PRIDE: A MULTI-DISCIPLINARY ENHANCEMENT OF SPACE SCIENCE MISSIONS

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in collaboration with

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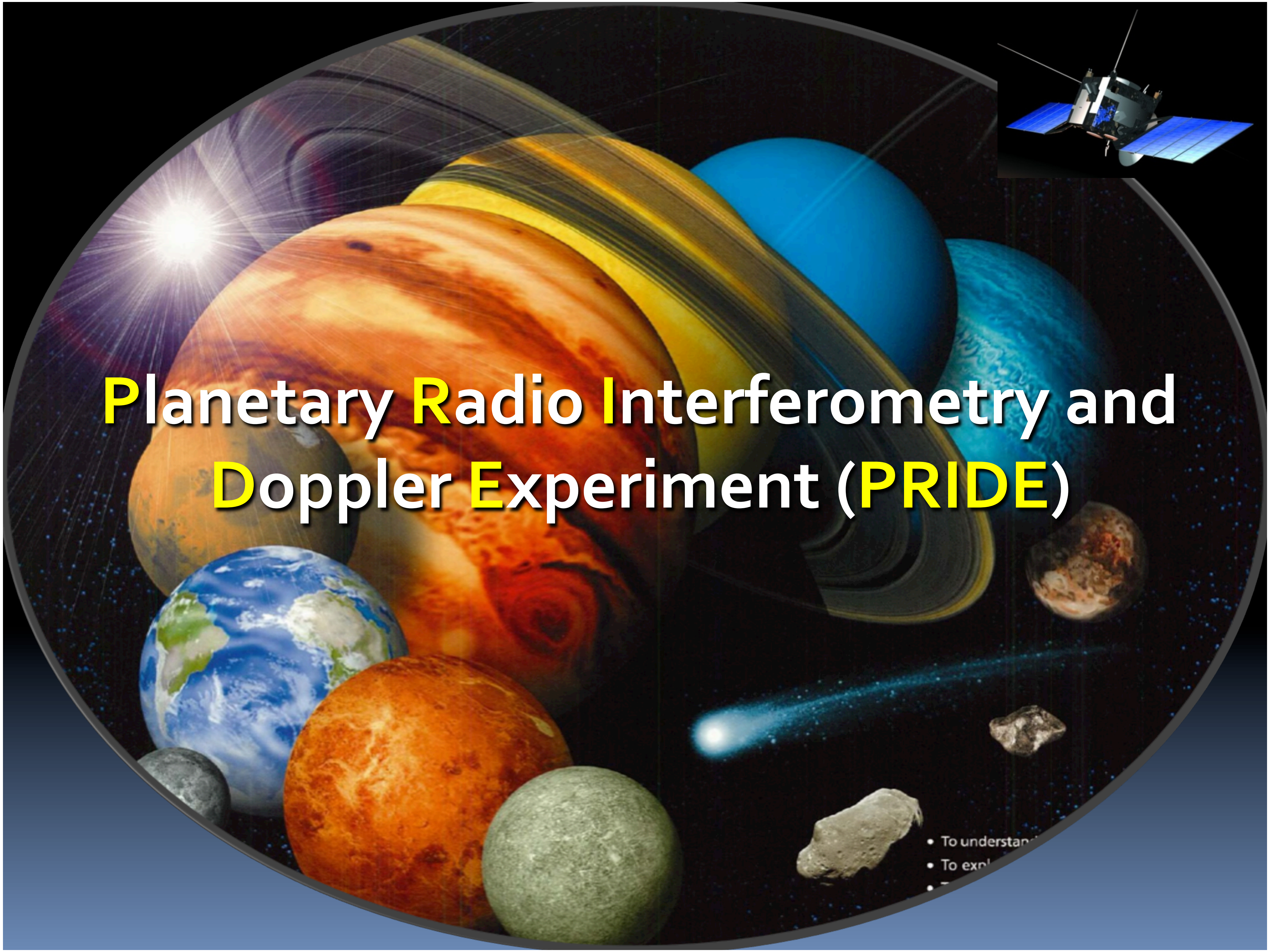
Planetary Radio Interferometry and Doppler Experiment (PRIDE)



Prehistory

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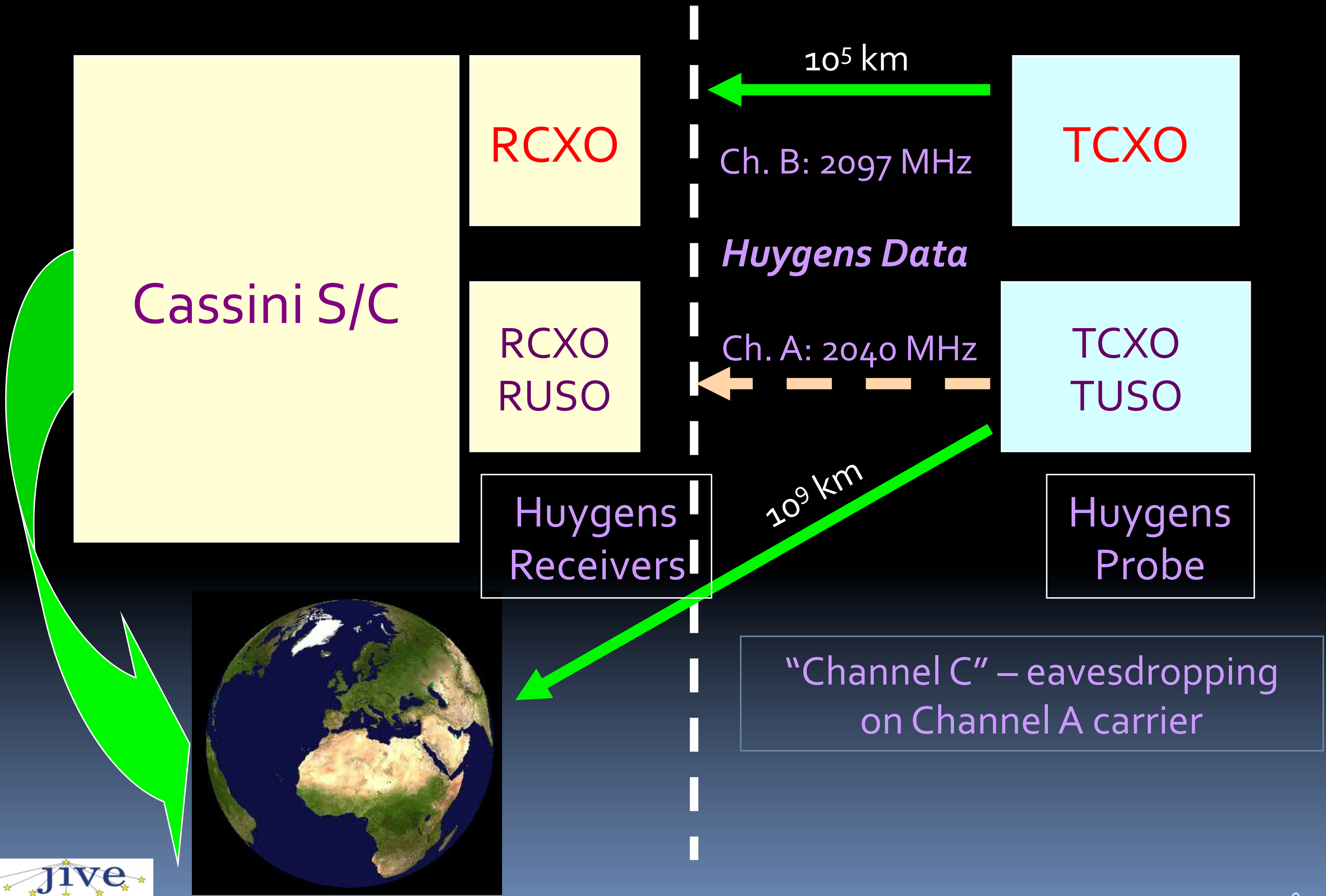
VEGA balloons VLBI tracking, 1986

f = 1.6 GHz, Δf = 2 MHz, 20 radio telescopes

σ_x = 10 km
σ_v = 1 m/s

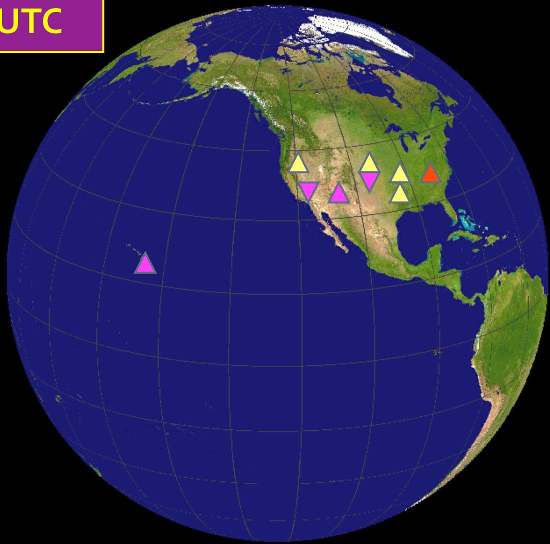
Preston et al. 1986, Science, 231, 1414

Huygens VLBI tracking: eavesdropping…

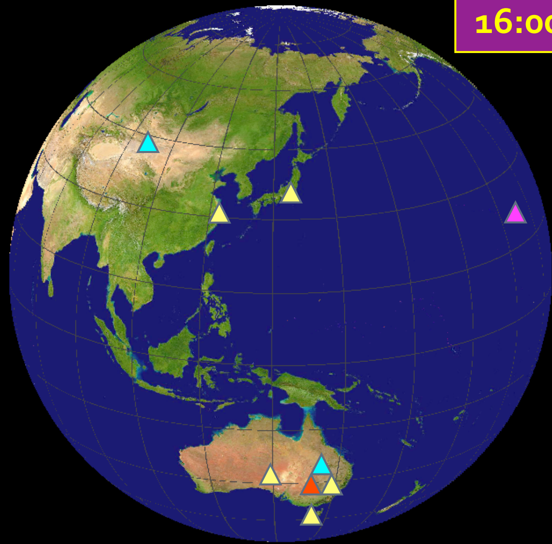


VLBI tracking of Huygens, 14 January 2005

09:30 UTC



16:00 UTC



~20 radio photons
per 25-m telescope
per second…

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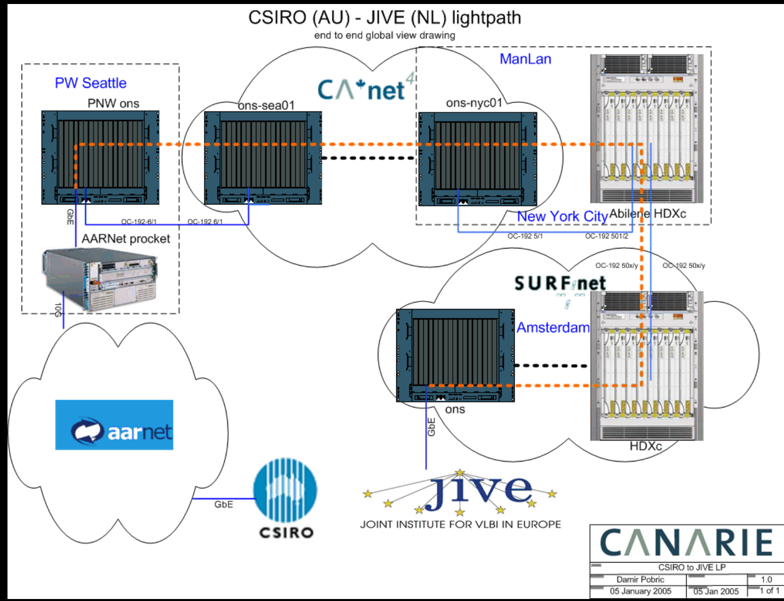
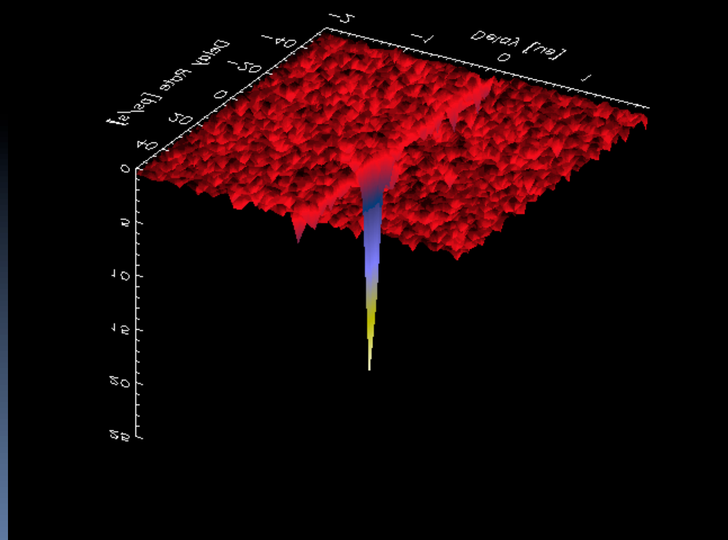
e-VLBI & “Night Flight”: 14 – 15 January



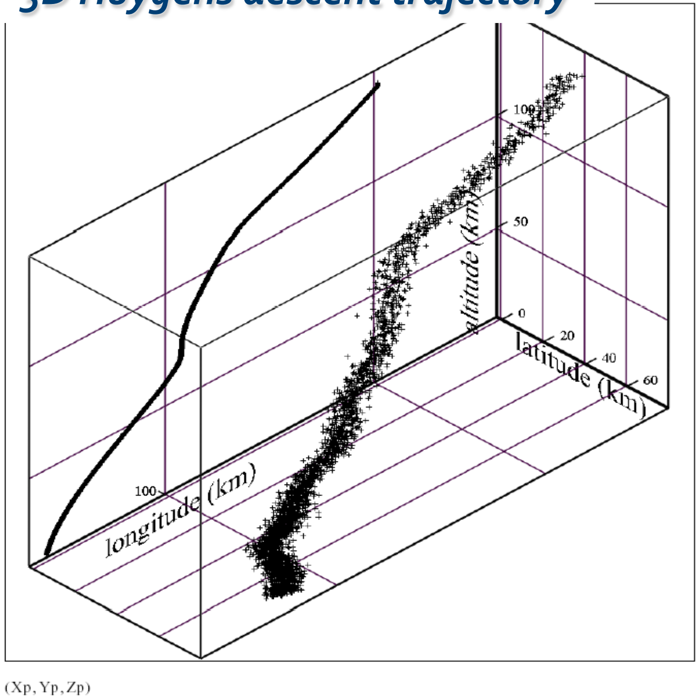


A.Tzioumis & C.Phillips, ATNF, acting in near-RT mode

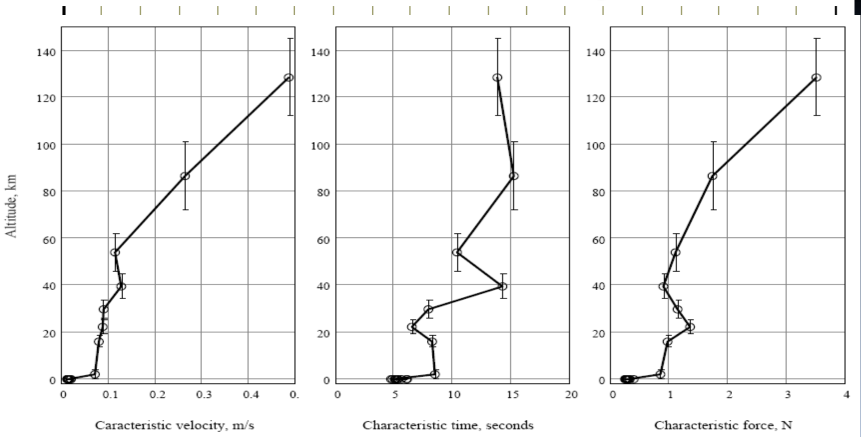
Huygens VLBI heritage: 20 photons/dish/s

