Radio tracking of and communication with planetary probes as a space science subject

S.V. Pogrebenko and L.I. Gurvits
Joint Institute for VLBI in Europe
Dwingeloo, The Netherlands

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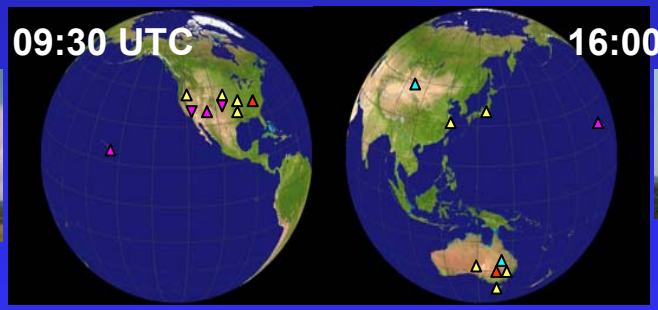
Radio system: indispensable component of planetary probes

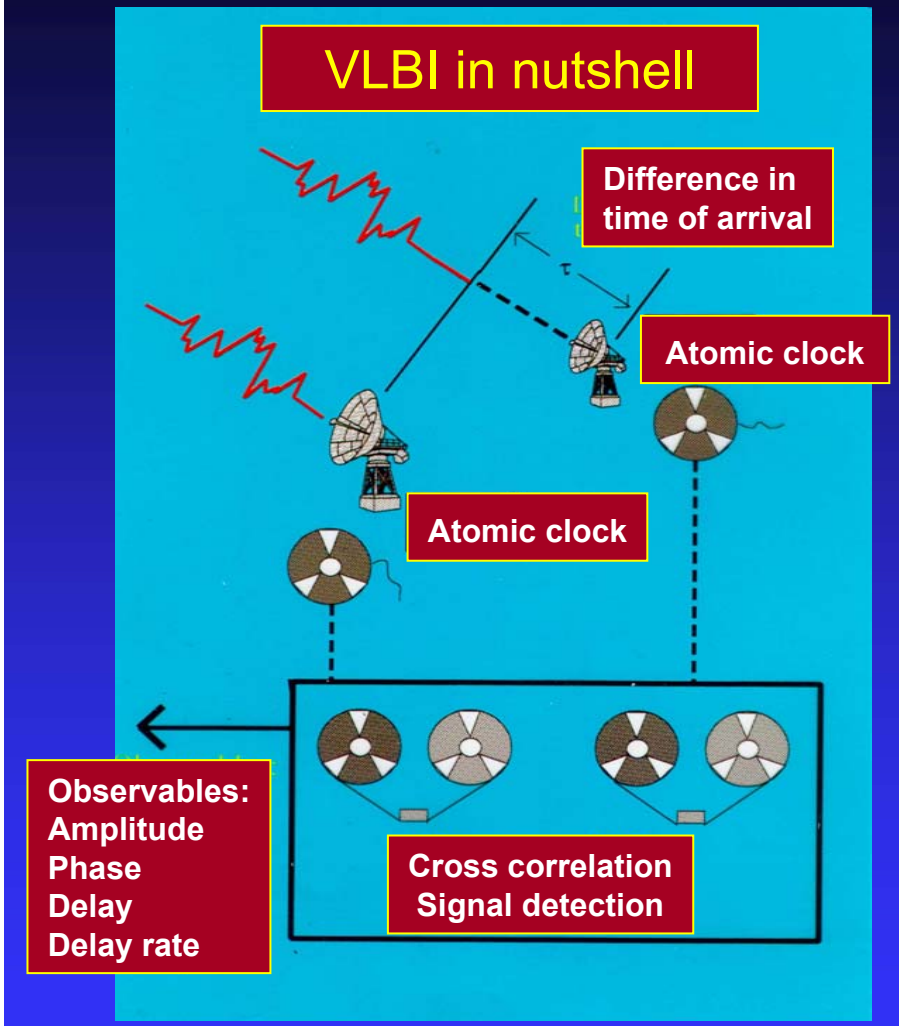
- **Functions:**
  - *Commanding*
  - *Science and housekeeping data downlink (telemetry)*
  - *Tracking (orbit determination and related tasks)*
- **Means:**
  - *On-board instrumentation (Receivers, transmitters, antennas)*
  - *Earth-based – commanding, tracking and data down-link stations*
- **This presentation emphasizes:**
  - *Earth-based segment*
  - *Synergy with radio astronomy methods and instrumentations*

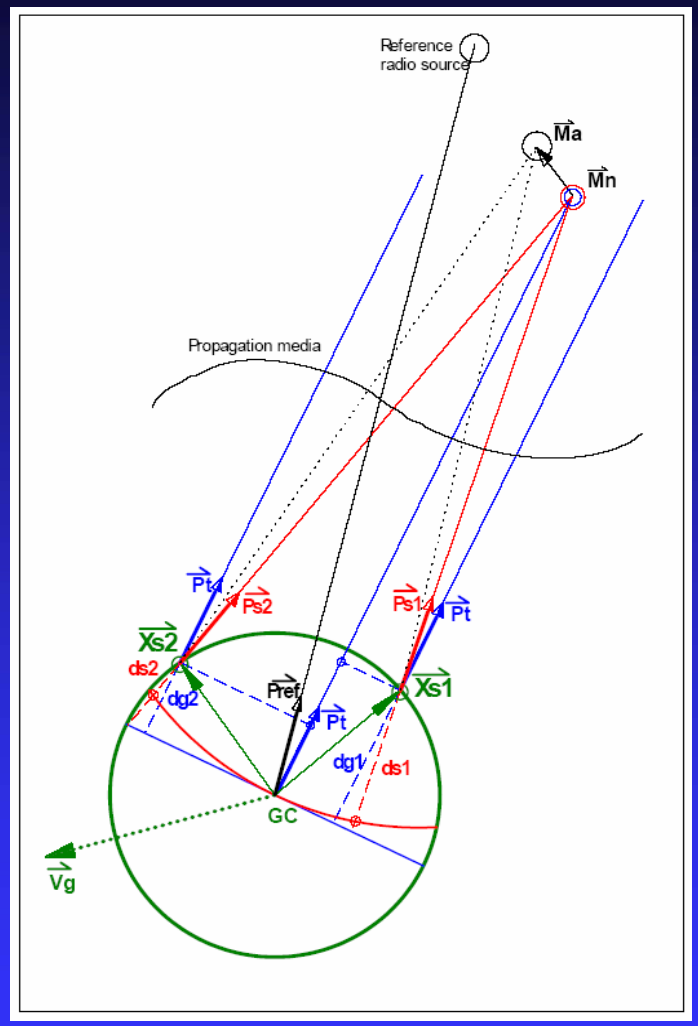
Space exploration & radio astronomy: 50 years together

- Glorious start: first sputnik and 76-m Jodrell Bank (now Lovell) telescope, 4 October 1957
- VLBI tracking of NASA planetary S/C since 1970s (see Thornton and Border 2003
- VEGA Balloons & VEGA/Giotto Pathfinder, 1984-86 (Sagdeev et al., 1992)
- Huygens VLBI Tracking experiment, 2005
- Smart-1 VLBI tracking, 2006
- PRIDE and DtE for prospective missions



VLBI within Solar System: what's different?

