JIVE
Joint Institute for VLBI ERIC

ASTRON

Phobos flyby observed with EVN and global VLBI

Giuseppe Cimò

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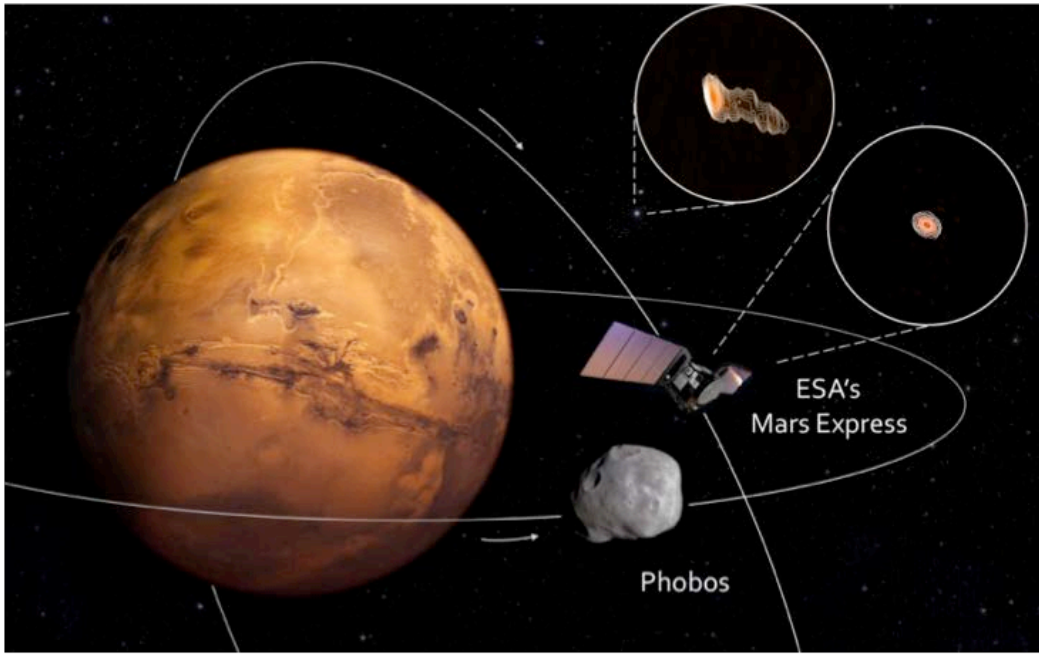
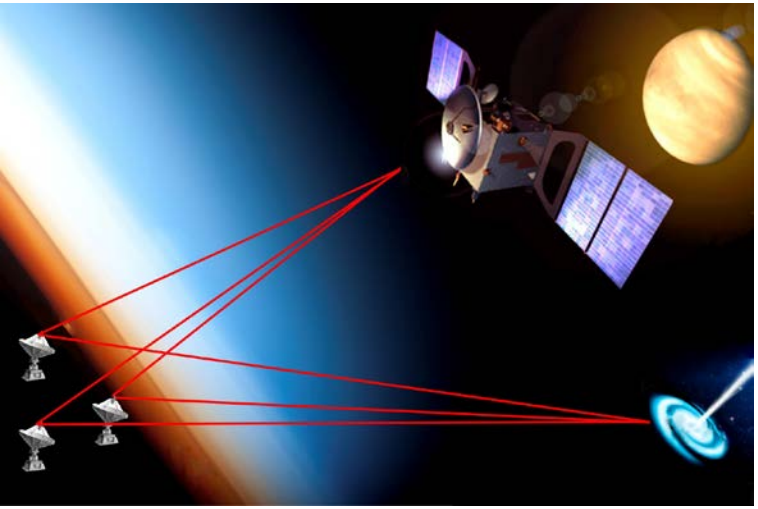
for the PRIDE collaboration



Why VLBI observations of Spacecraft ?

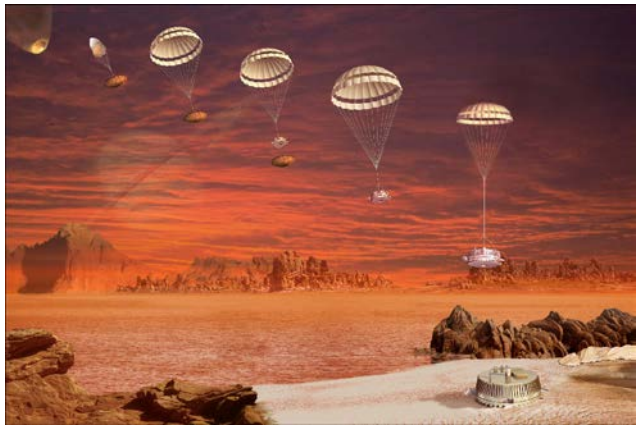


Planetary Radio Interferometry and Doppler Experiment (PRIDE) is able to provide highly accurate estimates of the state vectors for the orbiters and landers by means of Very Long Baseline Interferometry.

