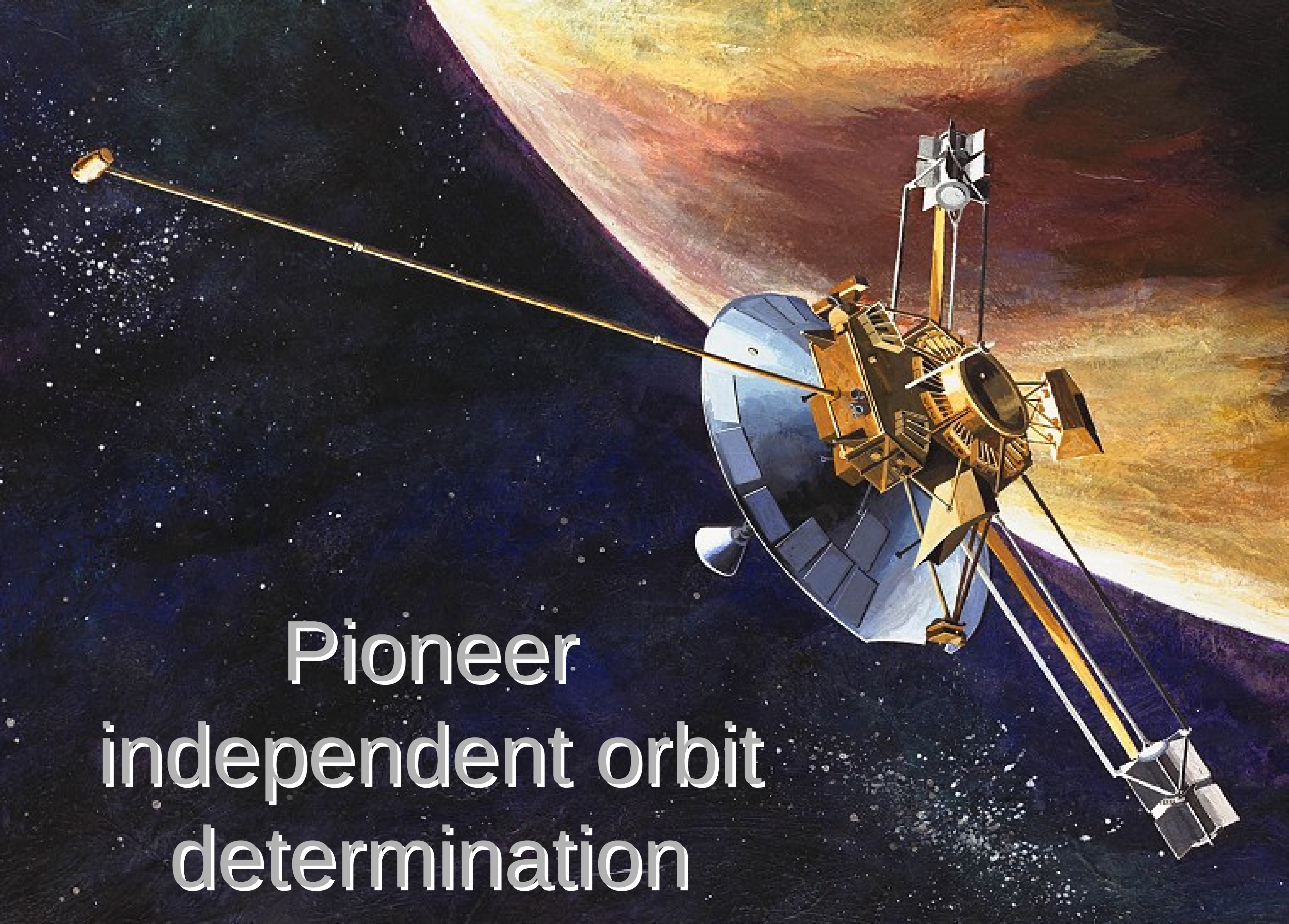


Pioneer independent orbit determination

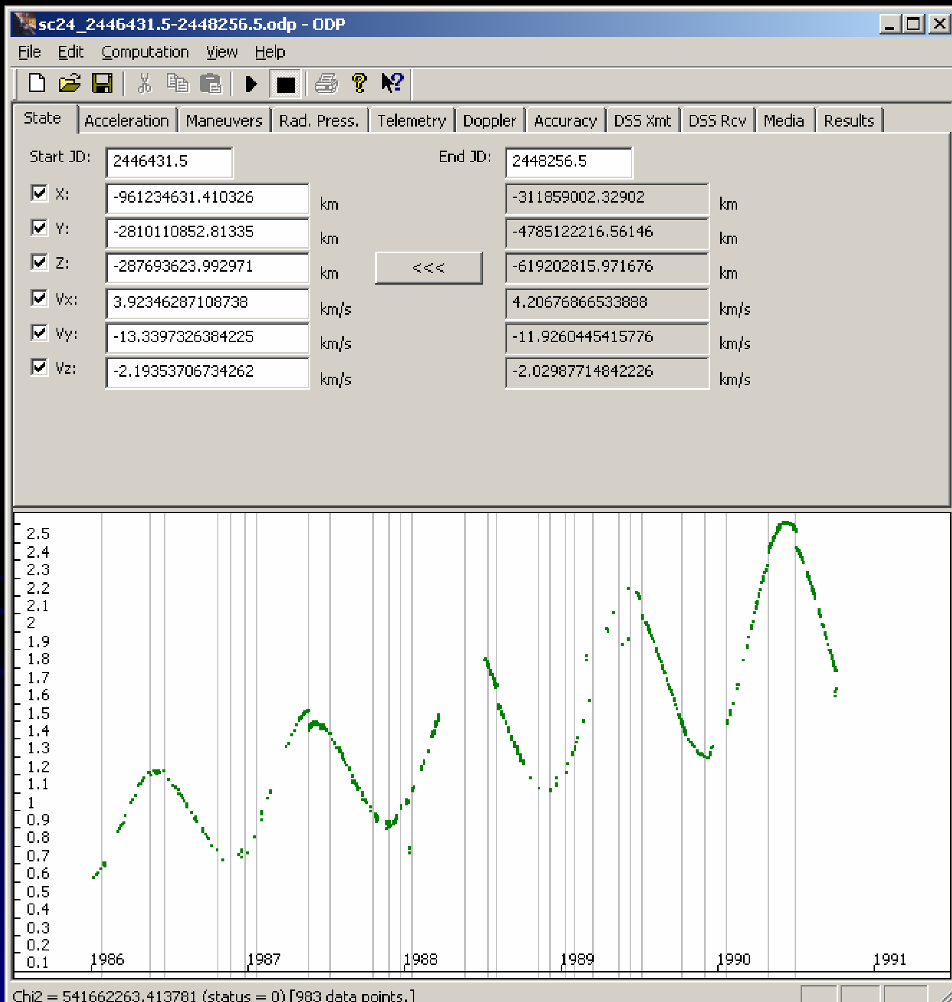
Rationale

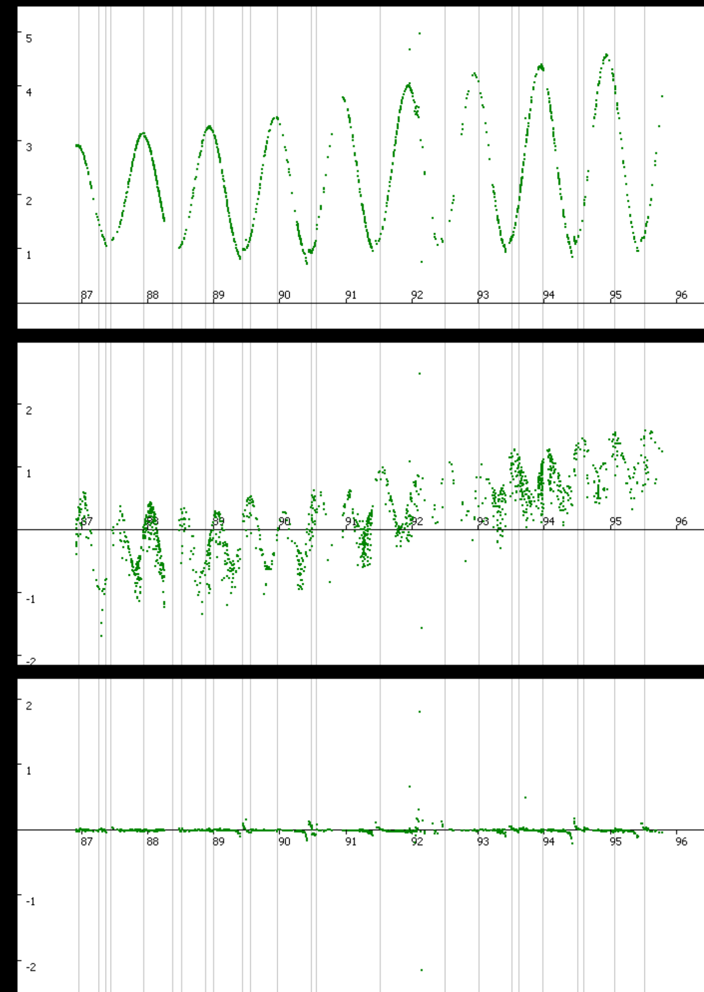
- Independent confirmation of anomalous acceleration
- <u>More importantly</u>: Ability to do precision orbit determination that incorporates <u>telemetry-based estimation of on-board forces</u> (or other theories!)

Orbit estimation

- Simple orbit estimation program (C++, some FORTRAN libraries)
  - Modular construction: separate front-end, use of well-known libraries
  - Uses JPL SPICE library for solar system ephemerides
  - Takes into account current and historical DSN station positions
  - Uses MINPACK for nonlinear least squares estimation
  - Simple fast integrator (Stoermer's rule with predictor-corrector algorithm)
  - Takes into account relativistic Doppler and Shapiro time delay
  - Uses relativistic equations of motion for spacecraft position
  - Includes corrections due to oblateness of Jupiter and Saturn
  - Includes simple troposphere and solar corona model
  - Includes simple (Earth-pointing flat plate) solar pressure model
  - Uses custom library to read Doppler and ramp data from ODFs
  - Maneuvers estimated as changes in velocity along spin axis
  - Custom library reads telemetry for maneuvers, spin, and on-board generated heat
- JPL HORIZONS used for initial Pioneer 10/11 state estimates