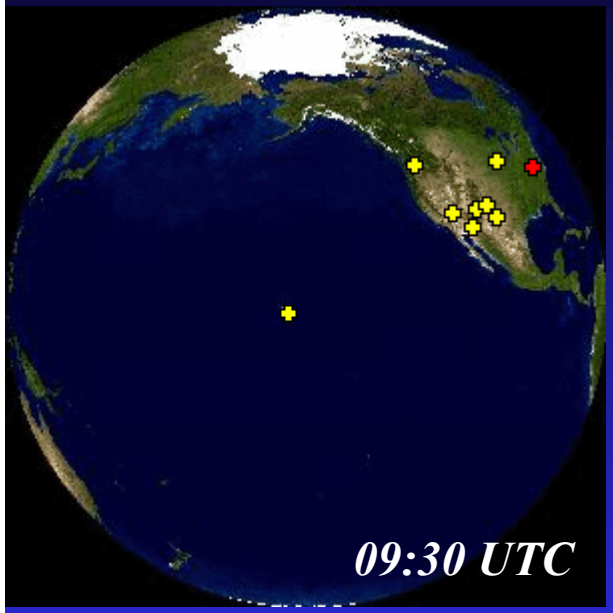


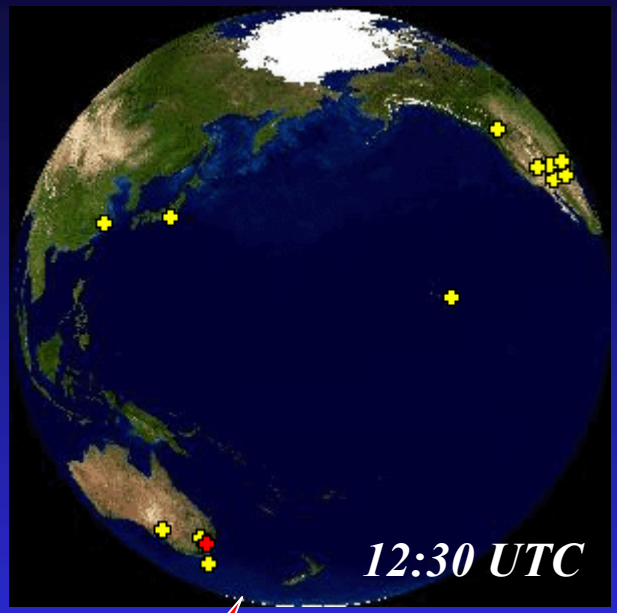


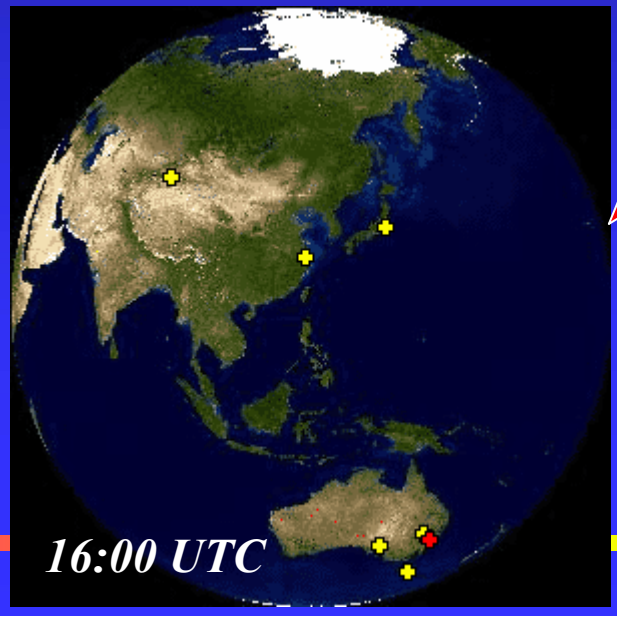
Angular resolution ~ λ/B;

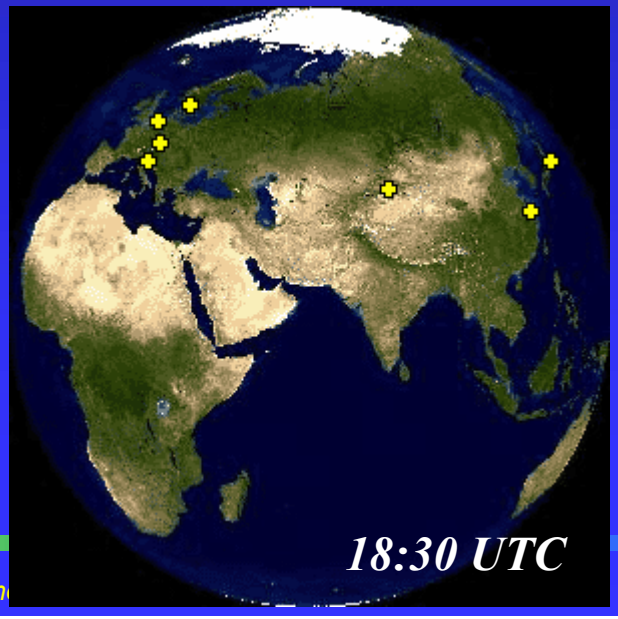
Near Field < B^2/λ

Huygens VLBI tracking, 14.05.2005

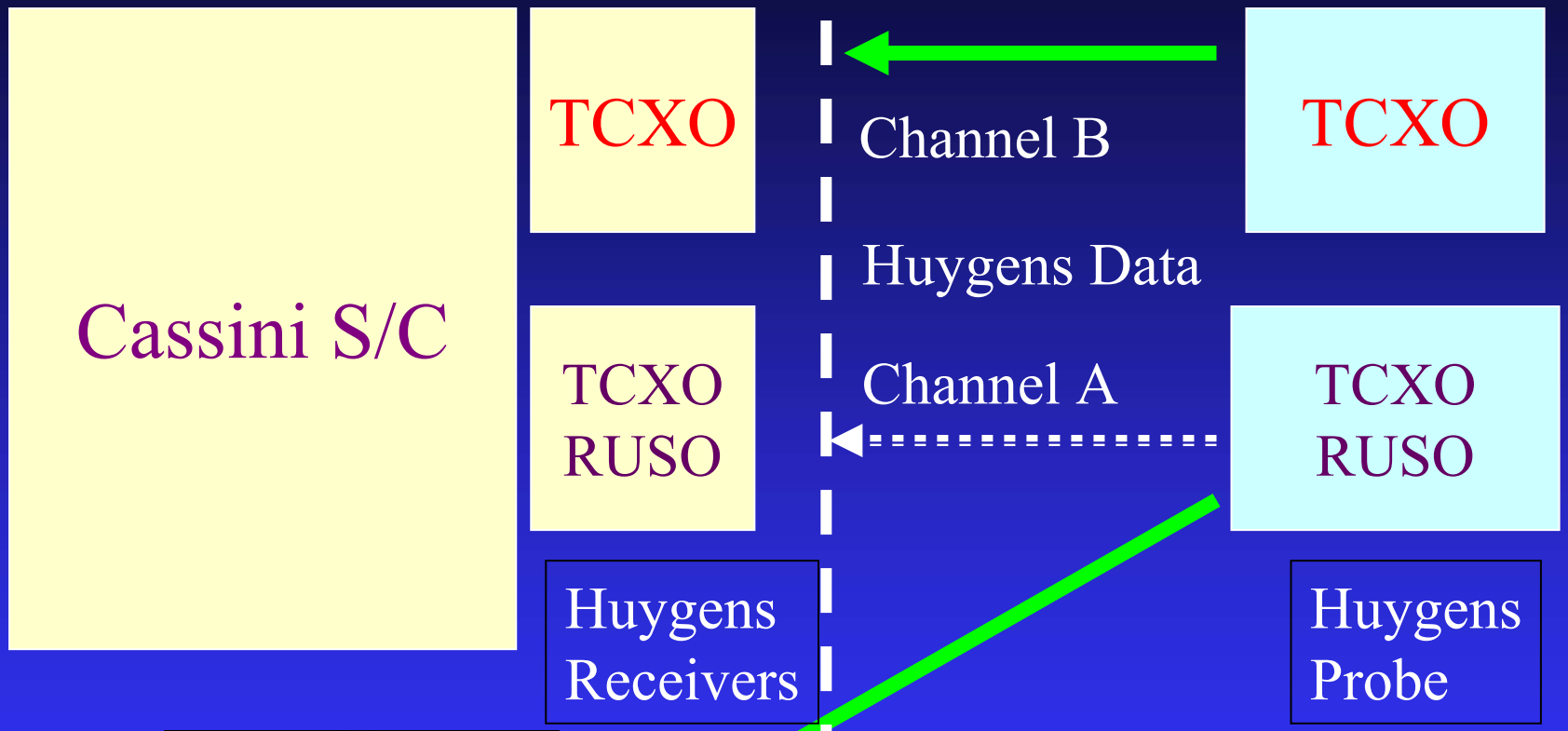








Huygens signal paths



"Channel C" – eavesdropping on Channel A carrier

Algorithm of VLBI processing

"Standard" broad-band VLBI correlation on calibrators

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Imaging of calibrators and calibration definition

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Extraction of narrow-band probe's Signal from Mk5 to HSC

