Timing & Synchronisation Concept Description

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Outline

- System context
- Requirements & Functionality
- Interfaces
- Design concept
- Impact of extensibility to SKA2
- Logistics
- Cost, Power, Reliability & Risk
- Process & Plans

System Context

Need for timing and synchronisation throughout the whole system

- Timing
  - Orientation
    - Pointing dishes, steering phased arrays
    - Correlation of signals from dishes, arrays
  - Astrophysical phenomena
    - Pulsar timing
    - Rapid transients, cosmic rays
- System time stamping
  - Calibration
  - System management & logging
  - HPC
- Array synchronisation
  - Coherent aperture synthesis array
- Frequency standards
  - Sampler clocks, (Local Oscillators), calibration tones/pulses, phase switching
  - Synchronous networks

System Context

Ubiquitous timing/sync needs:

- many independent clocks embedded in subsystems where required

  ... Would need calibration network, and/or tie each to GPS
- Central clock/freq standard + distribution network
- Hierarchical combination

→*Synchronisation network*

→Should be considered alongside data/M&C network

Opportunities to share infrastructure, electronics,...

Requirements and Functionality

- Timing
  - Dish pointing (main beam stability...)

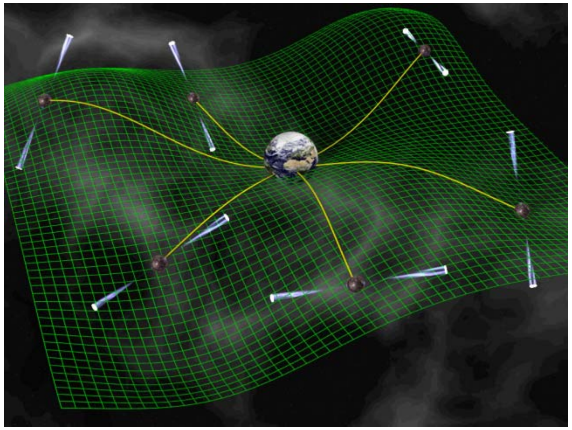
    1% change in (gaussian) main beam response caused by $(\Delta\theta/\theta_0)=0.0044$

    At 3 GHz θ_0 = 0.466dg $\Delta\theta$=0.002dg

    → 0.6s at max elevation rate.
  - AA pointing: beam is 1.8x smaller at 450 MHz
  - Correlation/Tied Array
    - Compute delay model for correlator
    - Similar argument but for synthesised beam, with max baseline of 200km → 45 usec

Requirements (cont)

Pulsar timing: Gravitational wave detection



DRM1.0 40 MSPs, 10 yr <100ns (see also Jenet 2005)

Phase 1 DRM <100ns

Challenging but possible, based on 1996-2008 data

(Verbiest et al 2009)

For SKA2 Smits et al (2011) assumes 10ns,

5-10x better than current

linear increase with sensitivity

but... Timing noise, variable propagation,

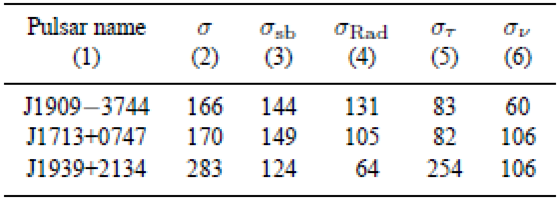
Lyne et al (2010) origin of 'timing noise'

may be possible to mitigate effects

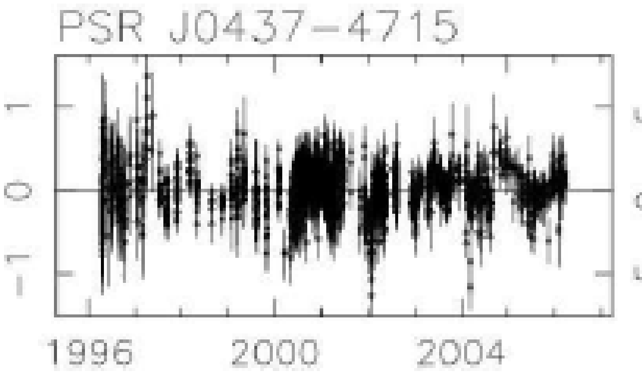
→ Instrumental timing error

Phase 1: <30ns

Phase 2: <3ns



Pulsar name (1)	σ (2)	$\sigma_{\rm sb}$ (3)	$\sigma_{\rm Rad}$ (4)	σ_τ (5)	σ_ν (6)
J1909−3744	166	144	131	83	60
J1713+0747	170	149	105	82	106
J1939+2134	283	124	64	254	106



Jenet 2005 ApJ, 625, L123
Smits et al 2011 A&A, 528, 108
Verbiest et al 2009 MNRAS 400, 951
Lyne et al 2010 Science 329,408

Requirements (cont)

Rapid Transients, exploration of the unknown

- DRM1.0: Time resolution Δt ~ 1/Δν ie ~1ns
- May require absolute timing at similar level for multi-wavelength comparisons, time series analysis,...

Requirements (cont)

System Time Stamping, Logging,Calibration

- Timestamping
  - Book-keeping typically at the > millisec level
- Calibration
  - Eg noise diode switching ~1ms
- HPC requirements
  - TBC

Requirements (cont)

Array synchronisation – Phase stability requirements

Coherence Loss: 0.2 rad rms → 2% loss

$$C = \left| \frac{1}{T} \int_0^T e^{i\theta(t)} dt \right|$$

Sensitivity loss

Dynamic range: DR ~ $M^{1/2}N/\varepsilon$ (Perley 1999)

For ε =1% variation over 100s, T=1000h, N=250

DR = 67dB

Memo 130: DR = 65dB (dishes)

(=Peak:rms for typical 100 mJy source in field; 1000h obs
Note that quiet fields may have brightest source 30 mJy)

[WP2-030.030.000-SRS-002 has 35dB, but also 74 dB]

Perley 1999, ASP Conf. 180, 275.

