VLBA Astrometry of Planetary Orbiters

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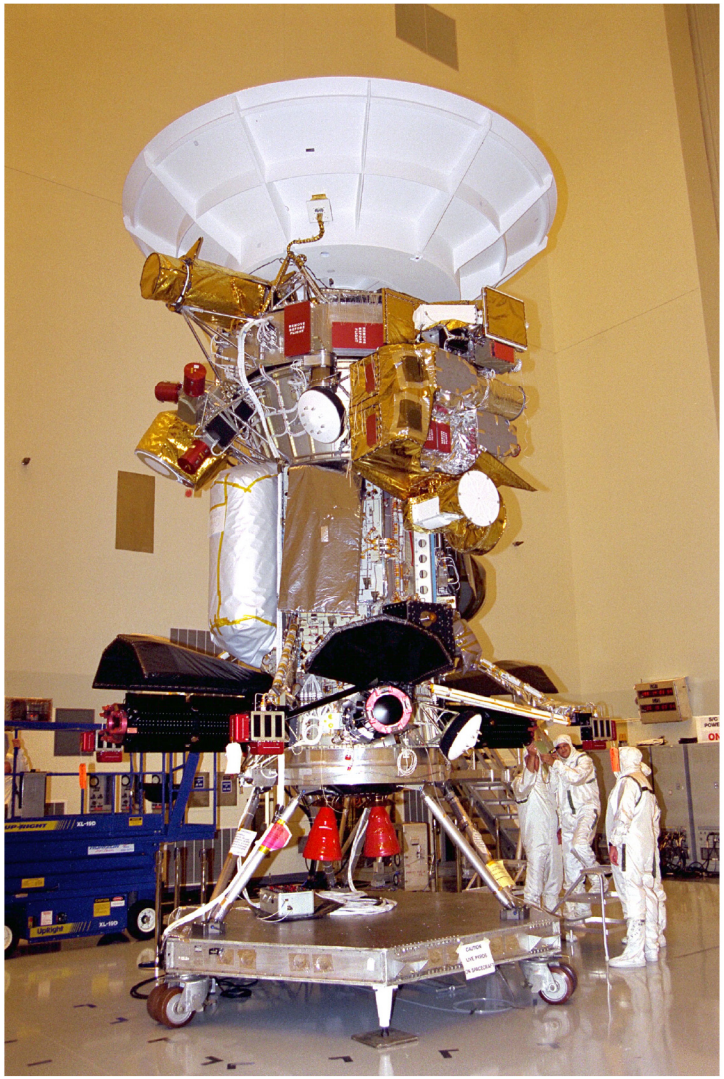
Outline

- Introduction
  - Cassini mission timeline
  - Planetary ephemeris
- Observing Strategy
  - Phase-reference astrometry with VLBA
  - Scheduling constraints and strategy
- Current Results
  - Cassini positions and ephemeris improvement
  - Issues currently being investigated
- Future Plans
  - Mars orbiters, JUNO mission, SKA



Cassini spacecraft in JPL clean room

Cassini launch, Oct 1997

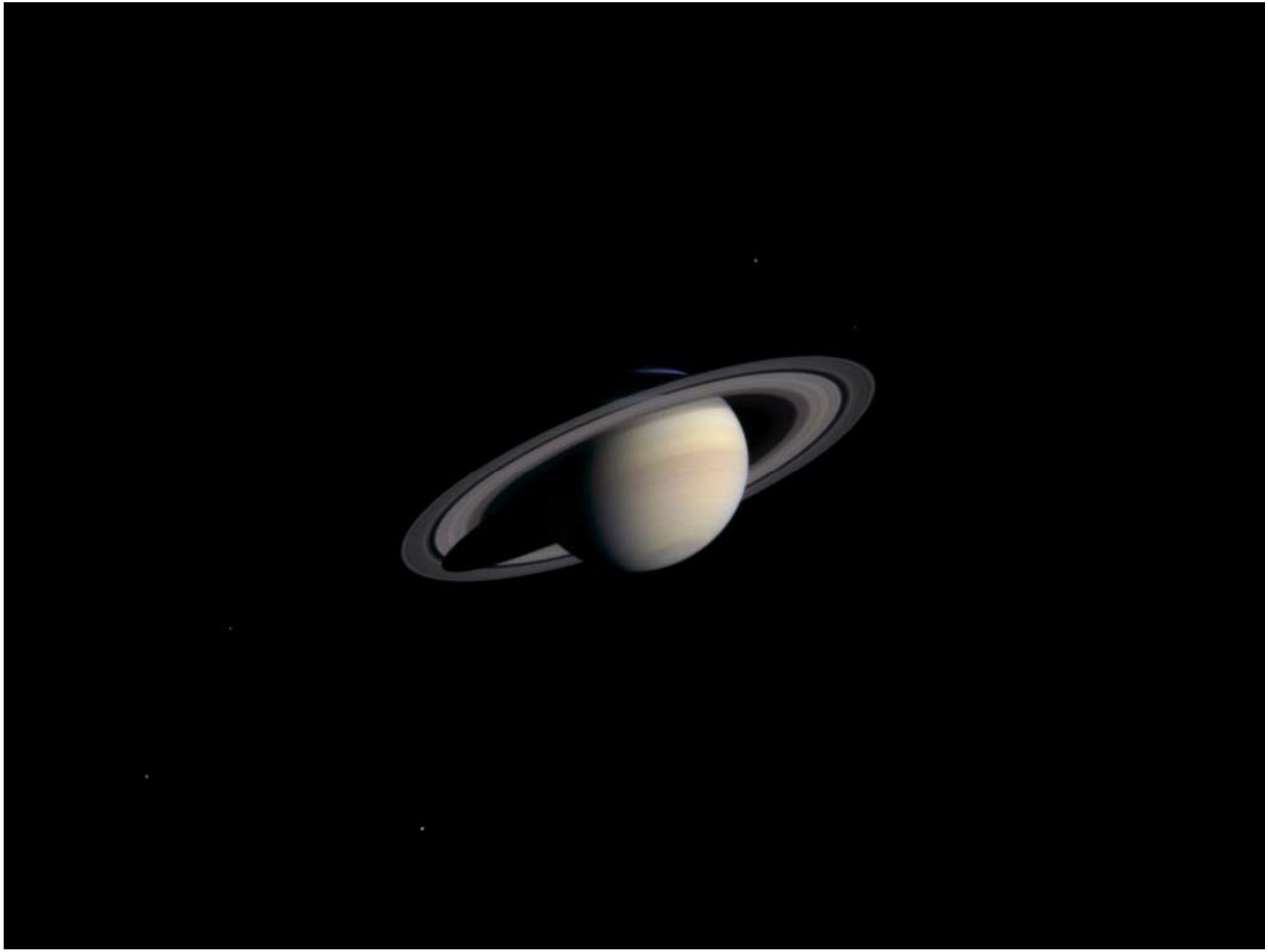
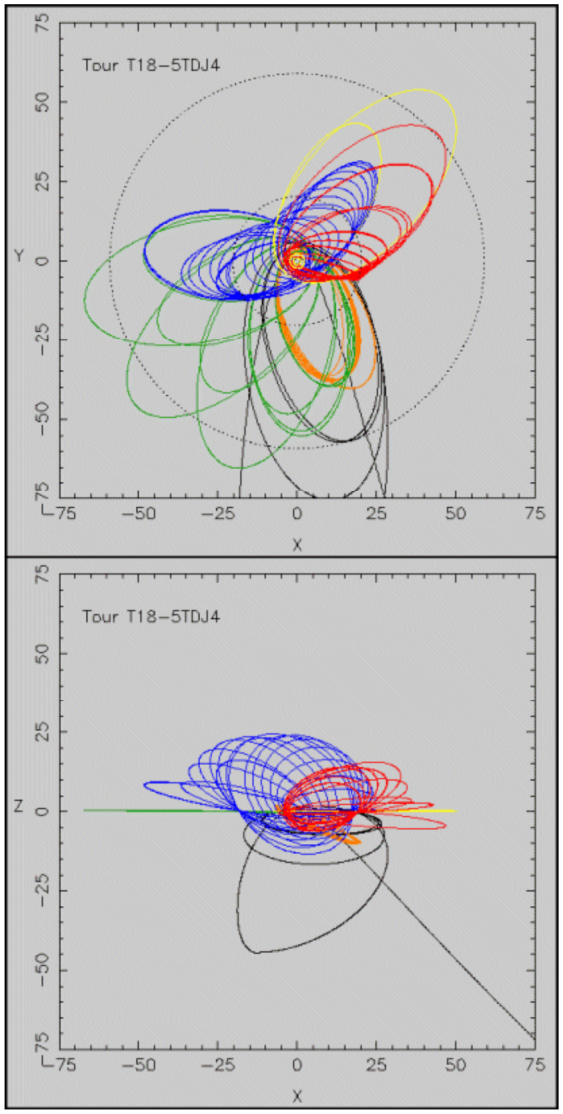


