Linking the Planetary Ephemeris to the ICRF

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Targeting Accuracy for Mars Landers

- Orientation of ephemeris to the celestial reference frame has been the limiting error source for Mars lander missions.
  - MSL required 200 m knowledge of Earth-Mars vectors (~ 0.2 mas)
  - Accuracy met through long program of spacecraft VLBI measurement with continued improvement in measurement accuracy
  - More accurate landing limited by wind speed and drift on parachute.
Spacecraft VLBI

• VLBI measures spacecraft angular position relative to radio reference frame
  • MGS, Odyssey, MRO
  • MGN, VEX, Ulysses, Cassini
• Doppler ties spacecraft position to center of planet
  • MGS, ODY, MRO accuracy <10m
• VLBI measurement types;
  • Doubly-difference range (ΔDOR)
    • DSN and ESA stations
  • Differenced carrier phase
    • Very Long Baseline Array
Baselines

Goldstone-Madrid

Goldstone-Canberra

Cebreros-New Norcia
Source Structure

- Long baselines give good measurement accuracy and high resolving power.
- Brighter sources are more likely to have observable structure, making center of source position dependent on baseline and frequency.

P. Charlot
IVS General Meeting
2002
Frequency and Media Errors

- DSN VLBI delay computed by phase differences $\Delta \phi / \Delta f$
  - Spacecraft and radio source have very different spectra
  - Narrow bandwidths about spacecraft DOR tones are sampled
  - Instrument phase response (ripple) can vary between S/C & radio source
- Signal delay due to troposphere and ionosphere is partly calibrated and partly canceled between s/c and radio source
Spacecraft Orbit Accuracy

• Spacecraft orbits generally determined by Doppler shift
• Low orbits give larger Doppler shift
  • More sensitive to gravity field and atmospheric drag
  • Better orbit accuracy after determination of gravity field
• MGS, Odyssey, MRO are low circular orbiters, with good Mars gravity field
• MEX, VEX, MGN (early mission) are elliptical orbiters
• Cassini has long orbit period

Konopliv et. al., Icarus 182, 23, 2006
Measurement Improvements

- Since 2001 VLBI measurement accuracy has been improved in stages by:
  - Observation of multiple sources near spacecraft to better cancel troposphere and ionosphere effects
  - Increased sampling bandwidth to increase radio source SNR
    - Allows use for fainter, more point-like sources
  - Digitization of signal at higher frequency IF
    - Reduces phase ripple effects
Mars VLBI Accuracy

Spacecraft VLBI Error Budget

- Quasar SNR
- Quasar Position
- Spacecraft orbit
- Spacecraft SNR
- Phase Ripple
- Clock Instability
- Station Location
- Earth Orientation
- Ionosphere
- Troposphere
- Solar Plasma
- Total

Error (mas)

2010 (mas)
2001 (mas)
Mars Spacecraft VLBI Residuals

Mars Spacecraft VLBI on Goldstone-Madrid Baseline

Mars Spacecraft VLBI on Goldstone-Canberra Baseline
Venus VLBI Measurements

- MGN and VEX measurements used telemetry harmonics
  - no DOR tones available
- VEX and early MGN orbits were elliptical so orbit accuracy also limits VLBI measurement accuracy
- Range to VEX ties Venus orbit orientation to Earth orbit and so to ICRF with more accuracy
Cassini VLBA Observations

- Cassini observed using VLBA using carrier phase rather than DOR tones
  - Measurement accuracy limited by radio source position accuracy
  - Will be improved by more observations of radio sources used

D. Jones et al., AJ 141:29, 2011
Summary

• Earth, Mars, Venus, and Saturn orbits now tied to ICRF 2.0 with accuracy of ~ 0.2 mas

• MESSENGER range will allow tie to Earth orbit & ICRF
  • Current data has only northern hemisphere periapses
    • Which limit orbit accuracy
  • Extended mission will have southern hemisphere periapses

• Juno arrival at Jupiter in July 2016
  • Will provide opportunity to perform VLBI to tie to ICRF
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