SKA Engineering Research at The University of Calgary and The University of Victoria

by Len Bruton, Jim Haslett, Leo Belostotski, Pan Agathoklis

University of Calgary/University of Victoria

Presented by Garey Hovey at SKA Workshop, Manchester, England, March 2010

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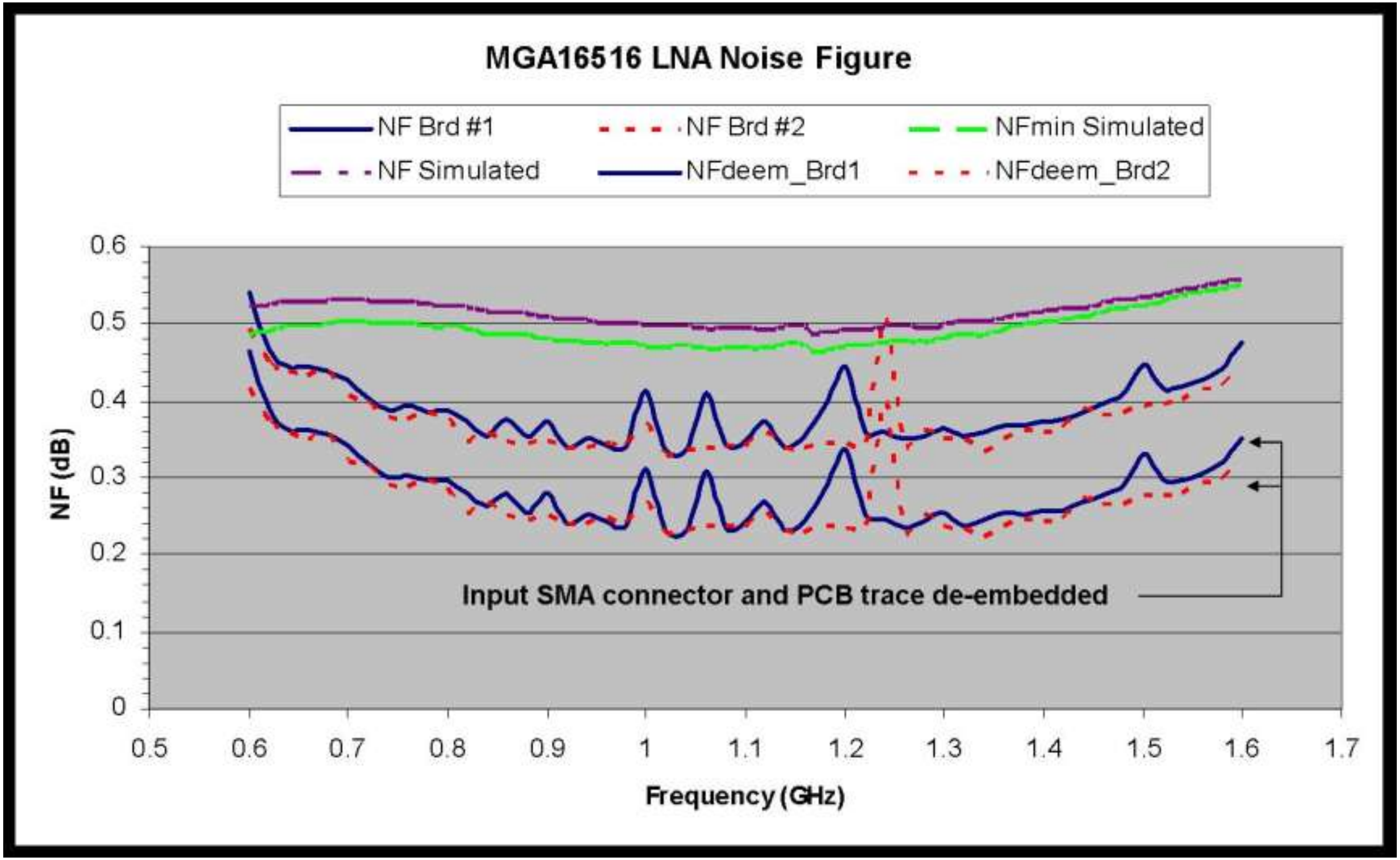
The current focus of SKA engineering research at the University of Calgary and the University of Victoria is the SKA mid-frequency range (0.7 – 2 GHz) and is in the following three areas:

1. **Low Noise Amplifiers (LNAs): Receiver Design and Fabrication** (Univ of Calgary and DRAO Penticton) - Leo Belostotski, PI
2. **A/D converters at GS/s** (University of Calgary) - Jim Haslett, PI
3. **Attenuation of LNA Noise, Mutually-coupled FPA Noise Reduction and Radio Frequency Interference (RFI)** (University of Calgary and University of Victoria) - Len Bruton and Pan Agathoklis, PIs

Summary of Recent Progress in Fabrication and Measurements

3. **Designed discrete LNA with Avago's MGA-12516 and MGA-16516**
   a. Reported measurements were made with the noise source that produces the highest noise figures (next slide)
   b. Forwarded two LNAs for tests at DRAO → Plan is to place two of these LNAs on the DRAO observatory telescope in Penticton during 2010
4. **Started Work on an Integrated Receiver and Antenna integration**
   a. Test chips sent for fabrication in July 2009 and December 2009
   b. Tests started on gain stage in 90nm CMOS
   c. Analyzed/Measured noise contributions from bond pads, bond wires, interconnects to LNA noise → Should be able to shave off ~5K to 10K of noise with improved designs
5. **Started work on noise source calibration**
   a. Calibrated four noise sources against a cryogenic noise source

