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Time and Frequency Distribution for mm-Wave VLBI

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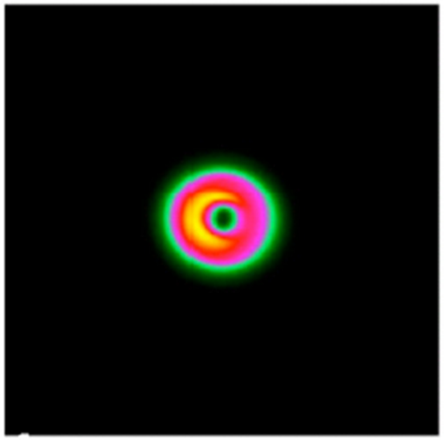
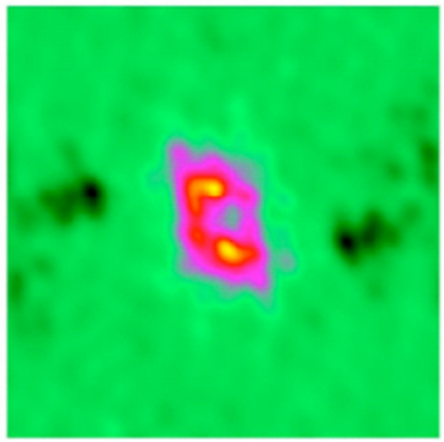
Application: Imaging Galactic Centre Black Hole

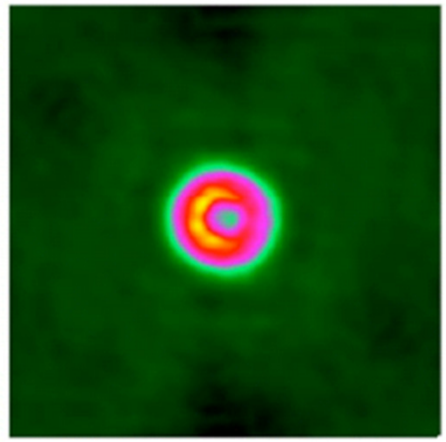
Expected appearance of Sgr A* at 345 GHz with VLBI



Model, scatter-Broadened in ISM



Simulated image reconstructed with 7 station array



Simulated image reconstructed with 13 station array

50 µas = 4 $R_{Schwarzschild}$

Gammie & Broderick (2009)

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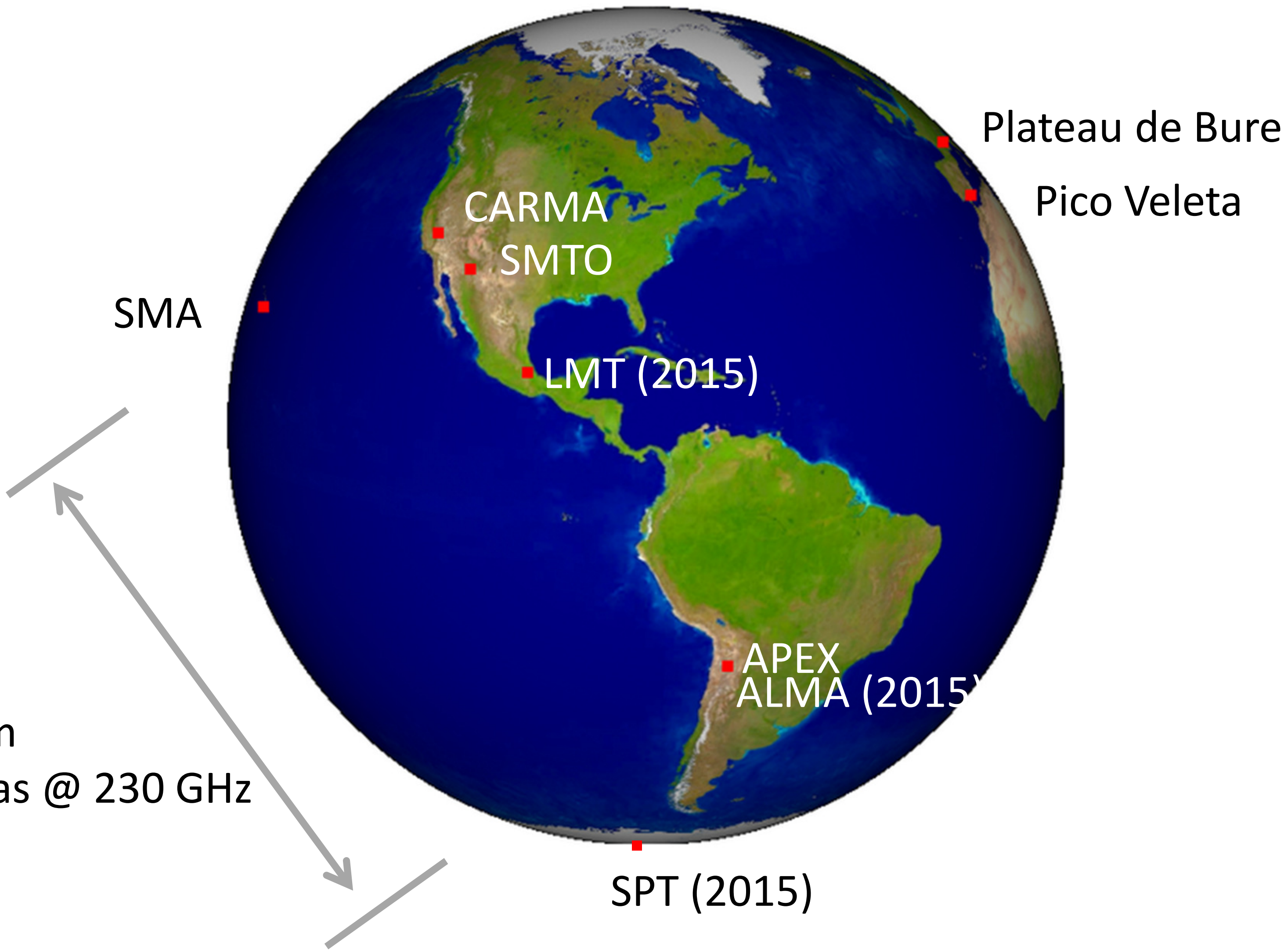
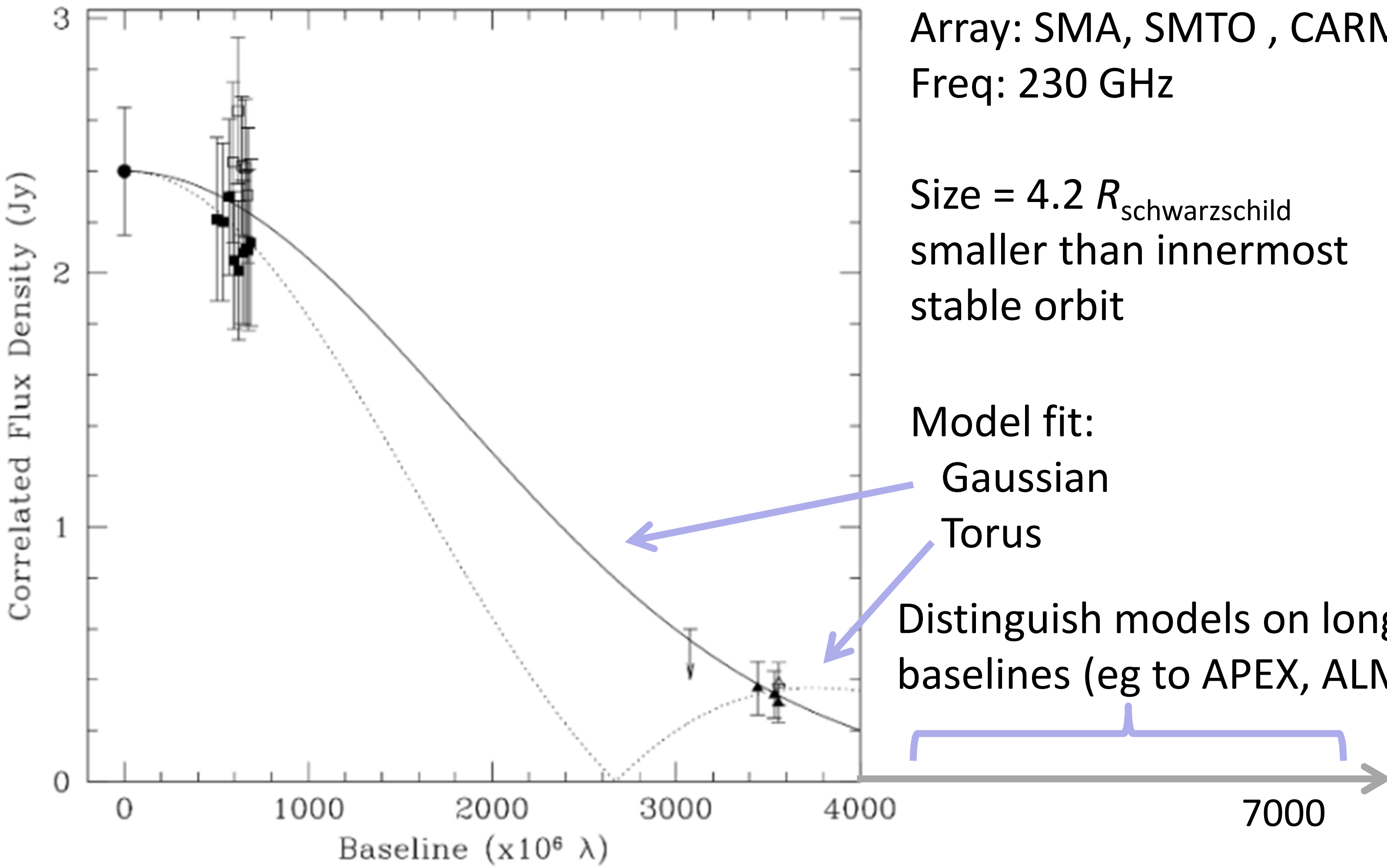
1 mm VLBI Array



9300 km
→ 28 µas @ 230 GHz

1 mm VLBI Sgr A* Size



Array: SMA, SMTO , CARMA
Freq: 230 GHz

Size = 4.2 $R_{schwarzschild}$
smaller than innermost stable orbit

Model fit:
Gaussian
Torus

Distinguish models on longer baselines (eg to APEX, ALMA)

Doeleman et al. 2008 Nature

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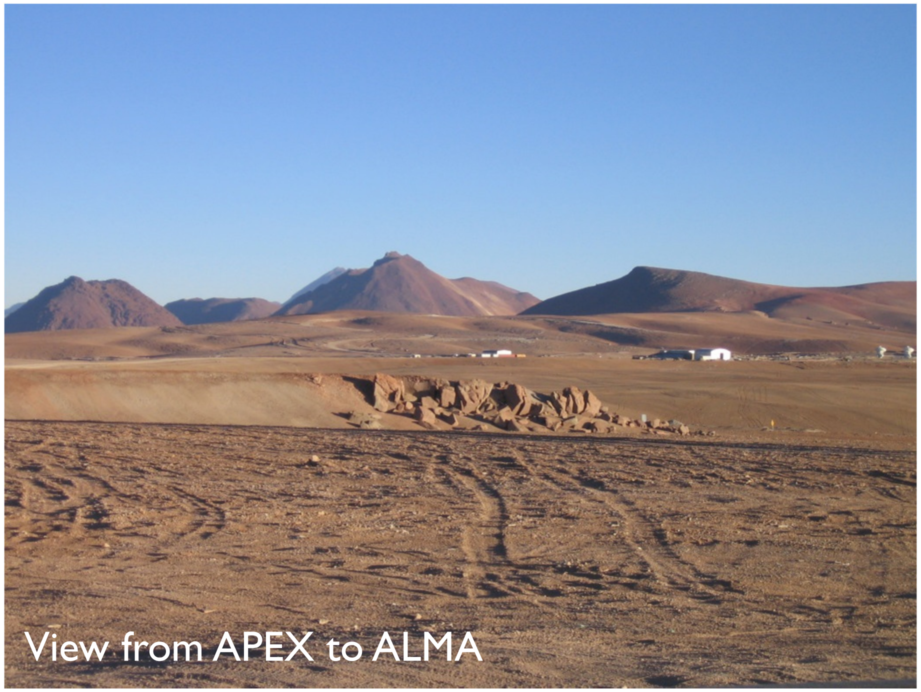
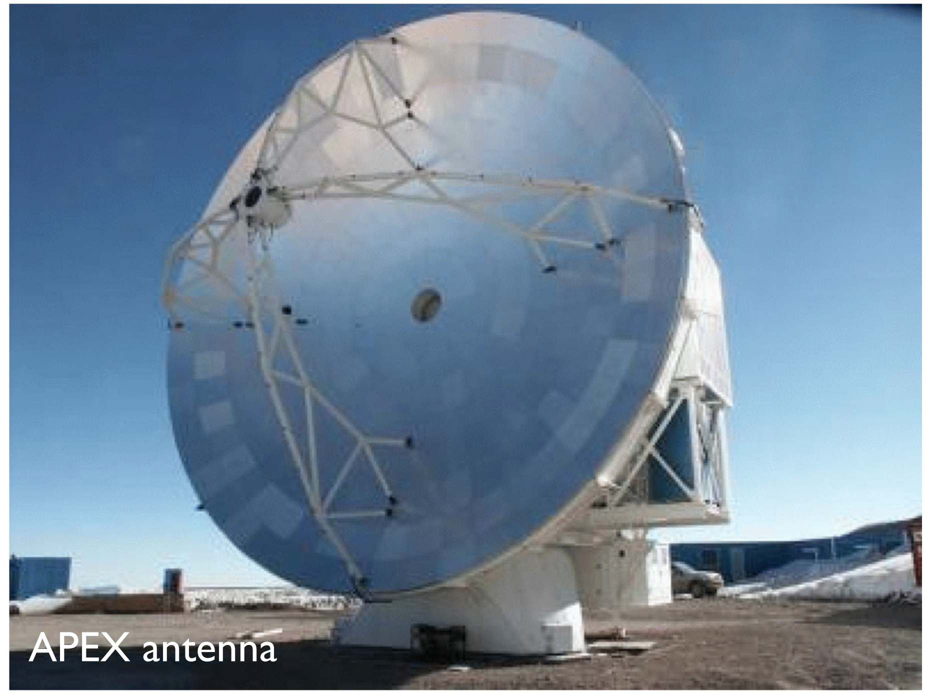
APEX Background



