Introduction to the VLBI technique

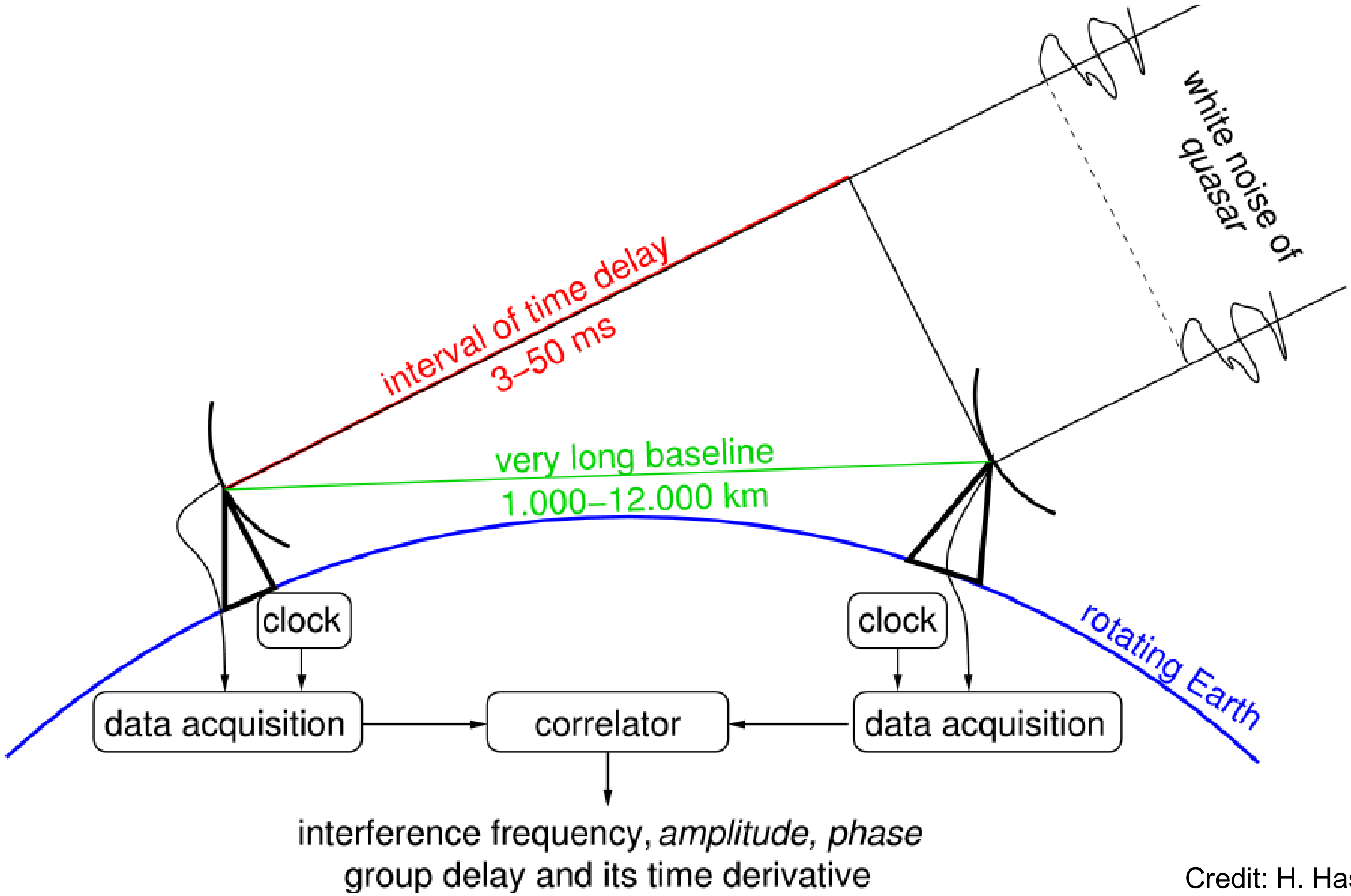
P. Charlot

Laboratoire d'Astrophysique de Bordeaux

Outline

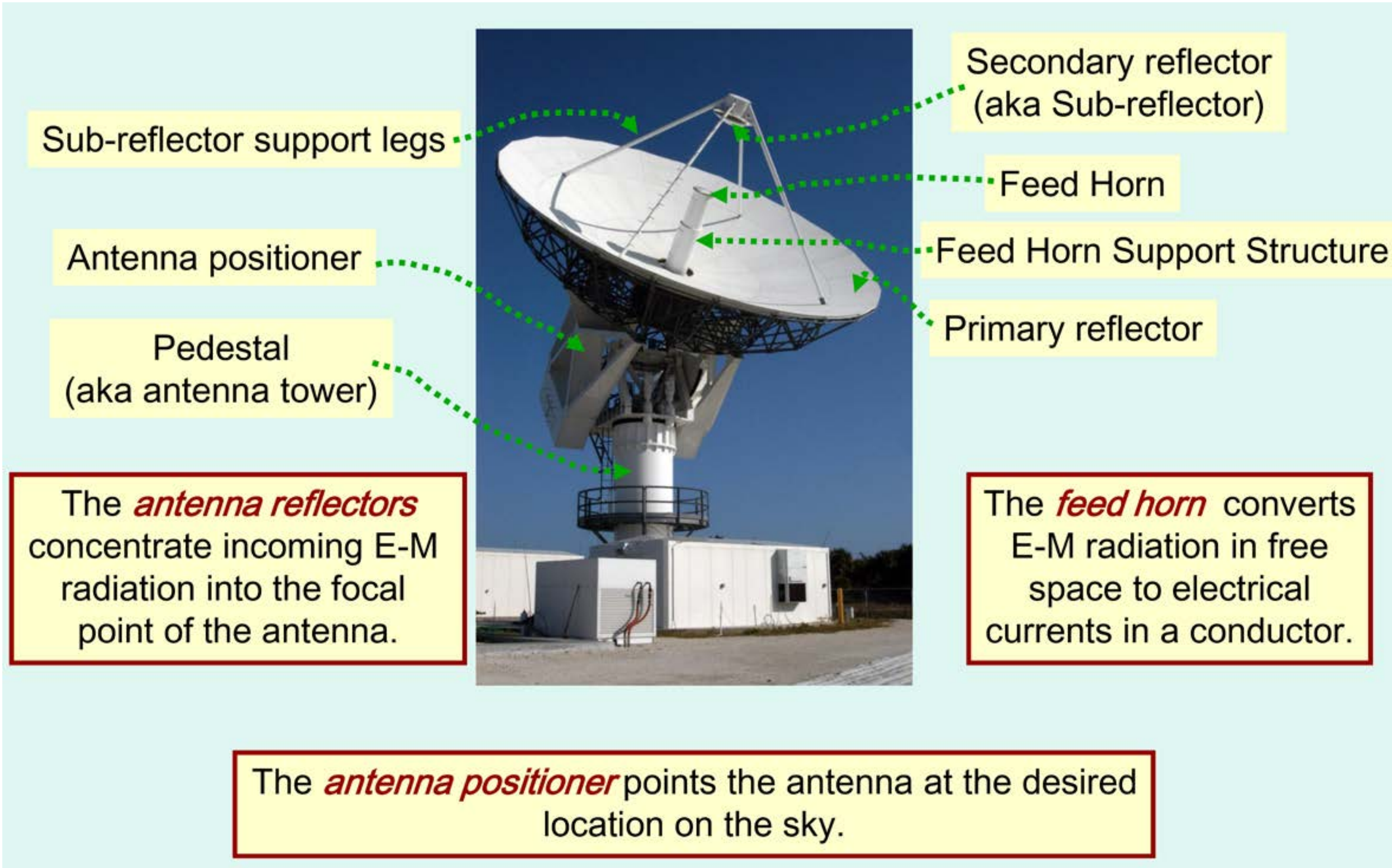
- VLBI instrumentation
- Correlation and post-processing
- VLBI networks and observations
- Data analysis
- The future system: VGOS