Requirements (cont)

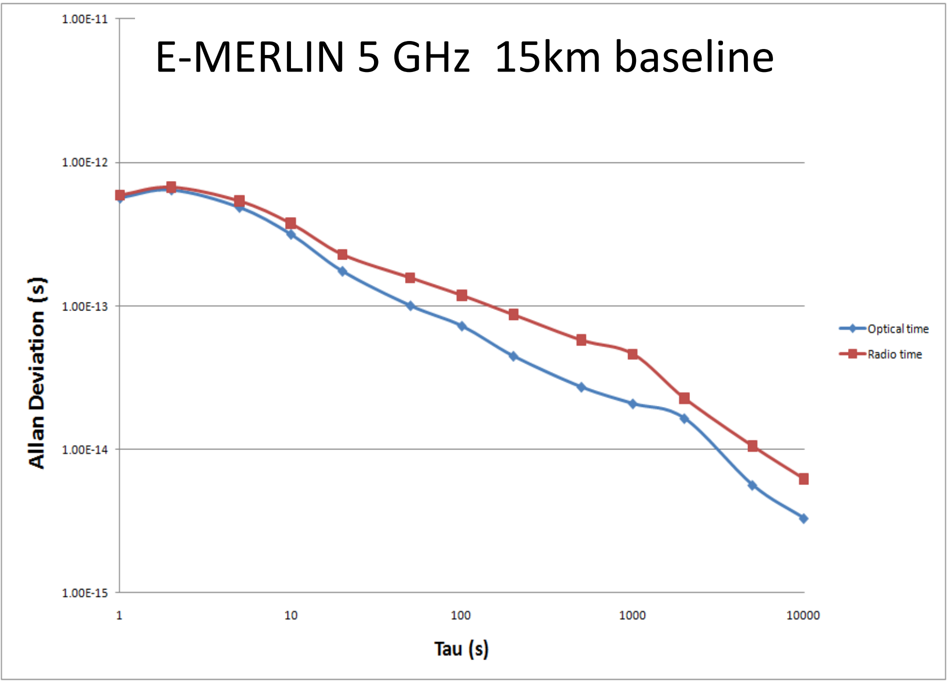
- Phase stability timescale & calibration strategy
  - Troposphere & Ionosphere produce large (≥1 rad) phase variations on timescales of 10-1000s for baselines ≥ 1km and frequencies 0.1-10 GHz
  - *Phase calibration* uses observations of nearby (on the sky) sources to solve for phases per telescope
    - how close, how often depends on baseline length, frequency
    - Experience (VLA, MERLIN, VLBI): for 0.5-5 GHz:
      - 10-30 min for <30km; 3-10min for >30km
      - 5-10dg for <30km; 1-5dg for >30km
    - Models/measurements of turbulent troposphere: 1 rad rms at 10km; 1000s timescale
  - *In-beam phase ref* use close, weak source to avoid switching
    - applies to lower freq, smaller dishes

  highly overdetermined: (N-1) phases; N(N-1)/2 measurements
  - *Self-calibration* solve for target source & phase terms

Switching and/or solution timescales are relevant

All phase calibration techniques cannot separate ‘clock’ and ‘atmosphere’ terms

Atmospheric p



Kolmogorov turbulence

2D power spectrum of phase f

Refractive index structure func

$D(d)=C_n^2 d^{2/3}$ for d: 0.01m

$C_n \sim 2E\text{-}7\ m^{-1/3}$

Rms phase $\sigma_\phi=1.7(2\pi/\lambda)C_n L^{1/2} d^{5/6}$

Baseline for $\sigma_\phi=1$ rad $d_0=0.06\ (\lambda/C)^{6/5} L^{-3/5}$ (10km)

Timescale: moving screen $\tau \sim d_0/v \sim 1000s$

Allan variance: $\sigma^2_y(\tau)=1.3x10^{-17}C^2 L v^{5/3}\tau^{-1/3}$

$\sigma_y \sim 1e\text{-}13$ at 100s

Requirements

In-beam phase referencing

- Requires (compact) source within primary beam sufficient SNR within solution period
- Used by VLA, MERLIN at 1.4 GHz, routine for EVLA, MERLIN
- For SKA-1 15m dishes at 1.4 GHz
  - Typical brightest source in beam 0.15 Jy (N(s)Ω=1)

  SNR ~ 3 on single baseline in 1s [30K, 100MHz sub-band]

  SNR ~ 50 using all baselines

  Phase error ~ 1 dg

  DR 74dB for 1000hr

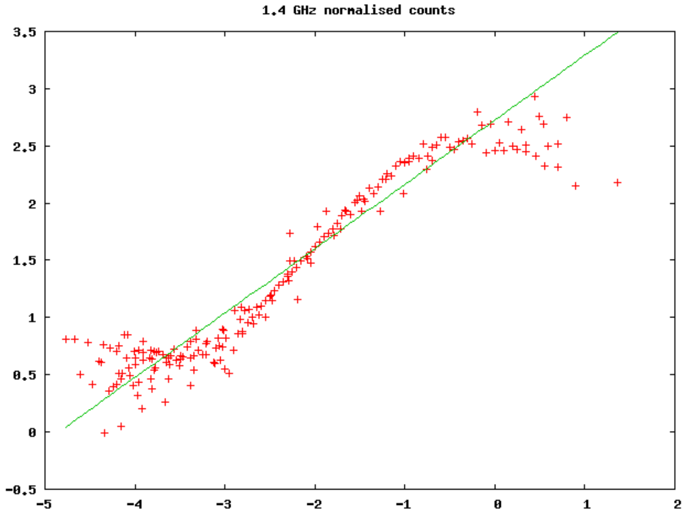
  Assumes compact source (>30% will be; Garrington et al, Mosoni et al)

  Can use multiple sources

  Quiet fields may be chosen for most sensitive expts

    Brightest source 0.03 Jy

    25s to reach 1dg phase error



Garrington et al 1999 NewAR, 43,629

Mosoni et al 2006 A&A 445,413

Requirements

- At higher frequencies

  SNR = 50 f $(\lambda/21\text{cm})^{2.7}$ (Tsys/30K η/0.7) $(\text{B}/100\text{MHz t/s N}/250)^{0.5}$