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

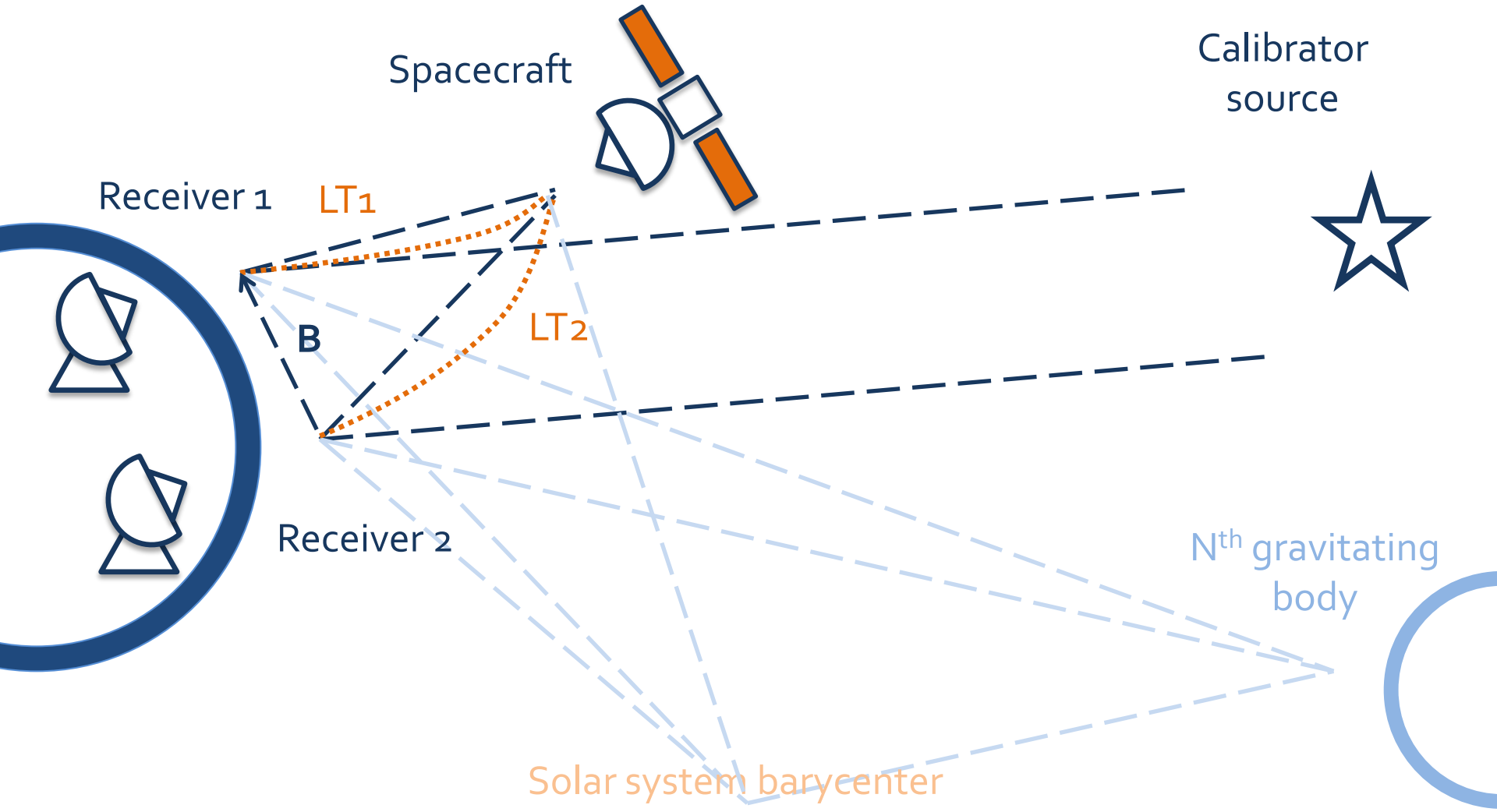
- Wind on other planets or moons
- Internal structure and composition
- Atmosphere dynamics → ESA's VEX drag
- Improve ephemeris of moons → JUICE!
- Interplanetary Scintillation
- General relativity experiments

Credits: NASA/ESA



A windy day on Titan!