Orbit estimation

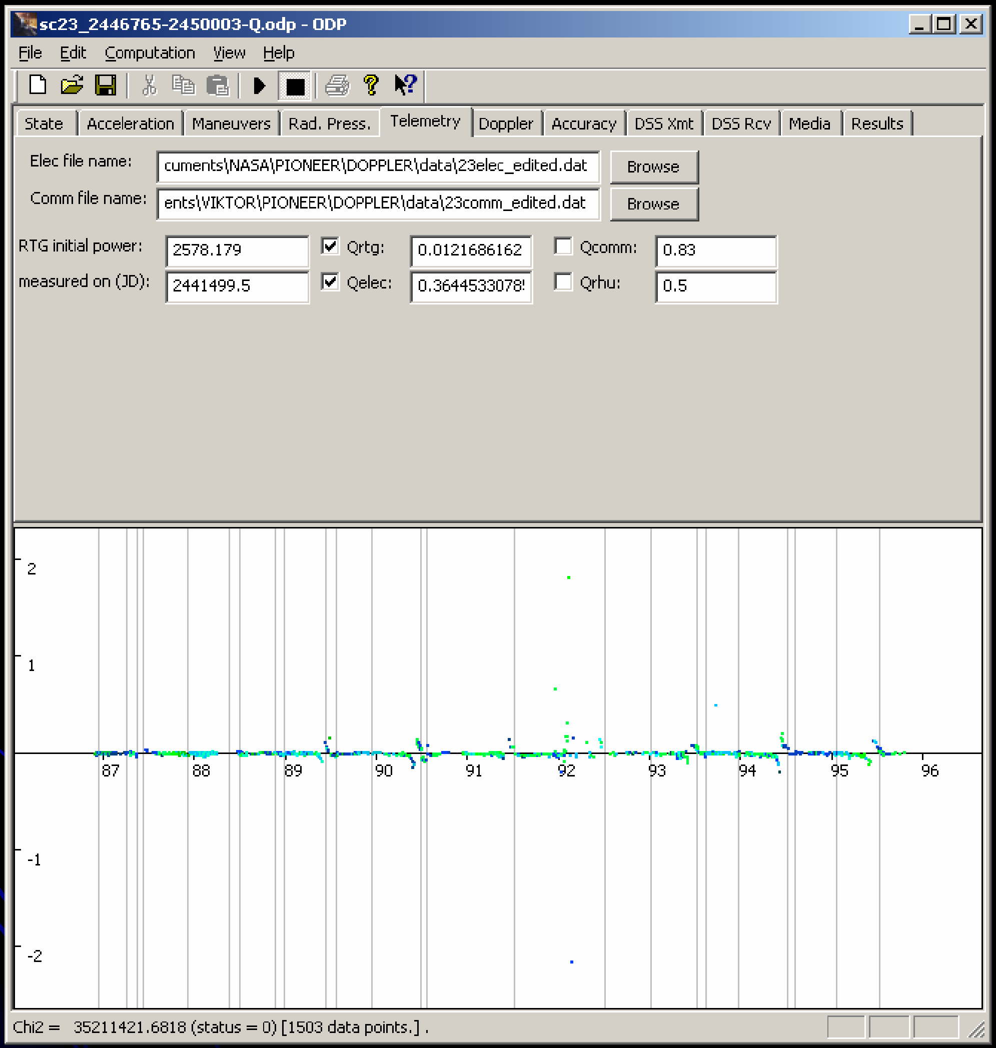




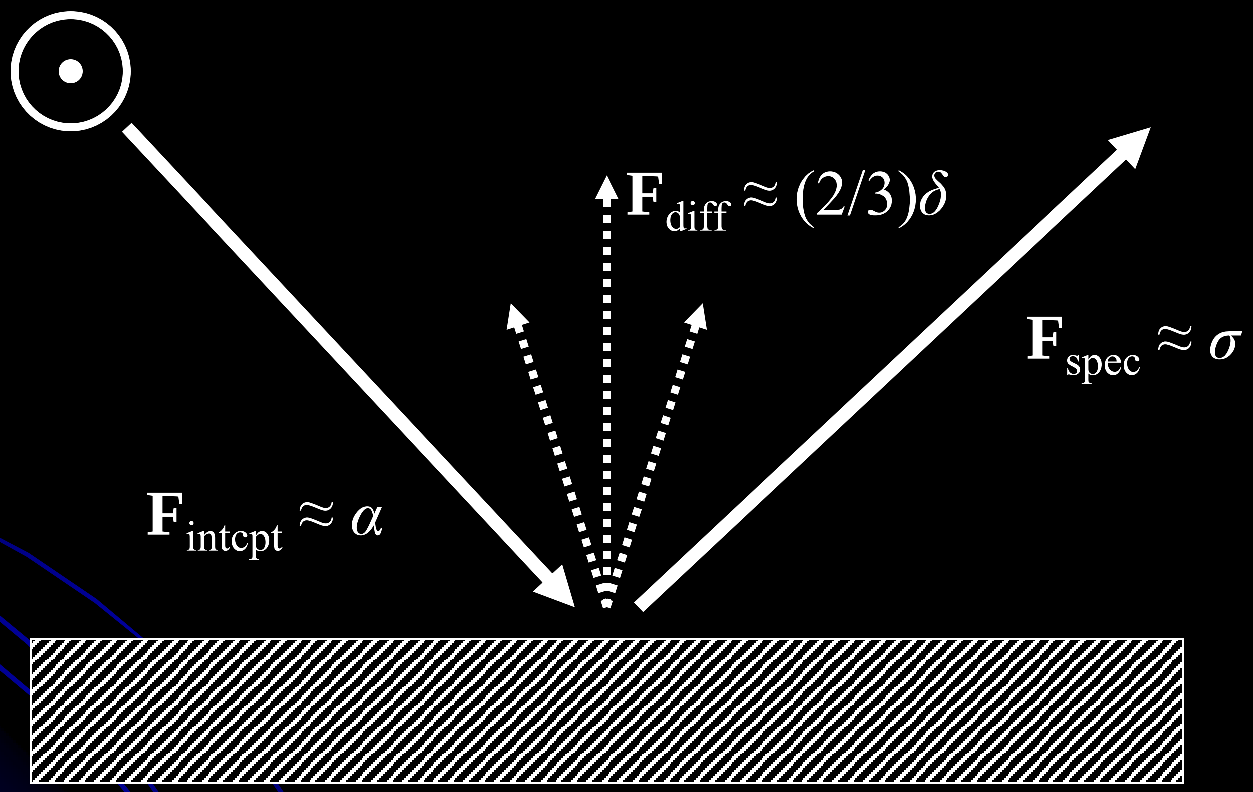
Estimating on-board forces

- Basic concept: in addition to "solving for" orbital elements, also solve for linear factors (q_i) of thermal acceleration. Equation of motion modified with thermal acceleration $a = (1/mc)\Sigma q_i P_i$ where the P_i are known from telemetry.
