Spacecraft observations and IPS with VLBI radio telescopes

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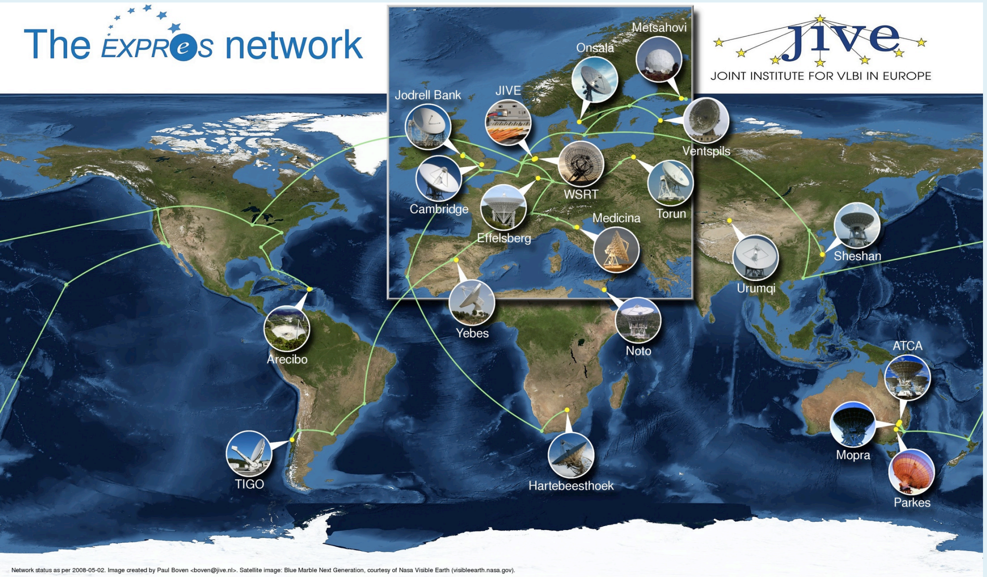
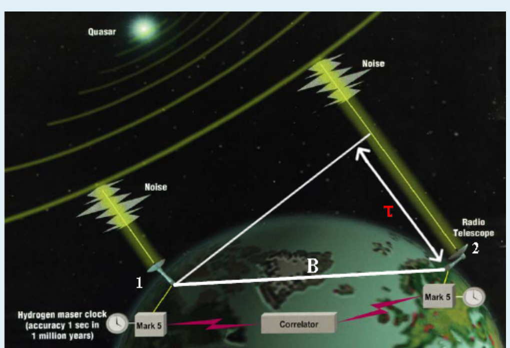
Very Long Baseline Interferometry (VLBI)

Our observing tools



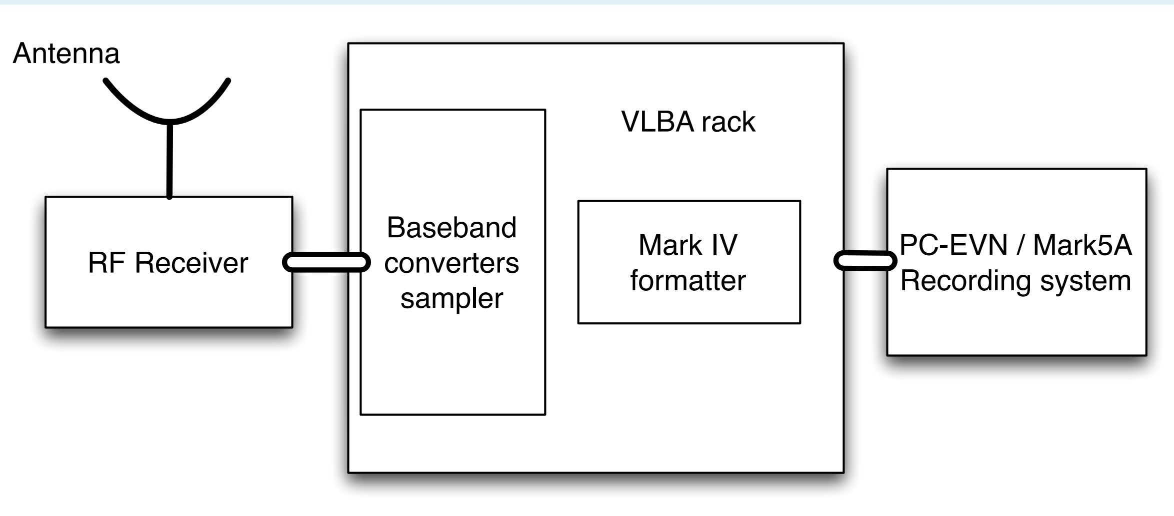
Metsähovi is a member of the **European VLBI Network (EVN)**. The current correlator node is at Joint Institute for VLBI in Europe (JIVE), the Netherlands.