VLBI principle



Credit: H. Hase

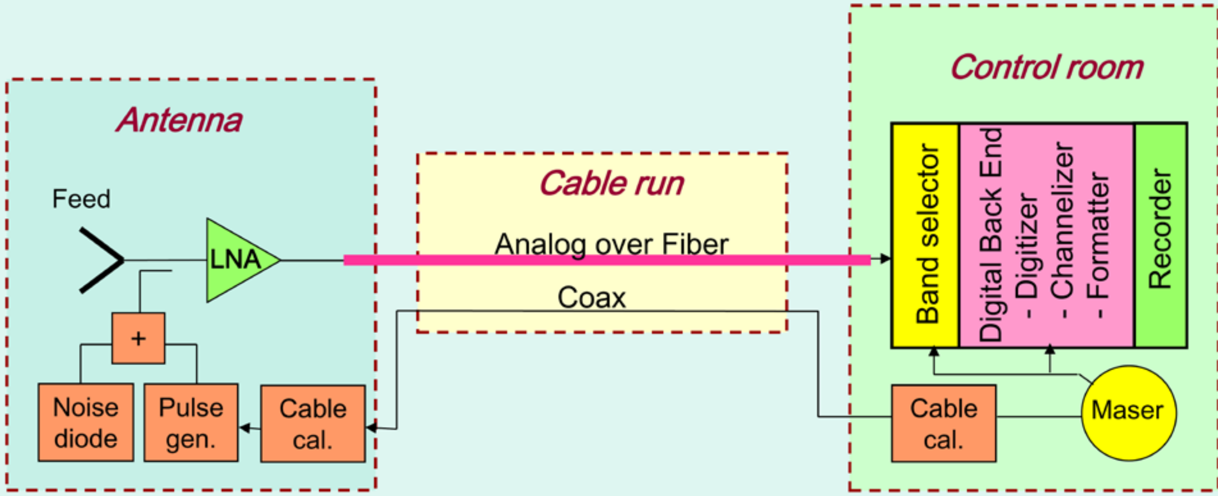
Parabolic reflector antenna



Credit: B. Petrachenko

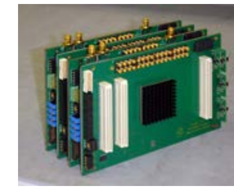
Signal chain





Front end receiver:
- Feed
- Low Noise Amplifier (LNA)
- Cryogenics
- Calibration equipment:
  - ~ Noise diode
  - ~ Phase Cal. (Pcal) Pulse Generator
  - ~ Cable Cal. Antenna Unit

Back end receiver:
- Band Selector (e.g. Up-Down Converter made up of analog amplifiers, mixers, filters, etc)
- Digital Back End (DBE)
  - ~ High rate/high resolution Digitizer/Sampler
  - ~ Channelizer:
    - * Polyphase Filter Bank (PFB), or
    - * Digital Baseband Converter
  - ~ Formatter
- Recorder
- Hydrogen Maser
- Cable Cal. Ground Unit




Credit: B. Petrachenko

Correlation

JIVE hardware correlator (as originally in 1997, with magnetic tapes)

VLBA hardware correlator (1992-2009)

JIVE correlator in 2008 (after replacement of tapes by disks)

DIFX software correlator (> 2009)