- Ad hoc use of the Huygens "uplink" carrier signal at 2040 MHz
- Utilised 17 Earth-based radio telescopes
- Non-optimal parameters of the experiment (not planned originally)
- Achieved 1 km accuracy of Probe's descent trajectory determination
- Assisted in achieving one of main science goals of the mission – vertical wind profile

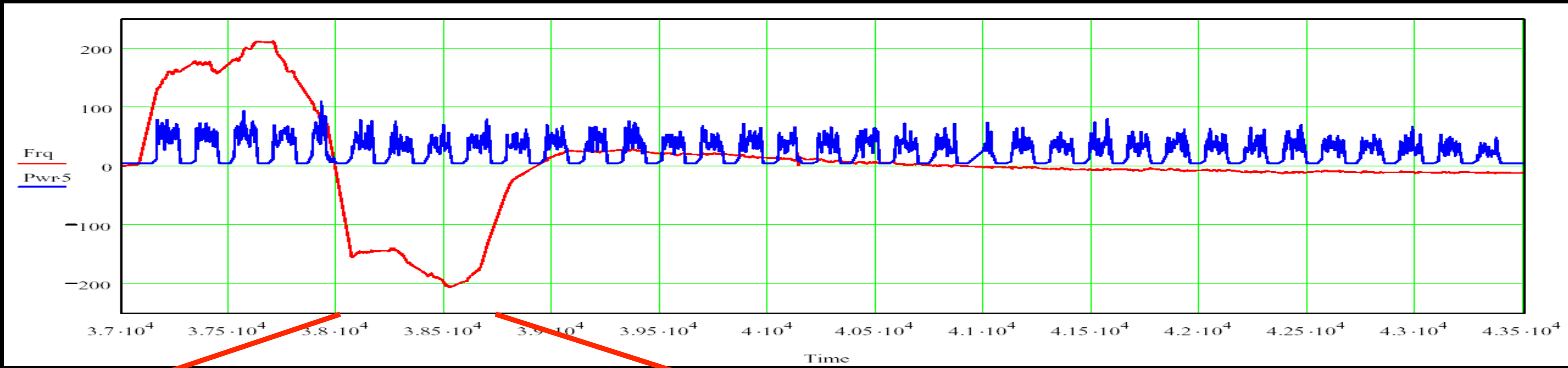
3D Huygens descent trajectory

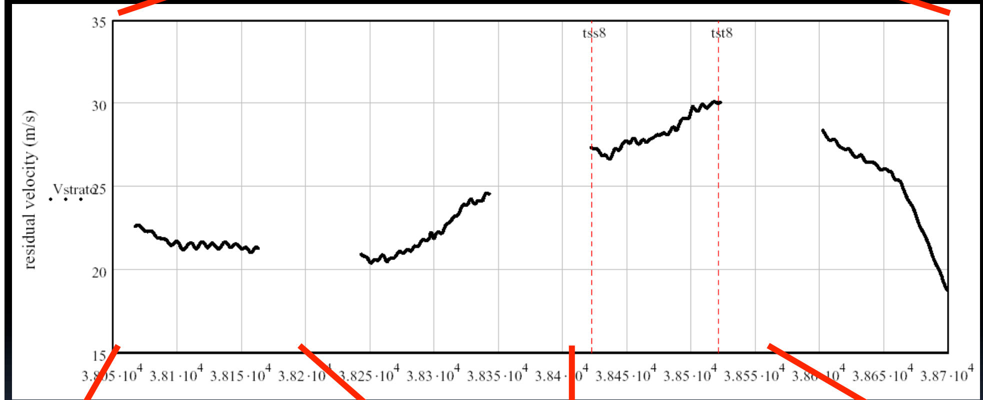


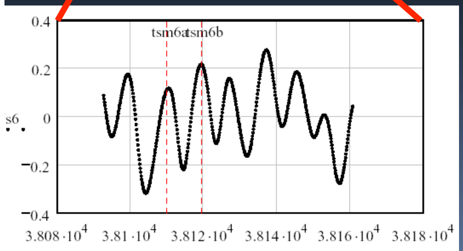
Titan atmosphere turbulence signature

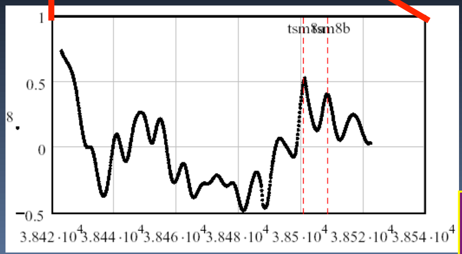


VLBI processing by-product: Doppler data (probe's motion)

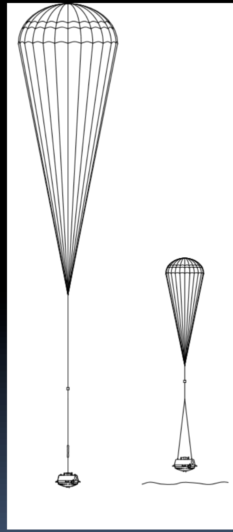


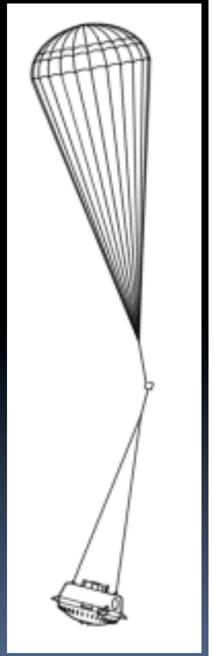






T = 8÷10 s
ΔV = 0.22 m/s
A ≈ 0.6 m





Data available for analysis!

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Methods and algorithms

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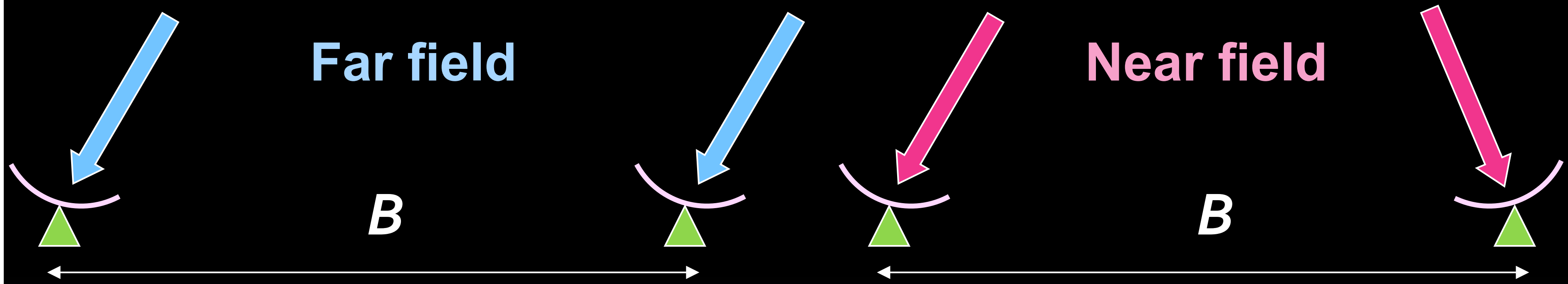
Working in the near field with PRIDE

While praying $\theta \propto \dfrac{\lambda}{B}$, let's not forget $R_{nf} \propto \dfrac{B^2}{\lambda}$



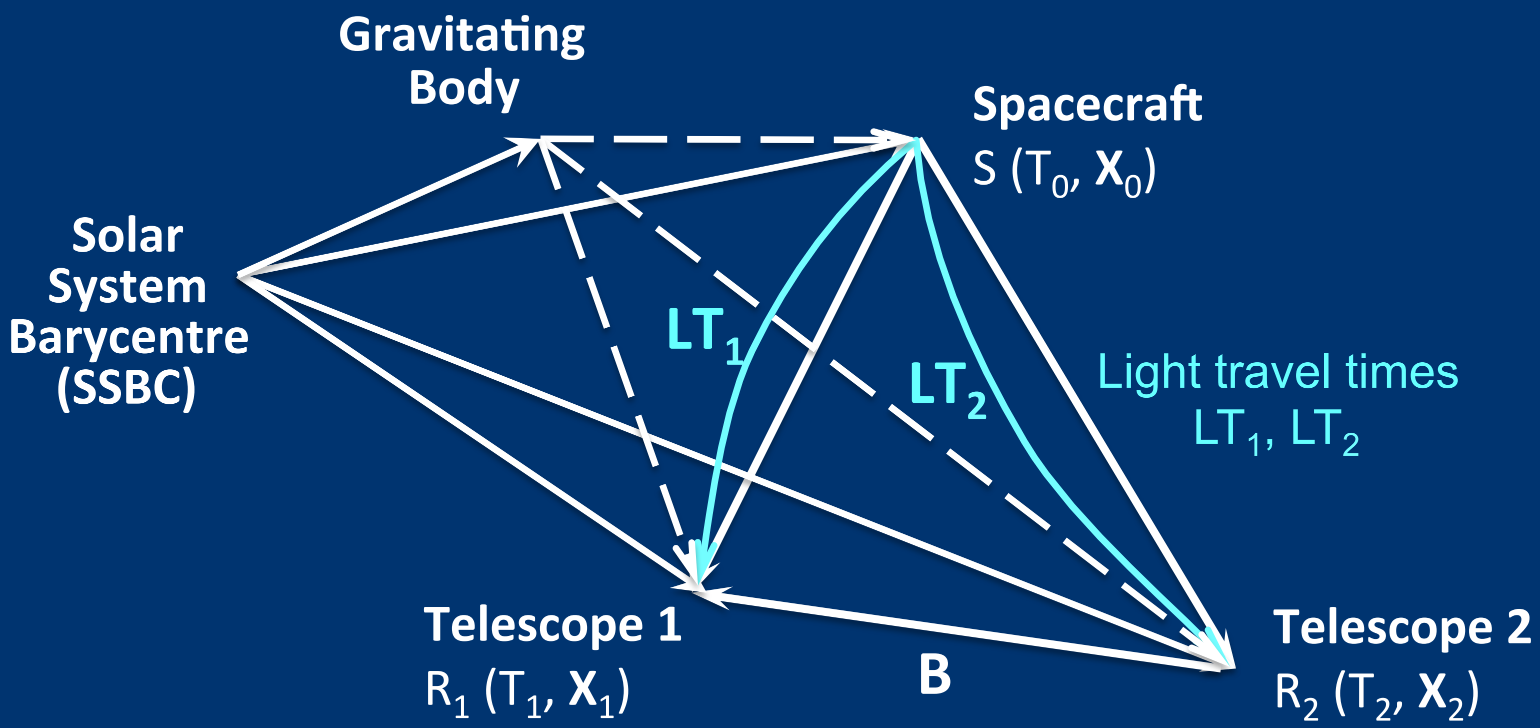
Baseline	100 km	1000 km	10^4 km
Facility	MERLIN	EVN_{WE}	EVN
λ = 3.6 cm X-band	2 AU	200 AU	0.1 pc
λ = 1 cm K_a-band	8 AU	750 AU	0.5 pc

Spacecraft "imaging" and state vector estimation by means of phase-referencing VLBI:

- Near-field delay model
- Propagation effects
- "*uv*-plane" for near-field case

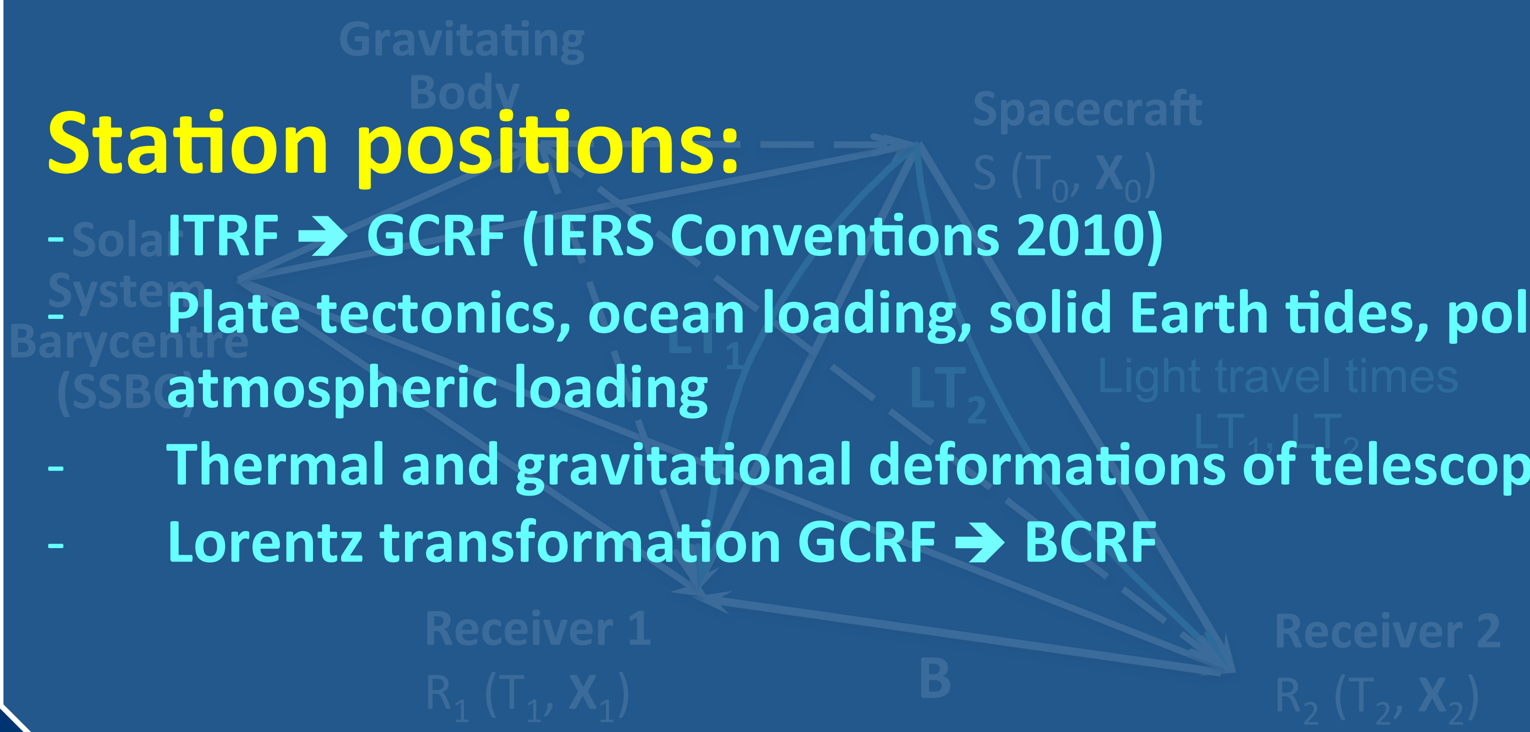
Details in: *Duev et al. 2012, A&A 541, A43*

