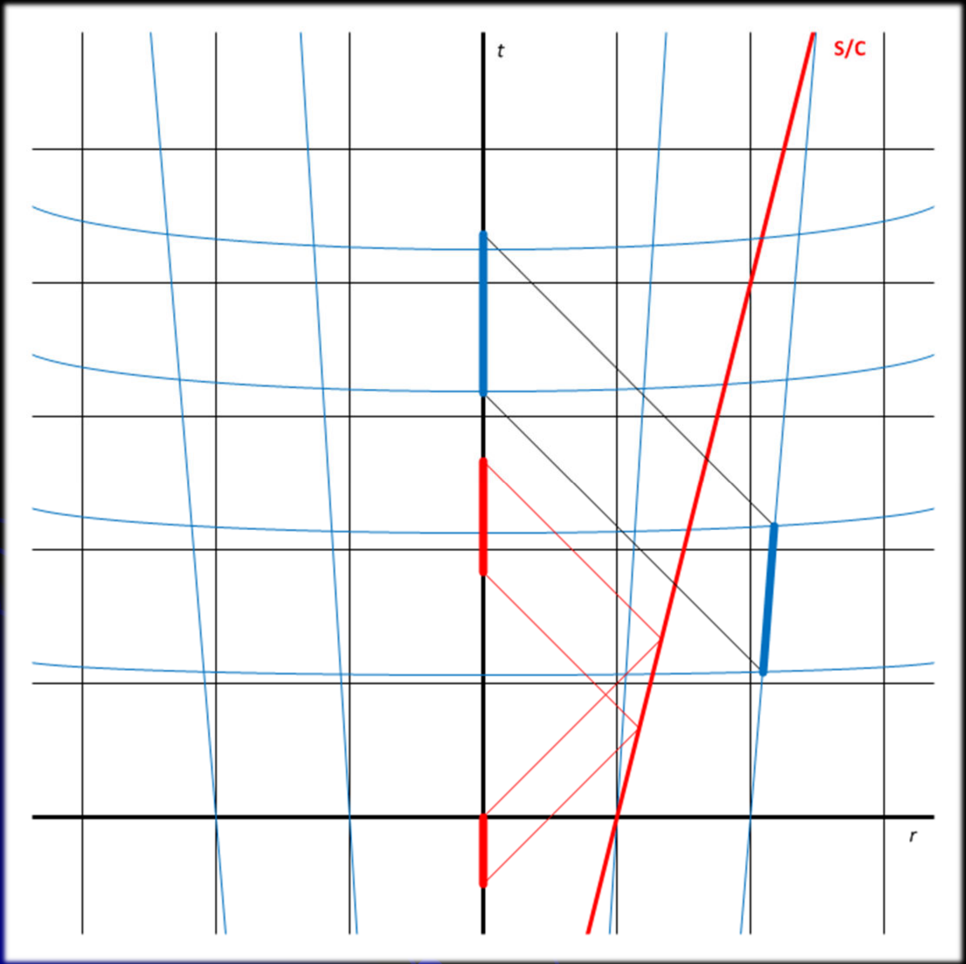
# The biggest known unknown

- RTG coating: “three mils of zirconia [$ZrO_2$] in a sodium silicate binder”
- Some similar paints gained emittance in thermal vacuum chamber tests
- Other paints lost emittance
- This specific paint was never tested
- RTG exterior temperatures may also play a role
- A 5% decrease in emissivity can result in a 50% increase in the RTG anisotropy; a roughly 25% error in the overall thermal recoil force

# So what if it is not all thermal?

- Numerical coincidences (e.g., $|a_P| \approx cH_0$) are certainly destroyed even if the sign can be explained somehow
- Do not assume constancy
- Do not assume direction