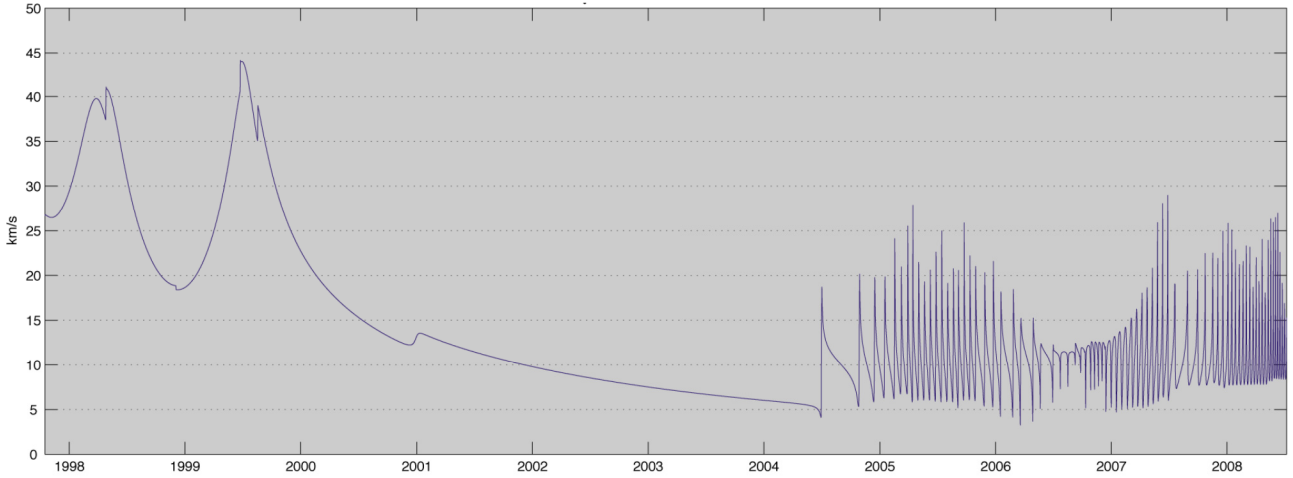
Image of Saturn taken shortly before Cassini orbit insertion, mid-2004



Cassini in orbit about Saturn:

Complex sequence to allow multiple close flybys of several moons, Saturn ring occultations, polar views of Saturn, etc.

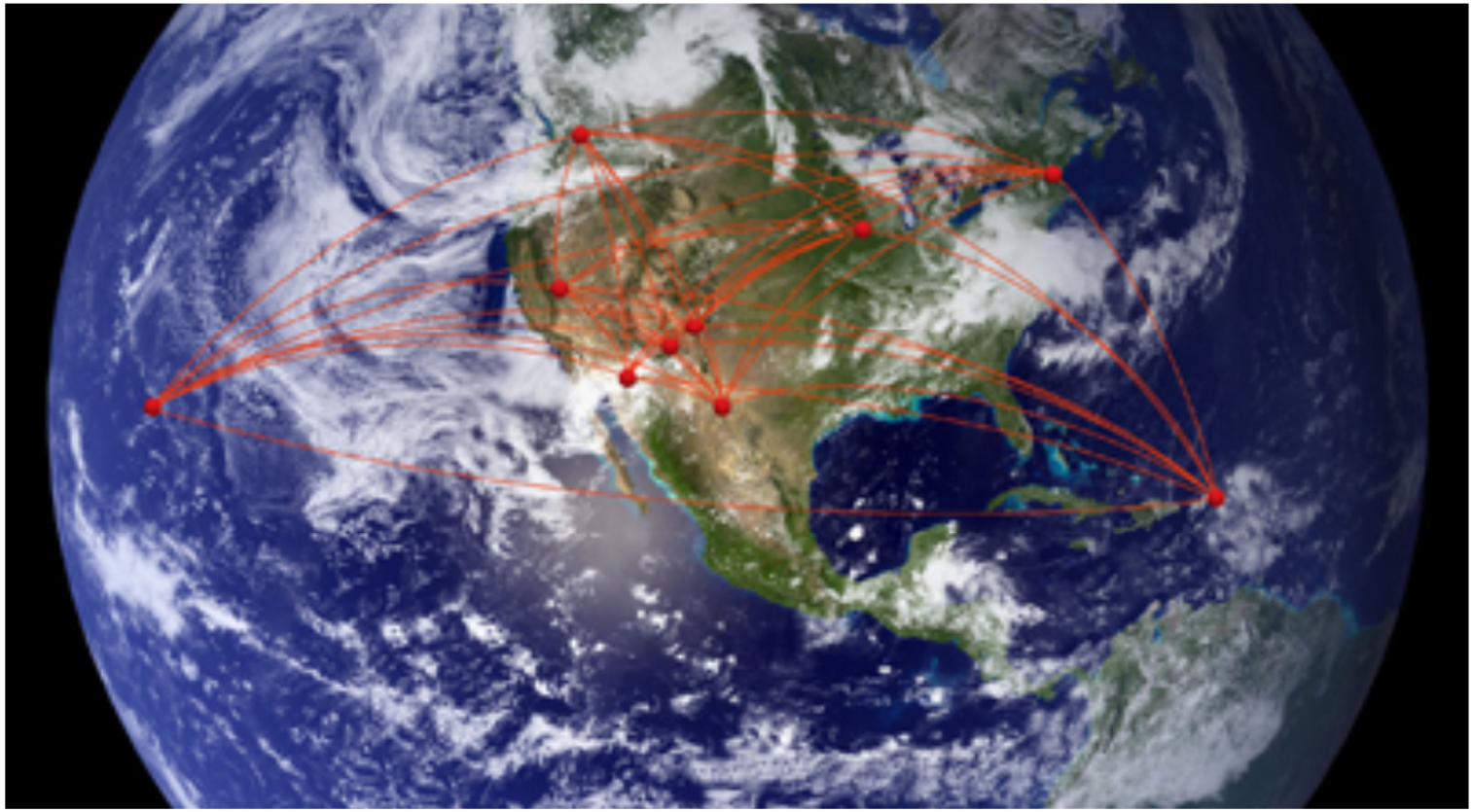
Trajectory correction burns and close flybys cause large, sudden changes in Cassini Doppler signal.