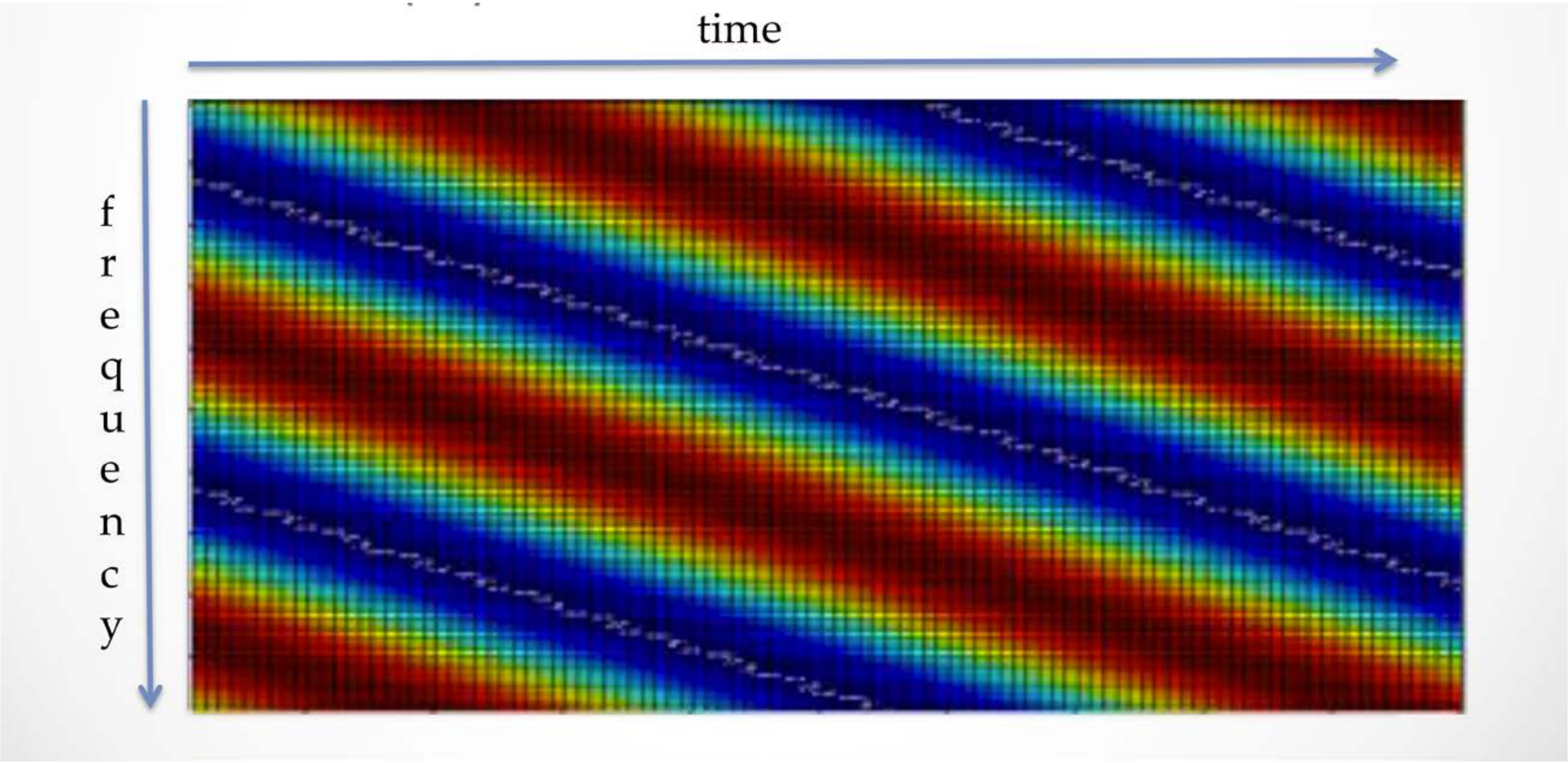
Fringe-fitting: why is it necessary?

- Correlator model is good but not perfect
- Antenna models and locations, source positions are typically very good… but atmosphere is time-variable and impredictable
- GPS clock information has significant errors at the level of accuracy

Fringe-fitting removes remaining non-random signatures by incremental changes to the correlator parameters

Concept of fringe fitting

Correlator produces a 2-D complex array of visibilities



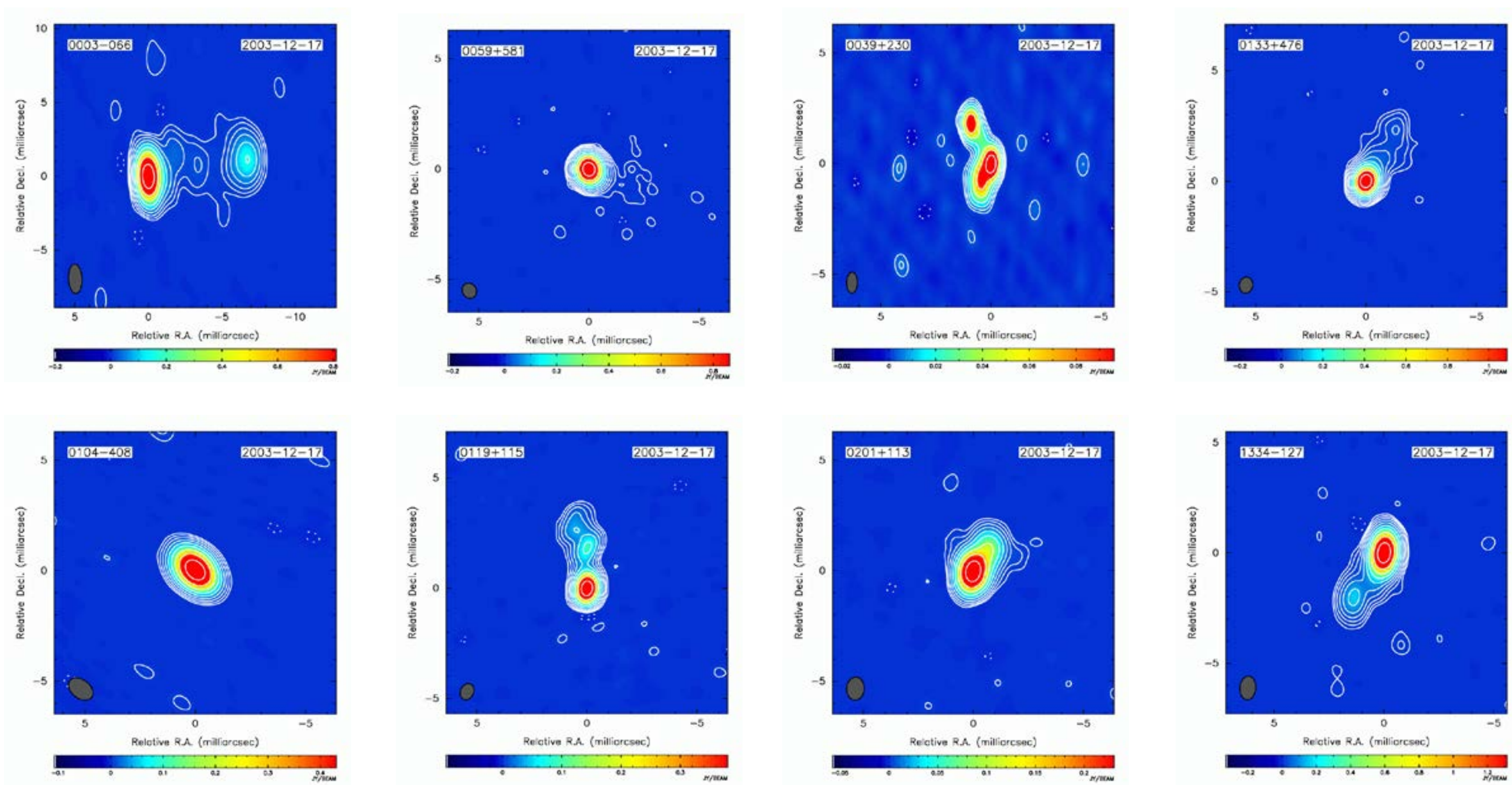
Credit: R. Cappallo

Extracted parameters

- For astronomy
  - ρ amplitude
  - Φ phase
- For geodesy
  - Group delay $\tau_g = \partial\Phi/\partial\omega$: variation of phase with frequency
  - Delay rate $\dot{\tau}_g = \partial\Phi/\partial t$: rate of change of τ_g, derived from the variation of phase with time