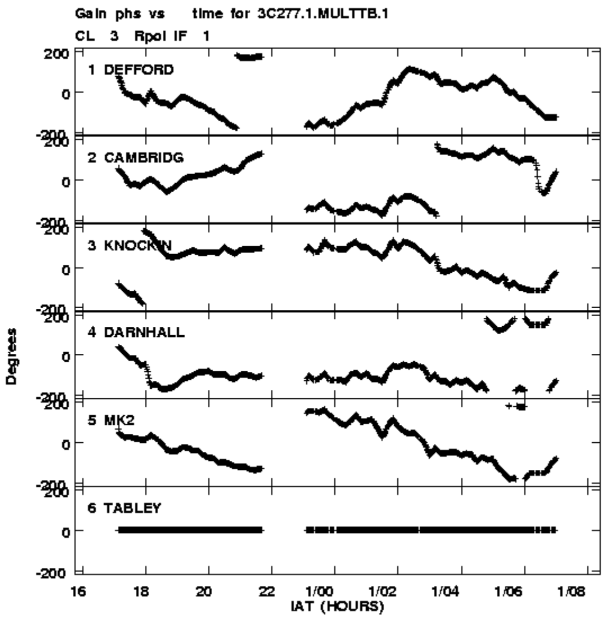
  For integral source count ~-1; spectral index -0.7

- At upper end of freq range for SKA1 (2.5 GHz)
  - SNR = 12.5 in typical field

→Need good coherence (<2% loss) over timescales of 10-300s even for in-beam phase calibration

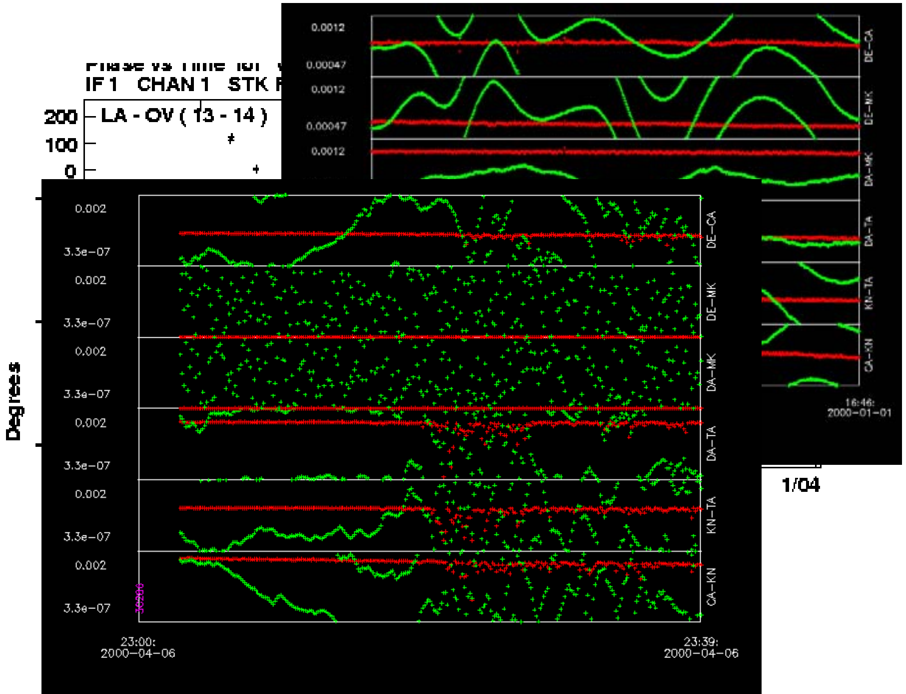
Not so different from requirement set by source switching

Requirement



- Comments on longer term stability
- Long baseline interferometers currently stable on hrs-days
- Clock and atmospheric instabilities are easy to see

Should consider as a requirement



Requirements Summary

	3 GHz	**10 GHz**	**Notes**
LO Stability			
Rms over 1 sec	<0.2 rad ≡ 9 ps	<0.2 rad ≡ 3 ps	1
Rms over 100 sec	<0.2 ≡ 9 ps	<0.2 ≡ 3 ps	2
Drift over 5 min	< 1 rad ≡ 48 ps	< 1 rad ≡ 16 ps	2
Timing			
Pulsar timing, current	~10 ns	~ 10 ns	3
Pulsar Timing, future	~1 ns	~ 1ns	4
Coherent addition	9 ps	3 ps	5

1 Assuming a 2 % maximum coherence loss in a given integration period

2 Drift rate limit so that phases can be tracked in switched phase reference observations

3 Current capability using GPS and H maser clocks over last 10yrs

4 Multi-station GPS common view techniques should be able to achieve this, though carrier phase techniques might be required.

5 To coherently add the signals from receptors and give less than 2 % coherence loss.

Interfaces

- The subsystem will need to interface in the following ways:
- With overall SKA operational control through the monitor and control system (operation, vitality of elements etc.)
- With the receiver and digital sub-systems on the antennas
- With the internal station LO and clock distribution sub-systems
- With the correlator and processors for phase correction, via the monitor and control system
- (Possibly) With HPC and SKA Office locations for time servers

Design Concepts Introduction

- Relative synchronisation of sampler clocks and/or local oscillators at each telescope/station to 9-3 ps over timescales 1 to 100s
- Provision of UTC at 0.001s level to individual telescopes/stations for book-keeping, telescope pointing/beamforming
- Absolute timing of station or tied-array data to within ~30ns of IAT
- Options
  - Independent clocks/frequency standards + GPS
    - Currently: VLBI, LOFAR
  - Central master clock + synchronisation network
    - Cable link: WSRT, VLA
    - Radio link: MERLIN
    - Optical links: EVLA, e-MERLIN, ALMA
    - 1-way or 2-way: measure & correct for delay variation in link

Synchronisation Networks

- Delay variations in 1-way link
  - <10 ppm/K for bare or loose-tube SMF; up to 60 ppm/K for others (eg Norrod 1992; Durand et al EVLA Memo 105)
  - Buried fibre has very low diurnal temp variation

