Real-Time Digital Signal Processing For Radio Astronomy and Beyond

1. Digital sideband separation
2. Digital polarization synthesis
3. Other applications for astronomy
4. Applications outside astronomy

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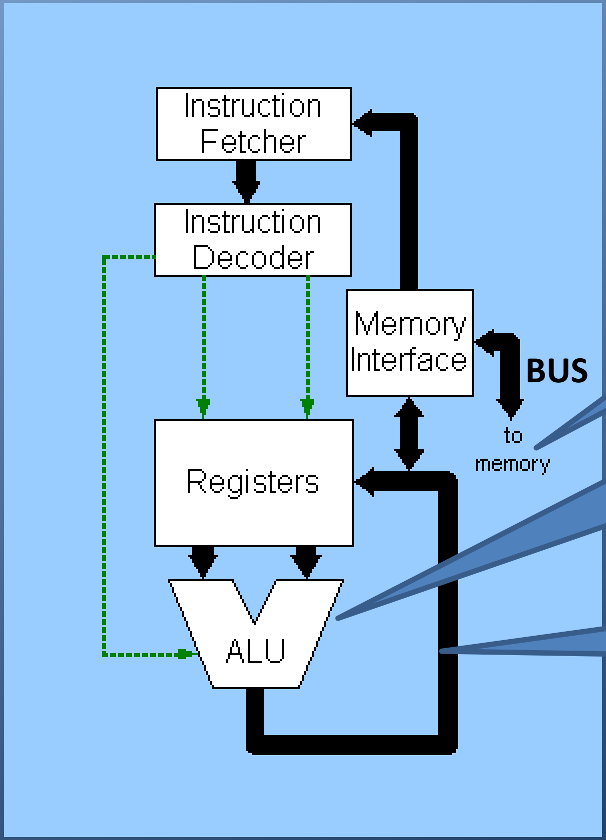
Mid term meeting, ESO
Garching, Jan 2018

Do you know how your computer works ??



Here is your code and your variables

Here is the core of your CPU, which performs only one operations at a time. ALU stands for Arithmetic Logic Unit.

This connection (CPU bus) carries each result back to the CPU registers

- *All instructions are evaluated in a sequential way*
- *There is no **real** parallel computing on your PC*
- *At best you can have a few cores / threads*

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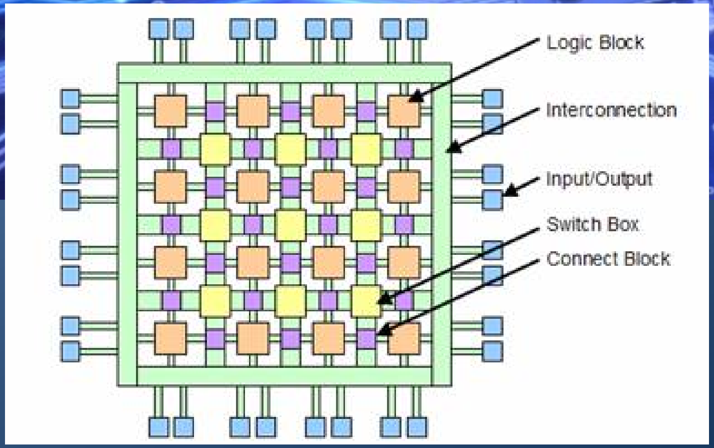
Field Programmable Gate Array (FPGA) (Re)Configurable Hardware: A new approach



