



Linking the Planetary Ephemeris to the ICRF

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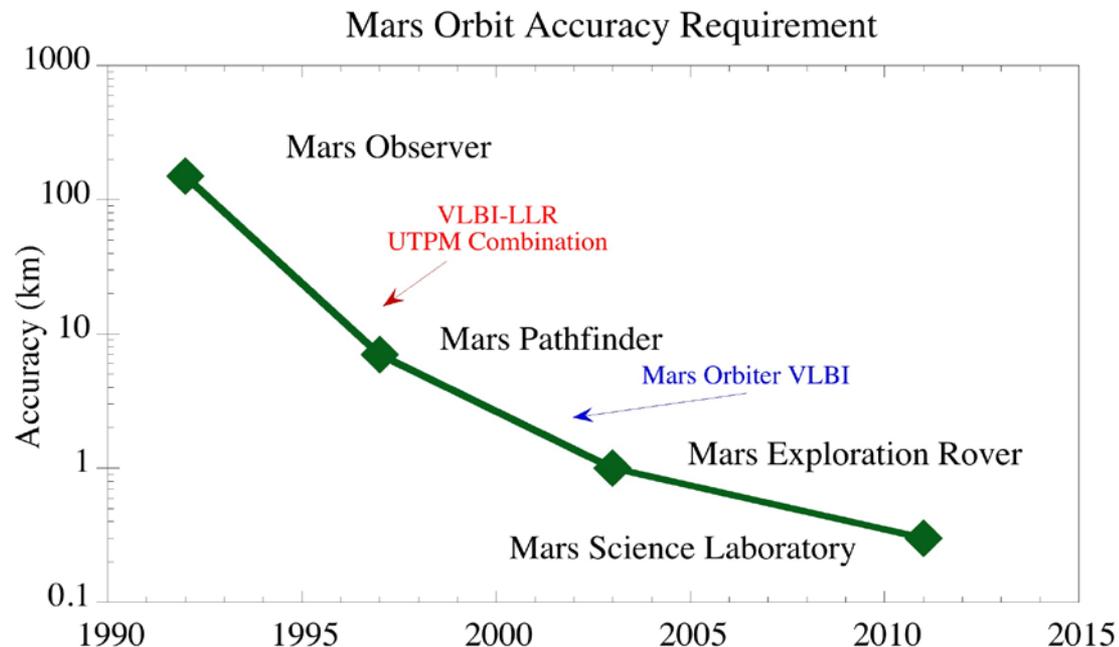
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Targeting Accuracy for Mars Landers

- 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.



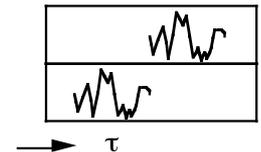


Spacecraft VLBI

- 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 (Δ DOR)
 - DSN and ESA stations
 - Differenced carrier phase
 - Very Long Baseline Array

