Recent tests for the BRAMS interferometer

Michel Anciaux

What are the tests about? And why?

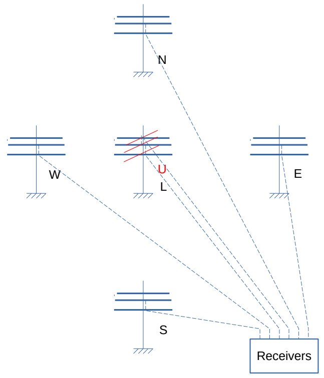
What?

- Phase difference measurement with the interferometers

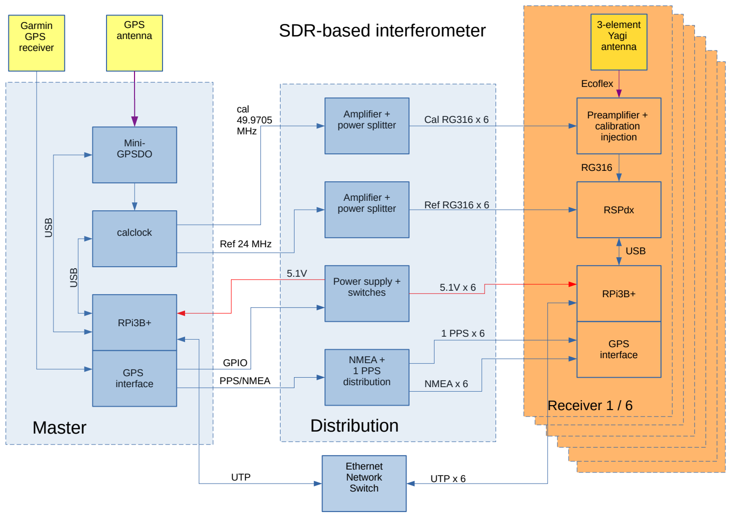
Why?

- Problems with retrieved azimuth and elevation from echoes with known trajectories (aircraft with ADSB, meteor echoes from optical observation) ==> Johannes Laur’s presentation
- Need to calibrate the interferometer to enable sensible phase measurements