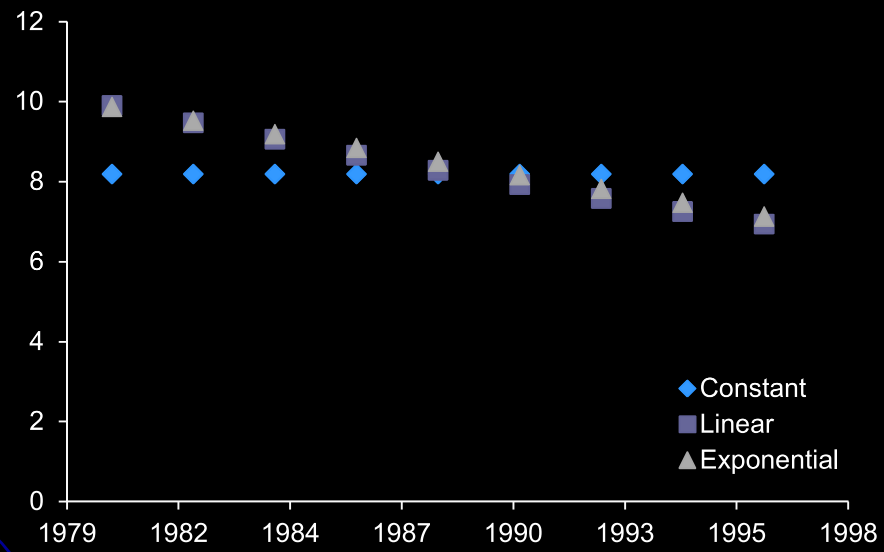
# The sign of $a_P$ vs. $cH_0$



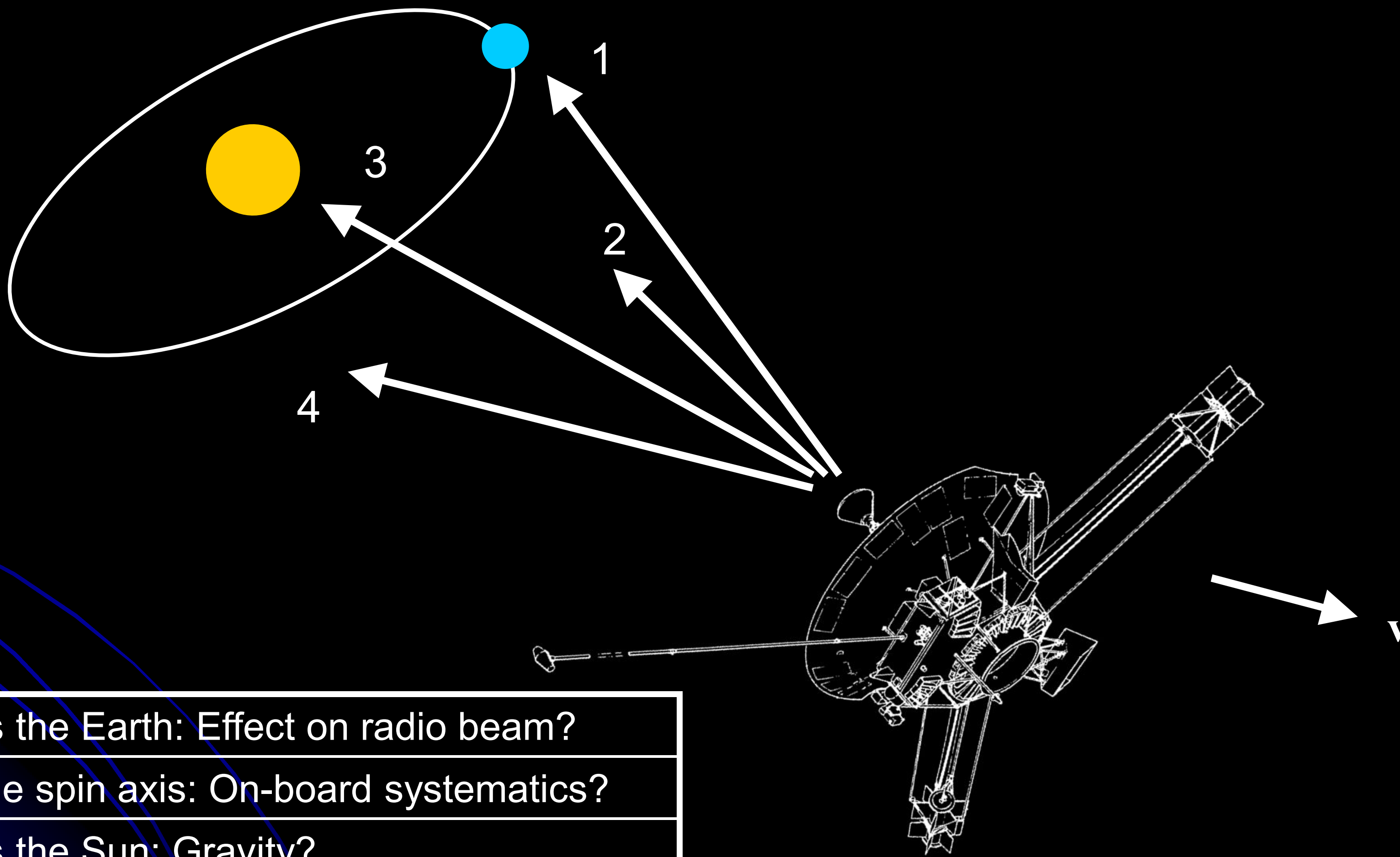

- Much has been said about $a_P$ having the wrong sign for a cosmological origin
- This argument is not universally valid: an example is a conformal metric
  - The light of a distant star (blue) appears redshifted in accordance with Hubble's law
  - A radio signal of unit duration (half unit, actually, for drawing convenience) sent to a receding spacecraft S/C will be returned with a redshift. However, in the conformally transformed coordinate system, less time will appear to have elapsed, resulting in an apparent, small, additional blue shift. Ref: Hill, Phys. Rev. D (68) 232 (1945).