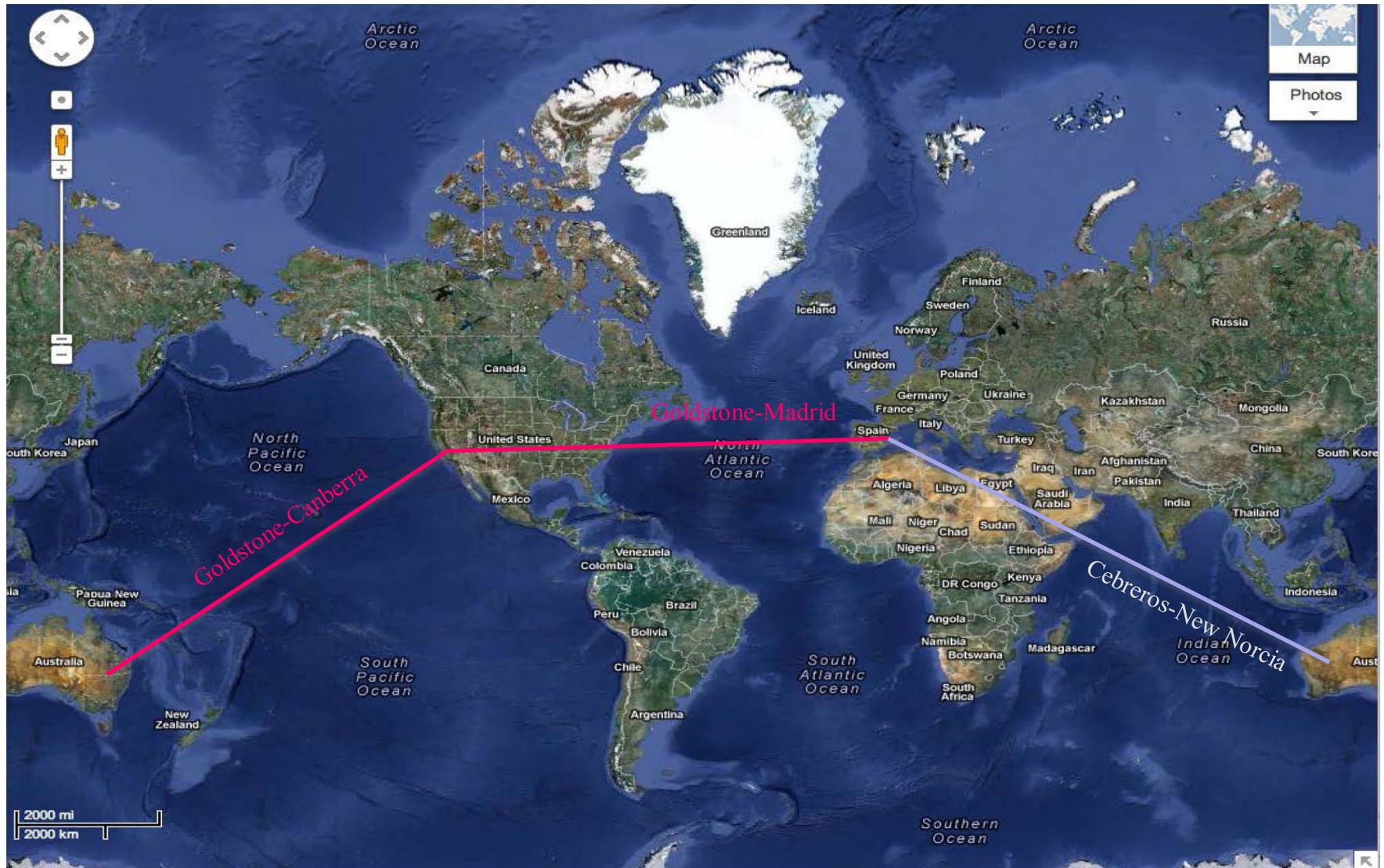


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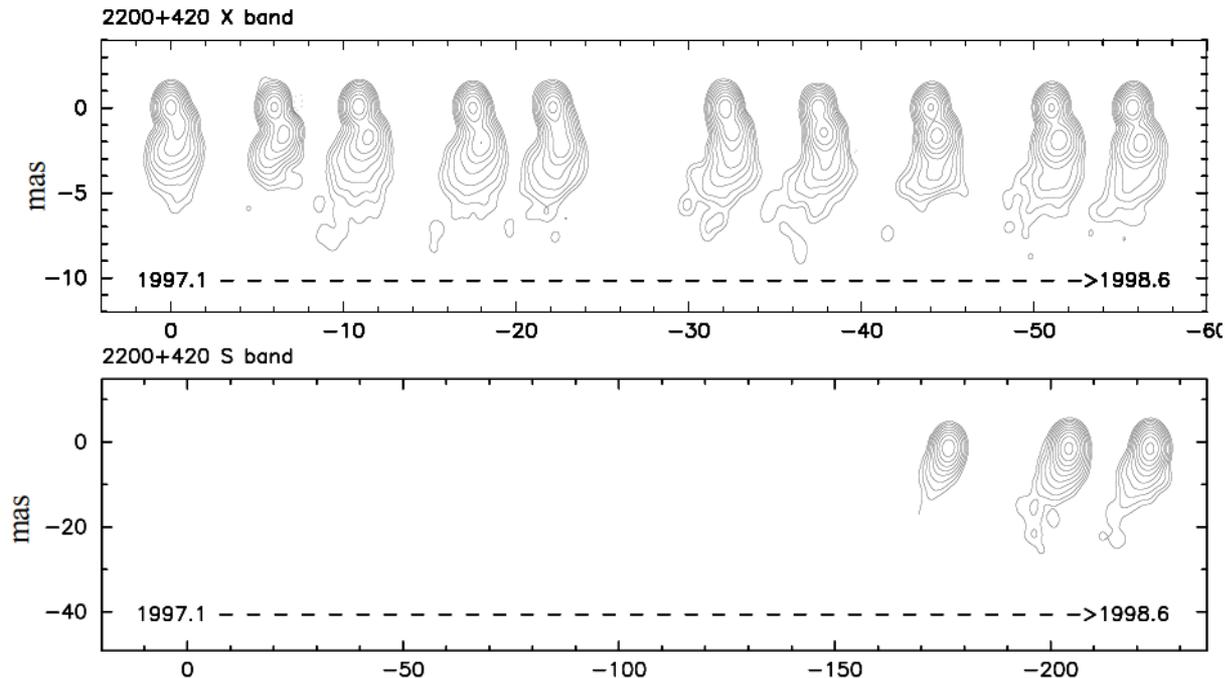
Baselines