- Method relies on no *a priori* assumptions about geometry, only about linearity and spin
- Most "correct" method from a modeling/statistical perspective

Estimating on-board forces

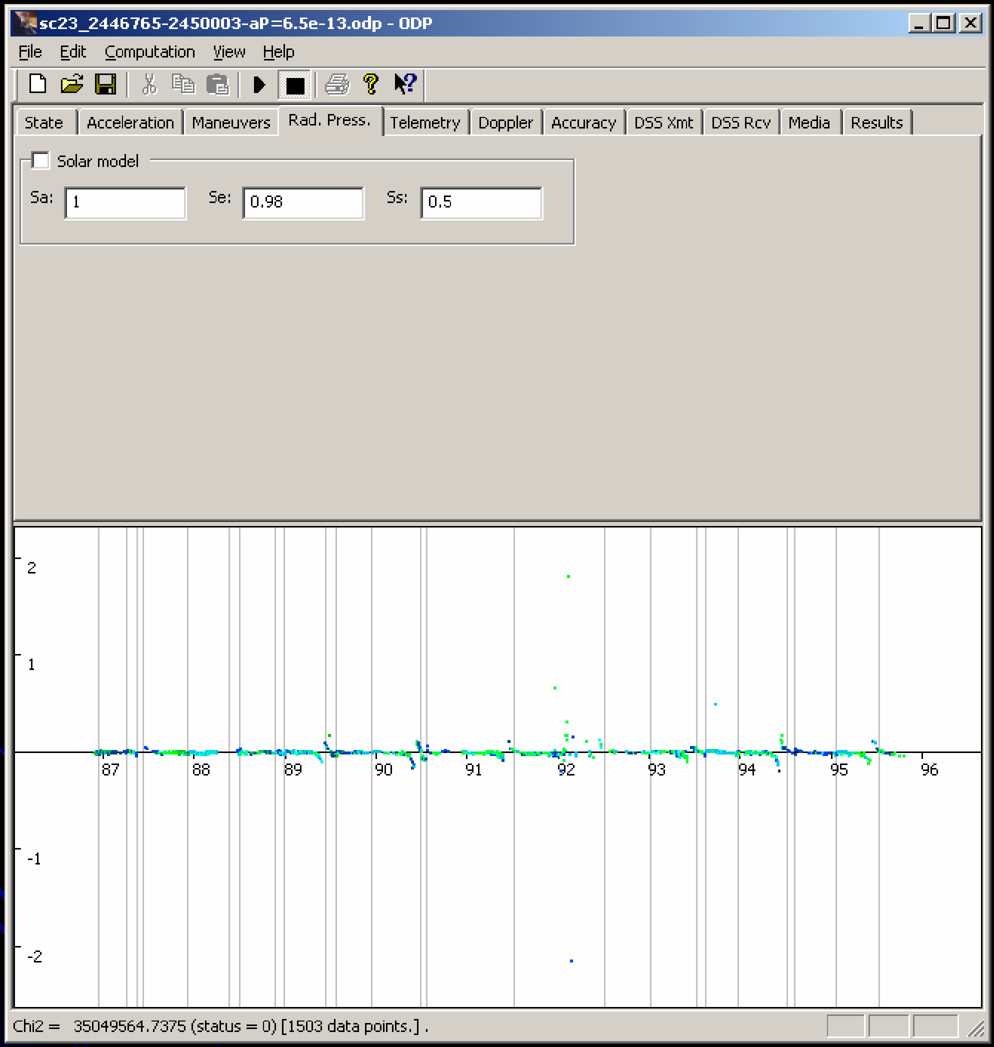


Solar model



$\mathbf{F}_{\text{diff}} \approx (2/3)\delta$
$\mathbf{F}_{\text{spec}} \approx \sigma$
$\mathbf{F}_{\text{intcpt}} \approx \alpha$