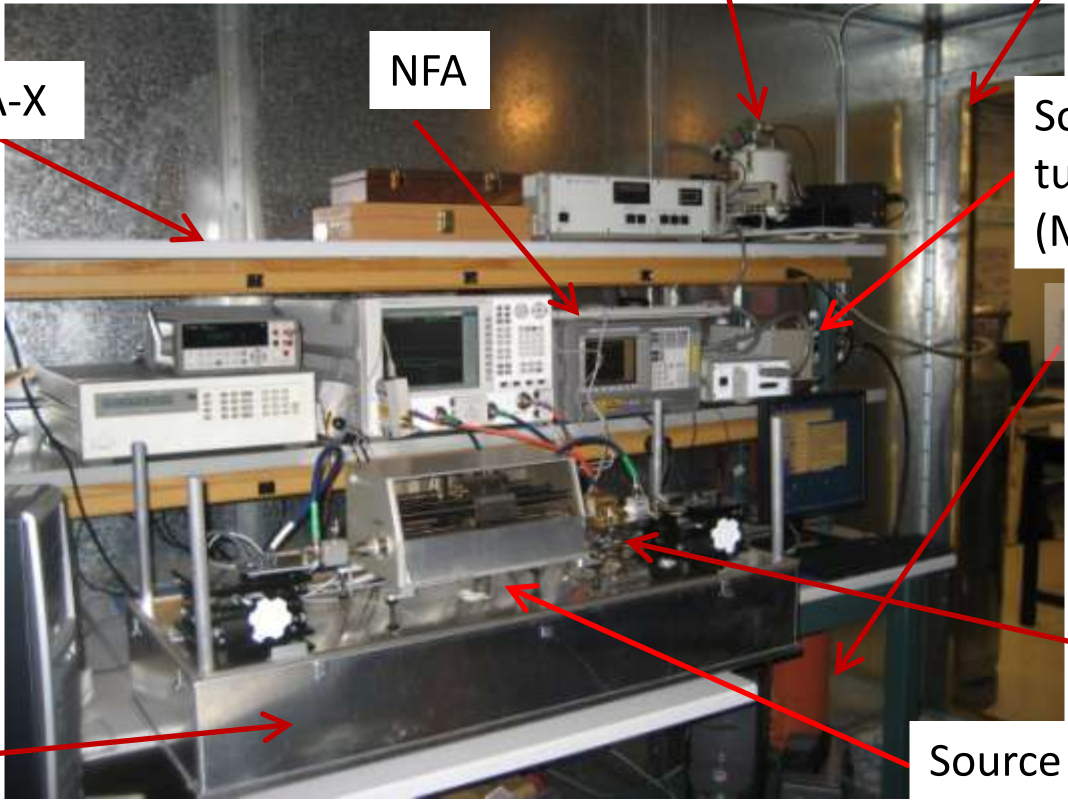
LNA Noise Figure Measurements 2009



The LNA Noise Measurements System 2009

University of Calgary

1. Built a noise parameter measurement system
2. This system is used in our measurements



Tri-state noise source

LN2 (outside on this photo)

NFA

PNA-X

Source tuner (Maury)

Helium

LNA

Shielded box

Source tuner (Focus)

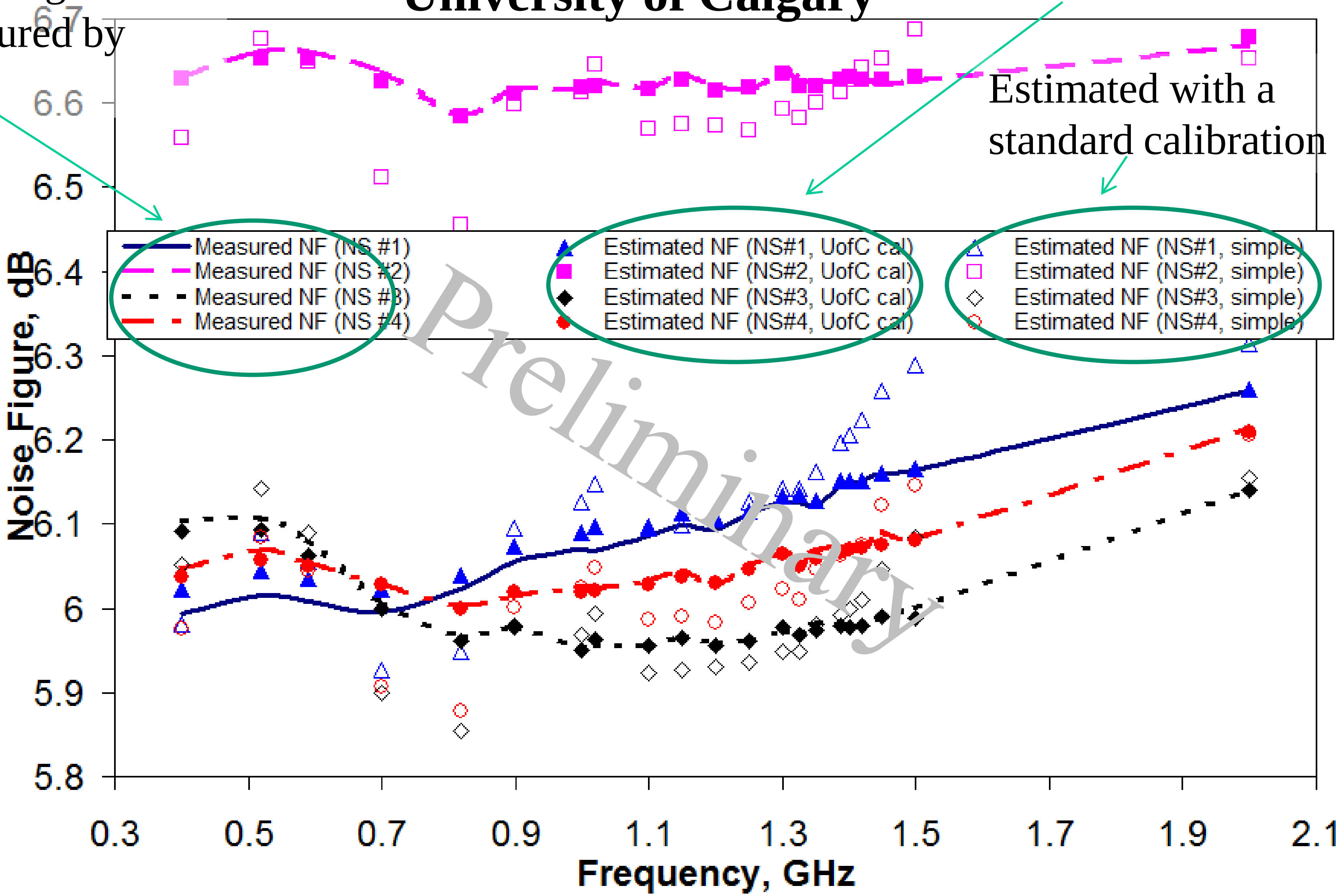
Noise source calibration

University of Calgary

Noise figures measured by NFA

Estimated with UofC calibration

Estimated with a standard calibration



AREA TWO: Time-Based Multi-Bit, Multi-GS/s Analog-to-Digital Converters and SerDes Data Communications

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Flash versus Time-Based ADCs

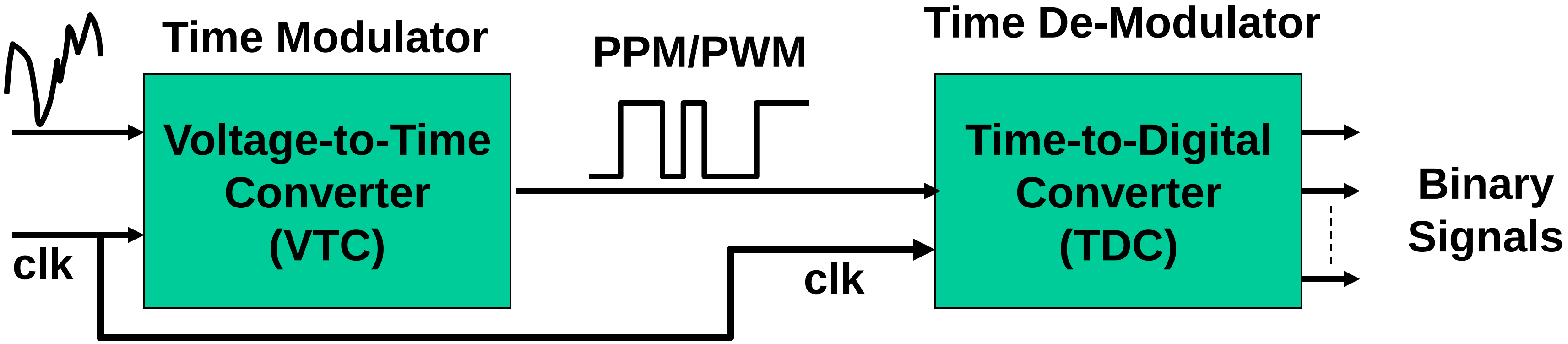
Flash ADCs:

- Flash architecture is logical choice for single-channel GS/s conversion rates at low power.
- An n-bit ADC using a simple flash architecture requires 2^n-1 comparators.
- Complexity/power consumption increases rapidly beyond 5 bits at GS/s sample rates.
- Performance degrades as technology scales because of smaller step size due to lower supply voltage.
- Architecture lends itself to digital self-calibration.

