Advancing spacecraft Doppler and interferometric data processing techniques for planetary science

Dmitry A. Duev

on behalf of the PRIDE team

California Institute of Technology

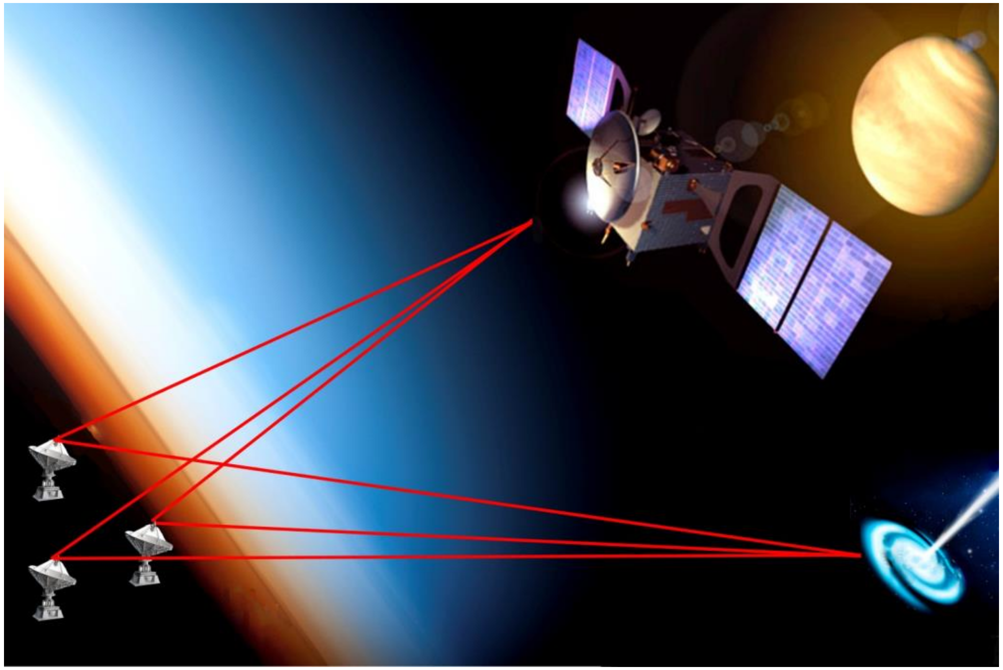
Caltech

JIVE
Joint Institute for VLBI
ERIC

Overview

- PRIDE overview, dataflow and processing pipeline
- PRIDE observations of ESA’s MarsExpress Phobos fly-by
- Conclusions and outlook

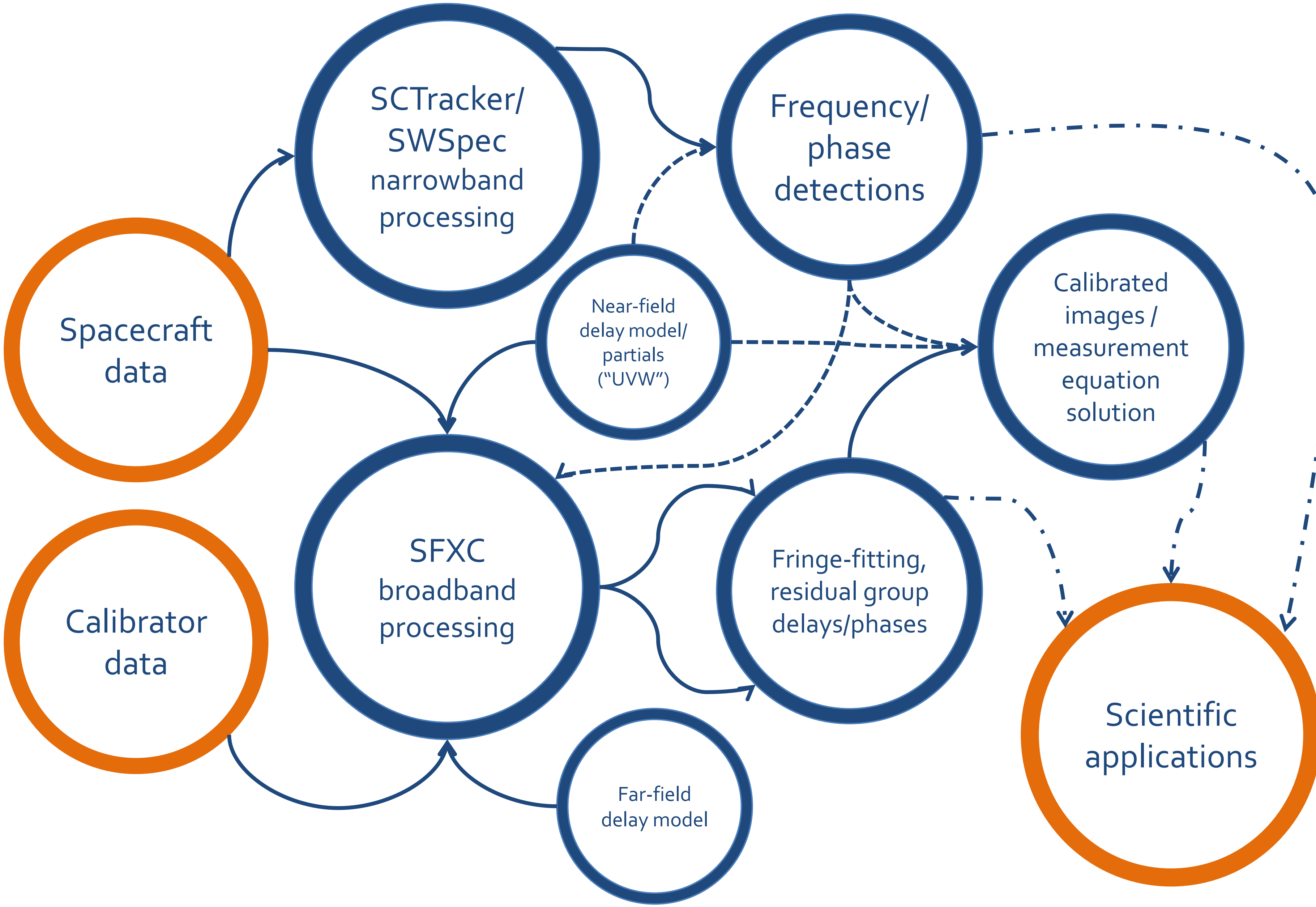
Planetary Radio Interferometry and Doppler Experiments (PRIDE)



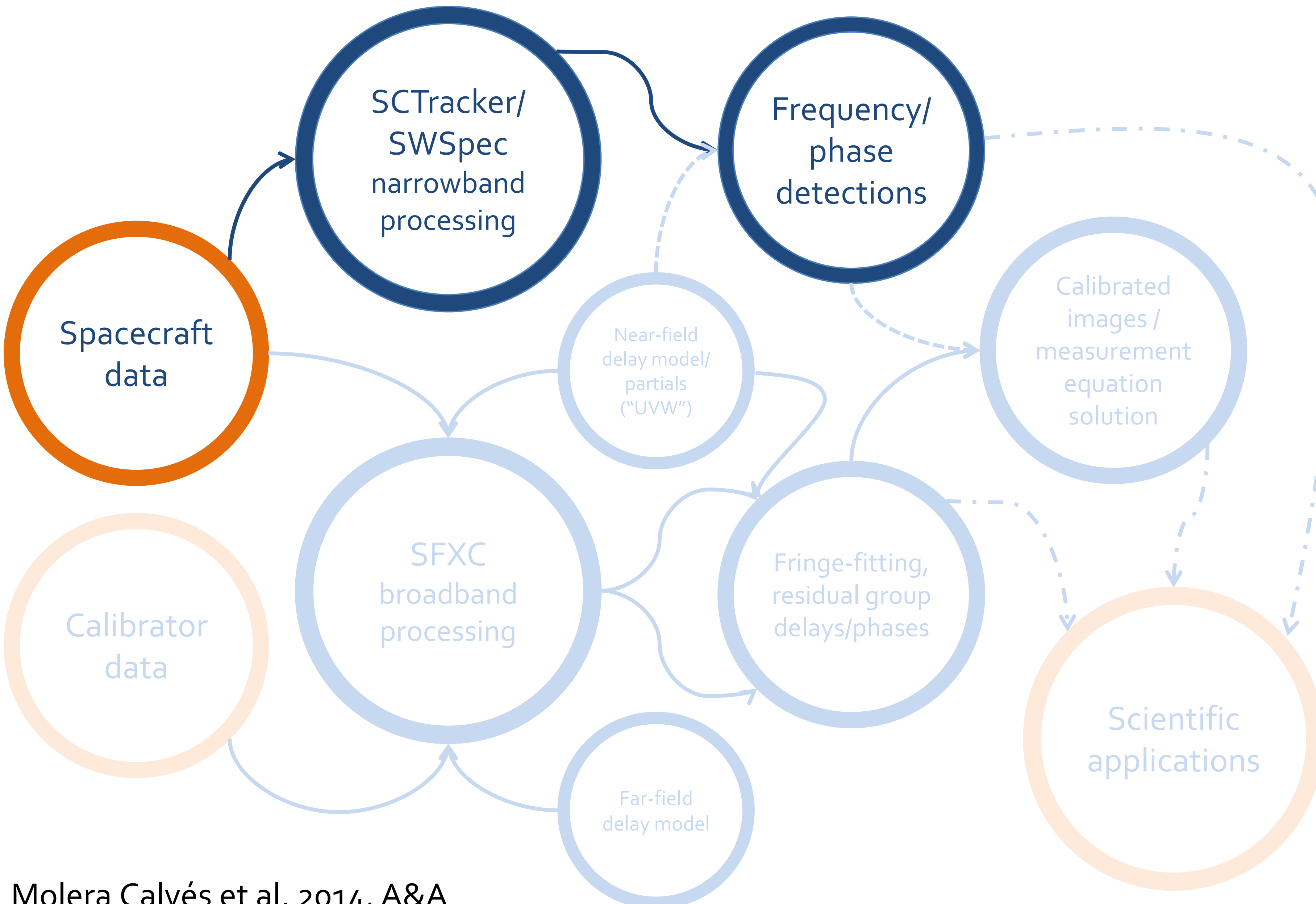
PRIDE: a multi-purpose, multi-disciplinary enhancement of mission science return, based on Doppler tracking and phase-referencing VLBI technology and science