Astrophysical VLBI

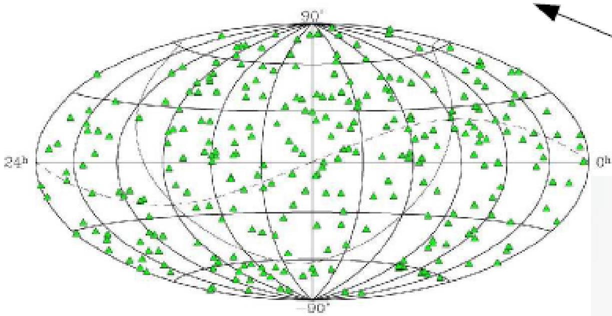
Cartographie d'objets célestes avec une résolution angulaire de 0.001″



Images de sources ICRF tirées de la base BVID (Bordeaux VLBI Image Database)

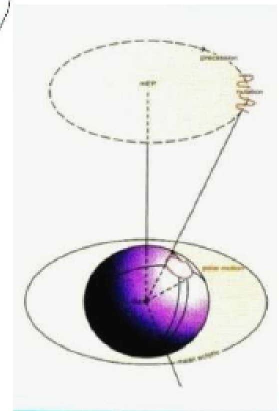
VLBI astrometry and geodesy

ICRF



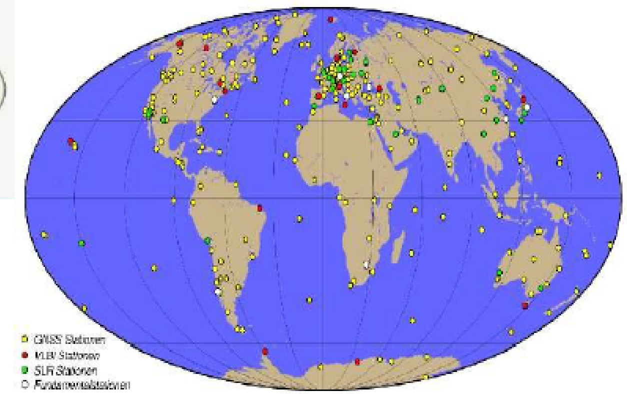
quasar positions

EOP



precession
nutation
polar motion
UT1-UTC

ITRF

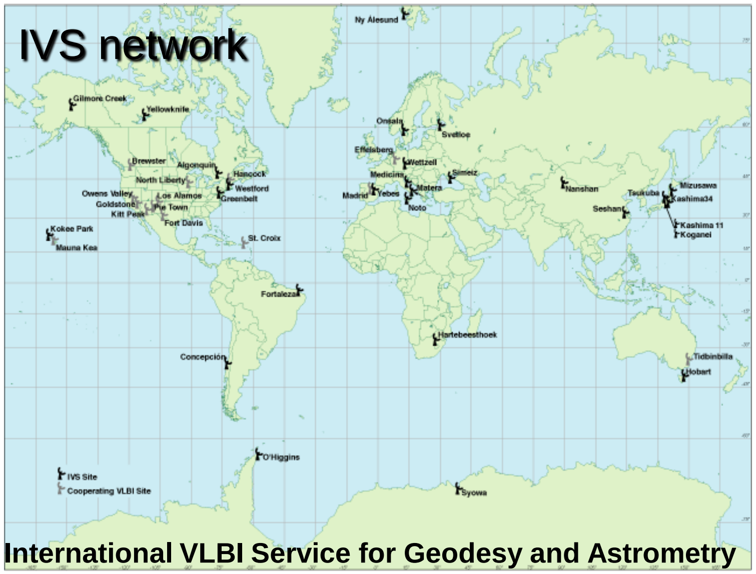


ref. point positions and velocities
time series
baselines

VLBI is the only geodetic space technique which provides:
ICRF, ITRF and the full set of Earth orientation parameters (EOP).

Credit: H. Hase

VLBI observing networks



Very Long Baseline Array (VLBA)

Geodetic sessions

A typical geodetic-type session:

- Observes at S/X band (2 GHz / 8 GHz)
- Has a duration of 24 hours
- Includes 8-10 radiotelescopes spread over different continents
- targets 50-100 extragalactic sources in various part of the sky

Geodetic data analysis

- Observables: $\tau = \partial\Phi/\partial\omega$, $\tau = \Phi/\dot{\omega}$

- τ can be measured to a precision of the order of 10 ps

  (1 mas = 3 cm ~ 100 ps)

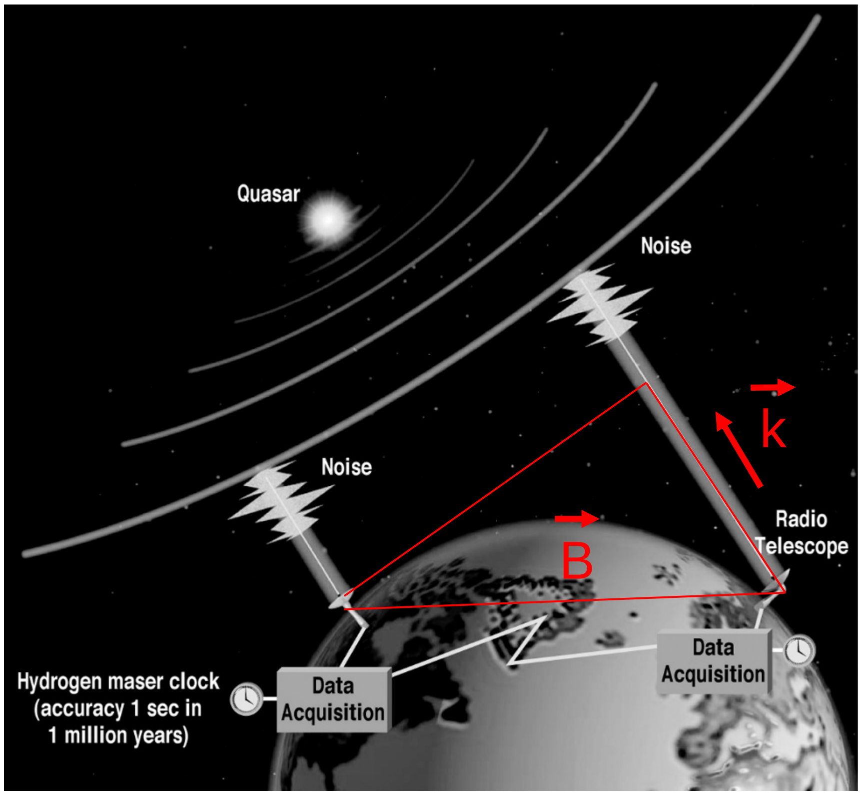
- Modeling:

$$\tau = \tau_g + \tau_{inst} + \tau_{trop} + \tau_{ion} + \ldots$$

τ_g = geometric delay τ_{trop} = tropospheric delay

τ_{inst} = instrumental delay τ_{ion} = ionospheric delay

Geometric delay



Credit: NASA/GSFC

τ_g max = 0.02 s

- $\tau_g = -(1/c)\, \vec{k} \cdot \vec{B}$ [...]
- Relativistic effects at the level of 10^{-8} s
- $\vec{B}_{cél} = Q\,(\vec{B}_{ter} + \Delta\vec{B}_{ter})$
- $\Delta\vec{B}_{ter}$ depends on:
  - Tectonic motions
  - Terrestrial tides
  - Oceanic tides
  - atmospheric loading
  - ...

Instrumental delay τ_{inst}

- Two terms:
  - Delay caused by the difference between the clocks of the two antennas

$$\tau_{hor} = \tau_{hor2} - \tau_{hor1}$$

  - Delay caused by propagation in the cables and electronics at each antenna.

$$\tau_{prop} = \tau_{prop2} - \tau_{prop1}$$

- In practice $\tau_{inst} = \tau_{hor} + \tau_{prop}$ is modeled by a linear or quadratic function where the coefficients are estimated

Tropospheric delay τ_{trop}

- Two components
  - Dry component → can be known to some level from meteo data
  - Wet component → difficult to model and very variable
- Modeling
  - For each station i : $\tau_{trop\ i} = \tau_{trpz\ i}\ R\ (H_i)$

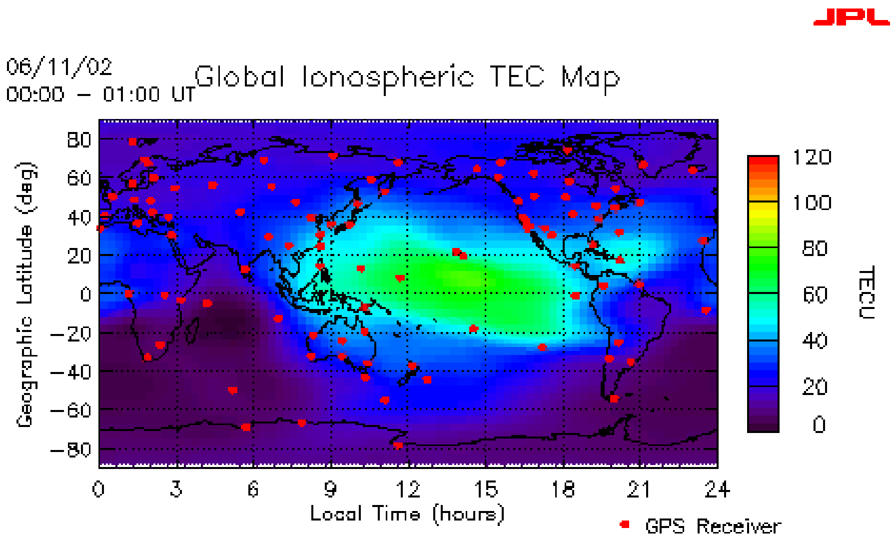
    $\tau_{trpz\ i}$ = zenith tropospheric delay

    R = mapping function (H_i = elevation angle)
  - Differential effect : $\tau_{trop} = \tau_{trop2} - \tau_{trop1}$
- In practice: $\tau_{trpz\ i}$ are estimated

Ionospheric delay

- Depends on the electronic content
- Diurnal cycle
- Proportionnal to $1/\nu^2$
- Differential effect

$$\tau_{ion} = \tau_{ion2} - \tau_{ion1}$$

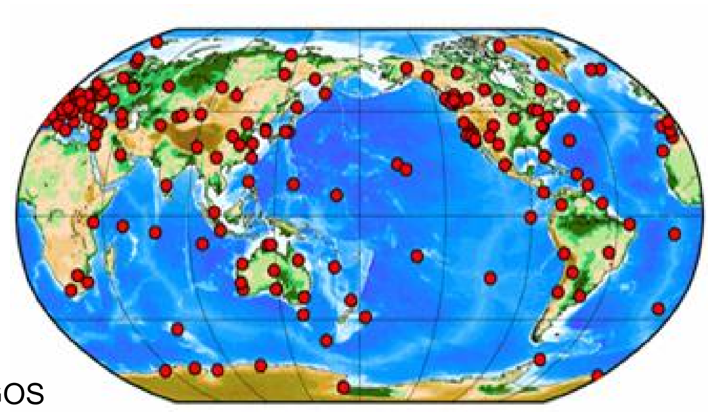


➔ In practice, the ionospheric delay is eliminated by combining the S band delay (2.3 GHz) and the X band delay (8.4 GHz).

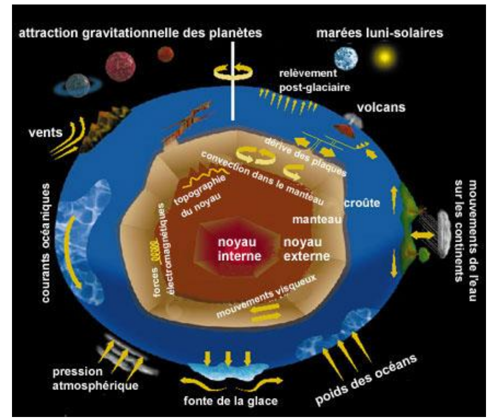
VGOS

Scientific motivation

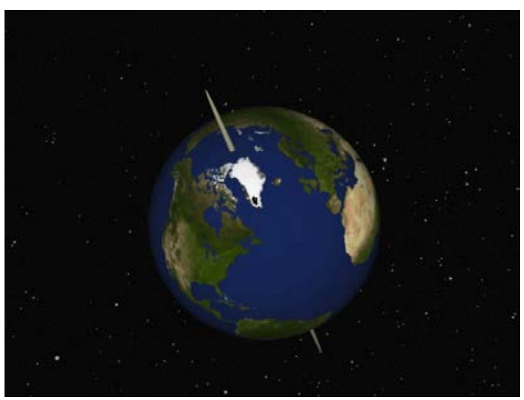
Reach 1 mm for geodetic positions



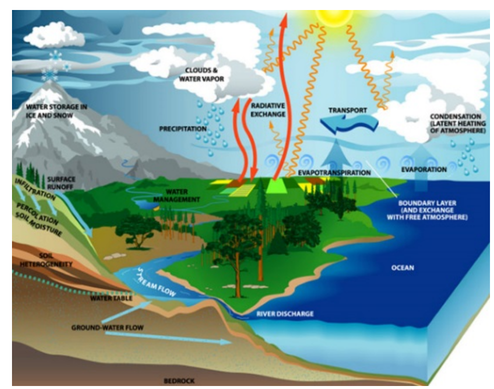
Credit: GGOS



Credit: J. Verheijen



Credit: Silver Spoon (Wikimedia Commons)



