Phobos flyby observed with EVN and global VLBI

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Why VLBI observations of Spacecraft?

Planetary Radio Interferometry and Doppler Experiment (PRIDE) is able to provide highly accurate estimates of the state vectors for the orbiters and landers by means of Very Long Baseline Interferometry.

By determining spacecraft state vectors we are given the ability to study a wide variety of phenomena:

- Wind on other planets or moons
- Internal structure and composition
- Atmosphere dynamics → ESA’s VEX drag
- Improve ephemeris of moons → JUICE!
- Interplanetary Scintillation
- General relativity experiments

A windy day on Titan!
Near-field delay model

Solar system barycenter

Spacecraft

Calibrator source

Nth gravitating body

Receiver 1

LT1

Receiver 2

LT2

B

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Near-field delay model

- Terrestrial to Celestial RF transformation of station positions (IERS Conventions 2010)
- Station displacements due to,
  - Geophysical effects (plate tectonics, ocean loading, solid Earth tides, pole tide, atmospheric loading)
  - Instrumental effects (thermal and gravitational deformations of telescopes)
- Signal delays due to GR and propagation effects
- Lorentz transformation
  Geocentric RF <-> Barycentric RF

Propagation effects:
Ionosphere
IGS Total Electron Content Maps
- Provide vertical TECs on a global grid
- Single thin layer model
  Single thin ionospheric layer with a TEC depending on geographic coordinates and time.

Troposphere
- Empirical models (VMF1, Niell)
- Ray-tracing through NWM data
  Tropospheric delays

Duev et al 2012
Imaging and uv-coverage for near-field VLBI

Traditional «uv»-projections of baselines

Elements of the Jacobian for the near-field VLBI case

Derivatives of differential delays with respect to the geocentric spherical coordinates of the source

\[
J_{ij} |_t = \begin{pmatrix}
\frac{\partial(\tau_1 - \tau_2)}{\partial \phi} & \frac{\partial(\tau_1 - \tau_2)}{\partial \theta} \\
\vdots & \vdots \\
\frac{\partial(\tau_1 - \tau_N)}{\partial \phi} & \frac{\partial(\tau_1 - \tau_N)}{\partial \theta} \\
\end{pmatrix}
\]

Near filed UV’s can differ from classic UV’s by hundreds of meters

Measurement Equation

\[
\Delta \phi |_t = (J_{ij} \cdot \Delta \alpha) |_t
\]

Differential phases and Vector corrections

To get corrections to the S/C a priori lateral position, solve measurement equation for \(\Delta \alpha\)
Data analysis pipeline

General overview

Signal processing

- Topocentric Doppler detections
- Clock search
- Spectrum compression and filtration in lag domain
- Spectrum masking in frequency domain
- Correlation at high spectral resolution
- Doppler phase correction
- Doppler detections, reduced to Geocentre
- Imaging, astrometric solution using phase delays
- Phase vs group delay fit to solve for time ambiguity
- Phase unwrapping
- Fringe fitting, calibration
- Dynamical modelling of MEX motion
- Scientific applications
- Astrometric solution
- Post-processing
- SFXC broadband processing
- Calibrator data
- SCTrack/WSpec/PLL narrowband processing
- Spacecraft data

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Data analysis pipeline

Signal processing:

Doppler detections to geocenter

Doppler phase corrections for Hh-Ww baseline

Without phase correction

With phase correction

Zoom into the carrier line – 10 sec integration time – Single scan

Spectrum masking

Spectrum compression and filtration
ESA’s Mars Express Phobos fly-by

28 – 29 December 2013
Closest flyby of MEX 45km

~26 hours of continuous observation time
3 consecutive Mars revolutions
7 hours long

Goal: High precision positional and Doppler measurements

- Study of the Interior of Phobos
- Improving models on the origin of the Mars system
- Ephemerides

This talk focuses on the technical aspect of the experiment

In preparation for ESA’s flagship mission JUICE
ESA’s Mars Express Phobos fly-by

VLBI phase-referencing
- Primary: J1232-0224 (0.717 Jy @ X-band)
- Secondary: J1243-0218 (85 mJy)
- 2min scans

Standard VLBI recording equipment
- Mark5 data acquisition system, mixed bandwidth setup:
  - 8x16 MHz most of the VLBI stations
  - 4x16MHz Wz and VLBA
  - 4x16 MHz S/X for Doppler stations

Standard VLBI data reduction
- AIPS

Too many scans → Parseltongue!
MEX Phobos flyby
Doppler results

Doppler detection noise, 10 s integration:
- mean value 2.5 mHz
- median value 2.2 mHz
- mod (maximum log-normal fit) value 1.7 mHz $\rightarrow$ 30 $\mu$m/s

Credits: ESA (for Mars, Phobos and MEX)
Spacecraft astrometry

Median 3σ formal error for the full range are:

RA 34 μas → 35 m
Dec 58 μas → 60 m

Displacements between measured and predicted MEX celestial position
2 min per point
Conclusions

Planetary Radio Interferometry and Doppler Experiment - PRIDE - has proven to be beneficial for a wide range of scientific applications.

Near-field model for VLBI
Addition to JIVE SFXC correlator
   Spectral masking and compression

We have observed the ESA's MEX spacecraft flying by Phobos using 30+ radio telescopes for 26 hours.

   Radial Doppler precision: 30 μm/s
   Lateral position precision: ~50 m

Improving ephemeris of Mars system
Helping to constrain dynamical models of Mars system
Geophysical parameters to understand the nature of Phobos

The experiment helped to improve our pipeline for VLBI observations of spacecraft. In preparation for ESA's flagship mission JUice ICy moons Explorer (JUICE).


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