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

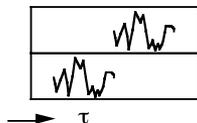
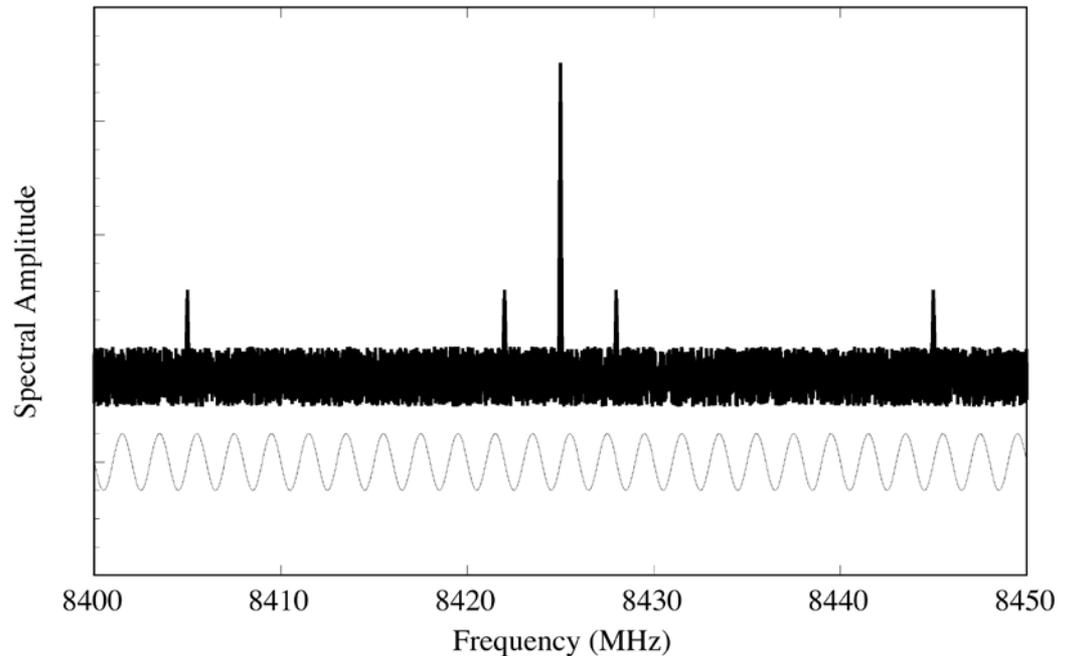


