Linking the Planetary Ephemeris to the ICRF

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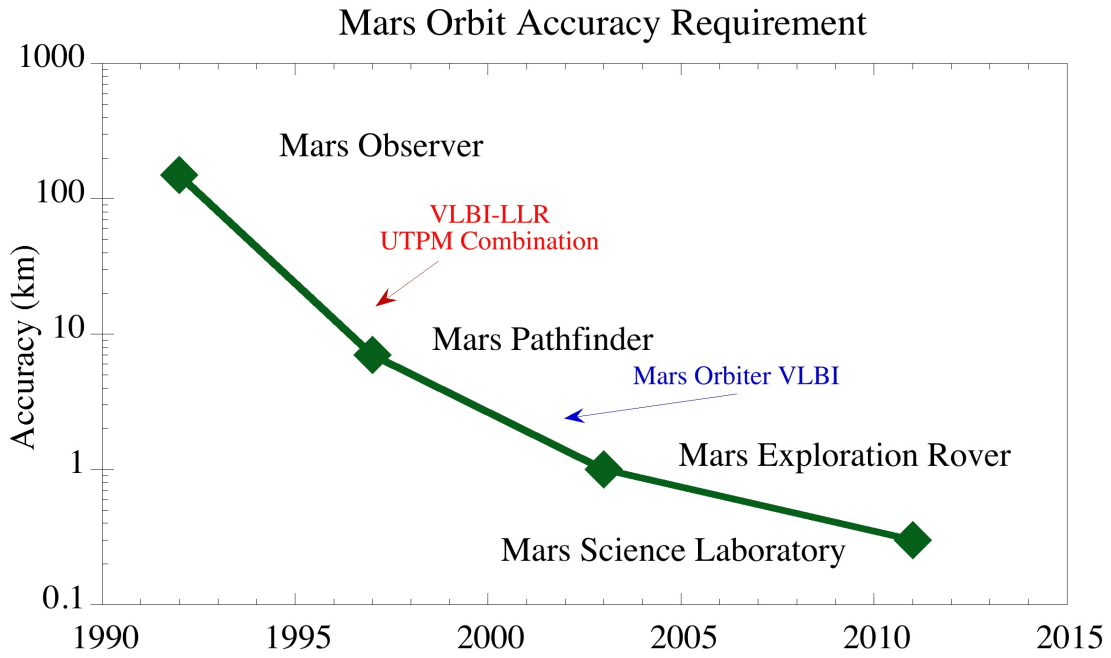
28 August 2012

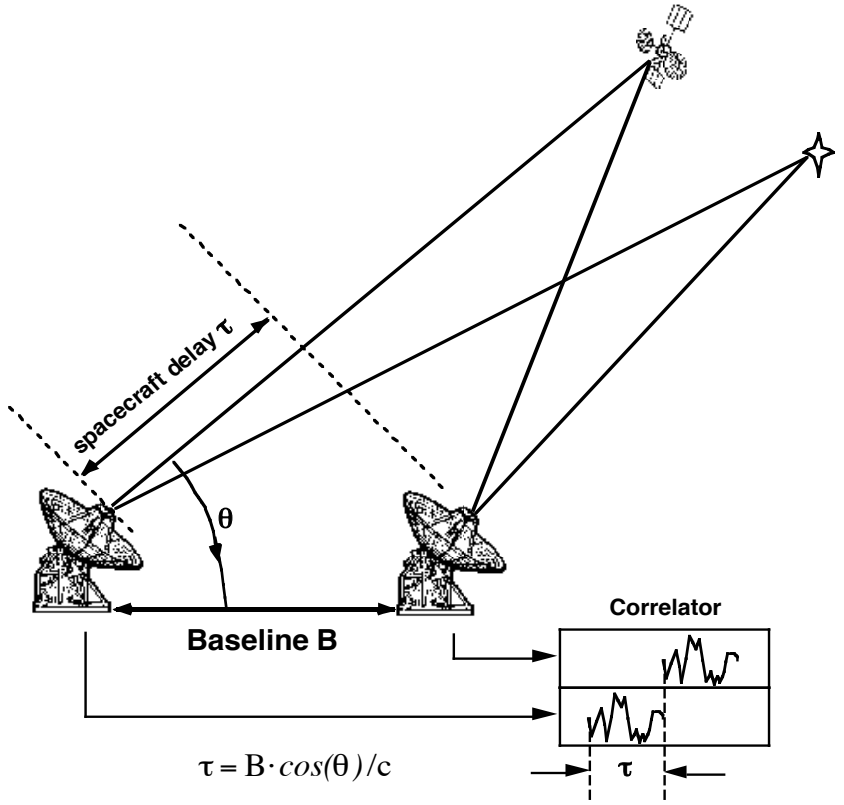
Targeting Accuracy for Mars Landers

- 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.