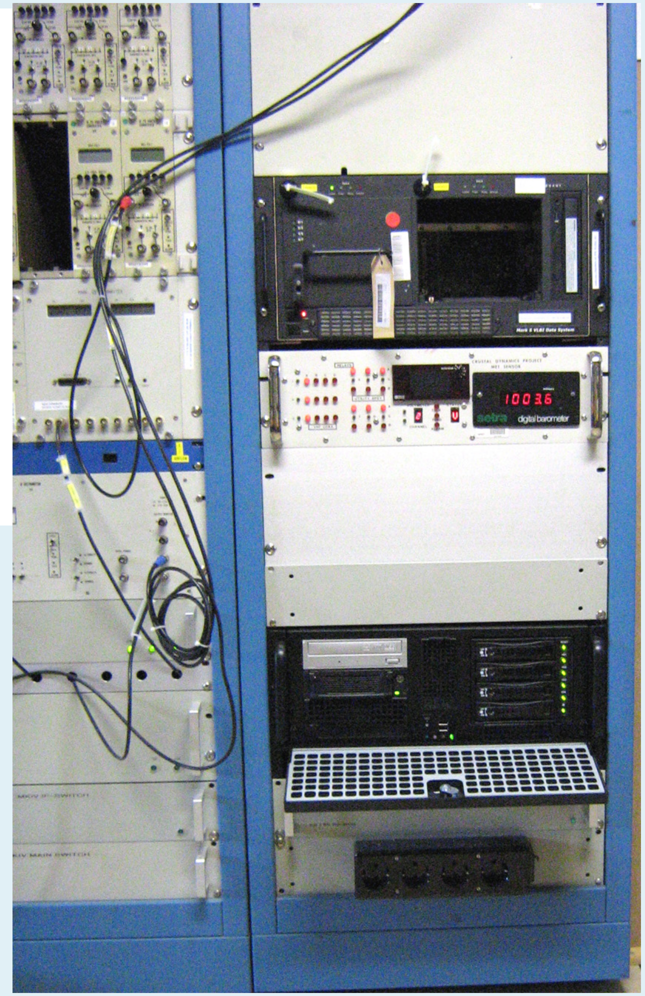
More than 20 radio telescopes worldwide are members of the EVN community and conduct VLBI sessions regularly.



VLBI configuration

Data acquisition and processing





1-16/32 subbands, 2-bit mode, 2-16 MHz bandwidth.

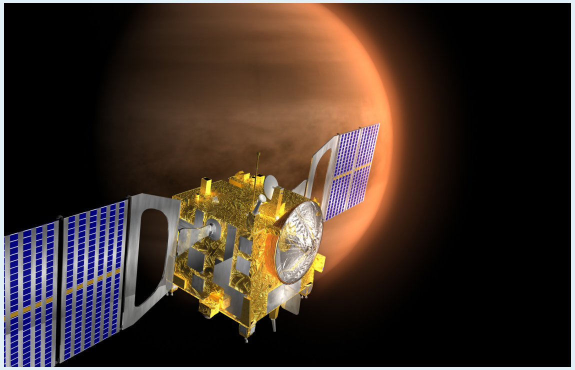
Aggregate date rate 128 MHz up to 4 Gbps

Data processing at JIVE:

- S/C signal: developed SW tools (Metsähovi, JIVE)
- Correlation: SFXC (Software FX Correlator, JIVE)

Spacecraft observations

Venus Express (VEX)



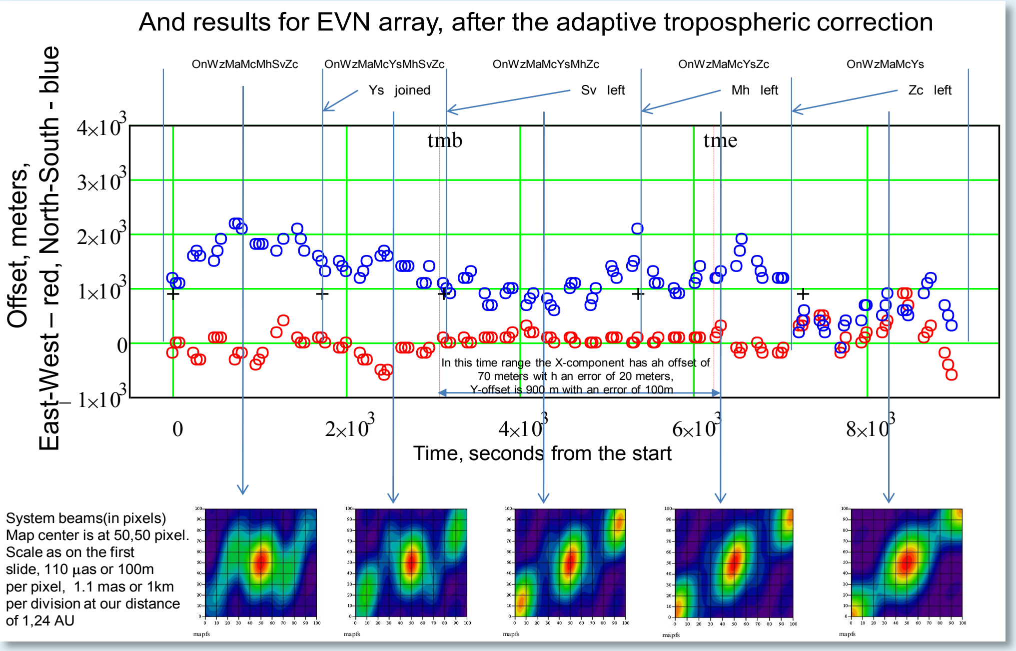
Huygens probe landing in Titan legacy, 2005.

First attempt, tracking of the signal transmitted NASA's spacecraft Ulysses in 2008.

We initiated observations of Venus Express spacecraft in coordination with the European Space Agency. The sessions have extended for 3 years (2009 to 2013).

Participant radio telescopes:

- Metsähovi (FI)
- Onsala (SW)
- Yebes (SP)
- Wettzell (DE)
- Matera, Medicina, Noto (IT)
- Harteebesthoek (SA)
- Warkwork (New Zealand)
- Urumqi, Shanghai, Kunming (CN)
- Kashima (JP)
- Badary, Zelenchukskaya (RU)
- St. Croix (USA)
- Hobart (AU)



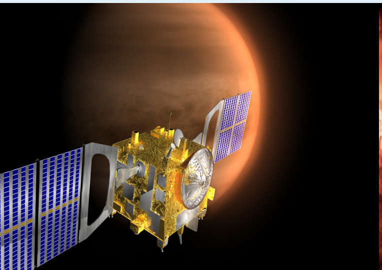
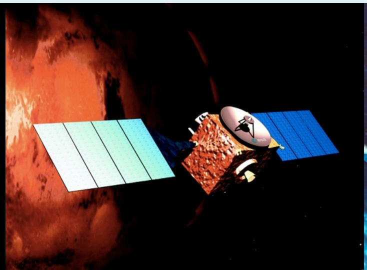
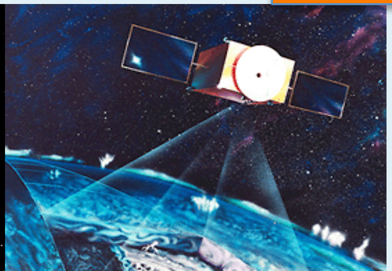
Our targets