Overview of the interferometer

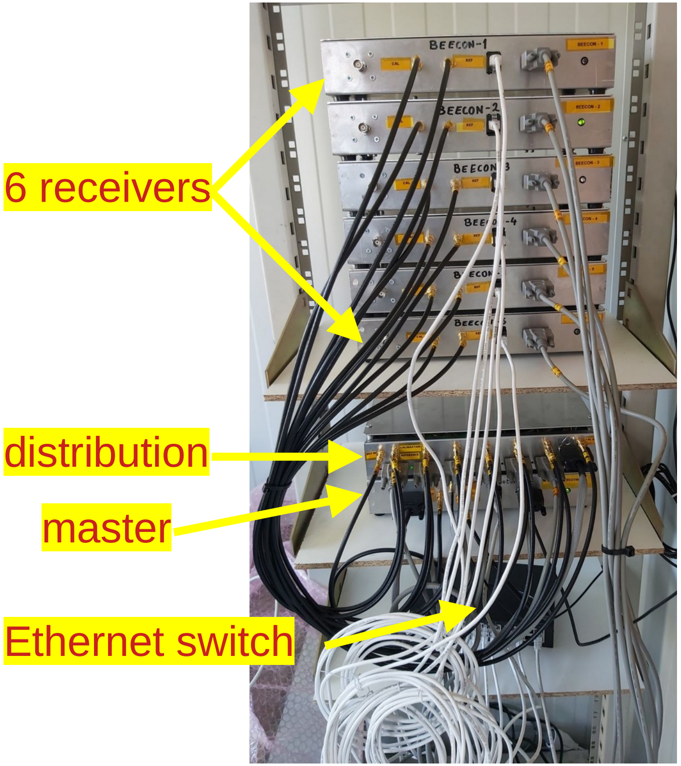


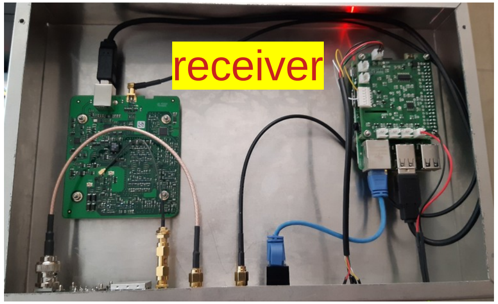
Array of 6 Yagi antennas

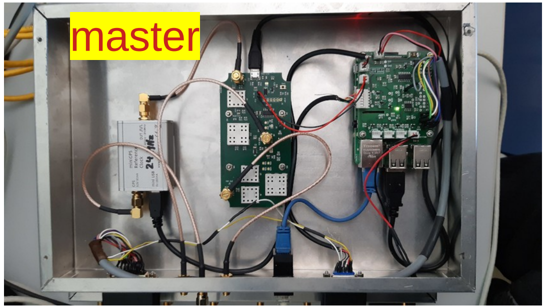


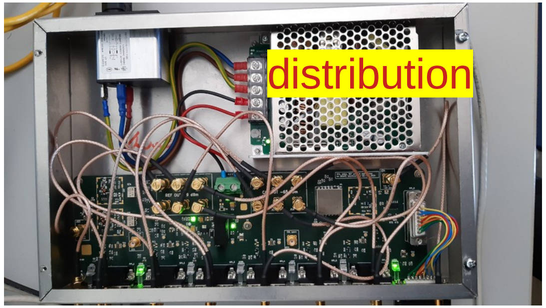
- 6 separate software-defined radio receivers (based on BRAMS stations)
- Each with LNA, RSPdx and RPi
- All Rpi clocks are GPS disciplined
- 24 MHz common GPS disciplined reference: same LO and sampling frequency
- Common calibration signal at 49.9705 MHz

Interferometer using SDR receivers









“old” interferometer in Humain

- 6 AR receivers, common reference (10MHz): same LO frequency
- 6 audio outputs and 1-PPS synchronously sampled at 11 kSa/s (NI9215 + Labview program)

Issues with this set-up:

- Unexplained frequency offset ~5Hz (from Fury GPSDO?)
- Sampling frequency based on crystal oscillator: poor longterm stability, temperature dependence, aging

Problems associated with the SDR-based interferometer

- “rsp” program running on each RaspberryPi independently from the others: **sample time offset** between receivers (it changes whenever a receiver is restarted)
- Time stamping method used for the individual BRAMS stations yields an uncertainty of a single sample <0.16ms ==> not adequate for interferometry
- USB bulk transfer avoids losing samples but may be delayed
- time-stamp every 1008 samples affected by scheduling jitter (~10ms)

Simple model of SDR receiver direct conversion

Real valued signal from antenna

$$u(t) = s(t) \cdot \exp(-j(\omega_c \cdot t + \phi_c))$$

Complex audio band signal

local oscillator

$$\phi_c = initial\ phase\ of\ the\ local\ oscillator$$
$$\omega_c = local\ oscillator\ angular\ frequency$$

Considering the calibration and beacon signals:

$$\omega_c = 2\,pi \cdot 49.969\ MHz$$
$$\omega_b = 2\,pi \cdot 1000\ Hz$$
$$\omega_{cal} = 2\,pi \cdot 1500\ Hz$$

$$u(t) = A_b \cdot \exp(j(\omega_b \cdot t + \phi_b - \phi_c)) + A_{cal} \cdot \exp(j(\omega_{cal} \cdot t + \phi_{cal} - \phi_c))$$

$$A_{cal}, A_b = amplitude\ of\ calibration\ \text{and}\ beacon\ signals$$
$$\phi_{cal}, \phi_b = initial\ phase\ of\ calibration\ \text{and}\ beacon\ signals$$