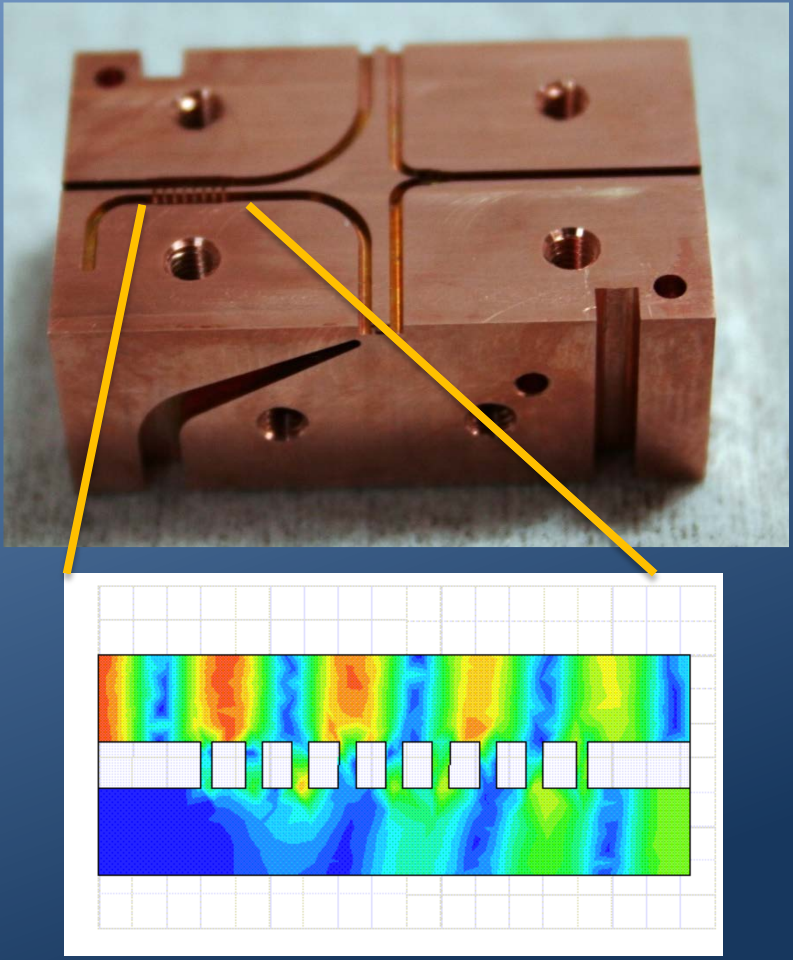
FPGA fabric schematic

- 1 GB FFT takes **~16 seconds** in a CPU
- In a FPGA can be done in **0.1 seconds**
- We can process a ~**100 Gbps data** rate in real time in a single FPGA chip.
- Large number of Input/Output pins, no input bandwidth bottleneck
- Easily scalable

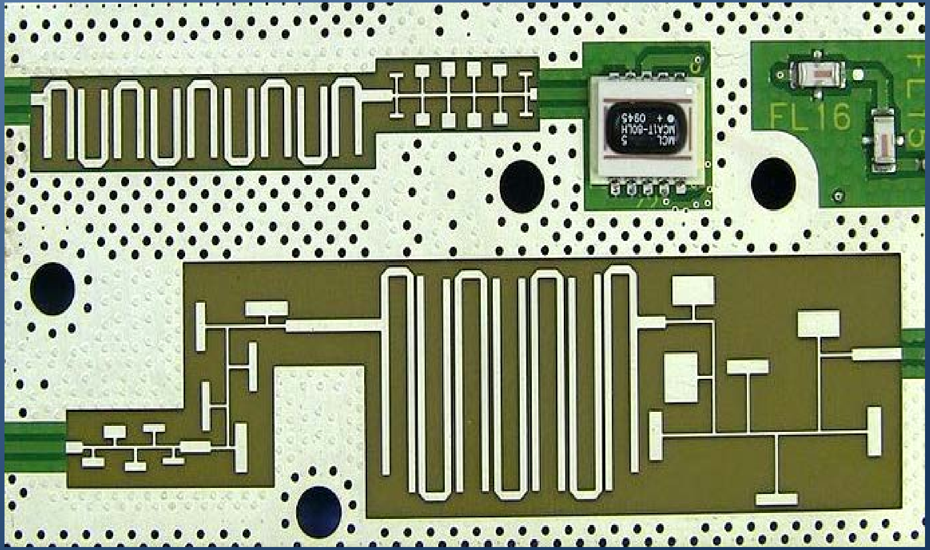
Two typical analog signal processing that can be done in digital