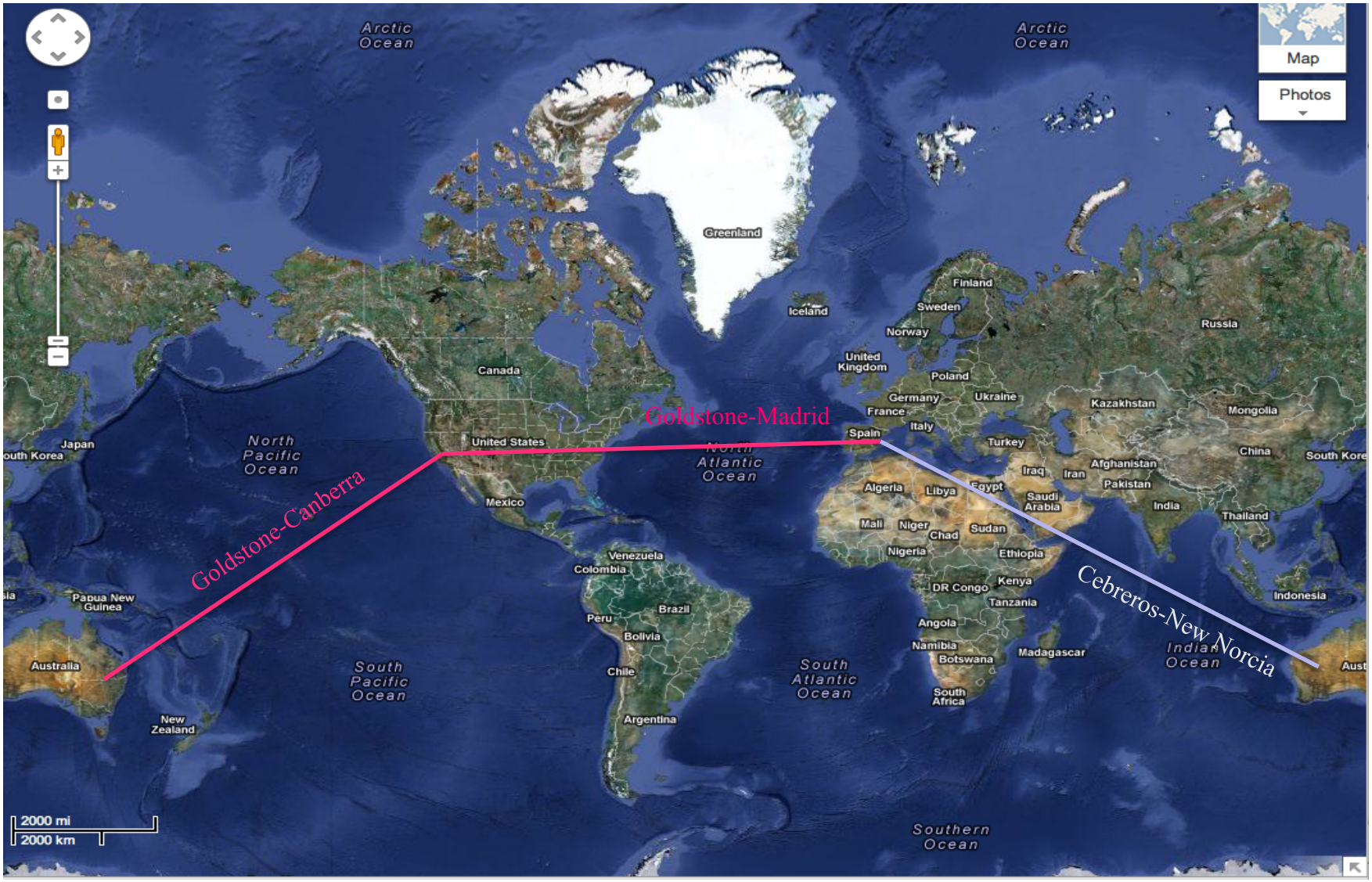


Spacecraft VLBI

- 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

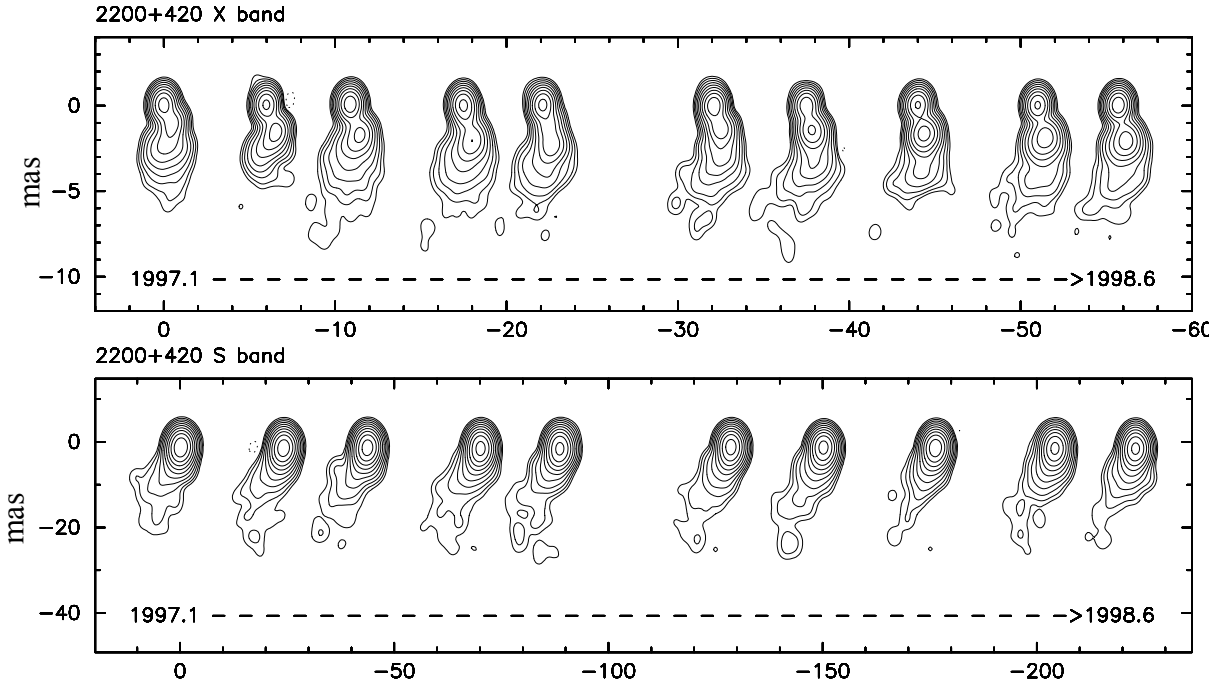


Baselines


Goldstone-Madrid
Goldstone-Canberra
Cebreros-New Norcia
Arctic Ocean
Arctic Ocean
Greenland
Iceland
Finland
Sweden
Norway
Russia
United Kingdom
Poland
Germany
Ukraine
Kazakhstan
Mongolia
France
Italy
Spain
Turkey
China
South Korea
Japan
South Korea
Canada
United States
North Pacific Ocean
North Atlantic Ocean
Mexico
Algeria
Libya
Egypt
Iraq
Iran
Afghanistan
Pakistan
Saudi Arabia
India
Thailand
Mali
Niger
Chad
Sudan
Nigeria
Ethiopia
Kenya
DR Congo
Tanzania
Indonesia
Venezuela
Colombia
Papua New Guinea
Brazil
Peru
Bolivia
Angola
Namibia
Botswana
Madagascar
Australia
Chile
South Pacific Ocean
South Atlantic Ocean
Indian Ocean
South Africa
New Zealand
Argentina
Southern Ocean
2000 mi
2000 km
Map
Photos