Near-field delay model



Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame

Near-field delay model



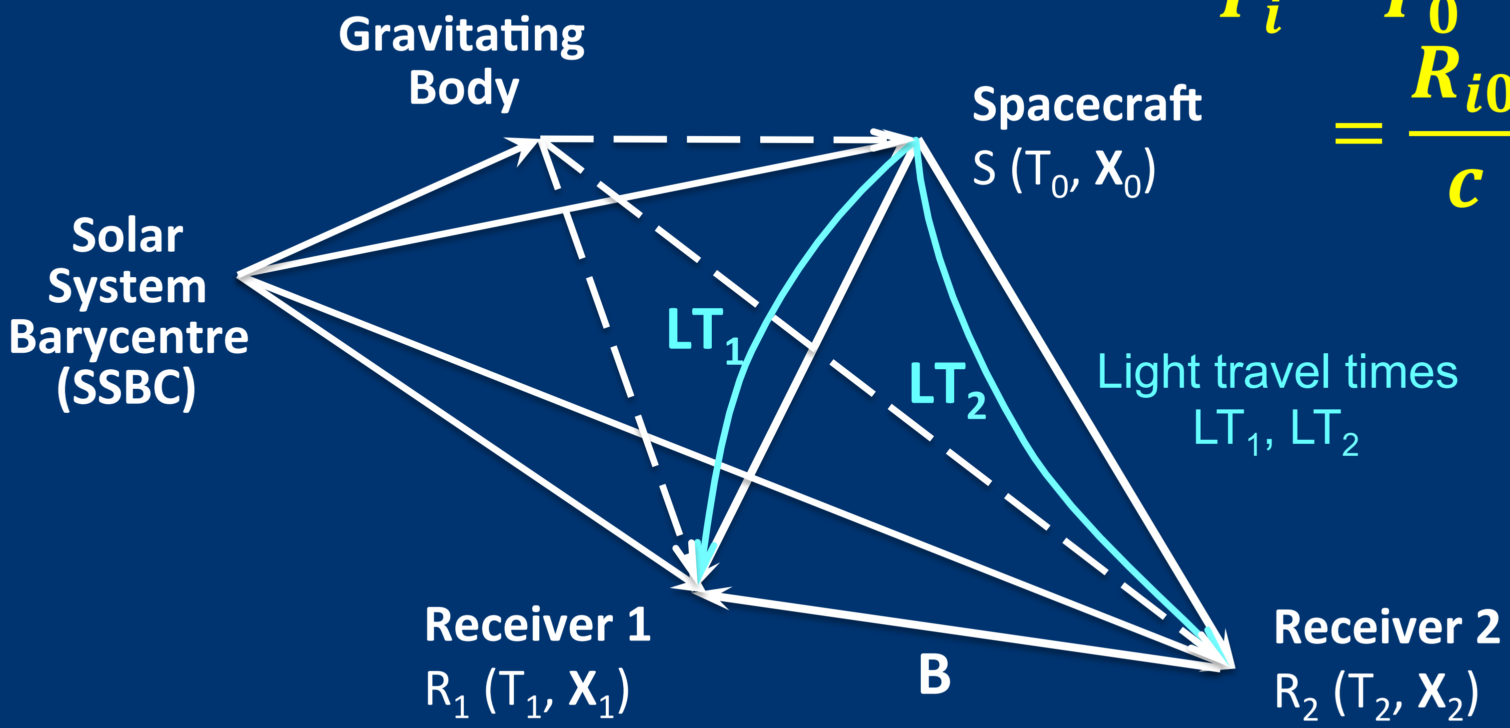
Station positions:

- ITRF ➔ GCRF (IERS Conventions 2010)
- Plate tectonics, ocean loading, solid Earth tides, pole tide, atmospheric loading
- Thermal and gravitational deformations of telescopes
- Lorentz transformation GCRF ➔ BCRF

Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame

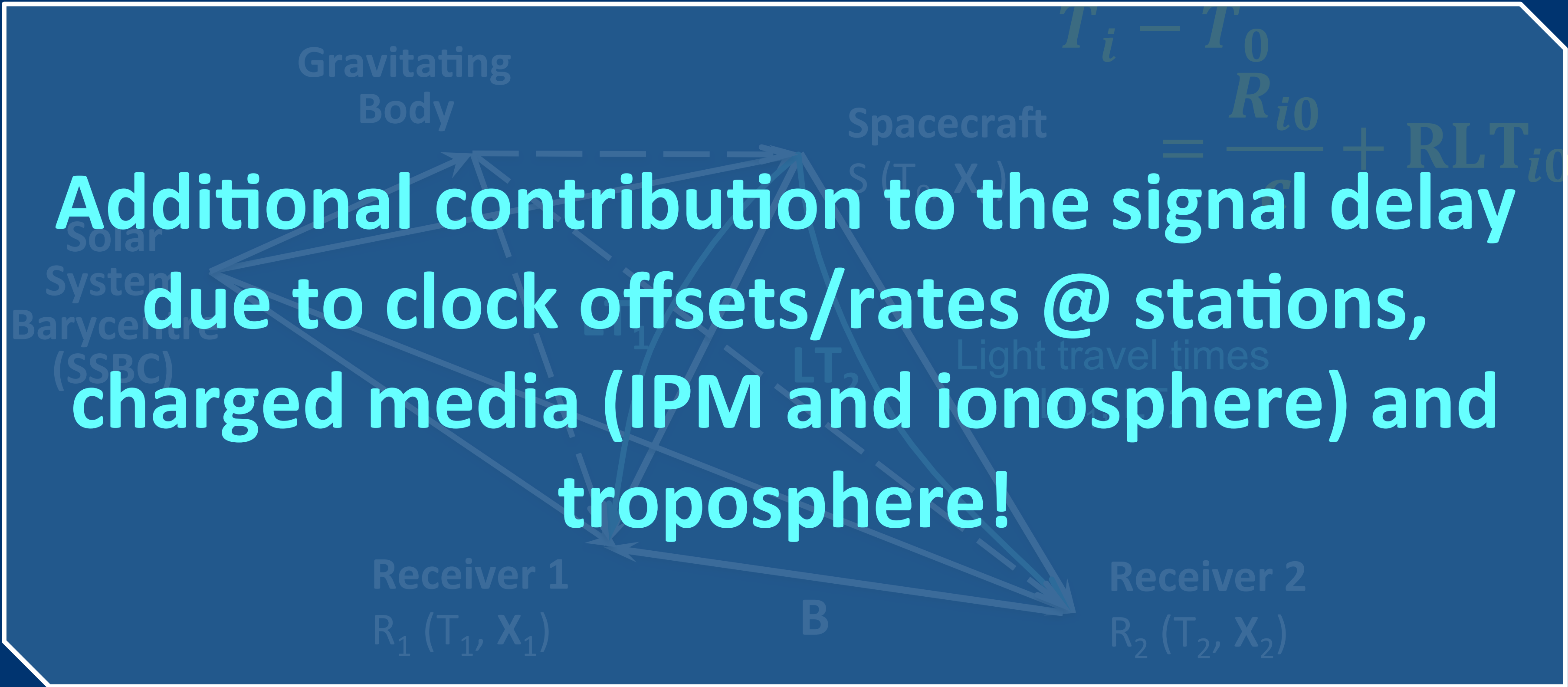
Near-field delay model

$$T_i - T_0 = \frac{R_{i0}}{c} + \mathrm{RLT}_{i0}$$



Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame

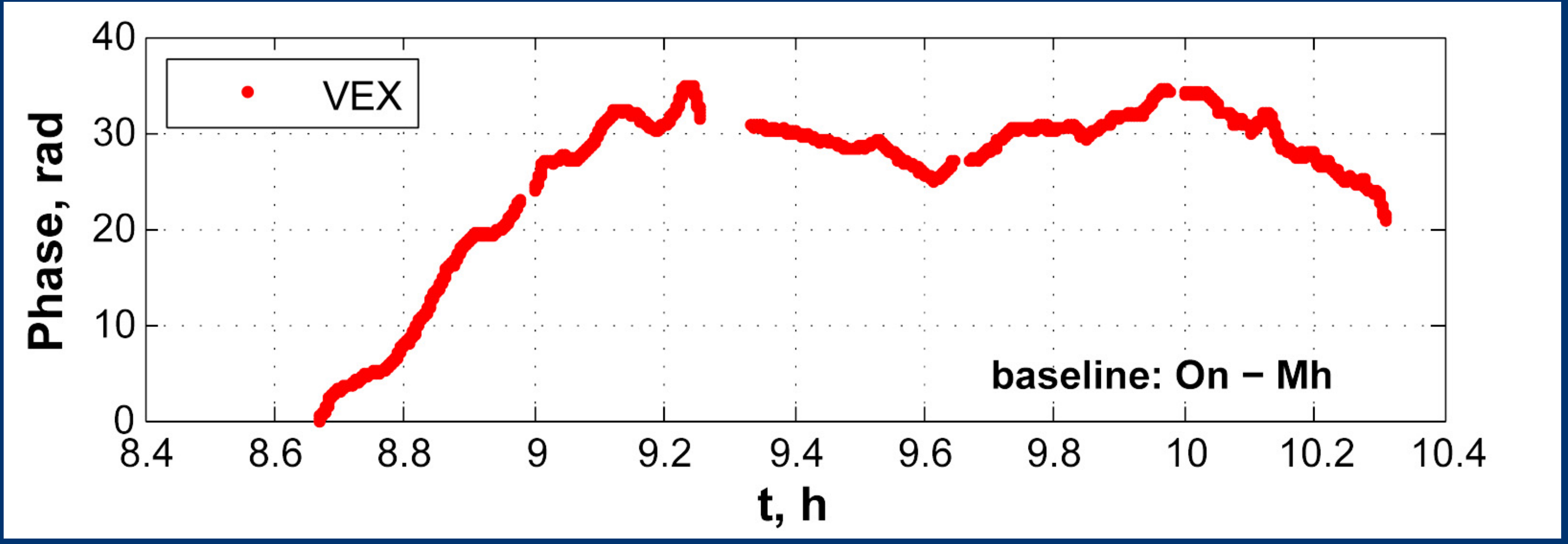
Near-field delay model



Additional contribution to the signal delay due to clock offsets/rates @ stations, charged media (IPM and ionosphere) and troposphere!

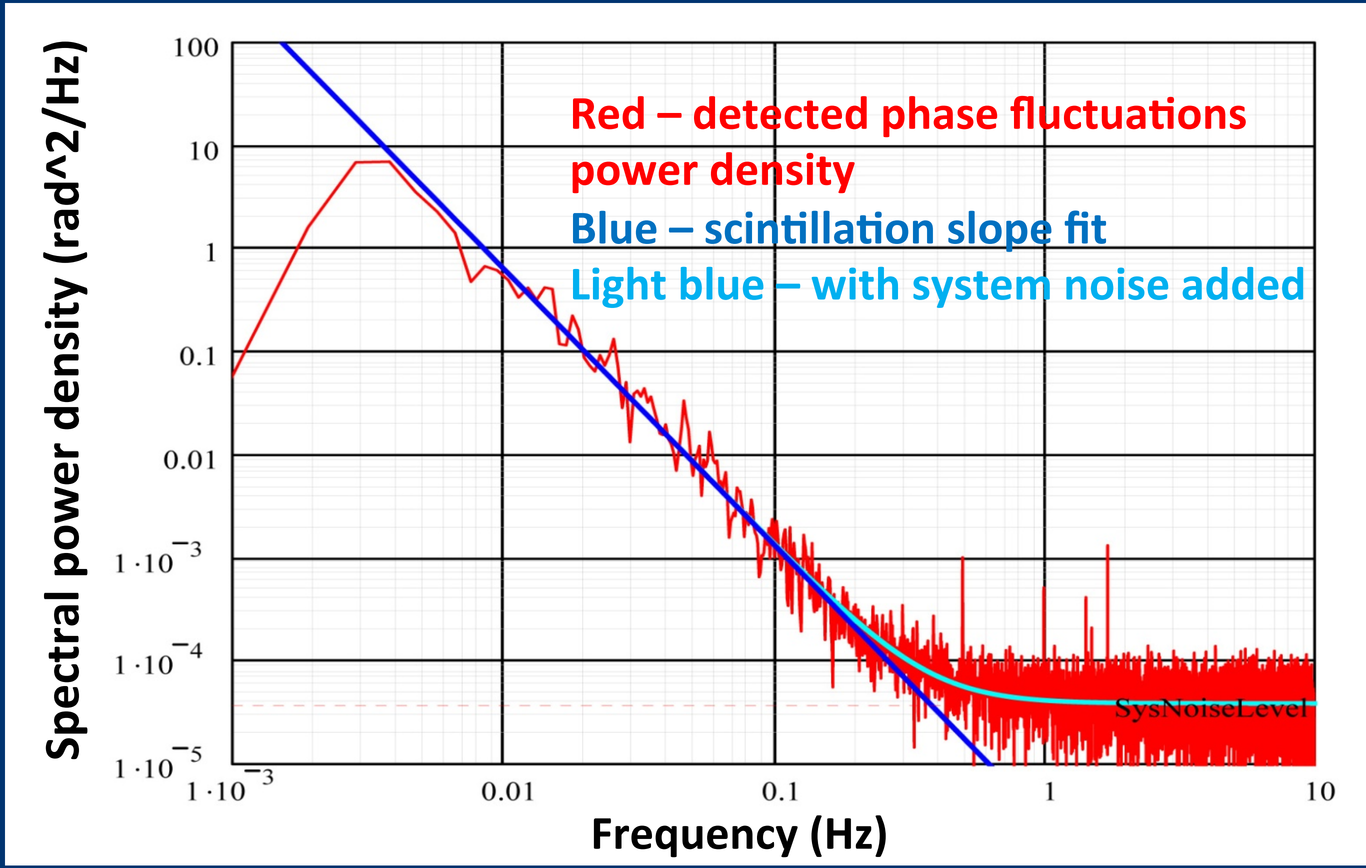
Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame

Why phase-referencing?



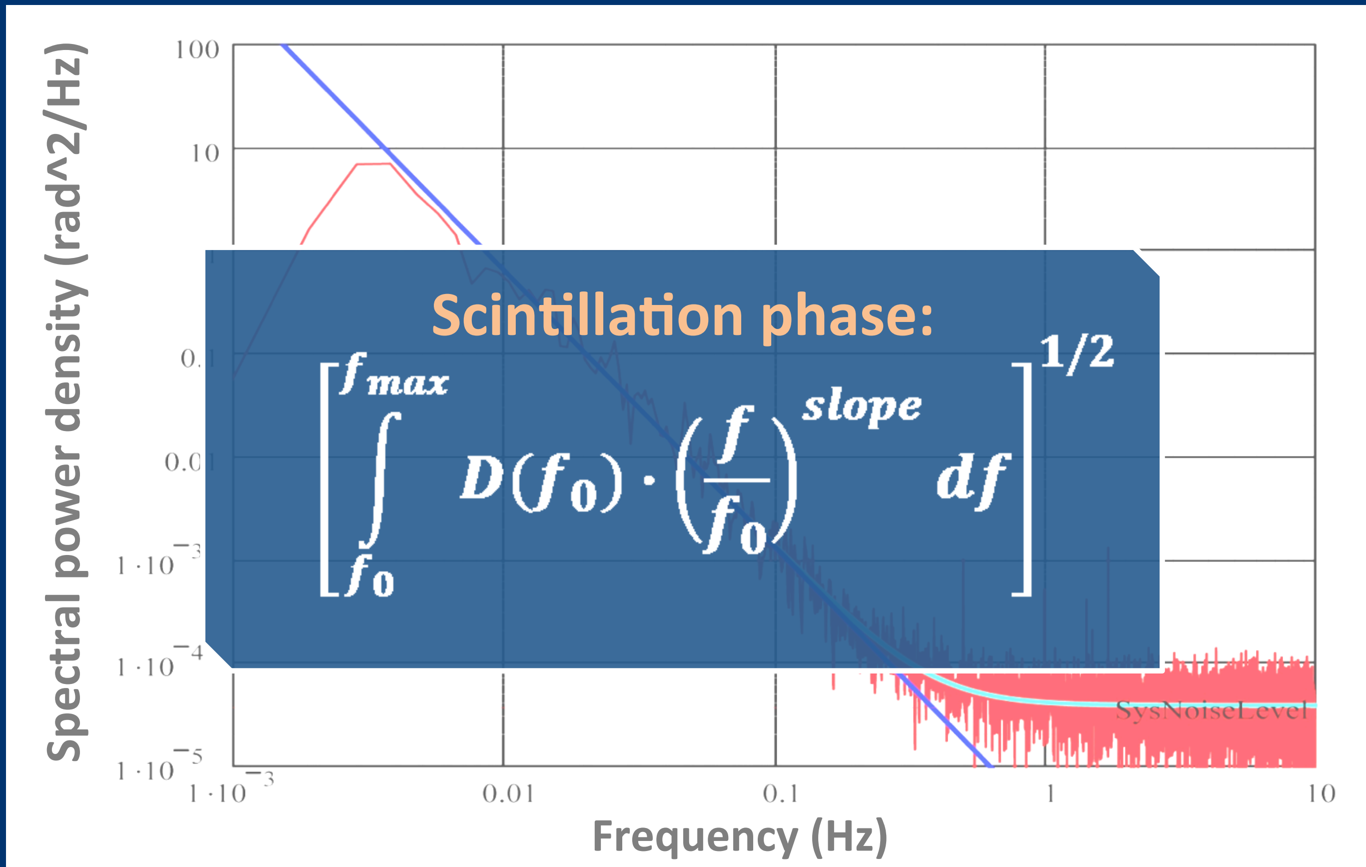
VEX phase behaviour on the baseline Onsala – Metsahovi, 25.03.2011, no phase referencing

Why phase-referencing?



Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

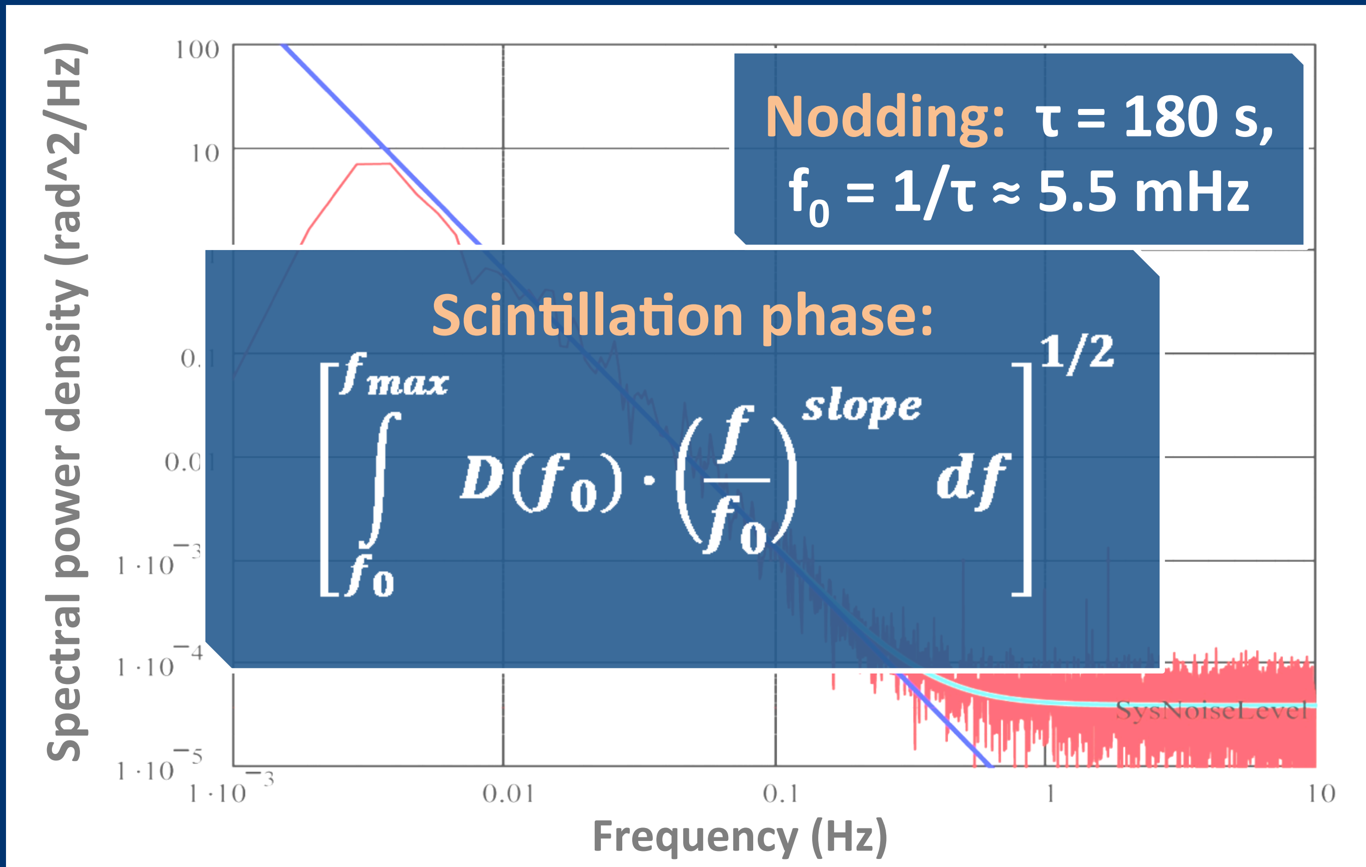
Why phase-referencing?



$$\left[\int_{f_0}^{f_{max}} D(f_0)\cdot\left(\frac{f}{f_0}\right)^{slope} df\right]^{1/2}$$

Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

Why phase-referencing?



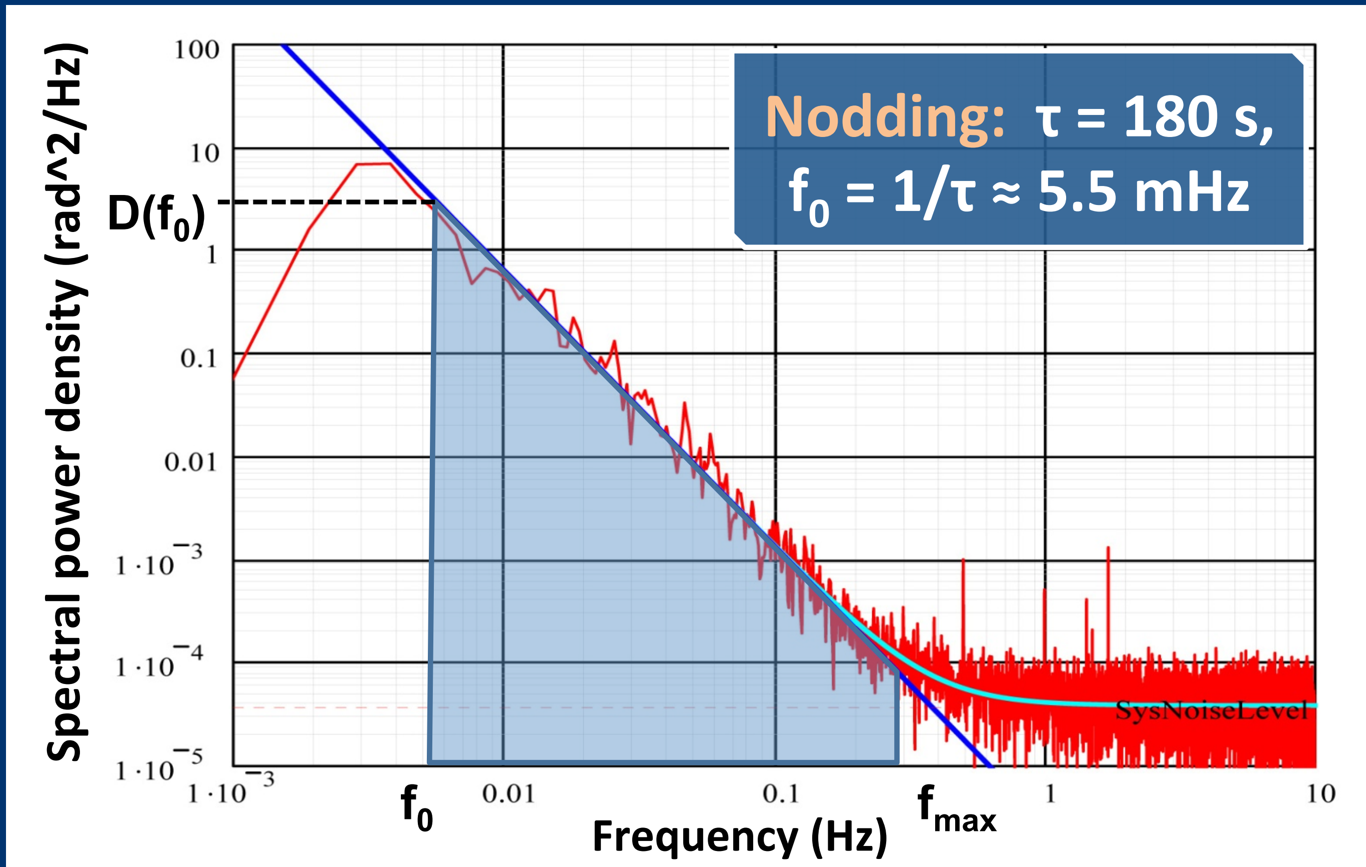
Nodding: $\tau = 180$ s, $f_0 = 1/\tau \approx 5.5$ mHz

Scintillation phase:

$$\left[\int_{f_0}^{f_{max}} D(f_0) \cdot \left(\frac{f}{f_0}\right)^{slope} df\right]^{1/2}$$

Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

Why phase-referencing?



Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

Propagation effects

Ionosphere:

IGS vertical TEC maps + proper projection onto the LoS

Troposphere:

Ready-to-use (empirical) models:

- Zenith delay + Mapping Function
  - *Niell Mapping Functions NMF*
  - *Vienna Mapping Functions VMF1*

On-demand (dynamic) models:

- Ray-tracing through Numerical Weather Models (ECMWF)

Tropospheric delay model

АСТРОНОМИЧЕСКИЙ ЖУРНАЛ, 2011, том 88, № 11, с. 1–9

УДК 520.8-77-852-653

МОДЕЛЬ ТРОПОСФЕРНОЙ ЗАДЕРЖКИ СИГНАЛА ПРИ РАДИОАСТРОНОМИЧЕСКИХ НАБЛЮДЕНИЯХ

© 2011 г. Д. А. Дуев[1,2*], С. В. Погребенко[2], Г. Молера Калвес[3]

$$\mathrm{mf}(e) = \frac{1 + \dfrac{a}{1 + \dfrac{b}{1 + c}}}{\sin e + \dfrac{a}{\sin e + \dfrac{b}{\sin e + c}}},$$

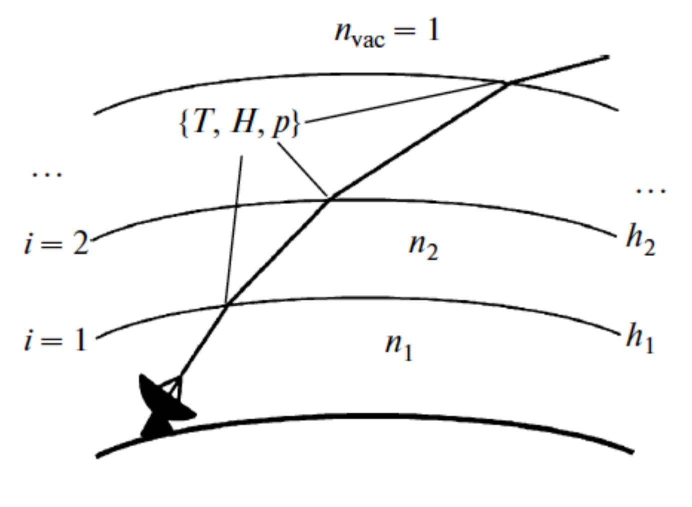
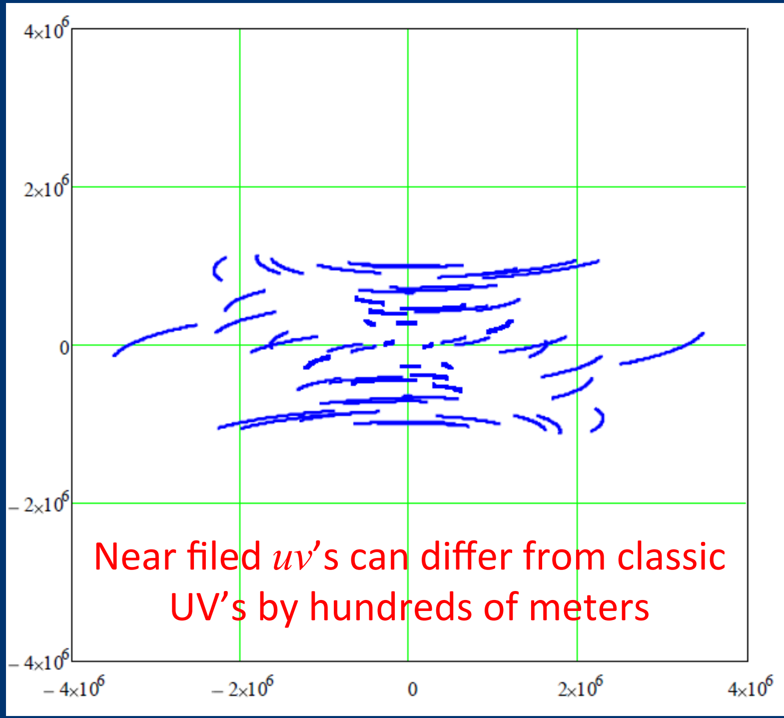


Рис. 1. Иллюстрация к вычислению полной тропосферной задержки.

"uv-coverage" for near-field VLBI

Near-field VLBI: Jacobians instead of uv-projections of baselines:

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



Near Field "uv's" for EM081c VEX pointings (in kilometers)
Longest East-West – Ys-Zc,
Longest North-South – Mh-Ys

Duev et al. 2012, AA541, A43

Spacecraft "imaging" and state vector estimation

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

$$S(u,v)\Big|_t = \sum_{i=1}^{N_s-1}\sum_{j=i+1}^{N_s} \delta(u-u_{ij}, v-v_{ij})\Big|_t$$ **- sampling function**

$$V(u_{ij},v_{ij})\Big|_t = w_{ij}\cdot e^{-2\pi i\cdot\phi_{ij}}\Big|_t$$ **- "visibility"**

Image:

$$I(l,m) = \sum_t I_t(l,m)$$

$$= \sum_{t=t_s}^{t_e}\left(\sum_{i=1}^{N_s-1}\sum_{j=i+1}^{N_s} w_{ij}\cdot e^{-2\pi i\cdot\phi_{ij}}\cdot \Re(e^{i\cdot 2\pi\cdot(u_{ij}l+v_{ij}m)})\right)\Bigg|_t$$

“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

Corrections to the S/C a priori lateral position:

$$\overrightarrow{\Delta\alpha}\,\Big|_t = \left((J^T\cdot J)^{-1}\cdot J^T\cdot \overrightarrow{\Delta\phi}\right)\Big|_t$$

Tips for "harvesting" in near field

- Use the most accurate delay model accounting for
  - "Classical" geometry (geodetic accuracy)
  - Propagation effects
    - *Dry atmosphere*
    - *Wet atmosphere (meteo data)*
    - *Local ionised medium (Earth ionosphere)*
    - *Total Electron Content (TEC, see presentation by G. Molera)*
    - *General relativity effects (light deflection)*
- Exploit phase-referencing
  - thus need for good nearby calibrators
- *Bonus: "free" radial Doppler*

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PRIDE practices

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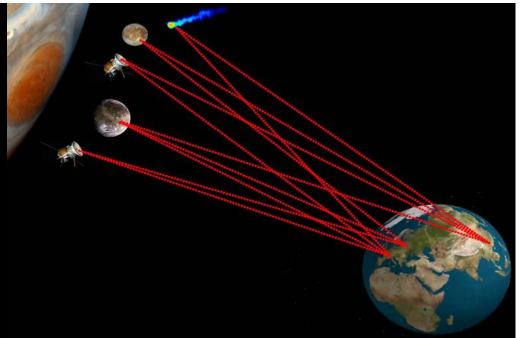
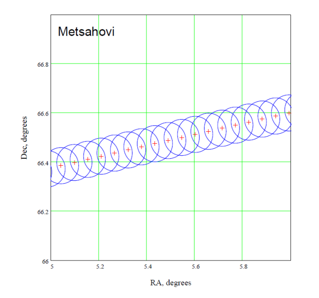
PRIDE in practice



- *Proposing the observations*
- *Contacting the telescopes*
- *Getting the ephemeris*
- *Scheduling*
- *The observations*
  - recording and shipping
- *Data analysis*
  - AIPS
  - S/C Spectrometer
  - SFXC implementation

- *Planning ahead*
  - Science
  - New observations
  - Search for calibrators

The Schedule



- JPL's SPICE software.

- SPICE “kernels” contain navigation and other ancillary information of a specific mission.

    - For RadioAstron these kernels are not currently available.
    - The spacecraft state vectors with respect to each station were evaluated using built-in SPICE routines.
    - The obtained state vectors in rectangular coordinates were converted to RA/Dec coordinates, to serve as input for the antenna pointing.