Near-field delay model



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

Duev et al 2012

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

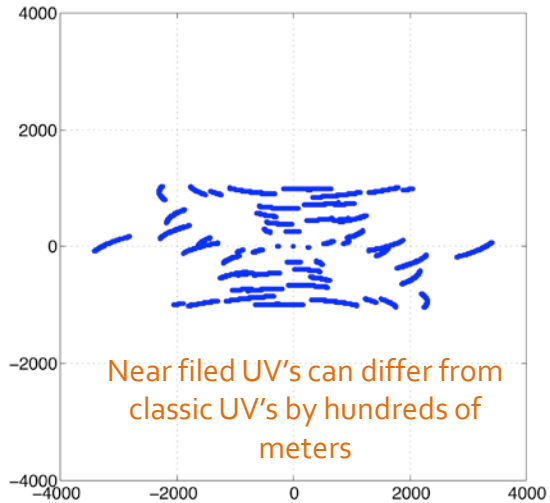
- Empirical models (VMF1, Niell)
- Ray-tracing through NWM data

↓

Tropospheric delays

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

$$J_{ij}|_t = \begin{pmatrix} \frac{\partial(\tau_1 - \tau_2)}{\partial\varphi} & \frac{\partial(\tau_1 - \tau_2)}{\partial\theta} \\ \vdots & \vdots \\ \frac{\partial(\tau_1 - \tau_N)}{\partial\varphi} & \frac{\partial(\tau_1 - \tau_N)}{\partial\theta} \\ \vdots & \vdots \\ \frac{\partial(\tau_{N-1} - \tau_N)}{\partial\varphi} & \frac{\partial(\tau_{N-1} - \tau_N)}{\partial\theta} \end{pmatrix}$$

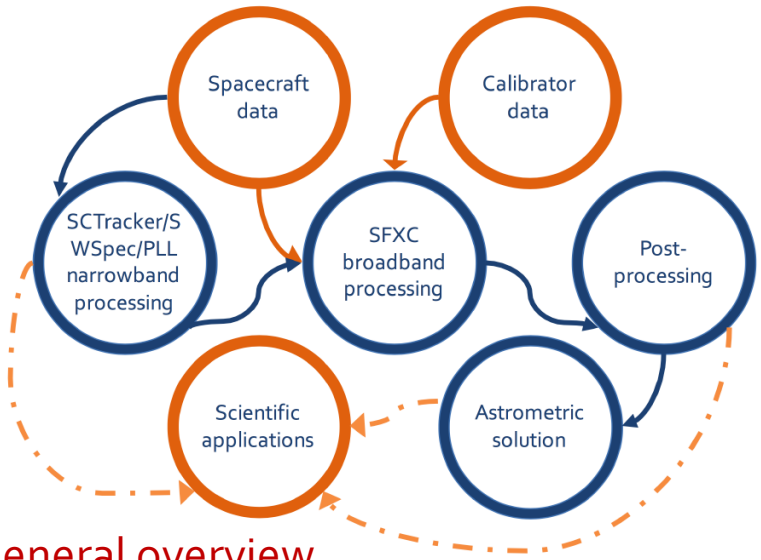
$$\overrightarrow{\Delta\phi}\Big|_t = \left(J_{ij} \cdot \overrightarrow{\Delta\alpha}\right)\Big|_t$$ Measurement Equation

$$\overrightarrow{\Delta\phi} = \begin{pmatrix} \phi_{12} \\ \vdots \\ \phi_{1N} \\ \vdots \\ \phi_{N-1,N} \end{pmatrix}, \quad \overrightarrow{\Delta\alpha} = \begin{pmatrix} \Delta\phi \\ \Delta\theta \end{pmatrix}$$

Differential phases
and
Vector corrections

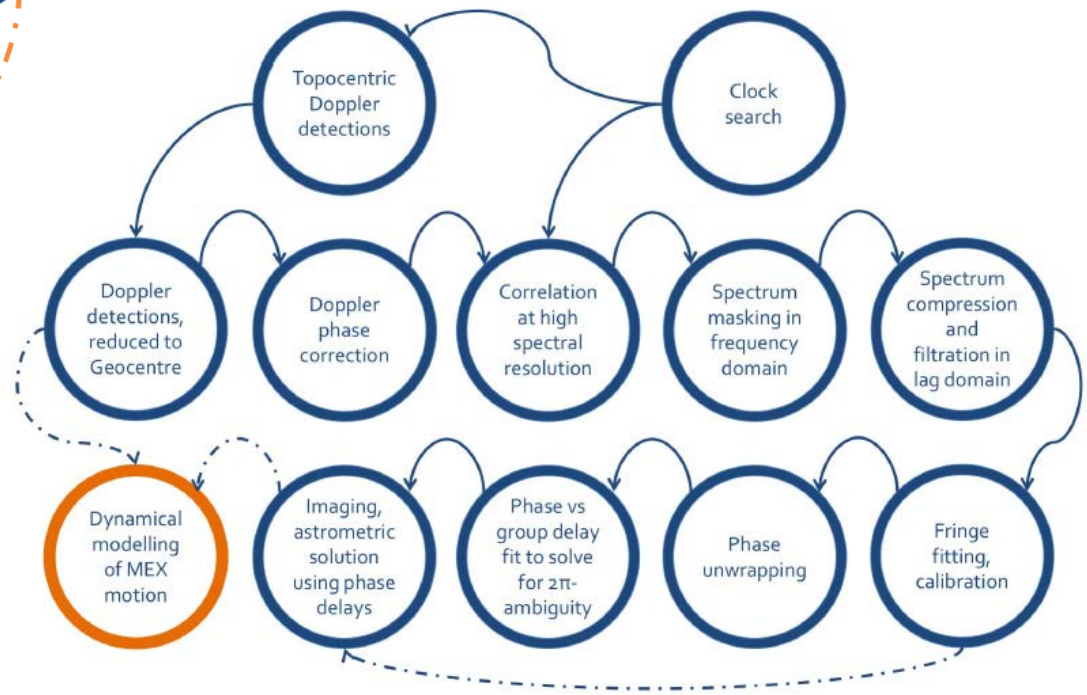
To get corrections to the S/C a priori lateral position, solve measurement equation for **Δα**