Frequency Hybrid

splitting and phase shifting



Equalizer / Filter

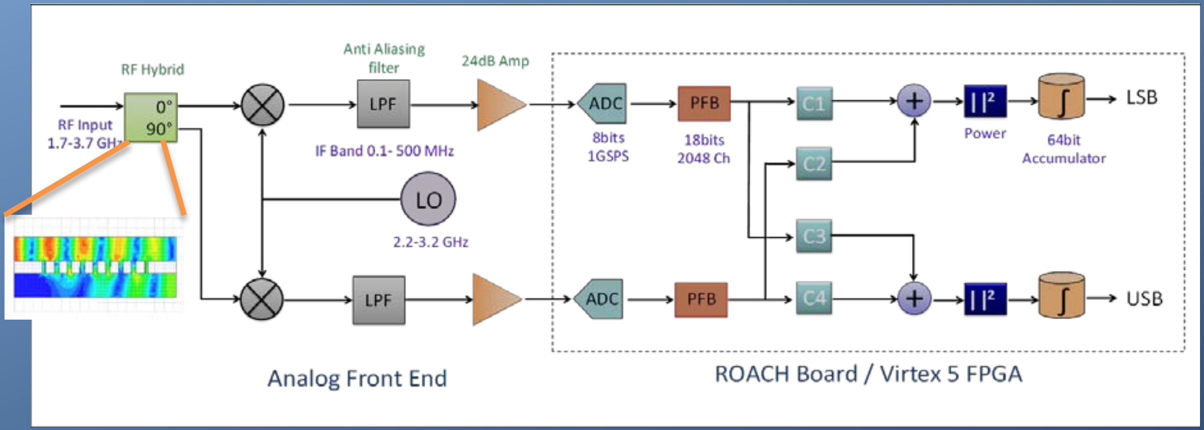


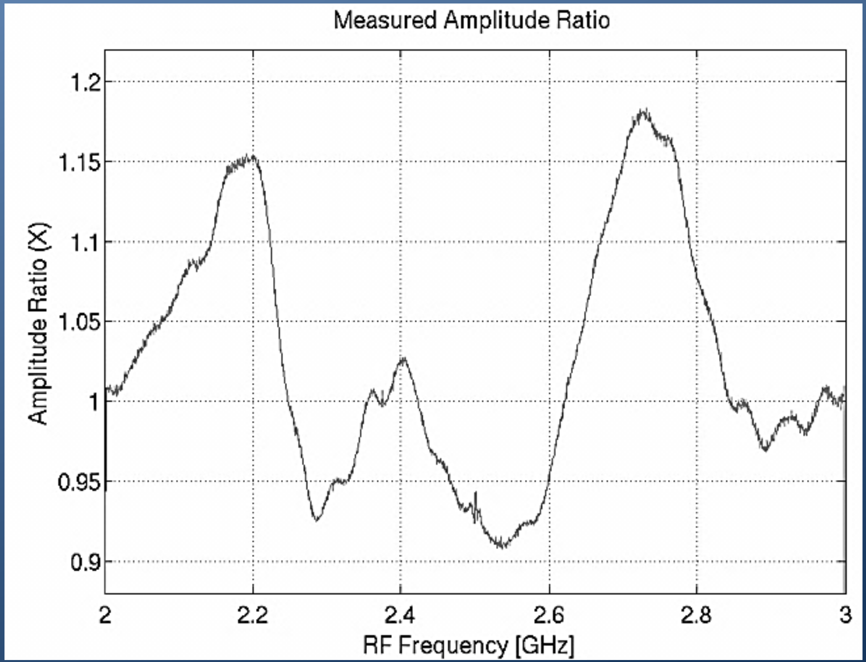
- The analog component only works well on a limited bandwidth
- Only simple gain/phase characteristics can be implemented in practice.