View from APEX to ALMA



APEX antenna

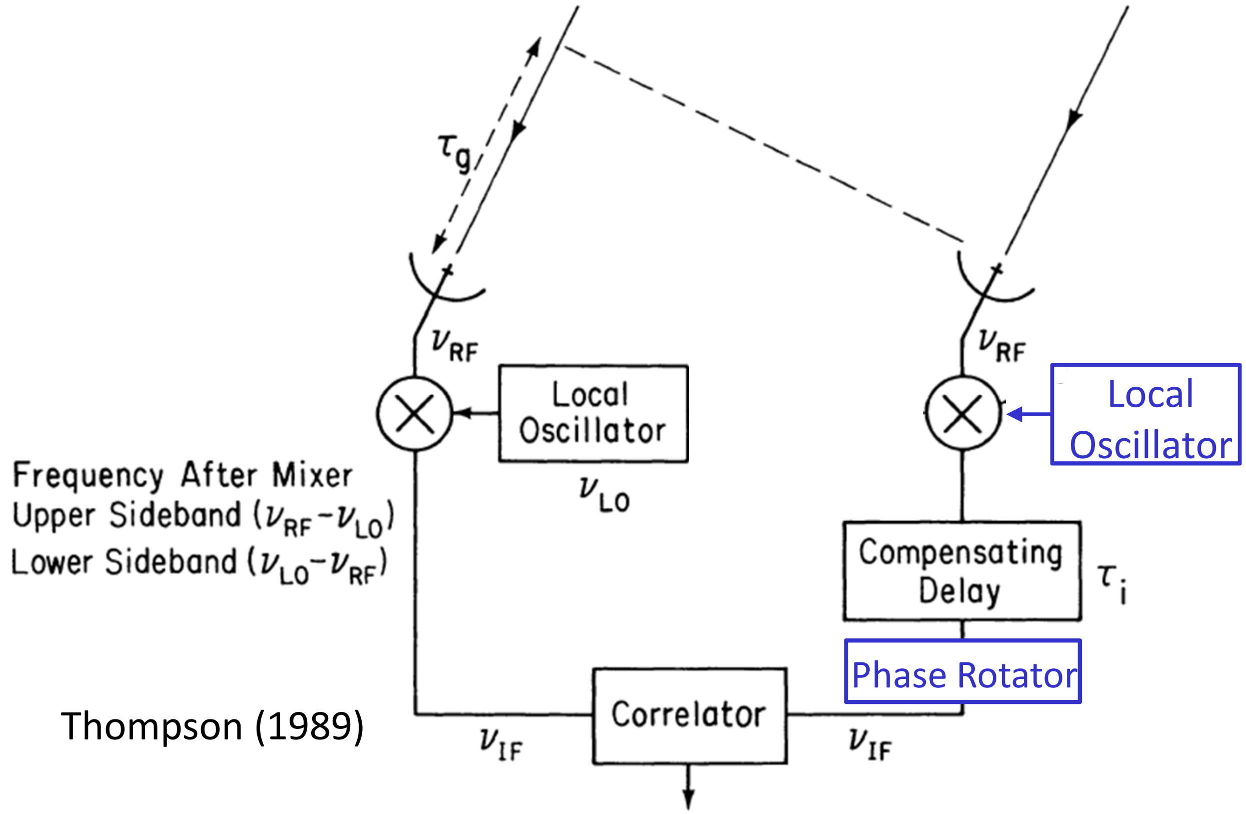
APEX: Atacama Pathfinder Experiment

Partners: MPIfR (50%), Onsala (23%), ESO (27%)

Modified ALMA prototype VERTEX antenna

Inauguration:	Sep 2005
First VLBI Fringes:	May 2012
Latest VLBI:	March 2013 – many detn on Sgr A*, M87, & other AGNs
Next VLBI:	March 2015 – with new stns ALMA, LMT, SPT + existing

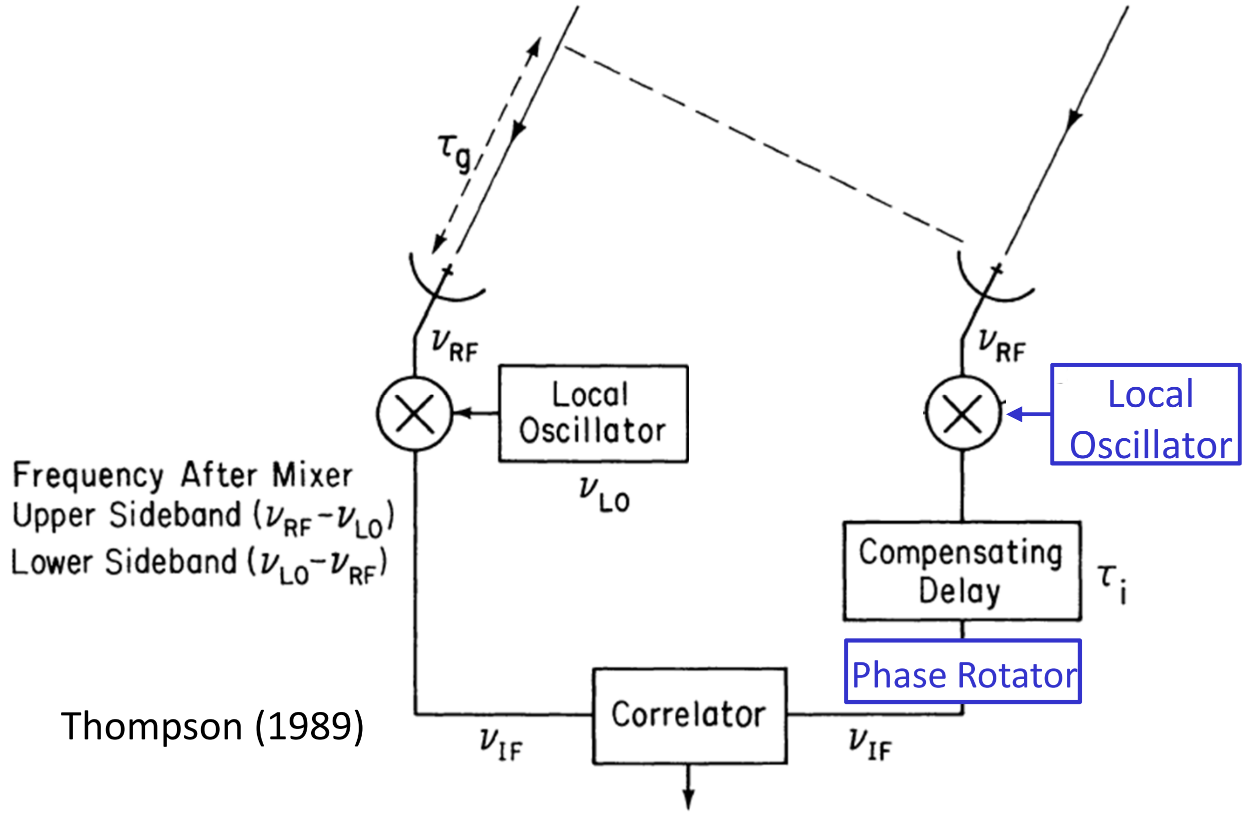
Interferometer (VLBI)



Thompson (1989)

- Natural fringe rate for 9000 km baseline, 300 GHz = 660 kHz (peak)
- **Phase Rotator:** (In correlator): De-rotates phases using model (geometry, SR, GR),
  Stops fringes to 0 Hz
  Allows long-term integration (1 s in correlator, 300 s in software)

Interferometer (VLBI)



Thompson (1989)

- **Local Oscillators**: At 345 GHz in 300 s: LO rotates $1\text{x}10^{14}$ turns.

  For 90 % coherence: error at 354 GHz $\leq$ 1/20 turn

  Coherent between stations

  → need $\leq 5\text{x}10^{-16}$ fractional error

  (linear drift is removed in analysis, but quadratic term this large not ok)

  → Need good hydrogen maser

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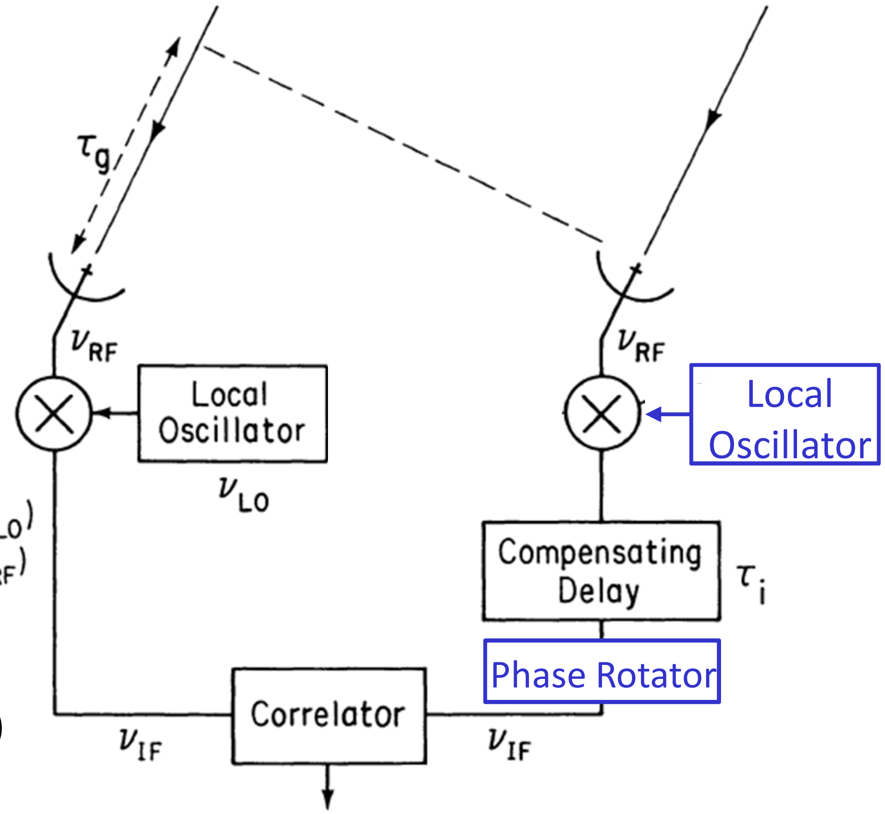
Interferometer (VLBI)



Thompson (1989)

- **Distribution of Reference Frequency**:

For < 1 / 20 turn at 345 GHz in 300 s, phase error in 10 MHz ref ≤ 1 / 6900 turns in 300 s

Cable length distributing ref to 1st LO: change ≤ 0.0006° at 10 MHz = 40 µm (0.13 ps) in 300 s

ie ref cable 80 m long in APEX should be stable to ≤ 0.5 ppm (!)