Data analysis pipeline



General overview

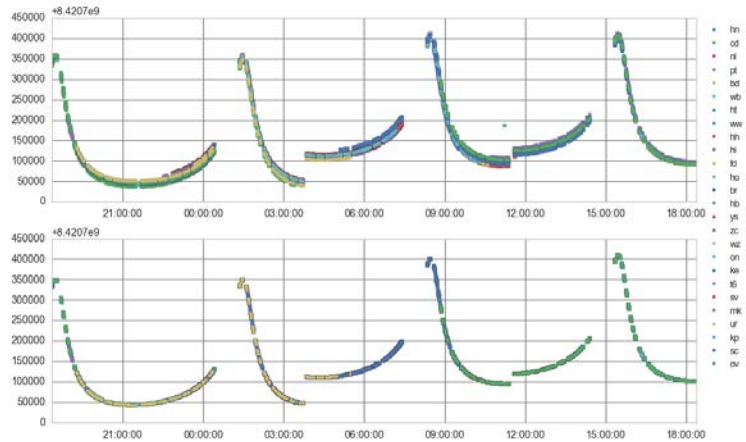
Signal processing



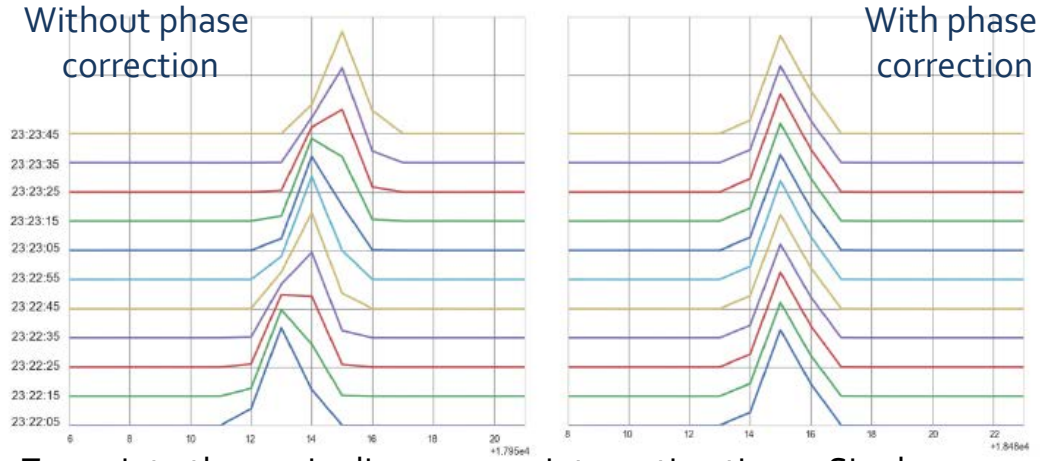
Data analysis pipeline

Signal processing:

Doppler detections to geocenter

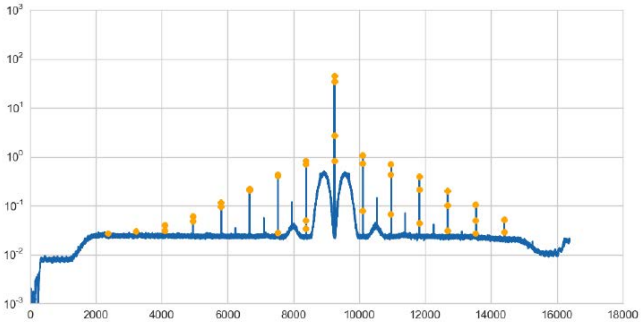


Doppler phase corrections for Hh-Ww baseline

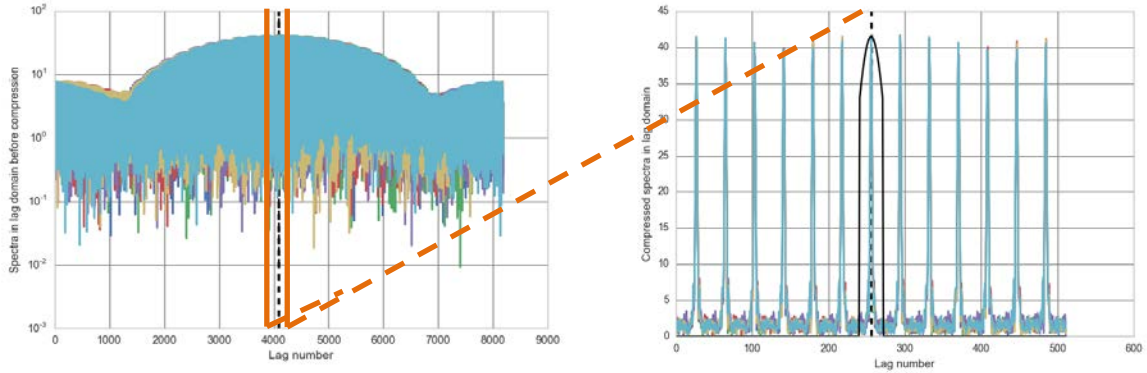


Zoom into the carrier line – 10 sec integration time – Single scan

Spectrum masking



Spectrum compression and filtration



ESA's Mars Express Phobos fly-by

28 – 29 December 2013
Closest flyby of MEX 45km

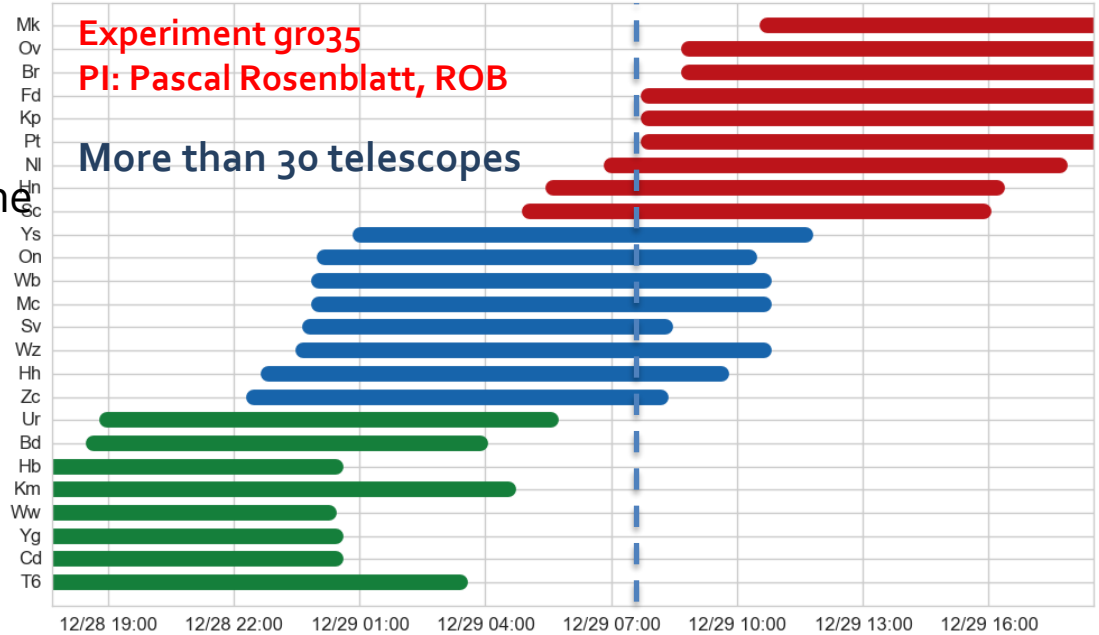
~26 hours of continuous observation time
3 consecutive Mars revolutions
7 hours long

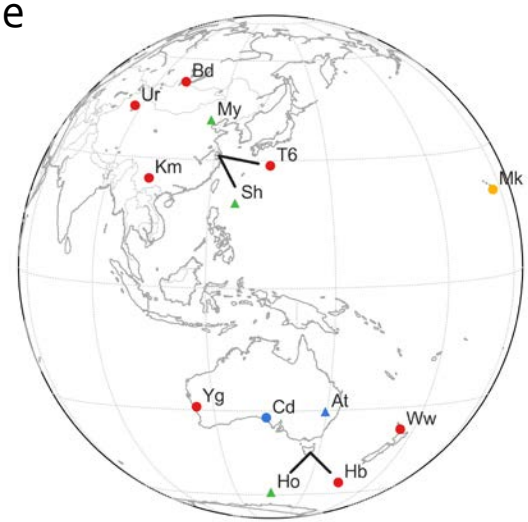
Goal: High precision positional and Doppler measurements

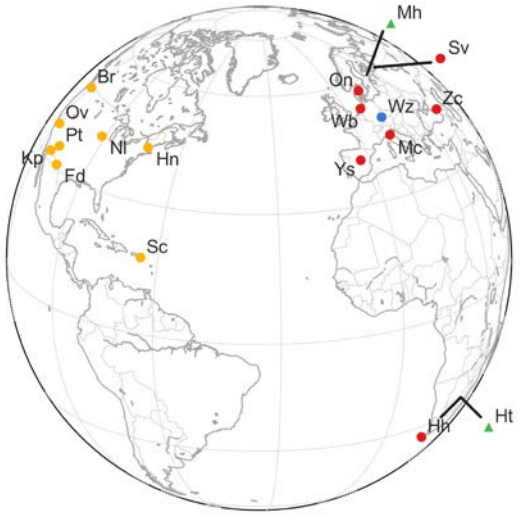
- Study of the Interior of Phobos
- Improving models on the origin of the Mars system
- Ephemerides