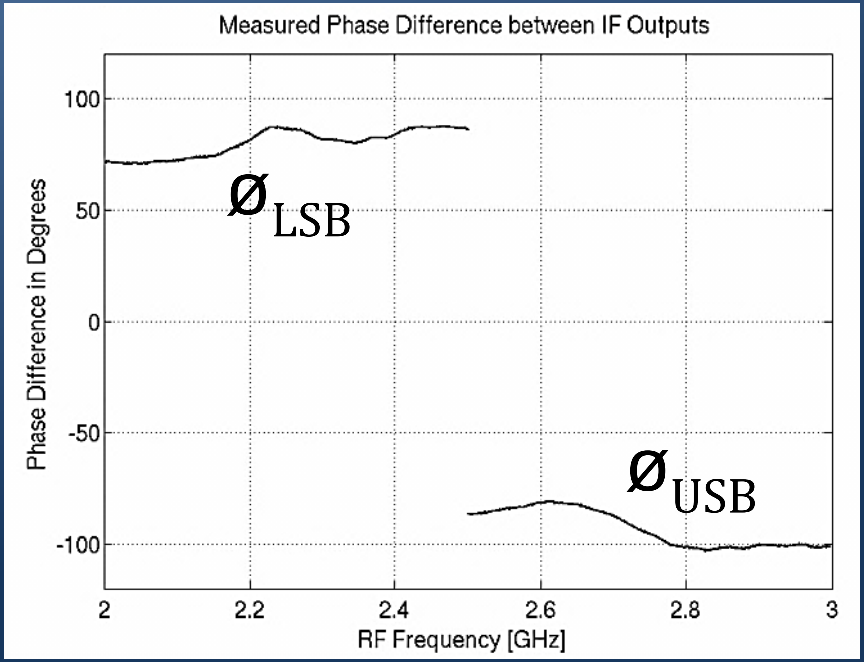
Calibration

$$\frac{C_1}{C_2} = \frac{1}{X} e^{-j(\emptyset_{LSB} - \pi)}$$

$$\frac{C_3}{C_4} = \frac{1}{X} e^{-j(\emptyset_{USB} - \pi)}$$

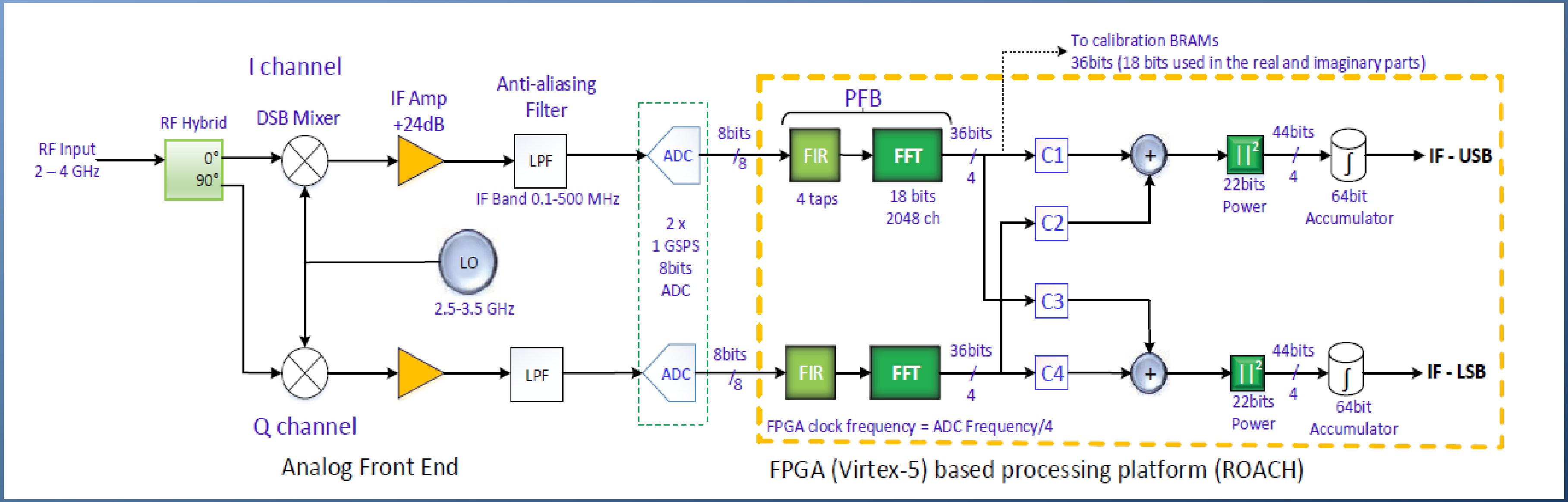






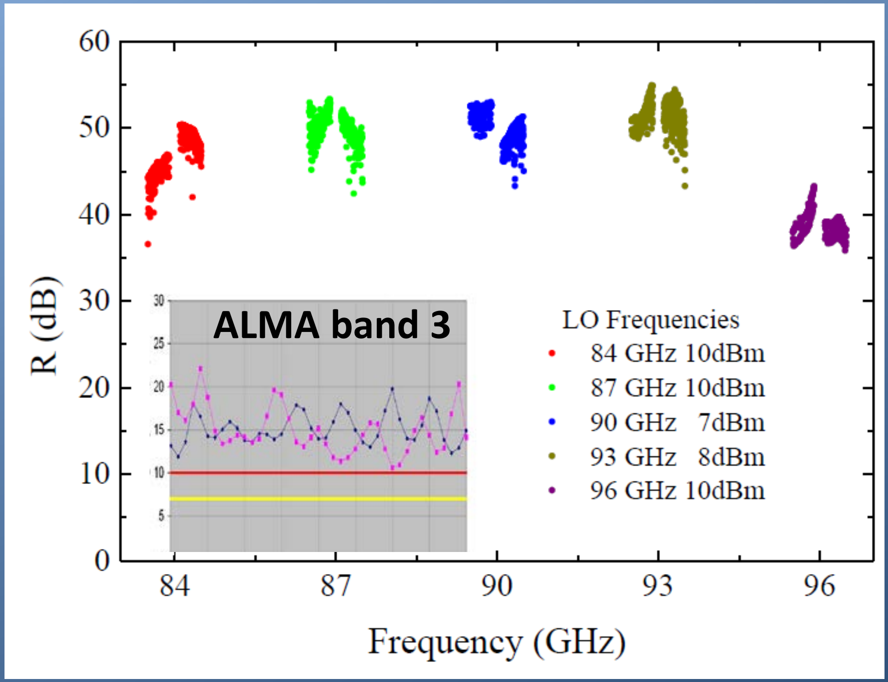
Measured USB and LSB amplitude ratio X (left) and phase imbalances $\emptyset_{LSB/USB}$ (right).

Digital Sideband Separation