(more on PRIDE – L.Gurvits, later today)

PRIDE dataflow and processing pipeline

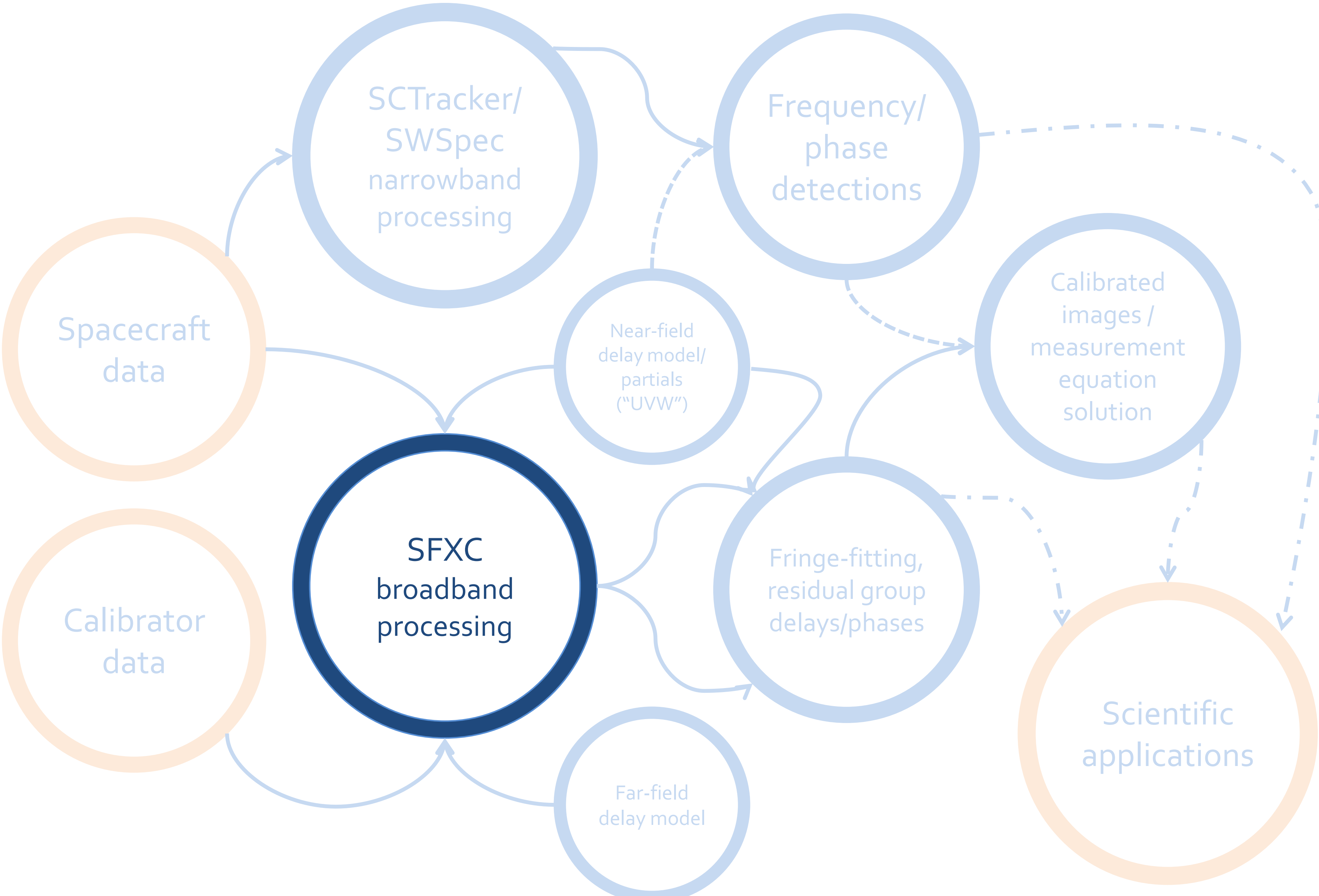


PRIDE dataflow and processing pipeline



Molera Calvés et al. 2014, A&A

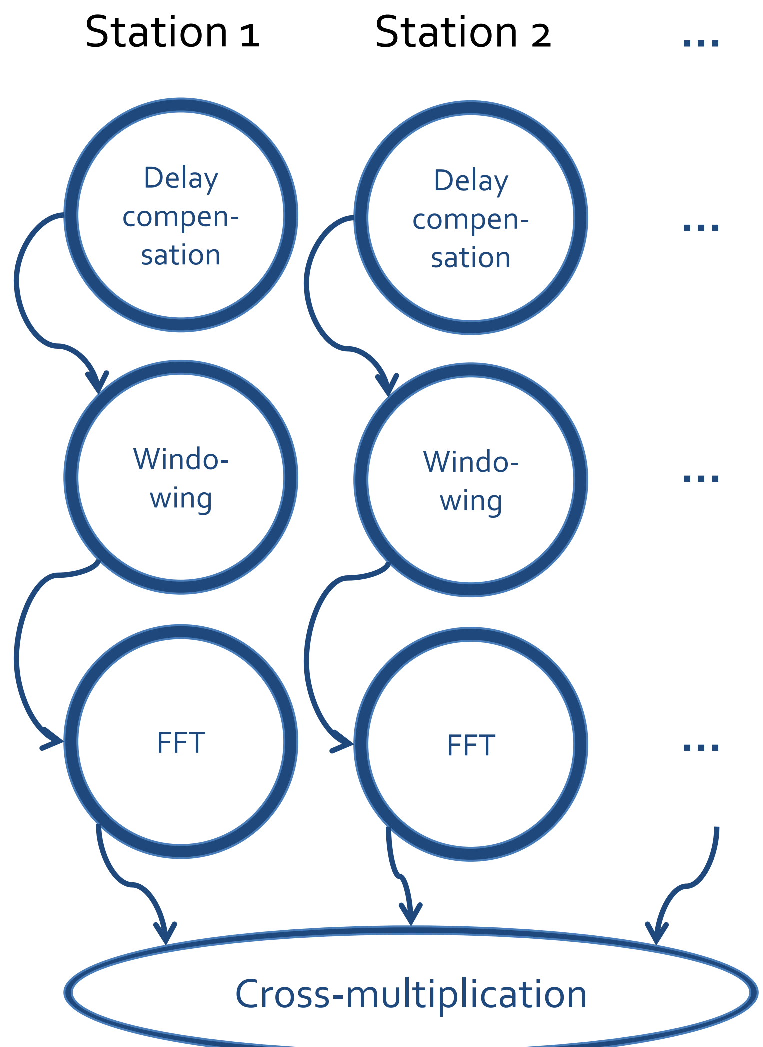
PRIDE dataflow and processing pipeline



Broadband correlation

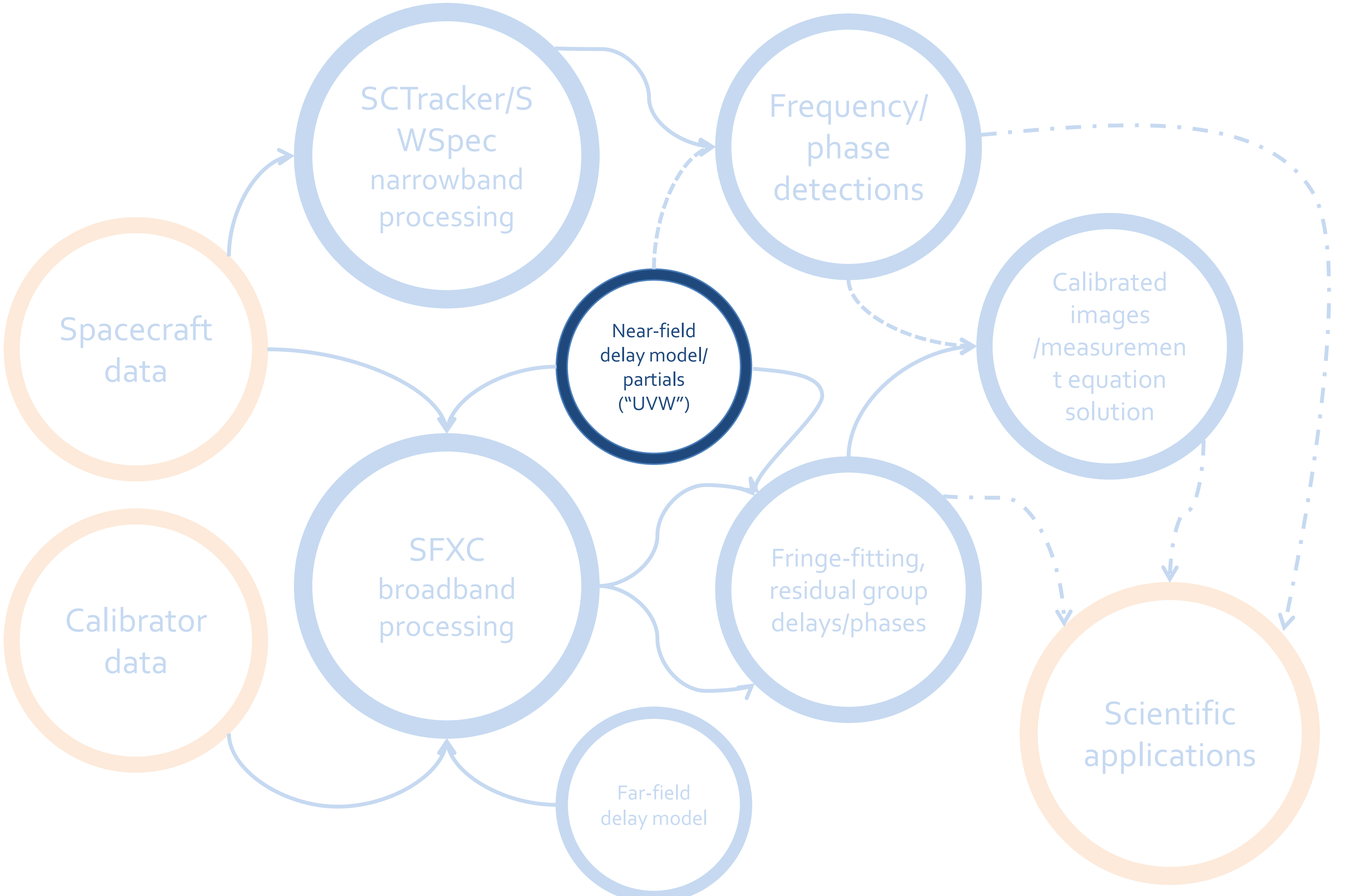
SFXC: European VLBI Network's software correlator at JIVE