P. Charlot
IVS General Meeting
2002



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

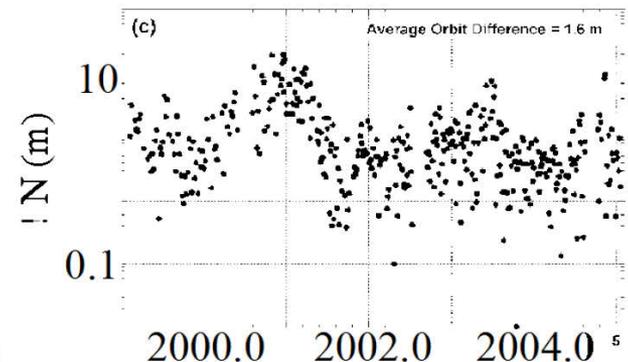
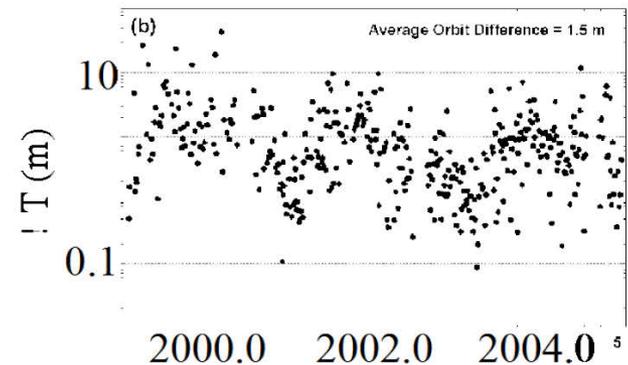
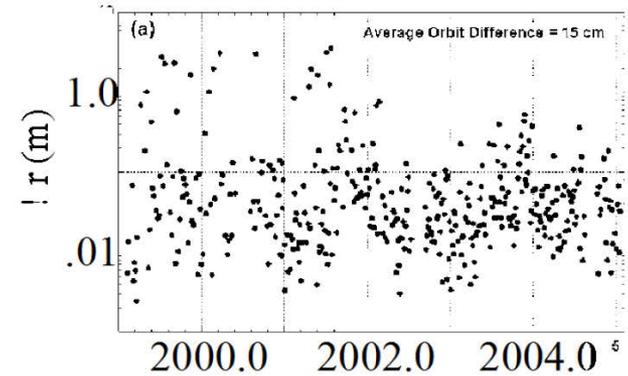