Current PRIDE missions

- ESA Venus Express (VEX)
- ESA Mars Express (MEX)
- JAXA Akatsuki & Ikaros
- NASA Stereo A/B
- NASA Mars Rover
- NASA Ulysses
- GLONASS satellites
- RadioAstron Space VLBI S/C

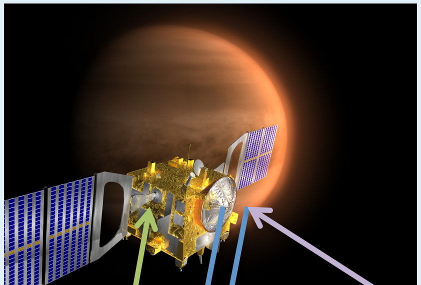
Prospective PRIDE missions

- ~~Phobos/Soil~~
- ESA GAIA 2014
- ESA-JAXA Bepicolombo 2015
- ESA ExoMars 2016
- ESA Jupiter Icy Europa moons 2020.
- ESA MarcoPolo-R 2020
- RSA Venera-D 2024

ESA Venus Express spacecraft

Venus Express (VEX) is operative since 2006.
Data links transmits in S & X-bands.
S/C observations made in X-band



S/C signal

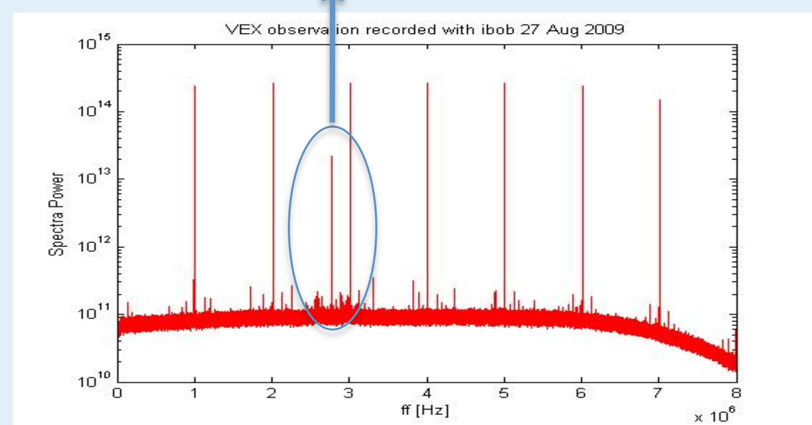
Uplink
X-band

Downlink
S & X-band

Power transmitted 1W

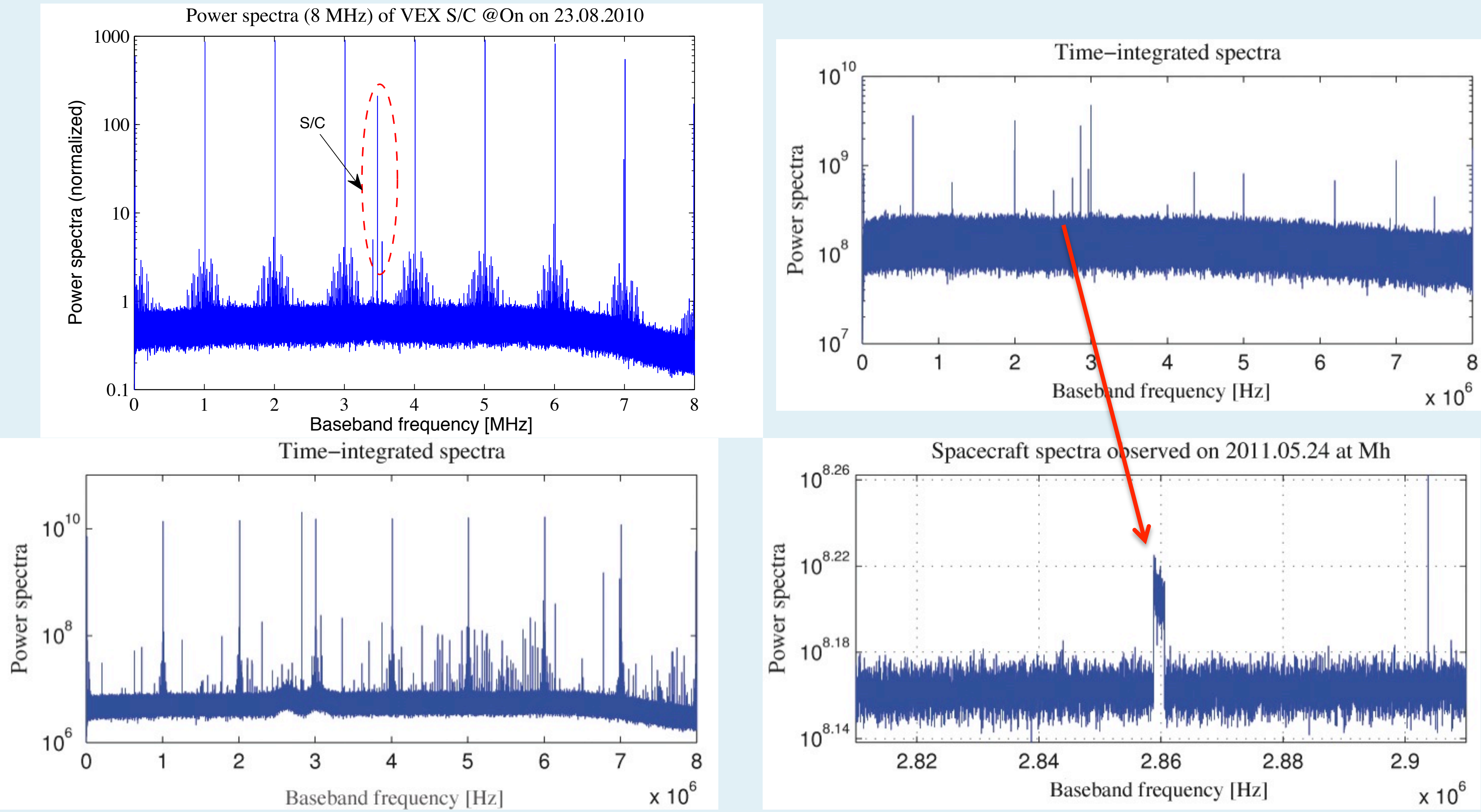
Flux denisty 0.5 mJy

Wettzell VLBI radio telescope



ESA/ESAC Cebreros ground station

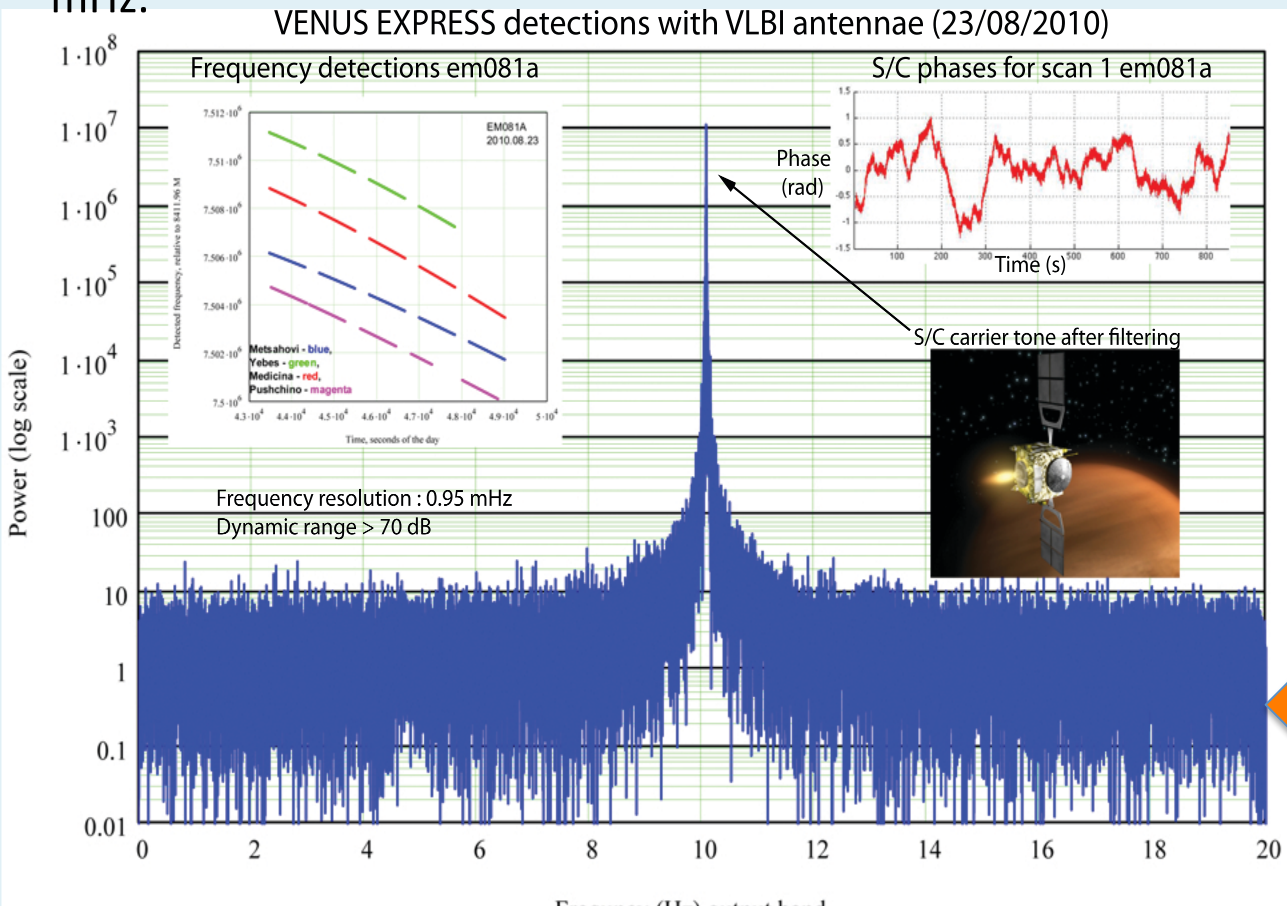
Detecting S/C signal

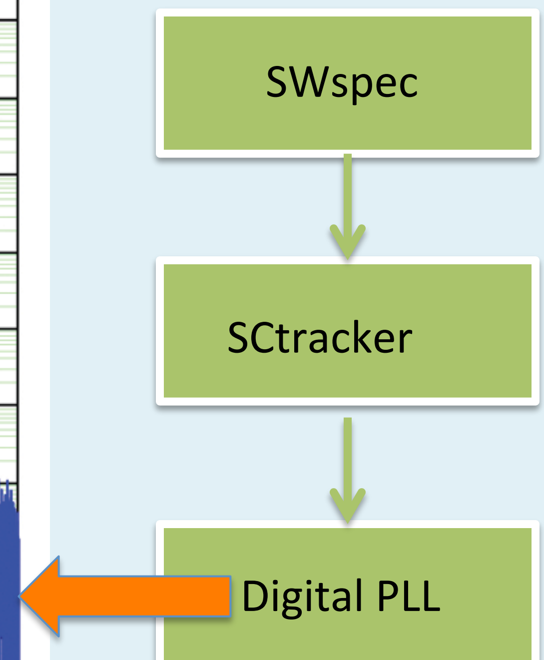


Detection of spacecraft in narrow band

The technic

Detection of the spacecraft signal viewed for 4 different radio telescopes in a narrow band of 20 Hz around the carrier with a frequency resolution better than 1 mHz.