↓

Application of calibration corrections to the narrow-band data

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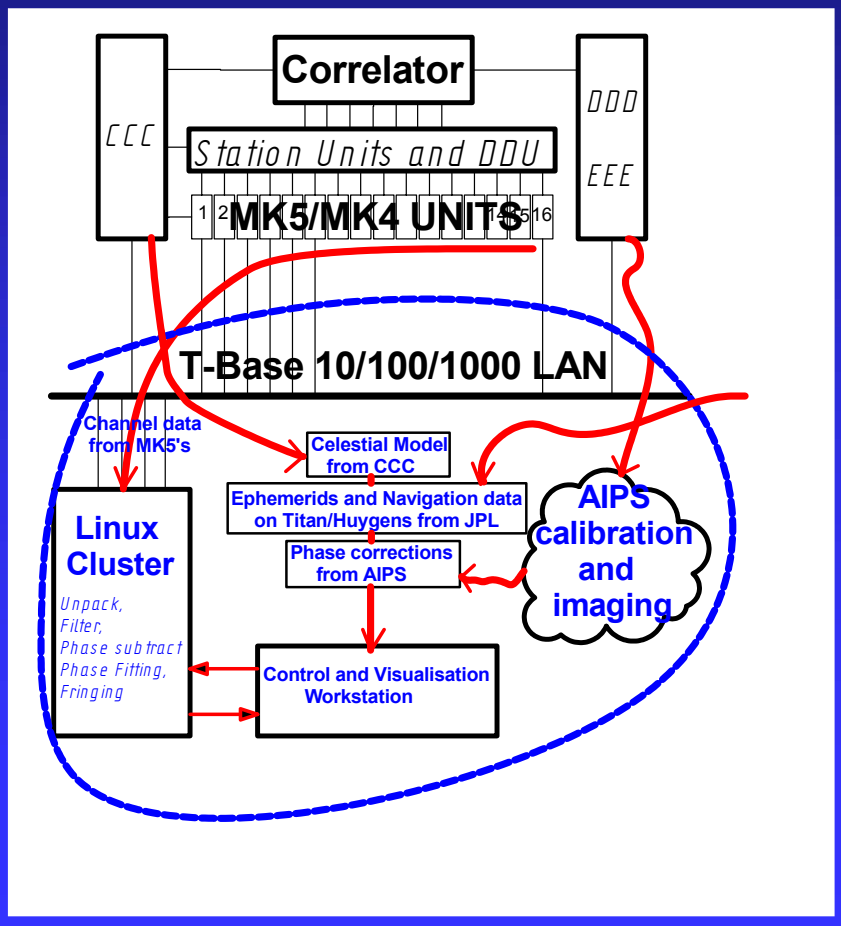
Iterative search for monocromatic (carrier) signal; Common Mode defined

↓

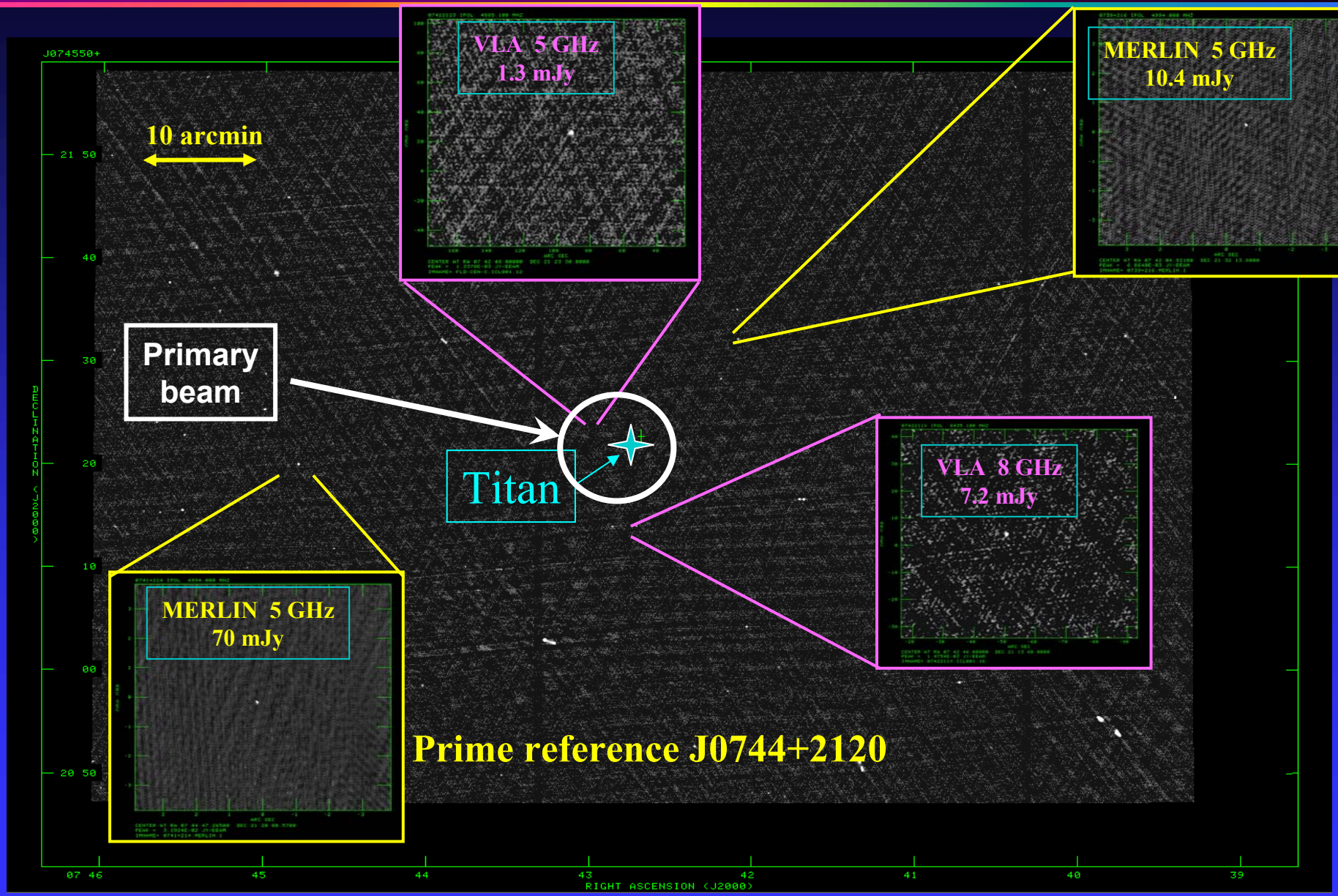
Phase-lock to Common Mode, narrowing down search window

↓

Iterative imaging (trajectory reconstruction)

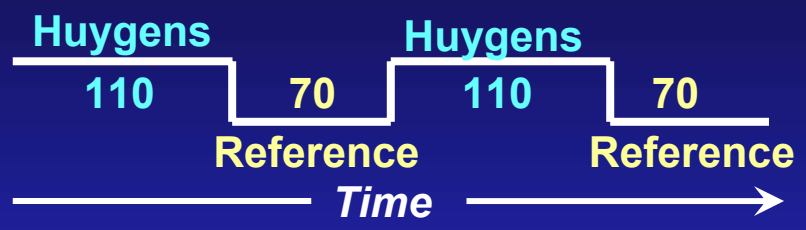


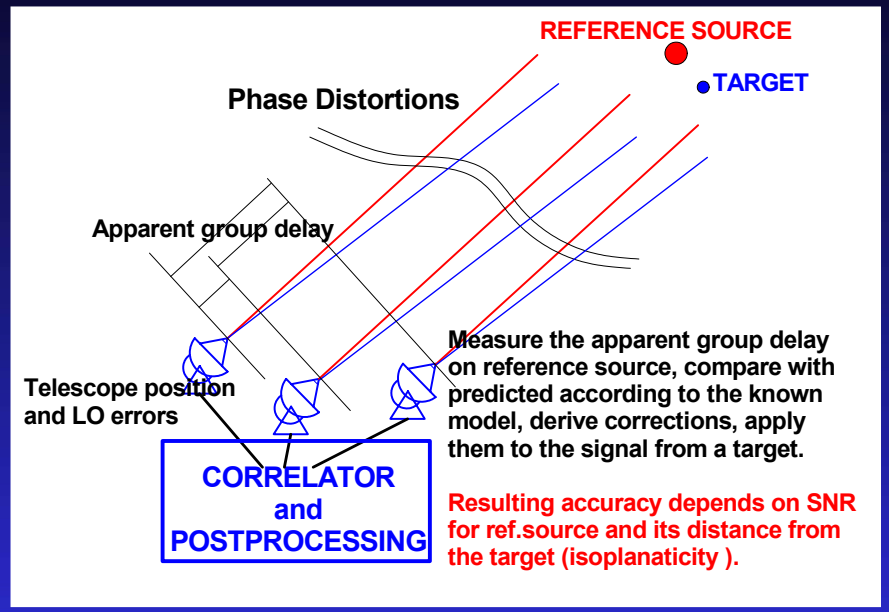
Phase-referencing in the Huygens Field



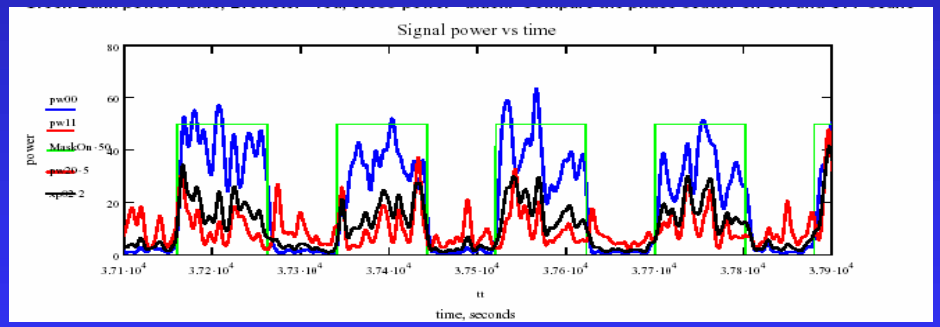
Phase-referencing: the price for being "weak"