Source Structure

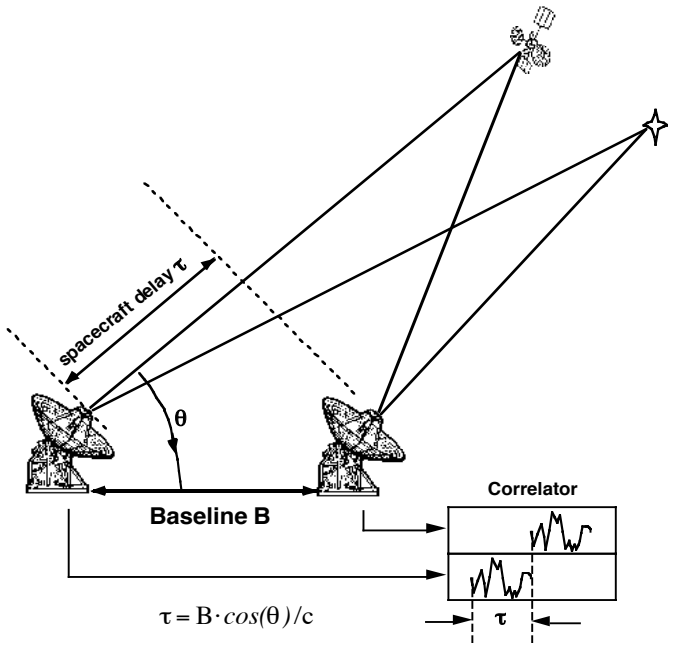
- Long baselines give good measurement accuracy and high resolving power
- Brighter sources are more likely to have observable structure, making center of source position dependent on baseline and frequency