Solar model

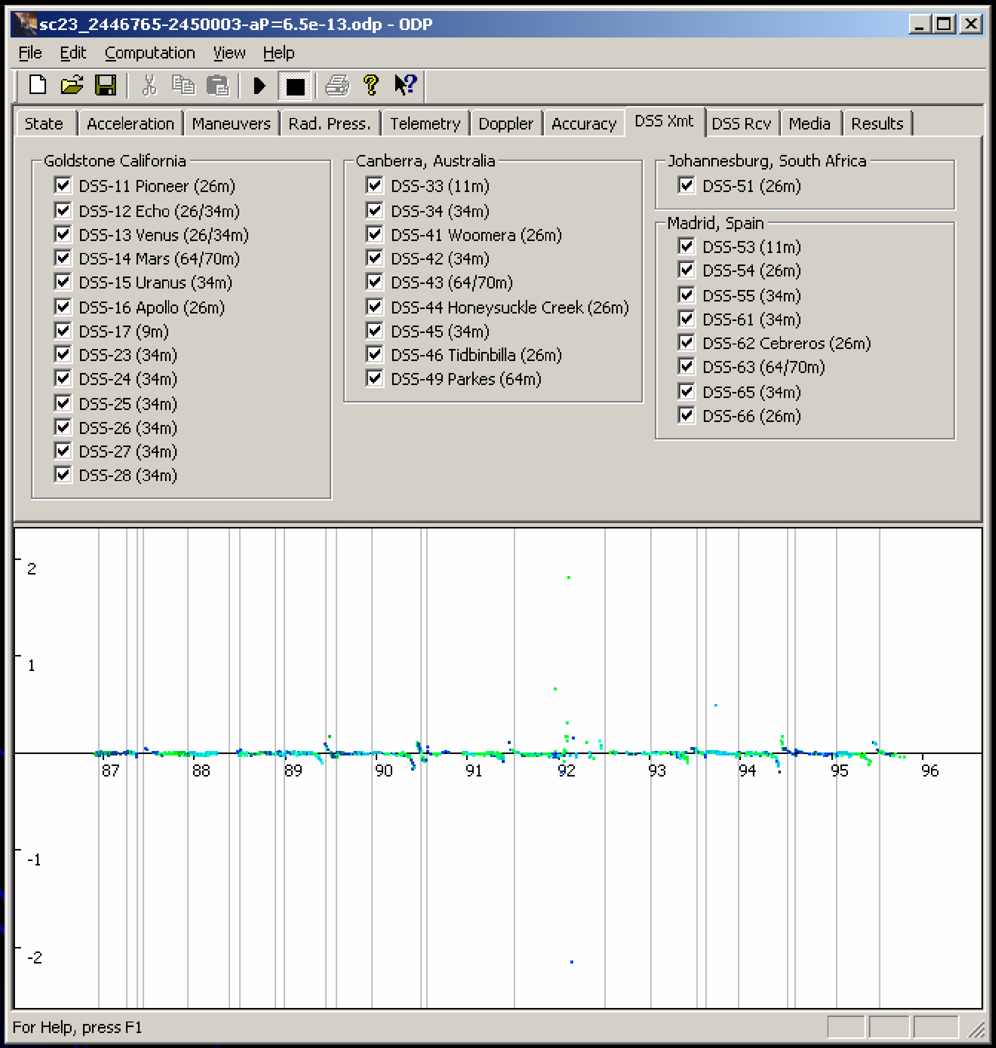


sc23_2446765-2450003-aP=6.5e-13.odp - ODP
File Edit Computation View Help
State Acceleration Maneuvers Rad. Press. Telemetry Doppler Accuracy DSS Xmt DSS Rcv Media Results
Solar model
Sa: 1 Se: 0.98 Ss: 0.5
2
1
-1
-2
87 88 89 90 91 92 93 94 95 96
Chi2 = 35049564.7375 (status = 0) [1503 data points.] .

DSN stations

- Pioneer data spans over 30 years
- During this period, many DSN stations have been
  - commissioned
  - decommissioned
  - moved
- Published data sets usually contain only current stations

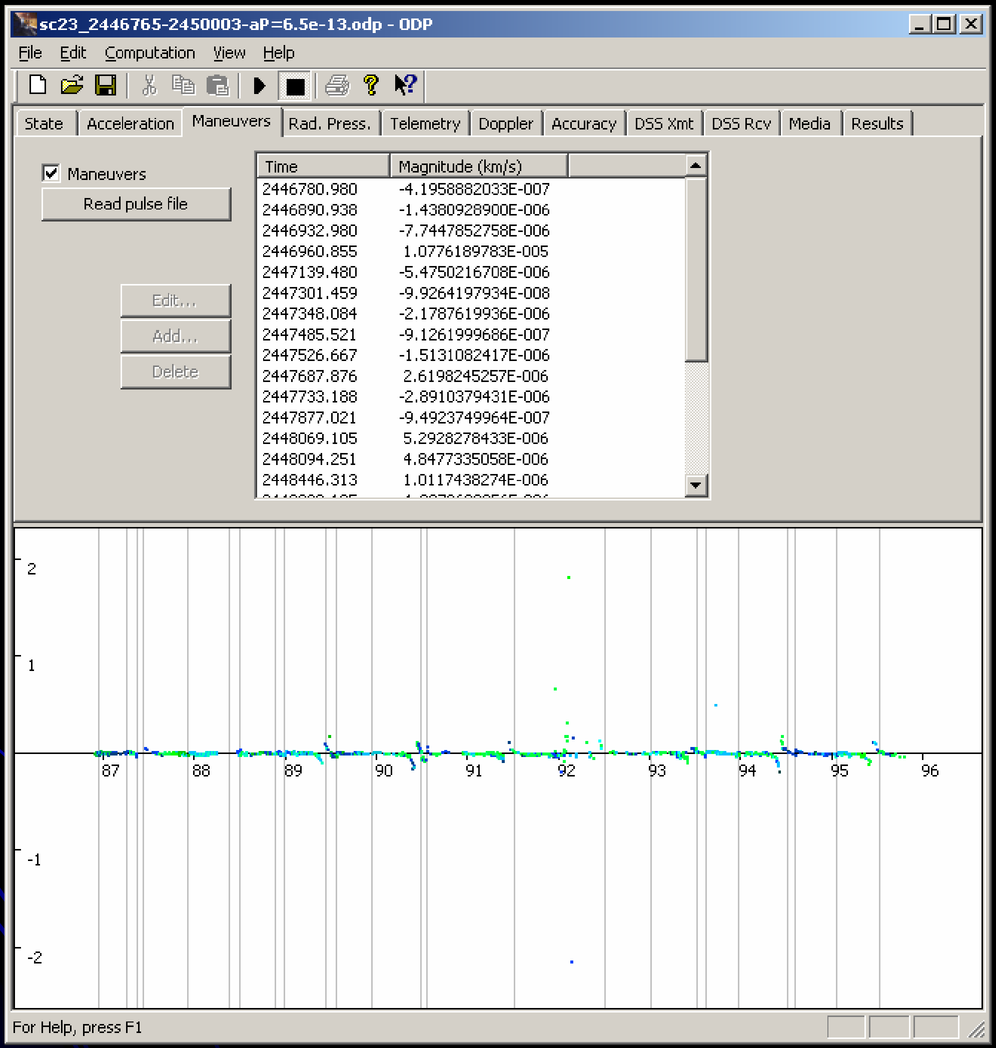
DSN stations



Maneuvers

- Attitude correction maneuvers are not supposed to change velocity; any velocity change is small and random (due to timing uncertainties, thruster alignment, etc.)
- Velocity changes perpendicular to the spin axis likely cancel each other as the spacecraft rotates
- Doppler observable not sensitive to such velocity changes anyway
- Instead of modeling each attitude correction as a three-dimensional maneuver, it is modeled as a velocity change along the Earth-spacecraft line, reducing the number of parameters to be estimated by a factor of three

