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Incoherent clocking and application to the ngVLA

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Canada

Outline

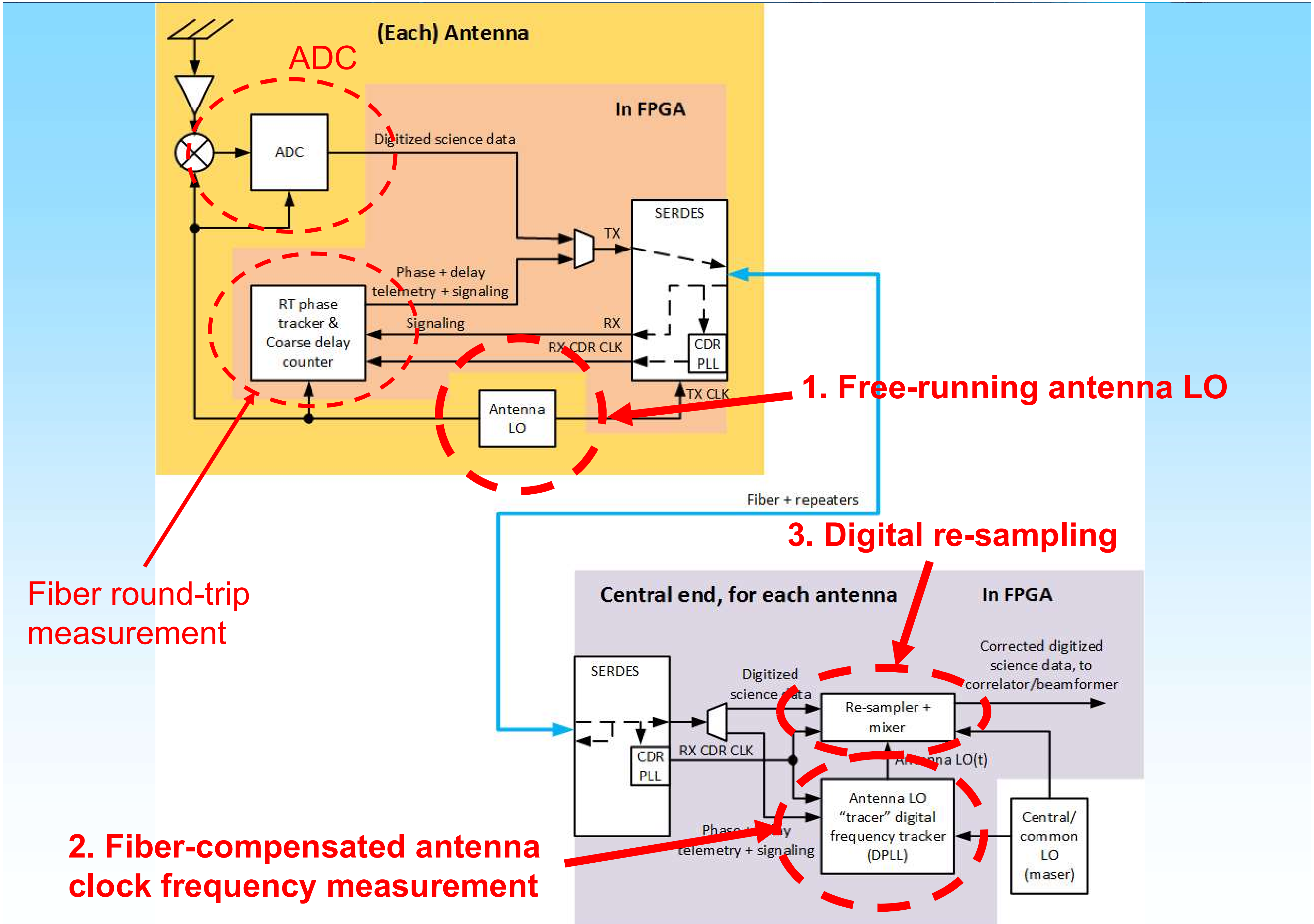
- Concept overview.
- Digital re-sampler.
- Measuring the antenna clock.
- Fiber link issues.
- Lab demonstrator.
- Geostationary satellite referencing?

Concept overview

1. Let each antenna use its own clock for LO/downconversion and digitization, with some constraint on frequency and df/dt, naturally afforded by low-cost oscillators.

2. Accurately and precisely measure each antenna clock's phase and frequency relative to a common clock using all digital methods and COTS digital fiber-optic connections to antennas.
   - *Need to compensate for fiber link variations!*

3. Digitally correct the digitized science data accordingly before correlation/beamforming.

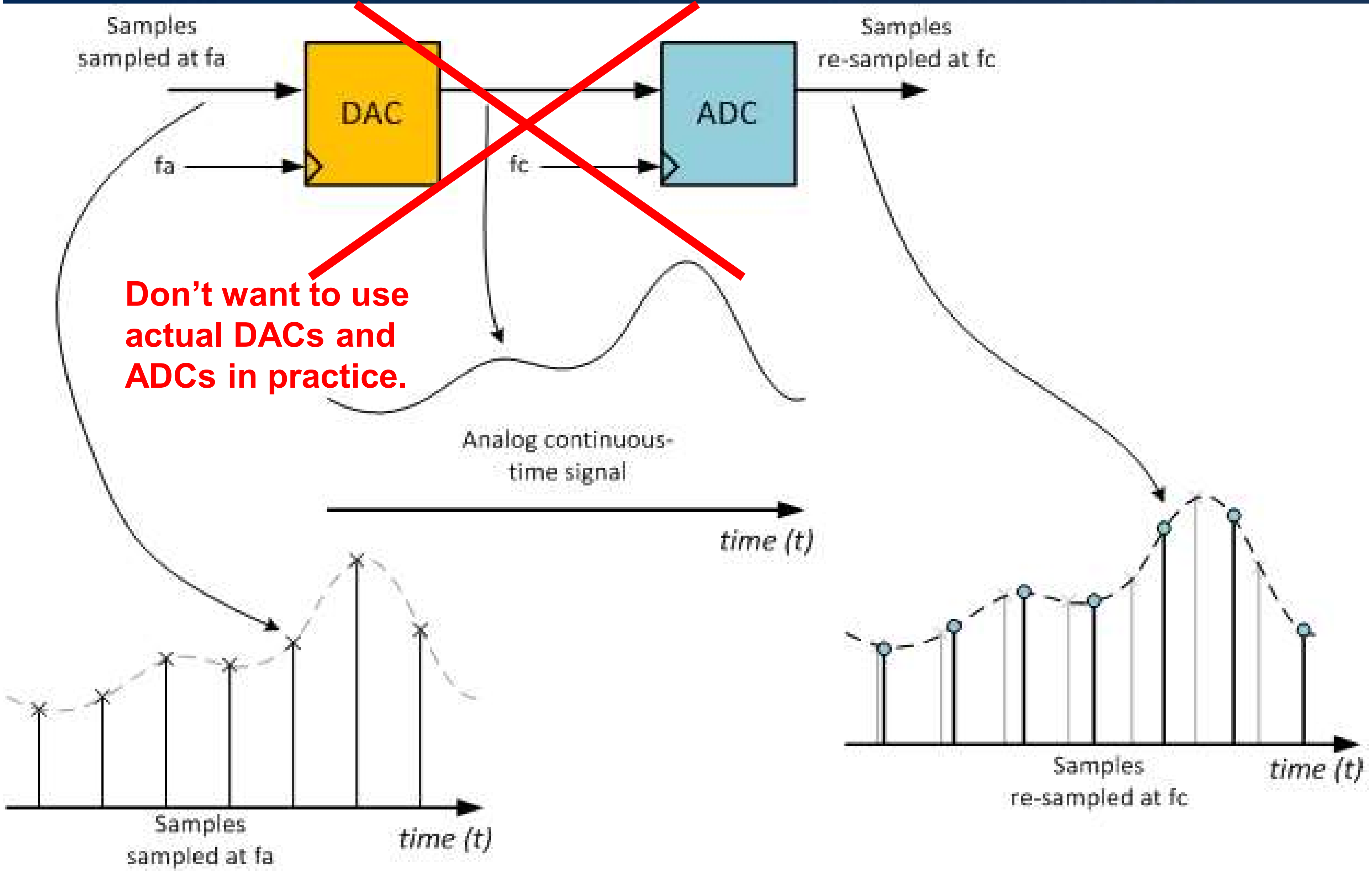

(Each) Antenna
ADC
In FPGA
ADC
Digitized science data
SERDES
TX
Phase + delay
telemetry + signaling
RT phase
tracker &
Coarse delay
counter
Signaling
RX
RX CDR CLK
CDR
PLL
TX CLK
Antenna
LO
1. Free-running antenna LO
Fiber + repeaters
3. Digital re-sampling
Fiber round-trip
measurement
Central end, for each antenna
In FPGA
Corrected digitized
science data, to
correlator/beamformer
SERDES
Digitized
science data
Re-sampler +
mixer
CDR
PLL
RX CDR CLK
Antenna LO(t)
Antenna LO
"tracer" digital
frequency tracker
(DPLL)
Central/
common
LO
(maser)
Phase + delay
telemetry + signaling
2. Fiber-compensated antenna
clock frequency measurement