Simple model with 2 receivers

Initial phases

$$\phi_c \rightarrow \phi_{c1}, \phi_{c2}$$
$$\phi_b \rightarrow \phi_{b1}, \phi_{b2}$$
$$\phi_{cal} \rightarrow \phi_{cal1}, \phi_{cal2}$$

Sampling time offsets

$$t \rightarrow \begin{matrix} t_1 = t + dt_1 \\ t_2 = t + dt_2 \end{matrix}$$

The complex audio signals become:

$$u_1(t) = A_{b1} \cdot \exp\{j[\omega_b \cdot (t + dt_1) + \phi_{b1} - \phi_{c1}]\} + A_{cal1} \cdot \exp\{j[\omega_{cal} \cdot (t + dt_1) + \phi_{cal1} - \phi_{c1}]\}$$
$$u_2(t) = A_{b2} \cdot \exp\{j[\omega_b \cdot (t + dt_2) + \phi_{b2} - \phi_{c2}]\} + A_{cal2} \cdot \exp\{j[\omega_{cal} \cdot (t + dt_2) + \phi_{cal2} - \phi_{c2}]\}$$

The phase difference at a single frequency is

$$\phi_{12} = arg[u_1(t) \cdot u_2^*(t)]$$

At the calibration and beacon frequencies, the measured phase differences are

$$\phi_{12b} = \phi_{b1} - \phi_{b2} + \omega_b (dt_1 - dt_2) - (\phi_{c1} - \phi_{c2})$$
$$\phi_{12cal} = \phi_{cal1} - \phi_{cal2} + \omega_{cal} (dt_1 - dt_2) - (\phi_{c1} - \phi_{c2})$$

Phase difference at the receiver inputs

Taking the difference of the measured phase differences to eliminate the LO phase offsets

$$\phi_{b1}-\phi_{b2}=\phi_{12b}-\phi_{12cal}\overbrace{-(\omega_b-\omega_{cal})\cdot(dt_1-dt_2)+(\phi_{cal1}-\phi_{cal2})}^{\text{Phase error}}$$

phase difference
at receiver inputs

measured phase difference
(from WAV files)

frequency offset from
calibration frequency

unknown sample time offset

distribution phase offset (< 5°)

Assessing the sampling time offset

Several methods have been considered:

- “pps” modulating the calibration signal at 1 Hz with the GPS 1-PPS
- “pulse” modulating the calibration signal by software once per minute
- “dt” using the time stamps over one 5-minute file
- “dtm” using the time stamps over many 5-minute files
- “cal2” using two calibration signals

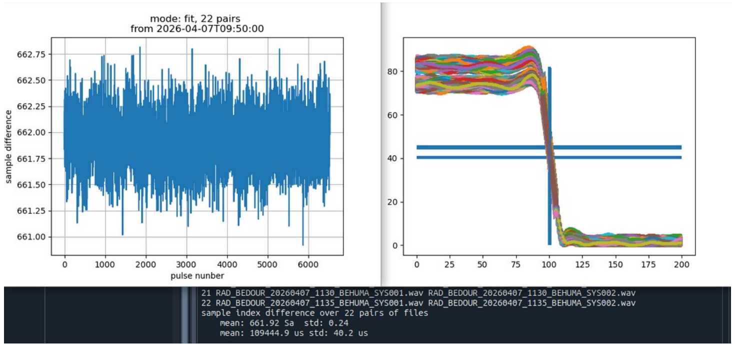
For the old interferometer in Humain, dt1 – dt2 is always 0 because of the simultaneous sampling.