# Temporal behavior

- These models yield equally good residuals



# Unknown direction



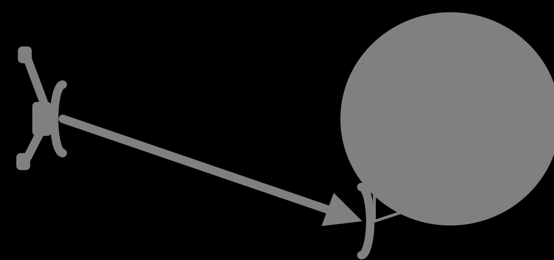

| | |
|---|---|
| 1. | Towards the Earth: Effect on radio beam? |
| 2. | Along the spin axis: On-board systematics? |
| 3. | Towards the Sun: Gravity? |
| ~~4.~~ | ~~Opposite the direction of motion: Drag force?~~ |

# Beware of traps

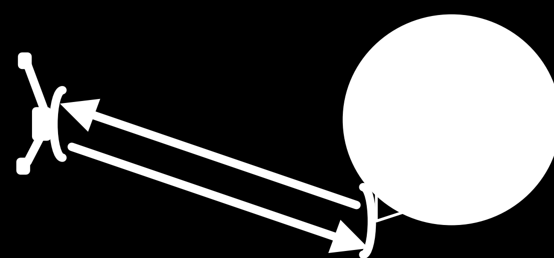
- All observations are two-way or three-way Doppler
- Doppler analysis is about counting ~~beets~~ ~~beasts~~ beats