Planetary Ephemeris

- Used for dynamical studies solar system evolution, tests of general relativity, prediction of occultations and eclipses, pulsar timing, and interplanetary spacecraft navigation.
- Inner planets are tied together in current ephemeris through radar and tracking of multiple missions including orbiters and landers.
- Outer planets not as well tied to inner solar system, or to each other.
- Cassini is the first outer planet mission to provide high accuracy, long term position measurements.

Very Long Baseline Array



Good baseline range, good stability, good calibration, good coverage of ecliptic declinations

Phase-Referenced Astrometry

Switch between sources faster than time scale of typical errors

- Phase differencing reduces model delay errors by 1/(ang. sep.)
- Troposphere and position offsets are main error sources in residual phase differences at X-band
- Unmodeled troposphere error between close sources is ~ 1 ps, so there is no cycle ambiguity in the differential phase:

  $1\ \lambda$ at 8.4 GHz = 120 ps

  $\Delta\Phi \sim$ (50 ps) / SNR

- Relative position accuracies of < 0.05 mas have been achieved
- Our goal is 0.1-0.2 mas (dominated by error in link to ICRF)

First new VLBA total delay data added to Doppler tracking data for Saturn ephemeris:

Saturn positions from Doppler tracking data:

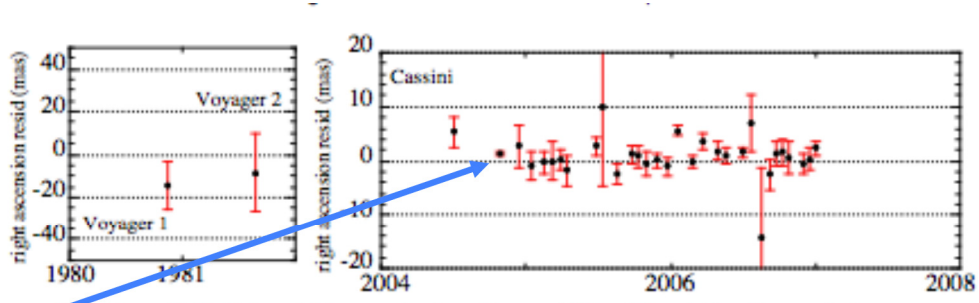


Figure B-18: Saturn right ascension from Voyage 1&2 and Cassini tracking analysis.

VLBA data

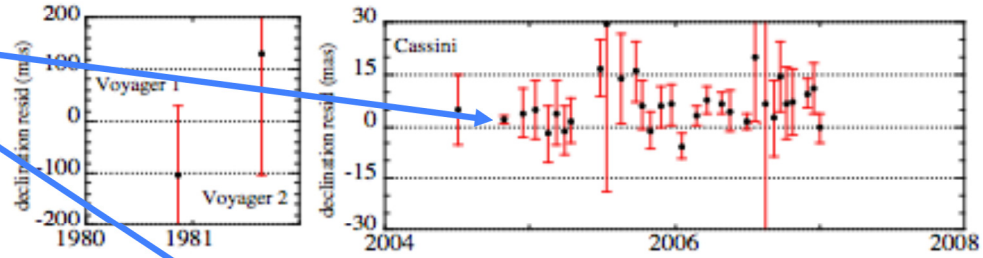


Figure B-19: Saturn declination from spacecraft encounters.

Note relative size of the VLBI and Doppler error bars.

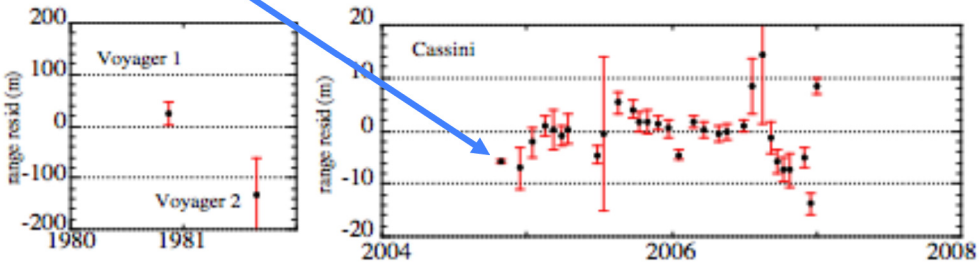
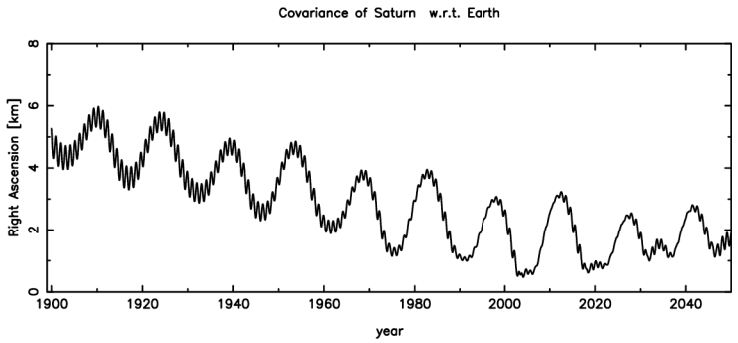
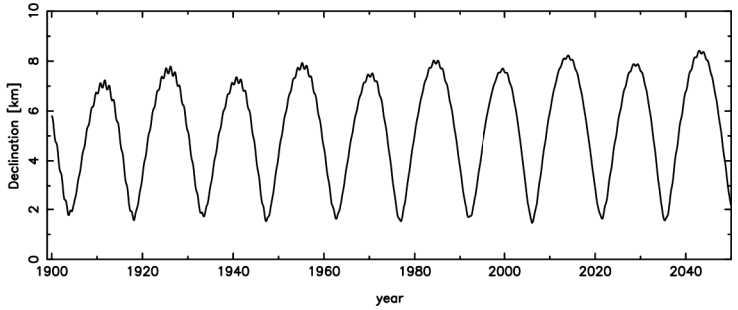


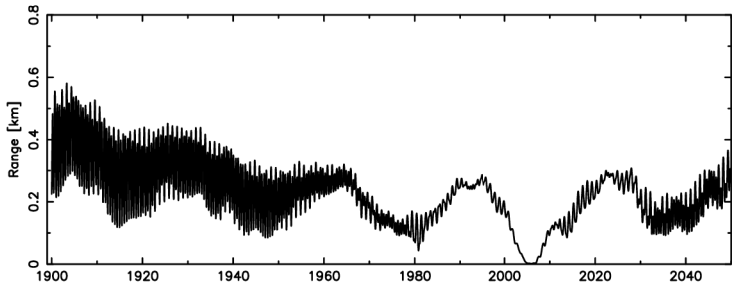
Figure B-20: Saturn-Earth range from spacecraft encounters.