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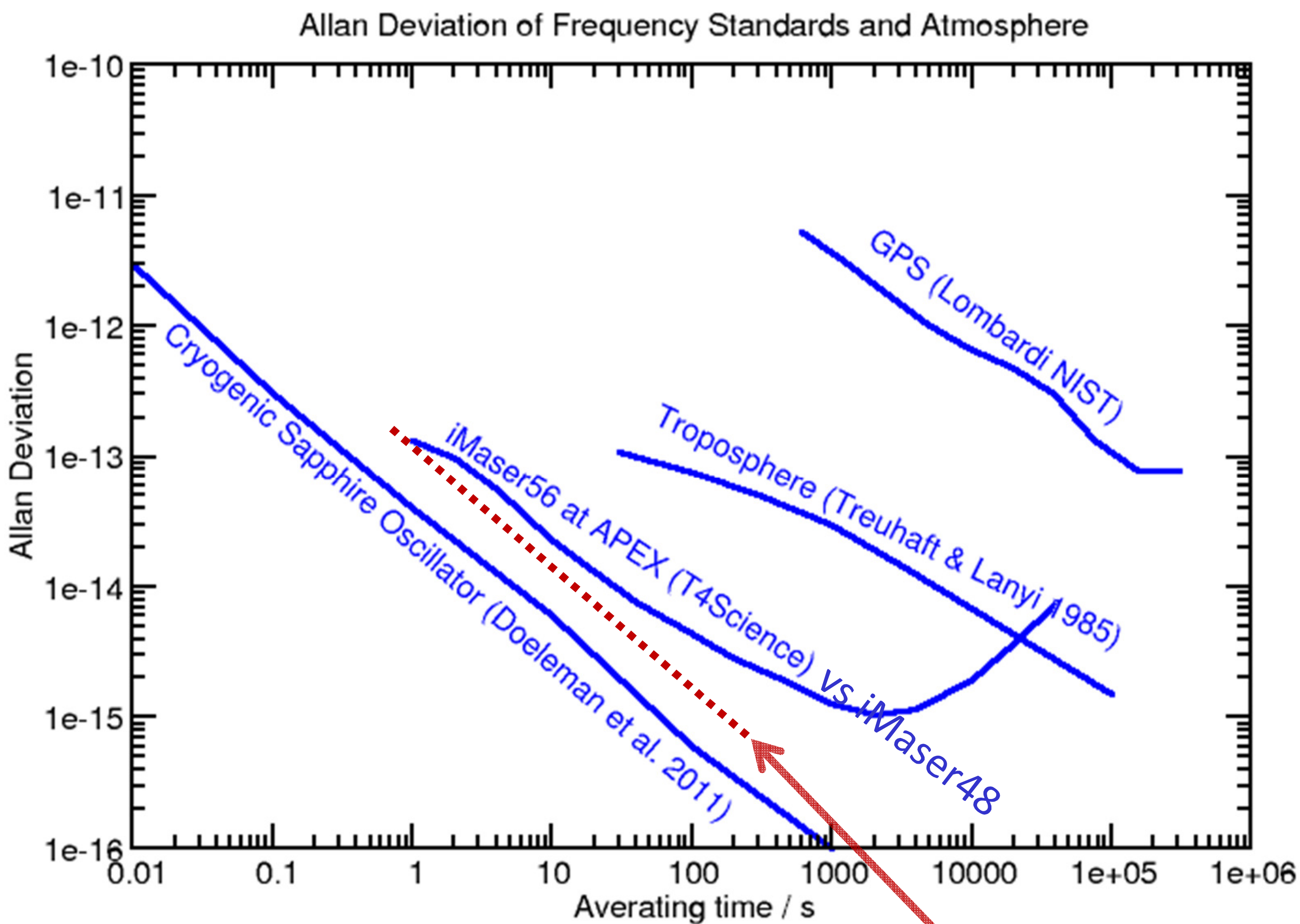
Requirements: Freq Standard Stability



Requirement for 90 % coherence at 345 GHz

Stability: Effect on Data

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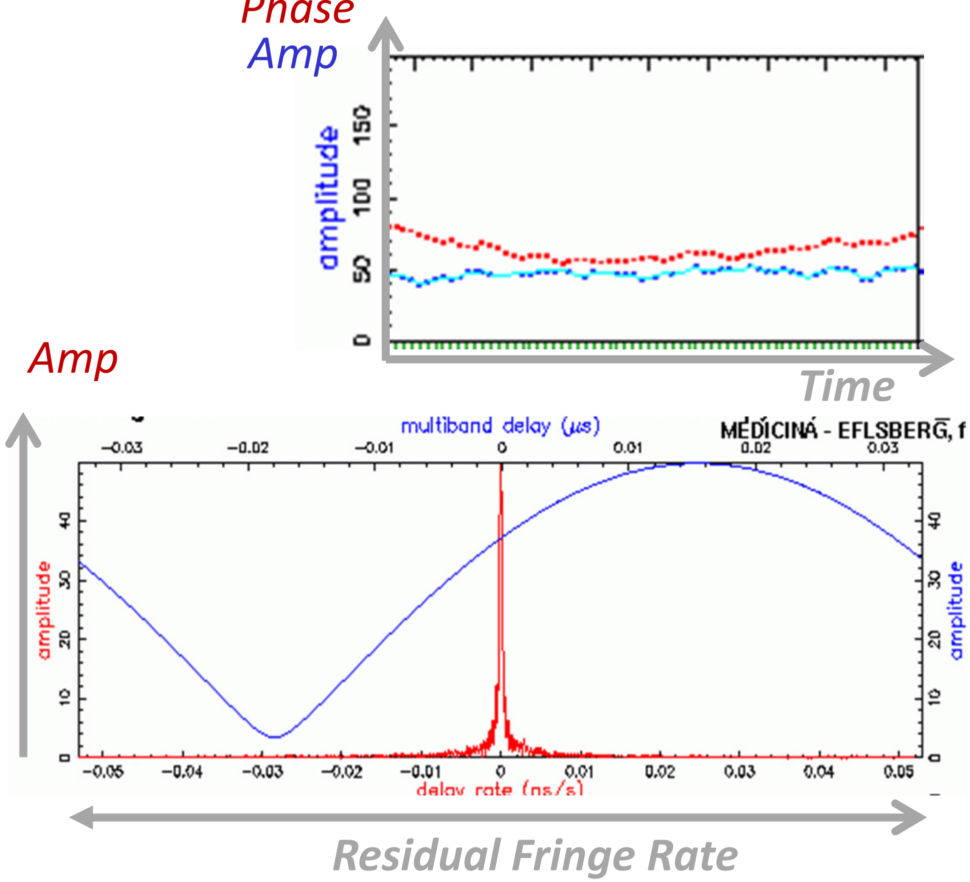
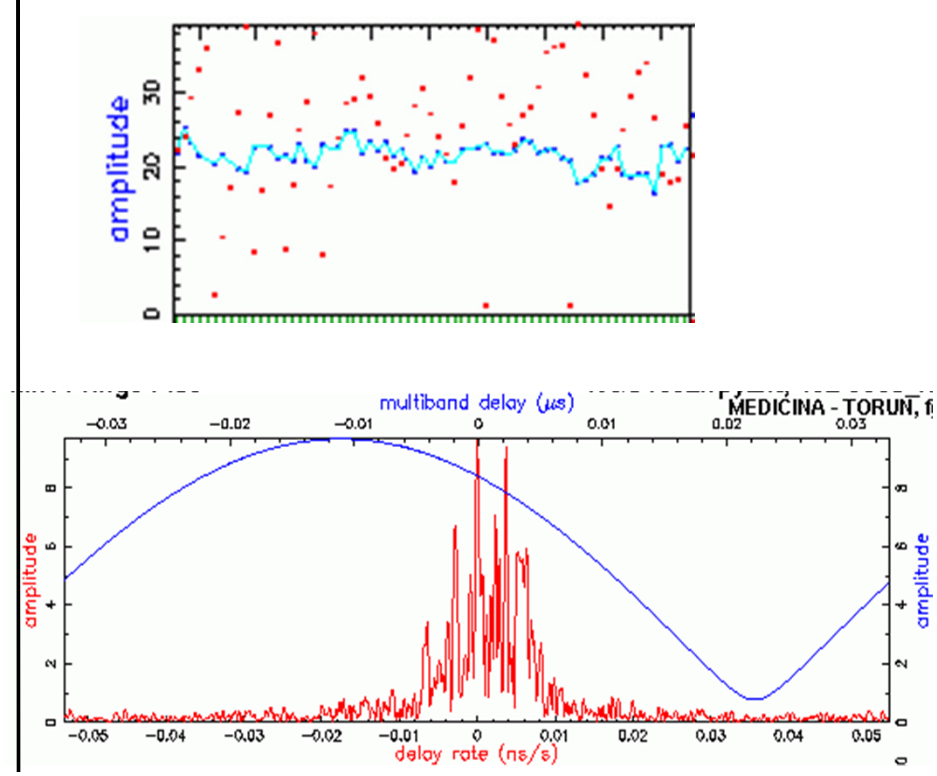
H maser - **H maser**

Medicina - Effelsberg



H maser - **Rubidium**

Medicina - Torun



EVN June 2005, Project EI008, Freq 6 GHz

Torun H maser was away for repair

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Frequency Stability: Maser Environmental Chamber

Environmental chamber at acceptance testing

HVAC: separated from chamber for vibration isolation

Maser: Stability: 1.1×10^{-15} in 2000 s. Sensitivity to *dT*: 5×10^{-15} °C^{-1}. → **want *dT* ≤ ± 0.1 °C**

Environmental chamber: **_dT_ = ± 0.1 °C over -20 °C to +30 °C**, humidification, magnetic shielding

Manufacturer: Klima Systems (Frechen, Germany) Price: 34 kEUR (15 % of cost of maser)

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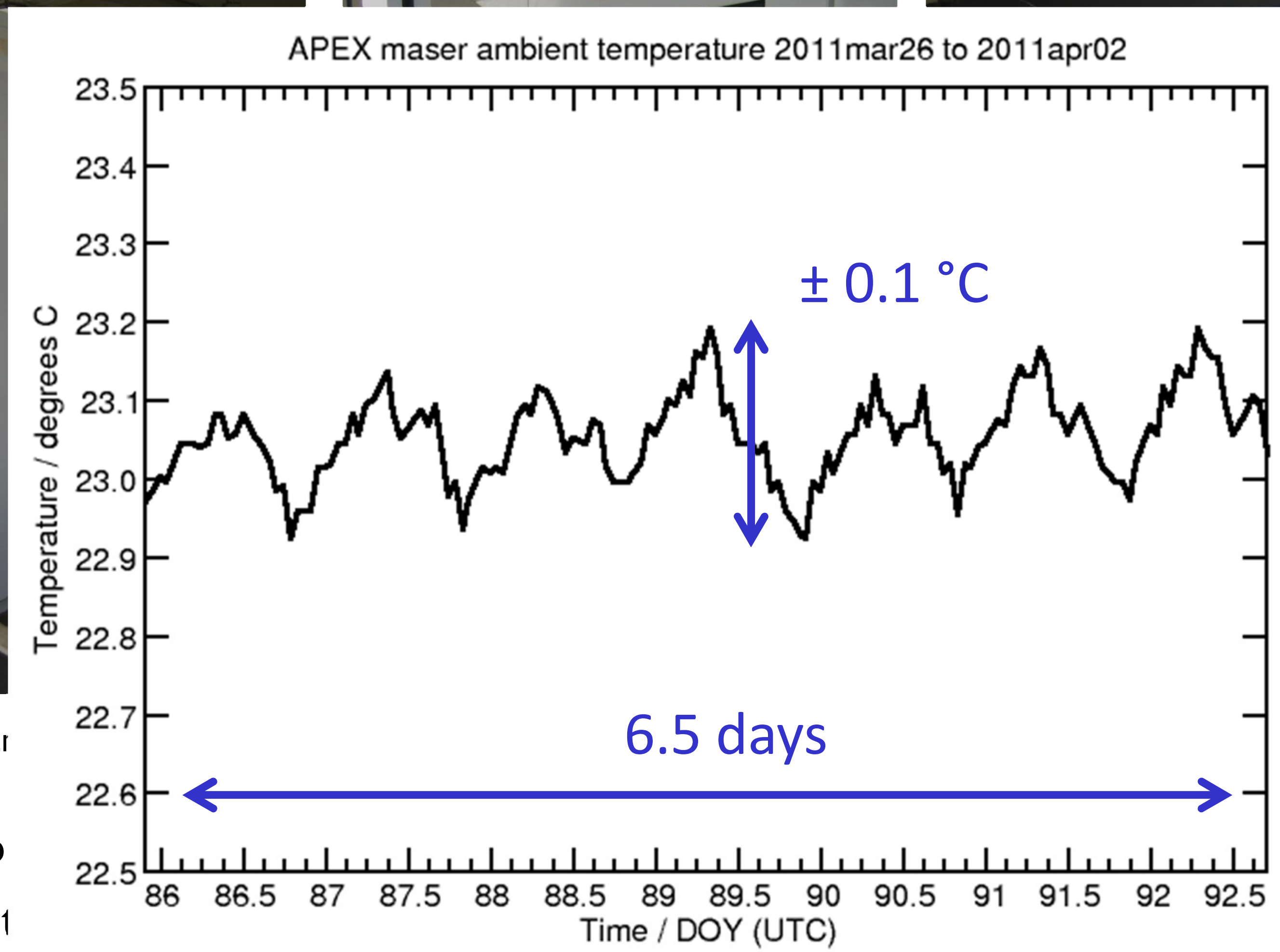
Frequency Stability: Maser Environmental Chamber