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

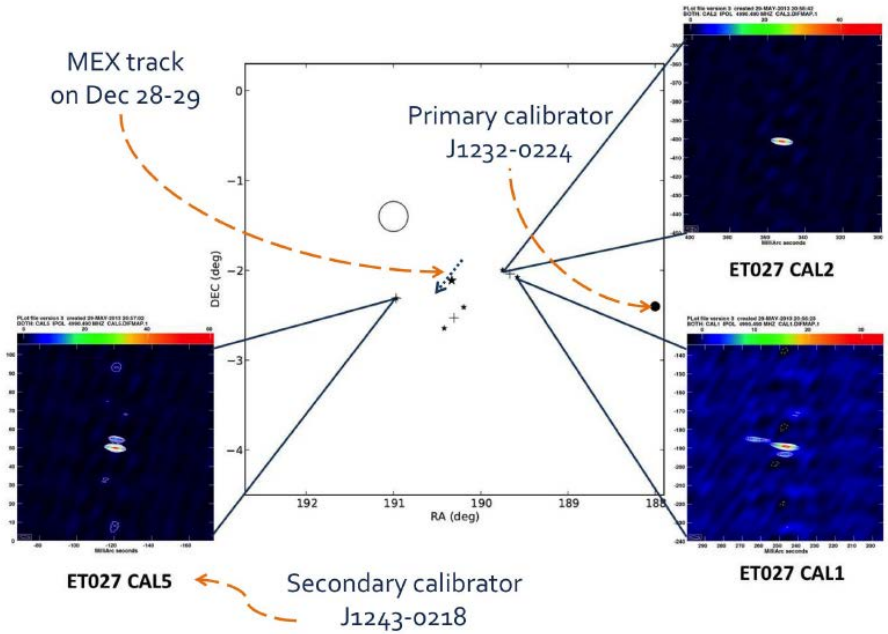
4x16MHz Wz and VLBA

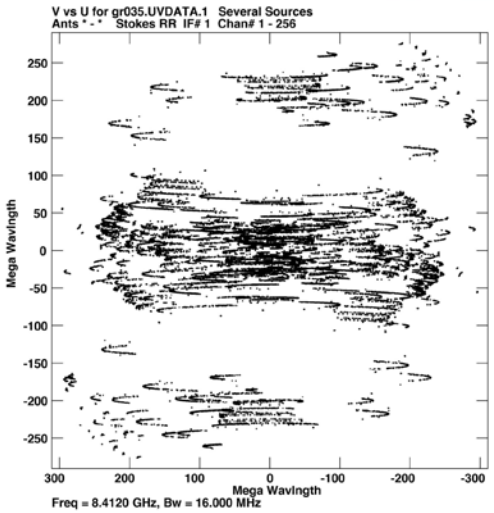
4x16 MHz S/X for Doppler stations

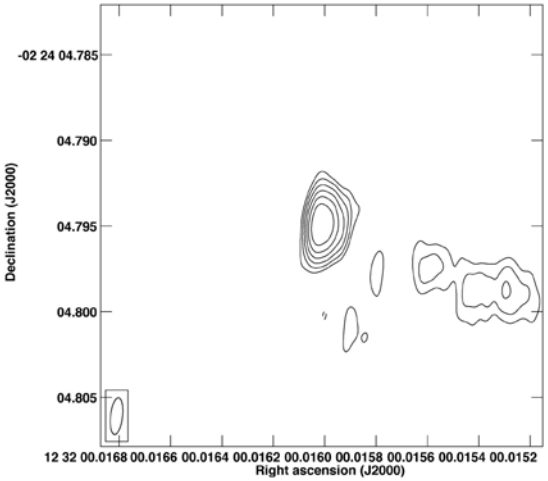
Standard VLBI data reduction

AIPS

Too many scans → Parseltongue!