- SCHED/VEX

- Tweaks and hacks for Geodesy/Astro patching.

```
scan No0193;
*     start=2011y319d03h49m18s <= original start, modified for tape start.
      start=2011y319d03h49m13s; mode=vex.x; source=34800;
*                 :data_good:data_stop:goto_foot: pass:  wrap :driv:tape at
      station=On:     5 sec:   15 sec:   47.705 GB:   :         : 1;
endscan;
scan No0194;
*     start=2011y319d03h49m34s <= original start, modified for tape start.
      start=2011y319d03h49m28s; mode=vex.x; source=34815;
      station=On:     5 sec:   16 sec:   47.953 GB:   :         : 1;
endscan;
scan No0195;
*     start=2011y319d03h49m49s <= original start, modified for tape start.
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      station=On:     5 sec:   15 sec:   48.201 GB:   :         : 1;
endscan;
scan No0196;
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scan No0199;
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scan No0200;
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scan No0204;
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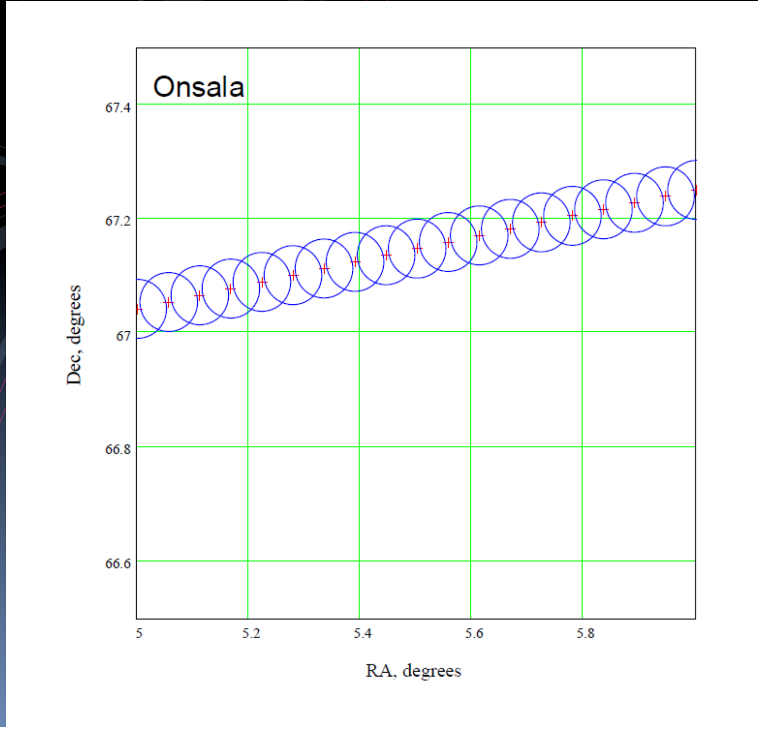

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The Observations

- Standard VLBI observations. Phase-referencing mode.

- 8-16 MHz filters. 512-1024 Mbps. Frequencies (tone in one sub bands). Wide band for calibration purposes.

- Recorded on Mark5 (or PCEVN).

    - All data can be transferred via Tsunami after the observations.
    - Or (possibly) the spacecraft data may be buffered locally (or at the JIVE correlator) while the phase-reference source may be correlated on real-time (e-VLBI) to check for problems. [in collaboration with NEXPReS].

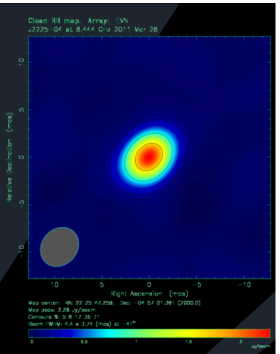
Tone → x-band RCP

Four channels of 8 MHz overlapped and shifted by 10 KHz (for better RFI determination) and/or wider separation for better S/N on the calibrator.

The Array:

Metsähovi (Finland)
Medicina, Noto, Matera (Italy)
Wettzell (Germany)
Yebes (Spain)
Pushchino, Svetloe, Zelenchukskya (Russia)
Onsala (Sweden)
Warkworth (New Zealand)
Hartebeesthoek (South Africa)
Fortaleza (Brazil)
VLBA antennas (USA)

Data Analysis

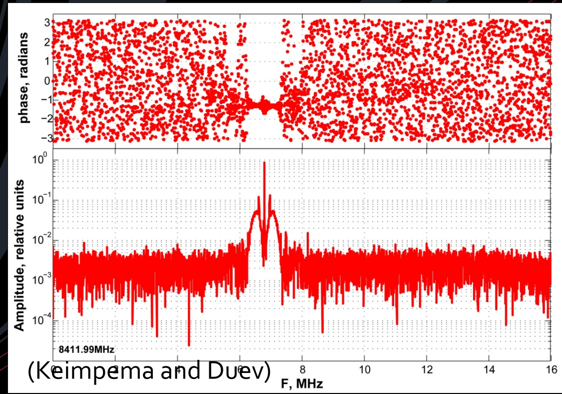


- SFXC correlation of the phase referencing calibrator.

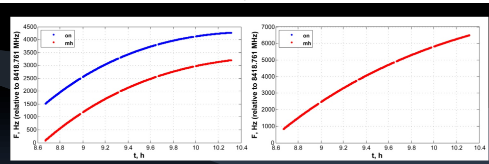
(SFXC is JIVE hardware correlator, which is based on the spacecraft tracking software: Huygens.)

- AIPS standard data reduction for the phase reference calibrator
  - Calculation of rates and delays