    $\Delta T(z)=\Delta T_0 e^{-z/D}$ with $D\approx0.1$ for typical soil

    At 0.5m deep ~0.1 °C for external variation of 20 °C

    →<1cm path variation for 10km fibre

    Dreher (ATA Memo 55) 0.4 dg phase/hr at 10 GHz for 1km
- For buried fibre, SKA-1, round trip may not be required to meet stability requirements within 5km
  - Requires careful lagging of any exposed fibre

    30m in sun/shade ~ 5km at 0.5m
  - Implications for deployment of AA stations/core

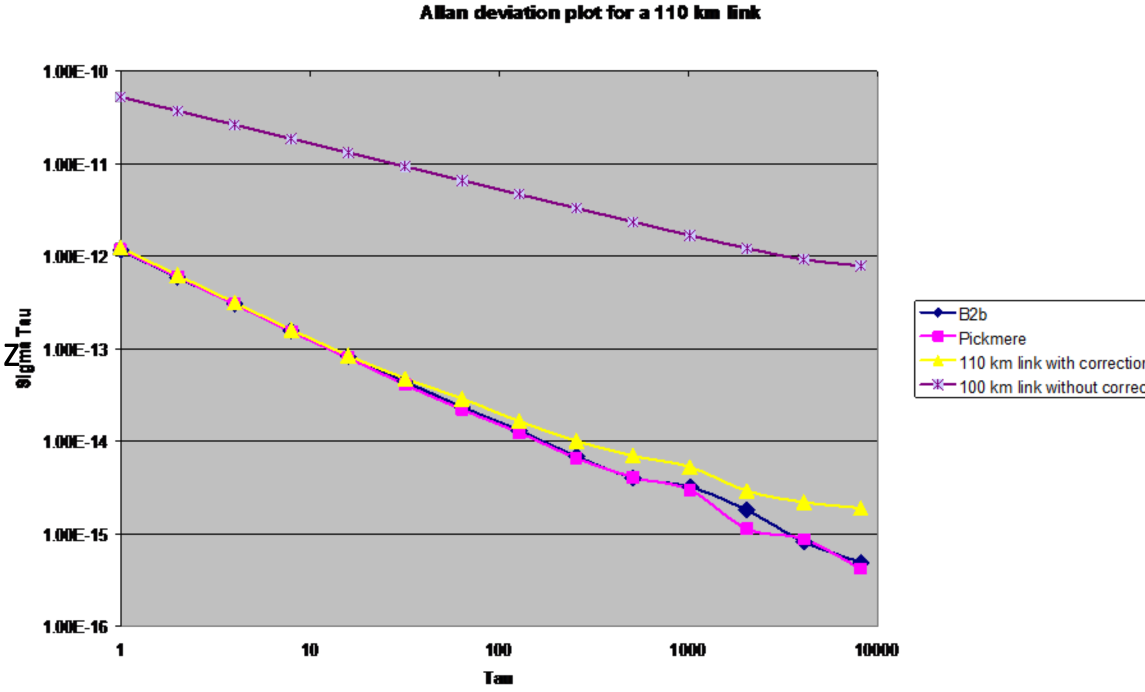
Synchronisation networks

- Round trip phase measurement systems
  - Used on almost all connected interferometers since 1960’s
  - Various techniques; key issue is to separate ‘go’ and ‘return’ signals
    - Modulated reflector; different frequencies; pulses
    - MERLIN: Extended to >100km using 1.4 GHz radio link
  - Natural extension to fibre
    - Low loss, multi-core cable
    - EVLA: 2 cores in same cable; reflect ~20km
    - E-MERLIN: single fibre; 1.4 GHz pulsed modulation
      - >100km demonstrated with stability of 1-2ps over 1-600s
      - Optical Tx/Rx cost €9k/link + oscillators, electronics

Synchronisation network

Demonstration of optical fibre link synchronisation using MERLIN L-band link (1.4 GHz pulsed; TDM) over 110km

McCool et al (JBO)



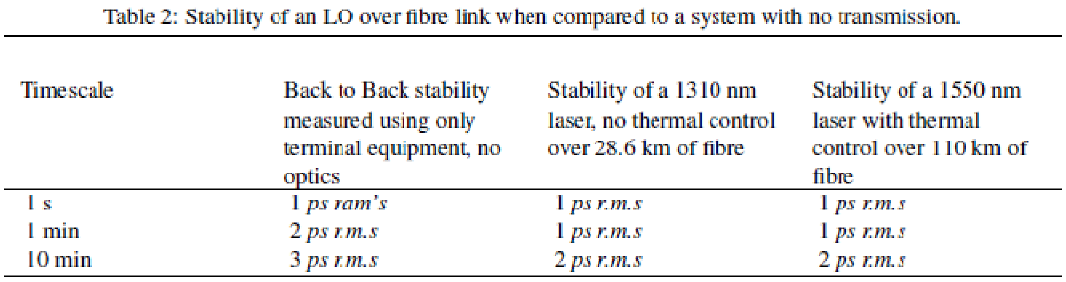
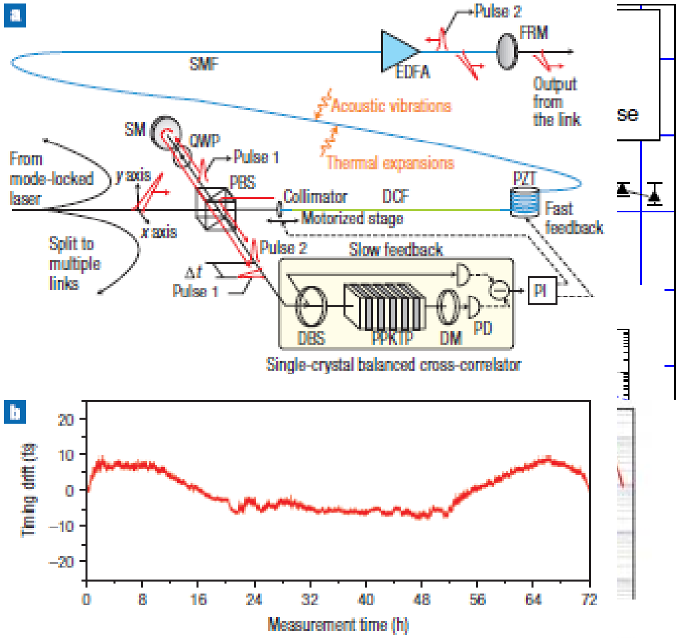