Concept overview

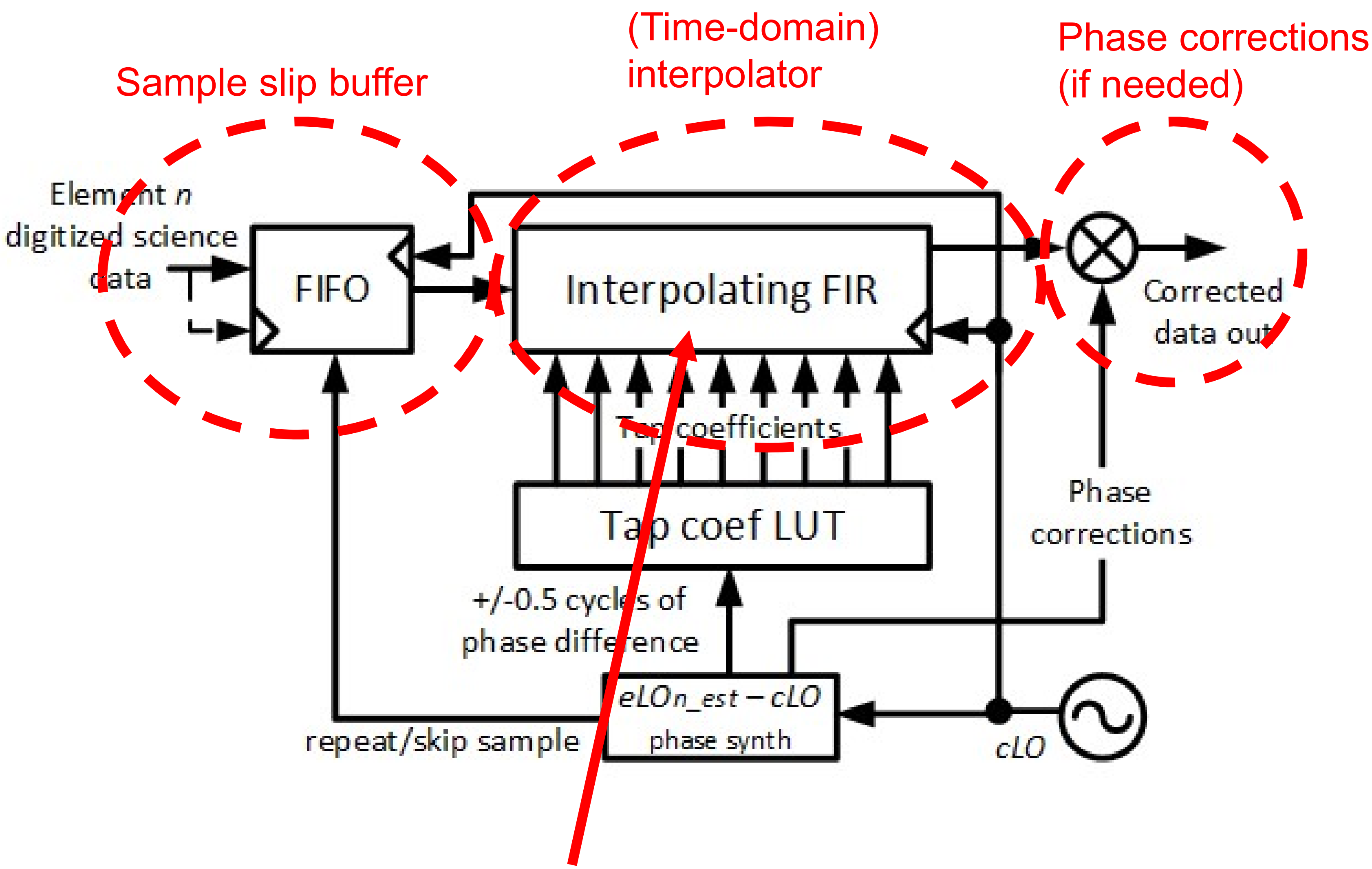
- **Goal for ngVLA:** *Coherent operation of the **entire** array with no limit on baseline length, using all digital methods and COTS components, with no separate round-trip LO distribution system.*

Digital re-sampling

- Digital re-sampling is equivalent to a DAC/ADC operation.
- It is also equivalent to a sliding delay operation…something we're all used to doing.
- To do this the sample rate into the DAC must be known (relative to the ADC clock).
- Background:
  - *Digital re-sampling used in SKA1 Mid.CBF to facilitate Mid telescope Sample Clock Frequency Offset (SCFO) sampling for RFI robustness.*
  - *Ergo: why not just let each antenna use its own free-running clock, measure it, then digitally re-sample?*



Don’t want to use actual DACs and ADCs in practice.



Could instead perform **phase-delay after a poly-phase filterbank** if the sample frequency differential is << a filterbank channel width.