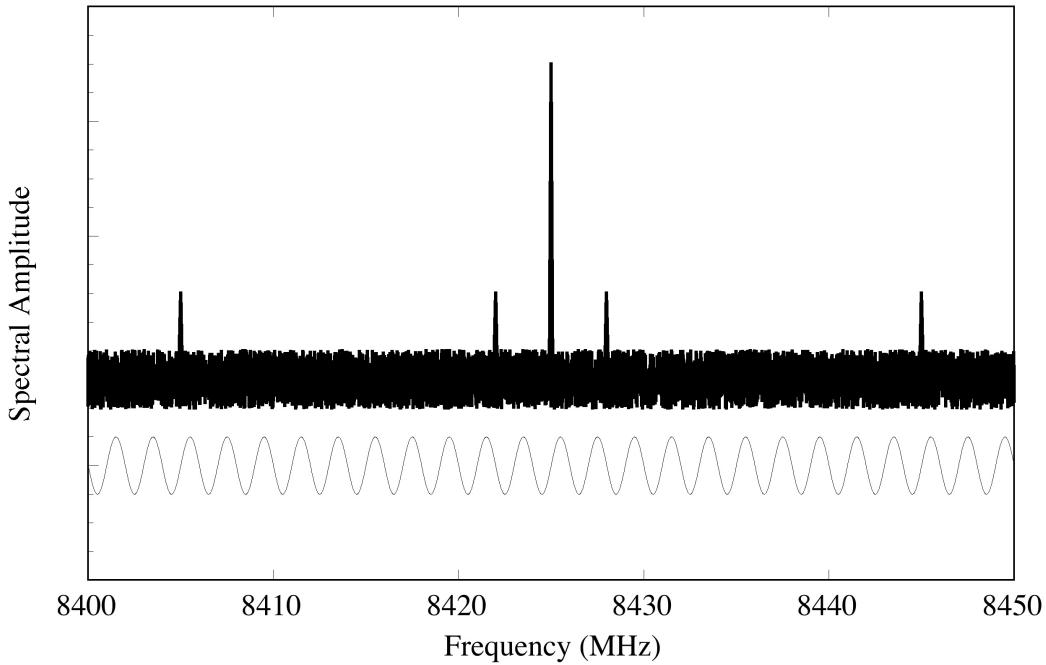


P. Charlot
IVS General Meeting
2002

Frequency and Media Errors

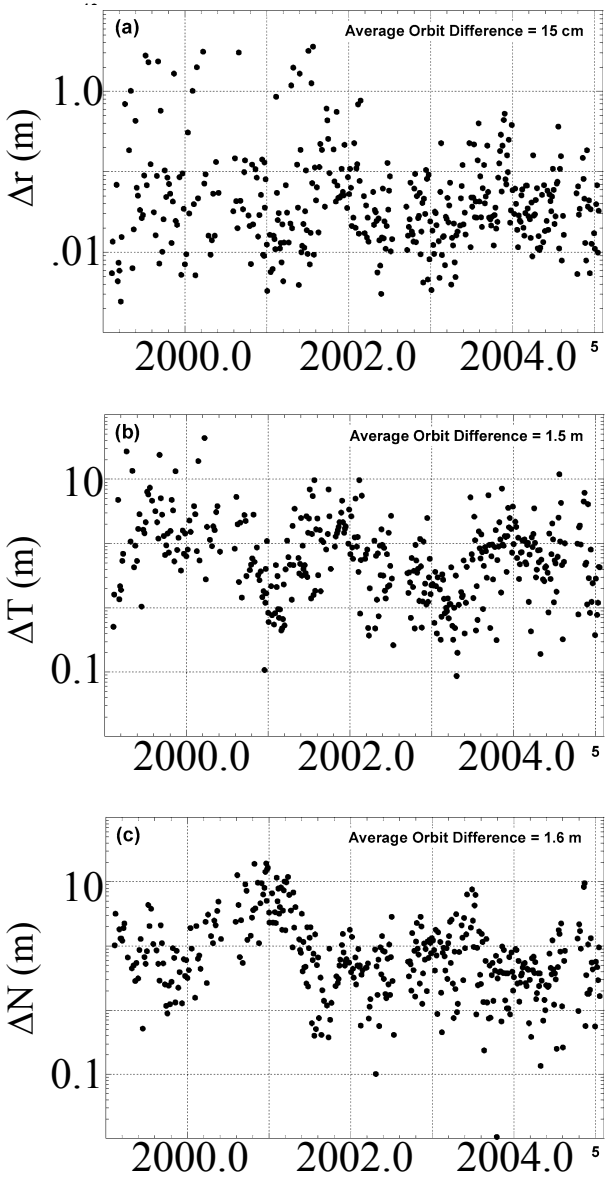
- DSN VLBI delay computed by phase differences $\Delta\phi/\Delta f$
  - Spacecraft and radio source have very different spectra
  - Narrow bandwidths about spacecraft DOR tones are sampled
  - Instrument phase response (ripple) can vary between S/C & radio source
- Signal delay due to troposphere and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