- **Phase-referencing duty-cycle 70-110 s:**





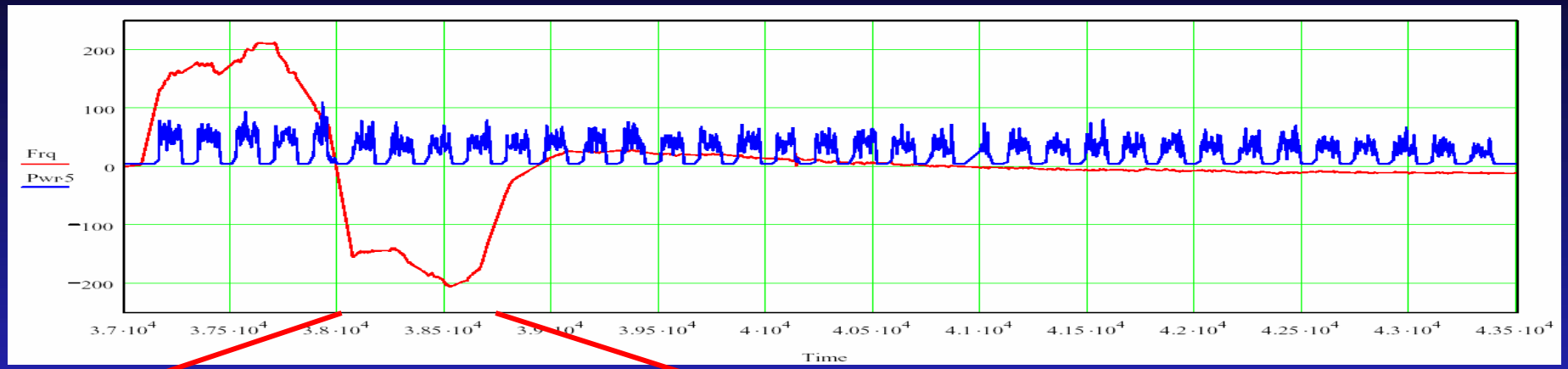
- **Phasing-up VLBI network makes possible detection of a ~2 W transmitter at 8 AU**

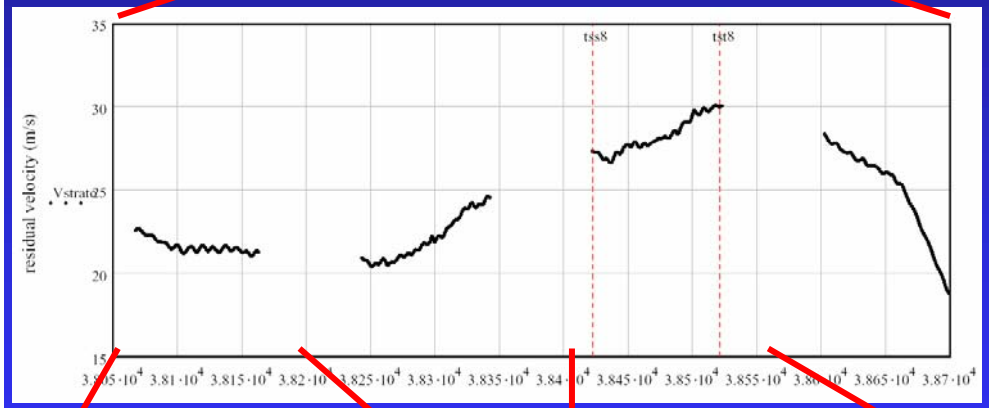


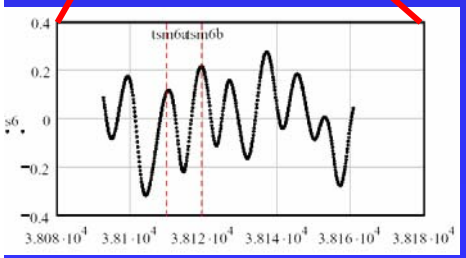
- **Can in-beam (no nodding) phase-referencing help for future missions?**

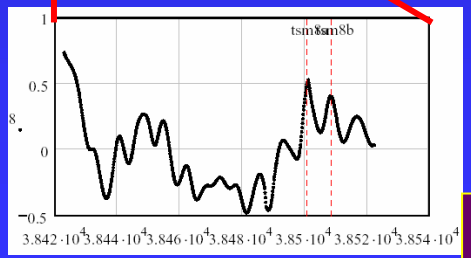
Need for strong enough and compact reference source within primary beam!