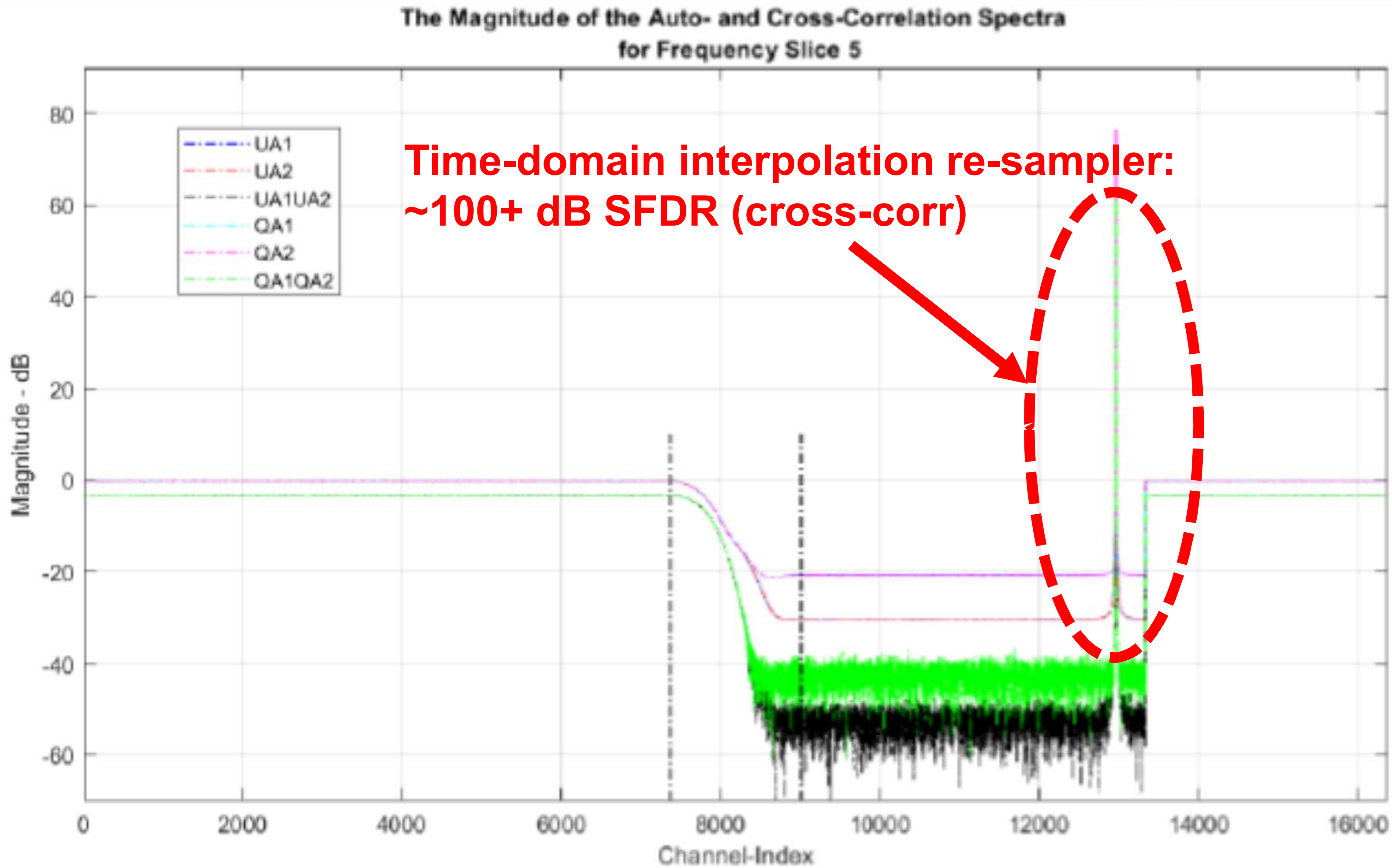


Figure 6-50 Magnitudes of fine channel auto- and cross- correlations for 1.4 s of integration evaluated with the realizable model – with a strong RFI source.

Re-sampling in the ngVLA Trident CBF ref design

- In the "Trident" CBF, integrate the re-sampler into the VCC and FSP, requiring no additional hardware to do so (*I claim…modeling to confirm!*):
  - VCC: super-sample rate on-chip delay slip buffer before (or after) the bulk coarse delay.
  - The residual (fine) interpolation delay is a delay (and phase) error function that is carried with the data thru the VCC-OSPPFB and applied in the FSP Frequency Slice Re-Sampler+mixer.

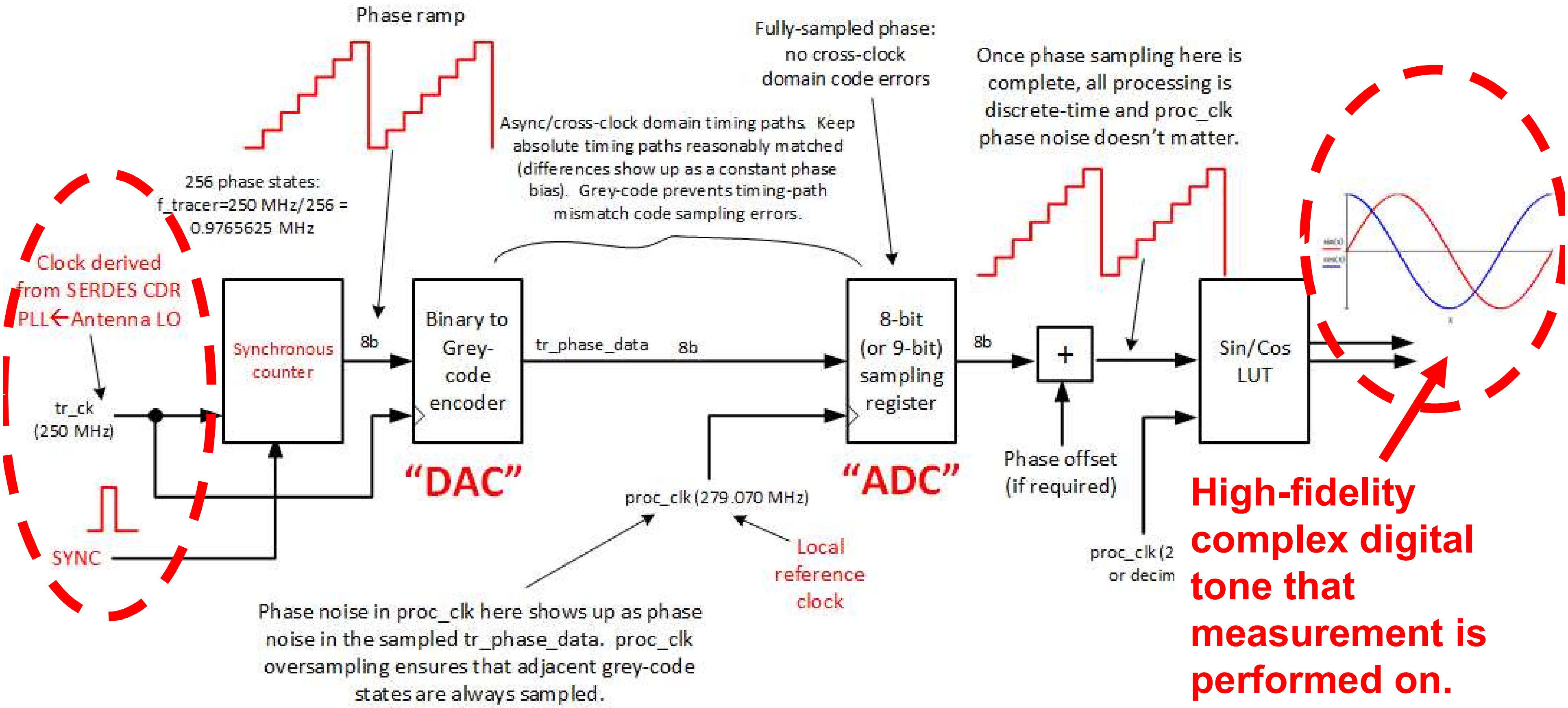
Measuring the antenna clock

- Transfer signaling for a trace frequency ("tracer") of the antenna clock across a digital link.

- At the central/common site, transfer the tracer from the antenna to the common clock domain, with digital **phase sampling**.

- All operations and the tracer link must retain antenna digitizer clock frequency variations.

Digital tracer generation and phase transfer across clock domains



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Fiber link issues

- Fiber length variations must be measured and removed, so that a measure of only the antenna clock frequency variations are determined. i.e. the fiber-induced variations are not intrinsically in the digitized science data.

- This is done via round-trip phase measurements of the tracer.

Fiber link issues

- Longer fiber means the natural frequency of the round-trip drops, which means we can’t rely on fast round-trip measurements to correct for link variation effects.