Er

chamber

:ion

Maser: Stab

≲ ± 0.1 °C

Environment

humidification, magnetic shielding

Manufacturer: Klima Systems (Frechen, Germany) Price: 34 kEUR (15 % of cost of maser)

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Requirements: Frequency Absolute Uncertainty

If we get 10 MHz ref frequency slightly wrong:

→ high fringe rate at correlator → no fringes after integration ✯

Frequency absolute uncertainty required:

For 1 s integration, fringe rate Nyquist search window is ± 0.5 Hz

→ **Max absolute frequency error: 0.5 Hz / 300 GHz = 1.7×10^{-12}**

Method now:

During setup: measure GPS - maser 1 PPS for ≥ couple of days

Remove bulk rate with maser DDS, then don't touch maser

During obs: log measured GPS 1 PPS – maser 1 PPS for clock rate

Correct fine clock rate in correlator model to apply in phase rotator

Next: Take person out of the loop: steer maser DDS with GPS - maser

Need long loop time-scale (> 10^5 s)

Need robustness against glitches

eg Doeleman, Mai, Rogers et al. (2011)

Phase Stability: Noise Sources in APEX

- Frequency reference
- Synthesizers
- Distribution of 10 MHz reference: cable electrical length changes with temperature, bending,
- RF Connectors
- Distribution amplifiers
- Atmosphere
- Receiver
- Downconversion chain

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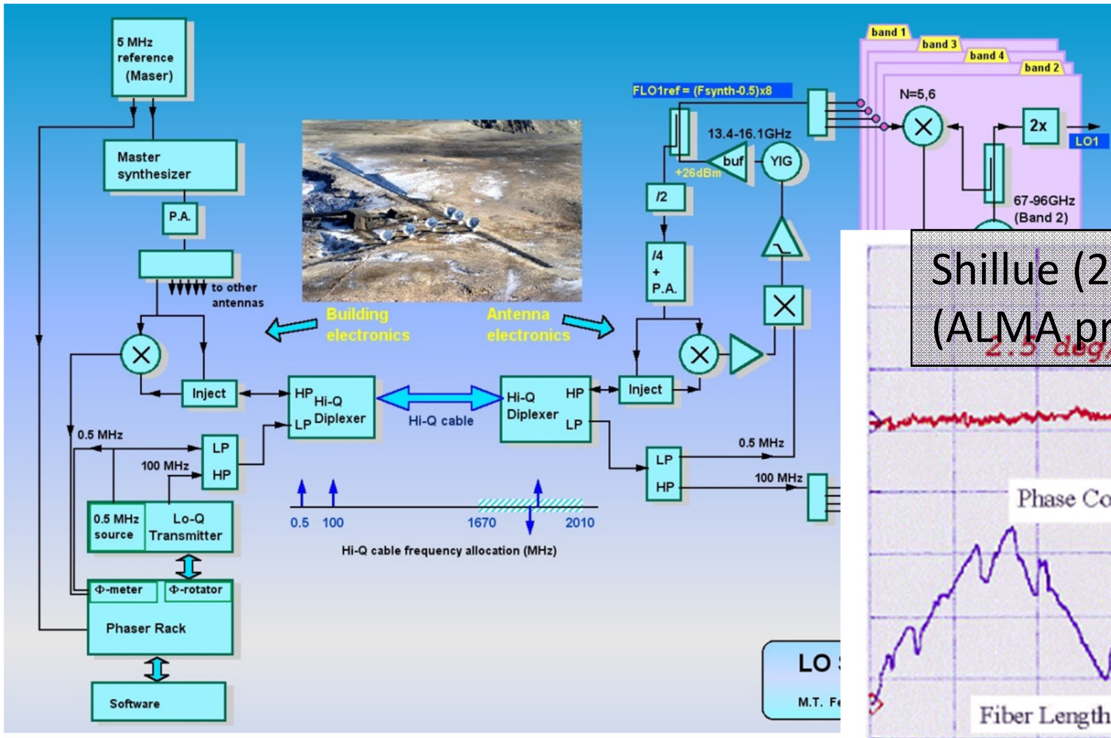
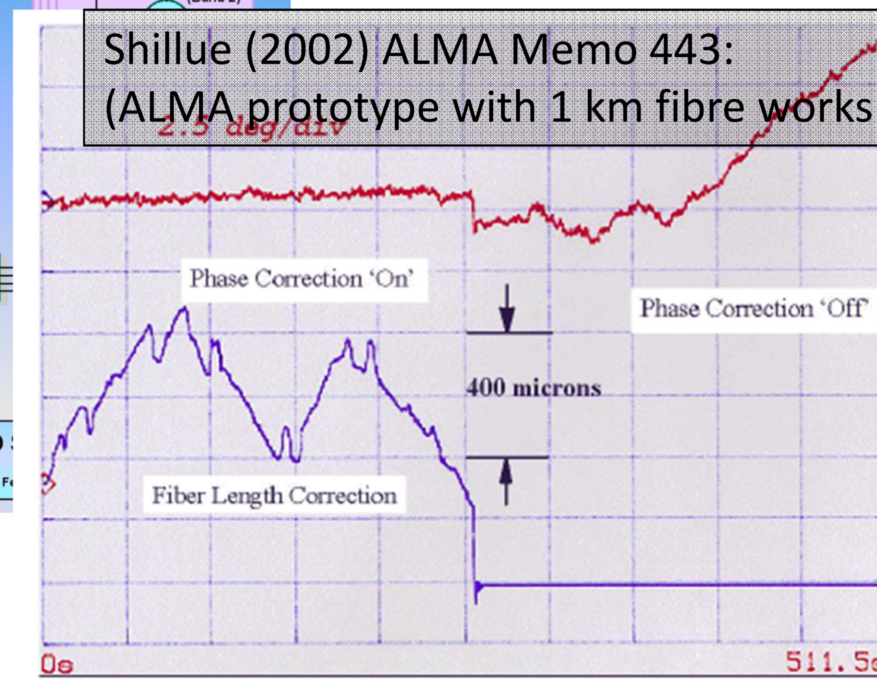
Phase Stability: Round-Trip Phase Measurement



LO system for Plateau de Bure with round-trip compensation (shows complexity)

Shillue (2002) ALMA Memo 443:
(ALMA prototype with 1 km fibre works well)



Round-trip compensation works, though complex.

Used at: Connected interferometers: Plateau de Bure, SMA, CARMA, ALMA
Geodetic VLBI stations log cable length, applied in post-processing.

Not at: Single-dish mm-VLBI stations: APEX, Pico Veleta, SMTO, LMT

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Phase Stability: Cables

Cables for maser 10 MHz reference, 1 PPS,
Optical fibre for 10 GB ethernet
500 m total length

Requirements: Phase Stability - Distribution

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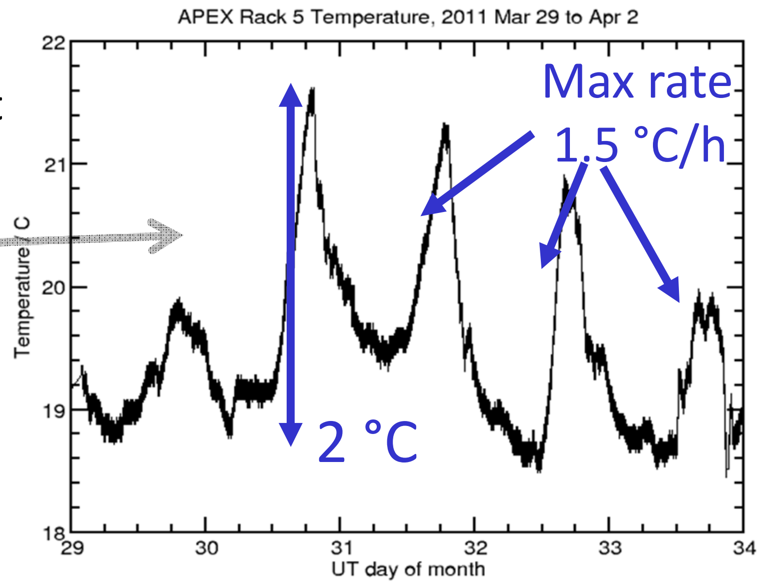
Aim:

Transport 10 MHz from maser over 80 m path to 1st LO synthesizer
Maser is located on ground in annex for low vibration
We want ≤ 18° phase drift in 300 s at 300 GHz to ensure ≥ 90 % coherence

Environment:

1. Underground: 50 m path with mK stability
2. Pit to cable wrap to ducts: 15 m path at ambient
3. Instrument container 15 m path with HVAC

T stability:



Effect on Phase:

Cable length exposed to dT:	15 m
Allowable length change:	40 µm (= 18° at 300 GHz)
Enviromental dT:	0.25 °C in 600 s
→ Need cable tempco:	≤ 10 ppm/°C

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Cable Selection for 10 MHz Ref from Maser

Cable	Tempco ppm / °C	Notes Tempco column is for range 10 to 20 °C	Ref
Sucoflex 104-PE	190 to 20		4
Belden 1673A	78		1
141 Semirigid	70		1
RG 213	42		1
RG 231	30		2
LMR 240	22	**Used in APEX**, PE dielectric, low loss	1
LMR 400	18	**Used in APEX**, foam PE dielectric, low loss	1
Phase Track II	-7 to +13	26 USD/m, solid inner no not good in wrap	3
FSJ1-50A	4	Rigid Heliax, no good in cable wrap	1
F057A	3	Rigid Heliax, no good in cable wrap	1
Air	1		2

Refs: 1 Norrod 2003, NRAO Memo *"Phase Stability Measurements versus Temperature for Several Coaxial Cable Types"*
2 Moore, C., *Bendix Field Engineering* 1987
3 Rogers, A. 2008, Mark 5 Memo 68
4 Huber+Suhner *Microwave Cables and Assemblies General Catalogue* 2007
(For more detail see plots collected from literature on last slide)

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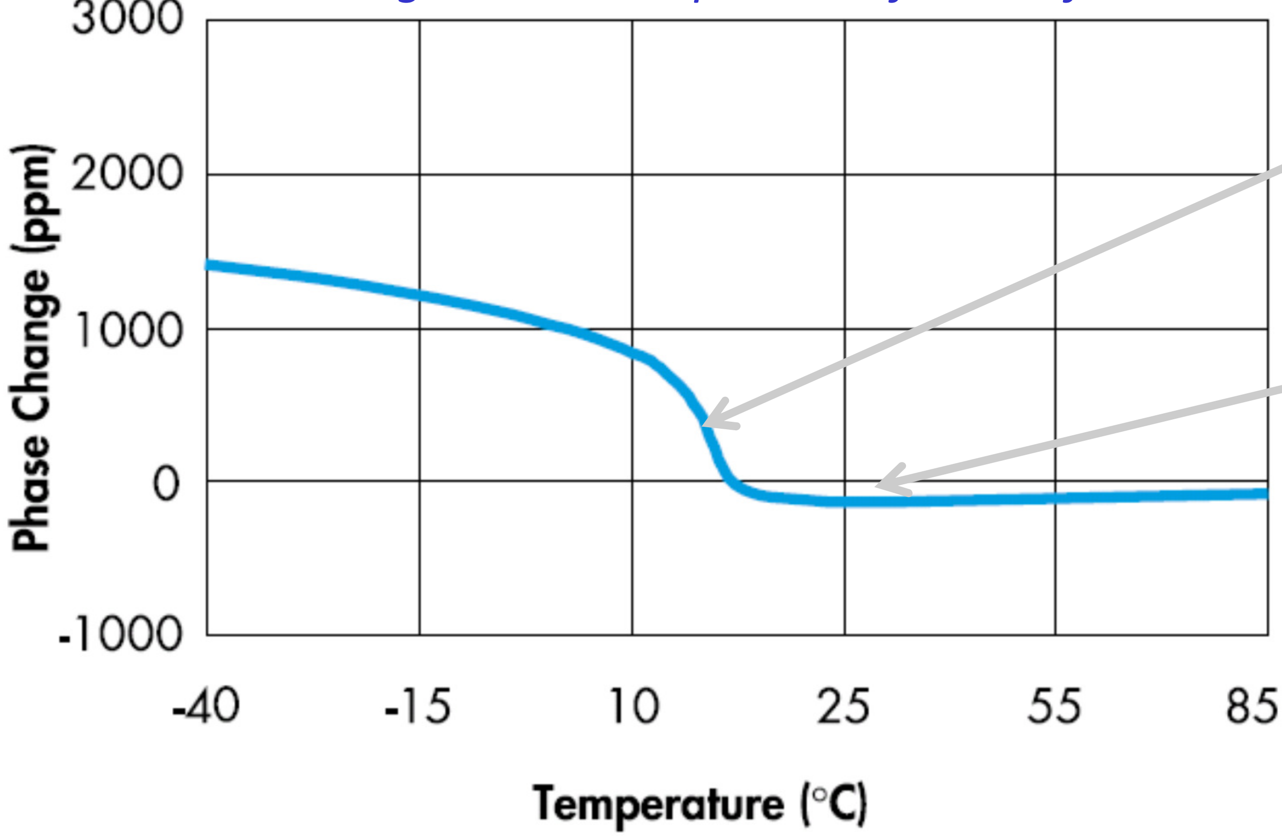
Cable Design for Low Tempco