  - Imaging

- S/C spectrometer for analysing the S/C tone.
  (see Sergei's presentation)



(Keimpema and Duev)



- SFXC correlation of the Spacecraft signal.
  - high spectral resolution needed. Not possible with hardware correlator.
  - SFXC specially modified for Near-Field VLBI and tropospheric corrections
  - strict collaboration with JIVE R&D

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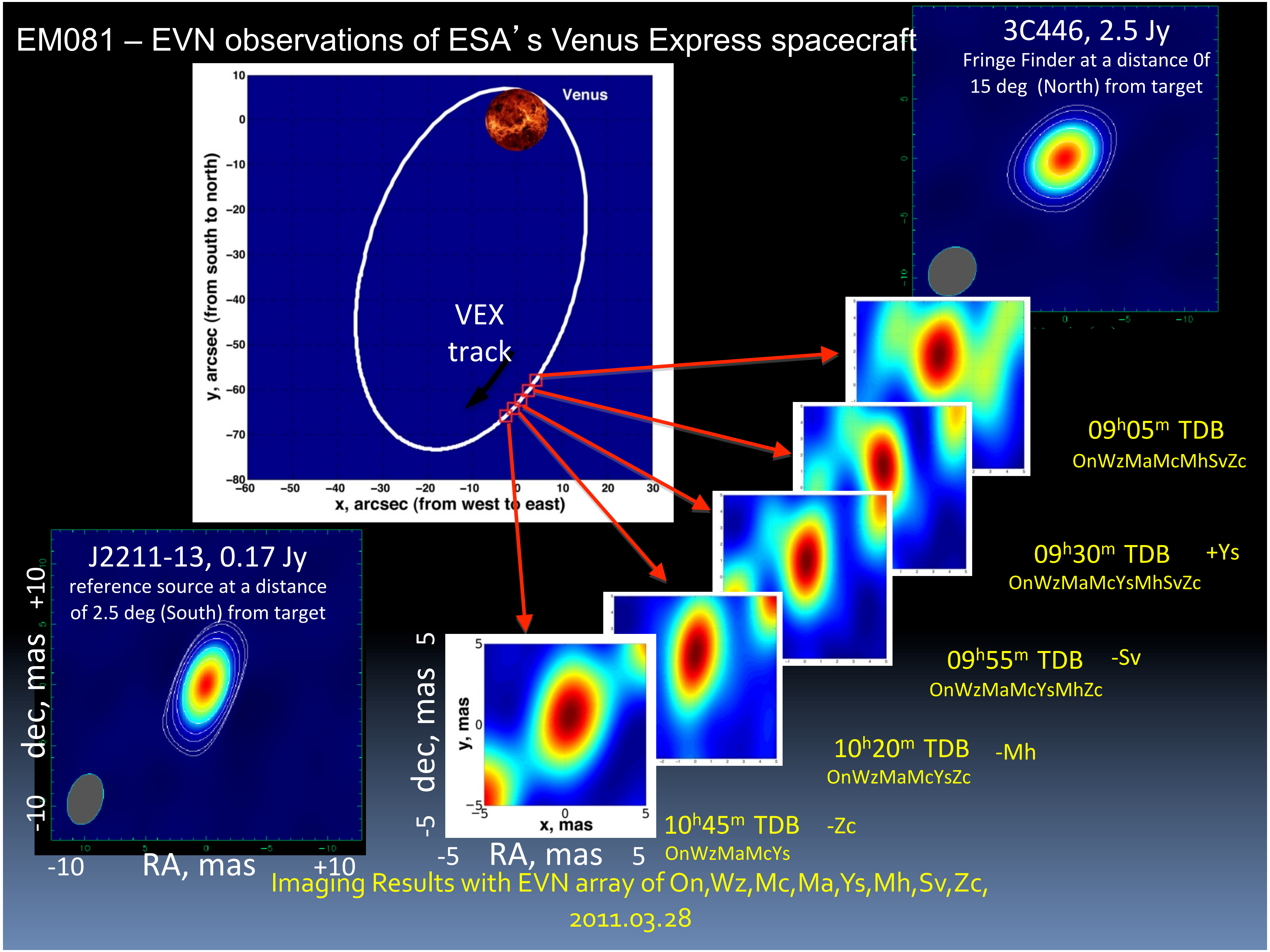
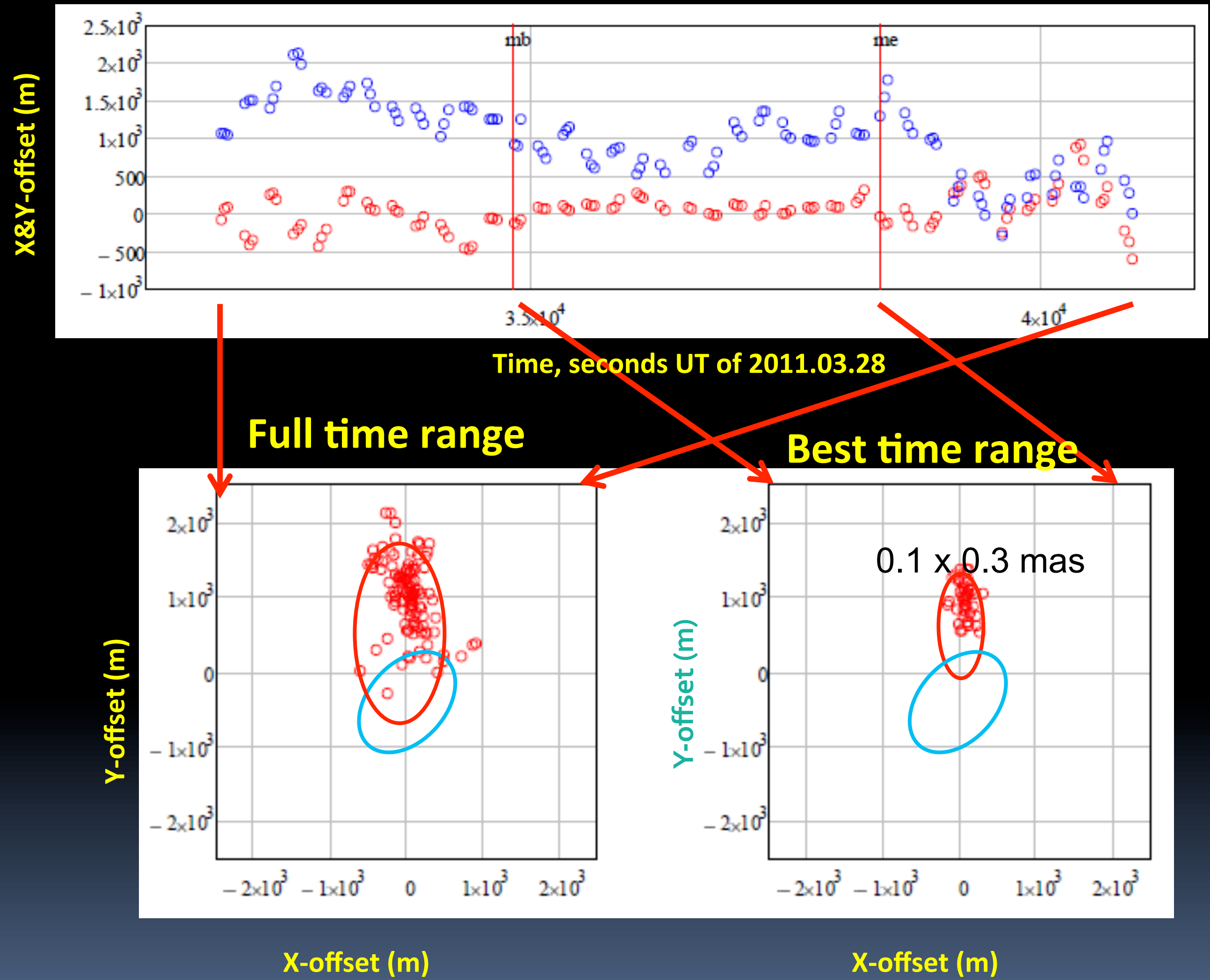

EM081 – EVN observations of ESA's Venus Express spacecraft
Venus
VEX
track
y, arcsec (from south to north)
x, arcsec (from west to east)
3C446, 2.5 Jy
Fringe Finder at a distance 0f
15 deg (North) from target
J2211-13, 0.17 Jy
reference source at a distance
of 2.5 deg (South) from target
dec, mas +10
-10
RA, mas
+10
dec, mas 5
-5
RA, mas 5
y, mas
x, mas
09h05m TDB
OnWzMaMcMhSvZc
09h30m TDB +Ys
OnWzMaMcYsMhSvZc
09h55m TDB -Sv
OnWzMaMcYsMhZc
10h20m TDB -Mh
OnWzMaMcYsZc
10h45m TDB -Zc
OnWzMaMcYs
Imaging Results with EVN array of On,Wz,Mc,Ma,Ys,Mh,Sv,Zc,
2011.03.28

Measured coordinate offsets wrt *a priori* trajectory, supplied by ESOC
X- offset – red, Y-offset – blue. X and Y are approximately RA and Dec.

Measurement sampling – 30 s,
1 km = 1.1 mas at 1.24 AU apparent distance



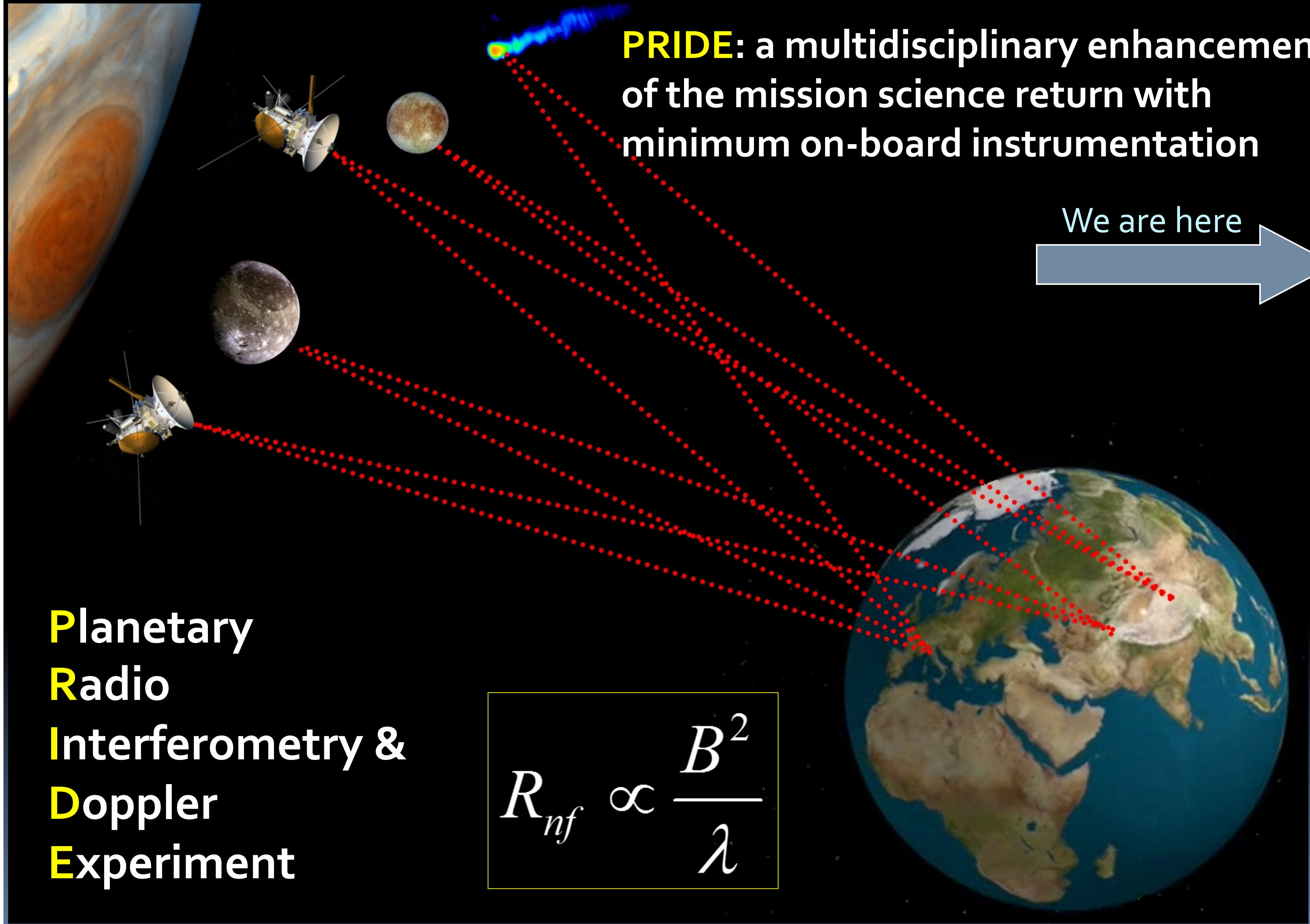
Software correlator fine tuned and intensively tested for near field delay model

and very high spectral resolution

PRIDE “users”

JOINT INSTITUTE FOR VLBI IN EUROPE

Generic PRIDE configuration



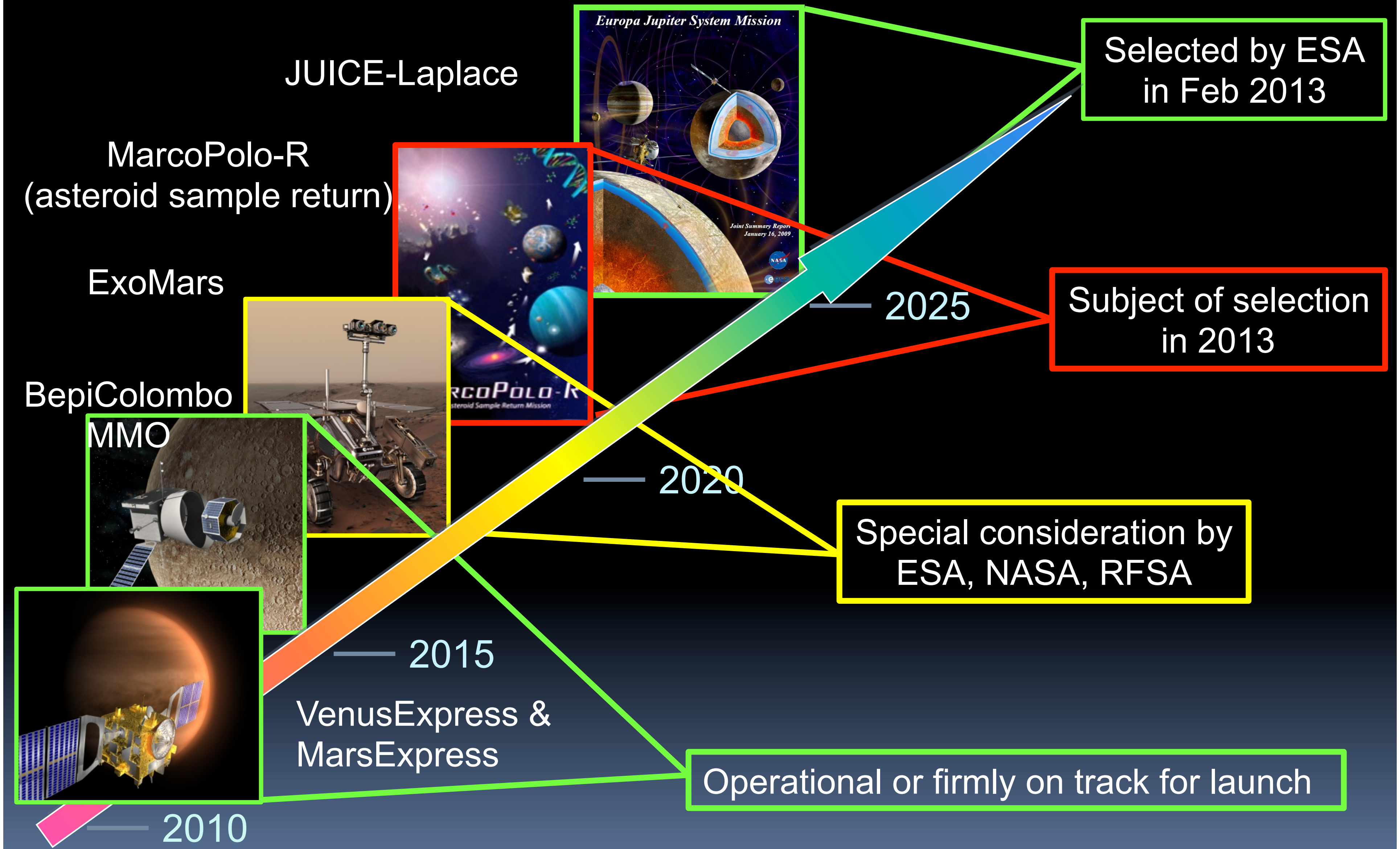
PRIDE: a multidisciplinary enhancement of the mission science return with minimum on-board instrumentation

We are here

Planetary
Radio
Interferometry &
Doppler
Experiment

$$R_{nf} \propto \frac{B^2}{\lambda}$$

ESA planetary science missions – VLBI “customers”



PRIDE-2013 vs Huygens VLBI tracking

Mission	Distance	Transmitter power/gain	Band	Time resolution	Delay noise	Positional accuracy (lateral)
	[AU]		*[GHz]*	*[s]*	*[ps]*	*[m]*
Huygens VLBI	8	3 W / 3 dBi	2.0 (S)	500	15	1000
PRIDE--2013	5	10 W / 6 dBi	2.3 (S)	100	5	120
			8.4 (X)	10	3	70
			32 (Ka)	10	1	23

Tom-Tom accuracy anywhere in Solar System

- Conservative estimate, today's technology
- Minimal special requirements for the on-board instrumentation

Science case for generic PRIDE

- Direct characterisation of the spacecraft signal by means of VLBI tracking and radial Doppler measurements

- VLBI estimates of the S/C state vector