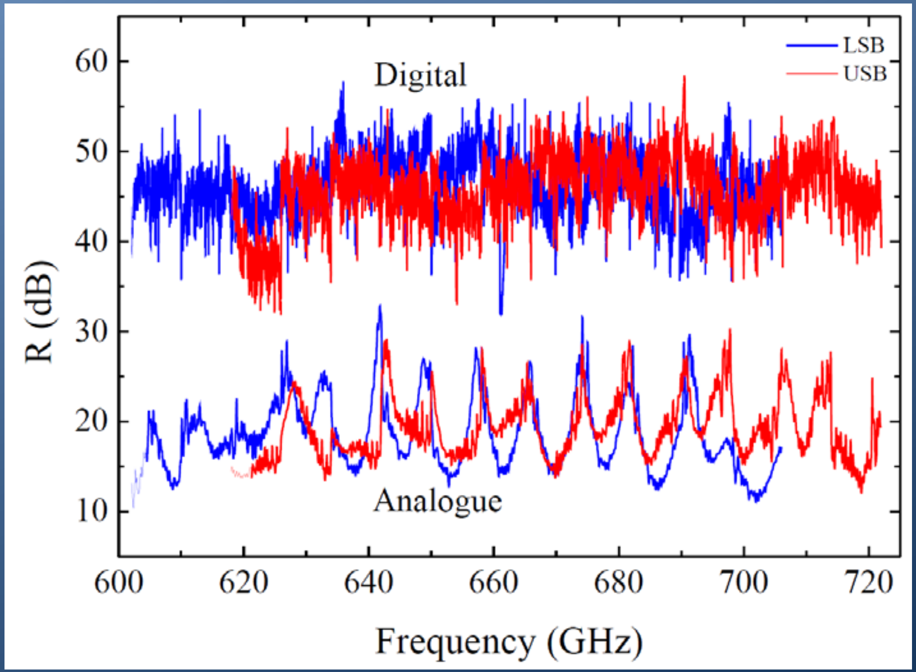


- I and Q amplitude and phase unbalances are measured after the FFT
- Calibration vectors C1-C4 (complex) are applied before adding. (C1=C4=1 if not equalization is required)
- Passband ripple calibration “for free” using all C vectors.
- “Perfect” sideband rejection can be achieved, only limited by ADC dynamic range and calibration accuracy.