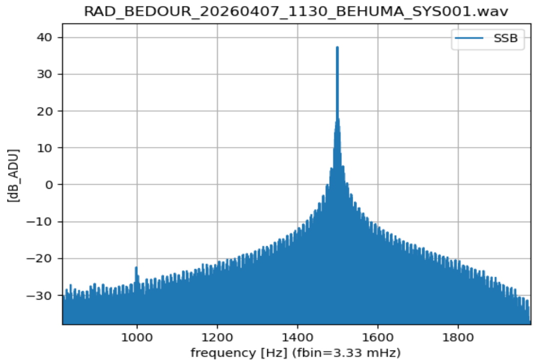
“PPS” method

- The **1-PPS** signal from the GPS interface board (on top of the RaspberryPi) is brought to the **calclock** unit via a short cable.
- **Calibration signal is turned off for 100 ms, every second**, starting within 1 μs of the start of the new second. This is saved in the WAV file at the rate of 6048 samples/second.
- The **falling edge** of the signal envelope is detected on all receivers and a dt1 – dt2 value can be determined for each pair of receivers.
- This method also provide an **independent check** on the **timestamps**.

“PPS” method

- dt1 – dt2 uncertainty of 40 µs (over 22 files, contributing 7° to phase error at beacon frequency).
- Calibration signal is absent 10% of the time and has to be reconstructed to cover those gaps.
- The spectrum presents a 1-Hz comb (still 60dB below cal peak at the beacon frequency). This may complicate things if a second beacon is ever used.



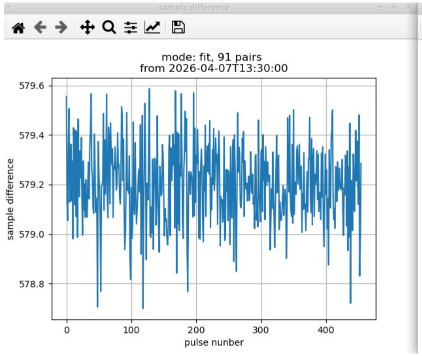


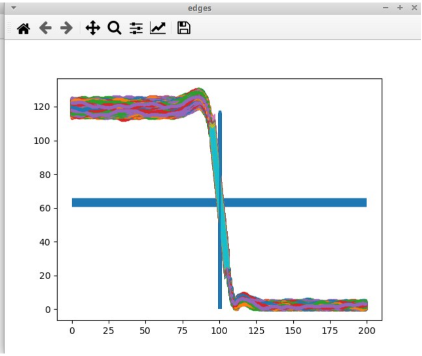
“Pulse” method

- The **calibration signal is turned off for 100 ms** by the master approximately **every minute**. This is saved in the WAV file at the rate of 6048 samples/second.
- The **falling edge** of the signal envelope is detected on all receivers and dt1 – dt2 can be determined for each receiver pair.
- Unlike the “PPS” method, it provides **no independent check on the time stamps**.
- No hardware modification is required (wrt Interferometer at ECOTRON).

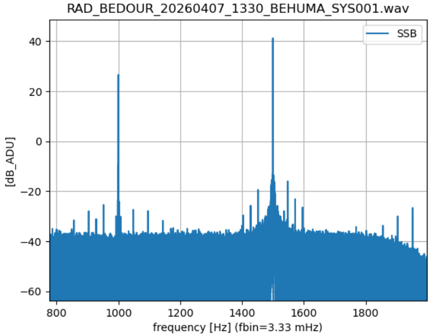
“Pulse” method

- dt1 – dt2 uncertainty of 83 µs (over 91 files, contributing 15° to phase error at the beacon frequency).
- Calibration signal is absent 0.16% of the time and has to be reconstructed to cover those gaps.





- Spectral contamination present (less than with the “PPS” method).