# Doppler measurements

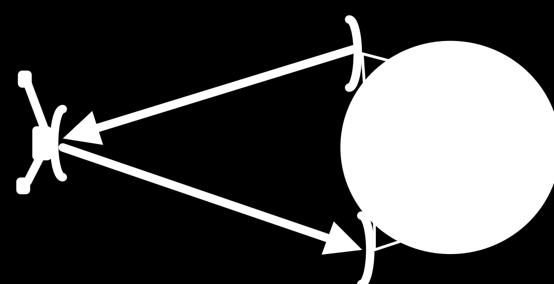
- One-way Doppler



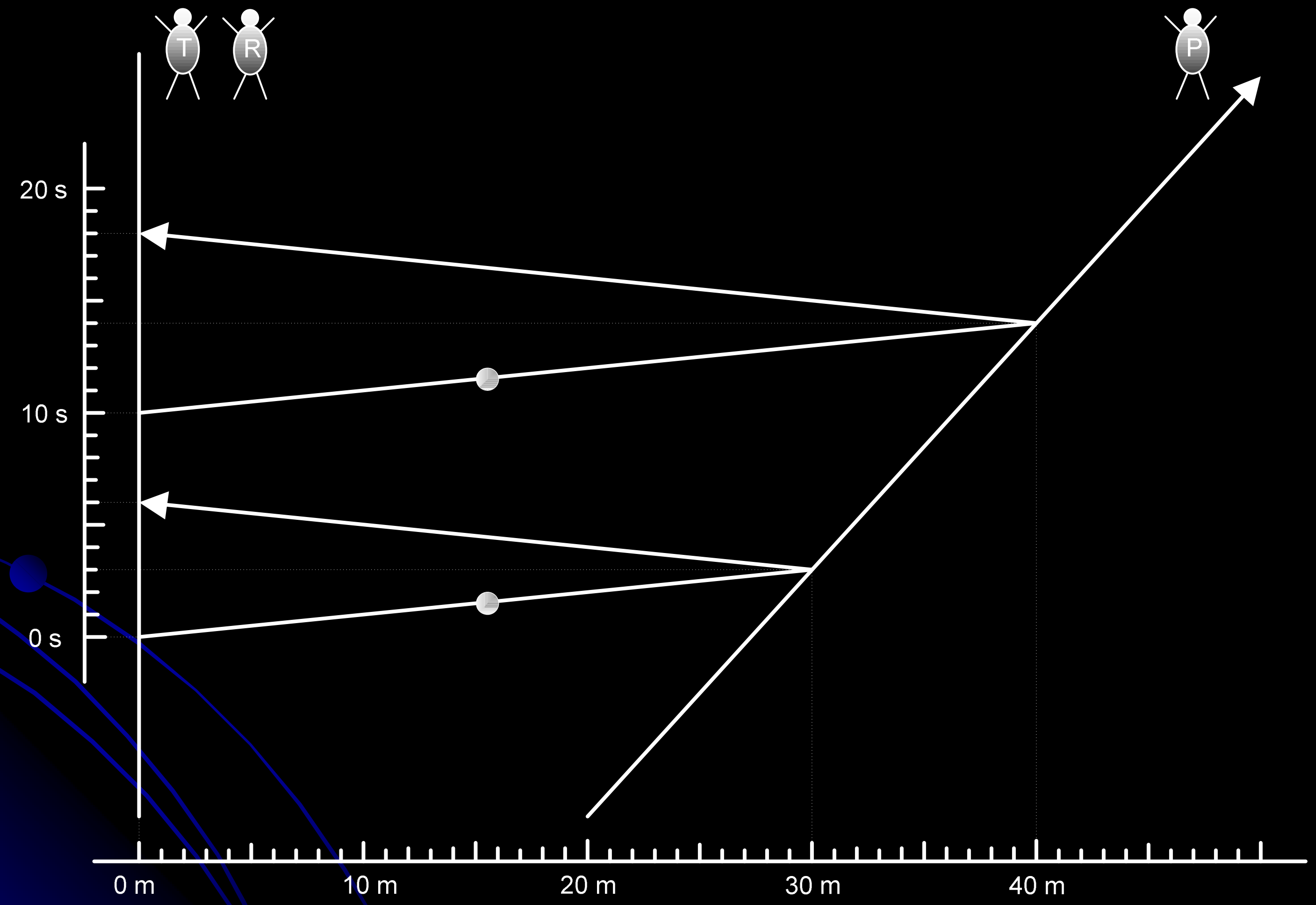
- Two-way Doppler



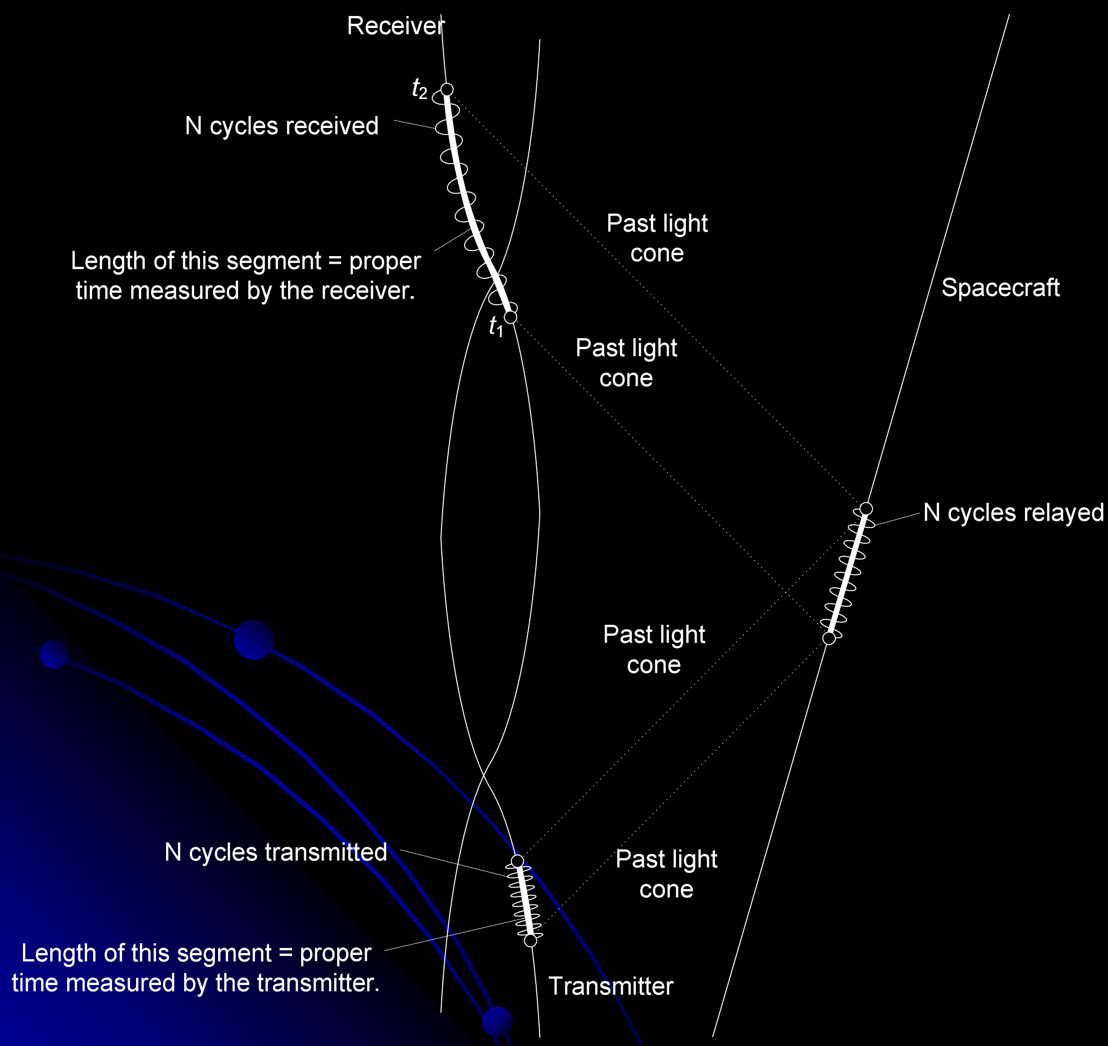
- Three-way Doppler



# Two-way (or three-way) Doppler



# Doppler measurements

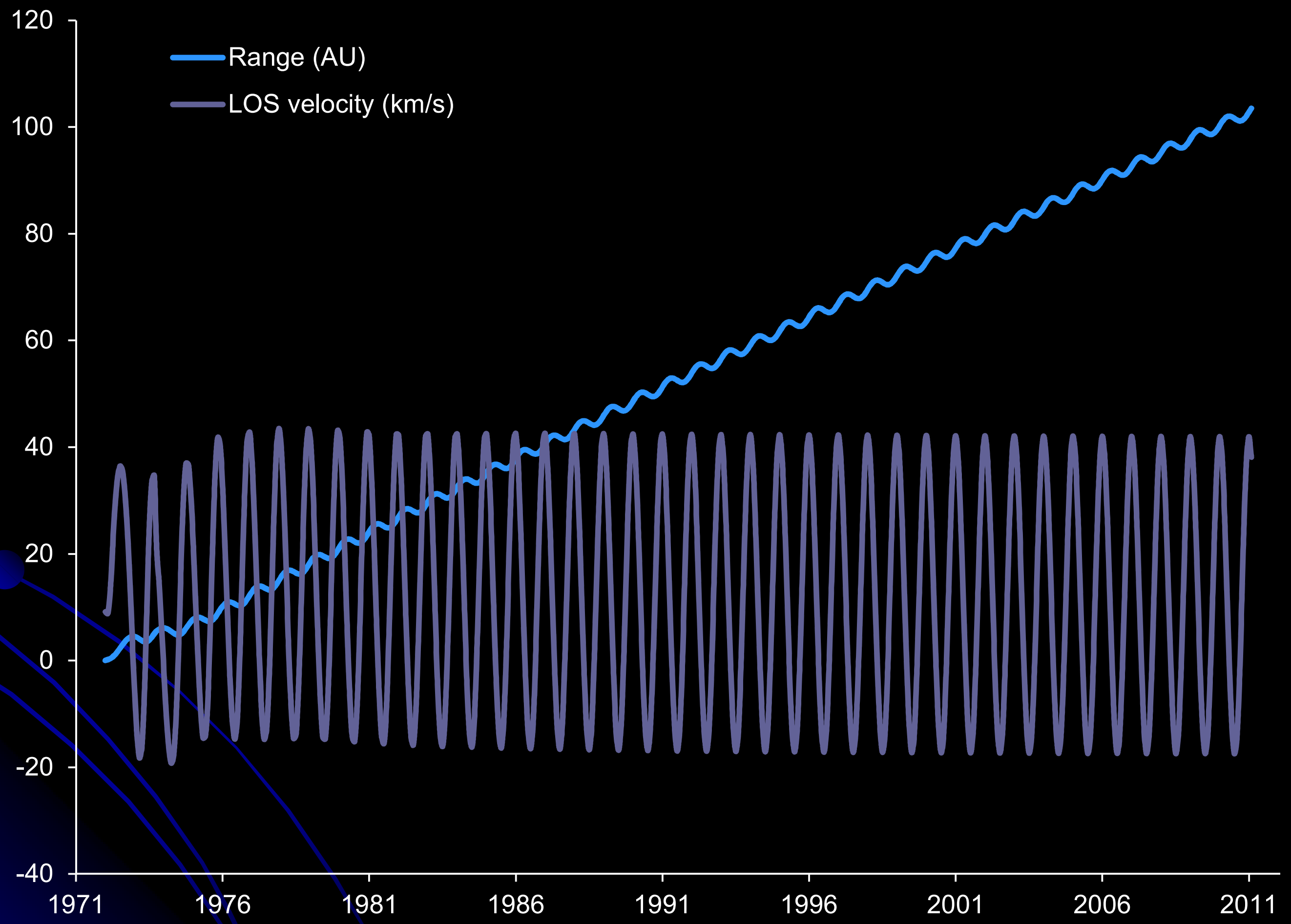



- A measurement at the receiver is made between $t_1$ and $t_2$
- These two instances of time are projected back onto the spacecraft's and then the transmitter's modeled world line; model accounts for
  - Post-Newtonian gravity of major solar system bodies
  - Maneuvers
  - Small non-gravitational forces (e.g., propellant leaks)
  - Shapiro delay
  - Effects of interplanetary medium (solar plasma)
  - Effects of the atmosphere
  - Motion of ground stations (tides, continental drift)
- The number of cycles transmitted is computed from the transmitter's known frequency
- This is then compared to the actual cycle count observed at the receiver
- Model is iteratively refined to reduce the residual difference.