Phase change versus temperature for Sucoflex-104-PE



Teflon "knee" due phase transition

Cable designed for low tempco above the transition

(from Huber+Suhner *Microwave Cables and Assemblies General Catalogue* 2007)

Avoid Teflon dielectric.
Prefer air, PE, specialty (SiO_2,TF4), …

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Cable Design Approach for Low Tempco

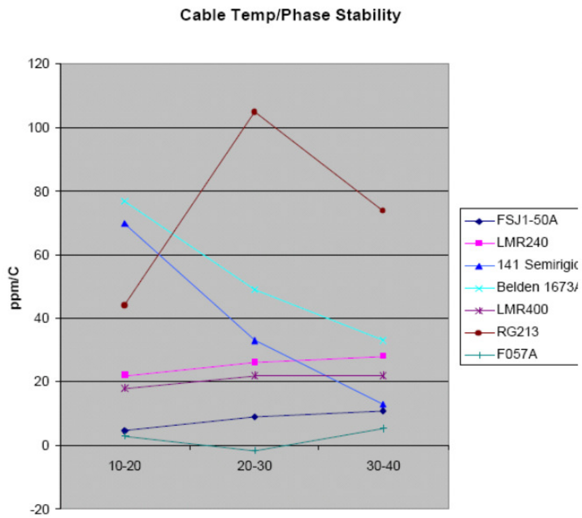
Consider cable stabilized at 25 °C, let temperature fall:

- Inner conductor shortens -> electrical length shortens
- Dielectric constant unchanged -> dielectric length constant
- Outer braid constricts dielectric more -> density rises, dielectric constant rises, electrical length lengthens.

Designer arranges braid to constrict dielectric to compensate length change with temperature.

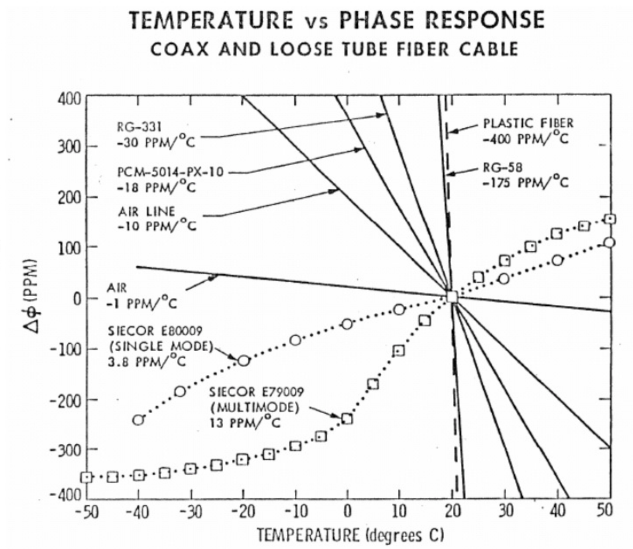
(from Times Microwave AN "*Current Innovations In Phase Stable Coaxial Cable Design*")

Cable Tempco Data from Literature

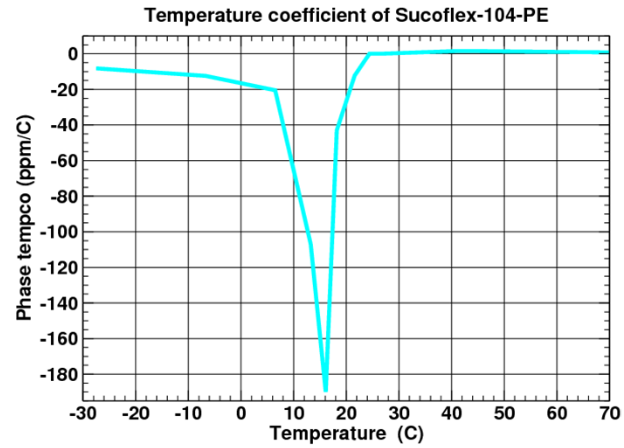


Norrod 2003, NRAO Memo

"Phase Stability Measurements versus T emperature for Several Coaxial Cable Types"

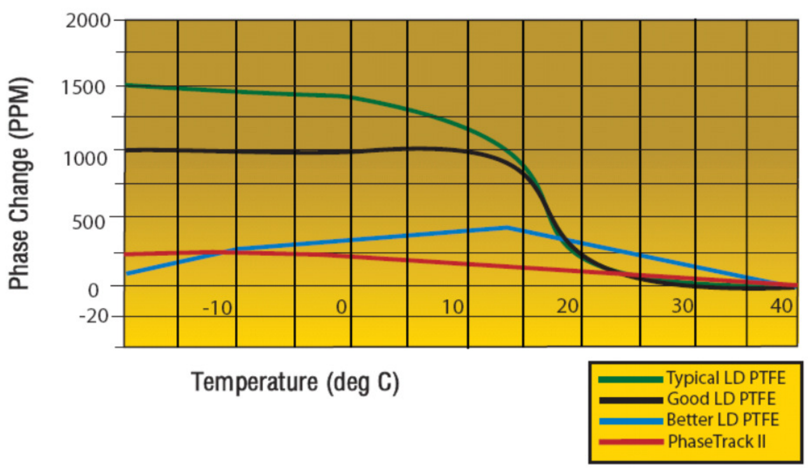


Moore, C., *Bendix Field Engineering* 1987

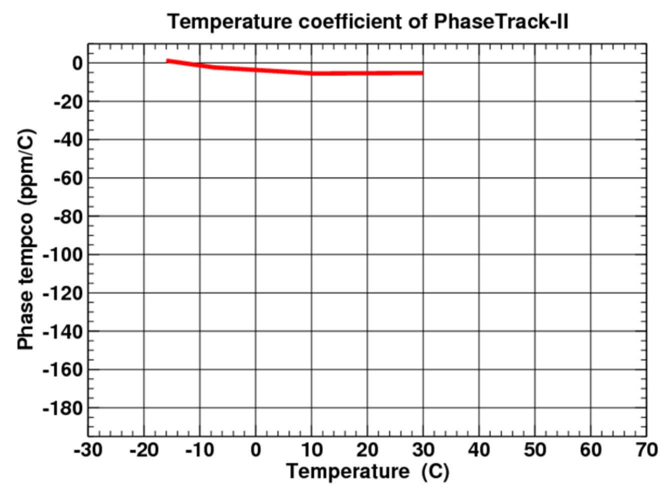


Huber+Suhner *Microwave Cables and Assemblies General Catalogue* 2007

First derivative wrt T of plotted data

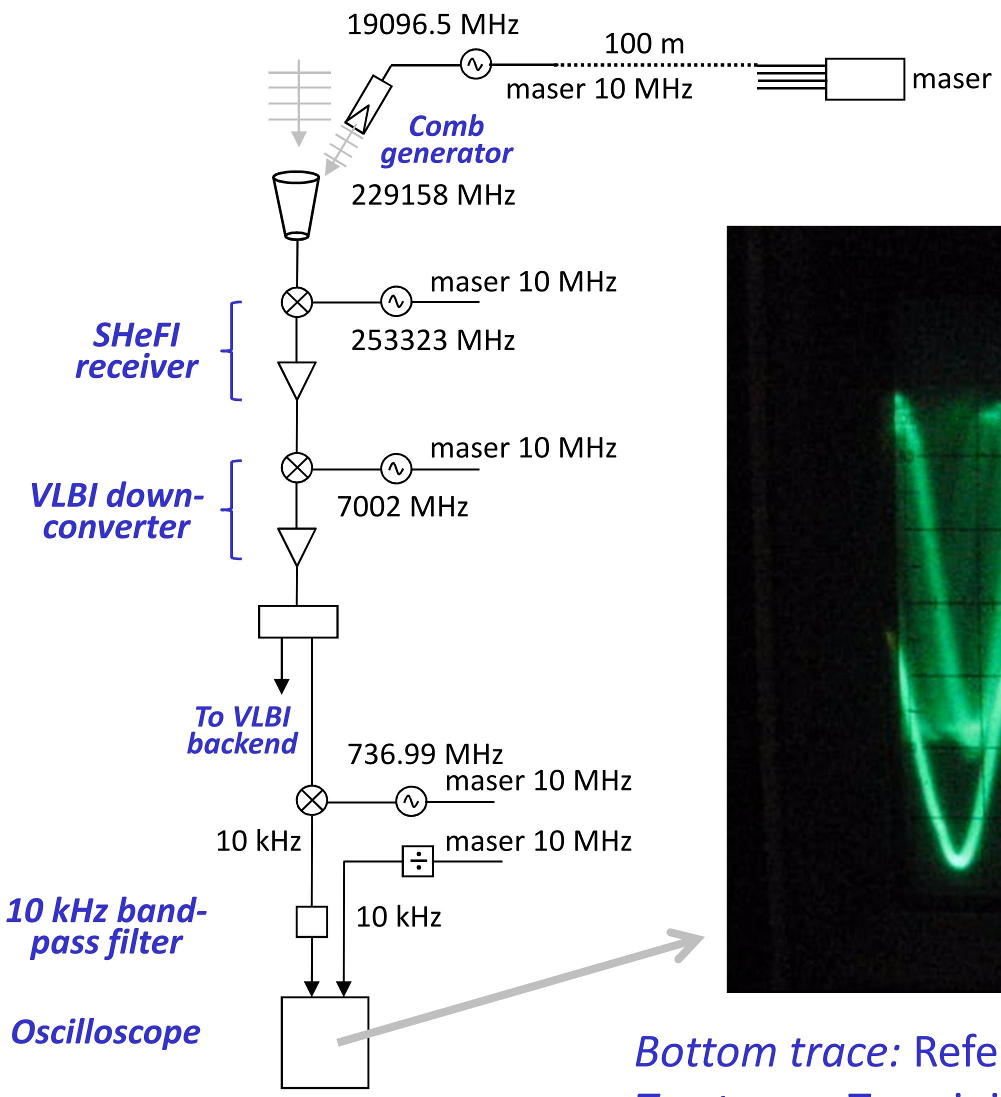


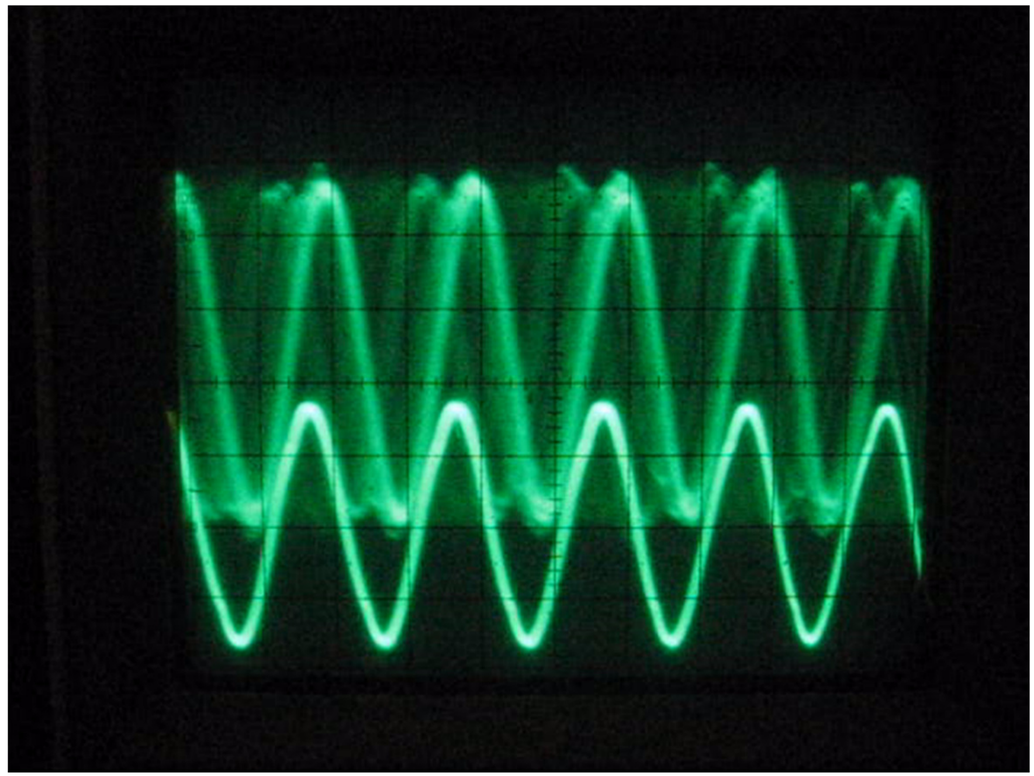
Times Microwave Data Sheet Phase Track II