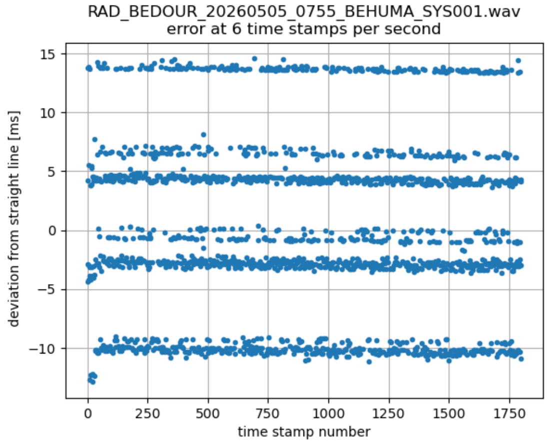


“dt” method

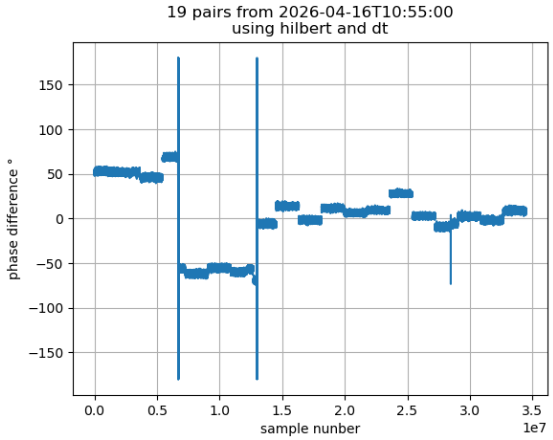
- This method processes one file (per receiver) at a time
- The initial time is obtained by fitting a straight line with a slope of 6048 samples per second to the 1800 time stamps.
- The difference in the intial time of a pair of receivers is used as the estimate of dt1 – dt2.

“dt” method

Time stamp error caused by scheduling jitter



- cable length difference to 2 receivers: -60cm, 60cm, 0 cm.
- steps correspond to 5-minute WAV files
- jumps are caused by the scheduling jitter

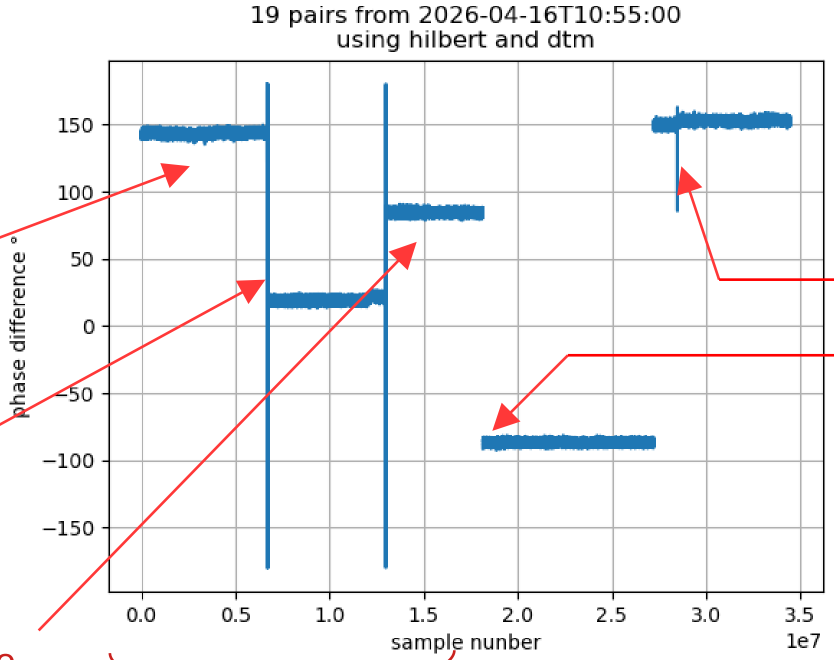


“dtm” method

- This method estimates dt1 and dt2 over many pairs of files (more than 100) by fitting a straight line with a slope of 6048 samples per second to all the time stamps.
- There must be no receiver restart in the time span covered by the files.
- The useable time spans have to be identified beforehand.