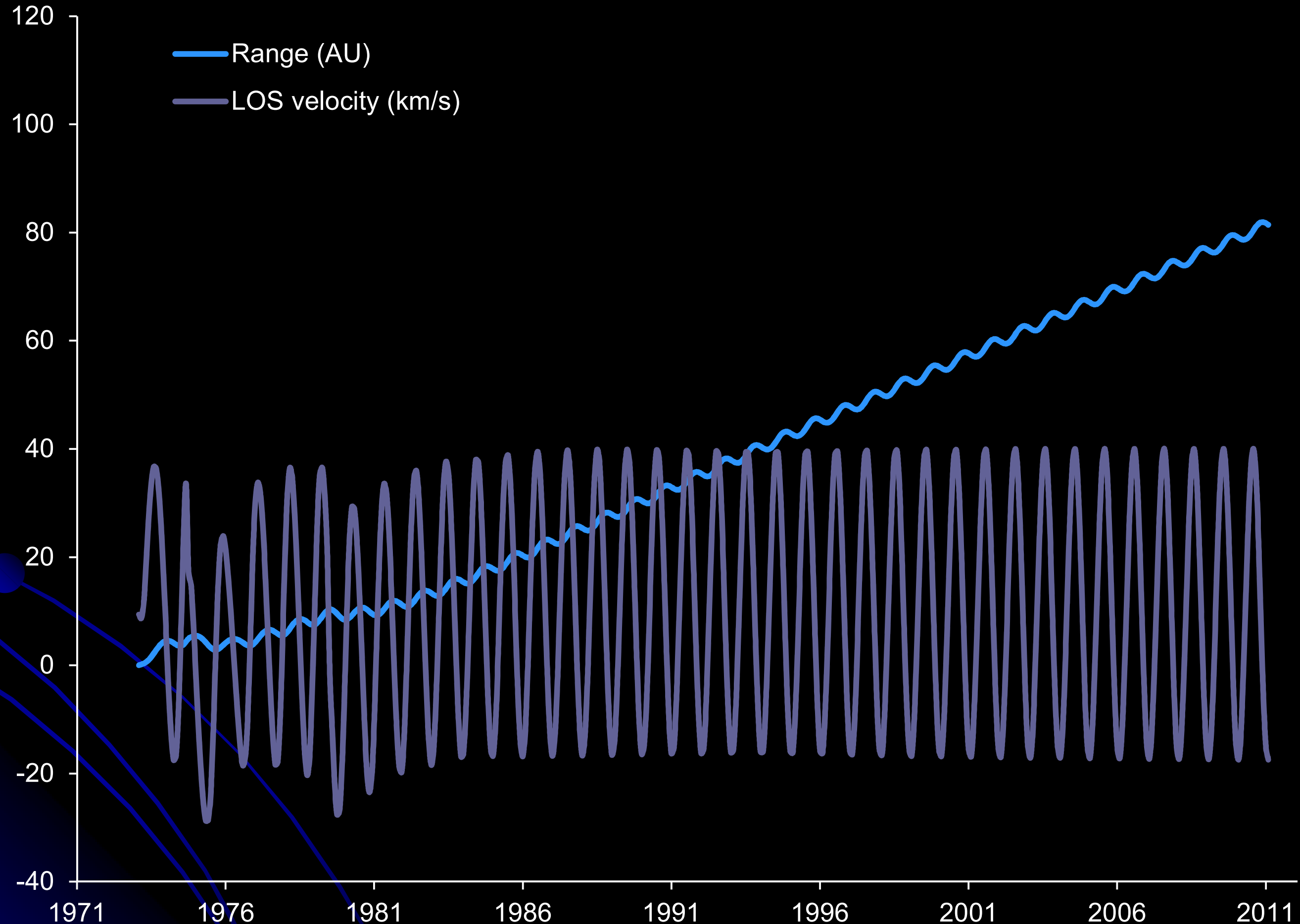
# Effects on the signal

- Solutions that depend on the path length (or travel time) of the signal are in trouble:
  - The geocentric velocity of the spacecraft is −20...+40 km/s
  - The spacecraft-Earth distance is not monotonously increasing