S/C narrow band software block diagram (Molera et al., IPPW-8 2011)

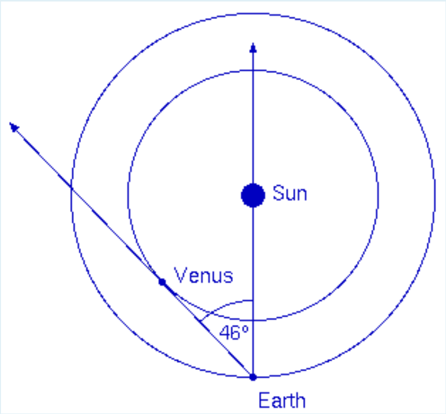
Software

1. SWspec – Software Spectrometer
    - A high performance software spectrometer used to detect the S/C tones. VLBA and MkIV formats and Mark5A, PC-EVN, Mark5B, VDIF and raw input.
    - Each pass extracts the 8 or 16 MHz BW data performs an accurate cos-square windowed overlapped discrete Fourier transform (3.2M DFT points) and spectrum time integration.
    - All settings are full adjustable.
2. SCracker – an ultra-high spectral resolution spectrometer-correlator.
    - The spacecraft tone tracking software uses and adaptive filtering extracts and filters stopped tones down to a several kHz wide BW using a 2nd order WOLA (Window-Overlap-Add) DFT-based algorithm of the Hilbert transform aprox.
    - Time-domain sample sequence of every filtered tone is written as an output for post-processing using Phase-Lock-Loop (PLL).
    - Residual phase in a stopped band is determined with respect of polynomials applied for phase stopping. Depending on the S/C SNR and individual tones, the final BW of phase detections can range from several kHz to several mHz.

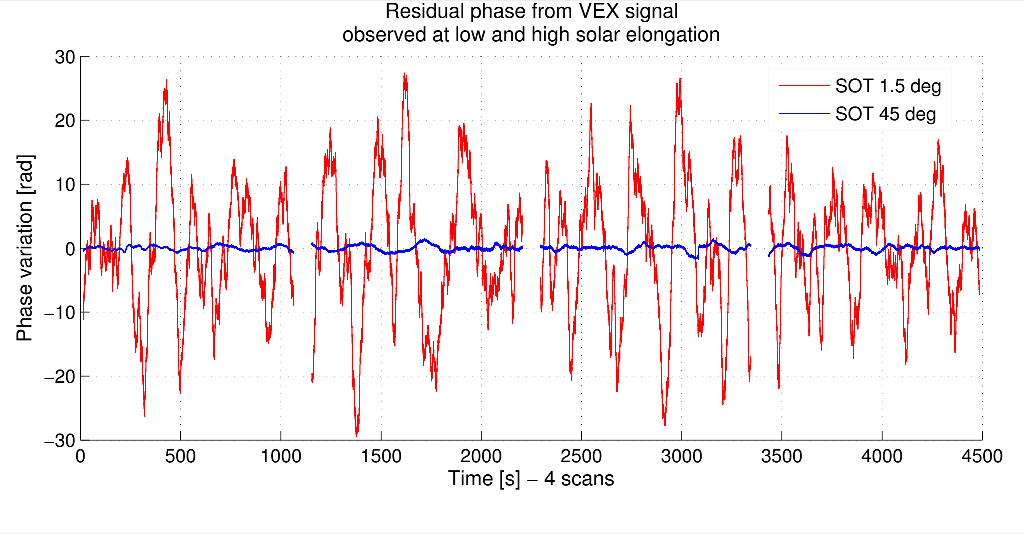
✓ VEX carrier line usually in the order of 10 – 100 Hz.

Propagation of the radio waves

Phase detection of the spacecraft signal

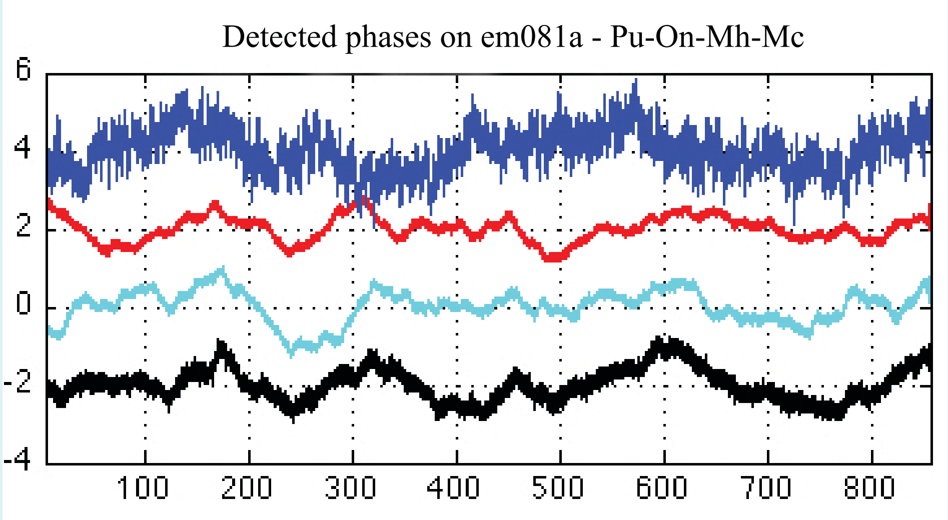


- We extracted Doppler detections and signal phase from the carrier line in all our observations.
- The phase fluctuations are used to characterize the IPS at any epoch.
- VEX campaign has lasted for more 3 years, covering 2 full orbits of Venus around the Sun.
- More than 100 sessions conducted.