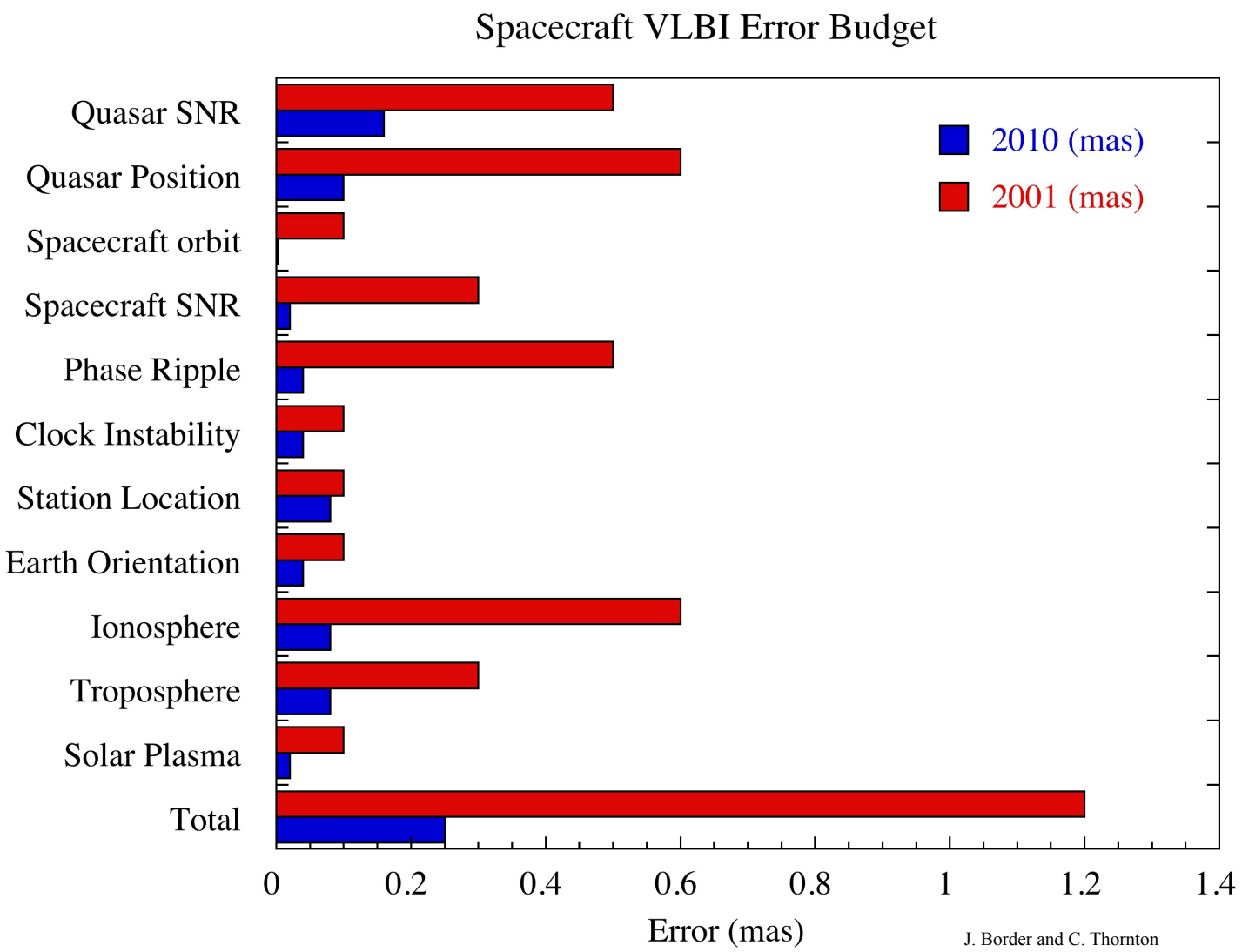
Konopliv et. al., Icarus 182, 23, 2006

Measurement Improvements

- Since 2001 VLBI measurement accuracy has been improved in stages by:

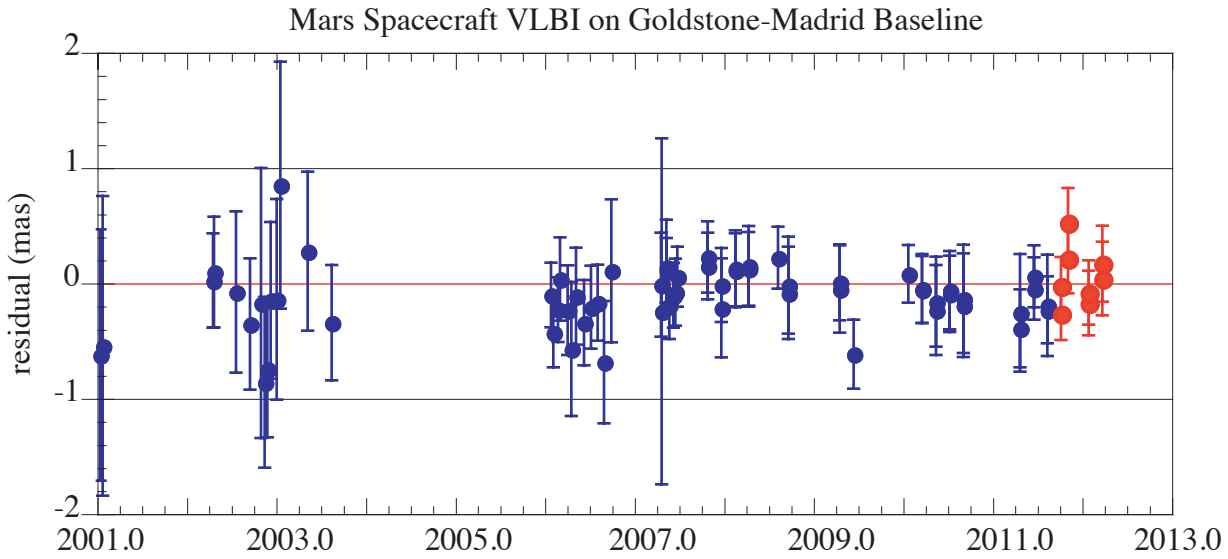
- Observation of multiple sources near spacecraft to better cancel troposphere and ionosphere effects
- Increased sampling bandwidth to increase radio source SNR
  - Allows use for fainter, more point-like sources
- Digitization of signal at higher frequency IF
  - Reduces phase ripple effects