First derivative wrt temperature of data from Times Microwave Phase Track II Data Sheet

Phase Stability: Coherence Check at 230 GHz





Bottom trace: Reference 10 kHz by dividing maser 10 MHz
Top trace: Tone injected at 230 GHz and mixed to 10 kHz

Movie taken at APEX 2013mar21 during setup for VLBI run

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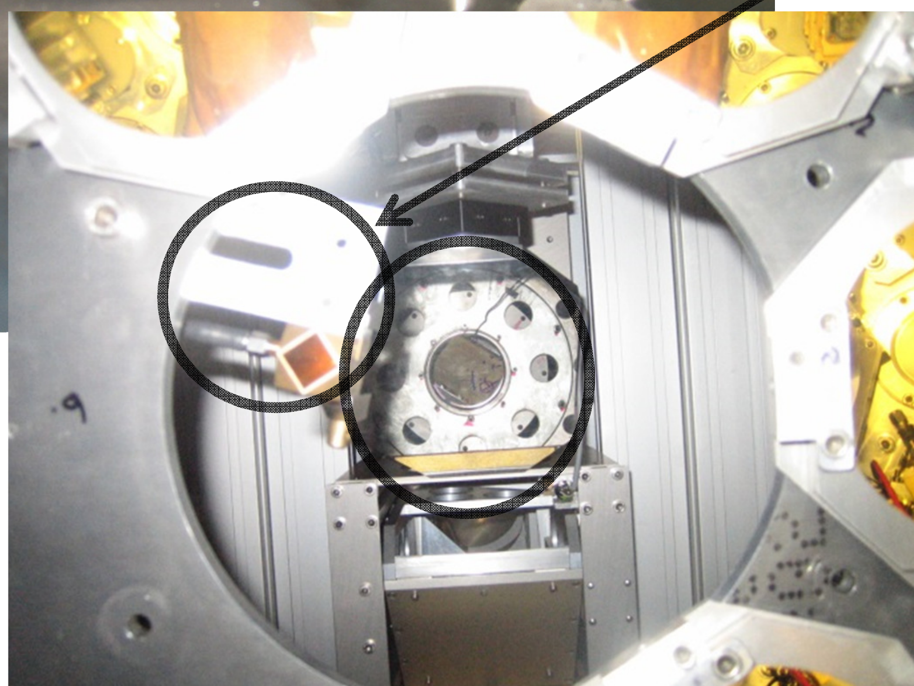
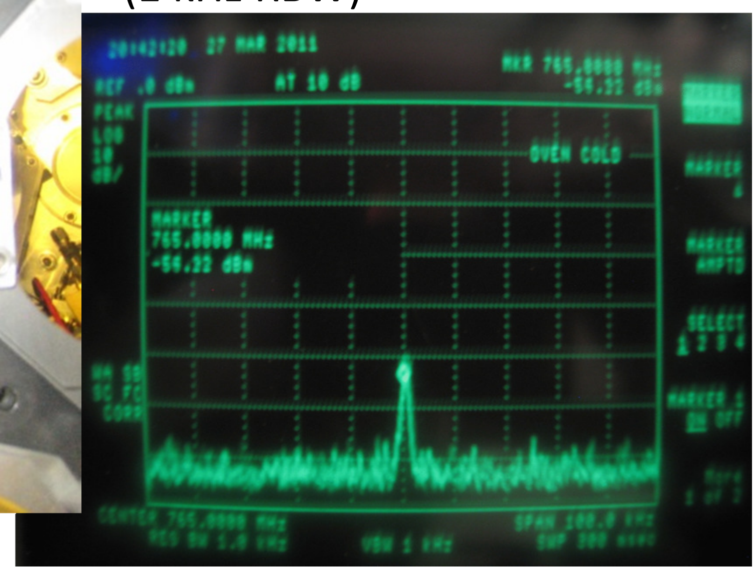
Phase Stabilization: Tone Injection

Comb Generator mounted in SHeFI for tone injection during observing

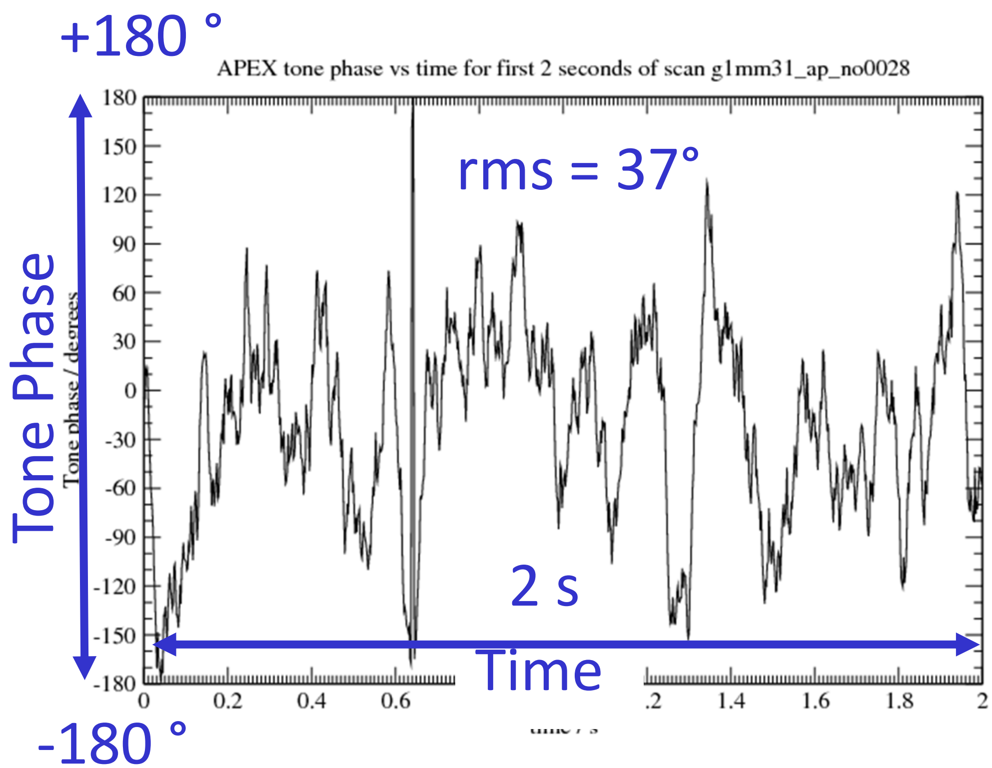


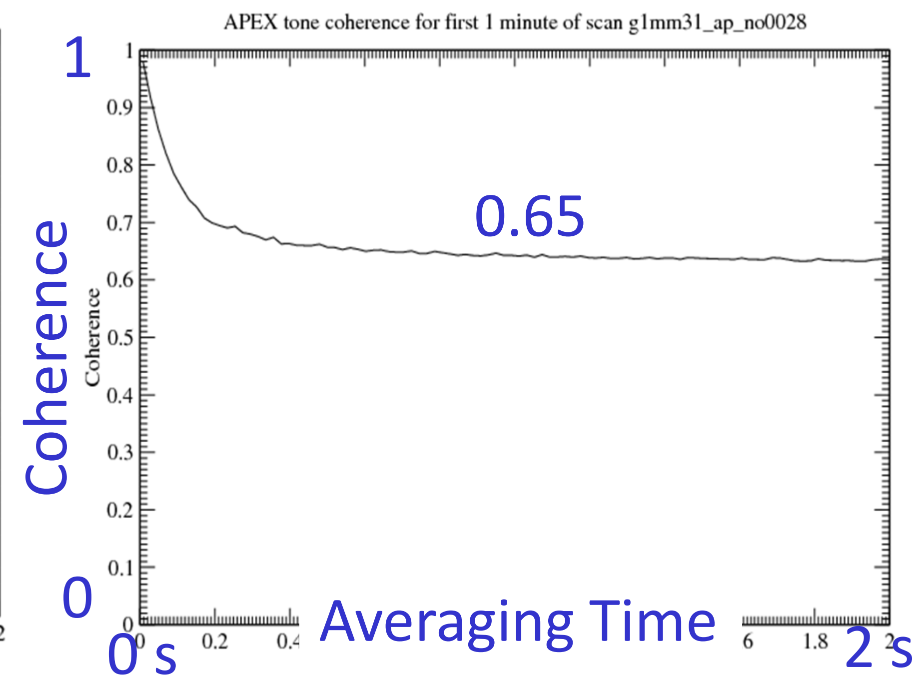
View from SHeFI up along beam showing beam blockage by comb generator as mounted when observing

Tone at VLBI downconverter output as used during observing (1 kHz RBW)



Phase Stabilization: Tone Extraction at Correlator

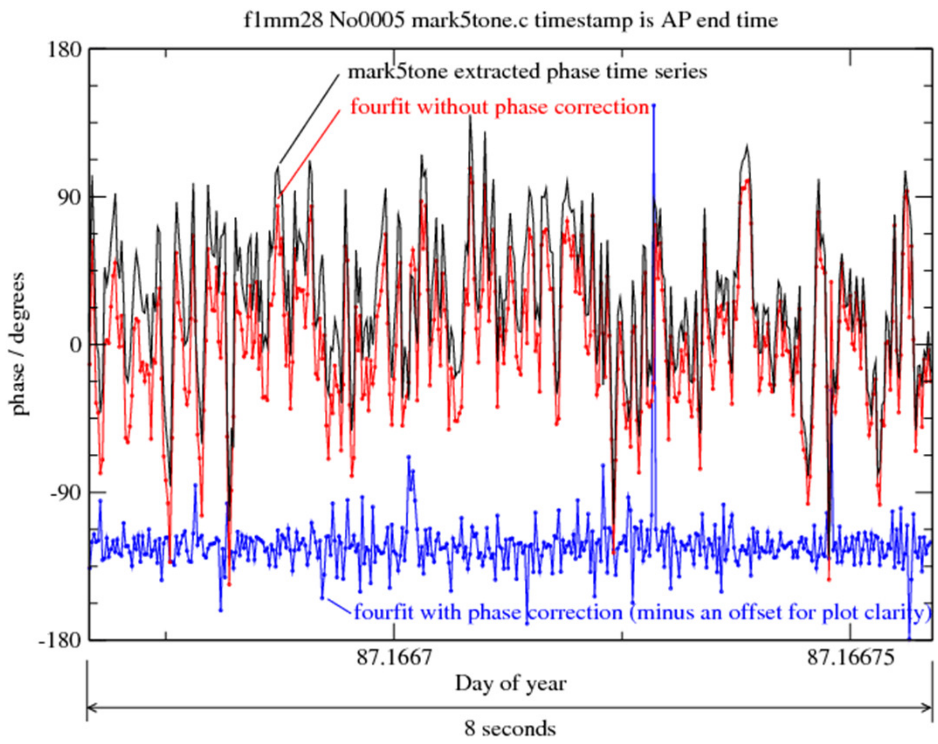


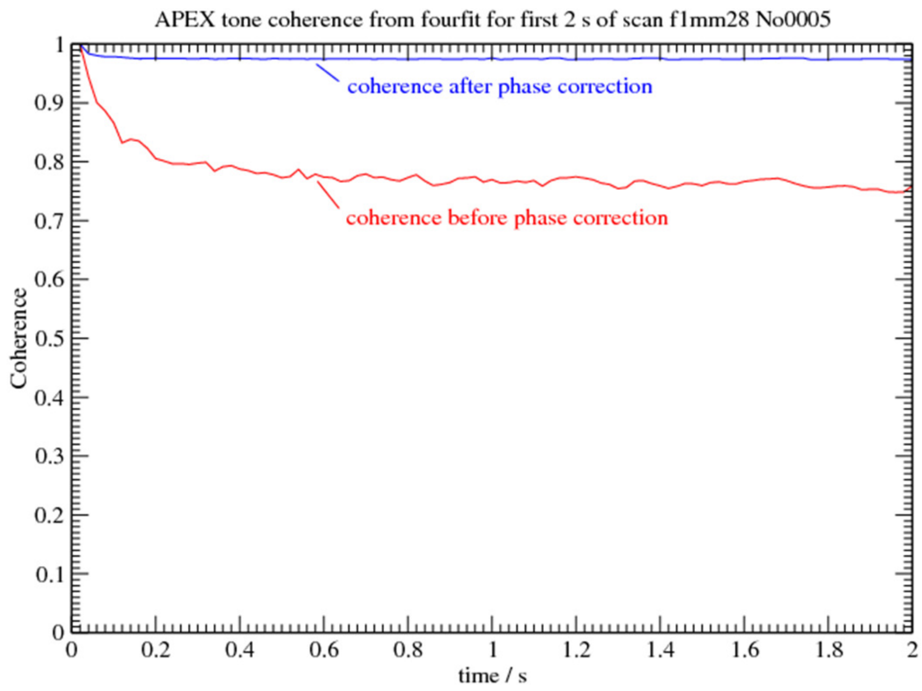


Phase vs time shows rapid phase fluctuations,

Requires correlation with 0.02 s integration time to permit phase correction.