  - Gravimetry
  - Celestial mechanics at the accuracy level of relativistic effects
  - Input to the fundamental physics

- "Cruise" ad-hoc science plus mission diagnostics ("health check")

- Complementary to DeltaDOR and "two-way" range measurements

plus

- Direct-to-Earth (DtE) delivery of critical data (e.g. via SKA after 2020)

ESA: Jupiter Icy Satellites Explorer (JUICE)

Progressing from exploration to characterisation of habitable worlds

JUICE Science Themes

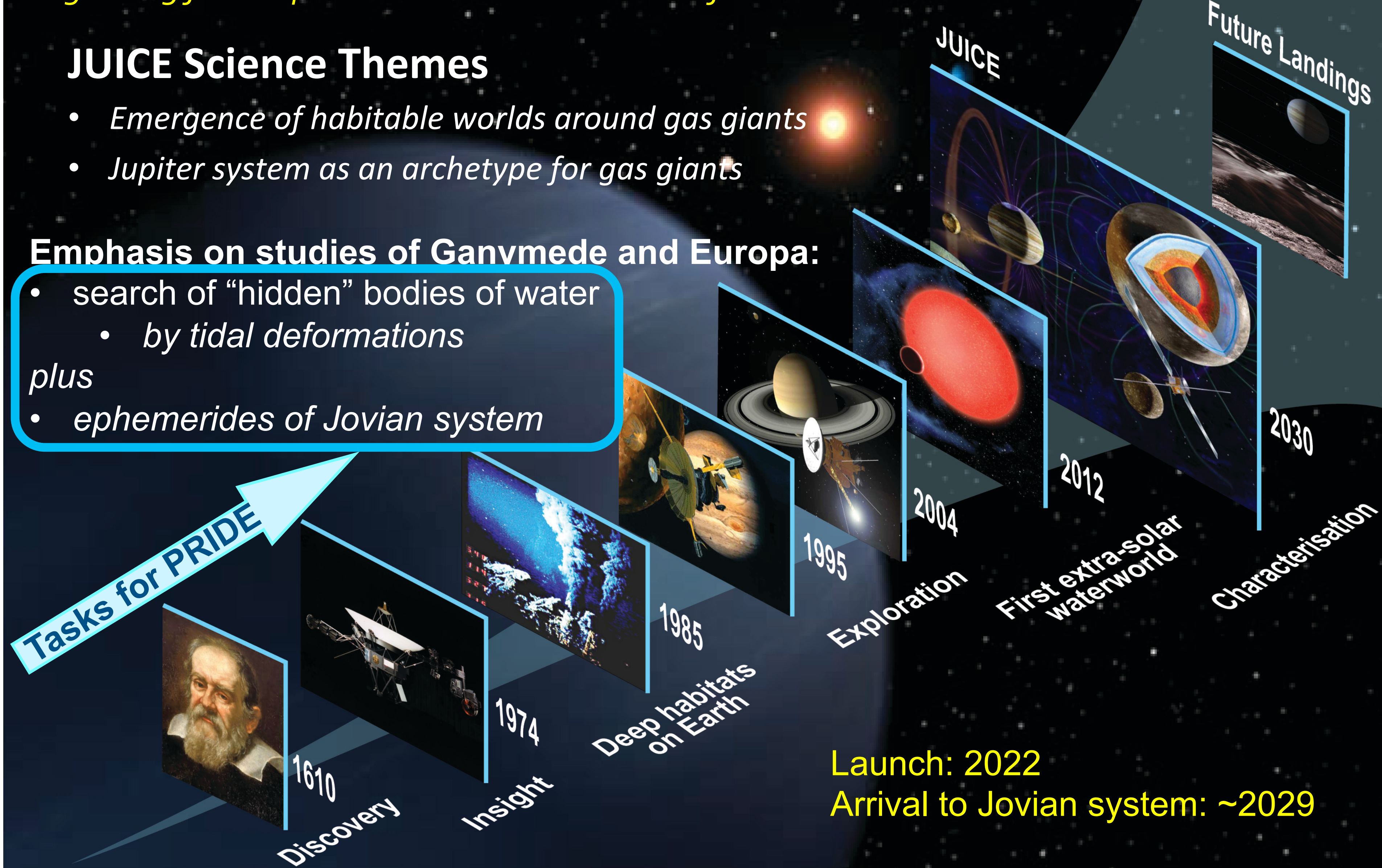
- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

Emphasis on studies of Ganymede and Europa:

- search of “hidden” bodies of water
  - *by tidal deformations*

plus

- *ephemerides of Jovian system*



Launch: 2022
Arrival to Jovian system: ~2029

Exploration of the habitable zone

JUICE

Three large icy moons to explore

Ganymede

- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

- Archetype of waterworlds
- Best example of liquid environment trapped between icy layers

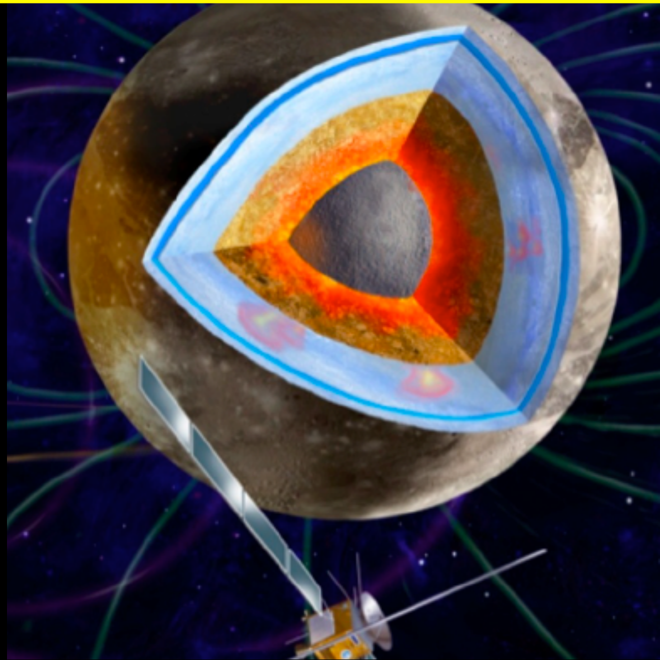
Callisto

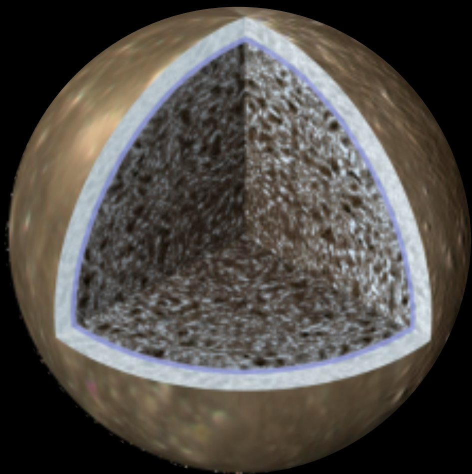
- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages

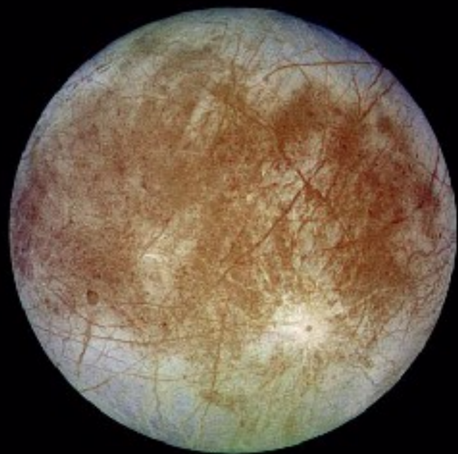
Europa

- A deep ocean
- An active world?

- Best example of liquid environment in contact with silicates

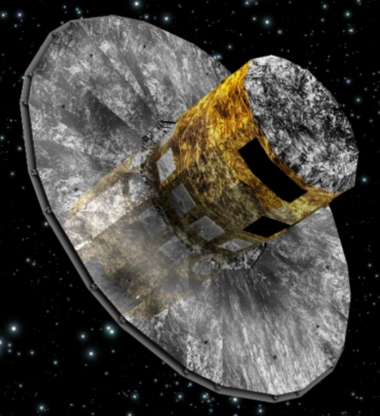


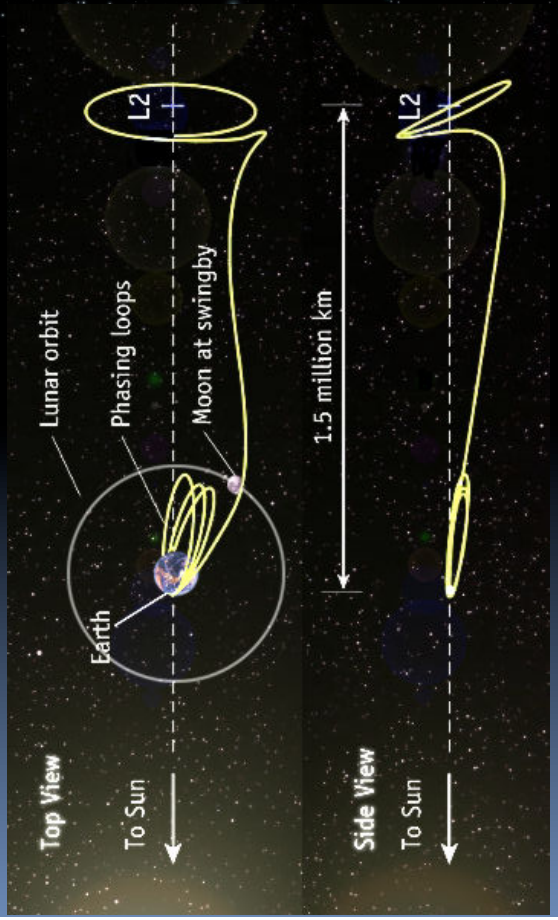




PRIDE for Gaia?

- **What is needed:**
  - Gaia S/C velocity
    - *Random error σ < 2.5 mm/s*
    - *Systematic error σ < 1 mm/s*
  - Gaia position
    - *σ < 150 m (for each cartesian component)*
- Can PRIDE deliver?
  - Yes, but…
    - *need understand how to work with phased array antenna*
  - Wait for EVN test with Herschel
- <u>Science-driven</u> support

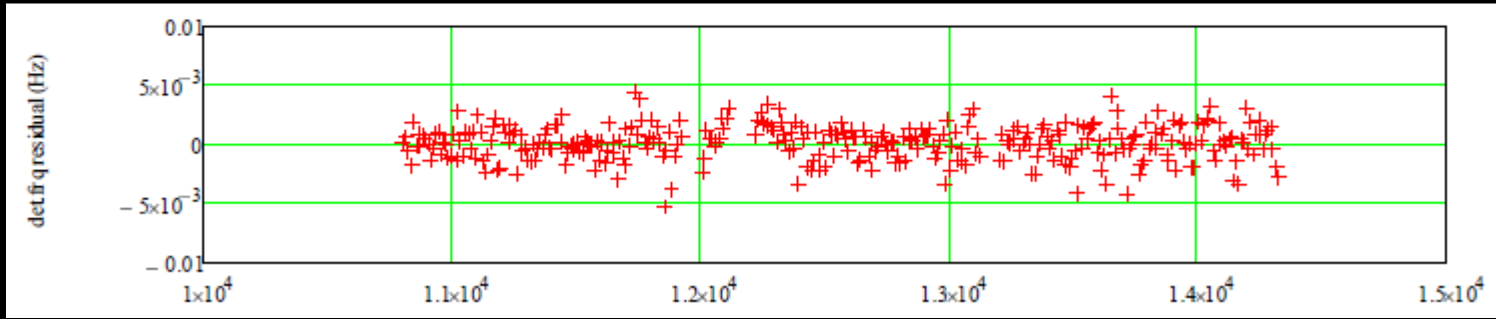


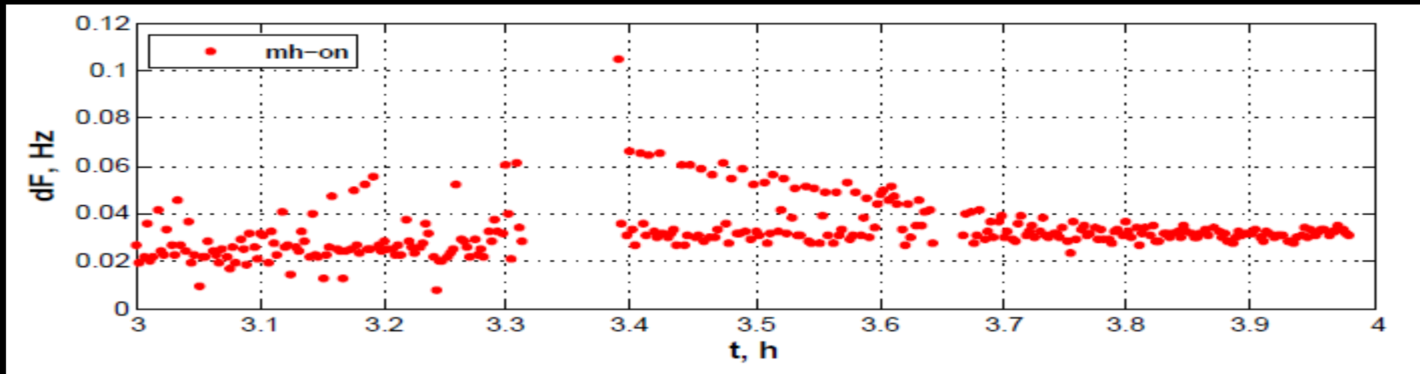


PRIDE for RadioAstron

JIVE
JOINT INSTITUTE FOR VLBI IN EUROPE

PRIDE tracking of Spektr-R, 2011.11.15

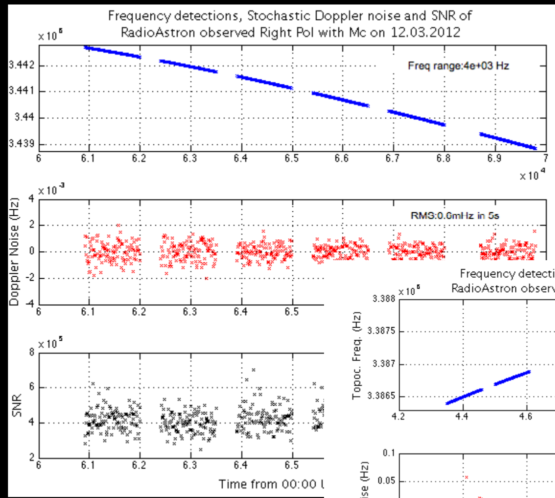




- Doppler tracking test of RadioAstron with Metsahovi and Onsala
- Processing with narrow-band software correlator

RadioAstron and PRIDE

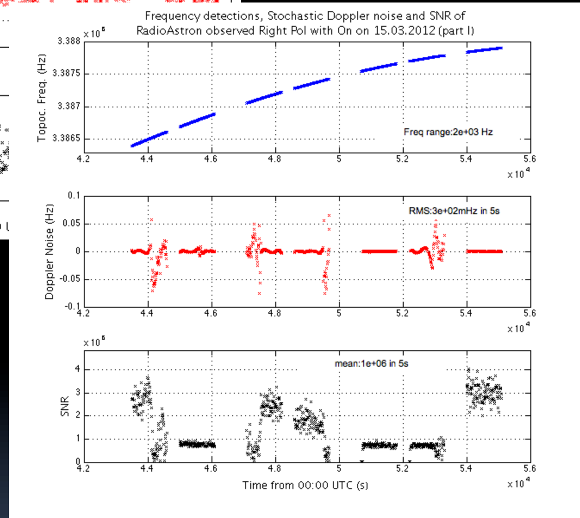
- PRIDE (near-field VLBI) tracking of RadioAstron
  - Several test runs conducted
  - Efficiency/accuracy – high
    - σ_v = 0.1 mm/s
    - *Corresponds to σ_x << 1 km*
    - *Improvements feasible*
  - **But**
    - Operational issues must be addressed:
      - *A subject of observing proposals?*