Maneuvers



sc23_2446765-2450003-aP=6.5e-13.odp - ODP
File Edit Computation View Help
State Acceleration Maneuvers Rad. Press. Telemetry Doppler Accuracy DSS Xmt DSS Rcv Media Results
Maneuvers
Read pulse file
Edit...
Add...
Delete
Time Magnitude (km/s)
2446780.980 -4.1958882033E-007
2446890.938 -1.4380928900E-006
2446932.980 -7.7447852758E-006
2446960.855 1.0776189783E-005
2447139.480 -5.4750216708E-006
2447301.459 -9.9264197934E-008
2447348.084 -2.1787619936E-006
2447485.521 -9.1261999686E-007
2447526.667 -1.5131082417E-006
2447687.876 2.6198245257E-006
2447733.188 -2.8910379431E-006
2447877.021 -9.4923749964E-007
2448069.105 5.2928278433E-006
2448094.251 4.8477335058E-006
2448446.313 1.0117438274E-006
2
1
-1
-2
87
88
89
90
91
92
93
94
95
96
For Help, press F1

Data sets

- I had two data sets available:
- "JPL2002" certified data set used in the 2002 JPL study, containing:
  - Nearly 11 years of Pioneer 10 data (~9 years usable; last ~2 years use different encoding)
  - Nearly 5 years of Pioneer 11 data
- "Jacobson" uncertified data set containing:
  - ~75 days of data surrounding Pioneer 10 Jupiter encounter, ~67 days a year later
  - Nearly 2 years of data leading up to, and including, Pioneer 11 Saturn encounter

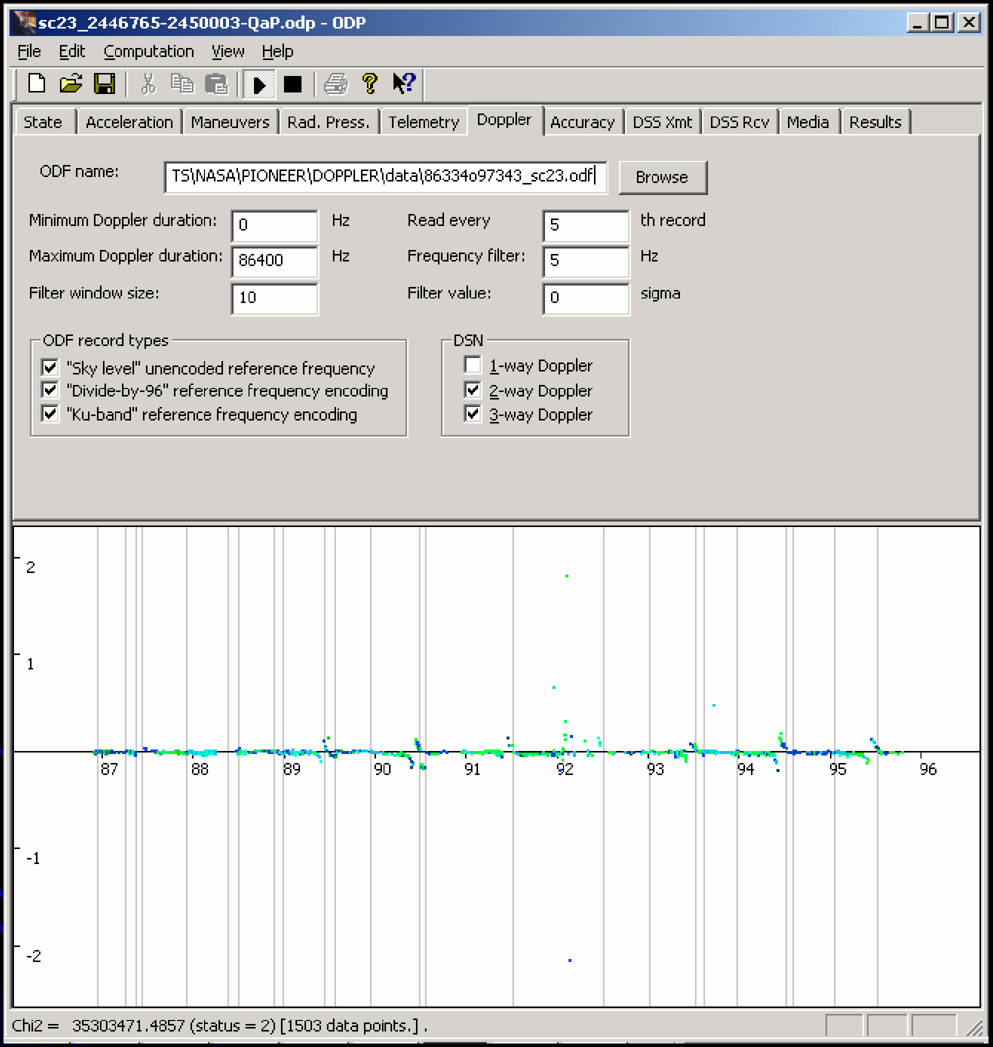
Using data sets

- "Early" data not yet certified, but it can be used to
  - Validate orbit determination code
  - Verify/calibrate solar model
- "Late" (certified) data set can be used to
  - (Re)-determine the value of a_P
  - Test the "thermal hypothesis"

Some problems

- “Ku-band” data
- Sky frequency
- “Banding” when ramp data not used
- Block 5 data reference frequency
- Motion of Earth station during Doppler count interval
- Timekeeping