Figure from W. Folkner, J. Williams, and D. Boggs, 2008, "The Planetary and Lunar Ephemeris DE 421", JPL Memorandum 343R-08-003.

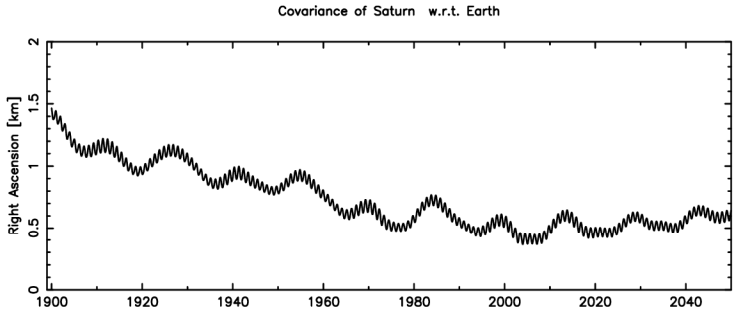
Covariance study showing value of VLBA measurements added to previous data types

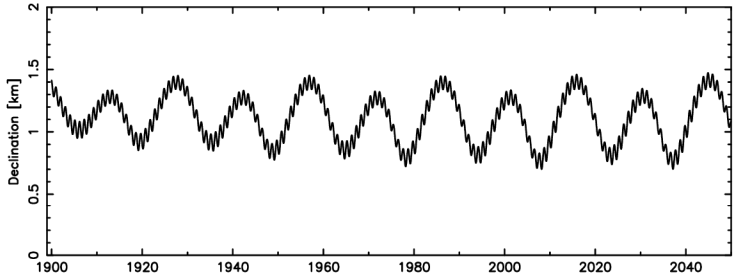


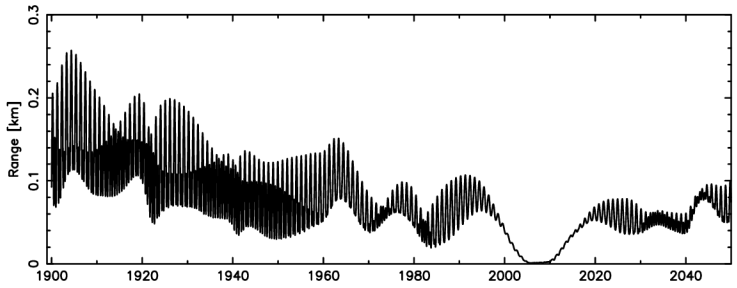




DE-421 using existing VLBI data







DE-422 with addition of 2012-2016 VLBA data

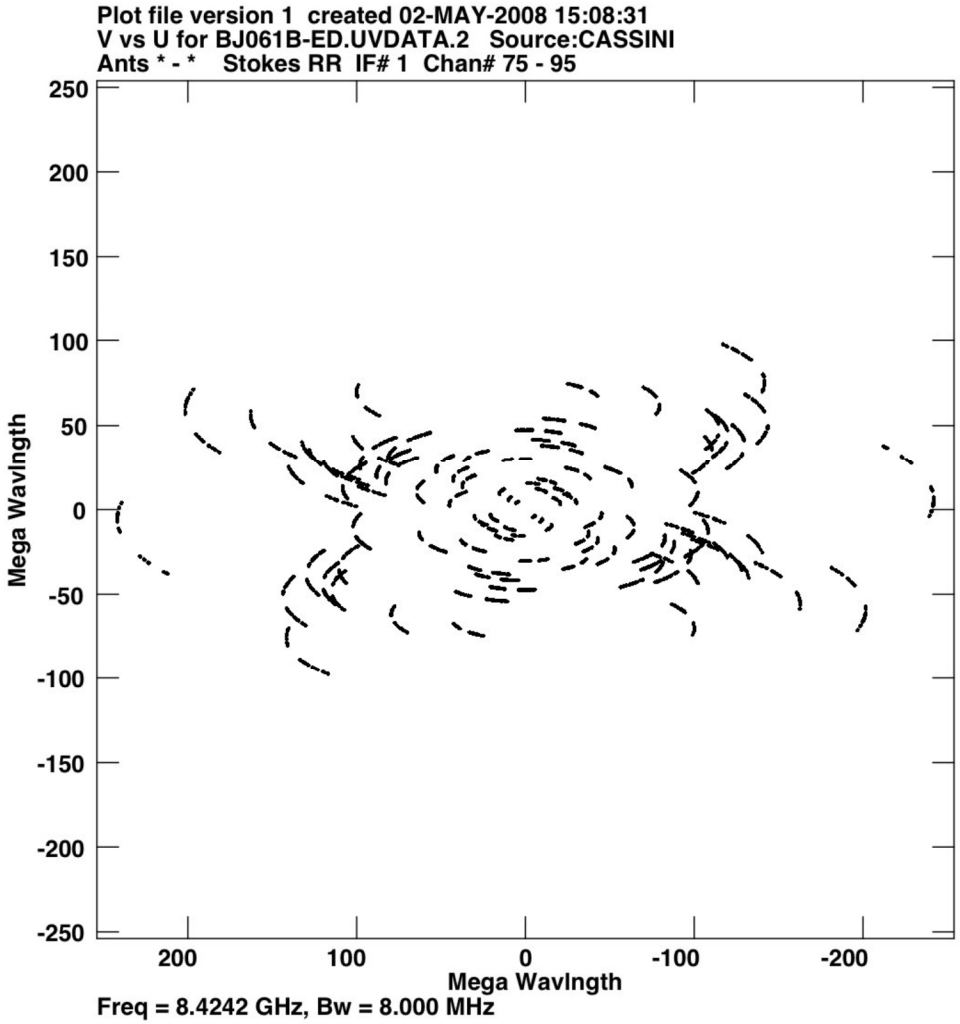
VLBA Scheduling Constraints

- Cassini needs to be transmitting high-rate telemetry to Goldstone at X-band (8.4 GHz)
- Need to avoid trajectory correction maneuvers, moon flybys, and ring occultations
- Need to avoid periods near Saturn conjunction with the Sun
- Need a reasonably strong phase reference source within 2 degrees
- Need some high accuracy ICRF sources within several degrees
- During each 4-hour epoch, multiple strong sources covering a wide range of elevations are observed for troposphere calibration
- Optimization: Because Saturn reverses its apparent motion on the sky every year, the same reference source can be used during multiple epochs. This reduces the number of phase reference sources we need to tie to the ICRF, and minimizes relative errors between epochs from structure or ICRF offset differences between separate reference sources.