Credit: GGOS

Motivations techniques

Constat vers ~2005

- Systèmes VLBI géodésiques/astrométriques vieillissants
  - Antennes anciennes et lentes (vitesse de déplacement)
  - Electronique ancienne
  - Problèmes d'interférences radio
  - Coût de fonctionnement élevé

…

- Nouvelles technologies disponibles
  - Antennes à moindre coût
  - Systèmes d'acquisition large bande (2-15 GHz)
  - Numérisation des signaux à haute vitesse
  - Disques de grande capacité et transfert possible par fibre optique

…

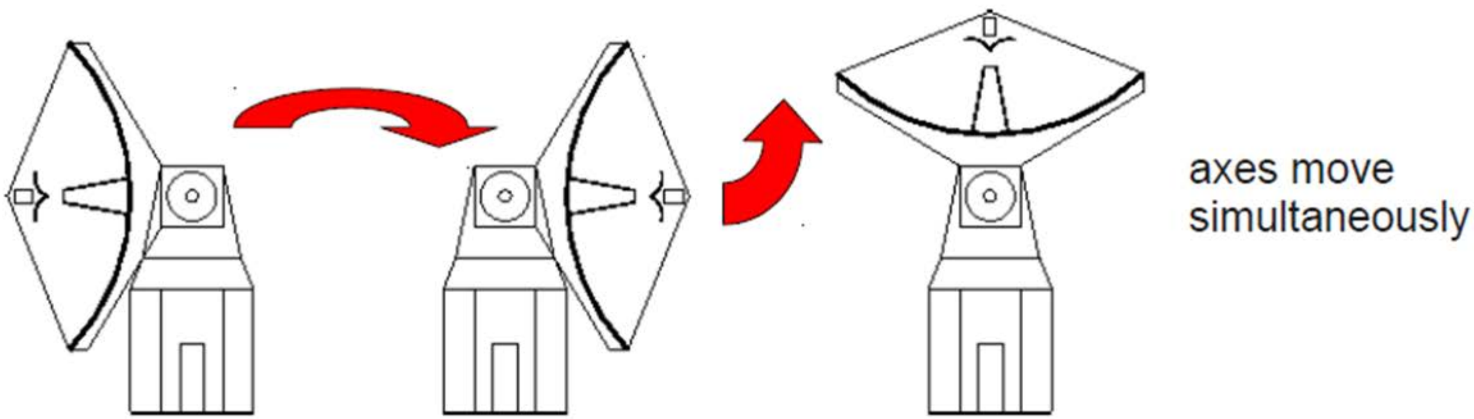
VGOS: the antennas

Azimuth

- range: -270°..+270°
- velocity: 12 deg/s
- acceleration: 3 deg/s²
- 180° turn ≈ **19s**

Elevation

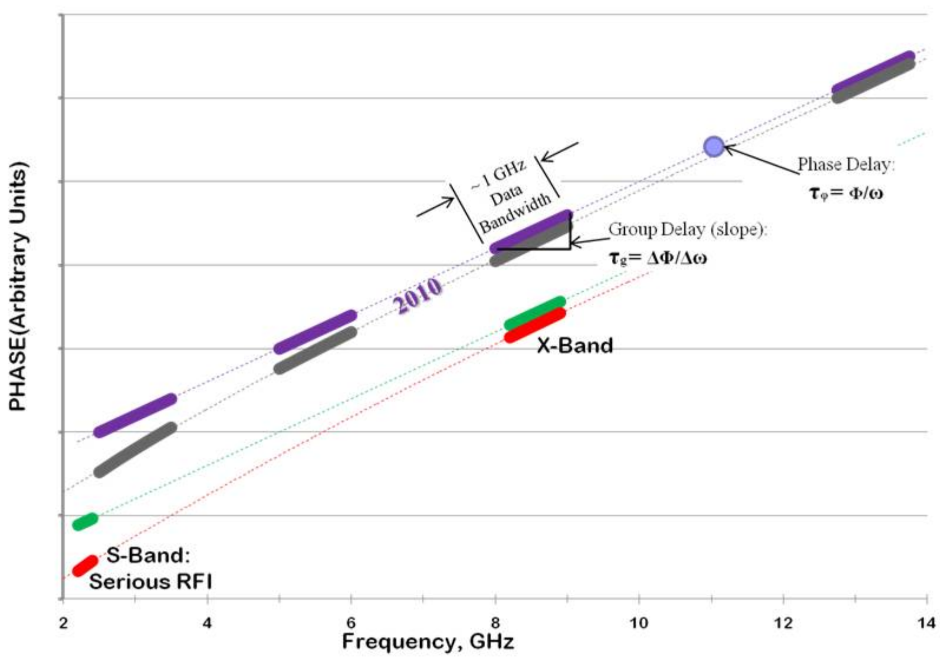
- range: 0°..90° (180°)
- velocity: 6 deg/s
- acceleration: 3 deg/s²
- 90° turn ≈ **17s**



Each direction in the sky will be pointed within 20s.