Band 9 Analogue and Digital Sideband rejection

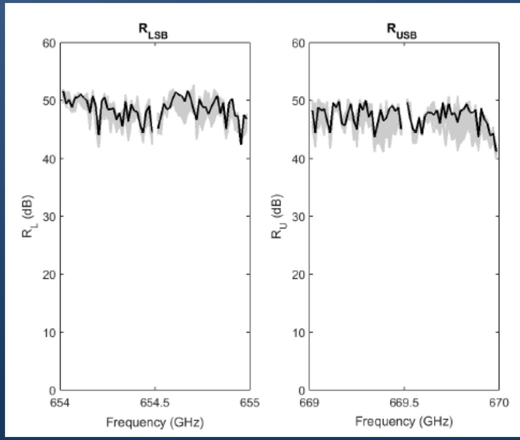


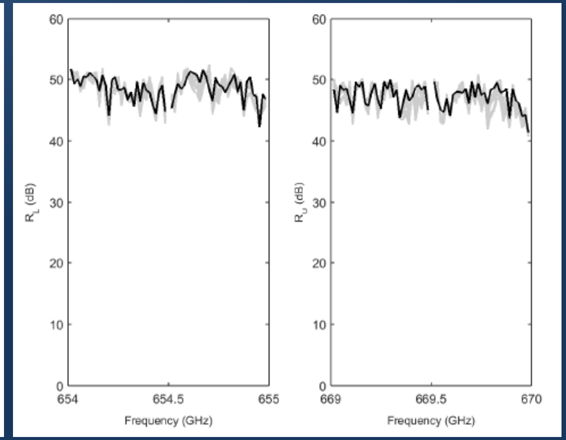
SRR at 3mm (84-96 GHz)



SRR at 1.2 mm (600 to 720 GHz)

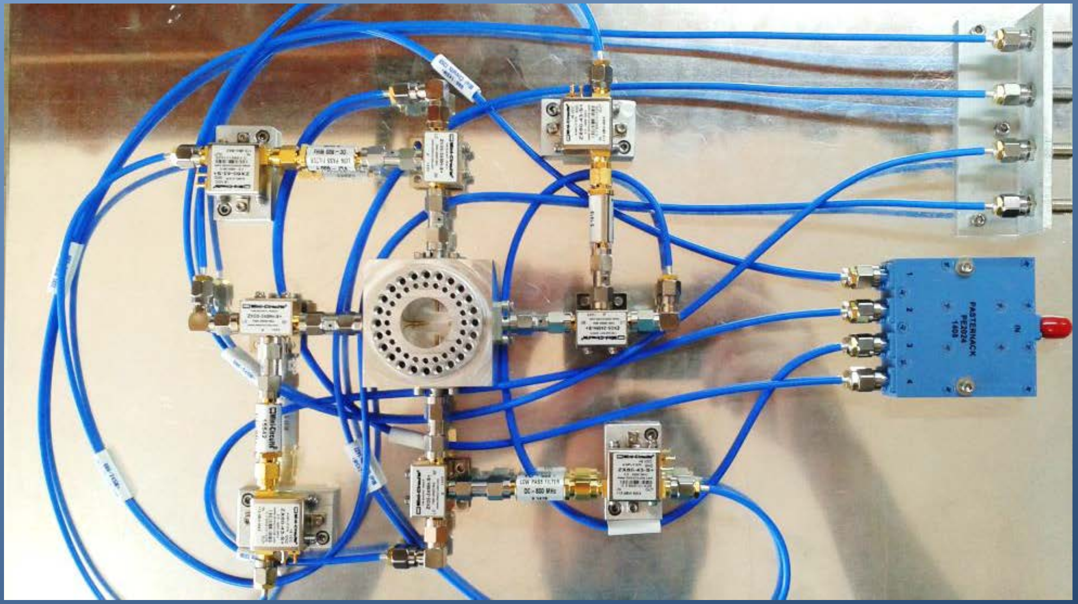
Stability with time, 48 measurements, every 30 minuts