Time-Based ADCs:

- Time-based ADCs scale linearly with the number of bits.
- Complexity is reasonable even at higher resolution and high sample rates. Result is very small footprint and low power consumption.
- Performance improves as technology scales because time resolution increases with scaling.
- Architecture also lends itself to digital self-calibration.

Time-Based ADCs



Time Modulator

Voltage-to-Time Converter (VTC)

PPM/PWM

Time De-Modulator

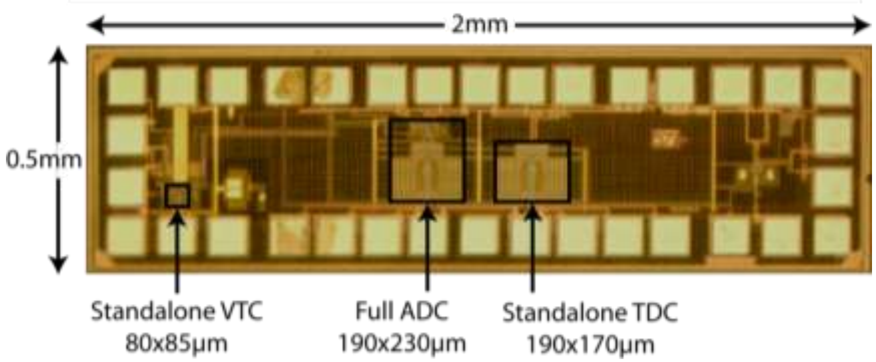
Time-to-Digital Converter (TDC)

clk

clk

Binary Signals

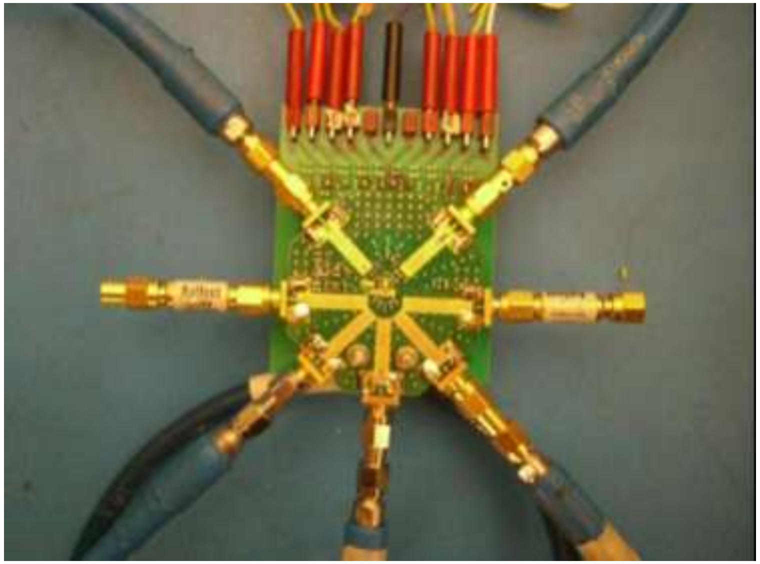
Example: 3 bit 5GS/s ADC in 90nm CMOS:

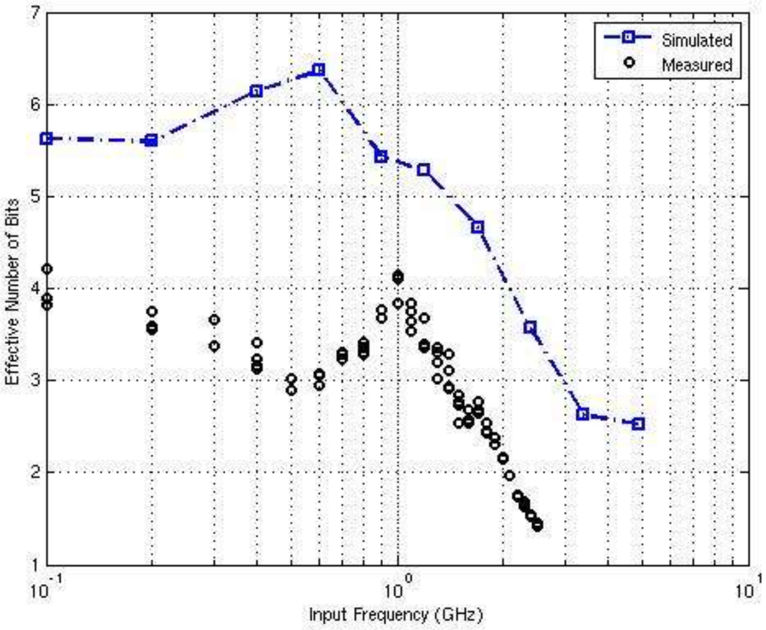


- Combines VTC with TDC
- Second silicon run
- Both circuits functional, ADC testing underway
- Power consumption < 20mW

VTC Measurements

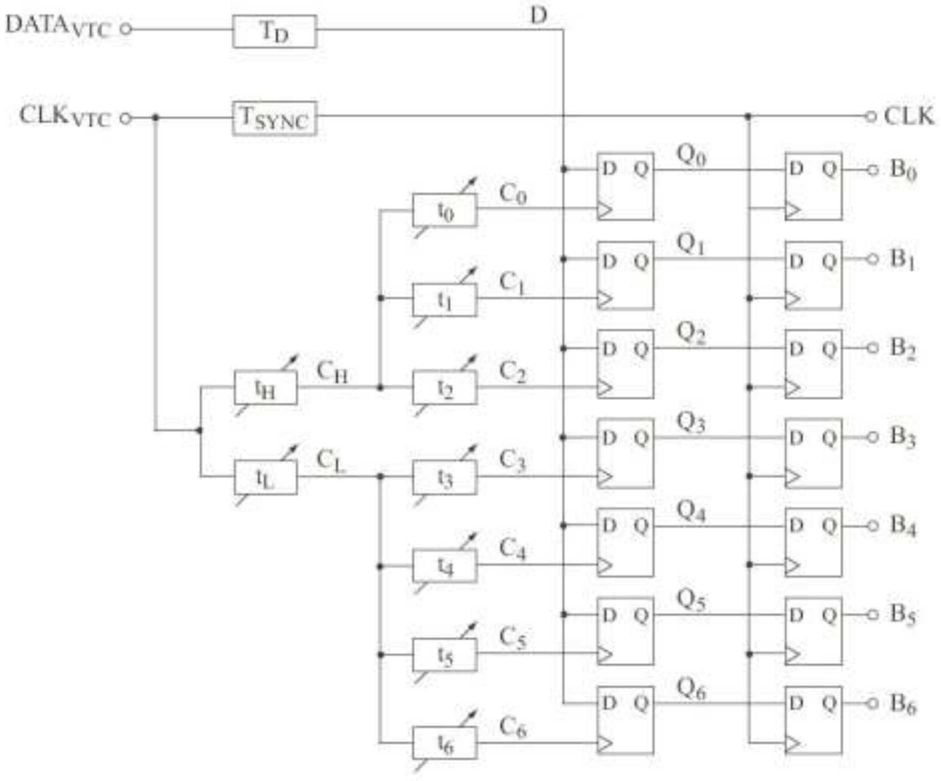
- Second silicon still has some track/hold issues
- Achieves 1.4 GHz input bandwidth at > 3 ENOB without track-and-hold so OK for 3-bit TDC (measured SNR used to calculate ENOB may be degraded by power supply noise, this is being investigated)
- Self-calibration circuitry being designed
- Some new VTC ideas being pursued