Credit: H. Hase

VGOS: observing mode

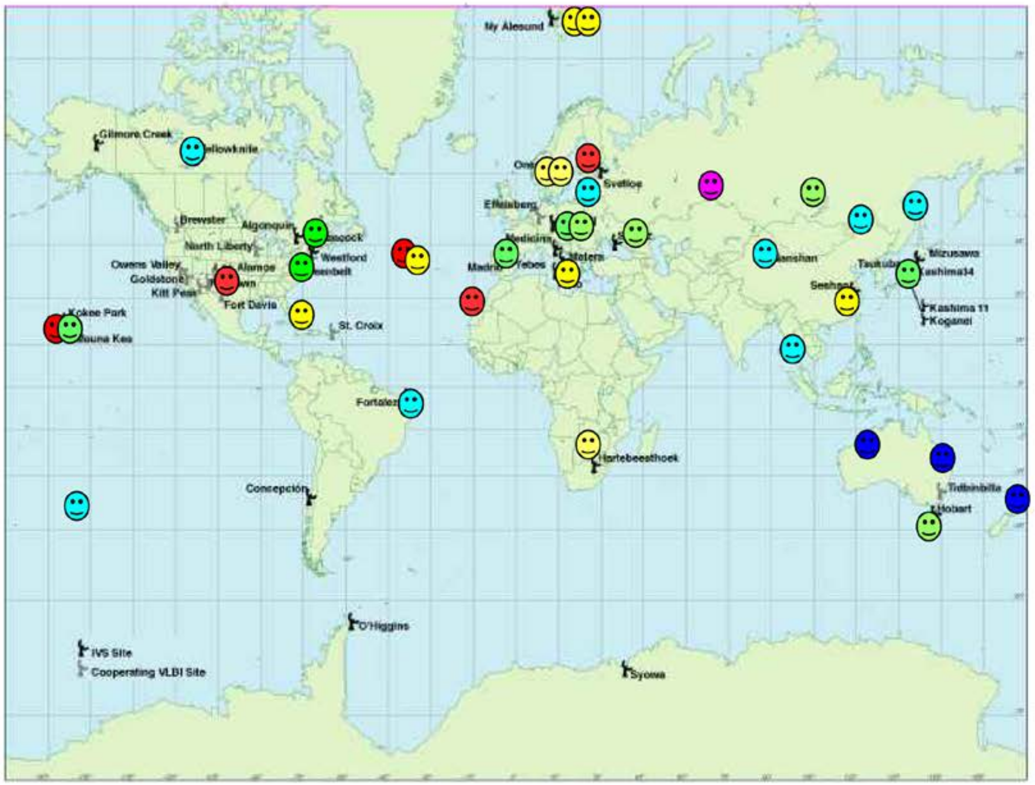


Credit: IVS

- **Current mode**
  - S band + X band
  - Group delay
  - Combination of X and S delay to eliminate ionosphere
- **VGOS mode**
  - 4 bands of 1 GHz between 2 and 14 GHz
  - Phase connection over the entire bandwidth
  - Increase in the temporal resolution and of the delay precision

Where are we?

New VGOS radio telescopes for IVS



- operational
- under construction
- funded
- proposal submitted
- planning phase
- planning phase upgrade

based on available information October 2016

Credit: H. Hase

First VGOS antenna type

Built by Vertex

Twin telescopes Wettzell (Germany)

Badary (Russia)

Second antenna type

<u>Built by MT-Mechatronics</u>

Yebes (Espagne)

Santa Maria (Azores)

Ishioka (Japan)

Twin telescopes Onsala (Sweden)

Twin telescopes NyAlesund (Spitzberg)

Third antenna type…

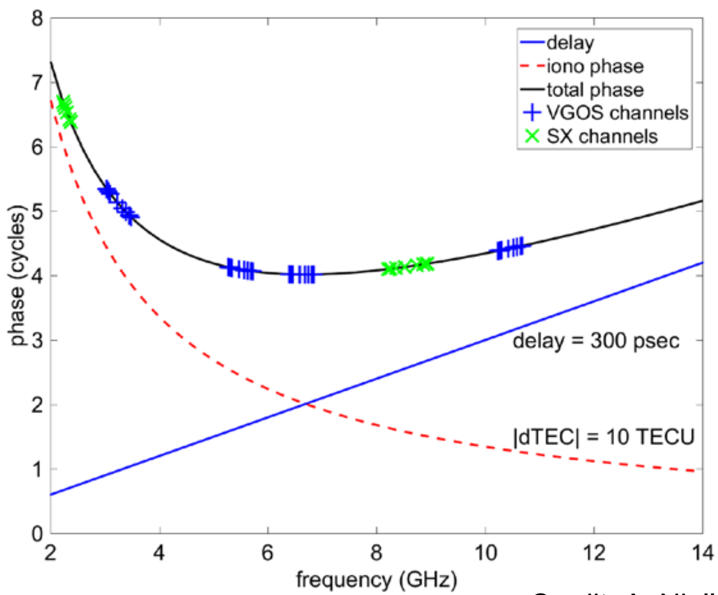
Built by Patriot/Cobham

Warkworth
(New Zealand)

Réseau Auscope (Australia)

GGAO (USA)

