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 $1/(\text{ang. sep.})$
- Troposphere and position offsets are main error sources in residual phase differences at X-band
- Unmodeled troposphere error between close sources is $\sim 1$ ps, so there is no cycle ambiguity in the differential phase:
  \[ 1 \text{λ at 8.4 GHz} = 120 \text{ ps} \]
  \[ \Delta \Phi \sim (50 \text{ ps}) / \text{SNR} \]
- 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:

Note relative size of the VLBI and Doppler error bars.

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

BR-LA for J1127+0555 and CASSINI

BR-LA Delay diff for J1127+0555 and CASSINI

DELAY (sec) vs TIME (sec)
Comparison of Total Delays
### Saturn Barycentric Position Residuals

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

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>Time (TDB)</th>
<th>RA offset vs. DE405</th>
<th>DEC offset vs. DE405</th>
<th>RA offset vs. DE422</th>
<th>DEC offset vs. DE422</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Sept.</td>
<td>18:00:00</td>
<td>0.1181</td>
<td>-0.0400</td>
<td>-0.0018</td>
<td>-0.0003</td>
</tr>
<tr>
<td>2004 Oct.</td>
<td>14:00:00</td>
<td>0.1293</td>
<td>-0.0442</td>
<td>-0.0000</td>
<td>0.0001</td>
</tr>
<tr>
<td>2006 Oct.</td>
<td>17:00:00</td>
<td>0.1306</td>
<td>-0.0451</td>
<td>0.0001</td>
<td>-0.0001</td>
</tr>
<tr>
<td>2007 March</td>
<td>07:00:00</td>
<td>0.1570</td>
<td>-0.0476</td>
<td>0.0001</td>
<td>0.0000</td>
</tr>
<tr>
<td>2007 June</td>
<td>00:00:00</td>
<td>0.1357</td>
<td>-0.0382</td>
<td>0.0002</td>
<td>0.0001</td>
</tr>
<tr>
<td>2008 Jan.</td>
<td>10:00:00</td>
<td>0.1491</td>
<td>-0.0479</td>
<td>0.0001</td>
<td>-0.0000</td>
</tr>
<tr>
<td>2008 June</td>
<td>00:00:00</td>
<td>0.1359</td>
<td>-0.0368</td>
<td>0.0001</td>
<td>-0.0001</td>
</tr>
<tr>
<td>2008 Aug.</td>
<td>22:00:00</td>
<td>0.1271</td>
<td>-0.0355</td>
<td>0.0000</td>
<td>-0.0001</td>
</tr>
<tr>
<td>2008 Nov.</td>
<td>17:00:00</td>
<td>0.1287</td>
<td>-0.0367</td>
<td>0.0001</td>
<td>0.0008</td>
</tr>
<tr>
<td>2009 Feb.</td>
<td>14:00:00</td>
<td>0.1493</td>
<td>-0.0409</td>
<td>-0.0001</td>
<td>0.0002</td>
</tr>
<tr>
<td>2009 April</td>
<td>06:00:00</td>
<td>0.1479</td>
<td>-0.0365</td>
<td>-0.0001</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
DE-422 Saturn Position Residuals

- Upper graph: 
  - x-axis: Dates from 1/1/2004 to 1/1/2010
  - y-axis: Residuals in mas (maseresiduals)

- Lower graph: 
  - x-axis: Dates from 1/1/2004 to 1/1/2010
  - y-axis: Residuals in mas (maseresiduals)
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