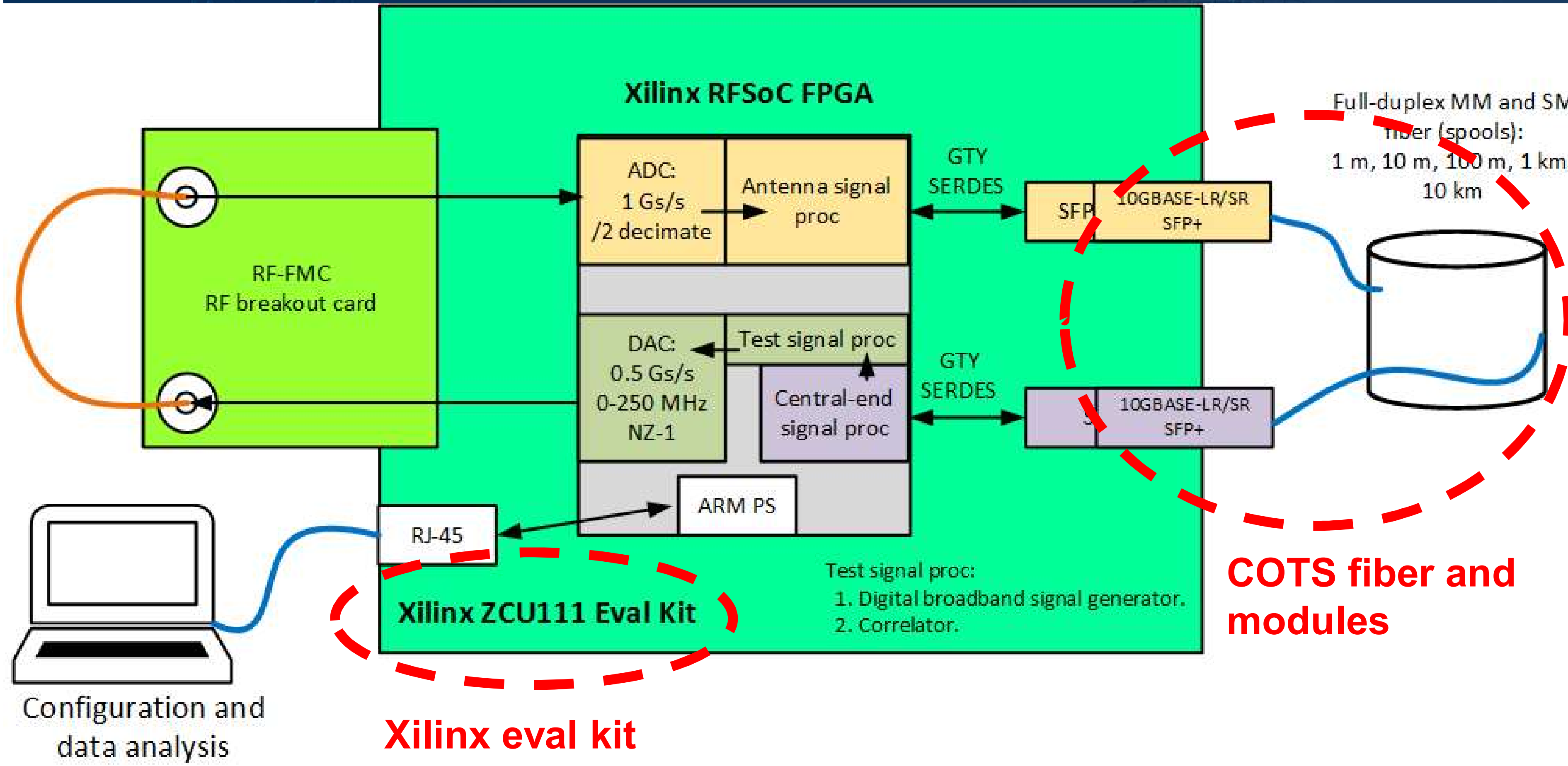
- Therefore:

  Use a more stable antenna clock so we can (digitally) filter out fast link-induced tracer phase/frequency variations we know are not intrinsic to the antenna clock.

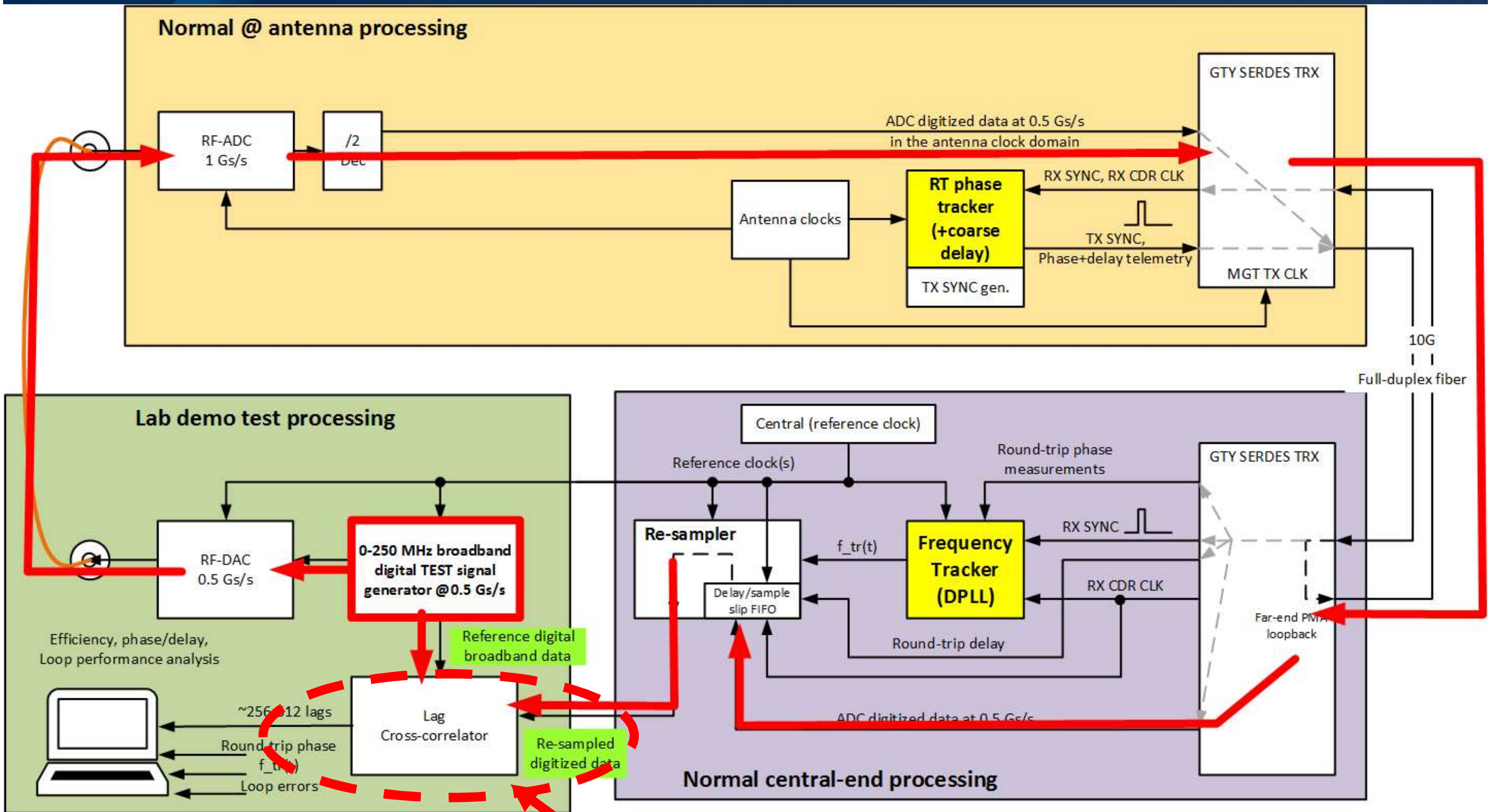
Laboratory demonstrator

- Show how all this fits together in practice by going through the lab demo design, current state, and some early RTL modelling results.
- Several parameters are based on what would work for a potential PT-VLA on-sky test and what is easiest for a first lab demonstrator:
  - In-band tracer, 10G full-duplex serial link.
  - Direct sample-rate processing, keep digitizer sample rate ~<=500 MHz (PT-VLA = 4 x 500 MHz-1000 MHz I/Fs).