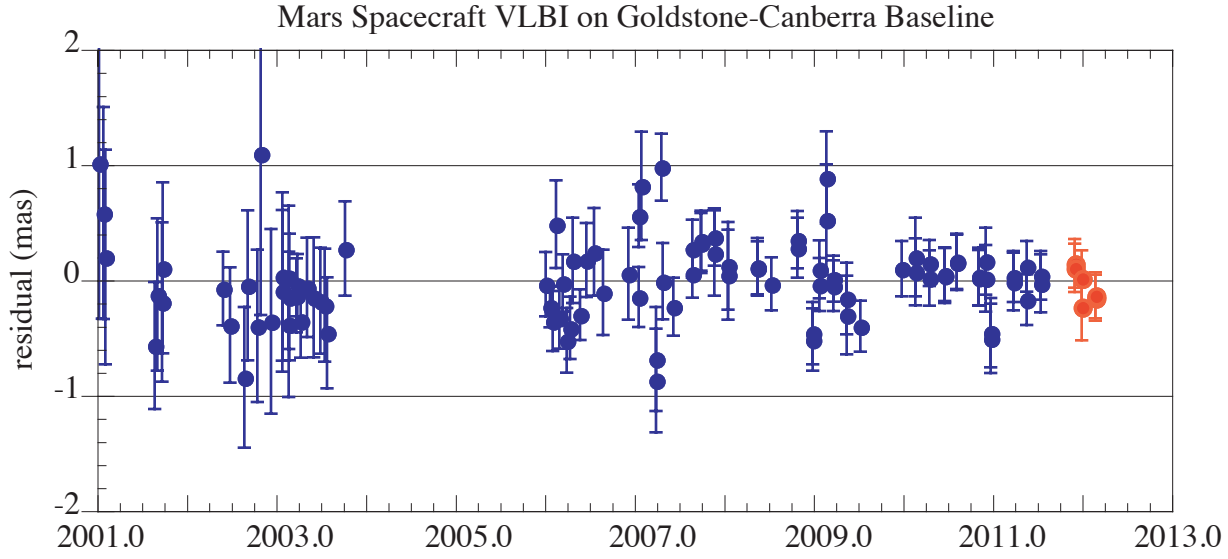
Mars VLBI Accuracy



J. Border and C. Thornton
Radiometric Tracking Techniques for Deep-Space Navigation 2000
descanso.jpl.nasa.gov/Monograph/series1/Descanso1_all.pdf