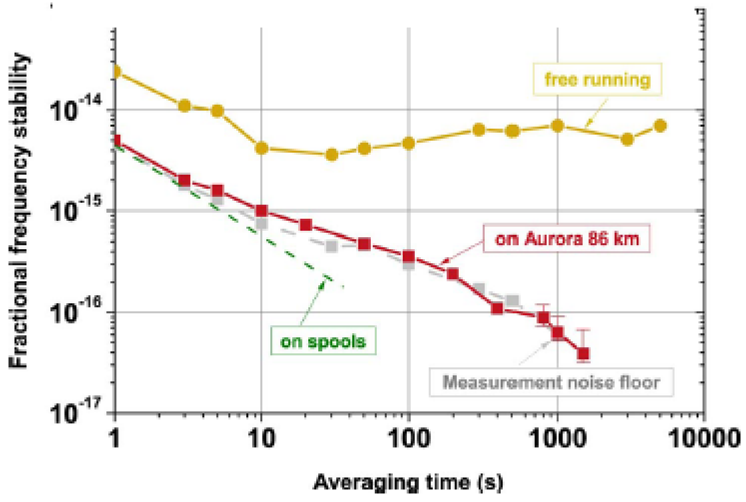
Table 2: Stability of an LO over fibre link when compared to a system with no transmission.

Timescale	Back to Back stability measured using only terminal equipment, no optics	Stability of a 1310 nm laser, no thermal control over 28.6 km of fibre	Stability of a 1550 nm laser with thermal control over 110 km of fibre
1 s	1 *ps ram's*	1 *ps r.m.s*	1 *ps r.m.s*
1 min	2 *ps r.m.s*	1 *ps r.m.s*	1 *ps r.m.s*
10 min	3 *ps r.m.s*	2 *ps r.m.s*	2 *ps r.m.s*

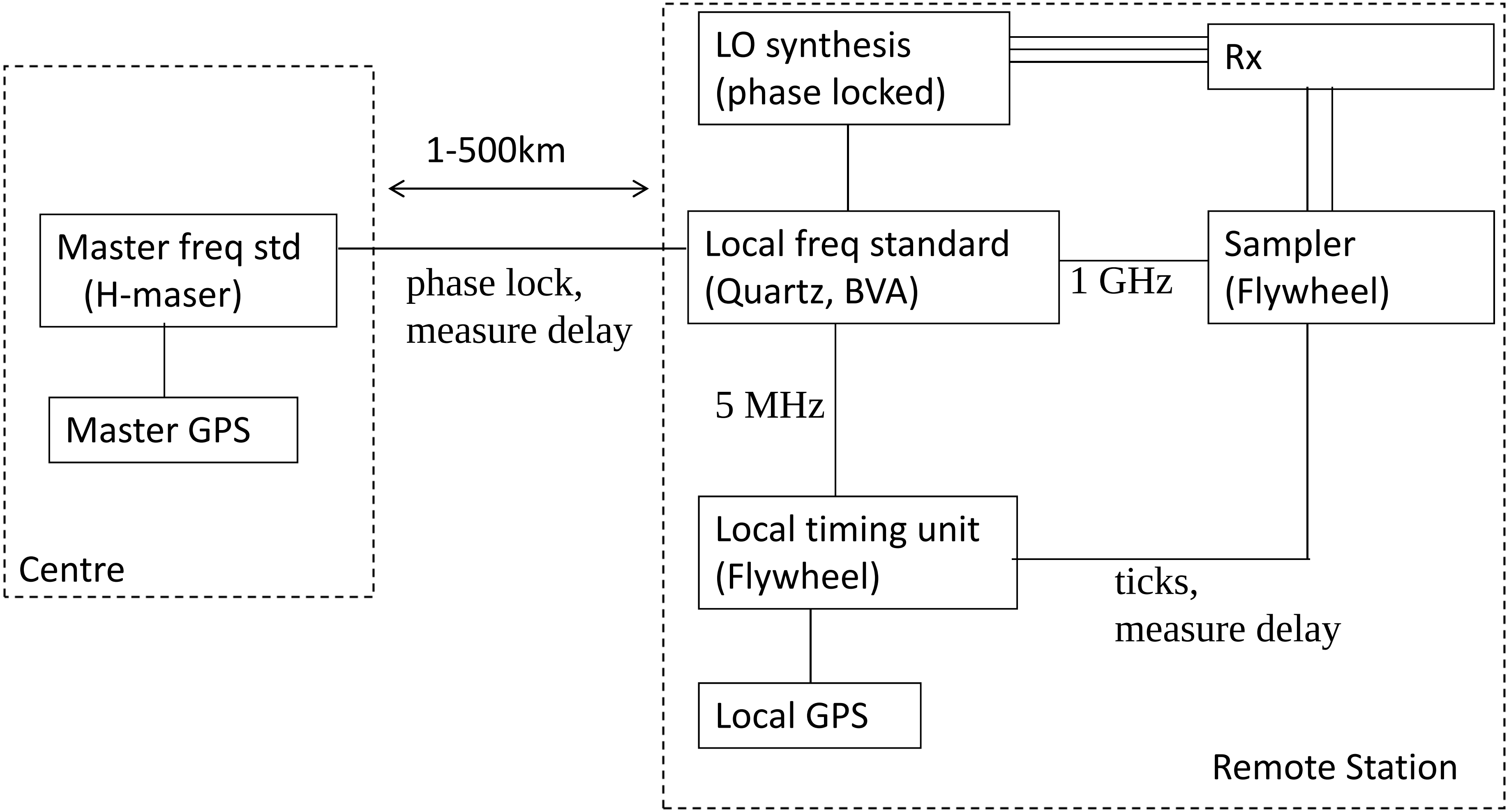
Related techniques

- Paris/SYRTE (eg Lopez et al 2008)
  - 86km; optical compensation; PMD scrambling
- PTB/Braunschweig (eg Grosche et al 2009)
  - 146km; AOM
- Tokyo (eg Kumagai et al 2009)
  - 114km; electo+optical
- NPL (eg Marra et al 2010,2011)
  - 86km; 250 MHz rep rate of mode locked lase
  - 50km; optical comb
- XFEL (eg Kim et al 2008)
  - 300m, 6fs over 72hrs