Lab demo: hardware set up

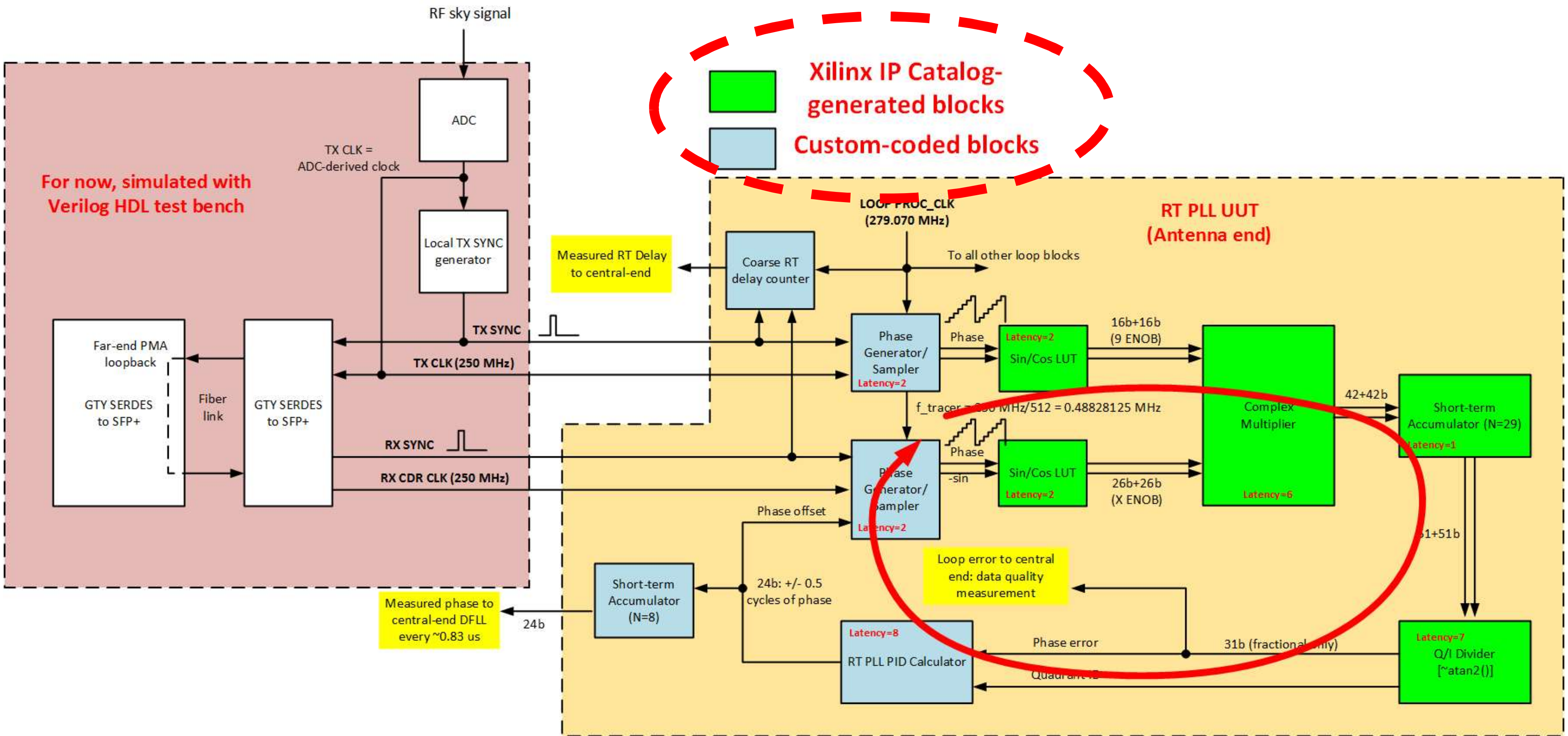


Lab demo: signal processing set up



Correlate→quality measurement

RT phase tracker + coarse delay counter



Fully synthesizable RTL model of all of this has been coded and functionally tested.

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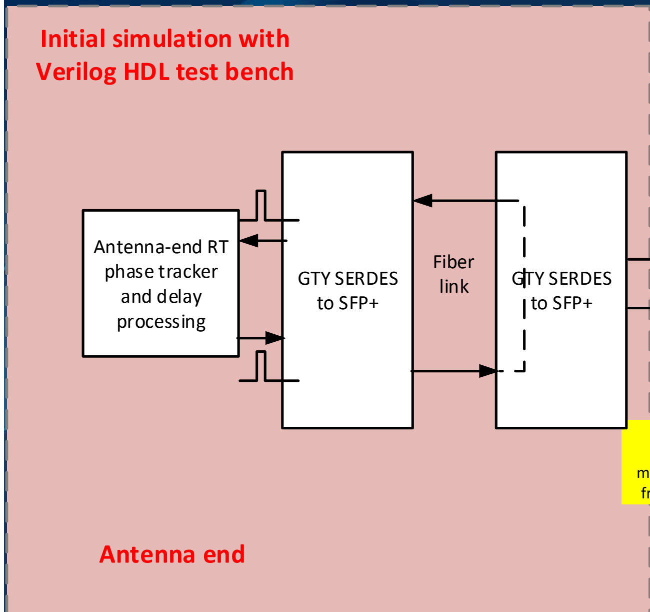
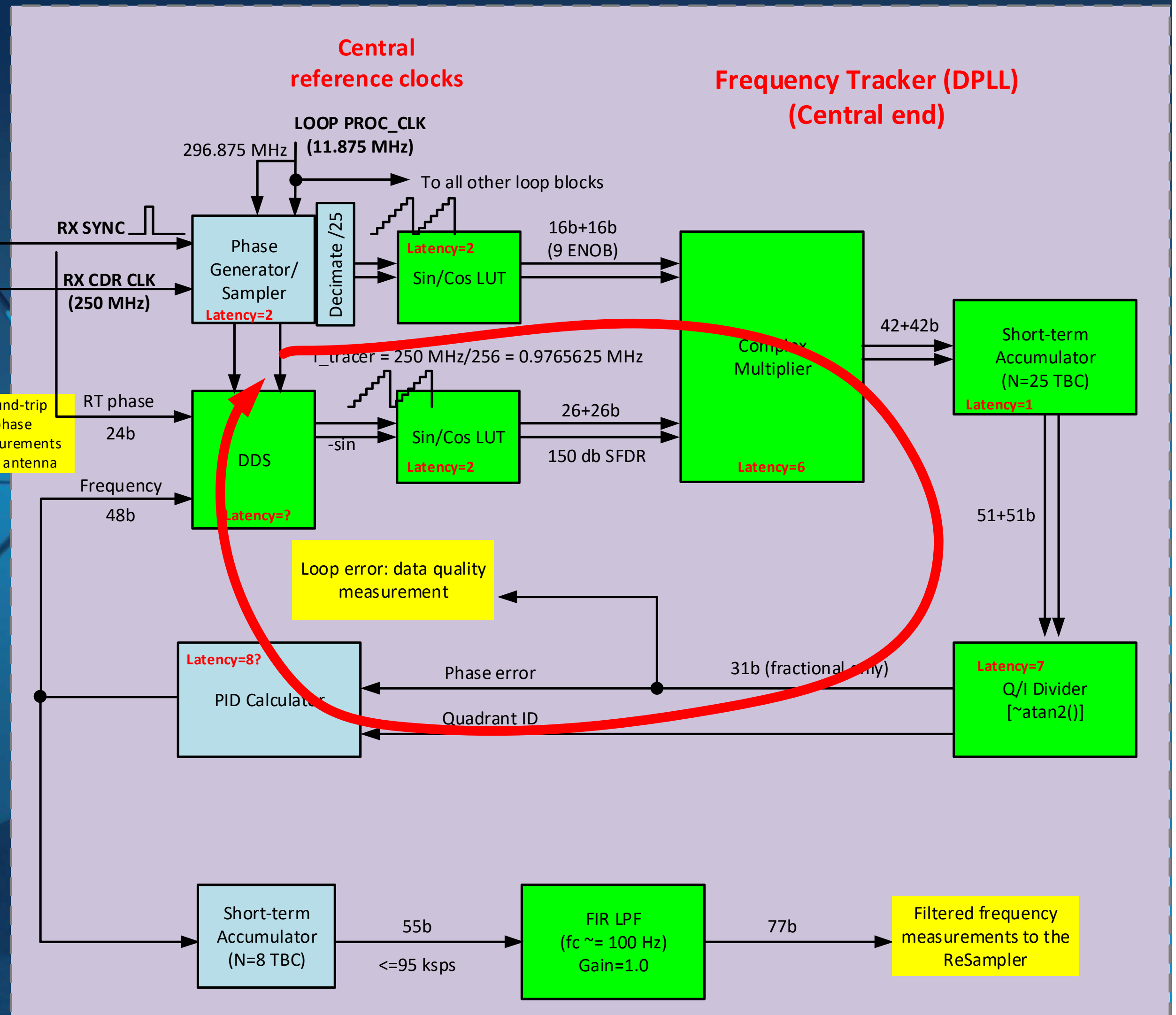
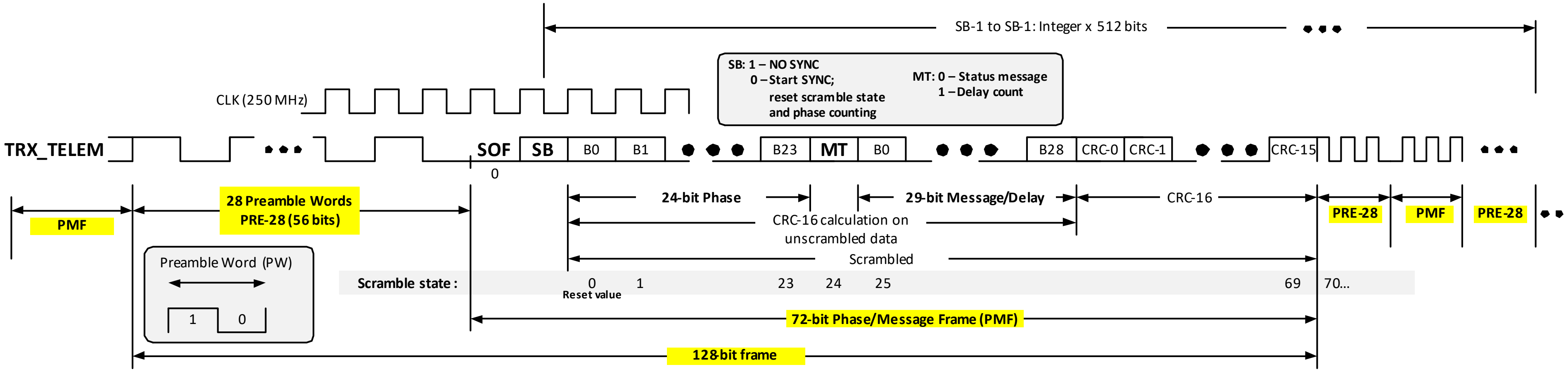
Frequency Tracker (DPLL)