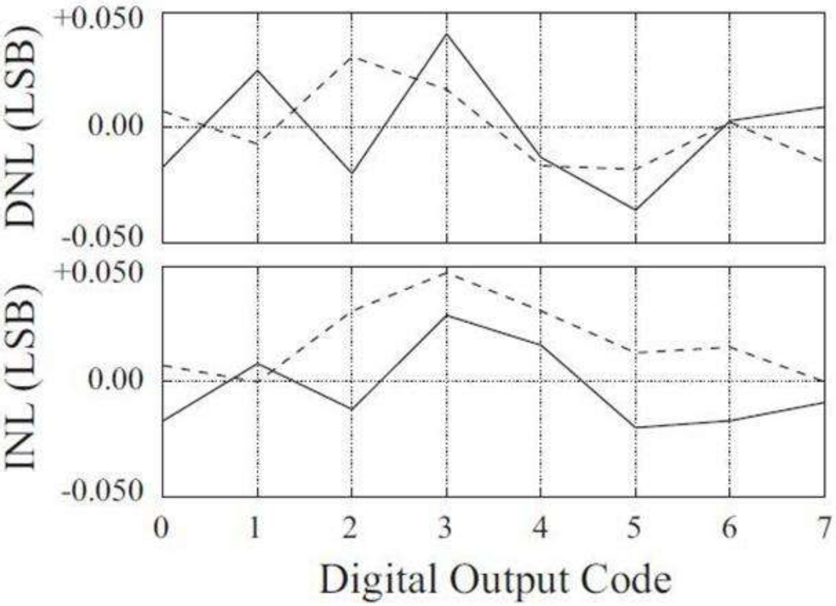




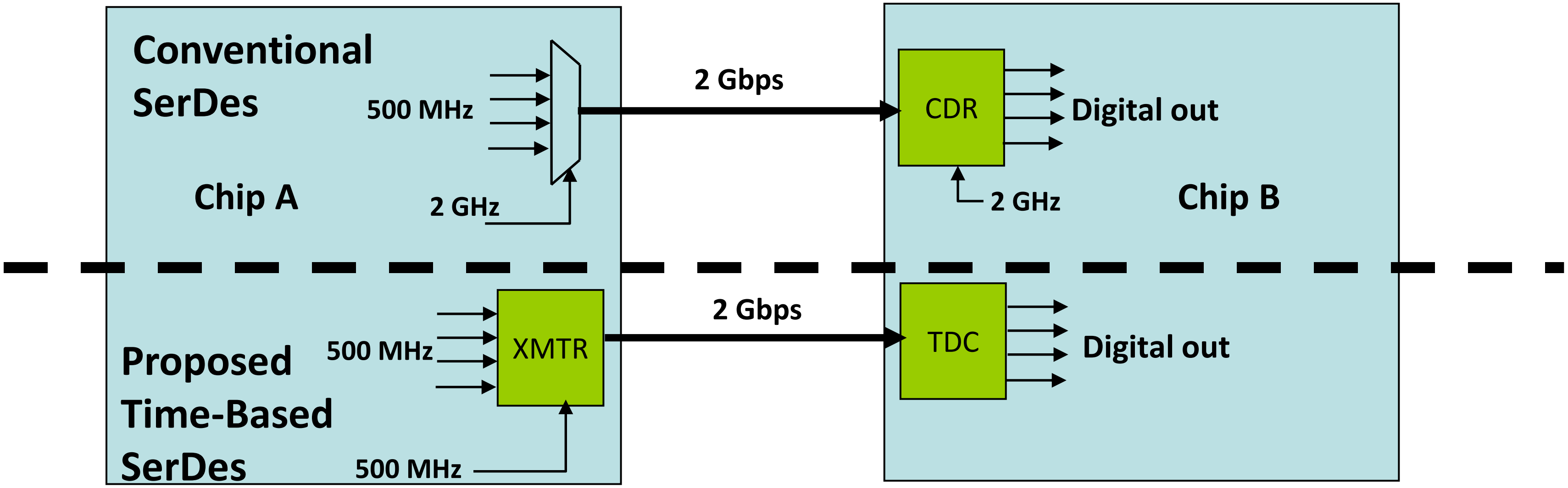
TDC Measurements

- Second 90nm CMOS run successful
- Digitally programmable delays
- Very small INL/DNL at 3 bits after calibration
- Self-calibration circuitry being designed



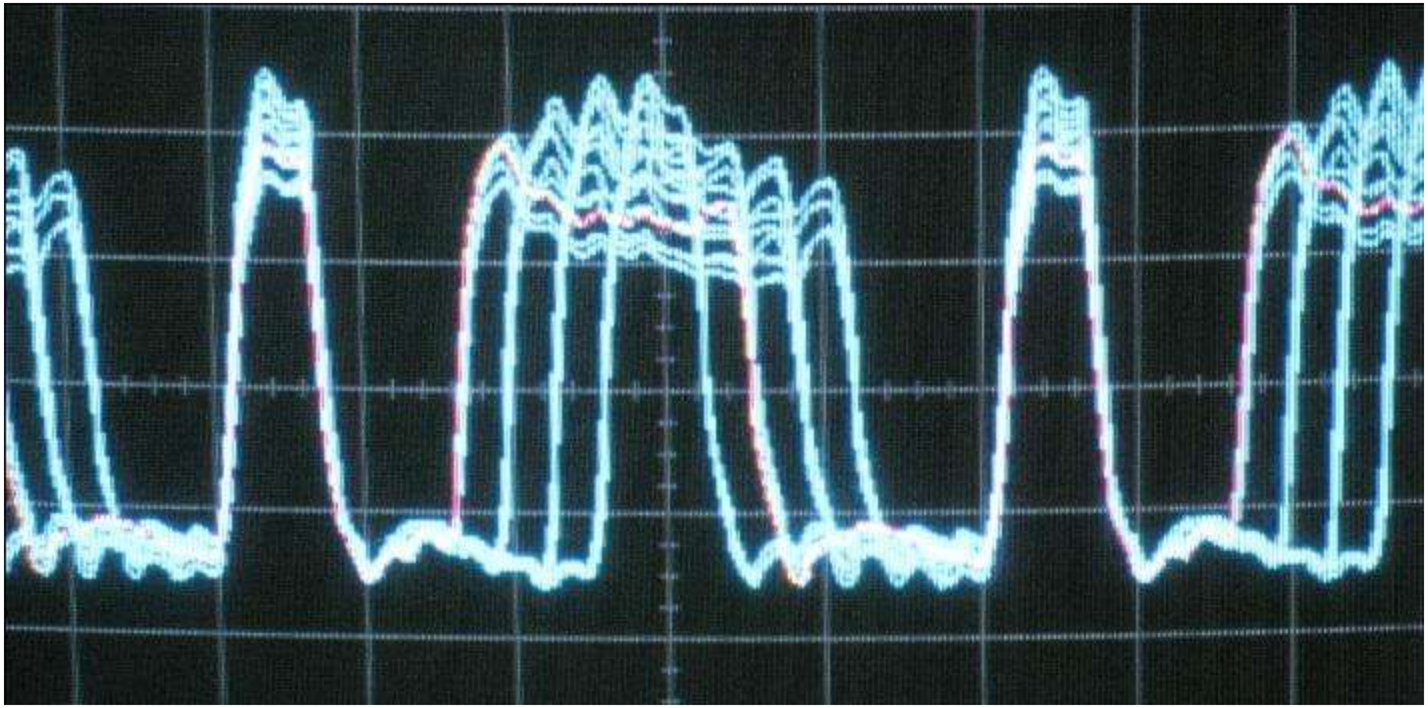


Time-Based Data Links vs Conventional SerDes



- Transmit/Receive circuitry very simple and low power, no CDR required at receiver
- Energy concentrated at lower frequency in the Time-Based System (2 GHz component disappears, but still achieve 2Gbps with 500MHz clock)
- May be able to use the transmitted signal to downlink from the feed to the antenna base