      - *Separate or a part of sci proposals?*
      - *In- and out-of-session runs?*
  - **RISC position on PRIDE involvement?**



Mc

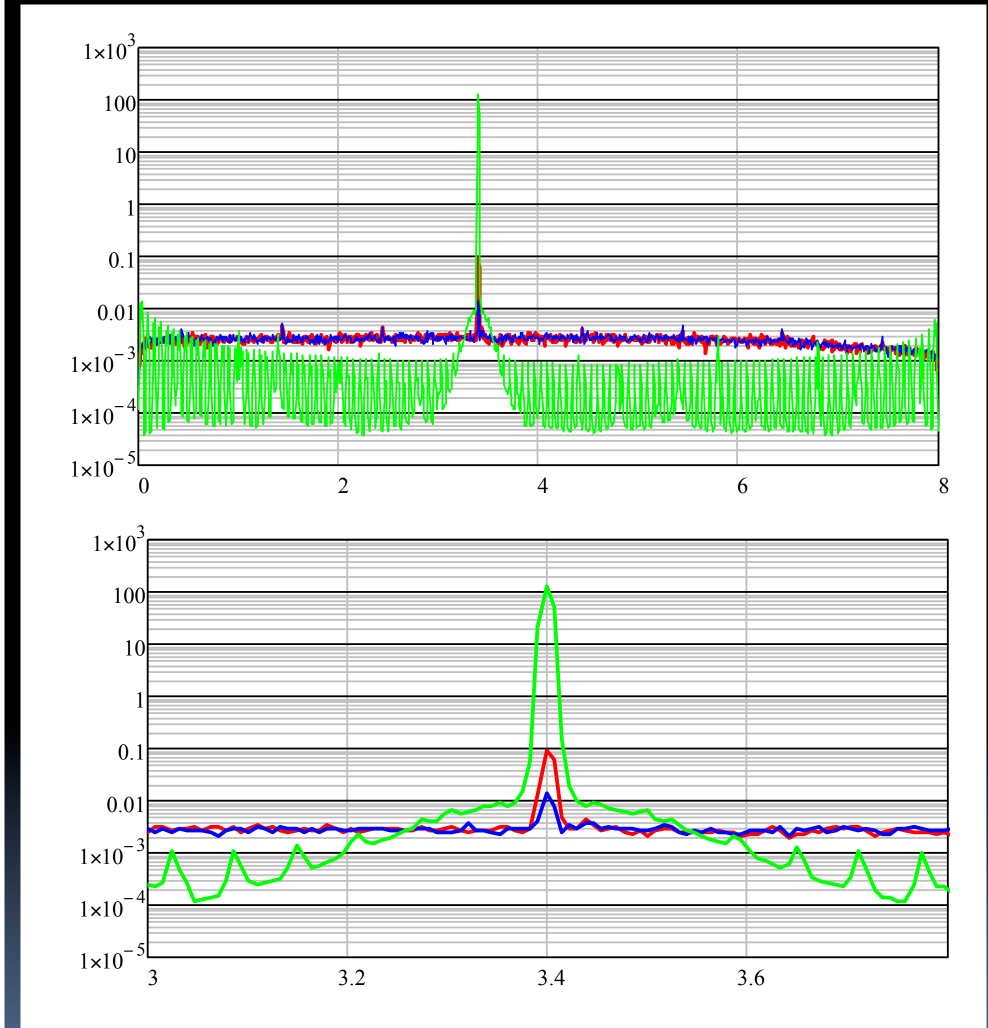
During EK032 March 2012

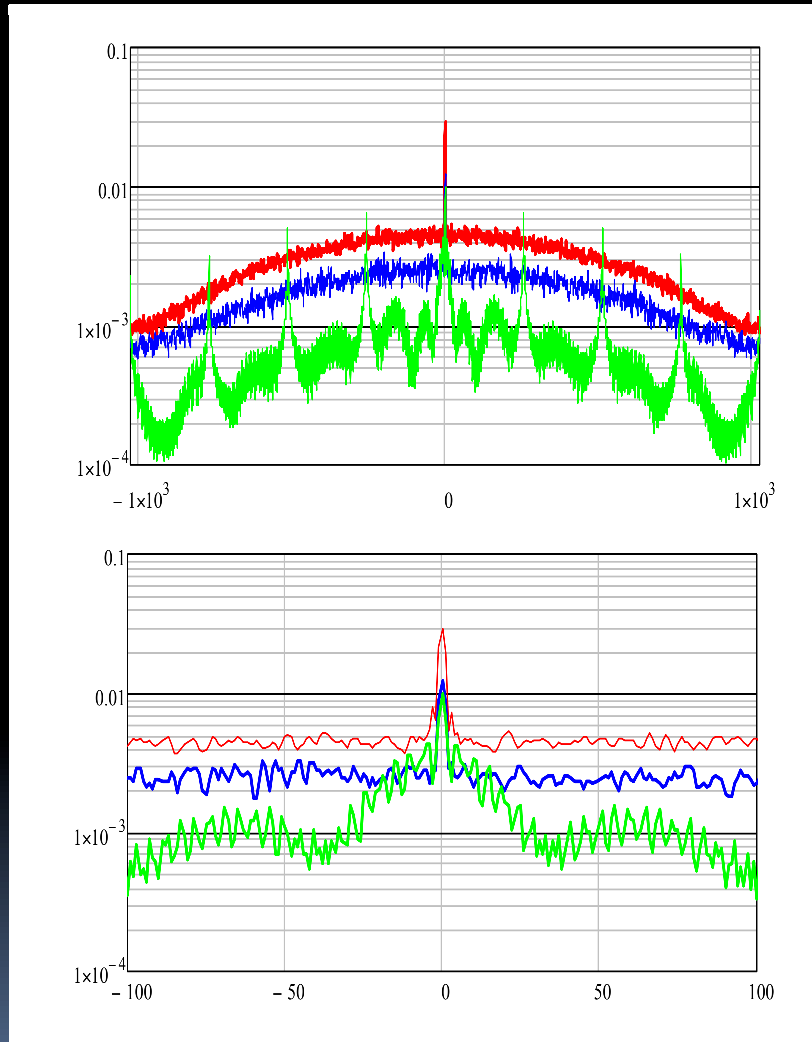
On



Example of RA X-band "PRIDE" fringes - I

Spectral domain On-Mh Lag domain

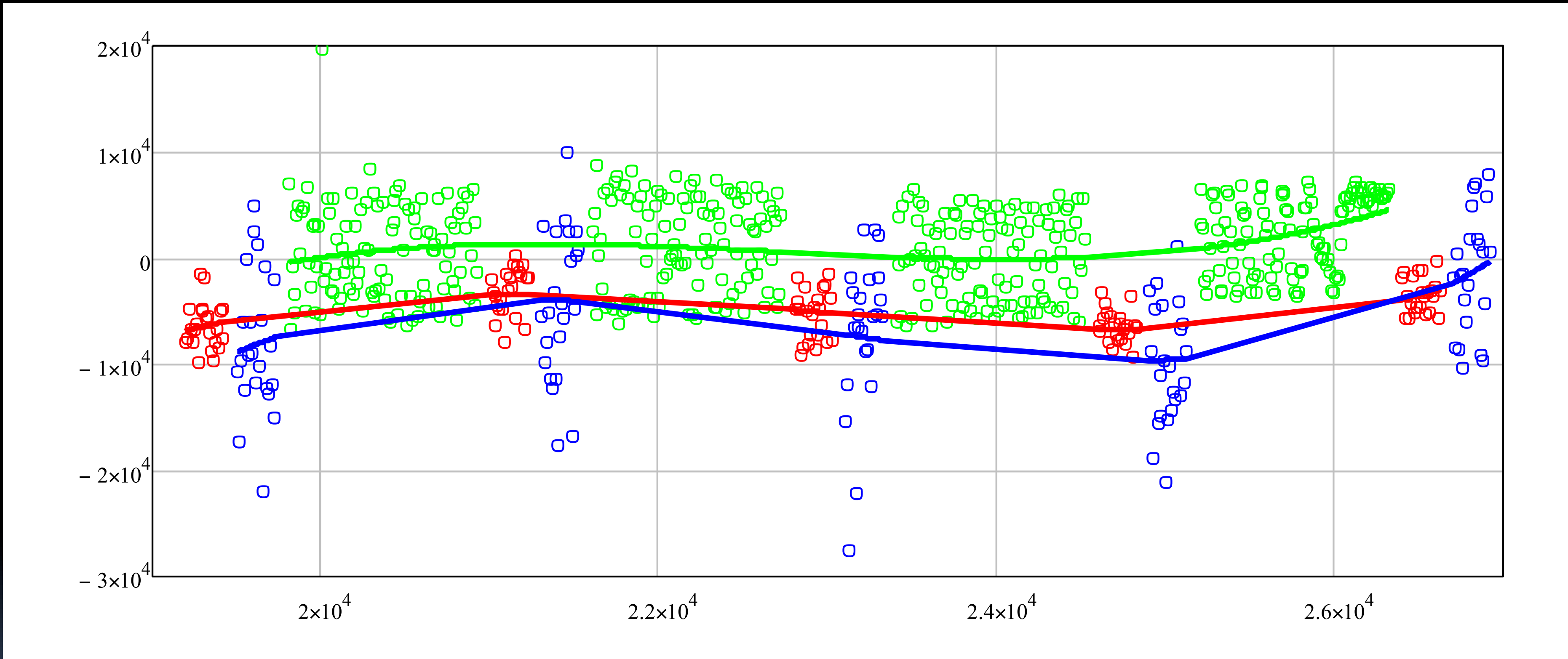




RA distance ~100,000 km, "visible RA motion" ~7.5 degr/hour, pointing difference On-Mh ~1.5 degr; Calibrators: red - J0217+7349, blue - J0019+7327. RA - green

Example of RA X-band "PRIDE" fringes - II

Post-correlation residual delays over *a priori* delay models.
Cubic time-trend fit shown as solid lines.



Goodness of fit over 2 hours
J0217+7349 180 ps
J0019+7327 600 ps
RadioAstron 190 ps

190 ps = (6/c) cm

SFXC correlation of RadioAstron data at JIVE

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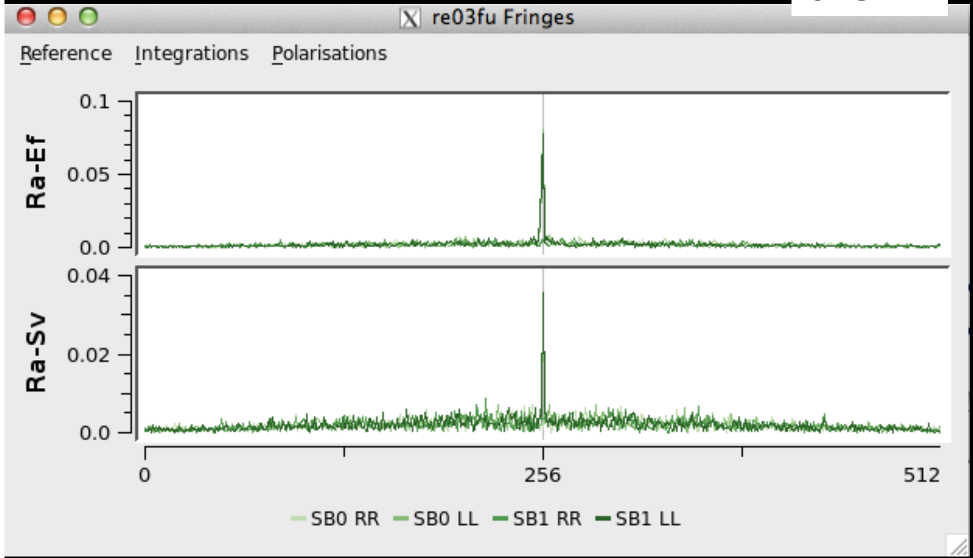
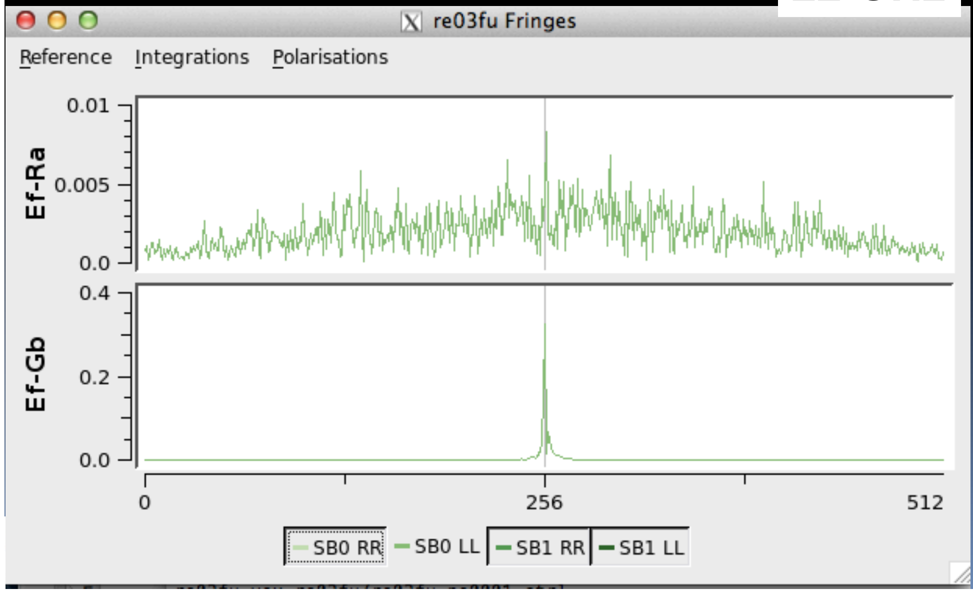
RA fringes on SFXC @ JIVE

5 GHz



22 GHz



RadioAstron AGN fringe survey experiment RE03FU:
test correlation with the SFXC correlator at JIVE

Report is prepared by: T. Bocanegra Bahamón, G. Cimò, D. Duev, L. Gurvits, A. Keimpema, M. Kettenis, G. Molera Calvés, S. Pogrebenko, H. Verkouter

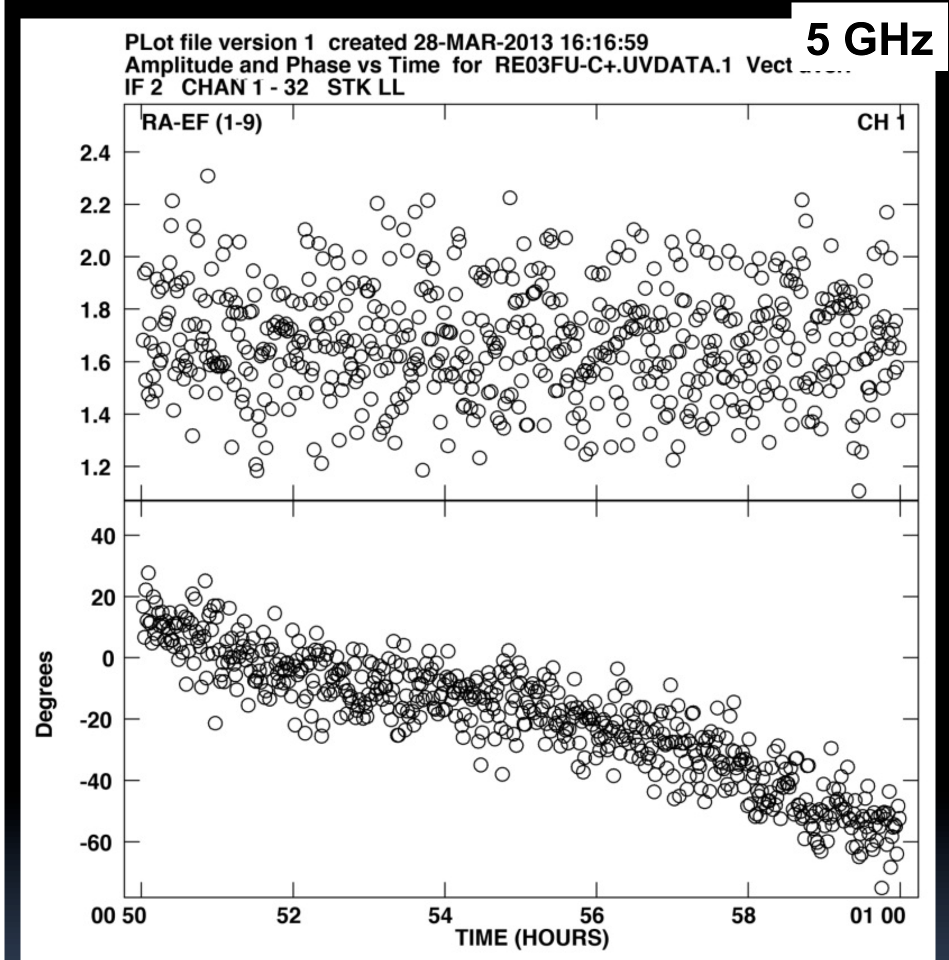
Summary:
Mk5B data from: Ra, Ef, Gb, Sv, Zc, Bd, Ys.
Source observed: 0716+714.
Fringes obtained to all stations that had observed.
Data were correlated using the a priori delay model developed at JIVE. The formatter offset for Ra was corrected using the a priori model, the clock offsets/rates were adjusted.

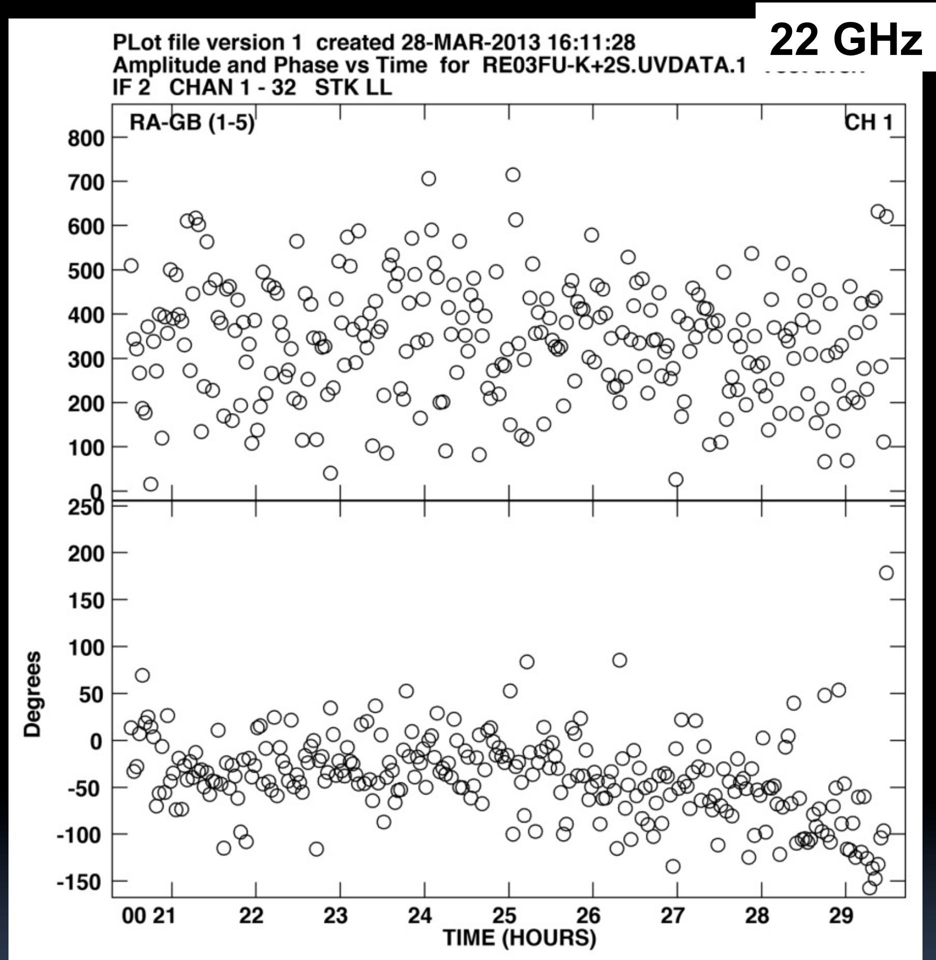
FITS-files available on demand provided a PI's permission.

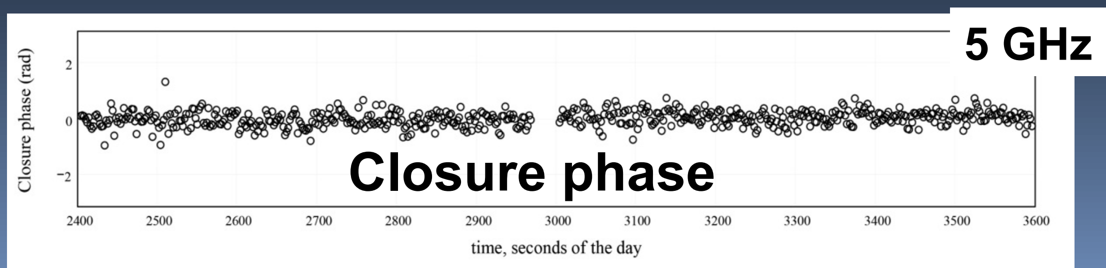
0716+714

$B \approx 2.5\ D_{Earth}$

RA fringes on SFXC @ JIVE







PRIDE outlook?

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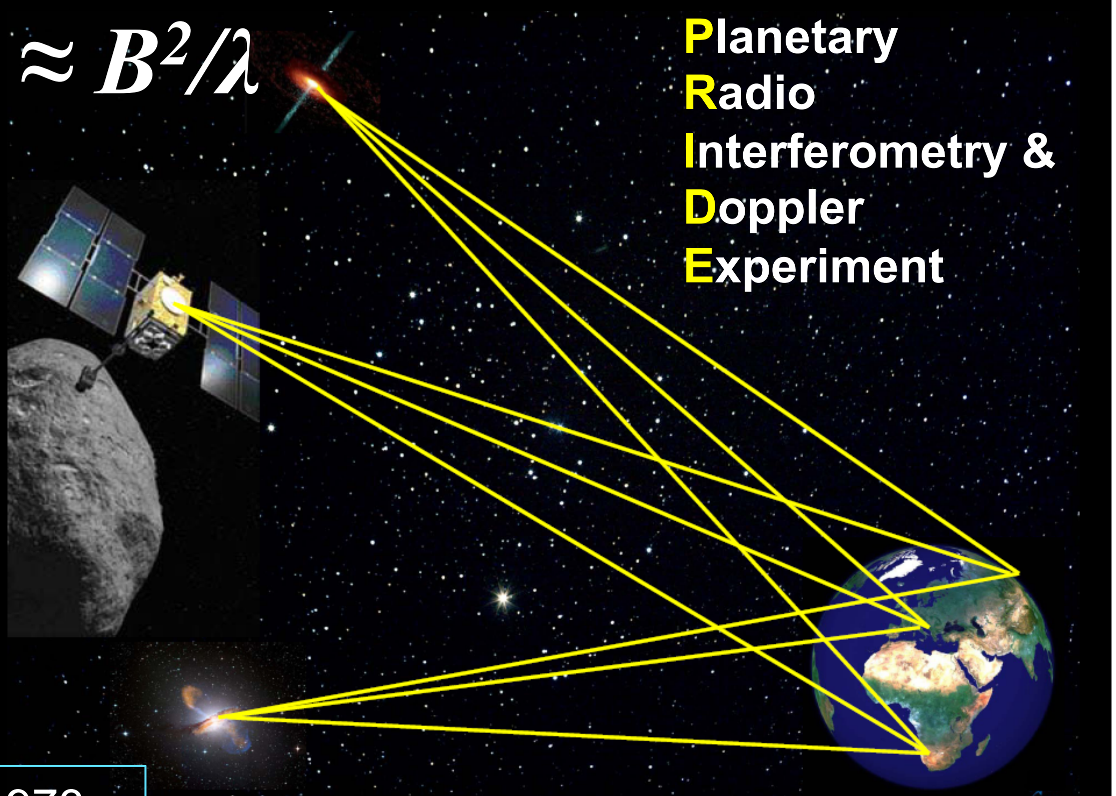
Near field VLBI $R \approx B^2/\lambda$

Planetary
Radio
Interferometry &
Doppler
Experiment

3D astrometry of high T_B objects

$T_B > 10^{18}$ K?



Kardashev, Parijskij & Umarbaeva, 1973

Baseline	**100 km**	**1000 km**	**10^4 km**	**10^5 km**	**10^6 km**	**10^7 km**	**10^8 km**
Facility	MERLIN	EVN *WE*	EVN	R-Astron	L2	-	~1 AU
λ = 3 cm	2 AU	200 AU	0.1 pc	10 pc	1 kpc	100 kpc	10 Mpc
λ= 30 cm	3×10^7km	20 AU	2×10^3AU	1 pc	100 pc	10 kpc	1 Mpc

Astrometry of extragalactic pulsars?

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