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Spacecraft Orbit Accuracy

- 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





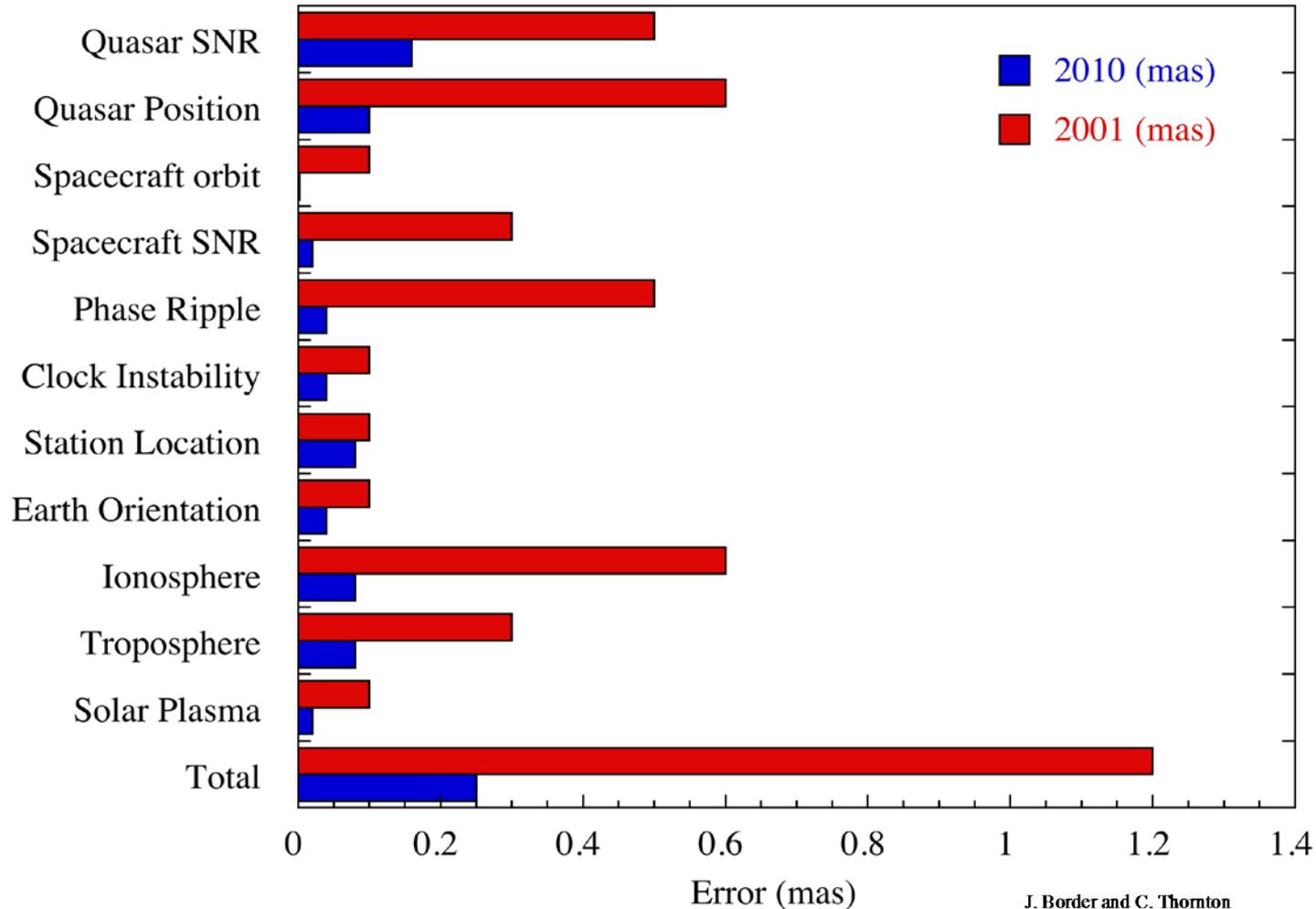
Measurement Improvements

- 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



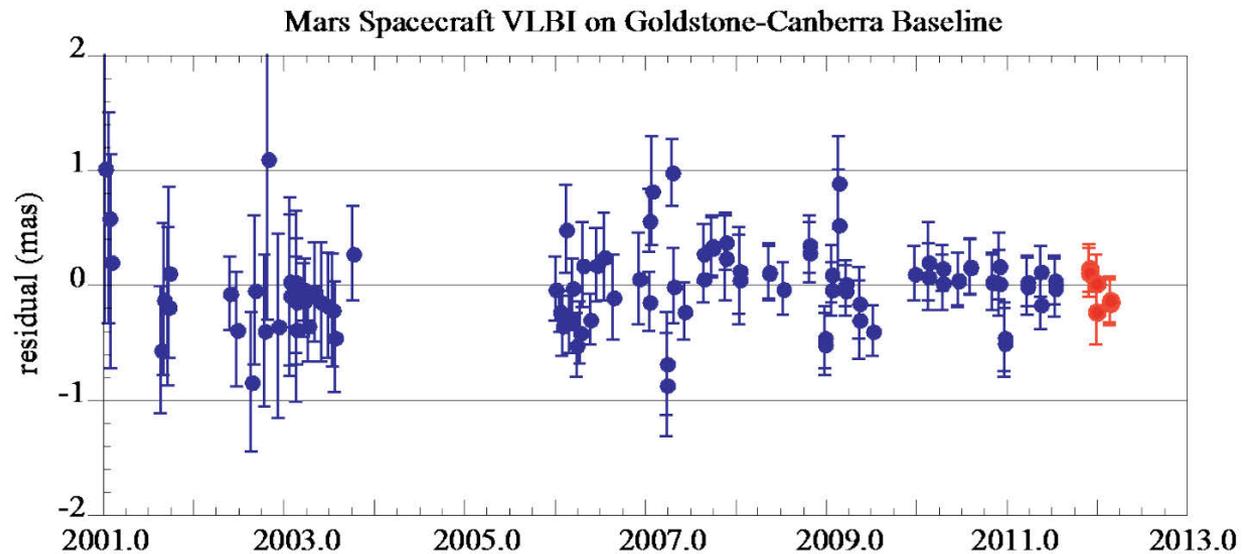
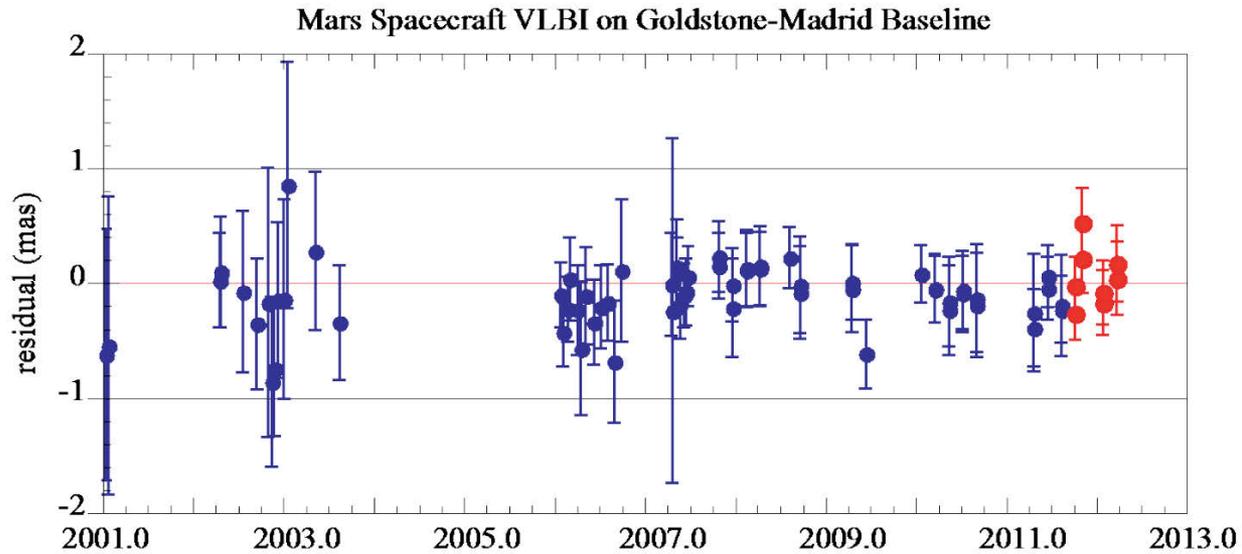
Mars VLBI Accuracy