- FX software correlator
- Data formats: Mk4, VLBA, Mk5B, VDIF
- Delay models: far-, near-field, space VLBI
- WOLA: Hann, Hamming, cos, rect
- Pulsar binning, gating
- Multiple phase-centers
- Mixed bandwidth correlation
- VEX driven, JSON config file
- Implemented using MPI

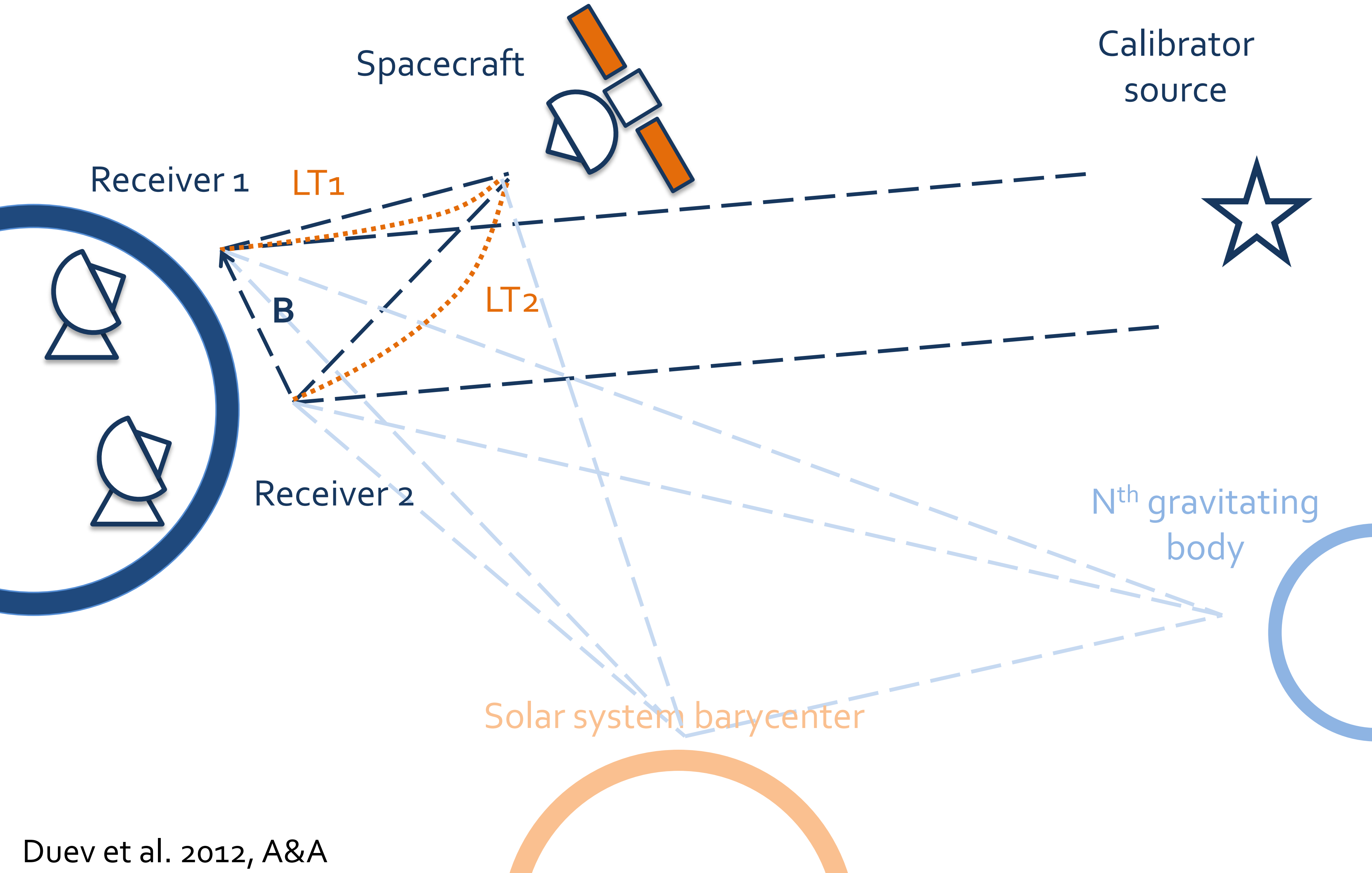


Keimpema et al. 2015, Exp. Astron.