U-V coverage for one VLBA epoch:

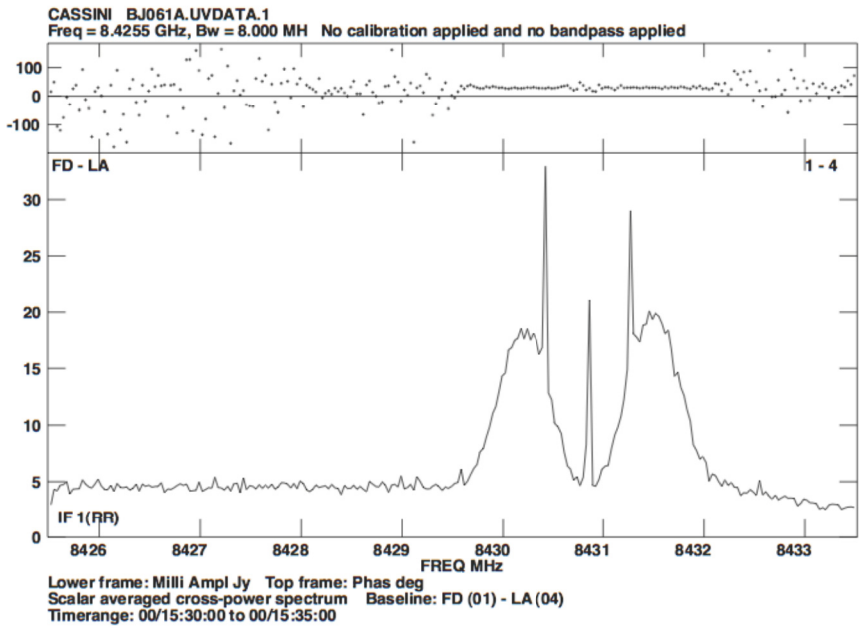
Because of Saturn's low declination, the angular resolution is typically about two times better in RA than in DEC.

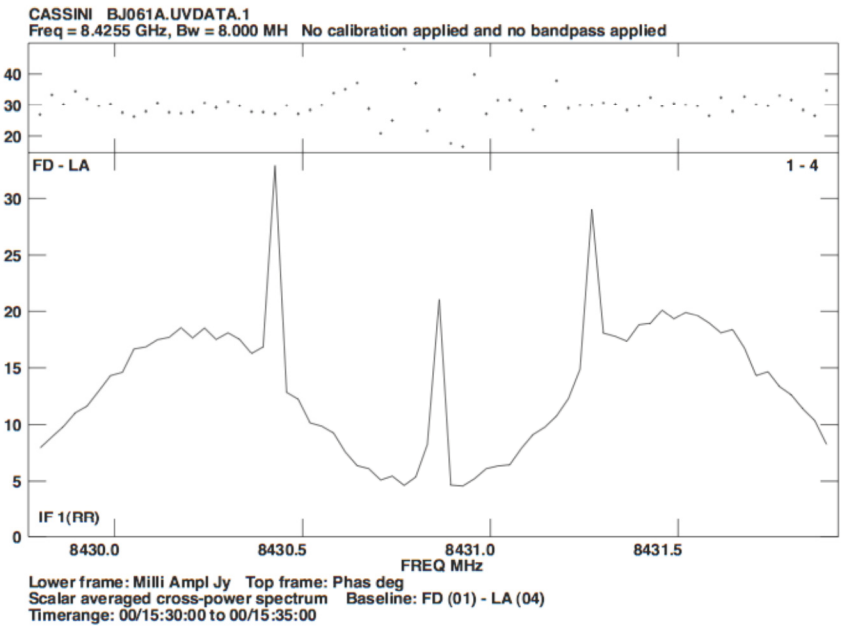
MK critical for E-W resolution, BR critical for N-S resolution.



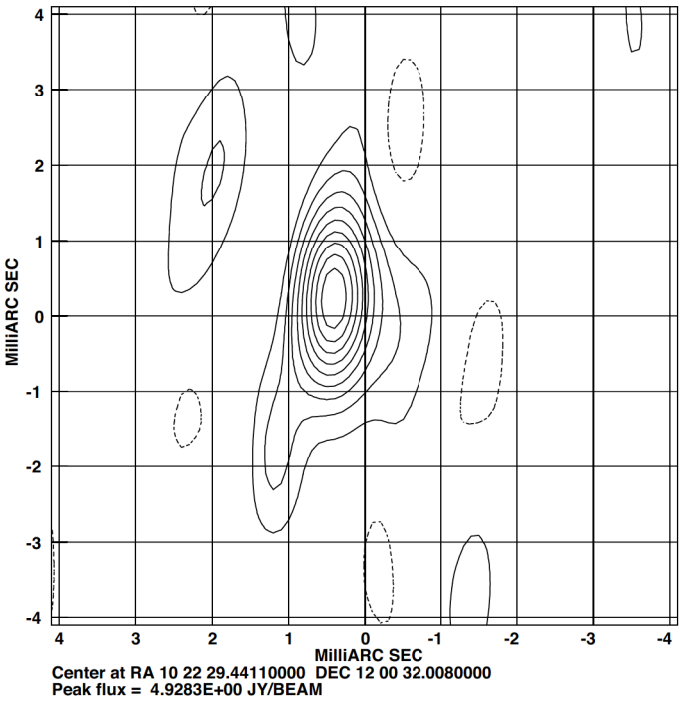
Cassini fringes from first epoch:

Cross-power spectrum shows carrier, sub-carriers, and wide sidebands from telemetry modulation. Total signal width is about 2.5 MHz at this epoch.