RTL coding and testing in progress.

Lab demo telemetry protocol: tracer signaling and RT phase (and delay) tx from antenna to central site



For <u>ngVLA unformatted data stream</u>, "**bit steal**" an LSBit every ~100 samples (@7 Gs/s=>70 Mbps channel) => 1 telemetry frame every ~2 usec—should be more than sufficient.

After frame extraction, just do random scrambling of that LSBit before further re-sampling, correlation/beamforming…virtually nil impact on sensitivity & won't correlate.

Inherently performs framing and error checking on the unformatted data stream.

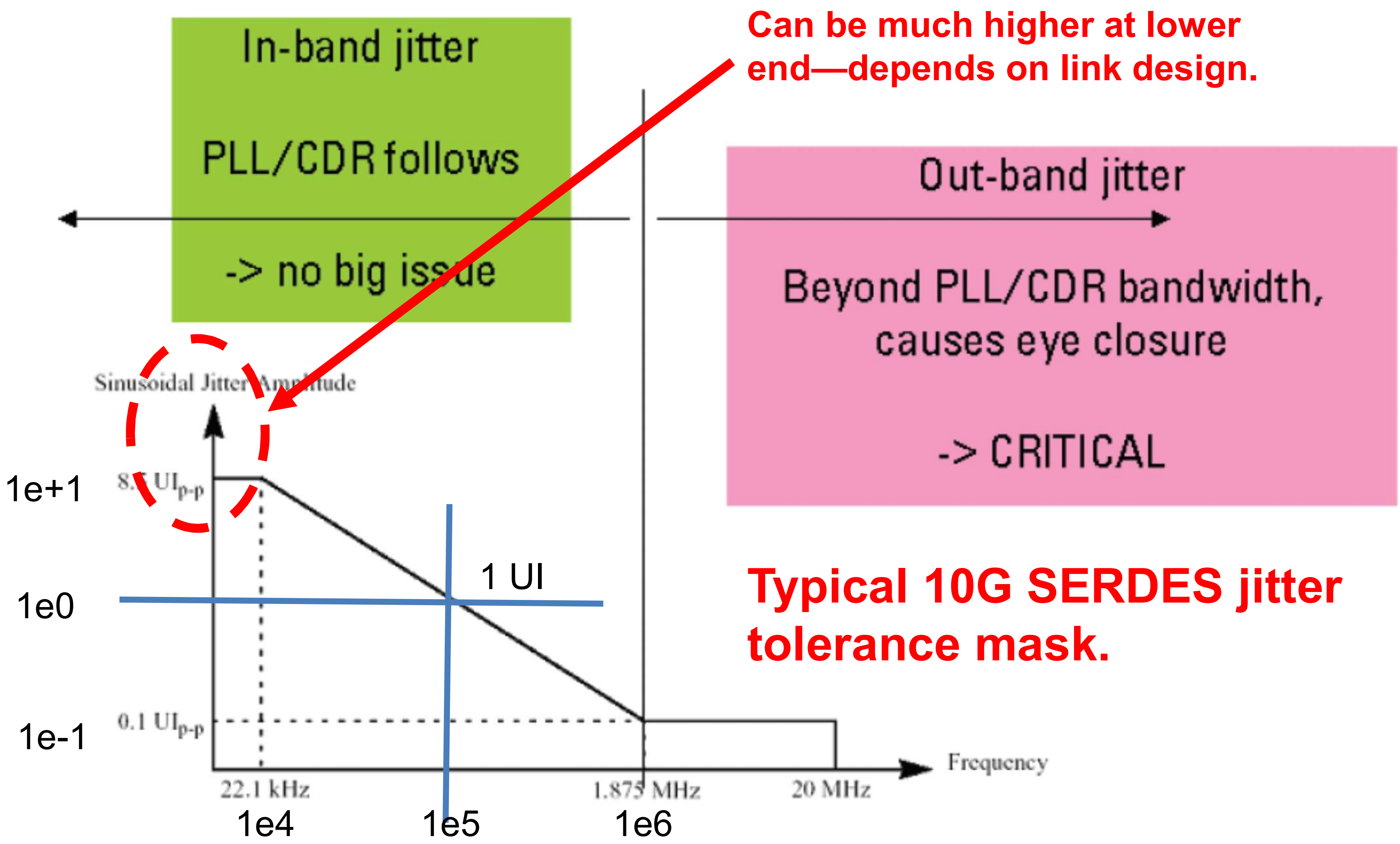
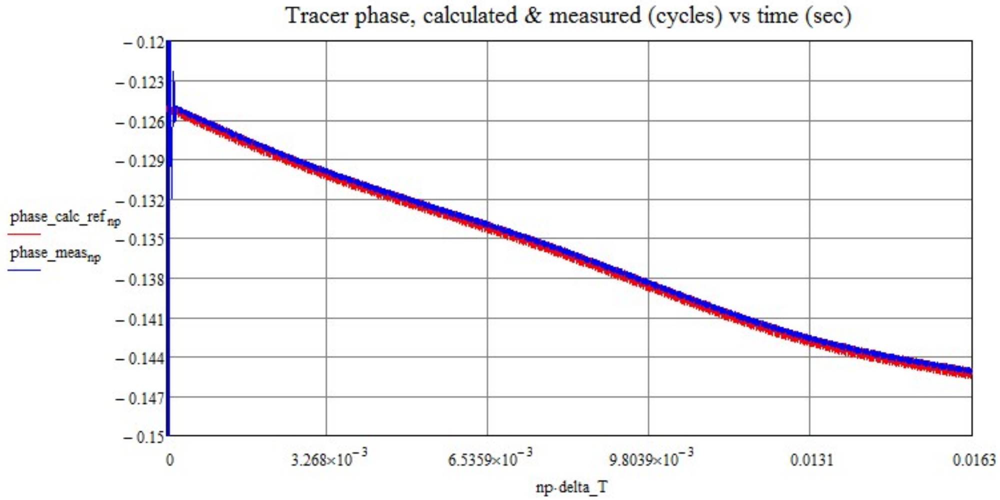
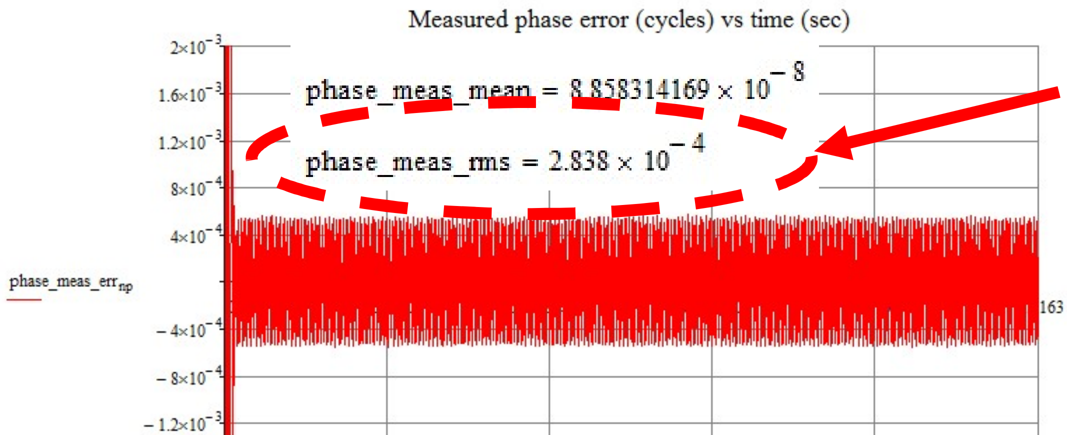
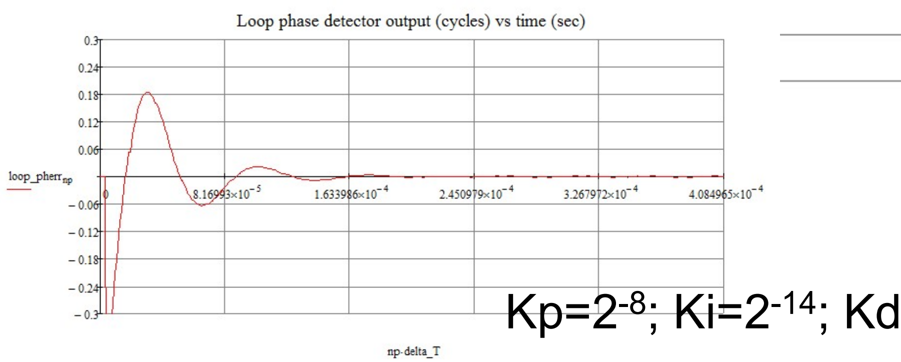