PRIDE dataflow and processing pipeline

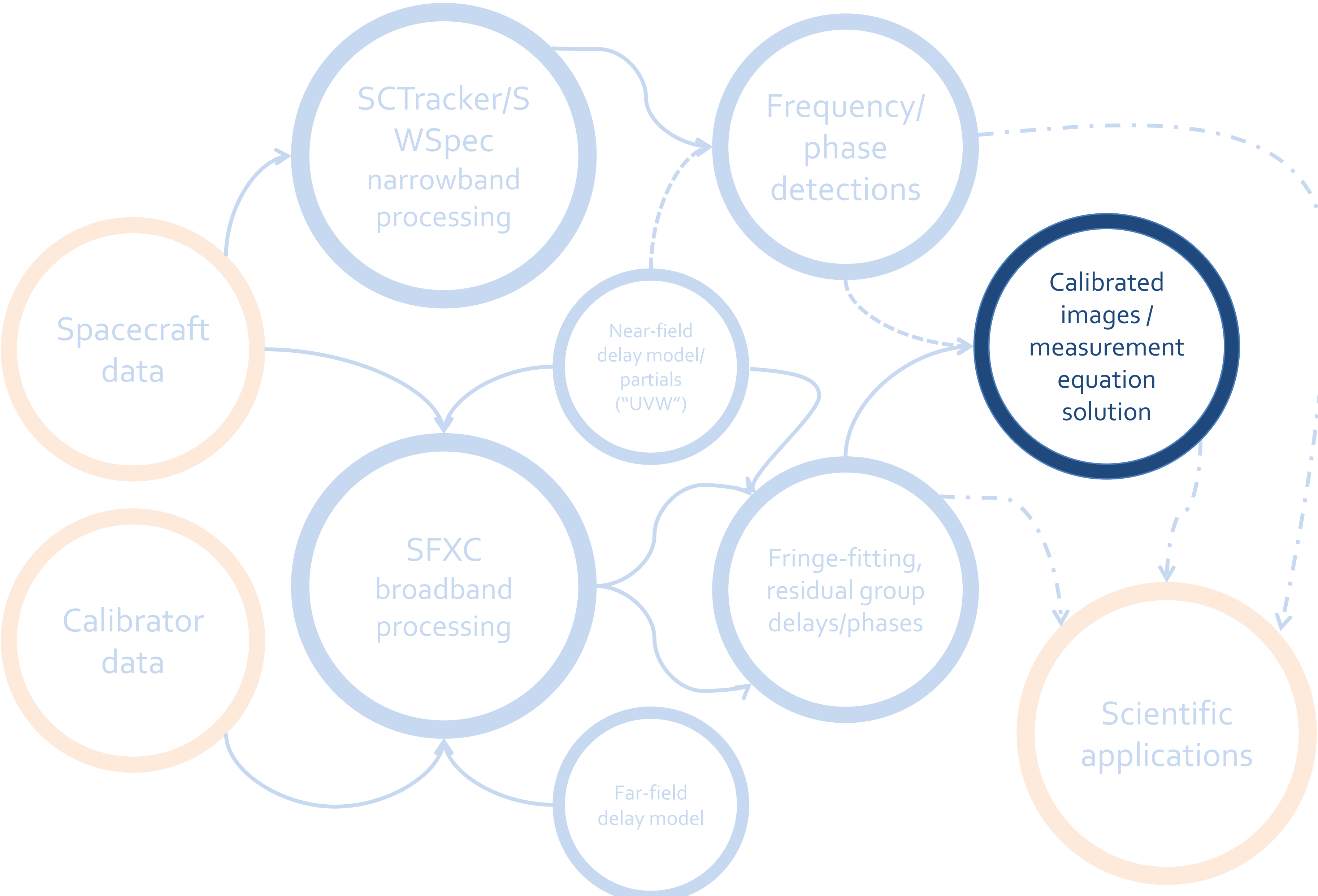


Near-field delay model



Duev et al. 2012, A&A

PRIDE dataflow and processing pipeline



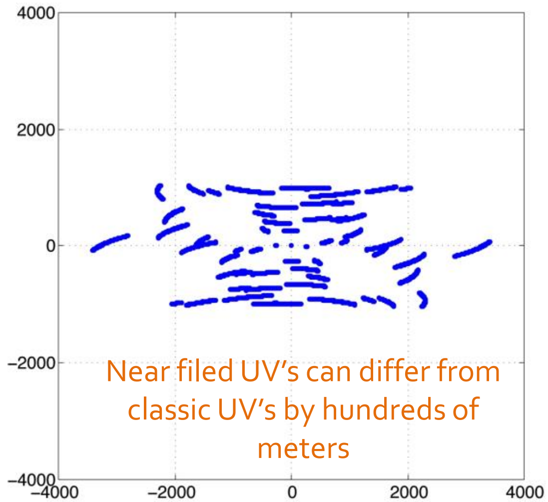
Imaging and *uv*-coverage for near-field VLBI

Van Cittert – Zernike theorem:

$$I_t(l,m) = \int S(u,v)\cdot V(u,v)\cdot \Re\left(e^{-2\pi i\cdot(ul+vm)}\right)\, \mathrm{d}u\, \mathrm{d}v \,\Big|_t$$