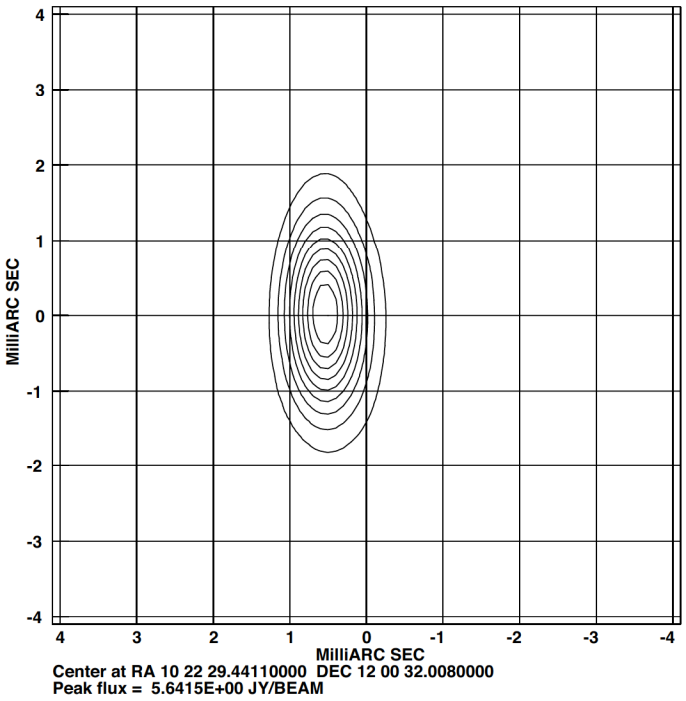




Troposphere Calibration

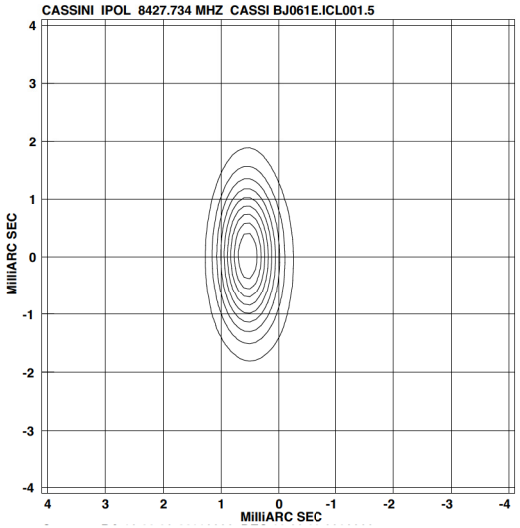


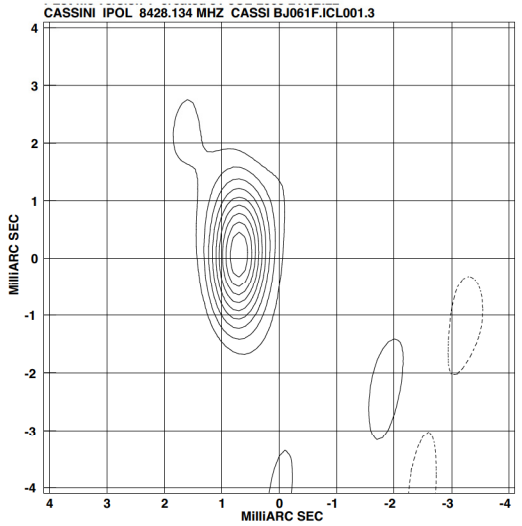
Peak flux density 4.9 Jy

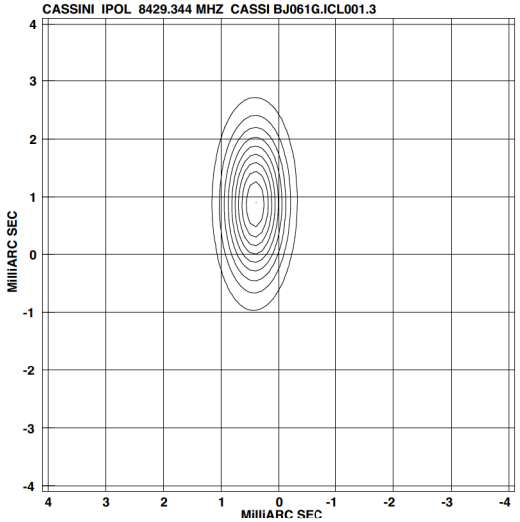


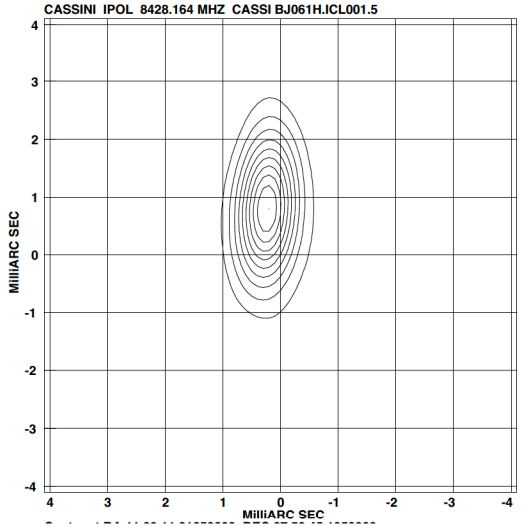
Peak flux density 5.6 Jy

Example Phase-Referenced Images

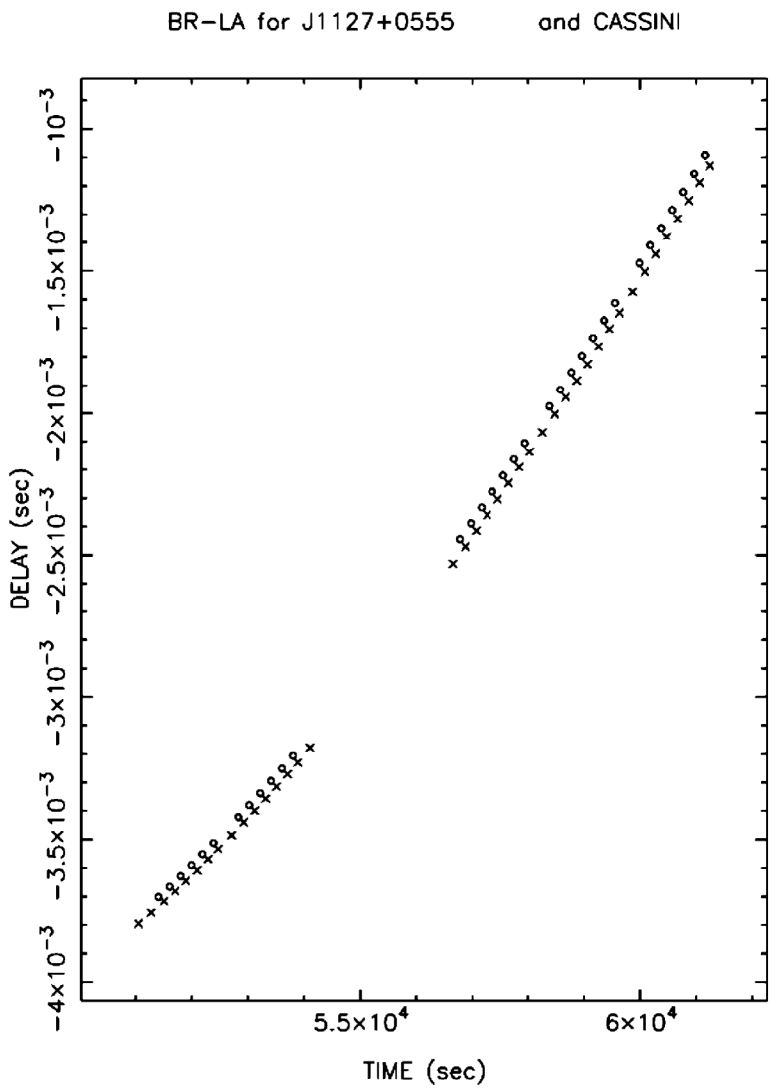


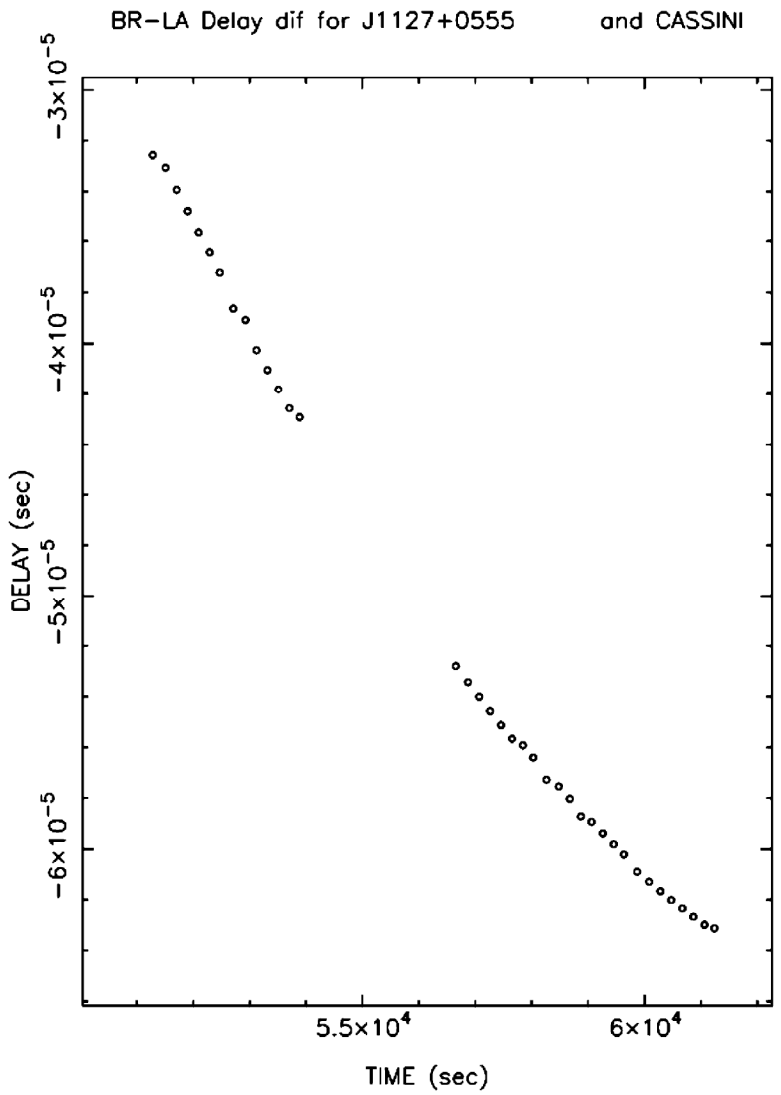




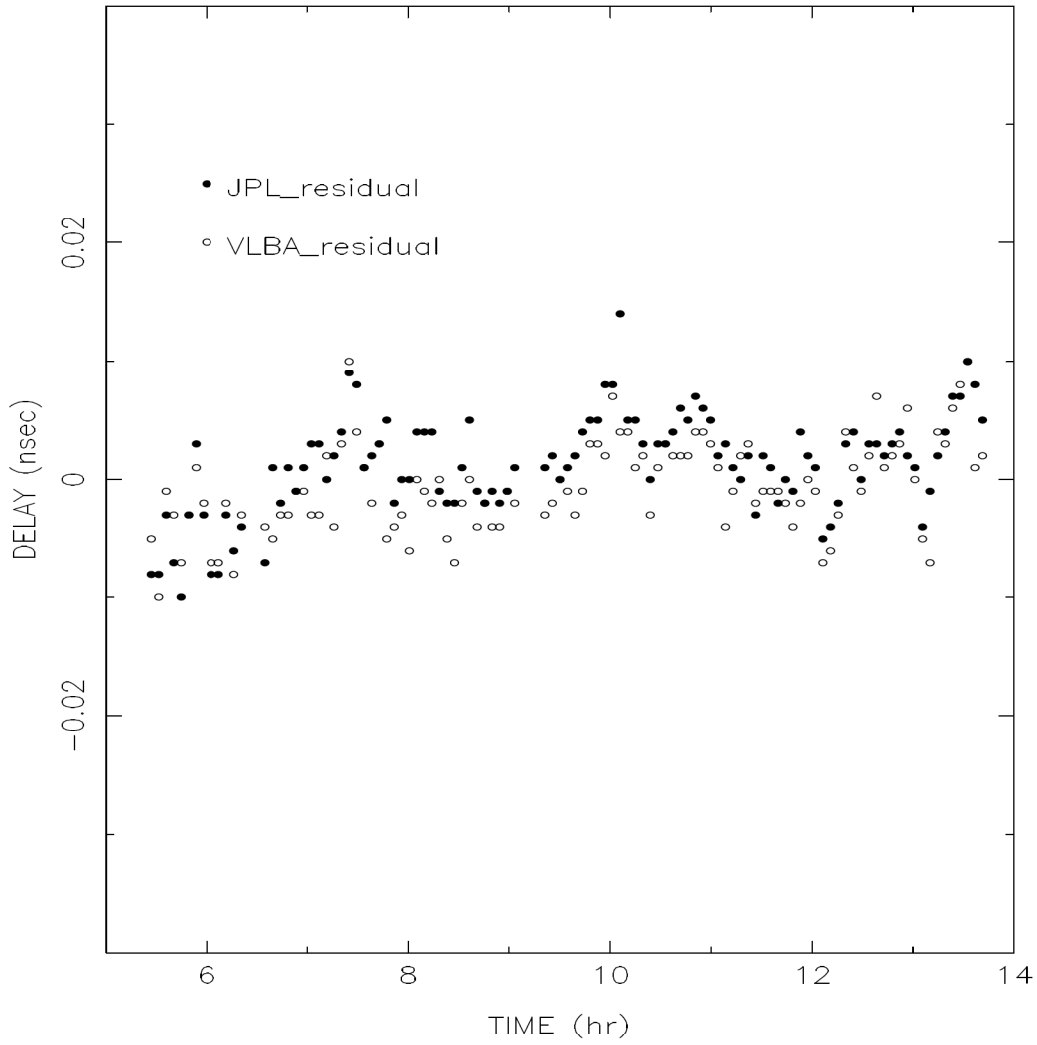


Baseline Total Delays





Comparison of Total Delays

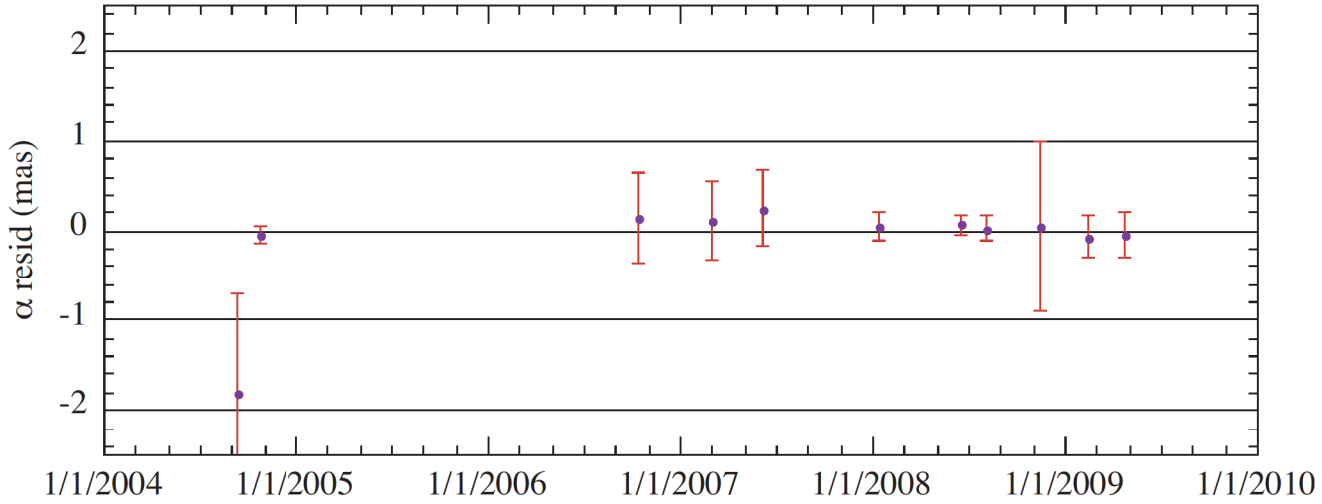


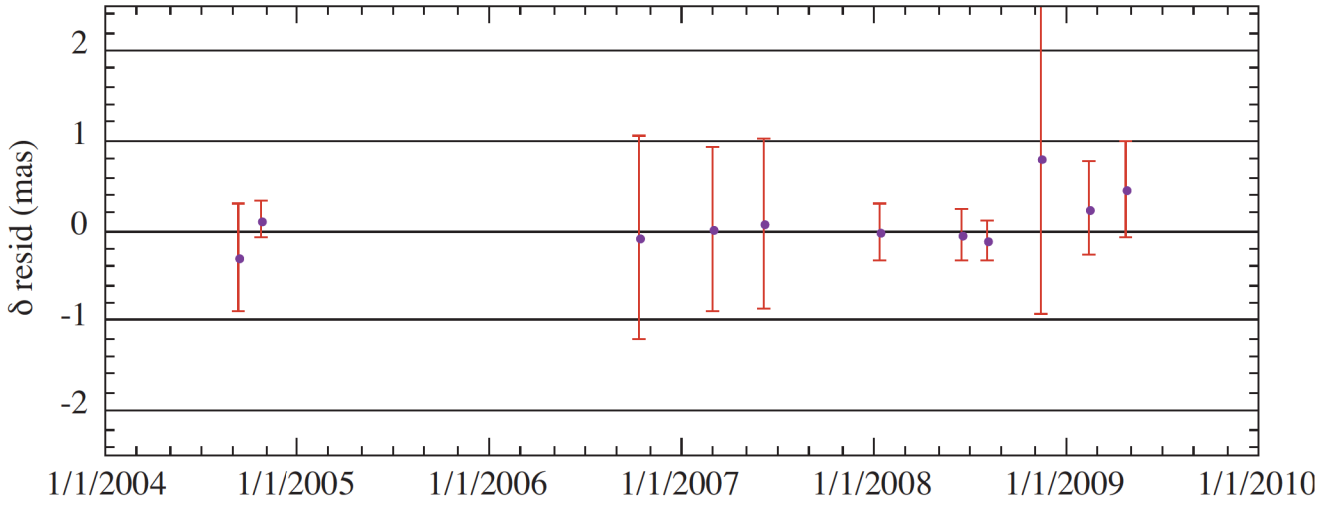
Saturn Barycentric Position Residuals

Table 2: Saturn Barycenter Position Residuals (arcsec) for DE405 and DE422 Ephemeris