“dtm” method – effect of including restarts/reboot

60 cm of RG58 corresponds to 54° of phase shift at 50 MHz



60-cm cable to Rx2

Swapped cables (60cm to Rx1)

Removed 60cm, same cable lengths

No restart or reboot

RPi1 reboot

Rx1 restart

The restart and reboot wreck the dt1 – dt2 estimate hence the offset in phase.

“cal2” method

- A second calibration signal is used (called Ref) at 100 Hz above Cal using the same hardware (splitter and cables).
- The measured phase difference at Cal and Ref frequencies is used to estimate dt1 – dt2

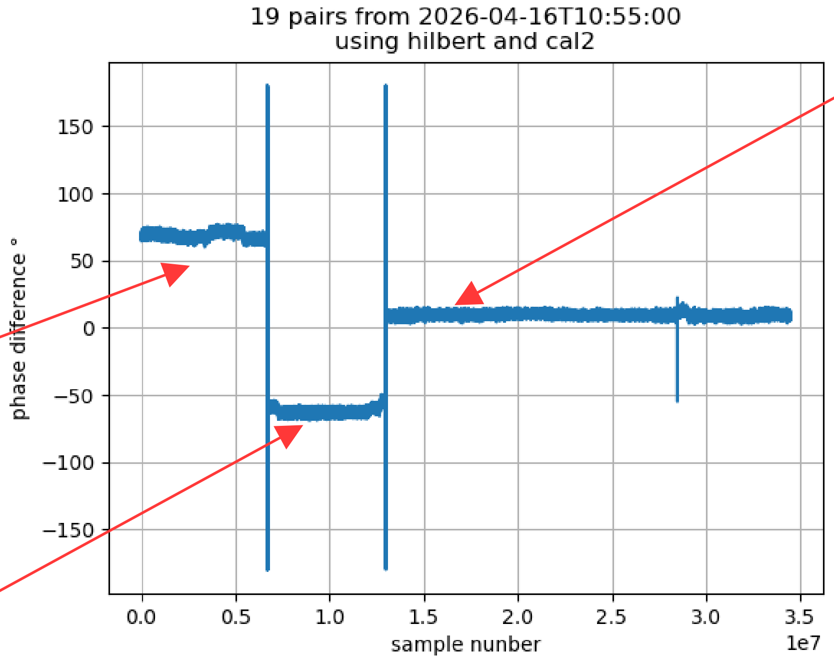
$$\phi_{12cal}-\phi_{12ref}=(\omega_{cal}-\omega_{ref})\cdot(dt_1-dt_2)+\underbrace{(\phi_{cal1}-\phi_{cal2})-(\phi_{ref1}-\phi_{ref2})}_{\phi_{rc}\approx 0}$$

$$dt_1-dt_2\simeq\frac{\phi_{12cal}-\phi_{12ref}}{\omega_{cal}-\omega_{ref}}$$

$$\phi_{b1}-\phi_{b2}=\phi_{12b}-\phi_{12cal}-\frac{(\omega_b-\omega_{cal})}{\omega_{cal}-\omega_{ref}}\cdot(\phi_{12cal}-\phi_{12ref}-\phi_{rc})+(\phi_{cal1}-\phi_{cal2})$$