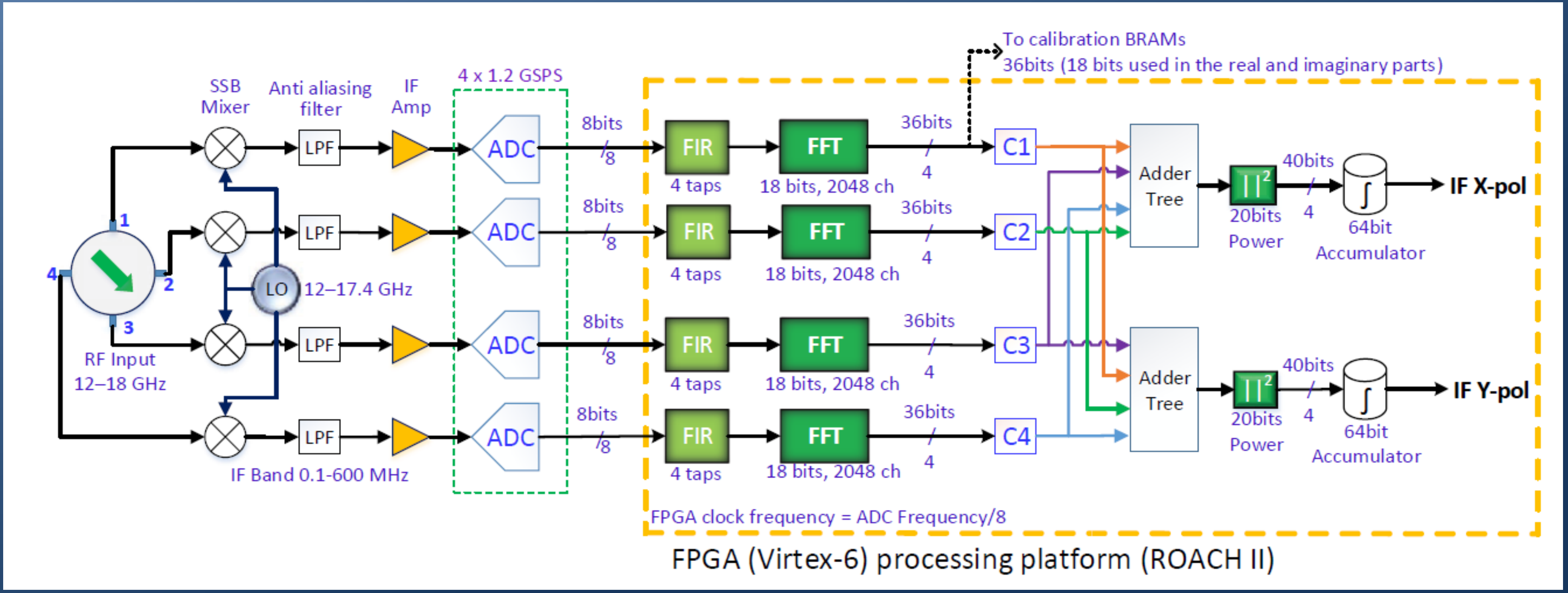




Stability after 9 deflux procedure

Digital Polarization Synthesis.