Observation Date	Time (TDB)	RA offset vs. DE405	DEC offset vs. DE405	RA offset vs. DE422	DEC offset vs. DE422
2004 Sept.	18:00:00	0.1181	-0.0400	-0.0018	-0.0003
2004 Oct.	14:00:00	0.1293	-0.0442	-0.0000	0.0001
2006 Oct.	17:00:00	0.1306	-0.0451	0.0001	-0.0001
2007 March	07:00:00	0.1570	-0.0476	0.0001	0.0000
2007 June	00:00:00	0.1357	-0.0382	0.0002	0.0001
2008 Jan.	10:00:00	0.1491	-0.0479	0.0001	-0.0000
2008 June	00:00:00	0.1359	-0.0368	0.0001	-0.0001
2008 Aug.	22:00:00	0.1271	-0.0355	0.0000	-0.0001
2008 Nov.	17:00:00	0.1287	-0.0367	0.0001	0.0008
2009 Feb.	14:00:00	0.1493	-0.0409	-0.0001	0.0002
2009 April	06:00:00	0.1479	-0.0365	-0.0001	0.0005

DE-422 Saturn Position Residuals



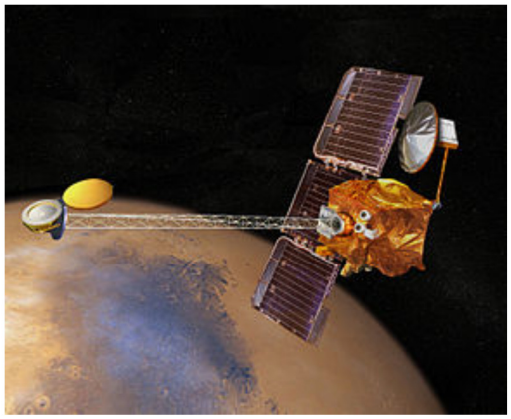