# Distance and geocentric velocity Pioneer 10



# Distance and geocentric velocity Pioneer 11



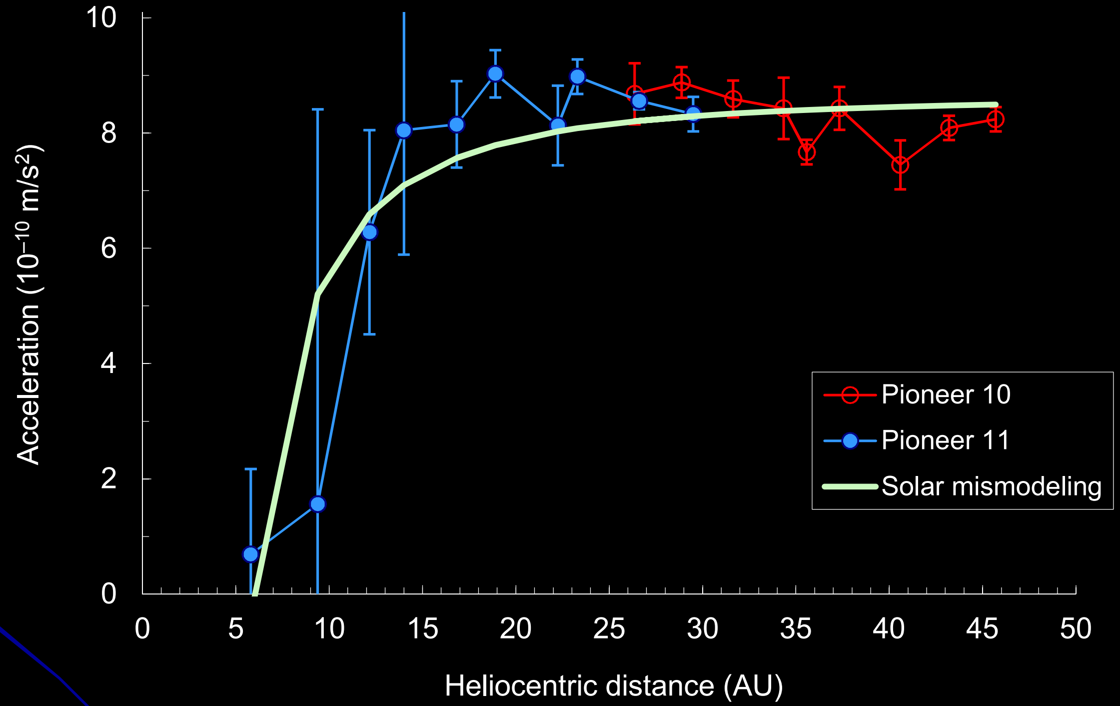
# The solar system

- Not all orbits are well known but the orbit of Saturn is known quite well thanks to Cassini
- Solution must not predict the wrong planetary orbits

# Onset

- The onset is almost certainly a model artifact
- Solar mismodeling can lead to apparent onset

# Onset




- At 6 AU, spacecraft still receives >225 W of solar heating

# The flyby anomaly

- Instantaneous small velocity change near perigee
- Completely unlike the Pioneer anomaly
- Quite possibly a modeling artifact: use of different, accelerating reference frames

# Other spacecraft

- New Horizons: no funding for Doppler tracking; opportunity to confirm "onset" lost
- Voyagers: 3-axis stabilized
- Other spacecraft: wrong orbit, large RTGs, frequent maneuvers, etc.

# Summary

- For the foreseeable future, Pioneer 10 and 11 remain the largest scale precision gravitational experiment ever conducted
- Ability to test post-Einsteinian gravity in the solar system would be marvelous
- Far more likely, this was just a wild goose chase
- Lessons to be learned:
  - Limits on navigational accuracy
  - Importance of preserving raw data and original documents
  - Dangers of “back of the envelope” estimation of small forces

# Thank you!

- Questions?



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