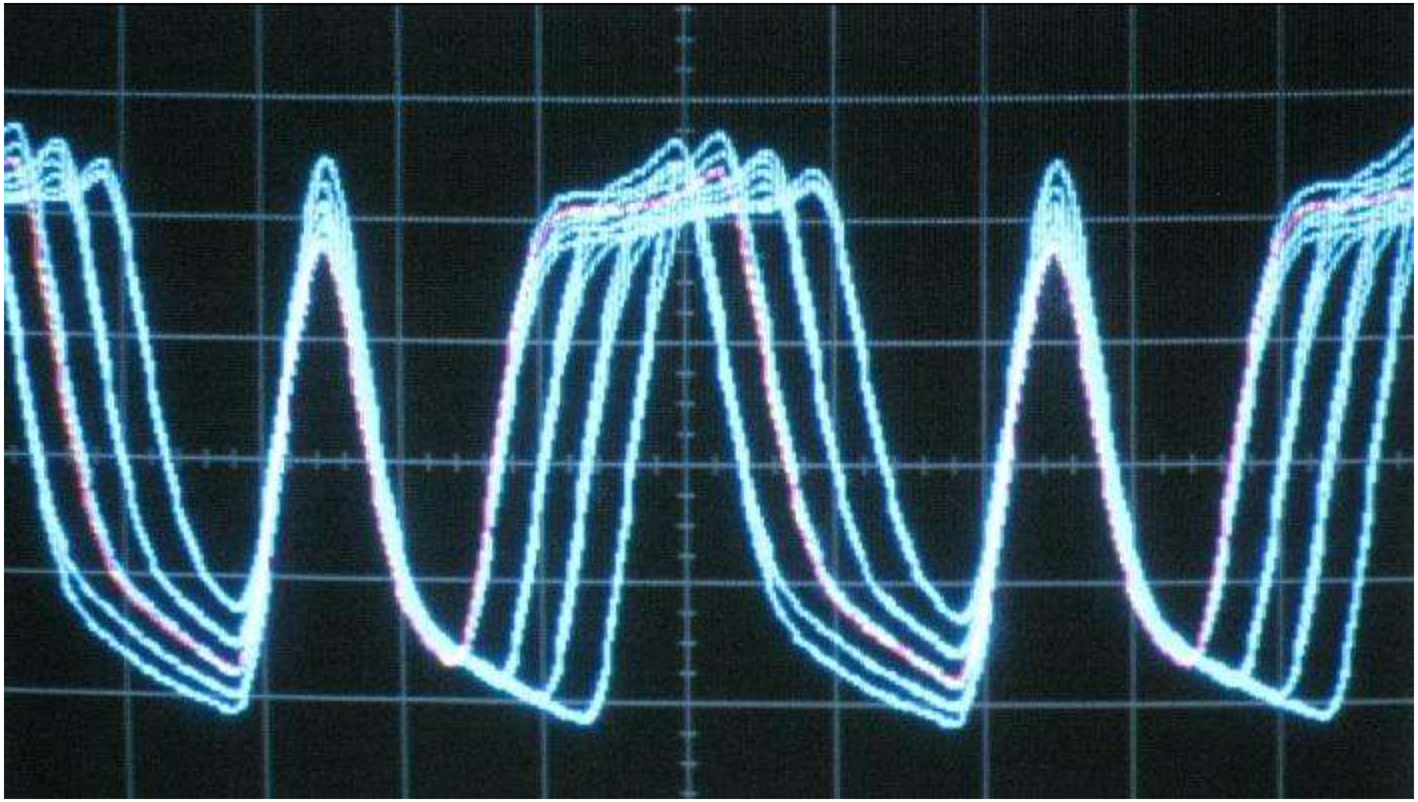
- 4-bit 1.6Gbps link using FPGA for proof-of-concept: transmitted signal with 2-tap preemphasis (measured)



400MHz Clock Data Data

- 4-bit 1.6Gbps link signal after 40-inch FR4 Channel without equalization (measured)

Very easy to decode with TDC (FPGA receiver being designed)



AREA THREE: 3-D Cone Filtering of SKA Signals

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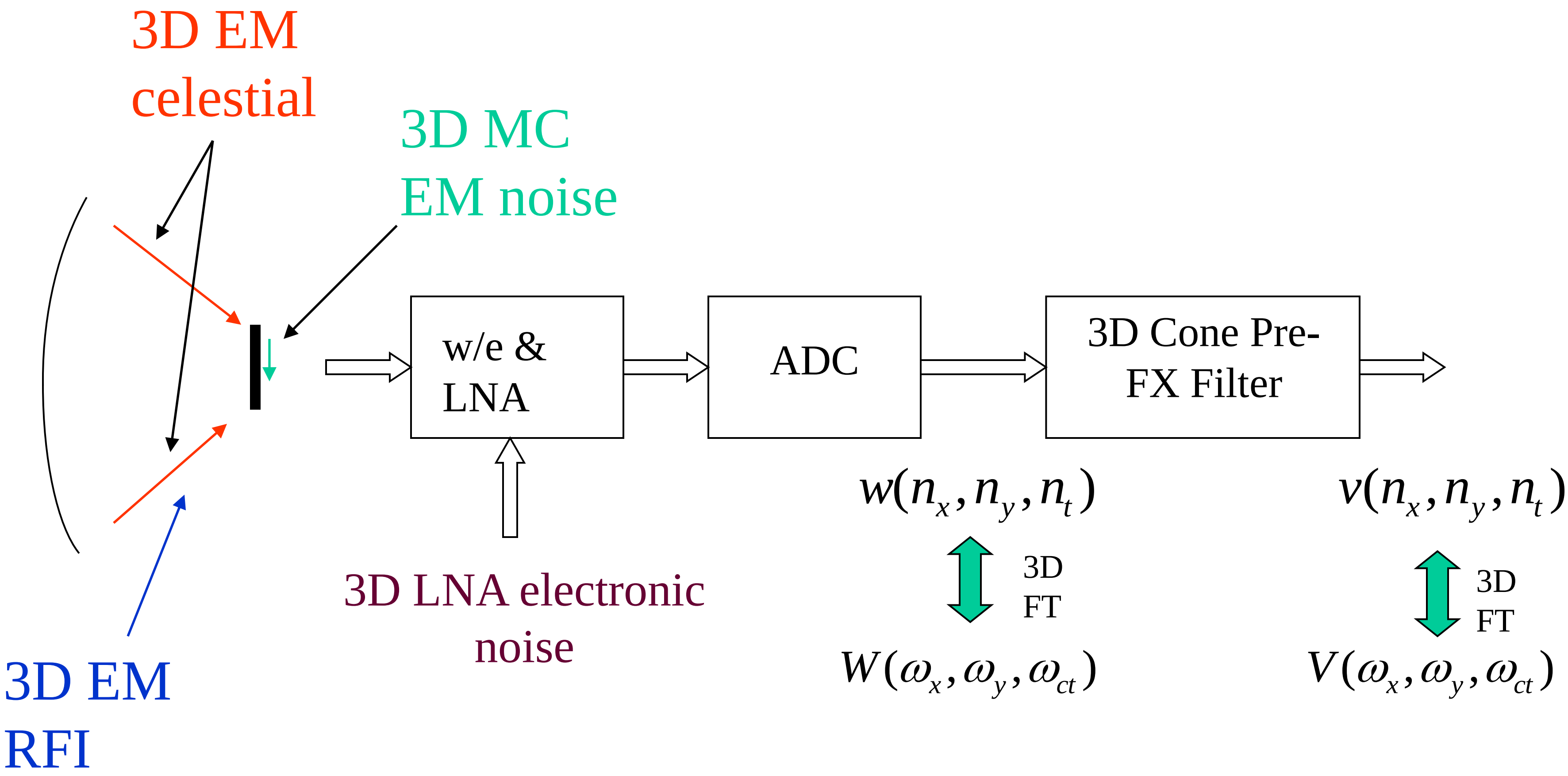
Principles of 3D Cone Pre-FX FPA Filtering