Future Work

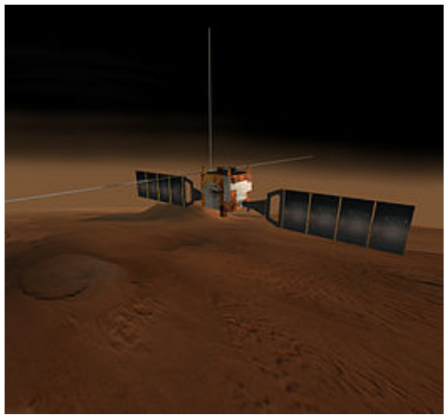
- Extension of Cassini mission to 2016 approved
- Renewal VLBA proposal for additional epochs approved
- By end of 2012 we will have high quality VLBI data from 1/4 of Saturn's orbital period
- Error is latitude decreases rapidly as data span approaches 1/4 of the orbital period
- Future work will improve ICRF tie of phase calibrators
- Future work will include astrometry of Mars orbiters
- Future opportunity: JUNO (Jupiter orbiter), scheduled to arrival at Jupiter in mid-2016

Mars Orbiters

Mars Express

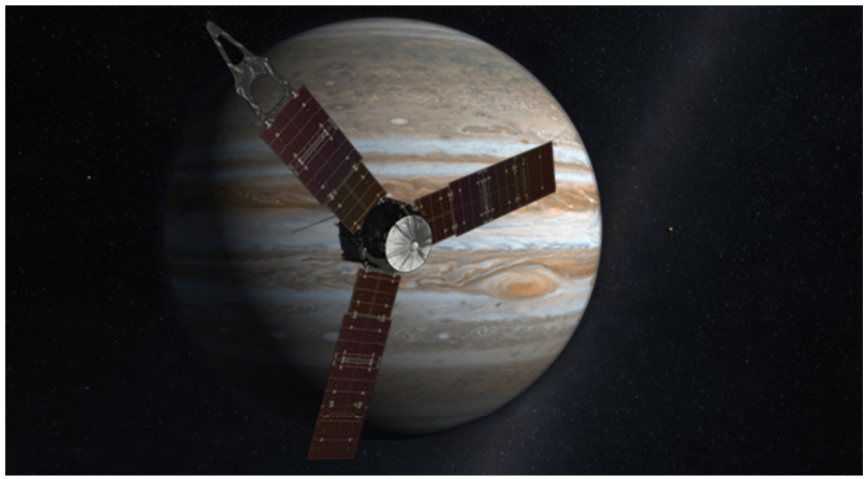


Mars Odyssey



Mars Reconnaissance Orbiter

Jupiter Orbiter

Jupiter orbit insertion in mid-2016

Juno