Traditional «uv»-projections of baselines

Elements of the Jacobian for the near-field VLBI case



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

Spacecraft imaging and state vector estimation

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

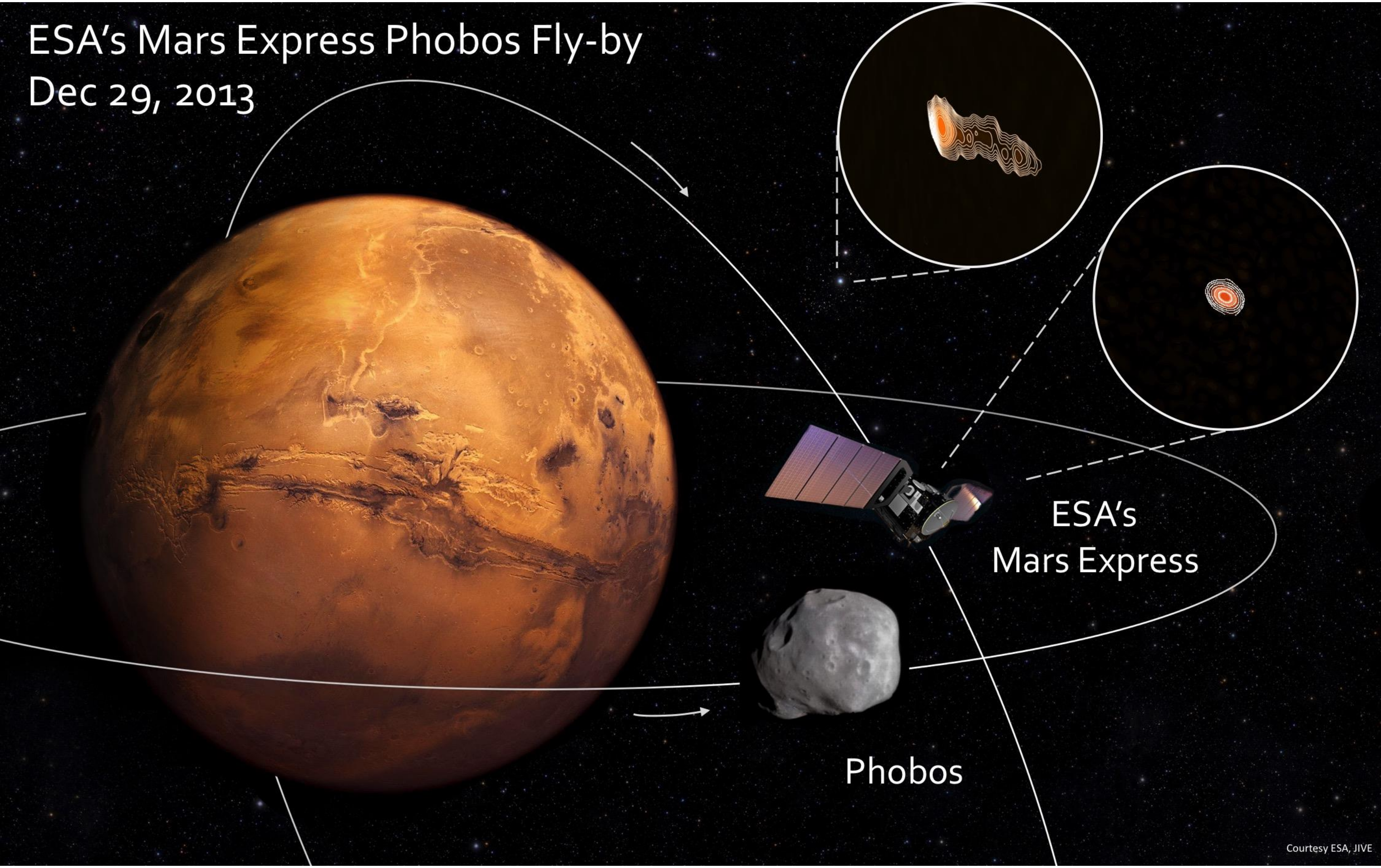
- measurement equation

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

- differential phases
- vector of corrections

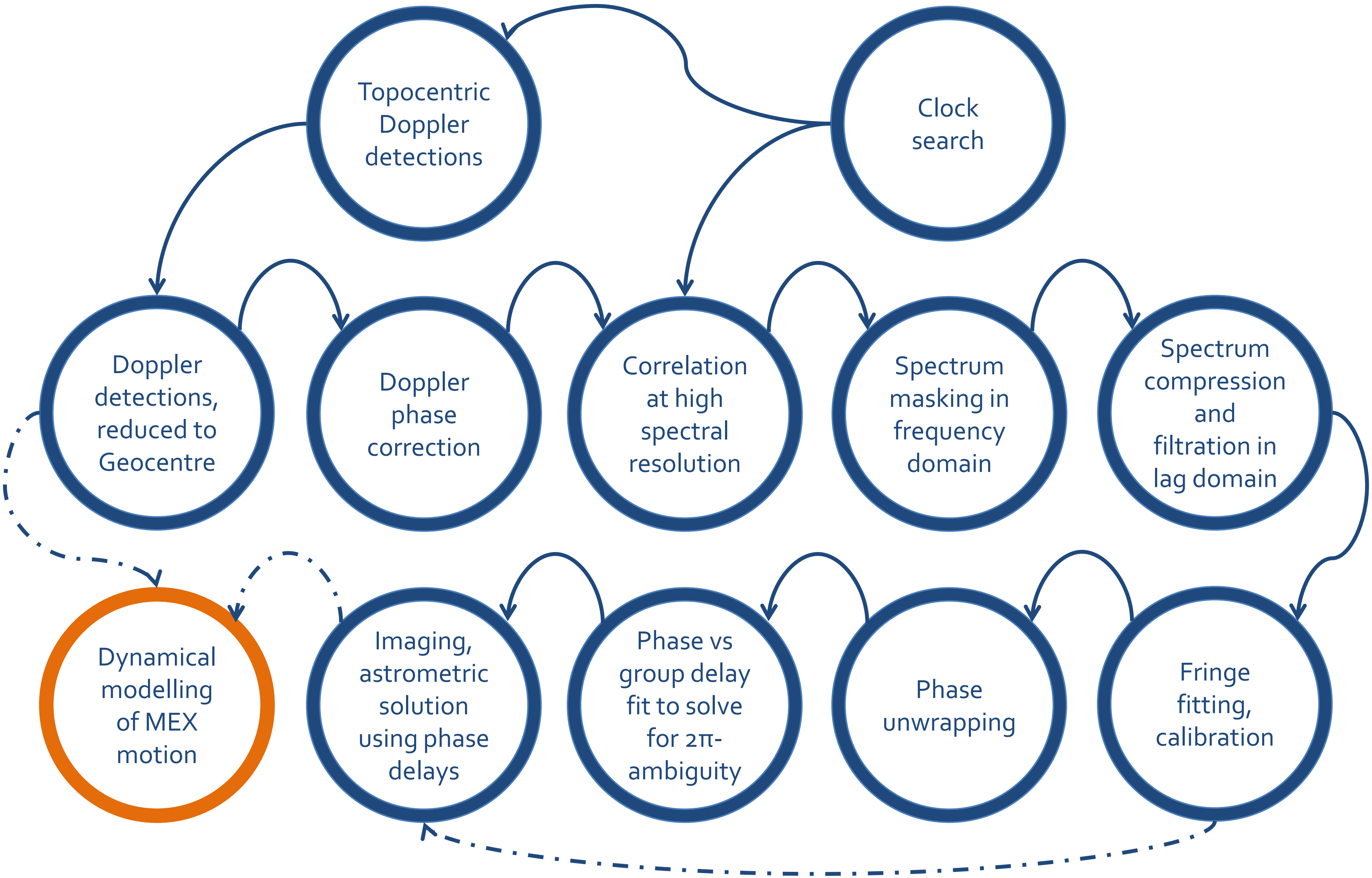
To get corrections to the S/C a priori lateral position, solve measurement equation for **Δα**