Figure 47–5—Single-tone sinusoidal jitter mask







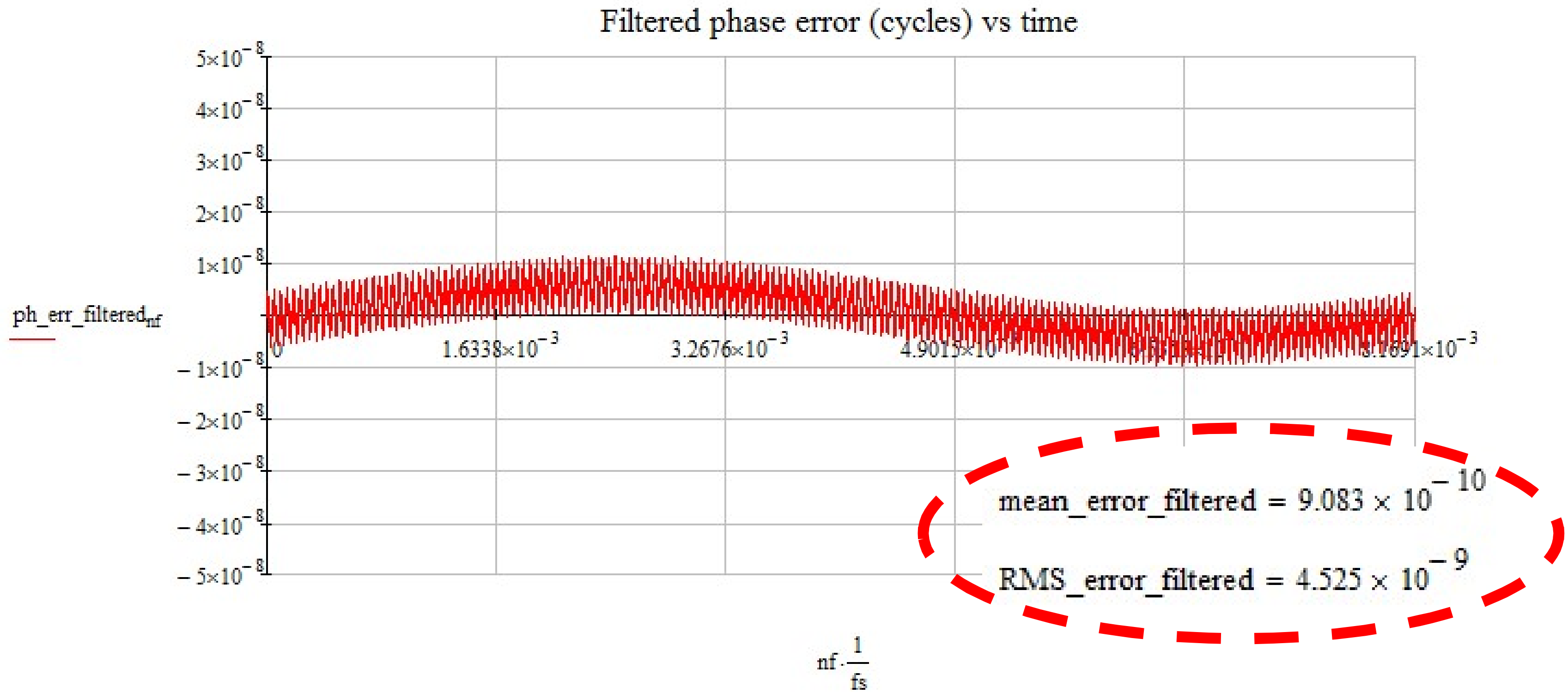
RT phase tracker fully synthesizable RTL model:

Link jitter simulation
(1 UI=1 bit @10G):

- 10 Hz: 1000 UI
- 100 Hz: 15 UI
- 22.1 kHz: 8.5 UI
- 100 kHz: 1 UI

Too high—but not intrinsically in the antenna LO, so can filter out.

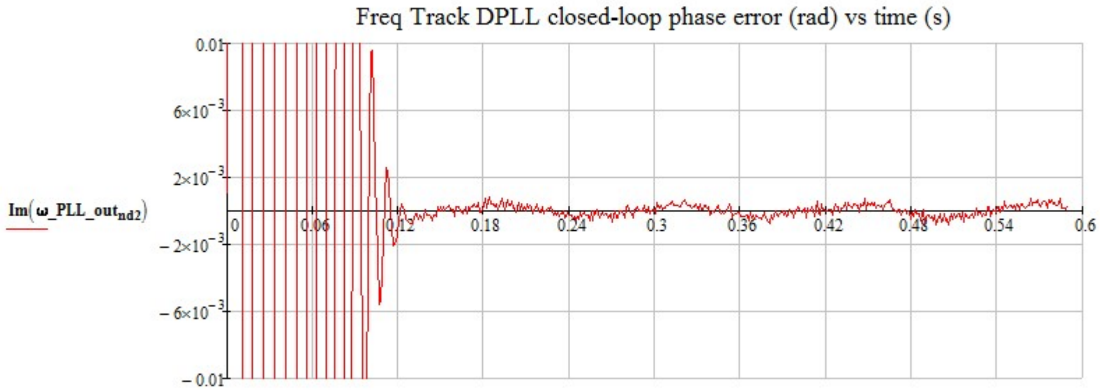
$K_p=2^{-8}$; $K_i=2^{-14}$; $K_d=2^{-8}$