Some problems



Model validation

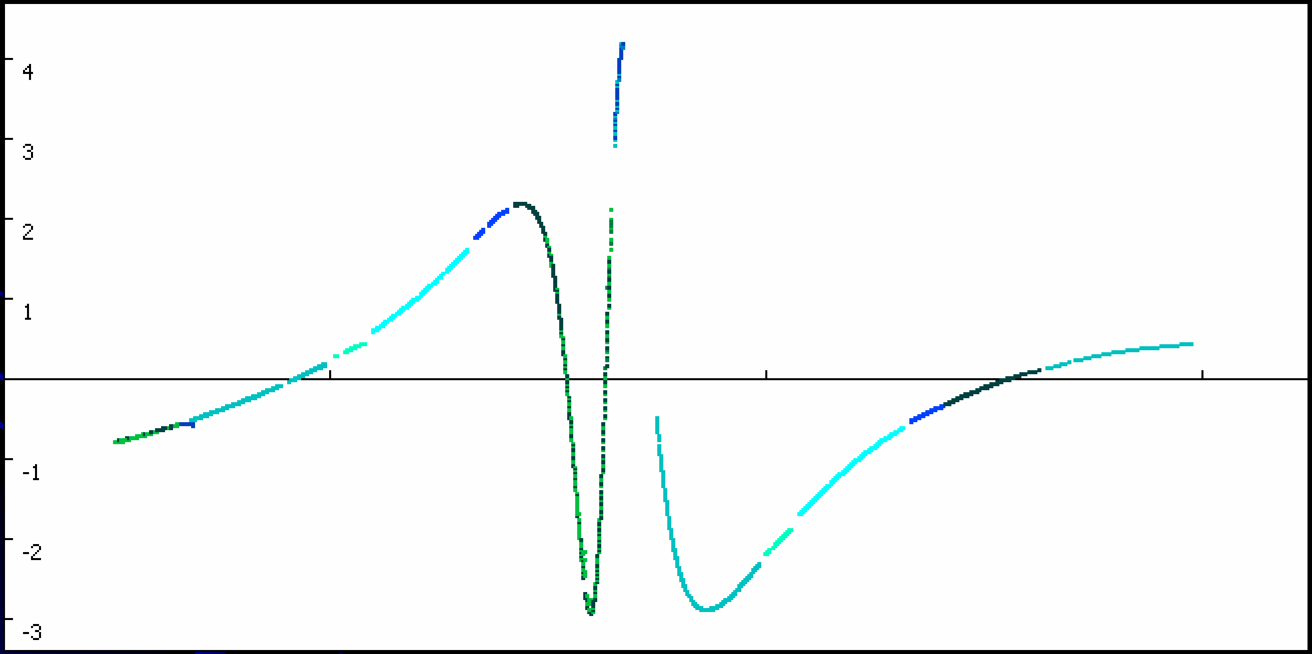
- Planetary encounter requires
  - Accurate orbit integration
  - Modeling of satellites
  - Relativistic equations of motion
  - Oblateness model
- Rapid change in spacecraft velocity stresses the model, allowing one to uncover subtle errors

Model validation

- Planetary encounter not perfectly modeled; discrepancy due to
  - Not modeling the changing velocity of the spacecraft during Doppler interval
  - Not modeling planetary thermal radiation pressure
- Mismodeling is very similar for the two encounters

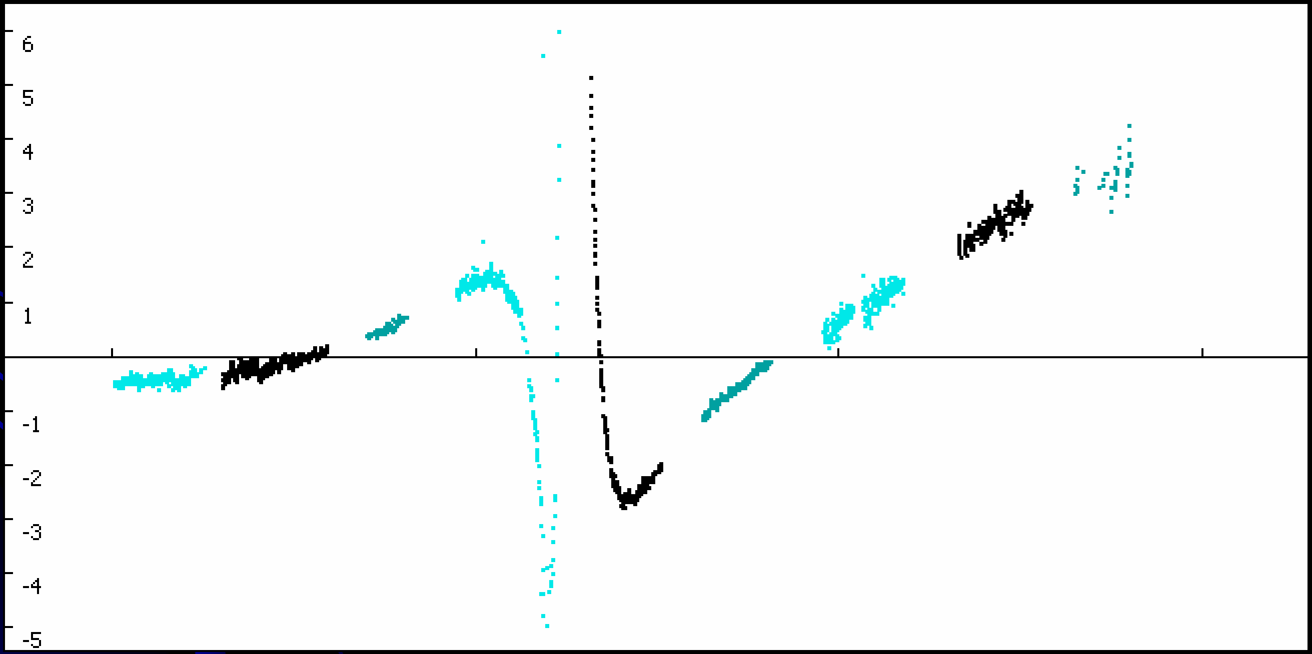
Pioneer 10 Jupiter encounter mismodeling

- Mismodeling magnitude ~5 Hz (~30 - 40 cm/s)
- Mismodeling limited to ~2 day period surrounding closest approach



Pioneer 11 Saturn encounter mismodeling

- Mismodeling magnitude ~5 Hz (~30 - 40 cm/s)
- Mismodeling limited to ~2 day period surrounding closest approach



Solar model validation

- Simple 3-parameter flat plate model (for now) modeling absorption, diffuse and specular reflection

	α	δ	σ
Nominal	1.00	0.98*	0.50
Pioneer 10	1.00	0.77	0.56
Pioneer 11	0.95	1.34	0.43