Phase comparison

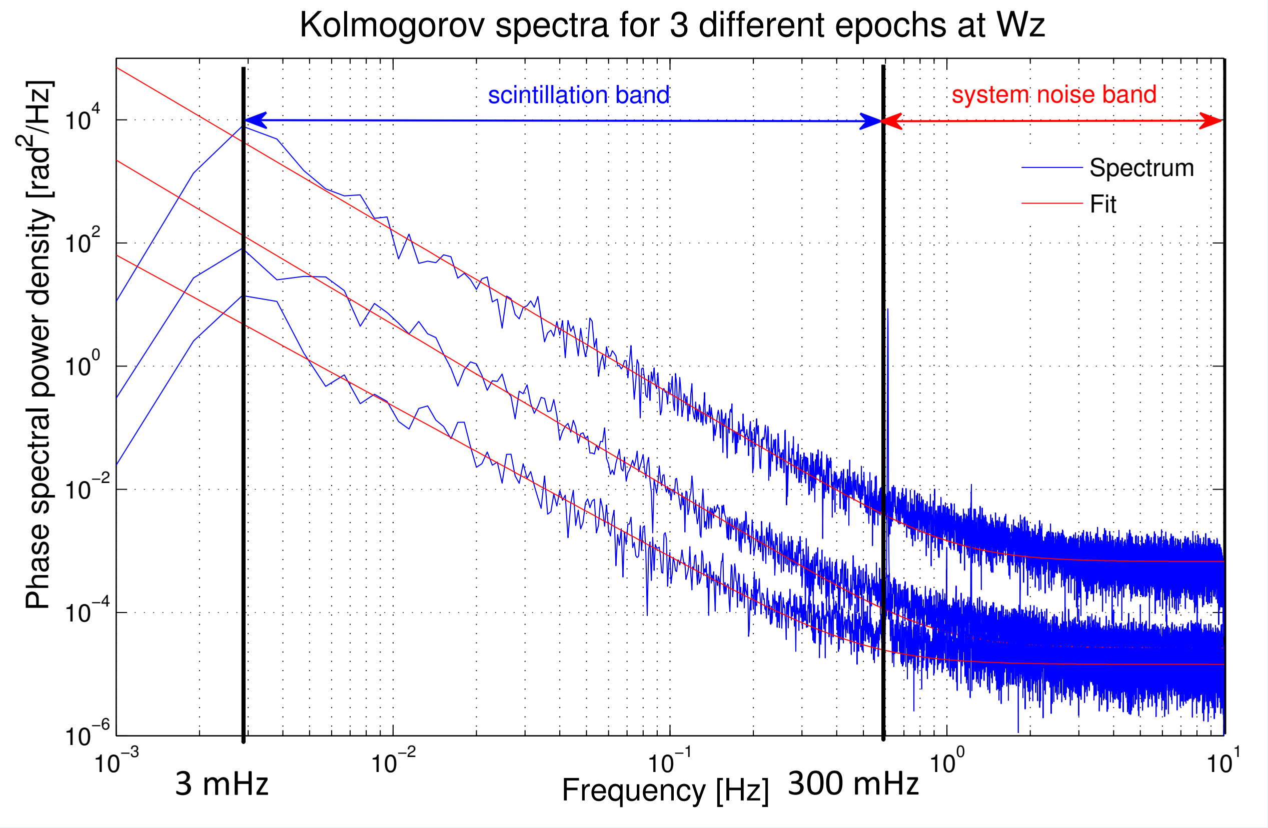
Phase from 4 simultaneous antenna



Phase is in radians, and we added +4, +2, 0 and -2, to make the view of the data more clear.

Spectral power density

of the phase fluctuations



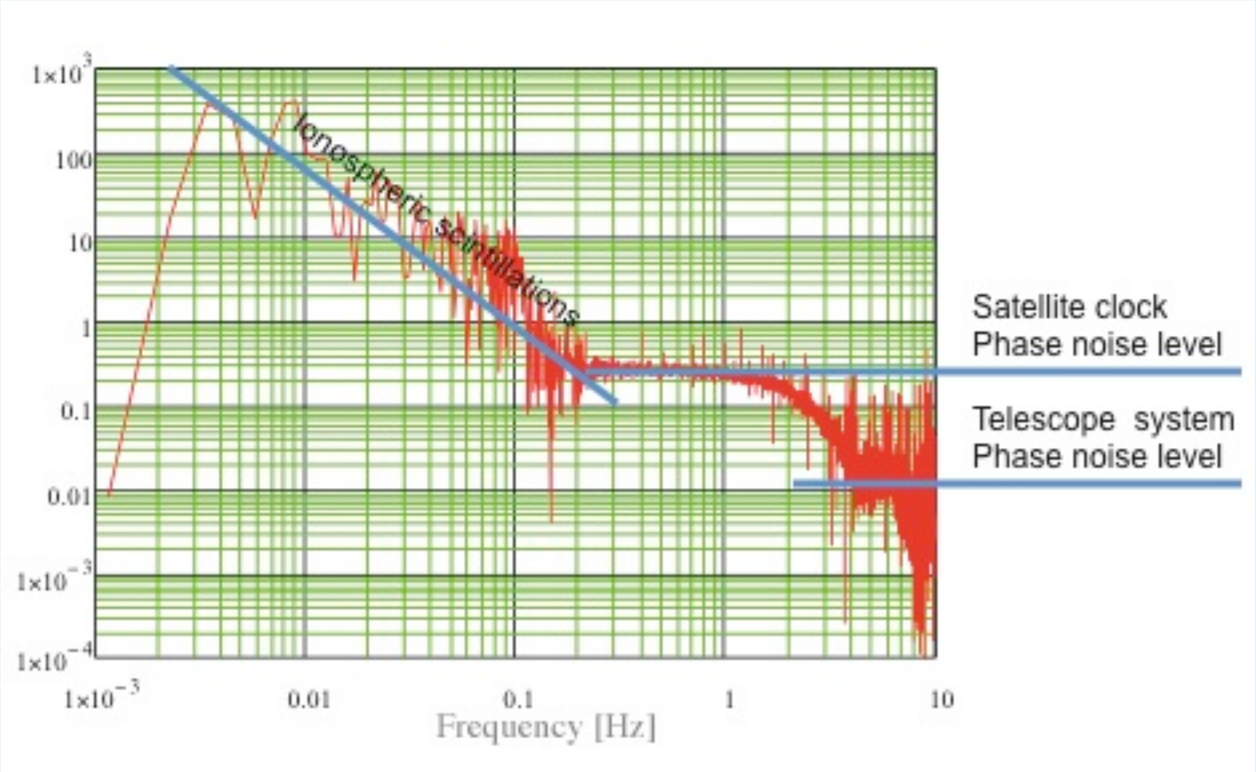
Respective slopes:

03.4 deg, -2.388
19.4 deg, -2.662
37.2 deg, -2.437

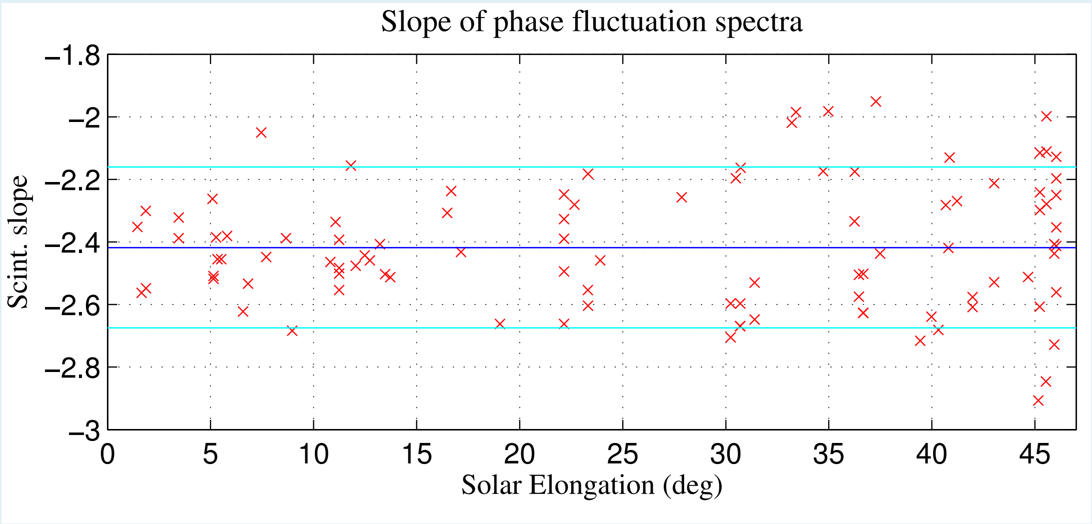
The spectral power density of the phase fluctuations showed a clear Kolmogorov-style spectrum.

The average slope (m) was equal to -2.42 with a standard deviation of 0.25.

Spectral power density
Glonass satellite



Spectral slope dependence?



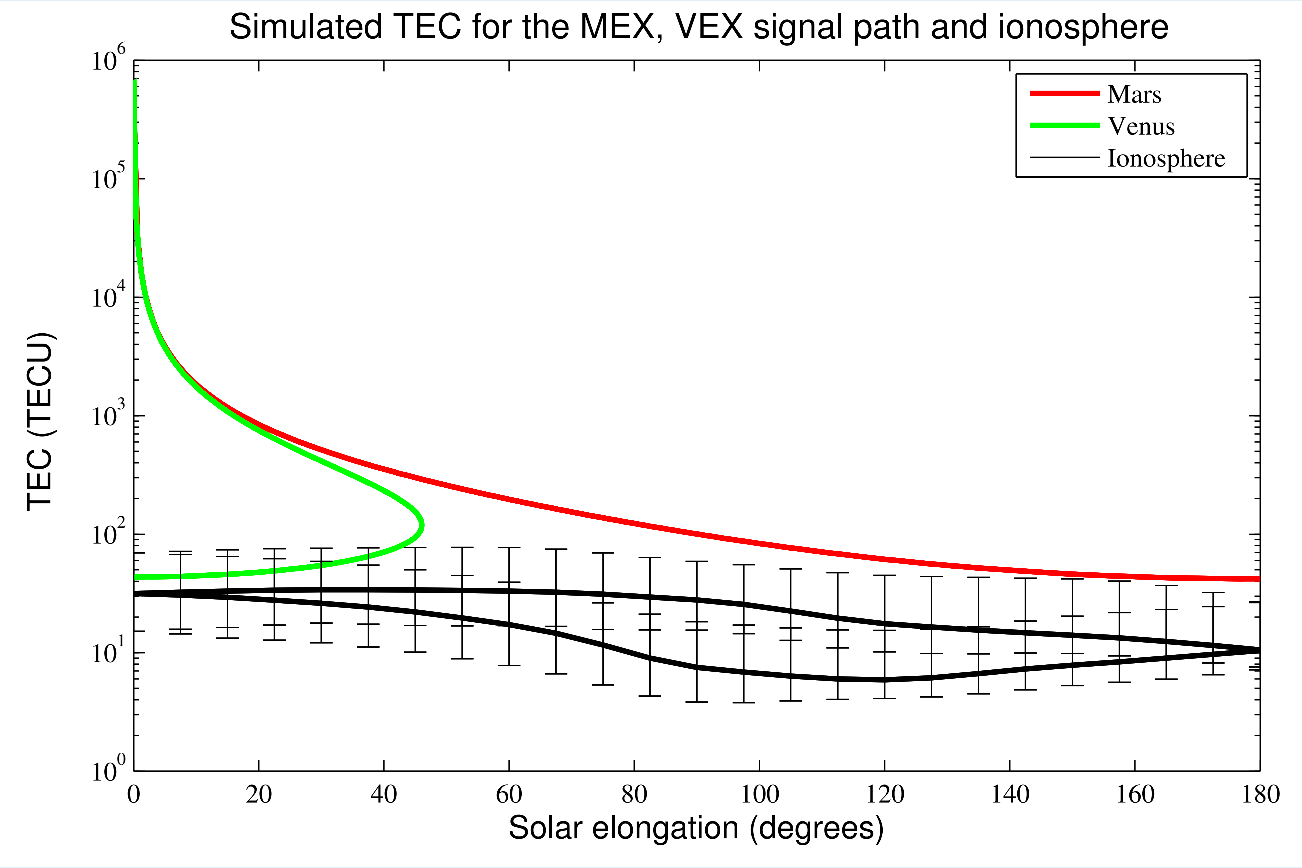
Averaged slope of hundred sessions as a function of the solar elongation

Averaged slope of hundred sessions as a function of the observing radio telescope.