3D EM celestial

3D MC EM noise

3D EM RFI

w/e & LNA

ADC

3D Cone Pre-FX Filter

3D LNA electronic noise

$w(n_x, n_y, n_t)$

3D FT

$W(\omega_x, \omega_y, \omega_{ct})$

$v(n_x, n_y, n_t)$

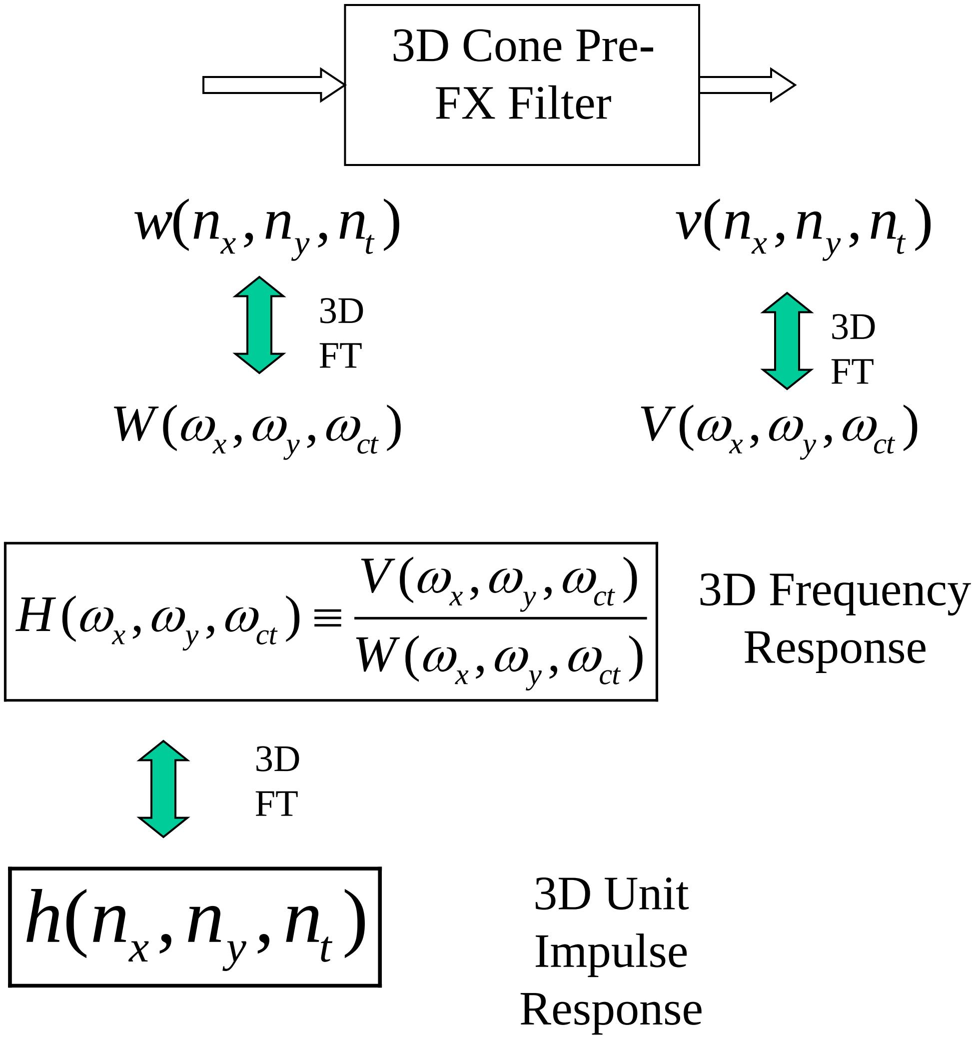
3D FT

$V(\omega_x, \omega_y, \omega_{ct})$

We design →

$$\boxed{H(\omega_x, \omega_y, \omega_{ct}) \equiv \frac{V(\omega_x, \omega_y, \omega_{ct})}{W(\omega_x, \omega_y, \omega_{ct})}}$$

Principles of 3D Cone Pre-FX FPA Filtering



3D Cone Pre-FX Filter

$w(n_x, n_y, n_t)$ $\quad$ $v(n_x, n_y, n_t)$

3D FT $\quad$ 3D FT

$W(\omega_x, \omega_y, \omega_{ct})$ $\quad$ $V(\omega_x, \omega_y, \omega_{ct})$

$$\boxed{H(\omega_x, \omega_y, \omega_{ct}) \equiv \frac{V(\omega_x, \omega_y, \omega_{ct})}{W(\omega_x, \omega_y, \omega_{ct})}}$$

3D Frequency Response

3D FT

$$\boxed{h(n_x, n_y, n_t)}$$

3D Unit Impulse Response

Problem Statement:

Design and implement the 3D filter in real-time custom VLSI such that

$$H(\omega_x, \omega_y, \omega_{ct})$$

i.e. $\quad h(n_x, n_y, n_t)$

transmits dish-reflected celestial FPA digital signal components of $w(n_x, n_y, n_t)$ while attenuating the EM RFI, EM MC noise and eLNA noise

The Ideal Spectrum of a 3D Plane Wave Signal

$w(n_x,n_y,n_t)$ $\quad$ $v(n_x,n_y,n_t)$

⇕ 3D FT $\quad$ ⇕ 3D FT

$W(\omega_x,\omega_y,\omega_{ct})$ $\quad$ $V(\omega_x,\omega_y,\omega_{ct})$

$$\boxed{H(\omega_x,\omega_y,\omega_{ct}) \equiv \frac{V(\omega_x,\omega_y,\omega_{ct})}{W(\omega_x,\omega_y,\omega_{ct})}}$$