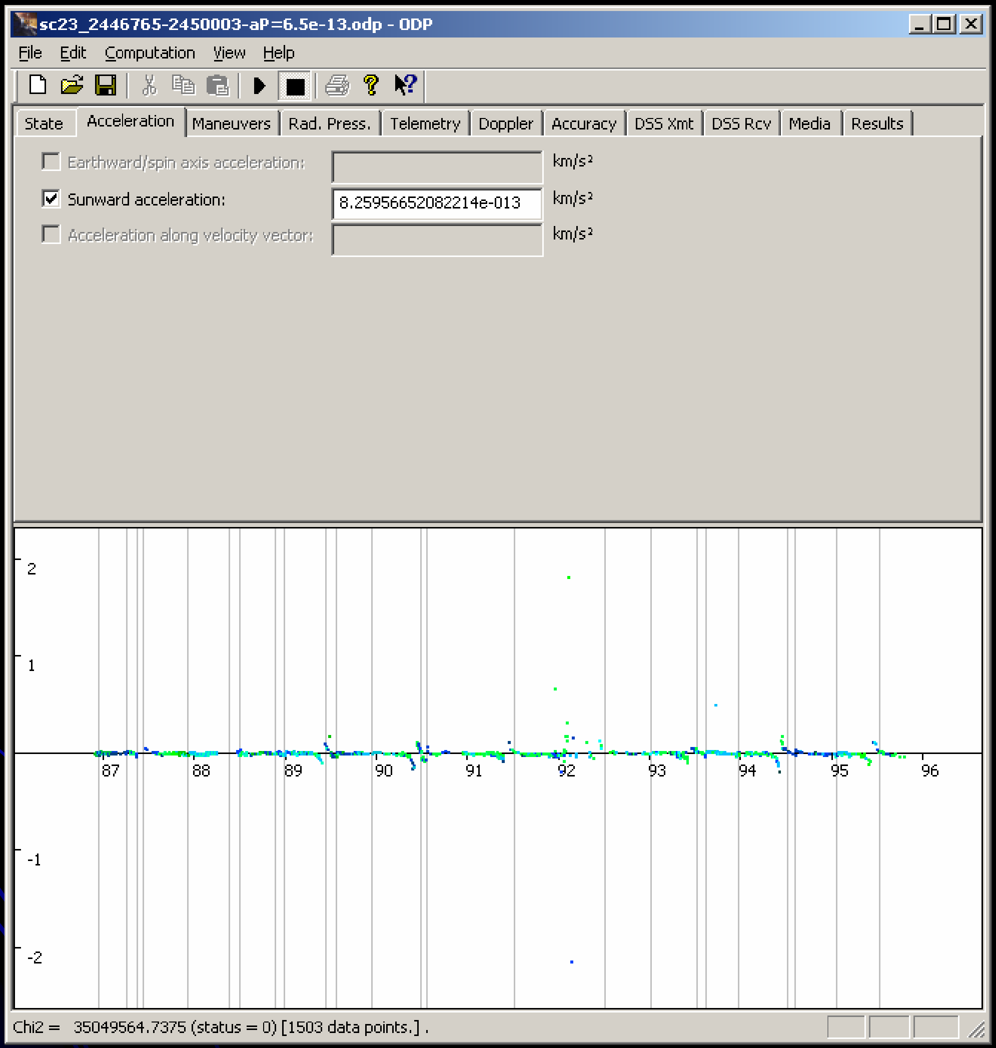
- Similarity between Pioneer 10 solution (<5 AU) and nominal values increases confidence that solar model is valid and orbit determination code works reliably

*Published reflectance of 0.79 is assumed to be “net” reflectance, from this and emittance figures, an effective reflectance of 0.96 is calculated. Results presented here used the figure of 0.98 (a result of a prior calculation); the difference between the two is negligible.

Solving for a_P

- Solution appears highly dependent on initial value (least squares optimization finds local minima near initial value; acceleration absorbed by maneuvers)
- The goodness of fit (χ^2) is similar in all cases
- Therefore, I cannot say that a particular value of a_P is “the” solution, only that it is consistent with the data

Solving for a_P



Solving for a_P

- All values in units of 10^{-13} km/s^2:

Data set	Initial value:	0	10	6.5
“2002”	Pioneer 10	4.77	8.06	8.26
	Pioneer 11	–0.15	7.38	5.84
“Jacobson”	Pioneer 11	–0.29	9.55	5.99

- **Conclusions so far (this is work in progress!): much depends on the choice of initial values and the least squares algorithm**
- **Same near constant acceleration consistent with all studied data sets**

Solving for a_P and q_i

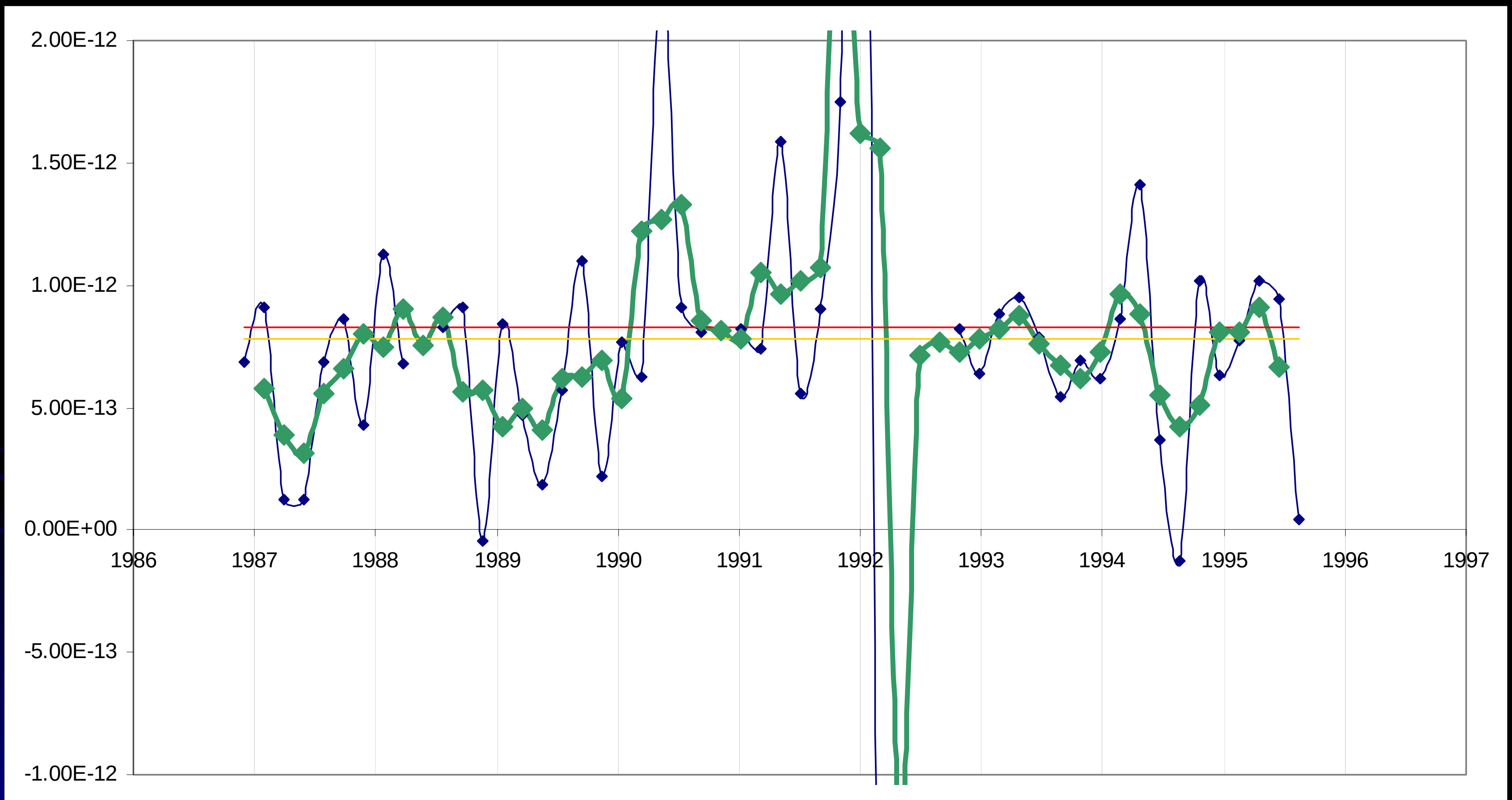
- Simultaneously solving for constant acceleration and thermal coefficients
- Initial thermal values are nominal:
  $q_{\mathrm{RTG}} = 0.01$, $q_{\mathrm{elec}} = 0.35$
- Two different initial accelerations used:

Initial a_P (10^{-13} km/s^2)	a_P	q_{RTG}	q_{elec}
0	0.15	0.012	0.36
4	2.05	0.010	0.36

Stochastic acceleration

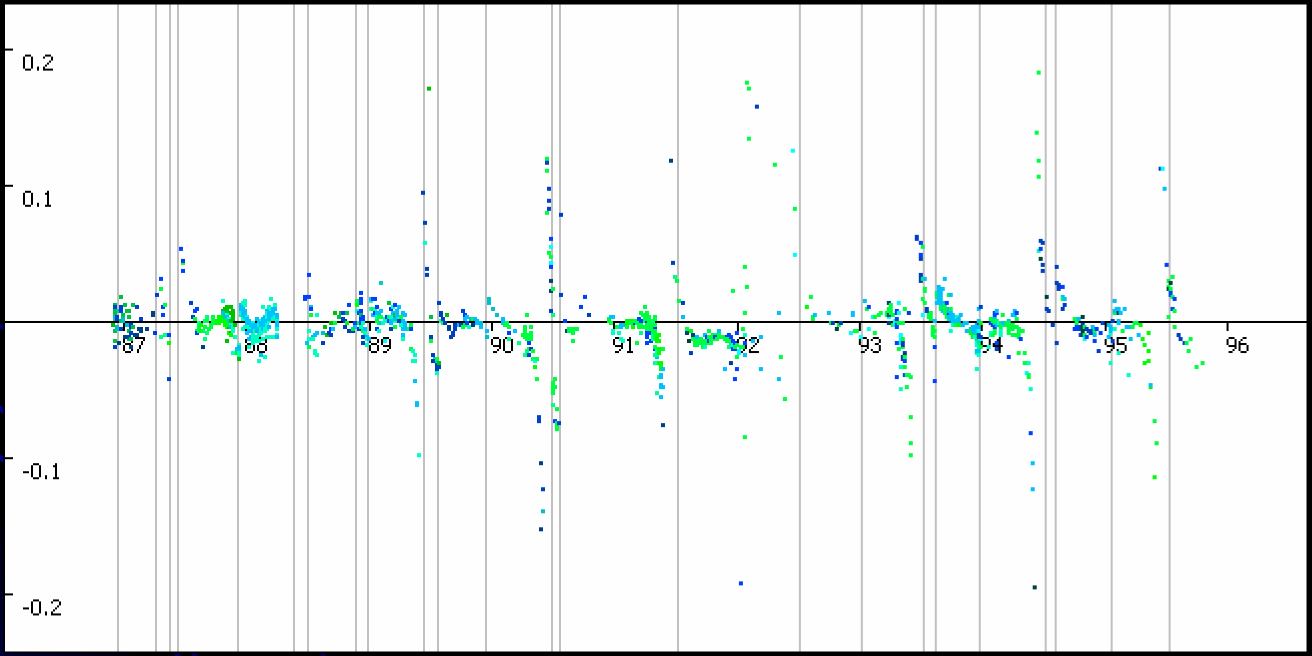
- After obtaining initial solution:
  - Divide data into 60-day (120-day) batches
  - Propagate solution through batches, solving for only
    - a_P
    - Maneuvers
- Used 9-year Pioneer 10 data set

Stochastic acceleration



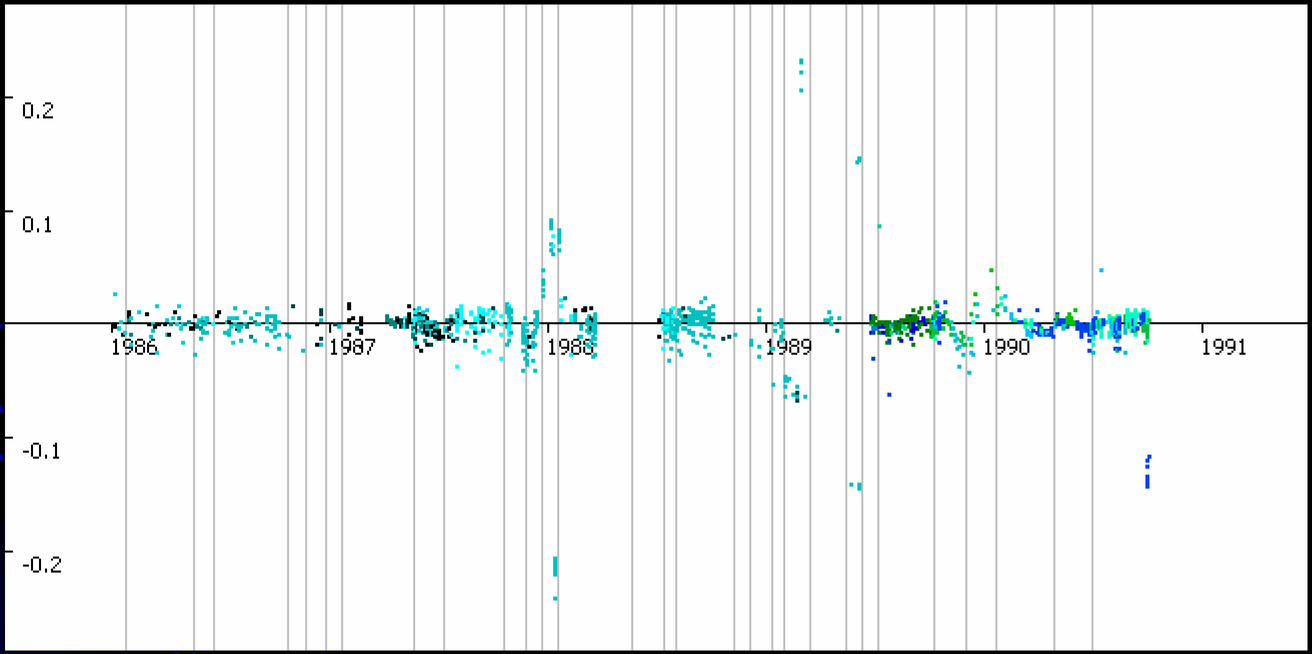
Stochastic acceleration

- Some annual periodicity is also visible in least squares solution (error in Shapiro code?)



Stochastic acceleration

- Same signature not apparent in Pioneer 11 data set



Plans (February 2007)

- Develop proper three-dimensional radiation pressure model using raytracing code
- Improve orbit determination code:
  - Improve flyby modeling accuracy
  - Solar and planetary radiation model
  - Ionospheric propagation delay
- Incorporate means to estimate acceleration (and jerk term!) in other directions (Earth-pointing, and along the direction of motion)
- Improve attitude and maneuver modeling
- Improve pointing information using AGC or SNR
- Improve data weighing, filtering, etc. capabilities
- FIND AND FIX BUGS!
- Utilize new Doppler data when available

Thank You!