ESA's Mars Express Phobos fly-by

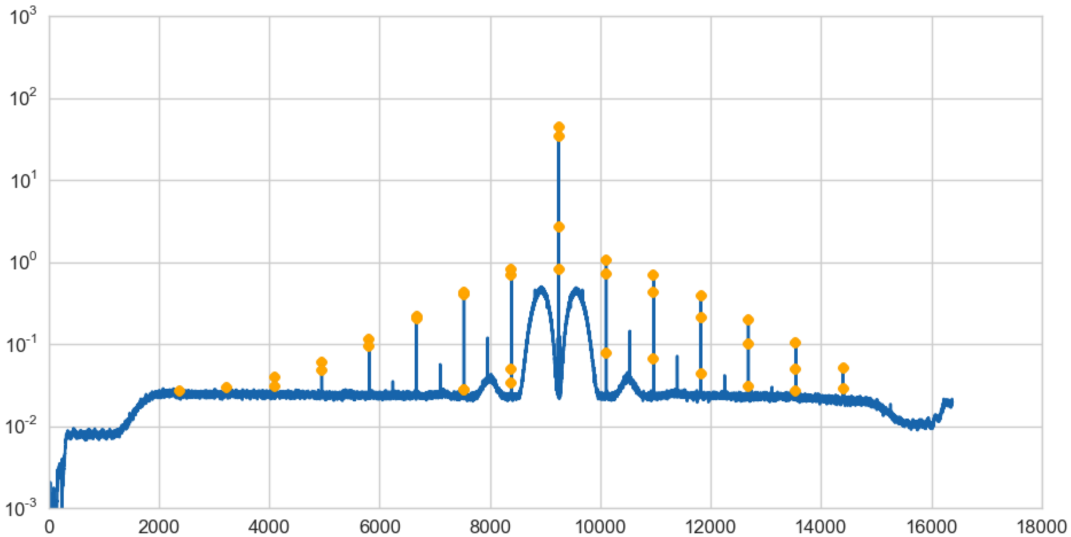


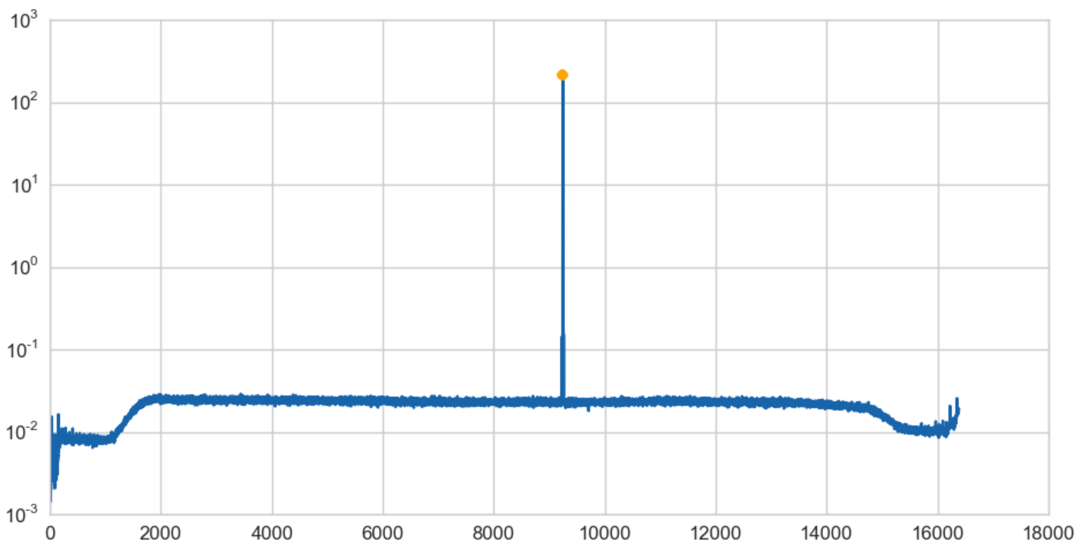
Duev et al. 2016, A&A

Data processing pipeline

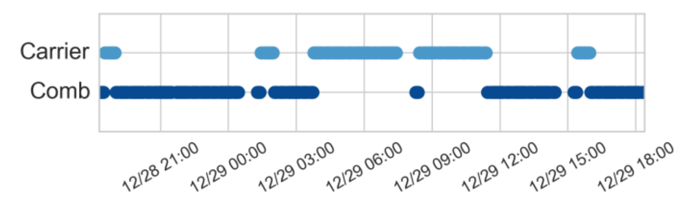


MEX spectrum

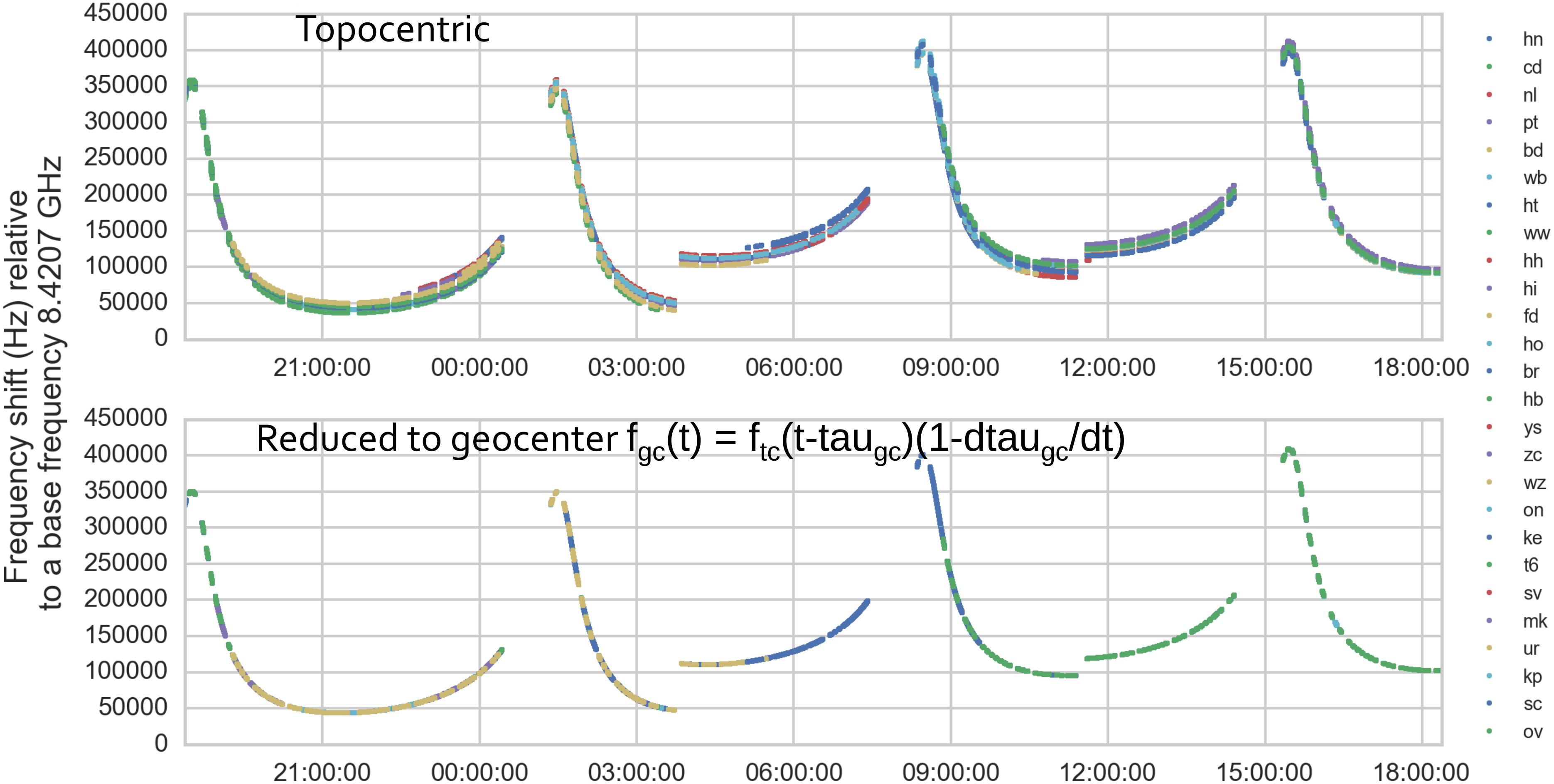




Averaged amplitude spectrum after applying the Doppler phase correction in arbitrary units, $2^{14} = 16384$ points spectral resolution, baseline T6-Sv, scan 209 (top) and 191 (bottom). Only the carrier line was present in the spectrum in the second case, as was the case for $\sim 50\%$ of the time during GR035. The spectral mask is shown in orange dots.

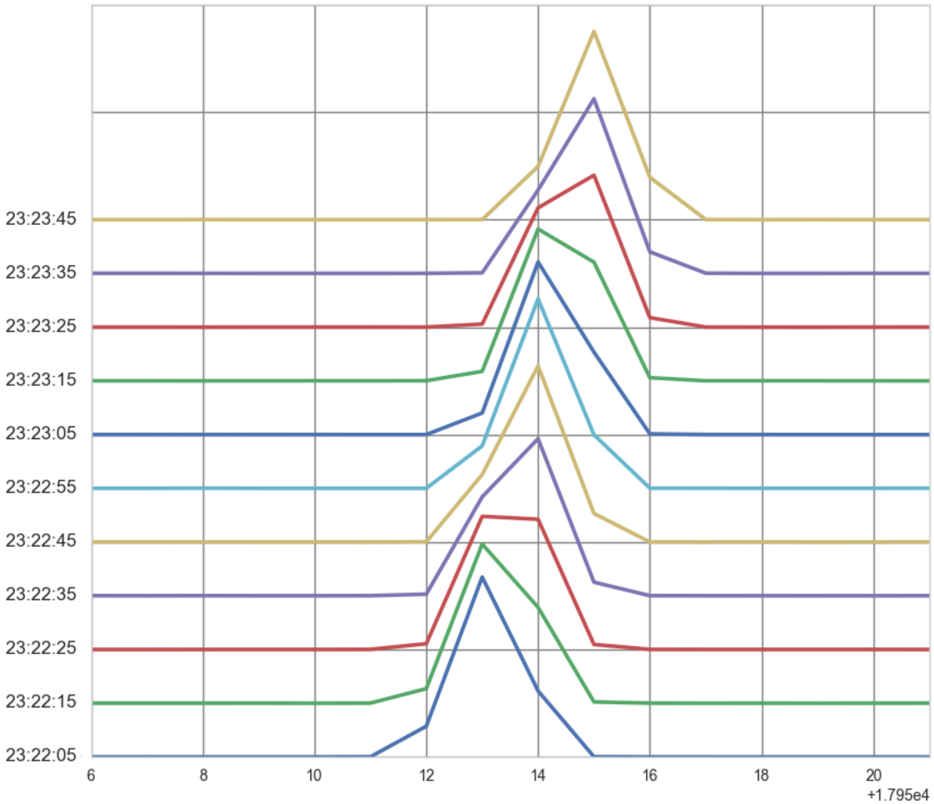


Doppler observables

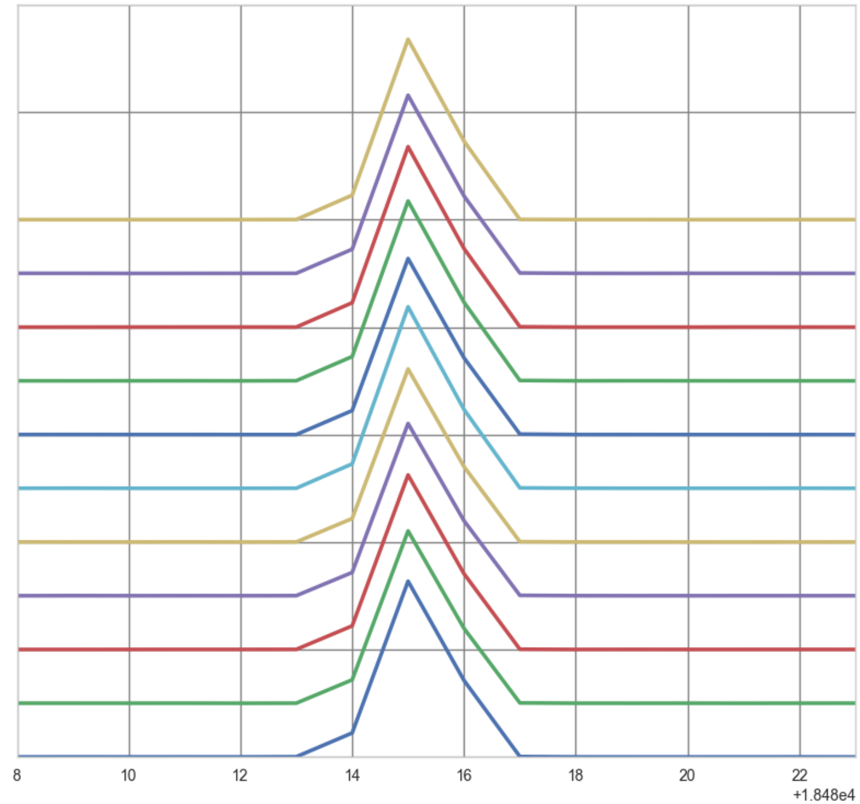


Doppler phase correction is applied to spacecraft signal to avoid frequency smearing