Outline phase transfer & timing system



Centre

Master freq std (H-maser)

Master GPS

1-500km

phase lock, measure delay

Remote Station

LO synthesis (phase locked)

Rx

Local freq standard (Quartz, BVA)

1 GHz

Sampler (Flywheel)

5 MHz

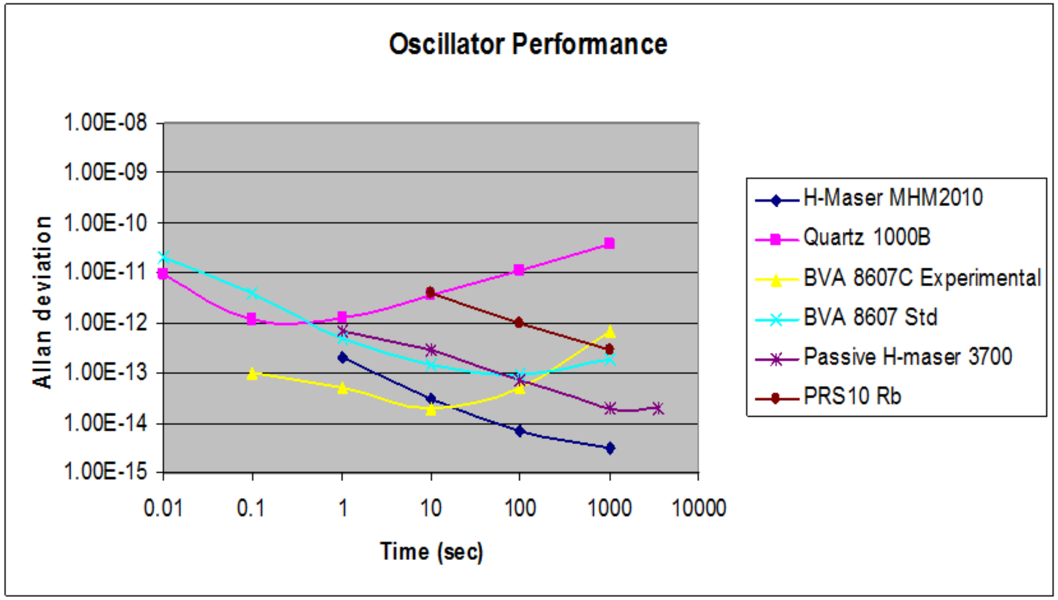
Local timing unit (Flywheel)

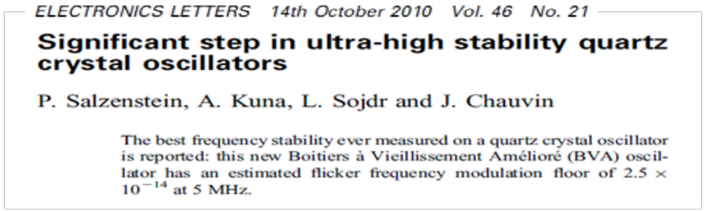
ticks, measure delay

Local GPS

Independent Clocks

- Active H-masers
- Passive H-masers
- BVA Quartz Oscillators





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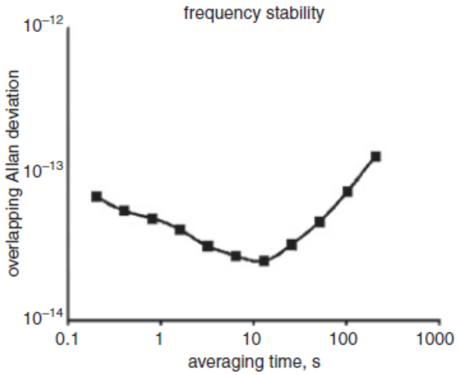
Significant step in ultra-high stability quartz crystal oscillators

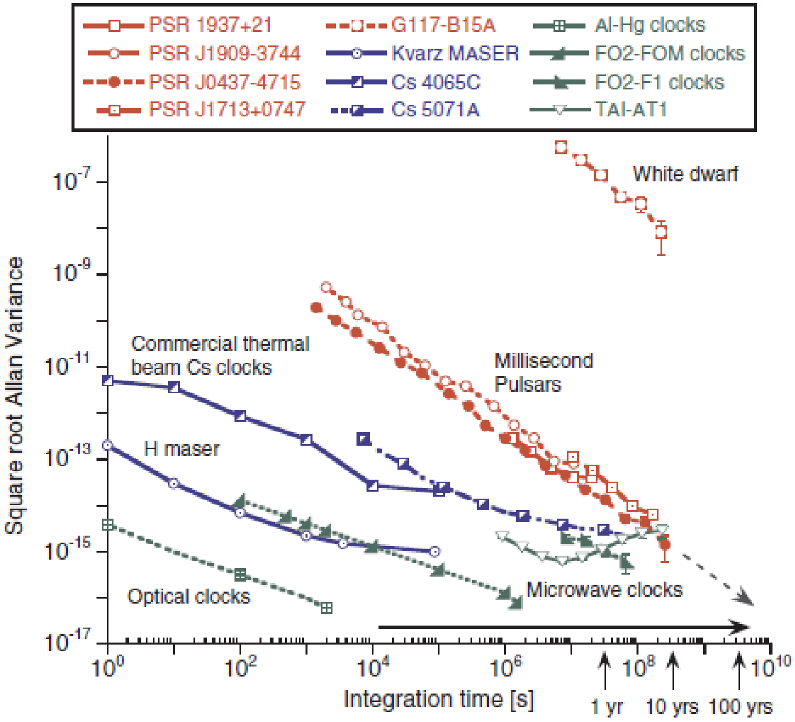
P. Salzenstein, A. Kuna, L. Sojdr and J. Chauvin

The best frequency stability ever measured on a quartz crystal oscillator is reported: this new Boitiers à Vieillissement Amélioré (BVA) oscillator has an estimated flicker frequency modulation floor of 2.5 × 10^{-14} at 5 MHz.