“cal2” method

60 cm of RG58 corresponds to 54° of phase shift at 50 MHz

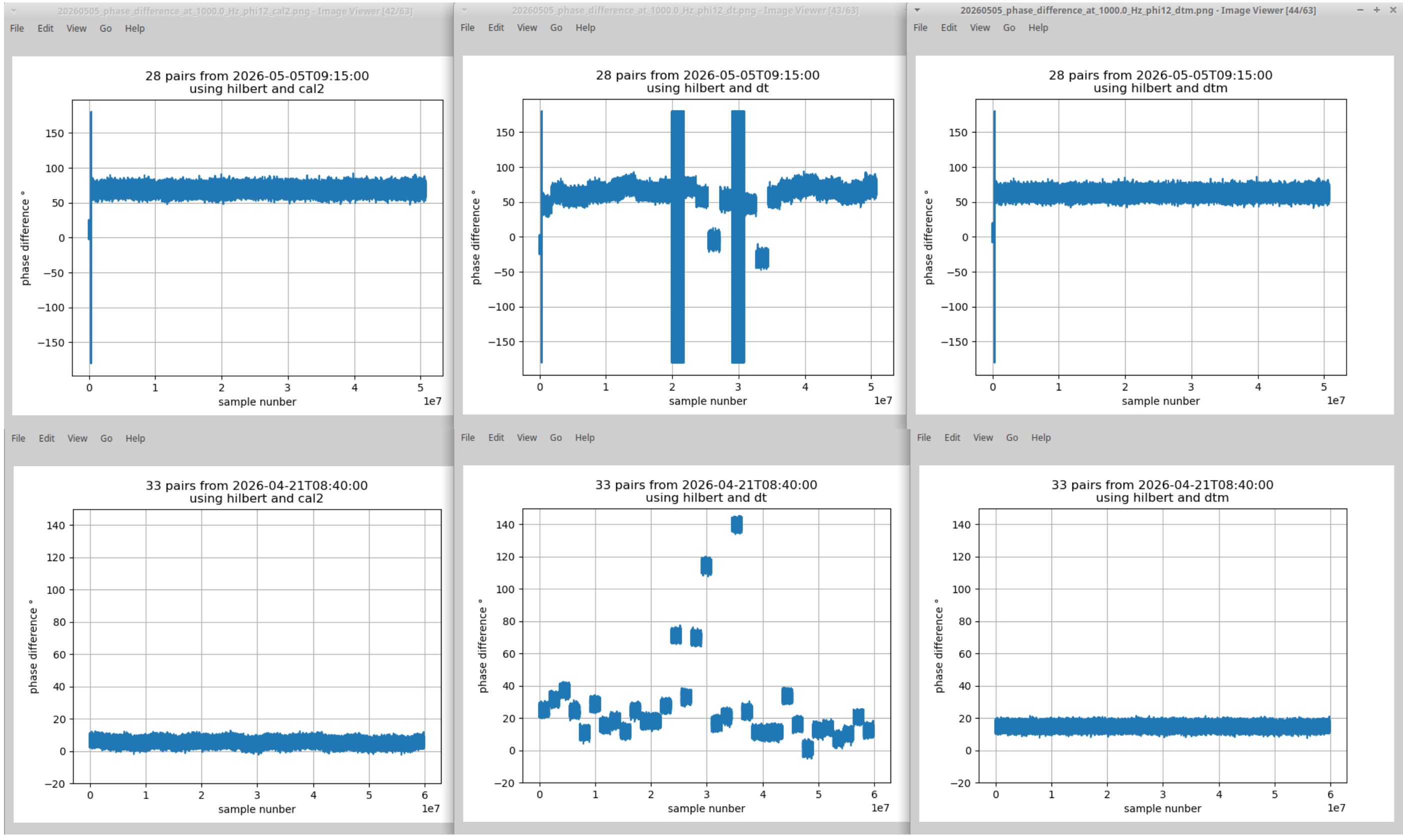


Removed 60cm, same cable lengths

60-cm cable to Rx2

Swapped cables (60cm to Rx1)

Comparison of “dt”, “dtm” and “cal2”



Effect of antenna mismatch

- The antenna feeds tend to degrade with time leading to a poor match.
- This affects the phase of the injected calibration signal through the existing current source injectors.
- Replacing them with directional couplers would mitgate the effect.
- A severely mismatched antenna may also introduce a phase offset in the antenna signal.

→ The antenna mismatch must be monitored.

Selected method

- Of the 5 methods considered only “cal2” and “dtm” showed promising results.
- “cal2” requires only a minor modification of the calclock unit and gives sensible results within the span of a single WAV file.
- “dtm” could be used with existing data once suitable time spans are identifed and provided the antenna match was good enough and stable.