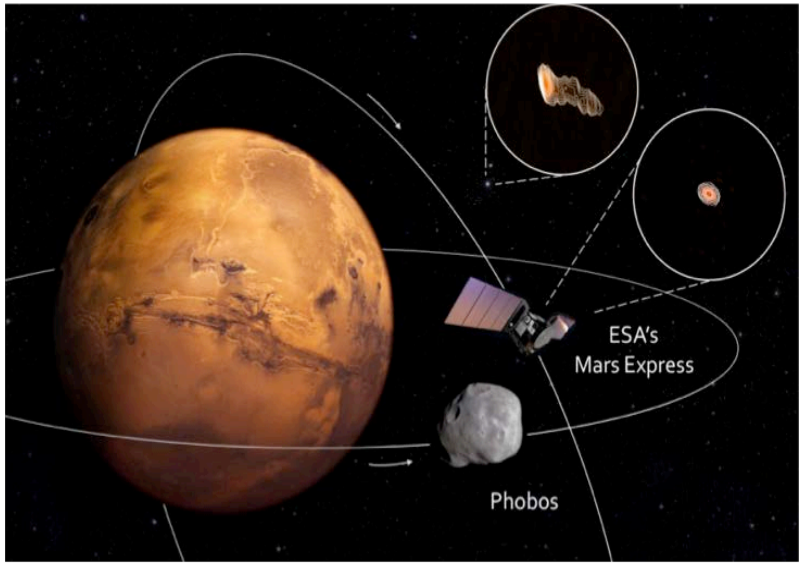






MEX Phobos flyby

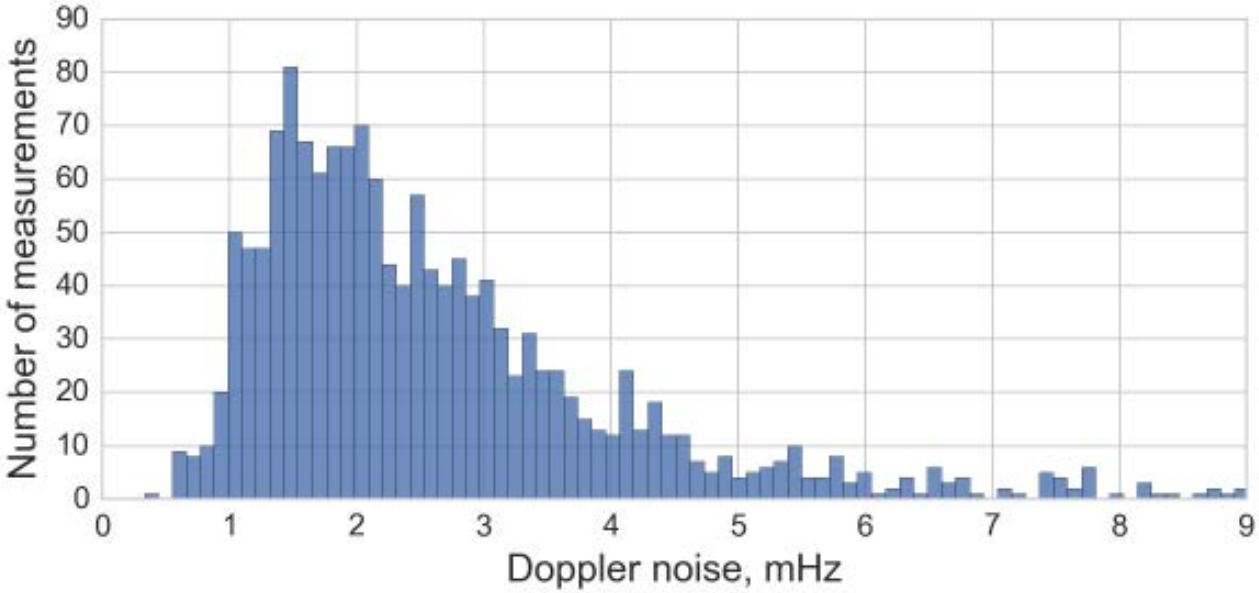
Doppler results



Credits: ESA (for Mars, Phobos and MEX)

Doppler detection noise, 10 s integration:

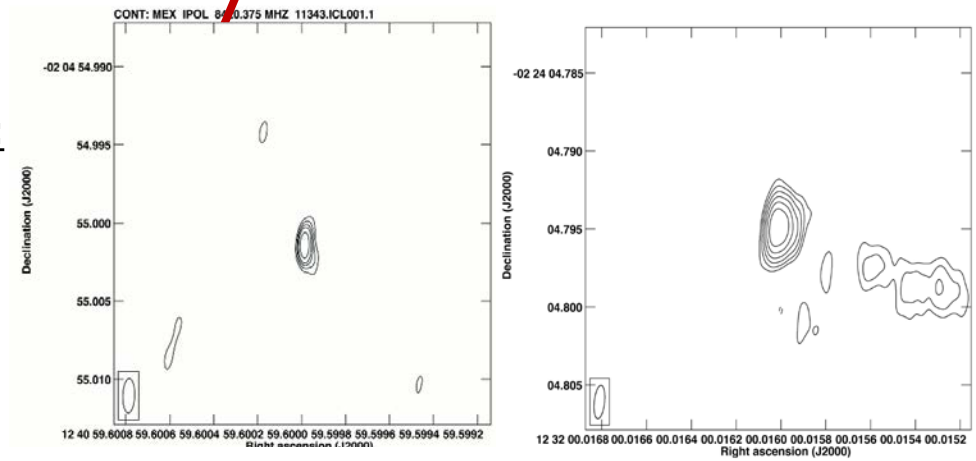
- **mean value 2.5 mHz**
- **median value 2.2 mHz**
- **mod (maximum log-normal fit) value 1.7 mHz → 30 µm/s**