Spacecraft VLBI Error Budget





Mars Spacecraft VLBI Residuals



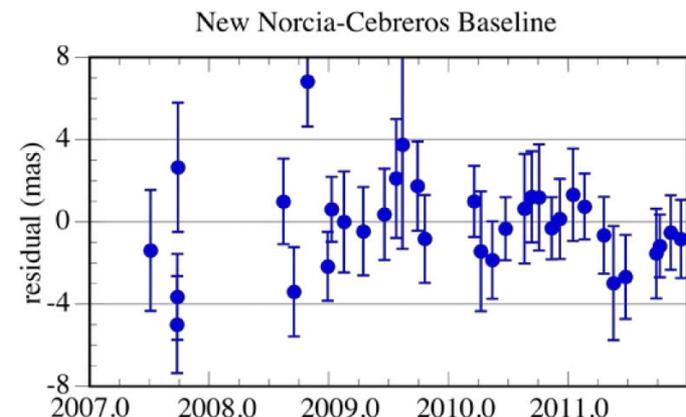
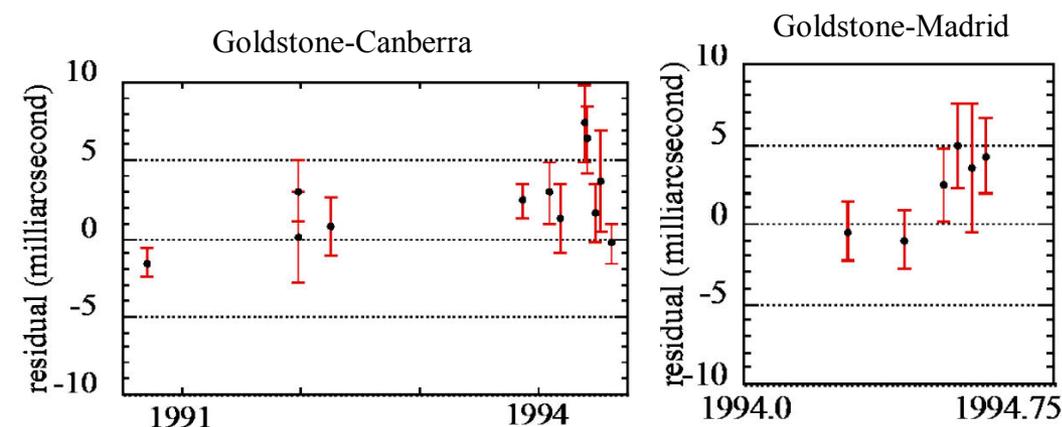