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





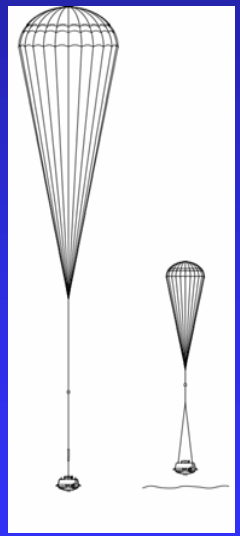


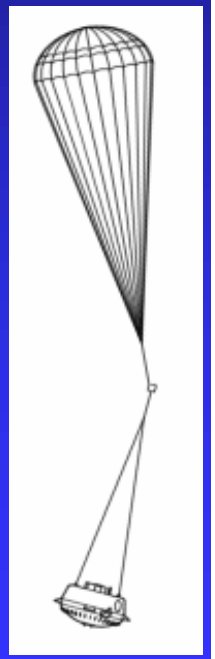


T = 8÷10 s

ΔV = 0.22 m/s

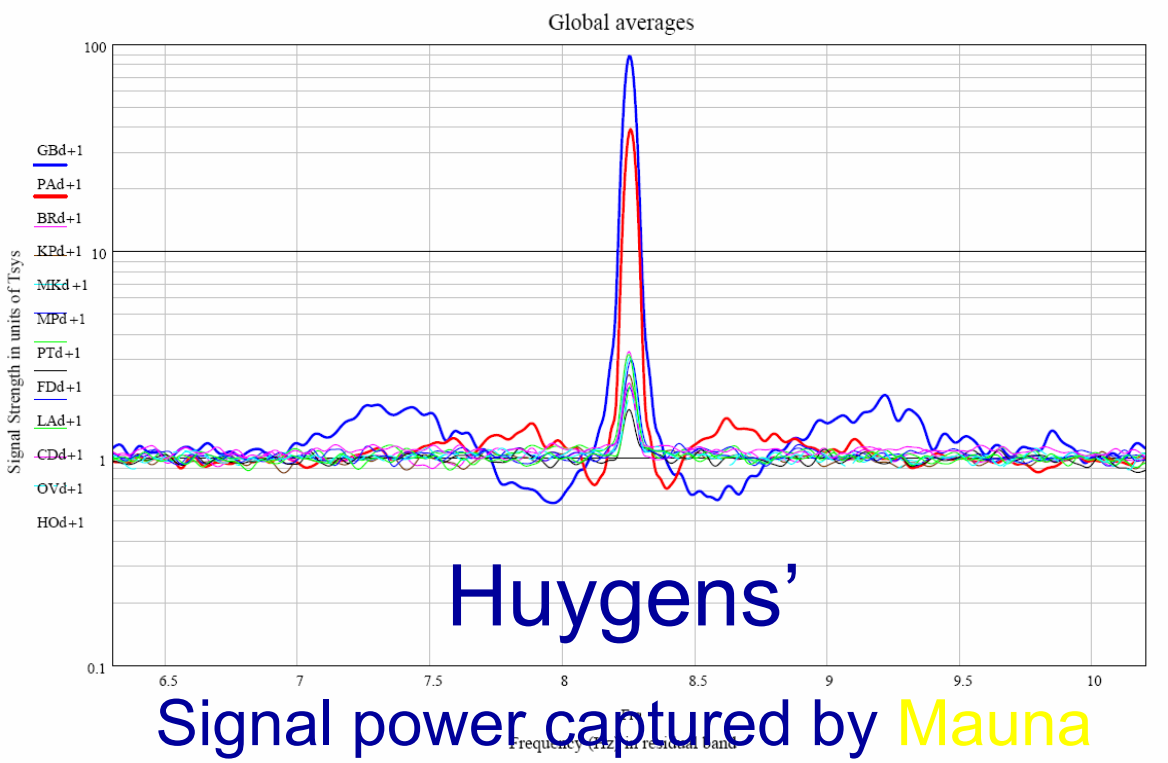
$A \approx$ 0.6 m





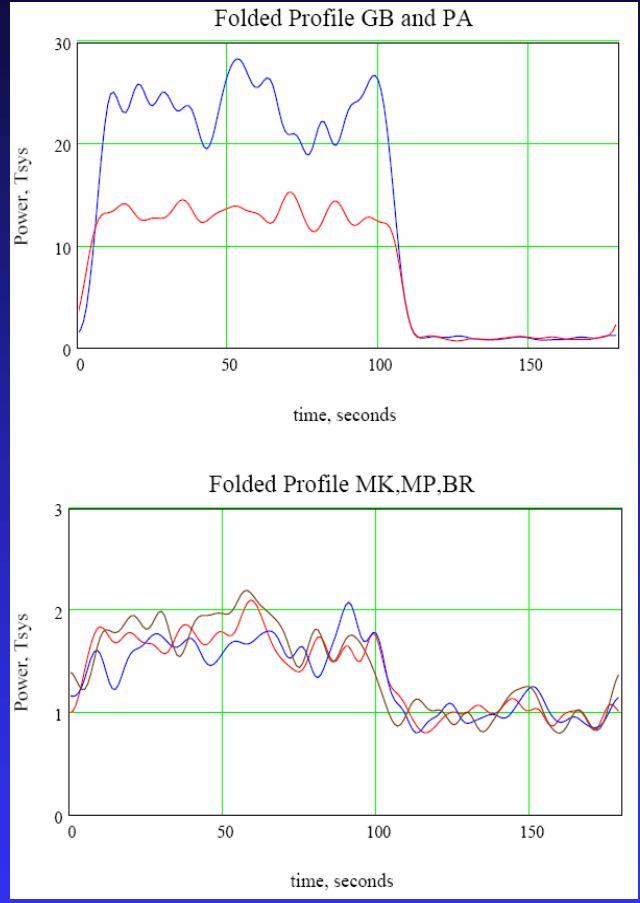
Data available for analysis!

Huygens VLBI tracking as a quantum process



Huygens'

Signal power captured by Mauna Kea antenna:



20 photons per second

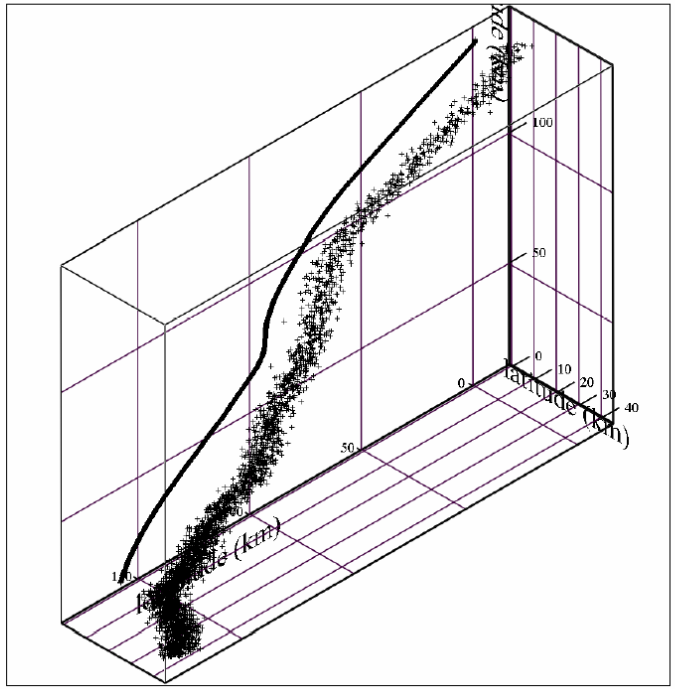
2040 MHz photons:

Photon Rate = P / $h\nu$

"Pulsar-style" folding

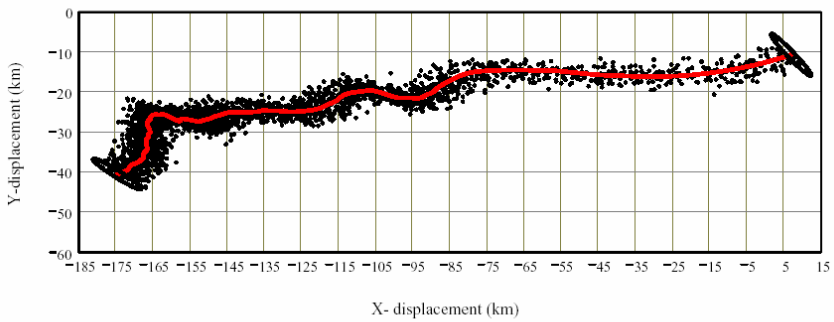
Reconstructed descent trajectory and its statistics

In 3D (altitude from DTWG trajectory)



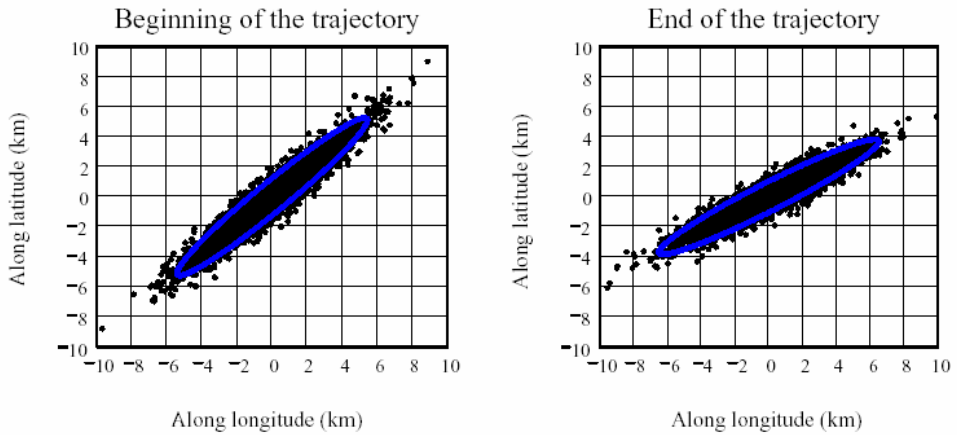
(Xp, Yp, Zp)

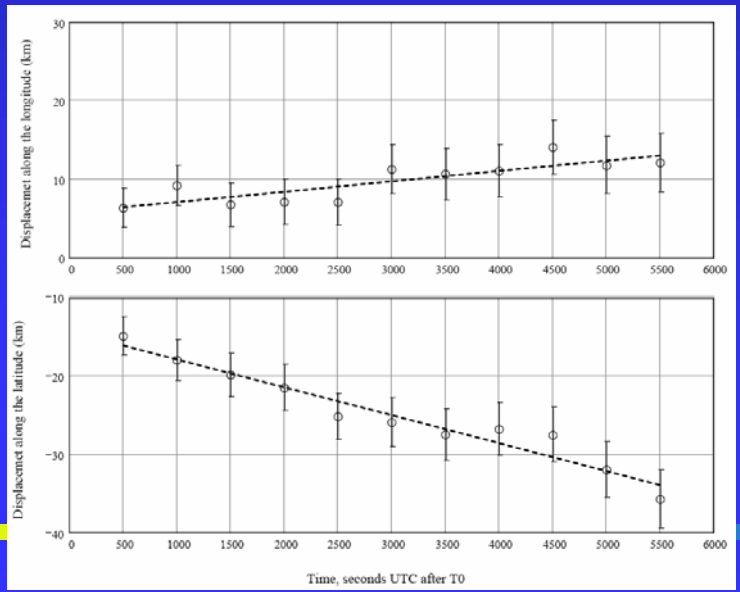
XY (Longitude/Latitude) Projection



+/- 3 σ error scatter ellipses are shown at the beginning and at the end of the trajectory

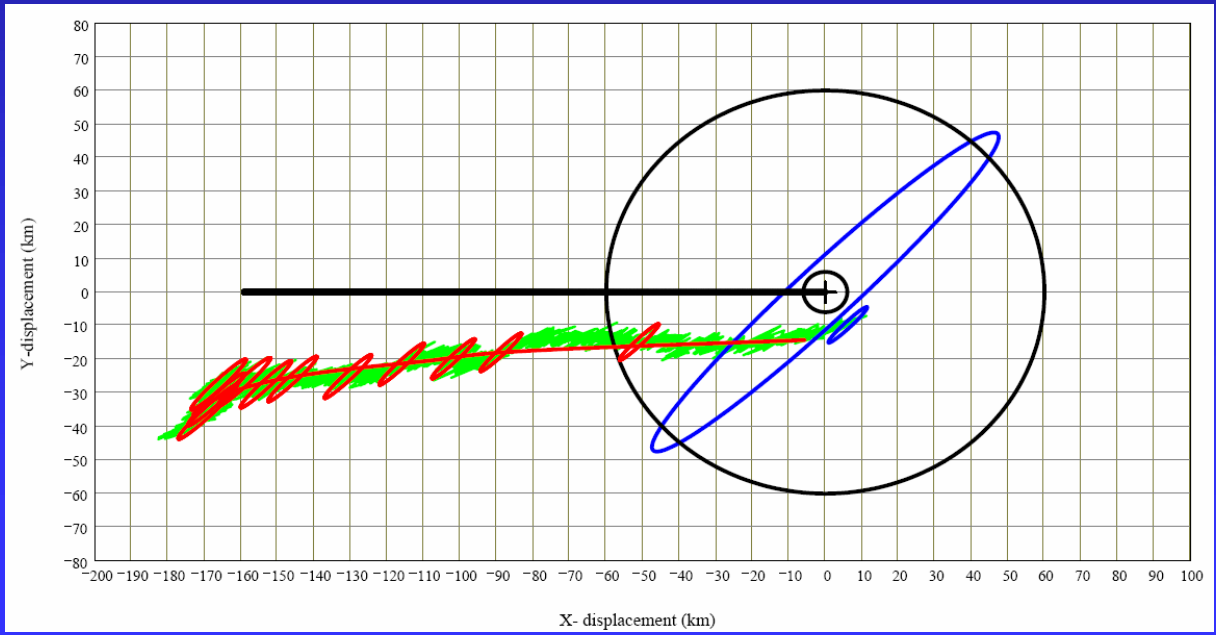
+/- 4 sigma error scatter ellipses on XY plane,
for GBT to FD,KP,LA,BR,MK array, 250s coherent averaging, 15 ps delay noise.
Scale - kilometers on Titan, ellipse 1 sigma semiaxis 2.5 km and 0.5 km,
or 500 μas X 100 μas in angular units.