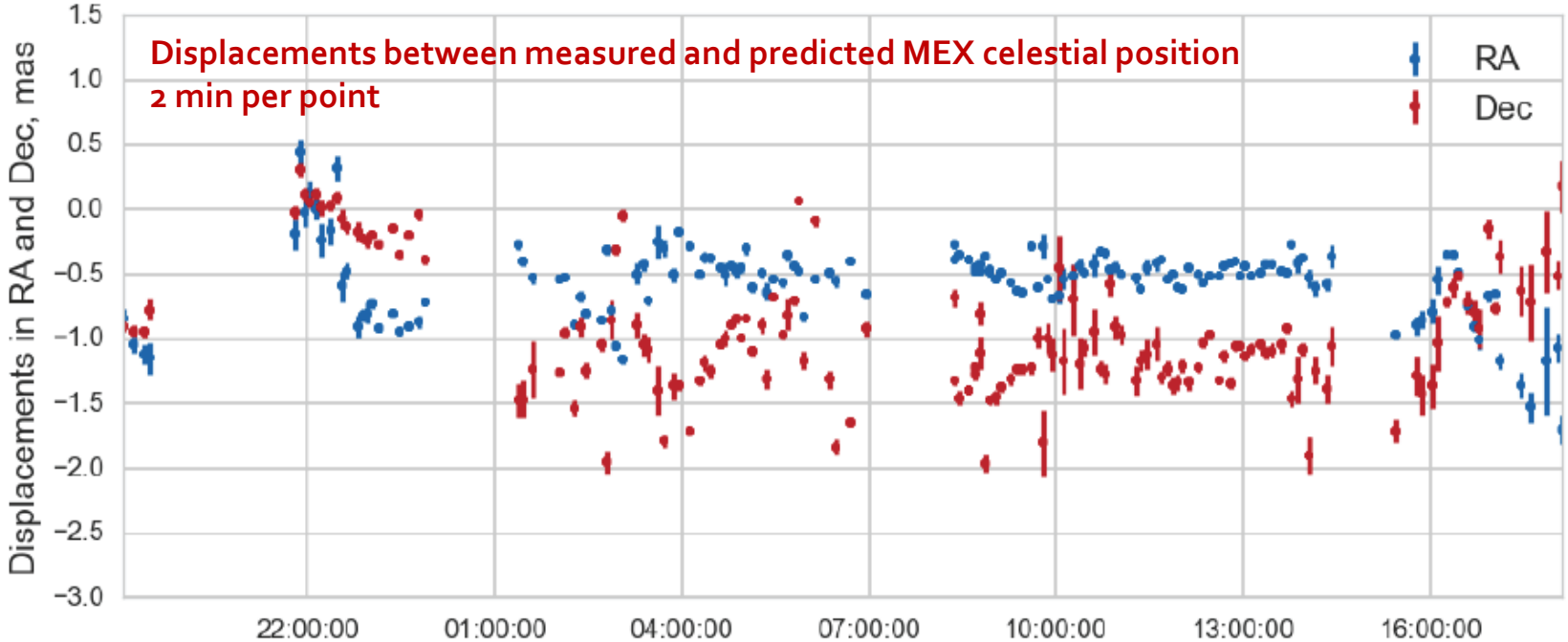


Spacecraft astrometry

Median 3σ formal error for the full range are:

RA 34 μas → 35 m
Dec 58 μas → 60 m





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).

Acknowledgements

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Planetary Radio Interferometry and Doppler Experiment (PRIDE) technique: A test case of the Mars Express Phobos fly-by.

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ABSTRACT

Context. The closest ever fly-by of the Martian moon Phobos, performed by the European Space Agency's Mars Express spacecraft, gives a unique opportunity to sharpen and test the Planetary Radio Interferometry and Doppler Experiments (PRIDE) technique in the interest of studying planet - satellite systems.
Aims. The aim of this work is to demonstrate a technique of providing high precision positional and Doppler measurements of planetary spacecraft using the Mars Express spacecraft. The technique will be used in the framework of Planetary Radio Interferometry and Doppler Experiments in various planetary missions, in particular in fly-by mode.
Methods. We advanced a novel approach to spacecraft data processing using the techniques of Doppler and phase-referenced very long baseline interferometry spacecraft tracking.
Results. We achieved, on average, mHz precision (30 μm/s at a 10 seconds integration time) for radial three-way Doppler estimates and sub-nanoradian precision for lateral position measurements, which in a linear measure (at a distance of 1.4 AU) corresponds to ~ 50 m.

Key words. astrometry – techniques: interferometric – instrumentation: interferometers – instrumentation: miscellaneous