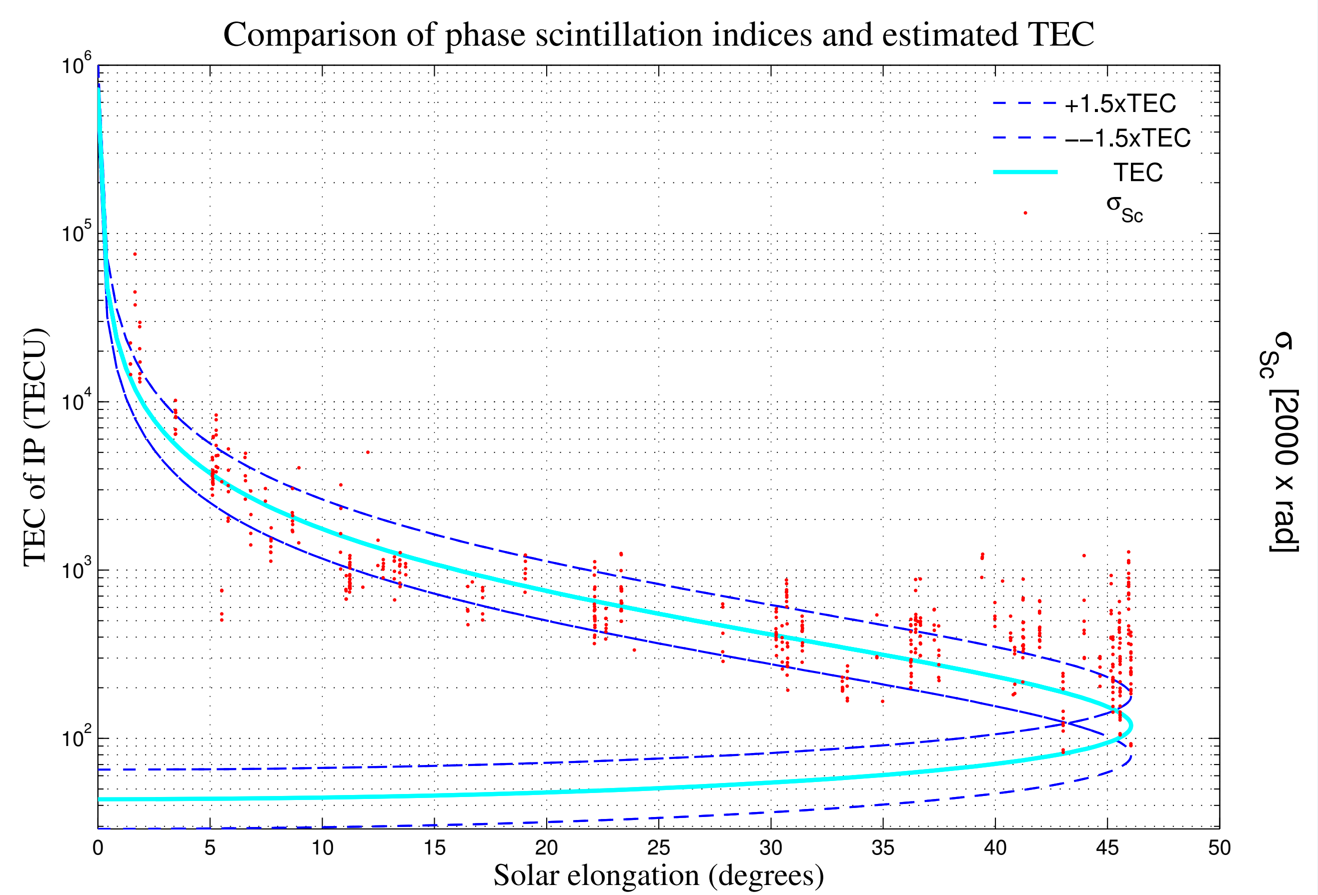
	Slope	Std dev.
Mh	-2.36	0.14
Mc	-2.54	0.18
No	-2.45	0.07
Ma	-2.55	0.04
Wz	-2.49	0.14
Ys	-2.45	0.09
On	-2.61	0.16
Hh	-2.64	0.25

The slope does not depend on the solar elongation, radio telescope or distance to the target.

Estimated TEC



Phase scintillation indices and estimated TEC



Improving the results?

A) Improving the phase scintillation indices by removing the scintillation noise

$$\sigma_{Sc}^{2}{}' = \sigma_{Sc}^{2} - \sigma_{N}^{2}$$

Improvement ~2 %

B) Improving the phase scintillation indices by removing the proportional contribution of the vertical Total Electron Content of the ionosphere

$$\sigma_{Sc}^{2}{}' = \sigma_{Sc}^{2} - VTEC_{ion}$$

Improvement ~6 %

C) Compare more carefully SNR observations, Doppler noise of the detection and level of the fluctuations.

D) Discard anomalous data for known events…

Future work

- VLBI observations to determine the velocity of the solar wind. At least, we will need 3 radio telescopes and good baseline coverage.
- Cover the inferior conjunction. We don't have almost data from that part of the orbit. Data will come in the following months.
- Combined EISCAT + VLBI observations.
- Suggestions are welcome.