First measurement in VGOS mode

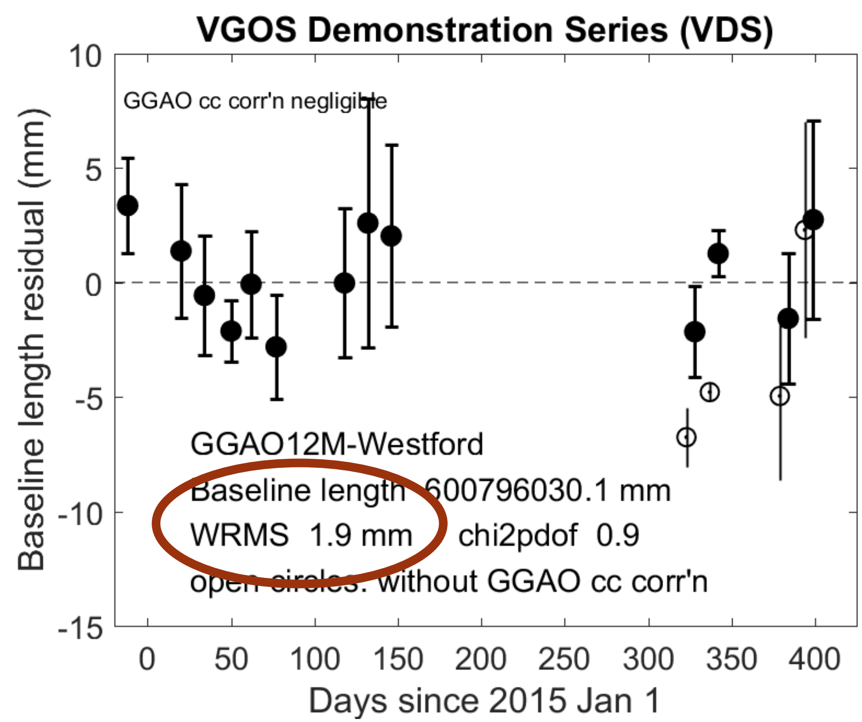


Credit: A. Niell

4 bands of width 0.5 GHz centered on 3.3, 5.5, 6.6 and 10.5 GHz

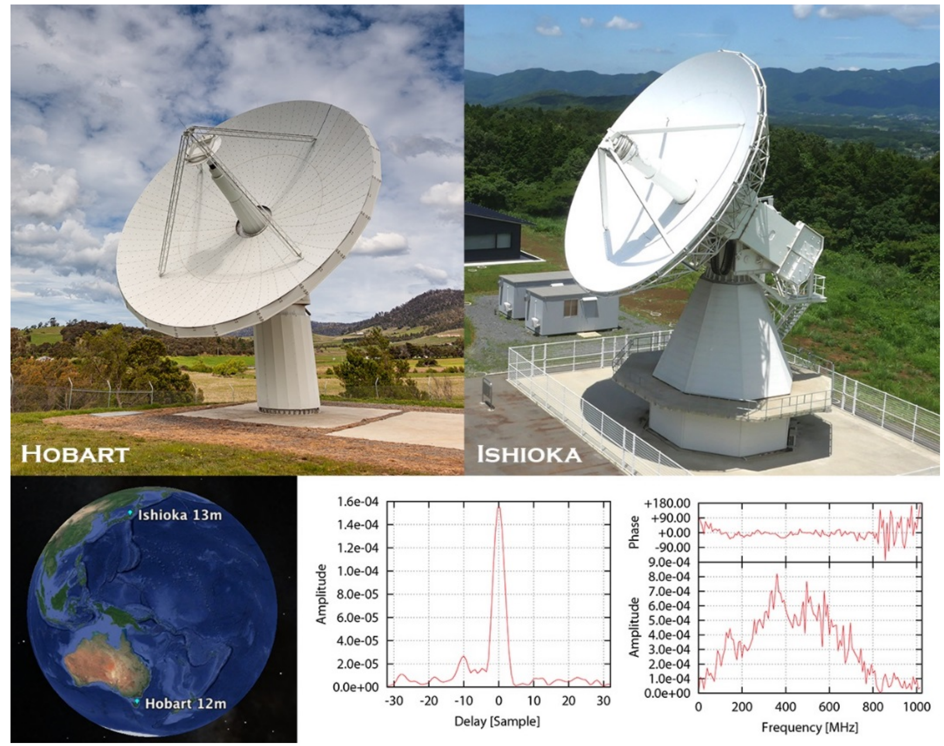
Test sessions on the baseline GGAO-Westford (600 km) since 2015

Niell (2016)



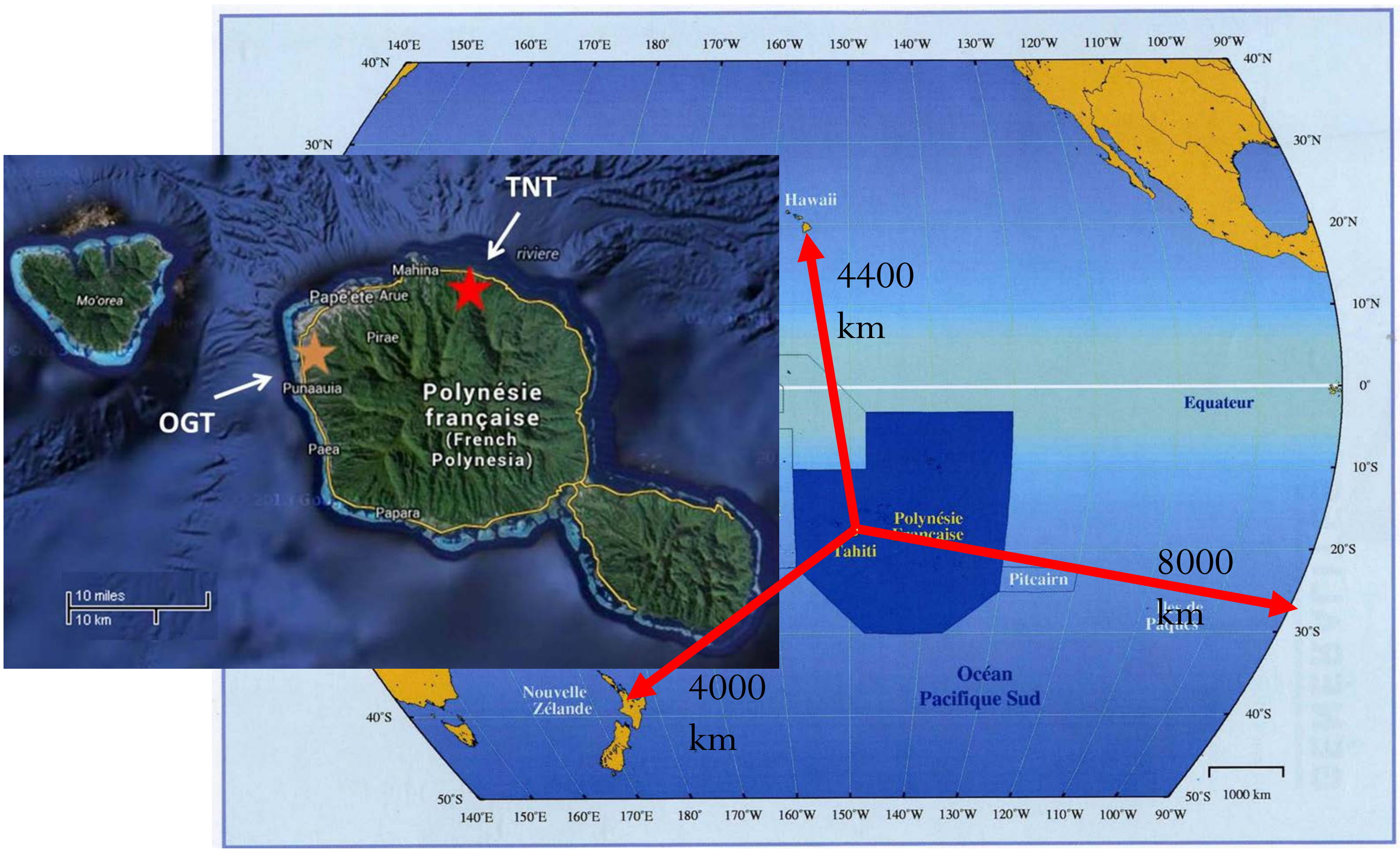
Intercontinental observations

- Test sessions with Kokee (Hawai), GGAO and Westford
- Other test session including also Ishioka, Wettzell and Yebes
- Sessions between Hobart et Ishioka



First trans-Pacific fringes 09/08/2016

A VGOS antenna in Tahiti?



Credit: R. Biancale