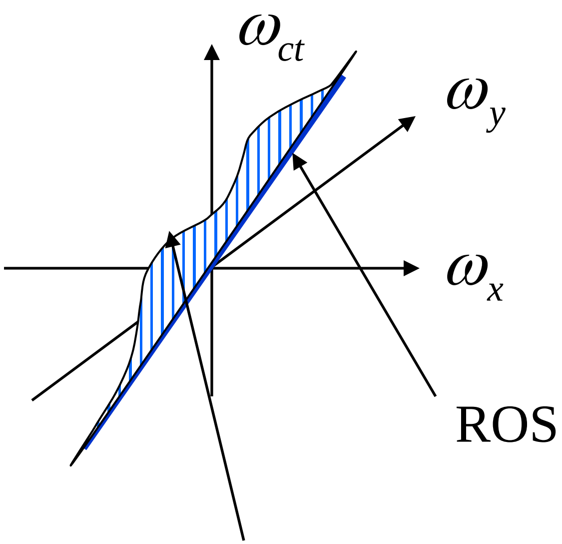
3D Frequency Response

⇕ 3D FT

$$\boxed{h(n_x,n_y,n_t)}$$

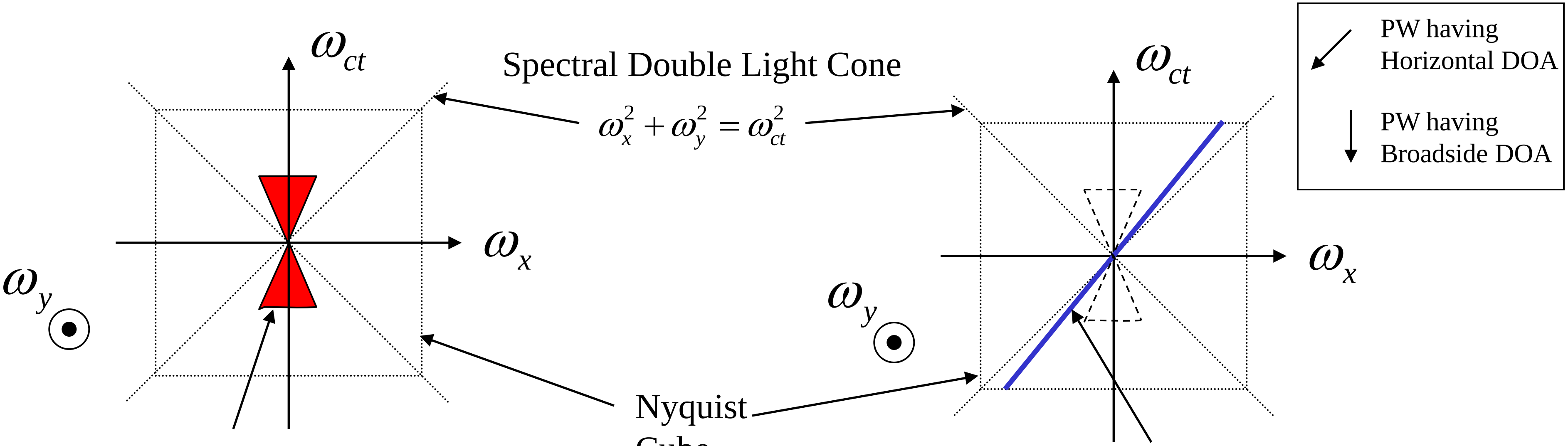
3D Unit Impulse Response

The ROS of the Spectrum of a 3D Plane Wave:



The 3D spectrum of a PW lies on a line given by its DOA in space-time. (Magnitude spectrum shown here).

FPA Regions of Support (ROS) of a component Radio Frequency Interfering (RFI) Signal (shown for a 2D slice)



↙ PW having Horizontal DOA

↓ PW having Broadside DOA

Spectral Double Light Cone

$$\omega_x^2 + \omega_y^2 = \omega_{ct}^2$$

Nyquist Cube

ROS of 3D FPA spectra of all celestial signals –

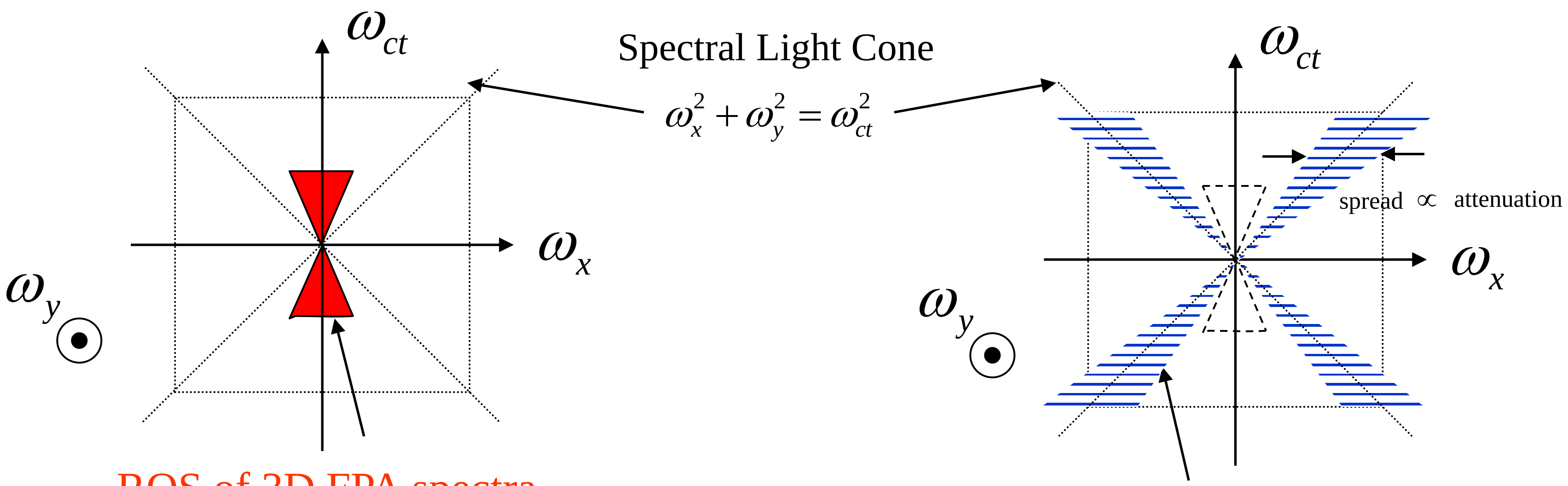
INSIDE BUT WELL REMOVED FROM THE SPECTRAL LIGHT CONE AND BROADLY DISTRIBUTED INSIDE THE 3D ‘PASS BAND’ DOUBLE CONE

FPA ROS of 3D spectrum of a non-dish

reflected RFI signal –

INSIDE THE SPECTRAL LIGHT CONE, CLOSE TO ITS SURFACE AND CLOSE TO A LINE

Region of Support (ROS) of Horizontally-Propagating Mutually-coupled FPA Noise Signals (shown for a 2D slice)