Doppler phase correction



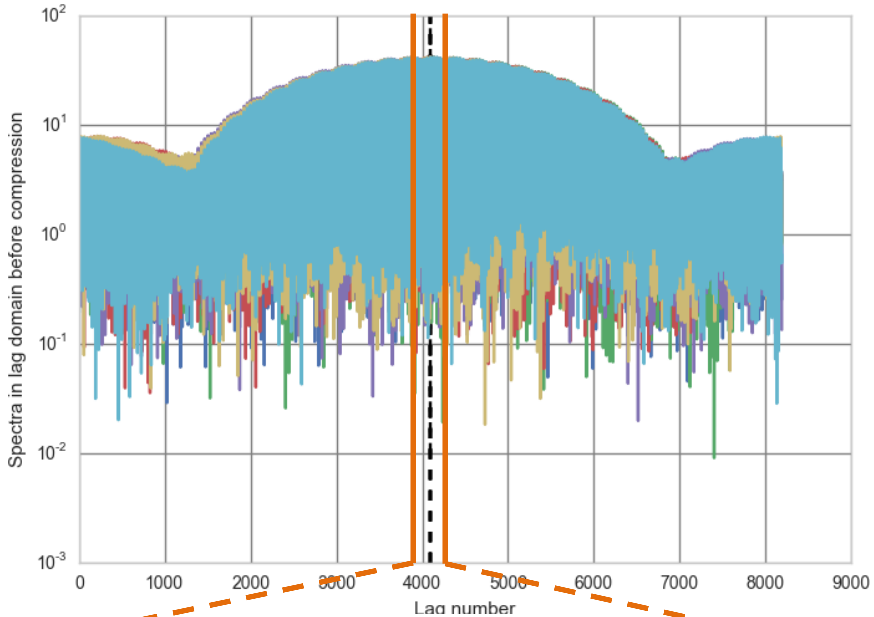
Without phase correction

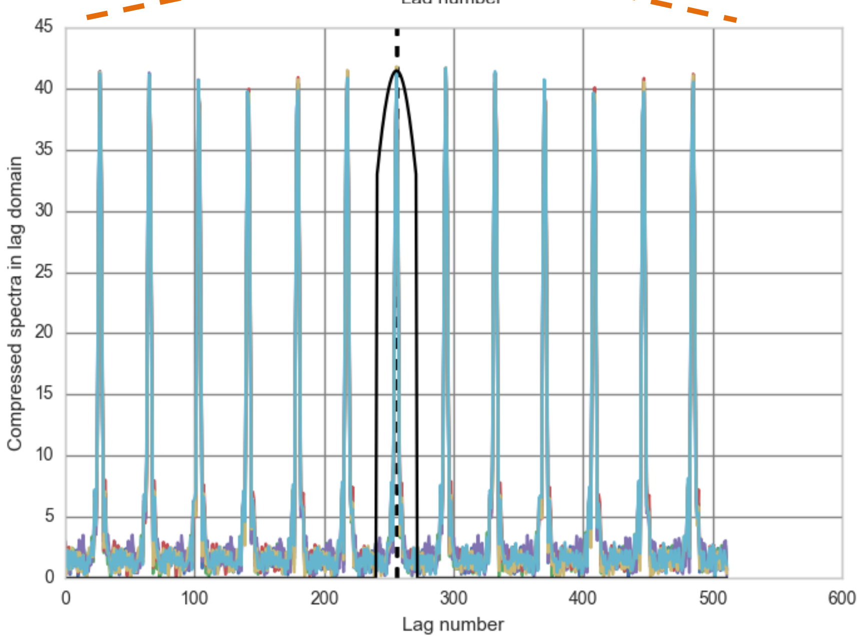


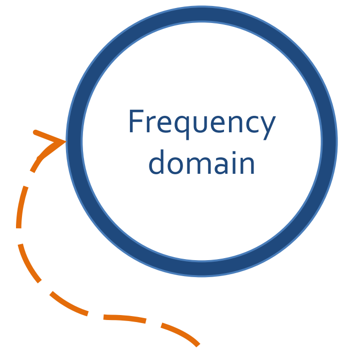
With phase correction

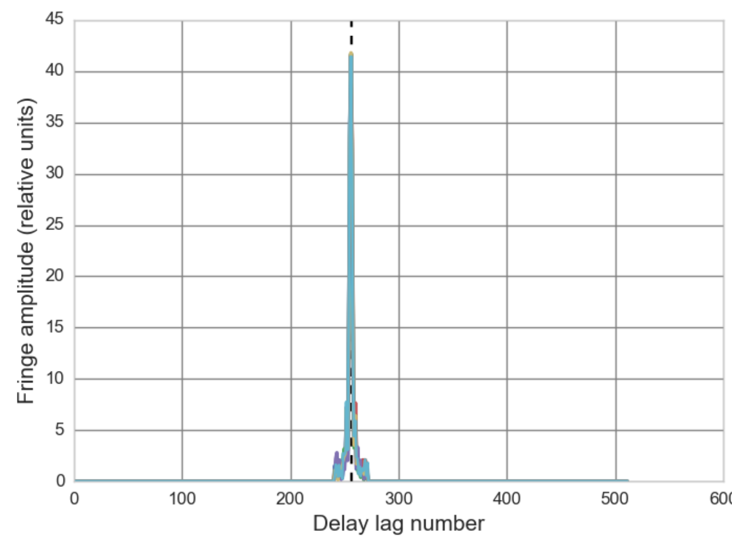
Zoom into the carrier line without (left panel) and with the Doppler phase correction (right panel). 10 sec integration time, $2^{15} = 32768$ points spectral resolution, baseline Hh-Ww, scan 135. 23:22 – 23:24, December 28, 2013.