Standard	3GHz 1 sec	3GHz 10 sec	3GHz 100 sec	3GHz 1000 sec	10GHz 1 sec	10GHz 10 sec	10GHz 100 sec	10GHz 1000 sec
Cheap Xtal	50	300	1.2x10^4	1.2x10^6	150	1000	4.10^4	4.10^6
Good Xtal	5	30	300	6x10^3	15	100	1000	2.10^4
Good BVA	0.1	0.3	11	500	0.3	1	36	1500
GPS+Rb	5	50	100	1.5x10^3	15	150	360	5.10^3
Cesium	5	15	50	150	15	50	150	500
Passive H maser	1.2	5	11	46	4	15	36	150
H maser	0.15	0.18	0.5	1.1	0.5	0.6	1.5	3.6

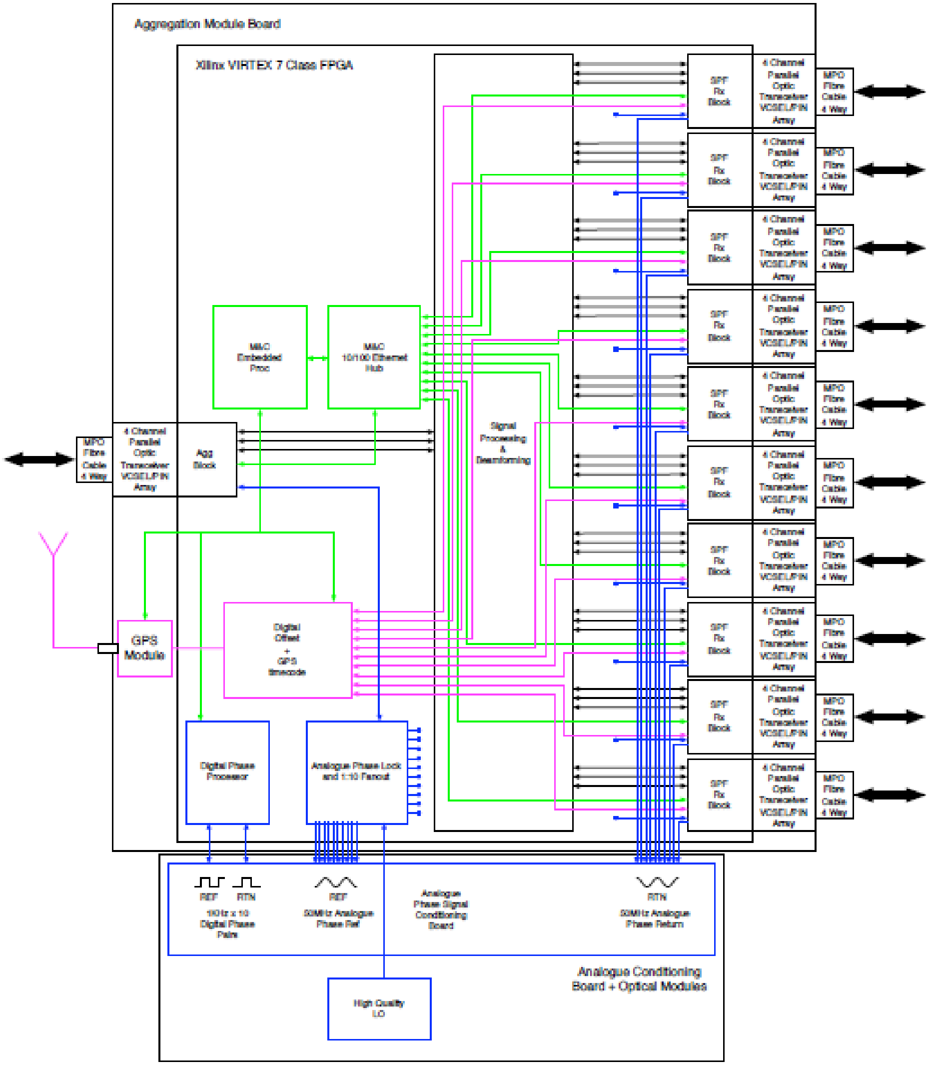
Master Clock



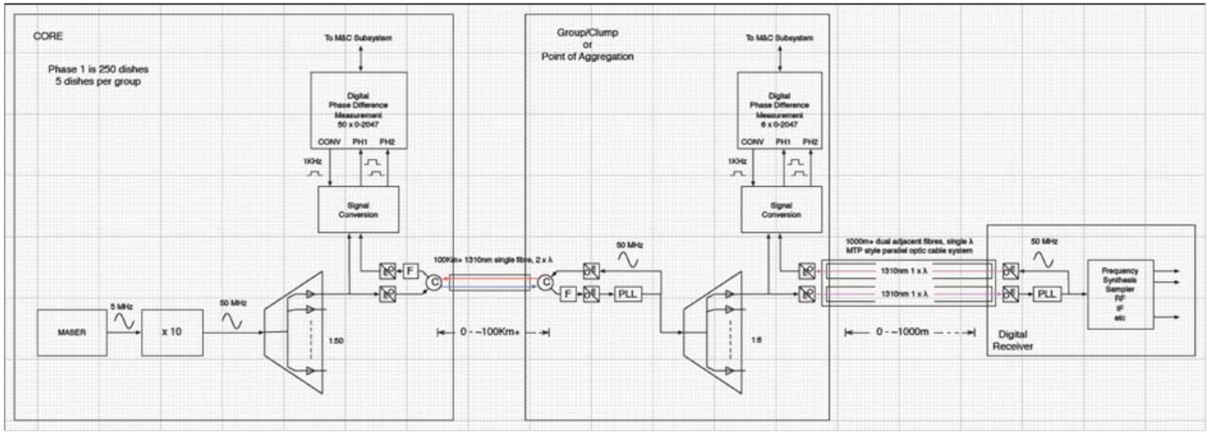
- Most major radio observatori
  use active H-masers
- Trapped ion clocks now reachi
- Have been considered for ESA
  stations
  - Cost ~€1M; environment
- Should SKA have similar ambition?
  - links to other time standard labs
  - links to astro timescales
    - Pulsar timescale: co-locate one of best clocks & psr observatory
  - links to s/c navigation, gravity experiments, optical clocks in space