Venus VLBI Measurements

- 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

Magellan VLBI

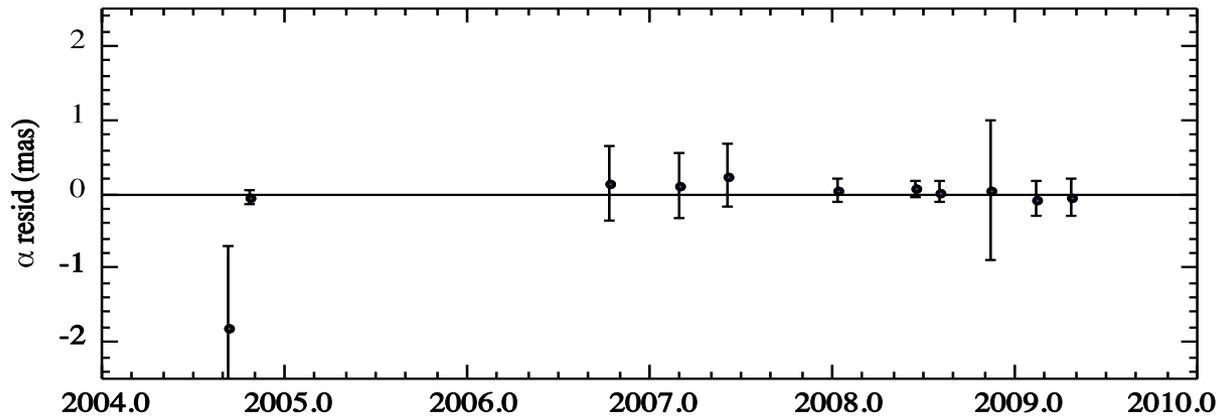
Venus Express VLBI



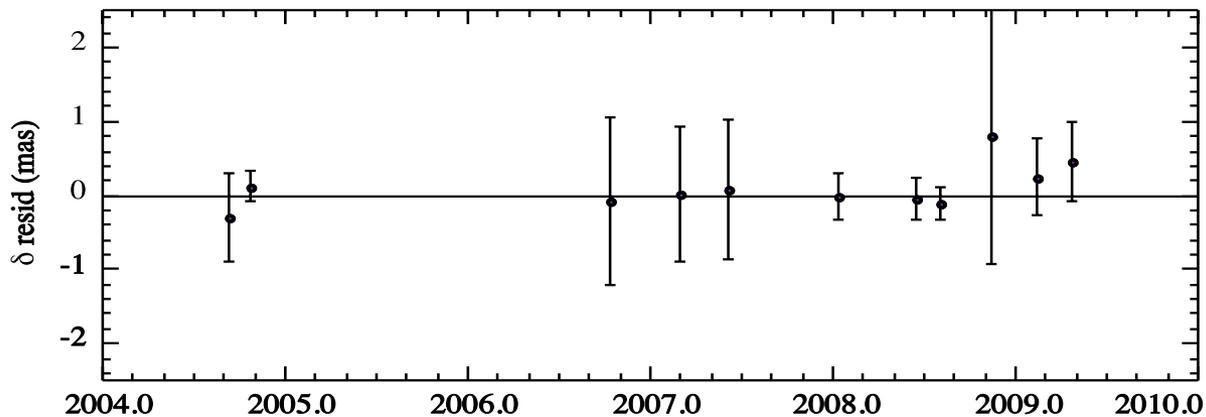


Cassini VLBA Observations

- 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



Acknowledgements

- Radio catalog - Chris Jacobs (JPL) & many others
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- Mars VLBI data - Jim Border (JPL)
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- Cassini spacecraft orbits - Bob Jacobson (JPL)