Spectrum filtration and compression



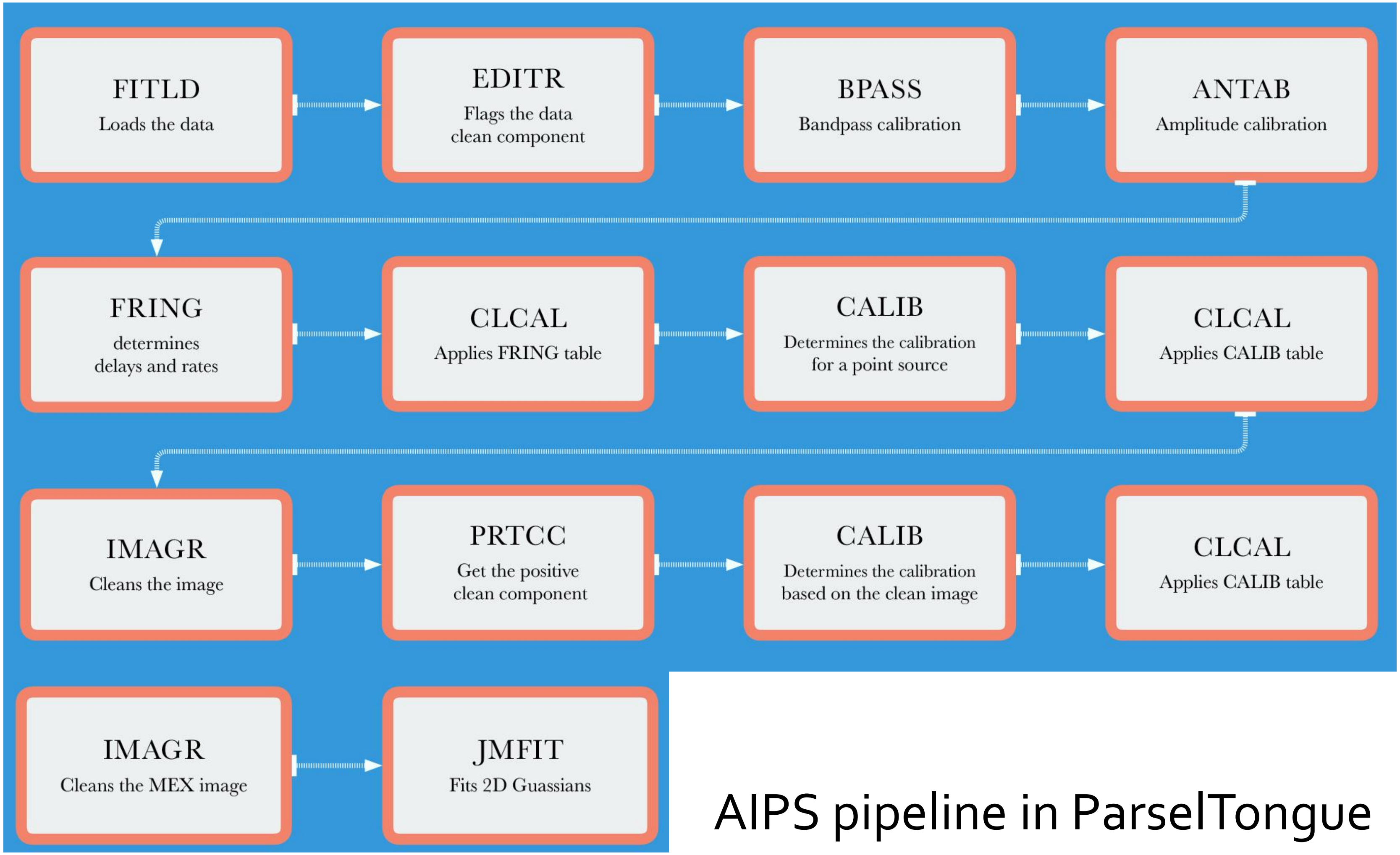






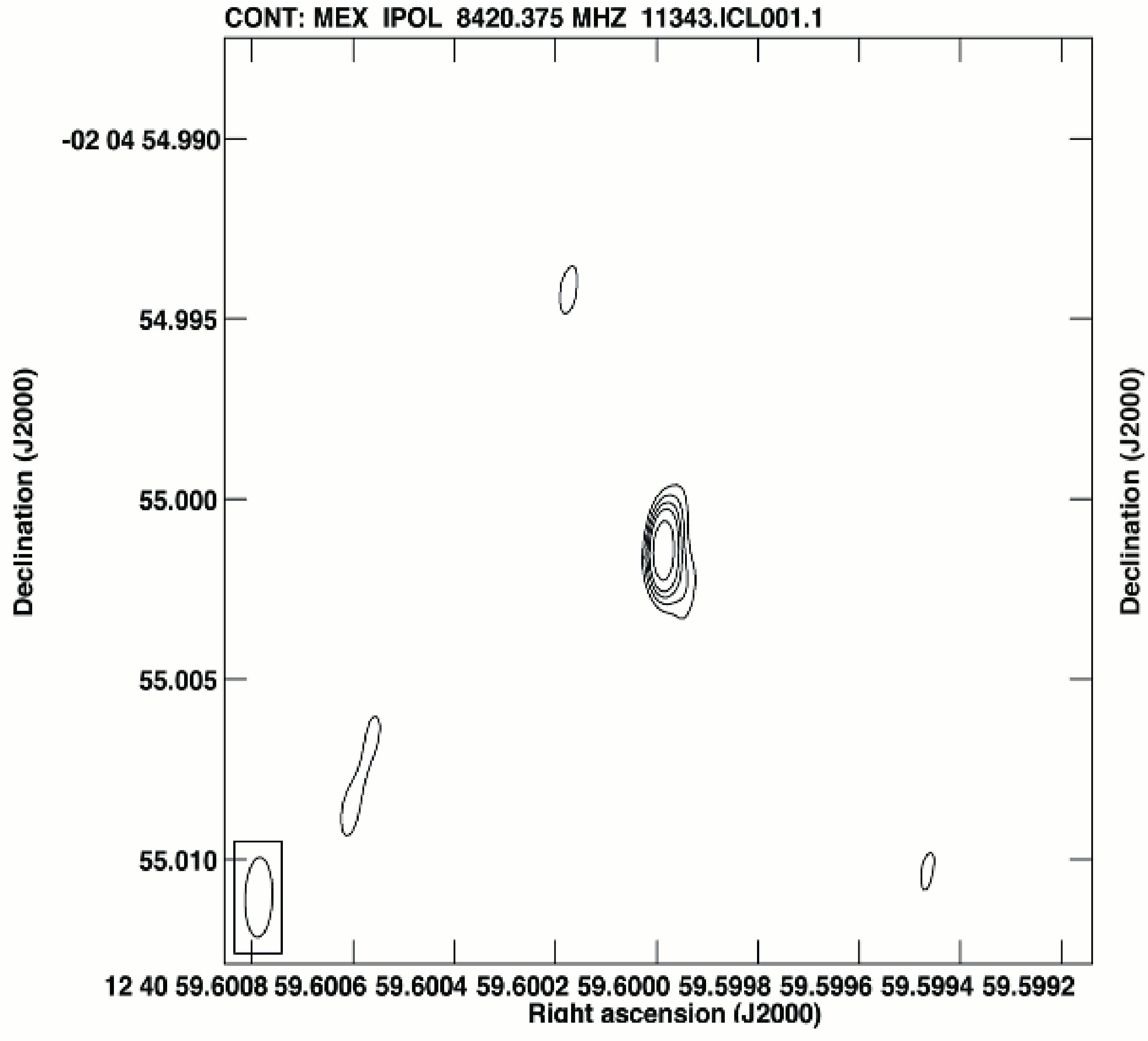
Spectrum compression and filtration in lag domain

Measuring position: imaging approach

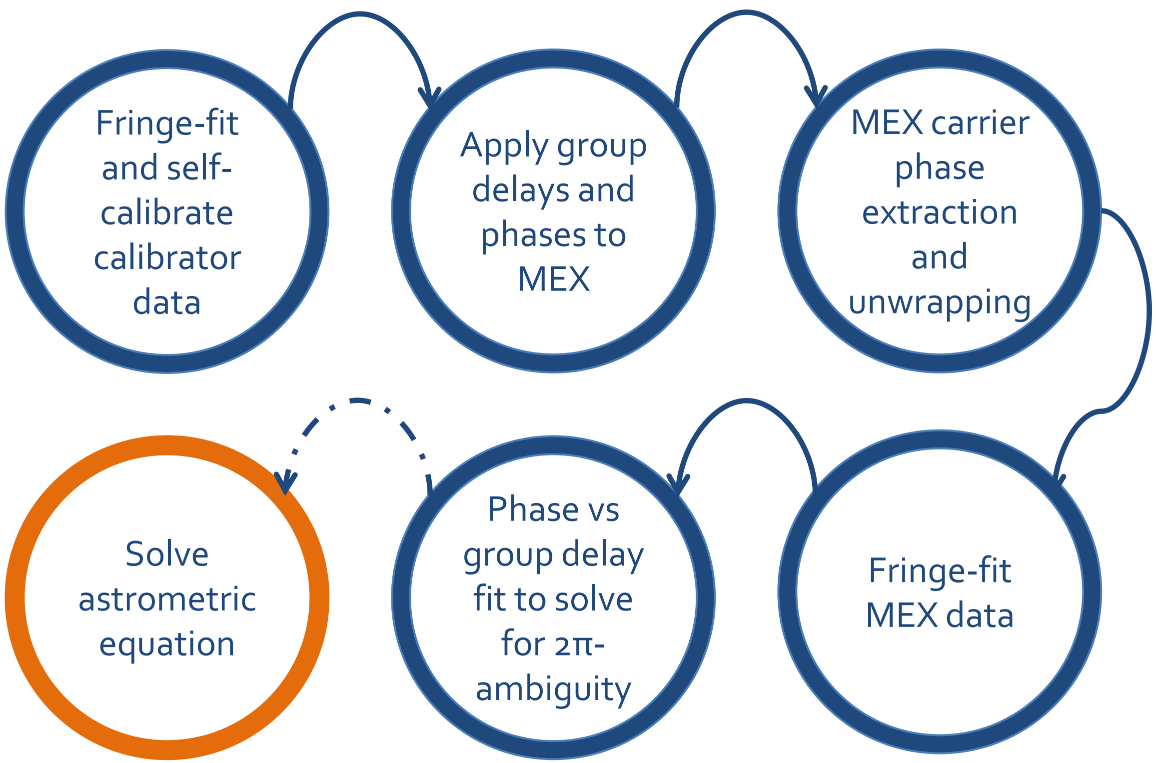


AIPS pipeline in ParselTongue

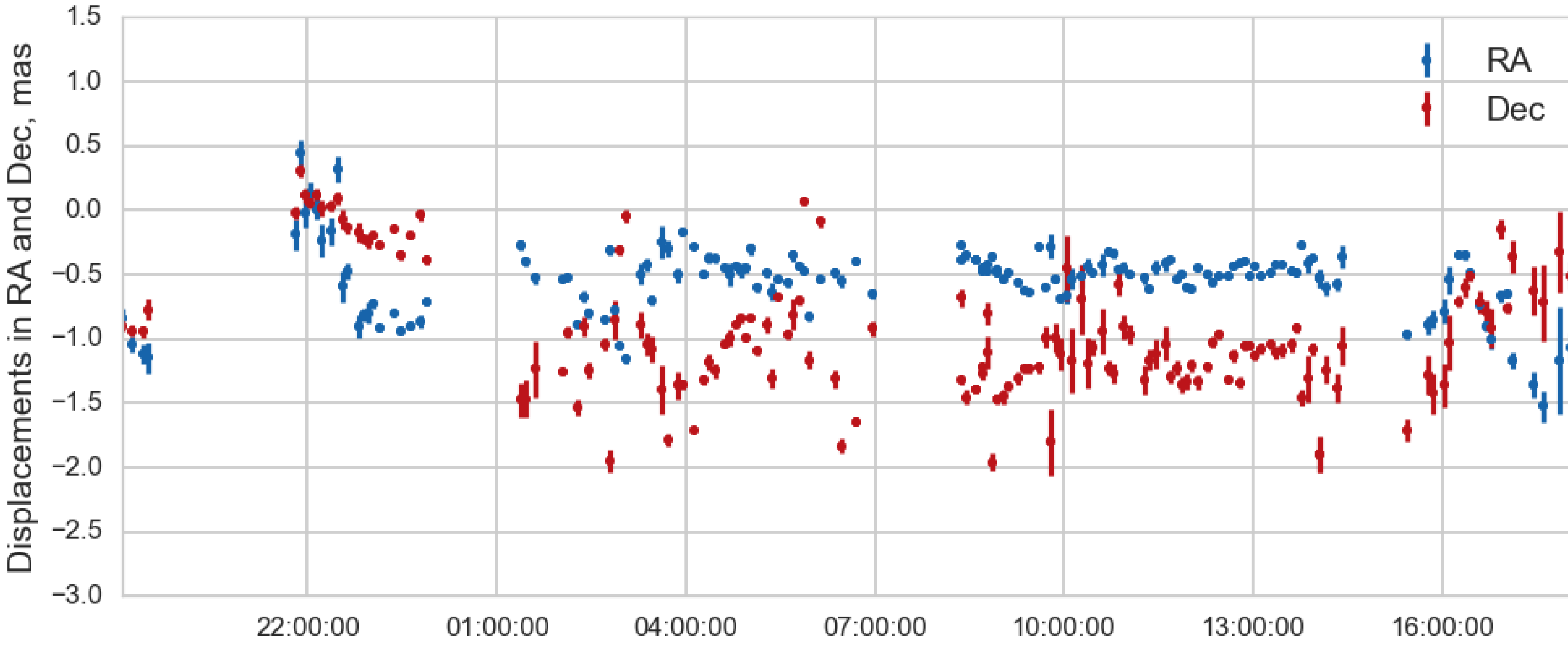
ESA's Mars Express Phobos fly-by



Measuring position: 'geodetic' approach



ESA’s Mars Express Phobos fly-by



Displacements from the a priori lateral position of MEX as a function of time, measured using the imaging approach. Displacements in Right Ascension (mas) are shown in blue, in Declination (mas) – in red. 2-minute integration time; net time ‘on target’ ~ 5.5h. December 28-29, 2013.

Conclusion and outlook

- Lateral position and radial Doppler of MEX spacecraft measurement precision:
  50 m and 30 μm/s, respectively
- Offsets in RA and Dec must be further investigated
- PRIDE for ESA's JUICE mission