Integrated Implementation

- Hierarchical MPO-based data transport system proposed in WP2-030.060.040-SD-001
  - data aggregator boards used for groups of dishes or groups of AA station elements
  - MPO cable assemblies
  - 850/1310/1550nm VCSEL arrays
- Integrate optical tx/rx for phase, M&C, data
- Incorporate PLL, tick generation, phase measurement, GPS referencing, +...
  on same device as data traffic handling



Integrated implementation (cont)



- Based on similar principles to demonstrated 1.4 GHz system
  - All links can be 1-way or 2-way; choice to depend on distance and fibre burial/installation
  - On longer links use 2λ, same fibre, temp stabilised DFB lasers
  - On shorter links use 2 fibres, one channel of VCSEL array

Extension to SKA-2

- Requirements
  - Top frequency: 3→10 GHz
  - Max distance: 100→3000km
  - Dynamic Range: 75 dB
  - Pulsar timing: ~ 3ns
- Infrastructure & technique will support 10 GHz; can be extended to ~1000km in multiple hops
- Outer few stations may need independent masers, as VLBI today.
- E-MERLIN is demonstrating analog phase transfer links on commercial installed fibre over 400km, with repeaters in telecom operators co-lo sites.

Cost (standalone)

	Cost	Basis	Supplier	N	Total/k€
2-way on arms					285
Optics (+power etc) Up to 150km	€9k	2011 purchase	Photonics inc	15	135
Oscillator BVA 8607	€5k	2011 quote	Oscilloquartz	15	75
Modulation, phase etc	€5k	Est		15	75
Distribution within clump					
1-way in inner 2.5km					1050
Optical tx	€3k	est		35+175	630
Mod, etc	€2k	Etc		35+175	420
Central H-maser	€250			2	500
TOTAL					1835

Cost (integrated)

	Cost	Basis	Supplier	N	Total/k€
2-way on arms					225
Optics (+power etc) Up to 150km	€9k	2011 purchase	Photonics inc	15	135
Oscillator BVA 8607	€5k	2011 quote	Oscilloquartz	15	75
Modulation, phase etc	€1k	Est		15	15
Distribution within clump					
1-way in inner 2.5km					
Optical tx	incl				
Mod, etc	incl				
Central H-maser	€250			2	500
TOTAL					725

Power

- Measured power consumption of 2 way link based on e-MERLIN development – up to 150km reach is 25W
- For integrated phase/M&C/data transport see power budget in C Shenton presentation

Reliability

- Integrated approach with MPO cable assemblies designed for maximum reliability
- Issues
  - VCSEL tx array lifetime?
  - 1550 tx lifetime
- Single point failure?
  - good BVA oscillators may allow significant subset of experiments without active 2-way links
  - Multiple H-masers at centre for redundancy

Risks

- Optical fibre phase transfer is in current use for higher frequencies (EVLA) and similar/longer baselines (e-MERLIN) than required for SKA-1.
- Several possible implementations available
- Scale is not an issue for SKA-1, especially with dish clumps/groups
- Phase transfer using MPO cable/tx assemblies is untested

Plans

- Continue experiments with e-MERLIN as test bed
- Characterise performance on longer links
- Further work on GPS timing
- Continue design work on integrated system
- Carry out phase transfer tests using MPO system at 850nm

Time & Freq Processing at dish/station

- e-MERLIN Implementation (B Anderson et al)

low cost iLotus (ex Motorola) GPS: 2-3 ns stability

5/10 MHz input (maser/crystal)

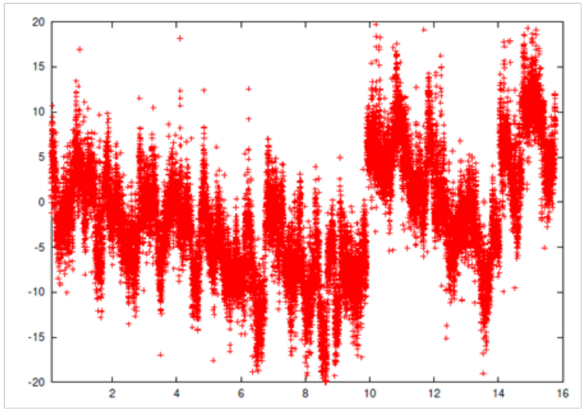
Clock synthesis chip: 128 & 512 MHz

FPGA: Flywheel divider chain by 2048, 625, 5 and 20 generates the 1 second ticks from the 128 MHz

Divide by 625, 5 and 20 are cleared by the 1 second ticks from the GPS receivers

The GPS ticks and the incoming TCs sample the divide by 2048 to measure coarse delay (8ns)

Fine delays (0.5 ns) are obtained by processing multiple copies of offset ticks.



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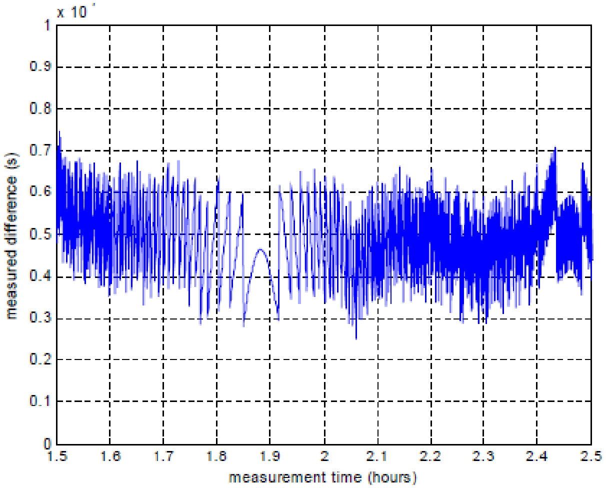

LOFAR 2007

Figure 5, Measured time difference for a measurement between a GPS receiver and an Rb-reference clock slaved to a second GPS receiver.