Phase Stabilization: Correction Applied





Phase correction using tone injection during observing gives coherence of 97 %

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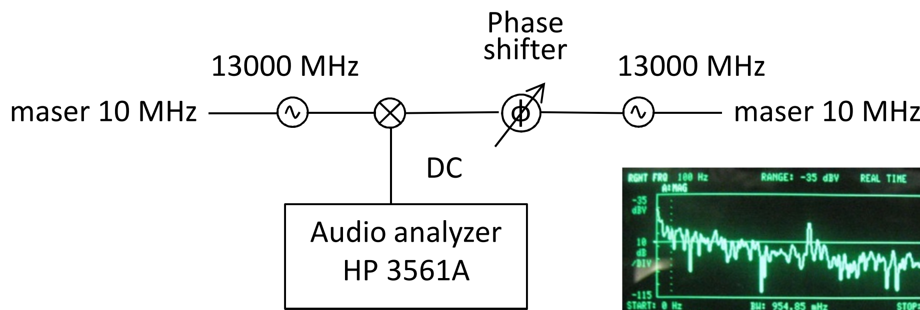
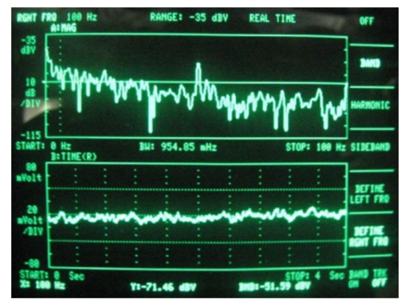
Phase Noise: Synthesizers

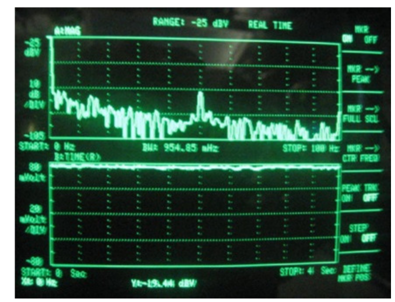
- Mix two synthesizers against each other to DC or 10 kHz
- HP 3561A FFT audio analyzer (100 kHz BW) to get close to carrier
- Phase shifter / mixer to set synthesizers in-phase / quadrature

Test at DC:



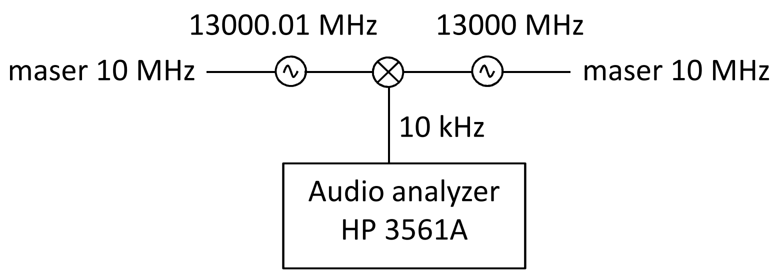


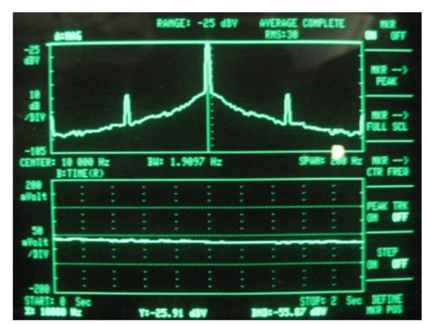
Quadrature: phase noise



In-phase: carrier

Test at 10 kHz:





Result: extrapolated to 230 GHz: rms = 1.4°

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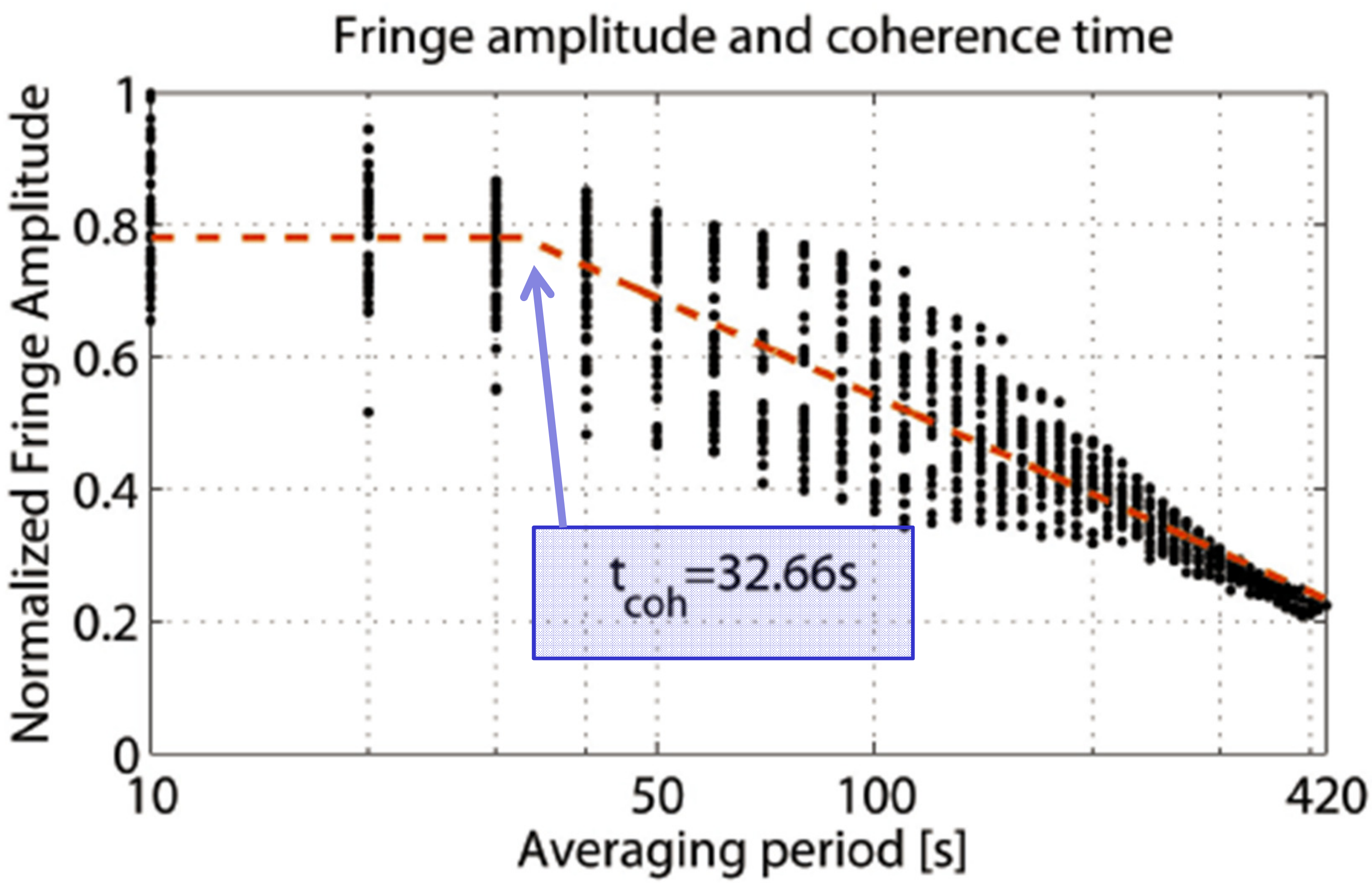
Observed Coherence Time

APEX - SMTO
230 GHz
2012may07
3C 279



Requirements: Absolute Time

CALC needs time when wavefront crosses axis intersection

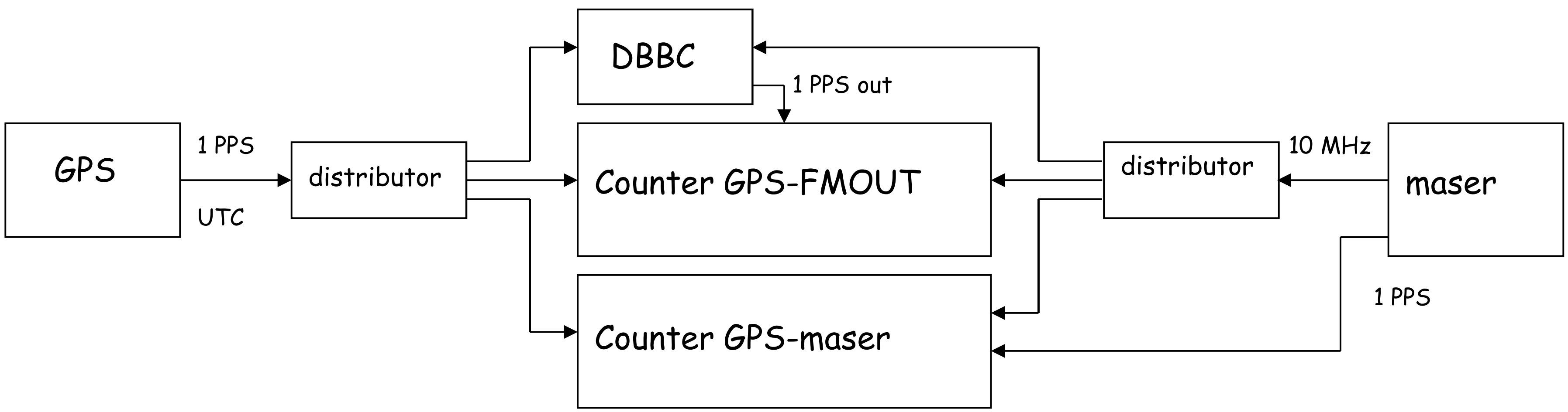
Accuracy: 1) Need fringes to land within correlator search window (± 5 μs)

2) Keep fringes within production window (1 μs)

Method: NTP gives time to nearest second for timestamping data.