Spectral Light Cone

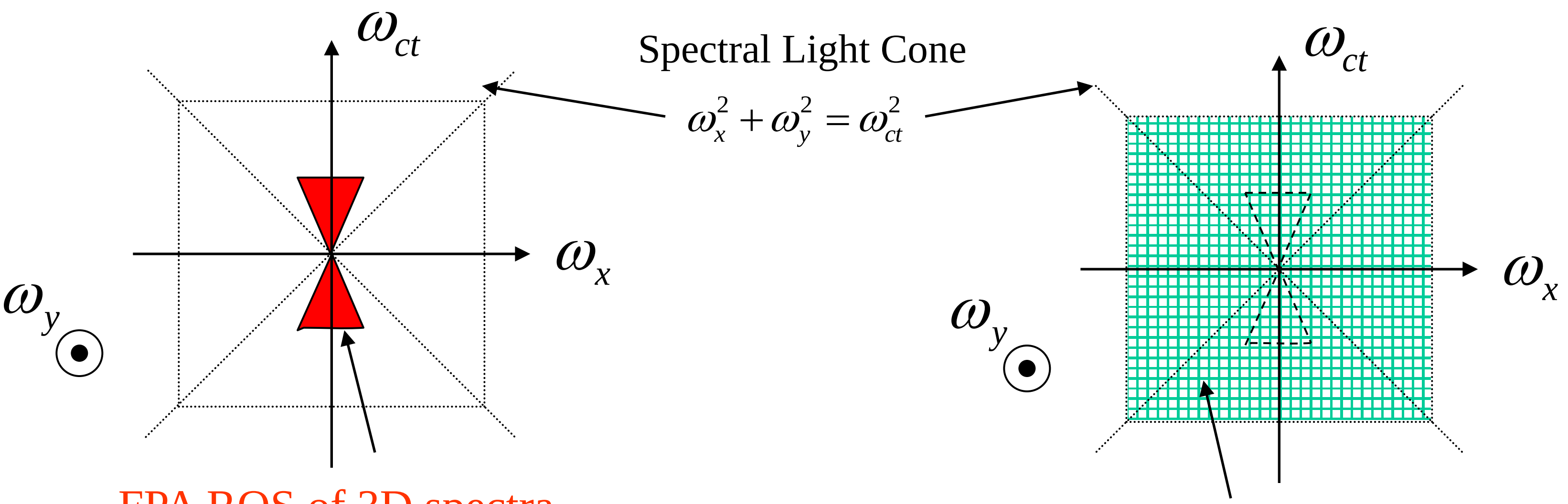
$$\omega_x^2 + \omega_y^2 = \omega_{ct}^2$$

ROS of 3D FPA spectra
of all celestial signals

ROS of 3D FPA spectrum
of MC noise signals –
CENTRED ON SPECTRAL
LIGHT CONE WITH SPREAD
THAT INCREASES WITH THE
ATTENUATION BETWEEN

ANTENNA ELEMENTS

3D Region of Support (ROS) of Electronically-Generated LNA Noise Signals after ADC (shown for a 2D slice)



Spectral Light Cone

$$\omega_x^2 + \omega_y^2 = \omega_{ct}^2$$

FPA ROS of 3D spectra of <u>all</u> required celestial signals

ROS of 3D spectrum of LNAs’ noise component of the digitized FPA signal – APPROXIMATELY-FLAT 3D SPECTRAL DENSITY THROUGHOUT THE

NYQUIST <u>CUBE</u>

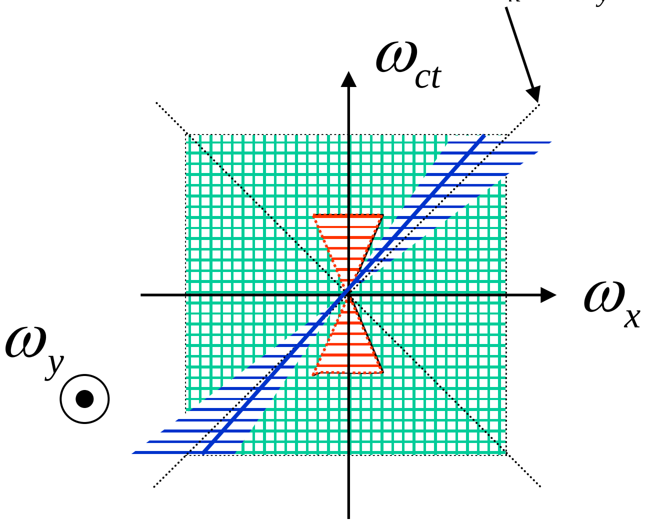
Idealized Analysis of ROSs of Four Classes of 3D Space-time FPA Signals and the Required Ideal Cone-Shaped Passband

🟥 Celestial – in cone-shaped interior region

🟦 MC noise – spread about light cone

🟩 eLNA noise – approx flat in 3D Nyquist cube

╱ RFI – spread about a line and mostly outside interior cone



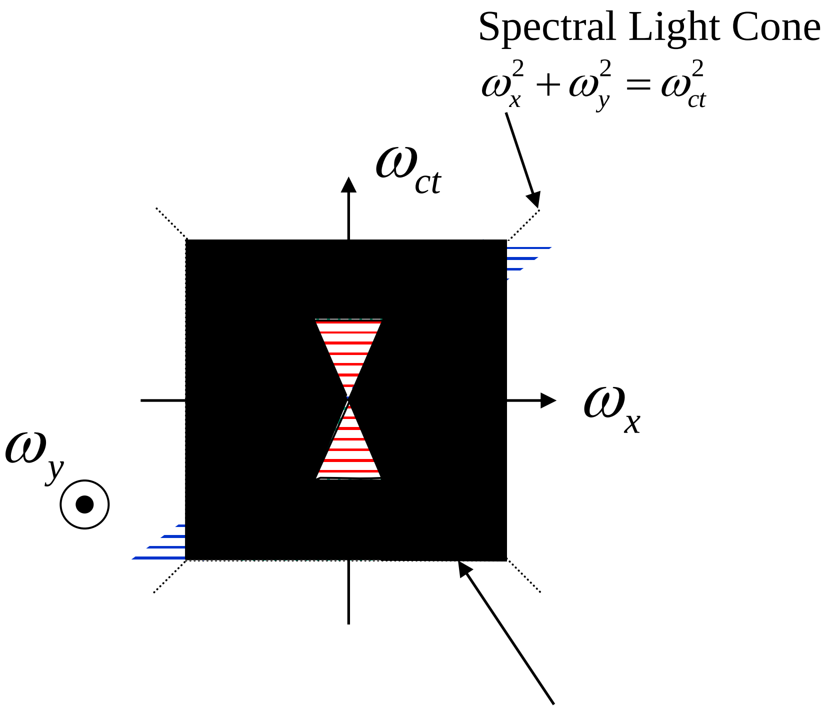
Spectral Light Cone

$\omega_x^2 + \omega_y^2 = \omega_{ct}^2$

Assign Interior Cone to the 3D Pass Band

Required Ideal Cone-Shaped Pass Band and Stop Band

- 🟥 Celestial signals – in 3D pass band
- 🟦 MC noise – in 3D stop band and pass band
- 🟩 eLNA – mostly in 3D stop band
- ╱ RFI – mostly in 3D stop band



Spectral Light Cone
$\omega_x^2 + \omega_y^2 = \omega_{ct}^2$

Required Stop Band

Results Using 3D FIR Cone Filters

Our simulations confirm:

1. Very low pass band distortion of all celestial FPA signals
2. significant attenuation of over-the-horizon RFI FPA signals
3. moderate attenuation of typical FPA MC noise signals
4. significant attenuation of FPA eLNA noise and thereby T_{LNA} over the mid-frequency range 0.7-2 GHz