Mars Spacecraft VLBI Residuals

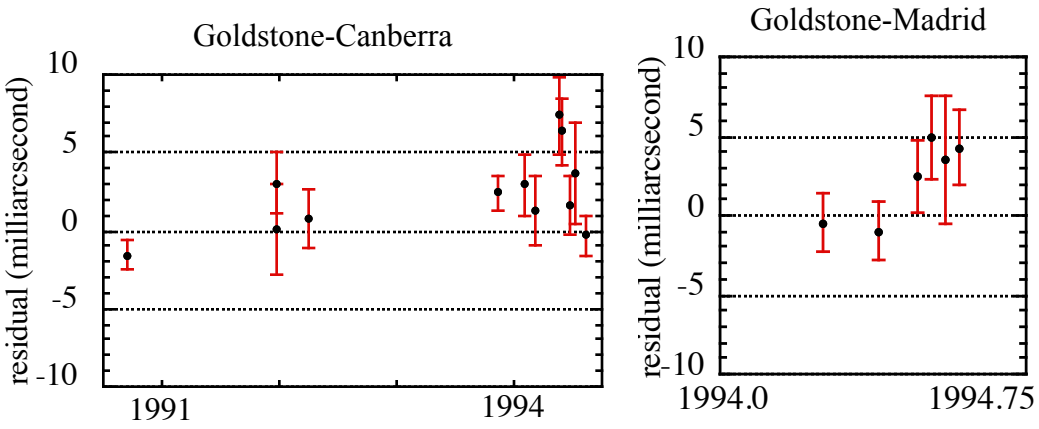




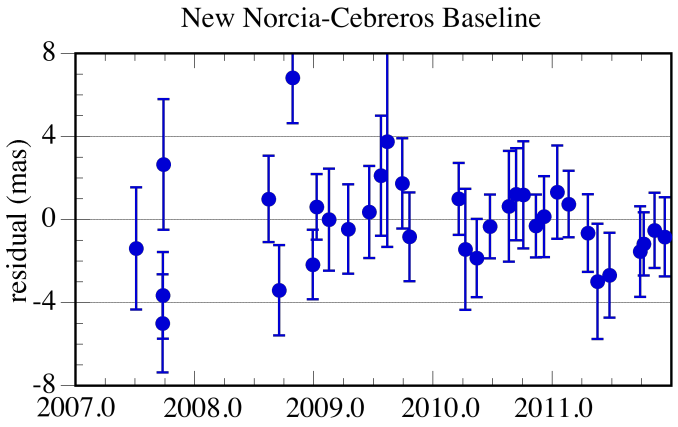
Venus VLBI Measurements

- 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

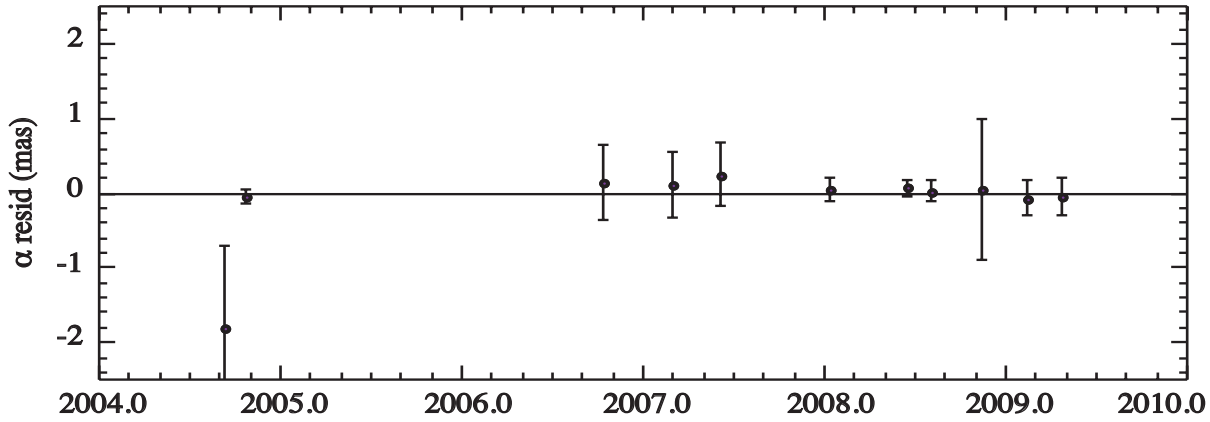


Venus Express VLBI

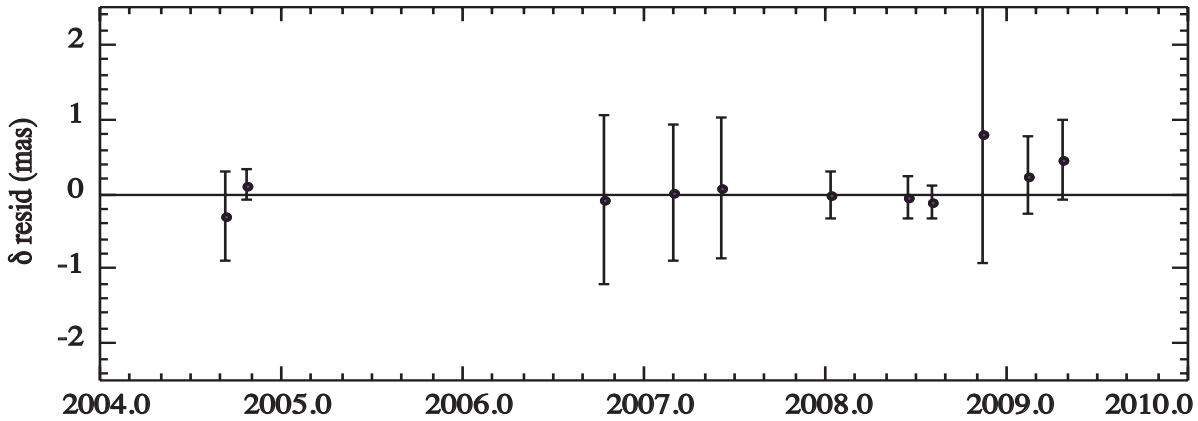


Cassini VLBA Observations

- 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
- Venus Express - Trevor Morley (ESOC)
- Mars VLBI data - Jim Border (JPL)
- Mars spacecraft orbits - Alex Konopliv (JPL)
- Cassini VLBA data - Dayton Jones (JPL), Ed Fomalont (NRAO)
- Cassini spacecraft orbits - Bob Jacobson (JPL)