GPS 1 PPS tick tells DAS when the second starts, then count 10 MHz

Monitor DAS timing offset wrt UTC (GPS – FMOUT) during observation:



Not usually accounted for: propagation delays in cables/optics

→ In APEX: wavefront arrives 230 ns late at sampler wrt time-tags

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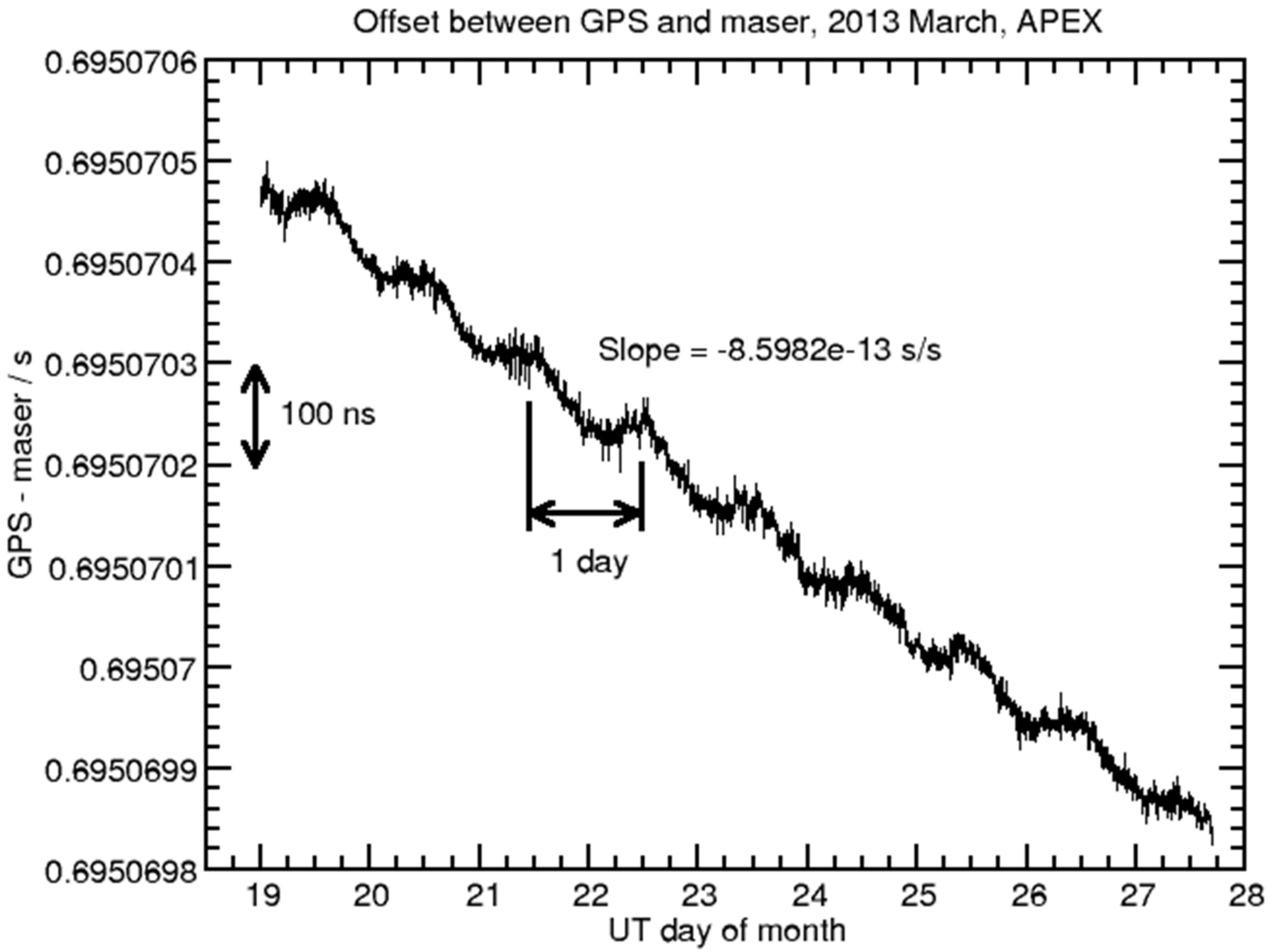
Absolute Time



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Absolute Time: what can go wrong…

Tales of woe from the Bonn correlator:

Unknown offset (miscabling GPS-FMOUT counter): APEX

3 s offset in DAS timestamps: APEX previous session

± 1 s offset in DAS timestamps: frustratingly easy

Sign error in GPS-FMOUT

Sense of rate from GPS-maser opposite sense of GPS-FMOUT

Leap second not applied / applied at wrong time / with wrong sense

Station does not deliver logs so no idea where clock lies.

(Partial) Fixes:

GPS receiver dedicated to DBBC automatically load time into register

Burn in timecode into analogue IF input to DAS: interrupt IF with 1 PPS

Display seconds on DAS front panel / check against another UTC display

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Requirement: Station Position Determination

Aim: Fringe rate < 100 mHz at 345 GHz

Need: < 3 m position uncertainty

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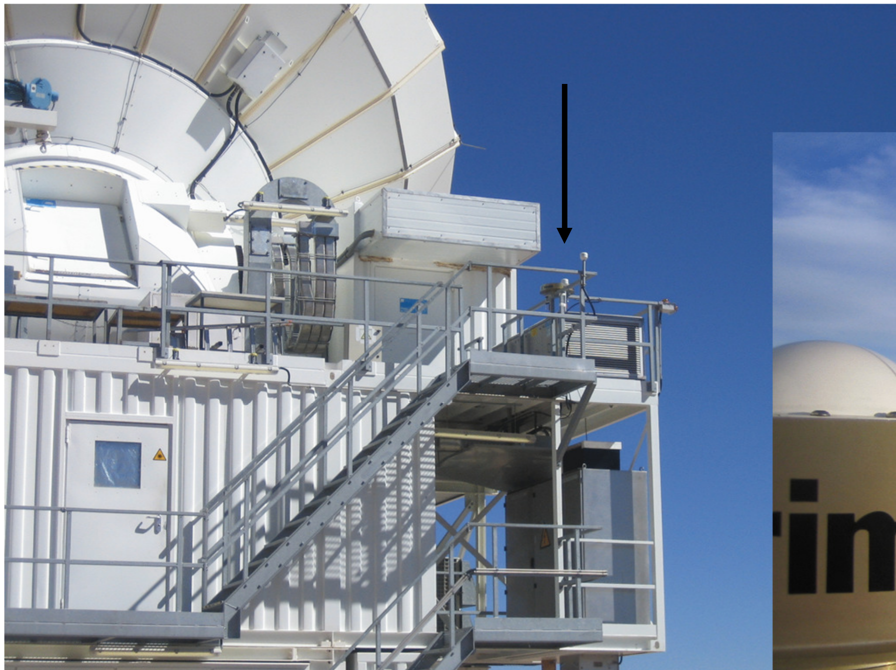
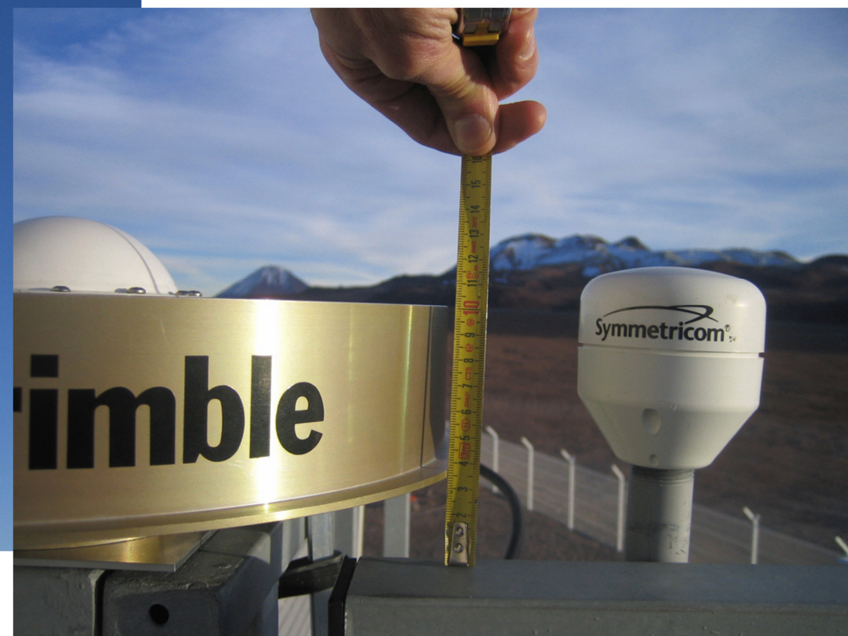
Station Position Determination



GPS antenna borrowed from TIGO (H. Hase) mounted on APEX

During measurement of GPS antenna reference plane height relative to APEX elevation axis



GPS receiver (Ashtech MicroZ) from Onsala (R. Haas) operating in APEX instrument container rack

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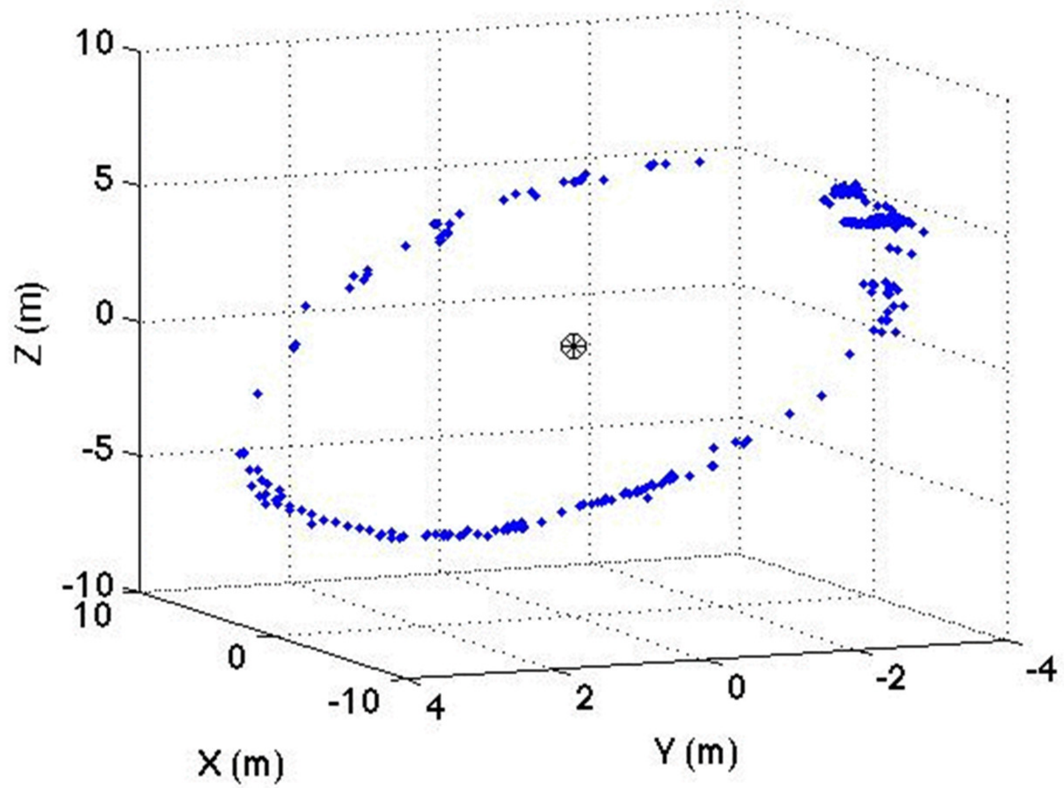
Station Position Determination



GPS kinematic position solutions by J. Johansson

Circle fit and display by R. Haas

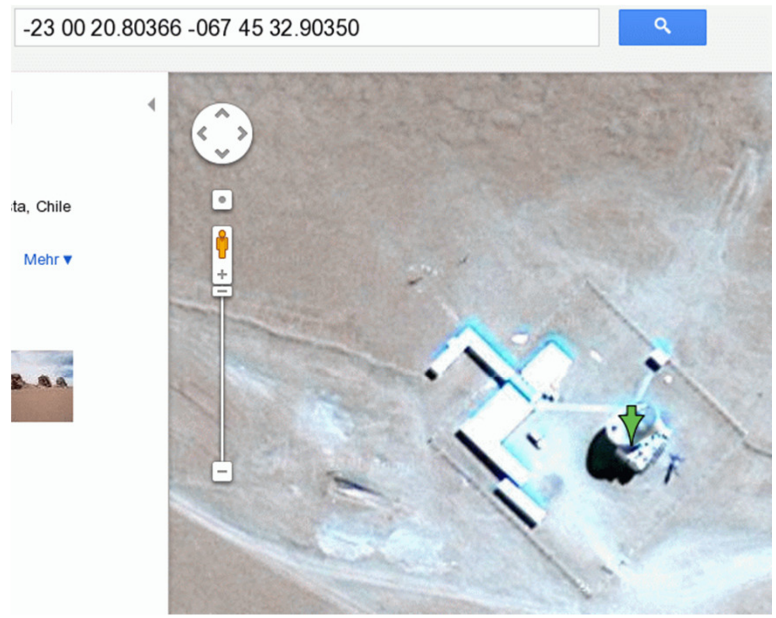
Rotation of APEX causes GPS antenna to rotate on circle

Azimuth axis is centre of circle.

Uncertainty on circle centre: [0.3, 0.2, 0.1] mm in [*X*,*Y*, *Z*]

Add 1 cm uncertainty for level to elevation axis intersection (Wagner / Roy)

(Need < 3 m uncertainty for fringe rate < 100 mHz at 345 GHz.)



Resulting coordinates lie within Google Maps image of APEX

Compare to position using TrueTime single-freq GPS by Oriel Arriagada & R. Haas 2011: dXYZ = 0.22 m

Good confidence in station position

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Future

Phase stability:

- Continuous tone injection during observing
- WVRs for phase correction
- Round-trip phase compensation on 10 MHz ref

Frequency standards:

- Don’t gain from improvement since already better than atmosphere.
- Steer maser DDS freq with GPS automatically; take person out of loop.

UTC:

- Improve reliability of synchronization of DAS to GPS 1 PPS

  -> multiple independent GPS
- Time-tagging analogue data stream