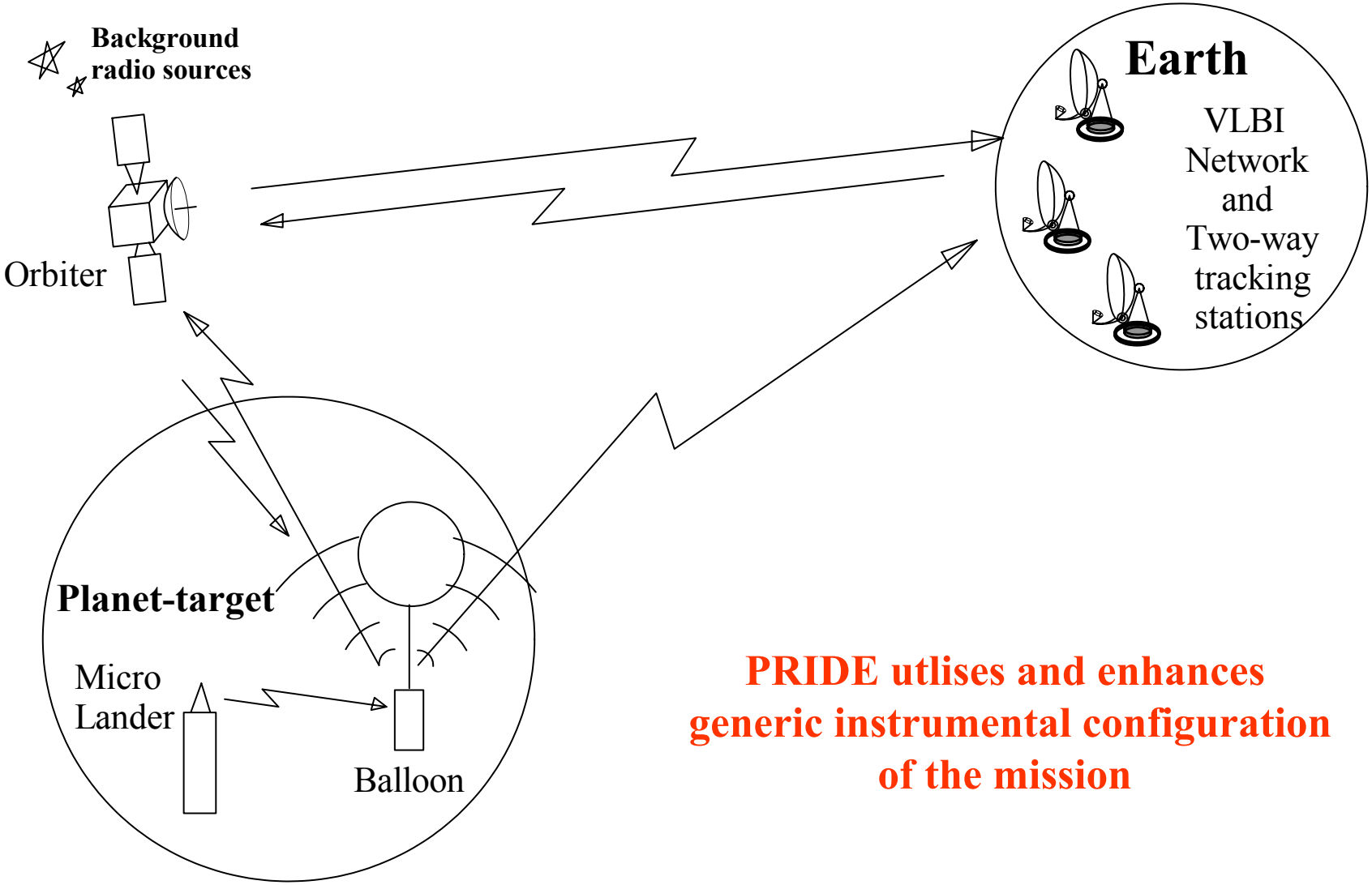


Huygens VLBI tracking experiment: results

- **2D VLBI and 3D combined DTWG-VLBI descent trajectory reconstruction with lateral accuracy ~1 km**
- **Evidence for meridional component of wind**
- **Doppler data available for further analysis**
- **The technique and algorithms are available…**



Generic PRIDE configuration



PRIDE utlises and enhances generic instrumental configuration of the mission

PRIDE versus Huygens VLBI tracking

	Huygens	PRIDE-T	Resolution gain
Radio link frequency	2 GHz	2/8/32 GHz	1/4/16
Distance	8 AU	~8 AU	1
VLBI "fringe" SNR	10 - 30	30 - 100	~3
Linear resolution (1σ)	1 km	360/80/20 m	~3/12/50

- Conservative estimate, today's technology;
- No special requirements for the on-board instrumentation
- In-beam "Orbiter-Probe" calibration can improve SNR further