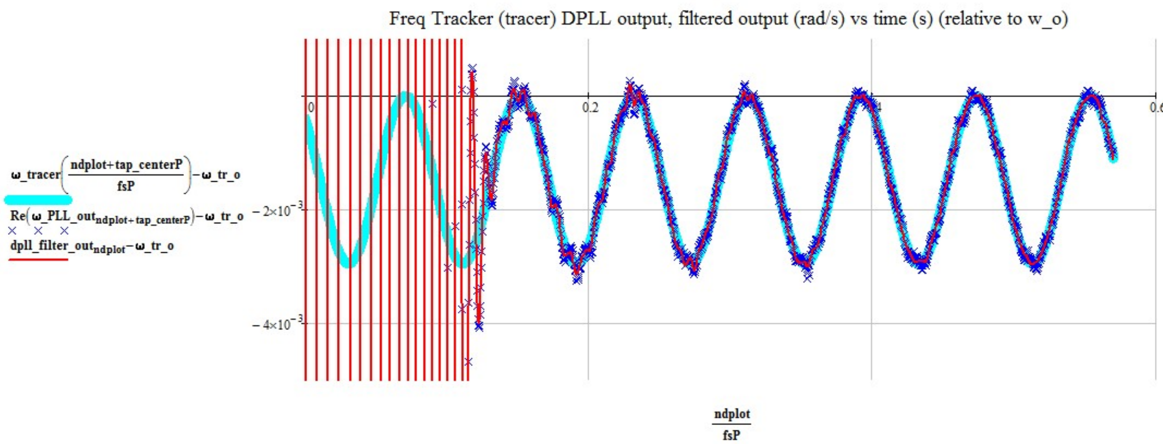


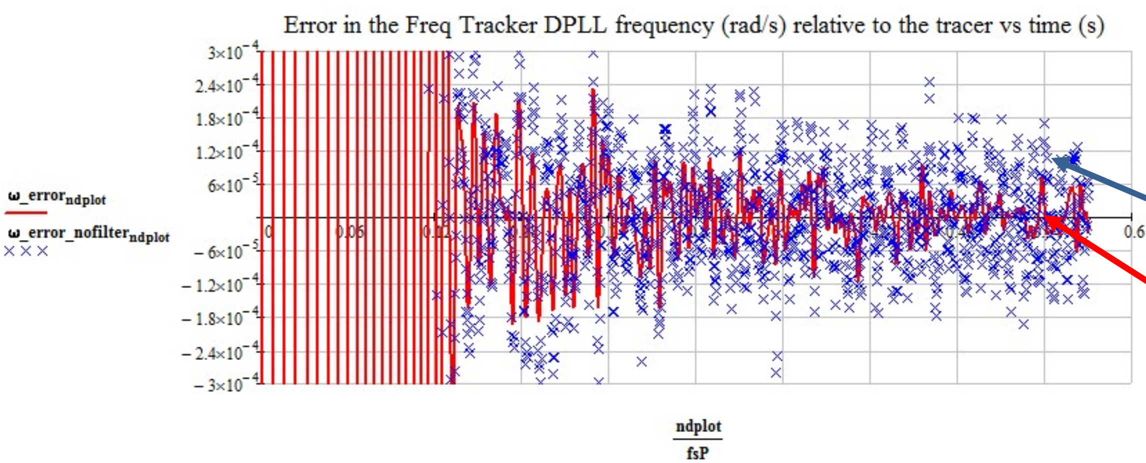
After 200 Hz FFT LPF (-60 dB reject band) of the error (simulating the LPF after the Frequency Tracker DPLL—the actual LPF could do much better).

RMS phase error of ~1e-8 cycles at ~0.5 MHz tracer, translates to an RMS phase error (i.e. uncertainty in our knowledge of it) of ~1e-4 cycles for a 10 Gs/s digitizer…more than enough for >10 ENOB in the Re-Sampler.

This translates to an uncertainty in our knowledge of an ngVLA 116 GHz LO of ~0.8 degrees RMS.







Mathcad modeling of the **Frequency Tracker DPLL**. Includes discrete-time effects except phase-sample bus skew.

This is a much faster rate of change of the tracer frequency than would be seen in practice.

After post-loop LPF:
Avg error: 5e-6 rad/s->7e-7 rad drift over the averaging time (last ¼ of simulation).

RMS error: 3e-5 rad/s->3e-10 rad drift over update period of 10 usec.

Before LPF

After LPF

Geostationary satellite referencing?

- Have applied for an NRC post-doc position to investigate using geostationary satellite(s) carrier tone(s) as fiducial references for measuring non-maser antenna clocks' phase/frequency vs time.

- Question: can this method provide longer coherence time than H-masers at ngVLA out-stations not connected to central via real-time fiber? Key issues:
  - (1) Are differential atmospheric effects, **that can't be separated from antenna LO behavior, *and that are a significant factor*** in the measured $f_{sat\_tone}(t)$ a show-stopper?
  - (2) Can the **differential Doppler due to satellite motion**, as seen by each station, be calibrated-out without an uplink? *(EVLA Memo 36, Barry Clark, 2002)*

- Some X-band satellite tone φ vs time data from the VLA, 20 km baselines, indicates the method has promise (provided by Vivek Dhawan, NRAO).

Summary

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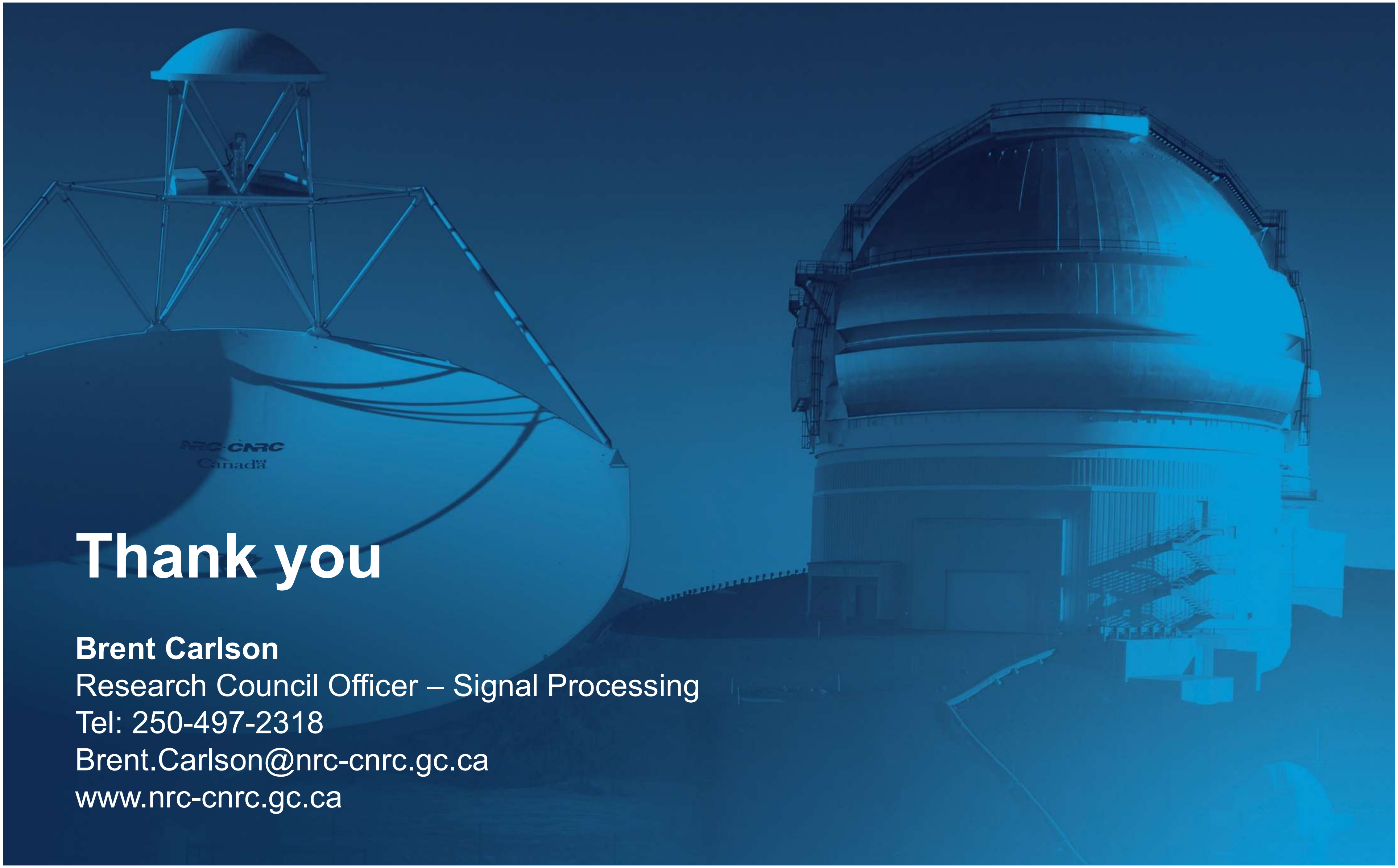

Thank you

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