Smart-1: a VLBI target 1 light-second away…

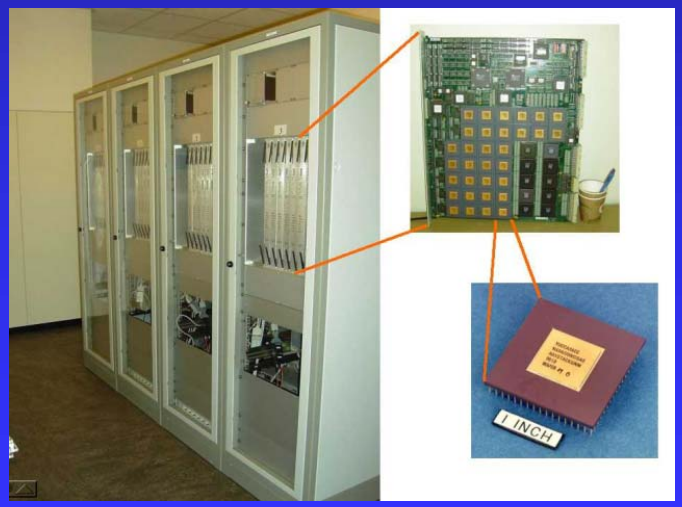
Medicina, 32 m, IT

Smart-1, circumlunar orbit

Metsähovi, 14 m, FI

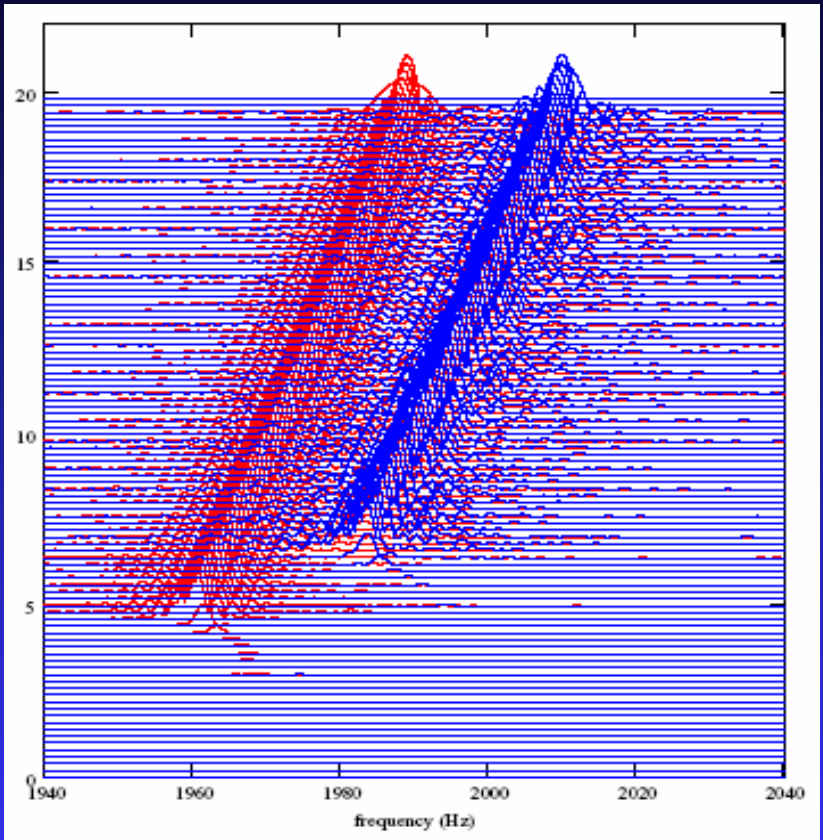
Westerbork, 25 m, NL

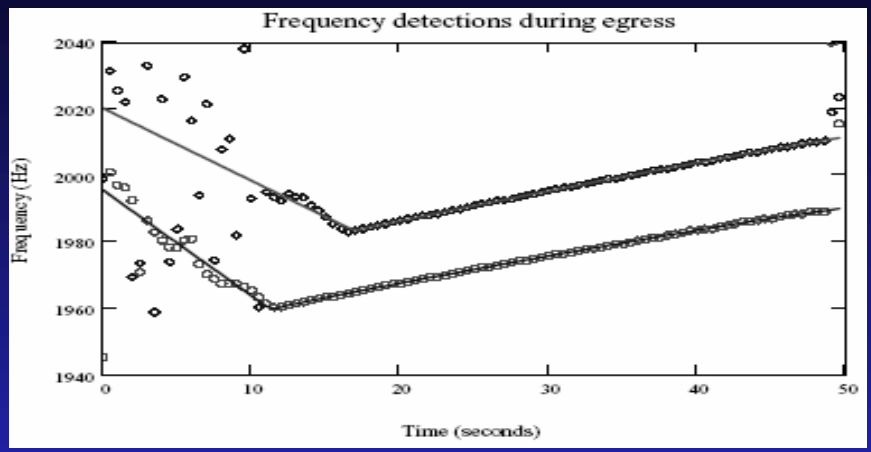
Goal: ultimate verification
of the Huygens VLBI correlator

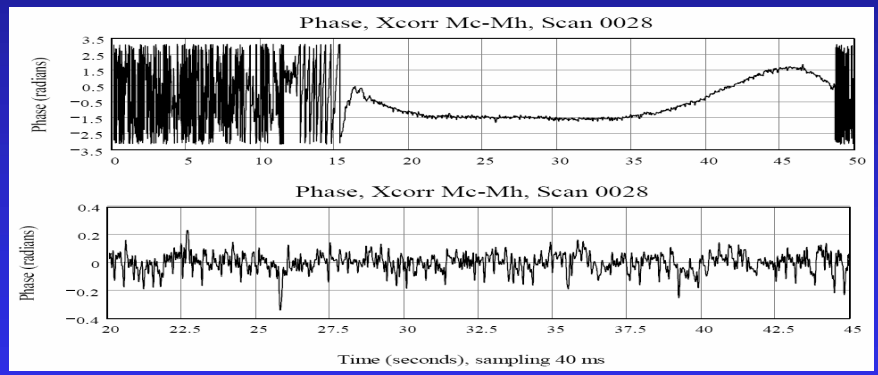


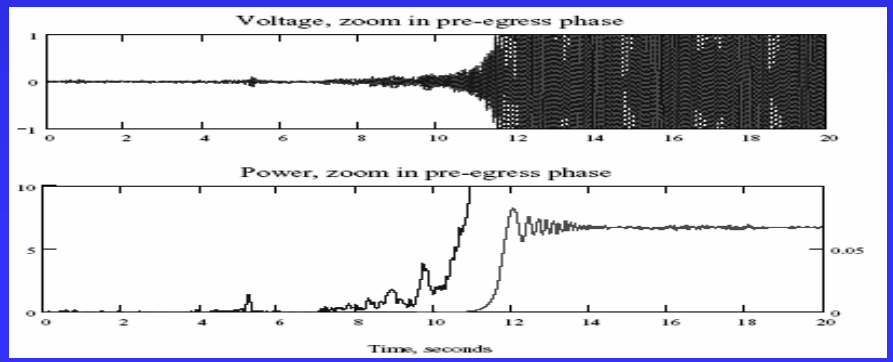
VLBI processor at JIVE, NL

Smart-1 at 2.3 GHz as seen by radio telescopes









Data show:

- Diffraction on the Lunar limb
- Propagation pattern
- "Reflection" intereferometry
- And much more …

Direct to Earth (backup) data transfer: an example

Estimate of data transfer rate from a Venus probe (balloon and lander) directly to Earth

Assuming an isotropic Tx power of 5 W@0dBi, frequency ~400 MHz, distance 0.7 AU

Shannon limit data rate $Dr=\Delta F \cdot \log_2(1+SNR_{1Hz}/\Delta F)$ for $SNR_{1Hz}/\Delta F = 4$

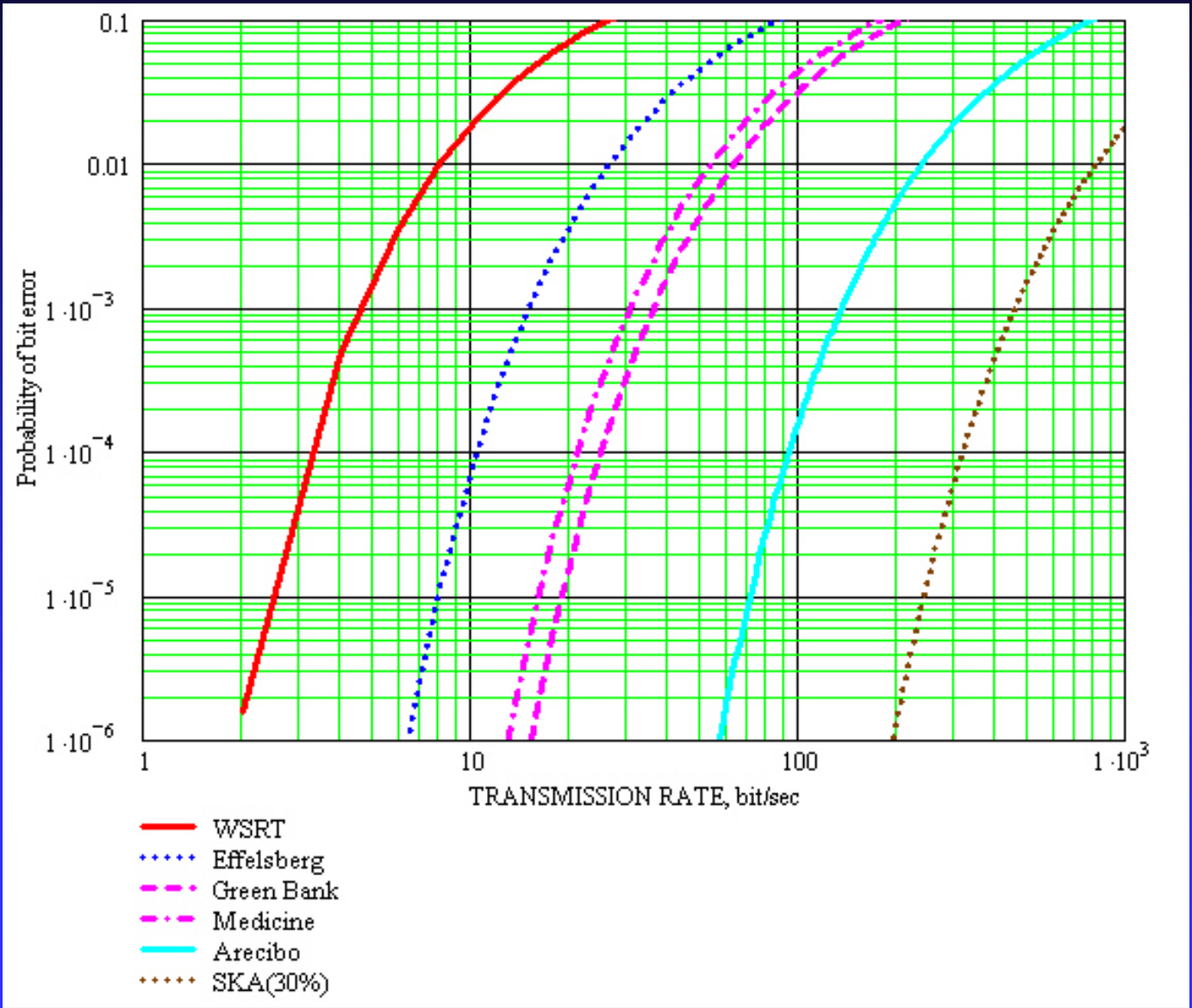
Several large-aperture radio telescopes with UHF frequency coverage are considered

Radio telescopes and their parameters:

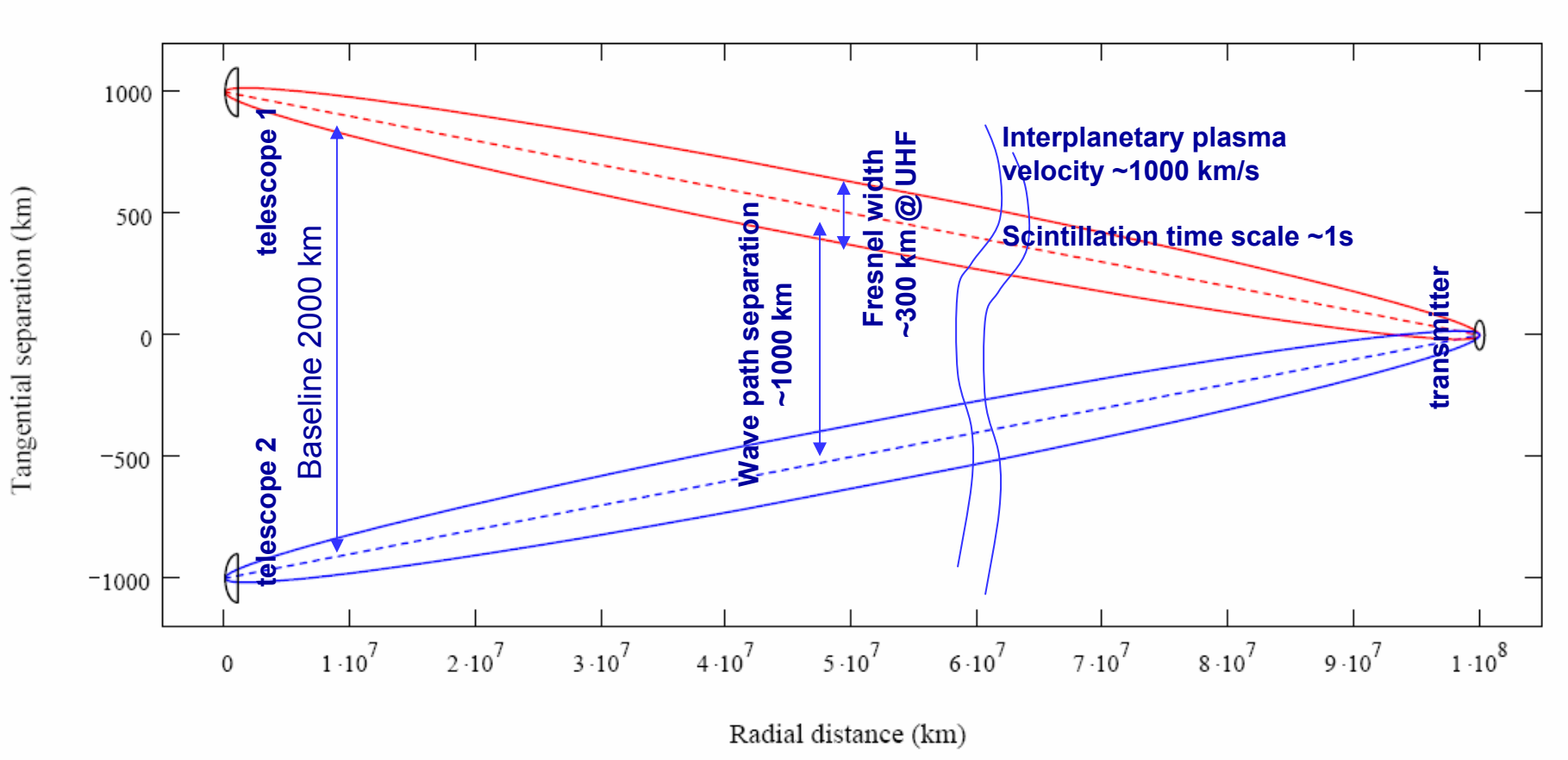
	Westrbork	*Effelsberg*	*Green Bank*	*Medicina*	*Arecibo*	*SKA=30%*
Aperture	14 x 25m	100 m	100 m	30,000 m^2	300 m	300,000 m^2
Frequency range (MHz)	300-450	350-450	300-500	407-409	425-435	300-500
Aperture efficiency	0.35	0.6	0.6	0.4	0.4	0.4
Tsys (K)	200	120	50	150	80	100
SNR(in 1Hz)	35	110	270	230	1100	3500
Shannon Limit (bps)	20	60	150	130	600	2000
BPSK @BER<10^{-3} (bps)	5	12	30	25	120	400
TRL (as per 2007)	8	7	8	8	8	3

ASTRON MAX-PLANCK-GESELLSCHAFT NRAO INAF ira SKA SQUARE KILOMETER ARRAY

DtE achievable data rates for BPSK modulation



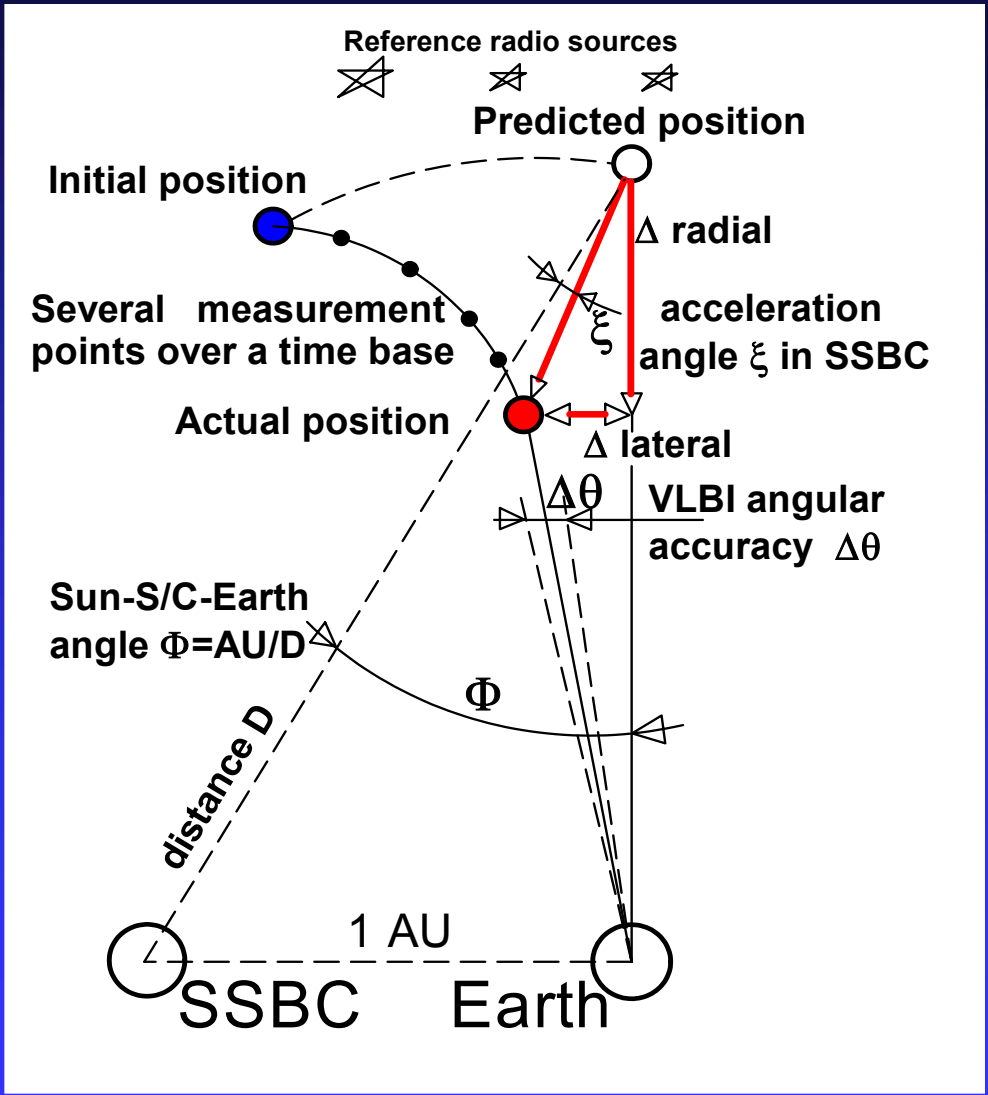
Signal fading due to interplanetary scintillations



Signal fading patterns for widely separated receiving antennas will be uncorrelated, so the robustness of the reception will be improved

Implications for the Pioneer Anomaly research mission

Vectorization of the residual acting force at distances up to 50 AU



Conclusions

- **Radio astronomy techniques and facilities offer tracking and link parameters beyond reach of "standard" instrumentation**
- **Rich "by-products"**
  - ***Doppler tracking data "for free" (see Huygens data);***
  - ***Near-planet propagation effects (occultations) – see Smart-1 example***
  - ***"Traditional" radio astronomy diagnostics of planets and interplanetary medium (water in the Saturnian system?)***
- **Multi-facet applications achieved by limited on-board suit of instrumentation**