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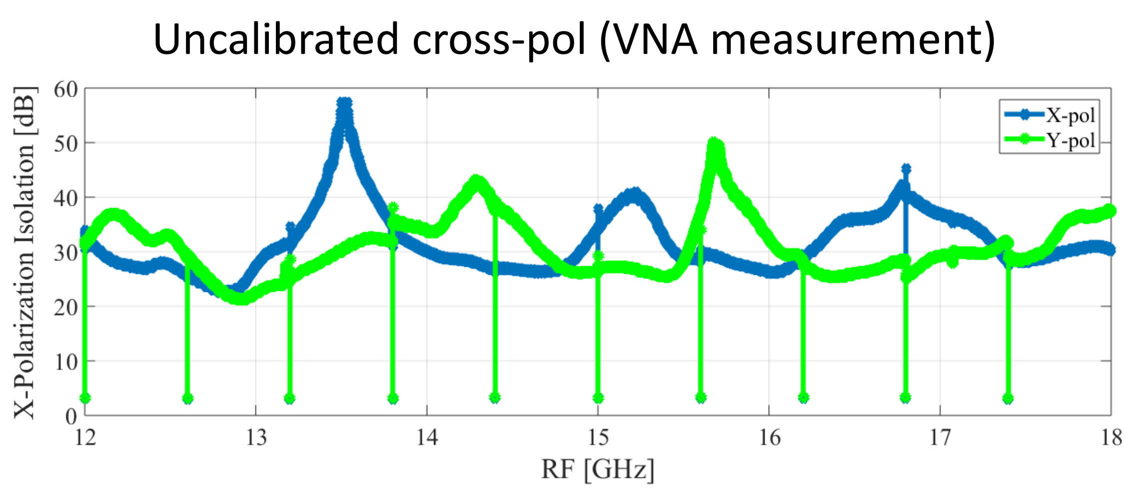
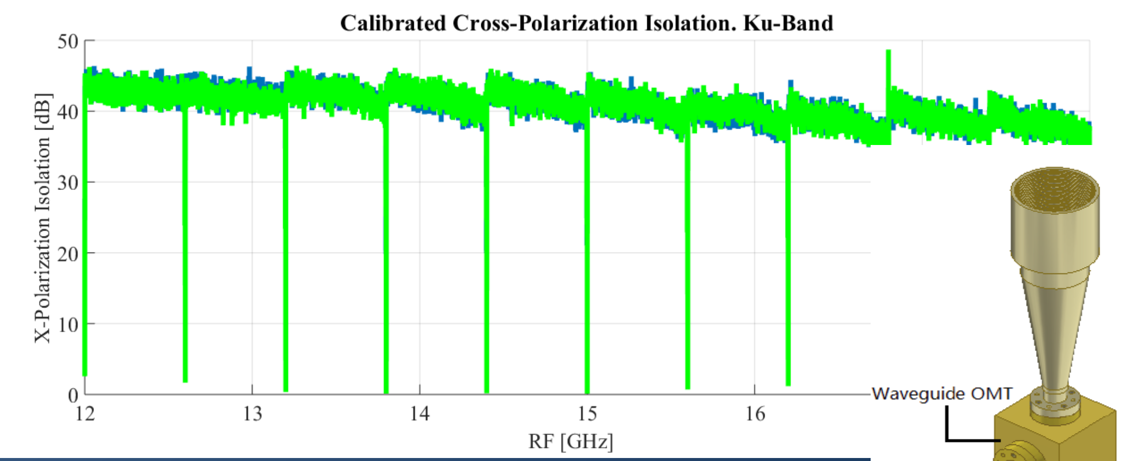
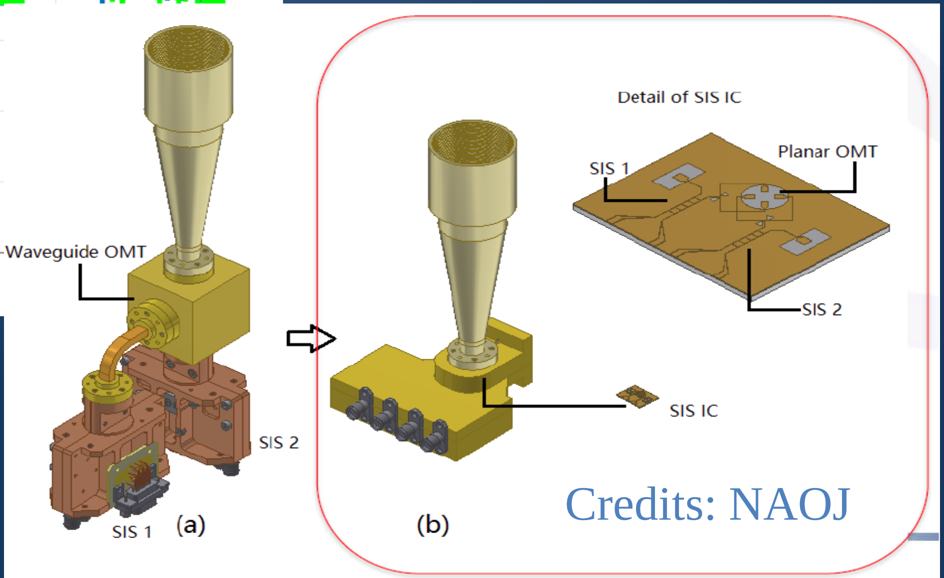
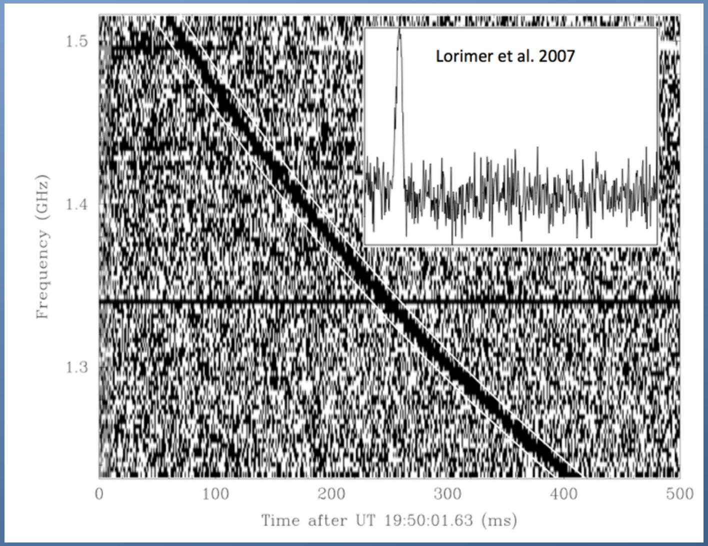
Digital Polarization Synthesis (DOMT)



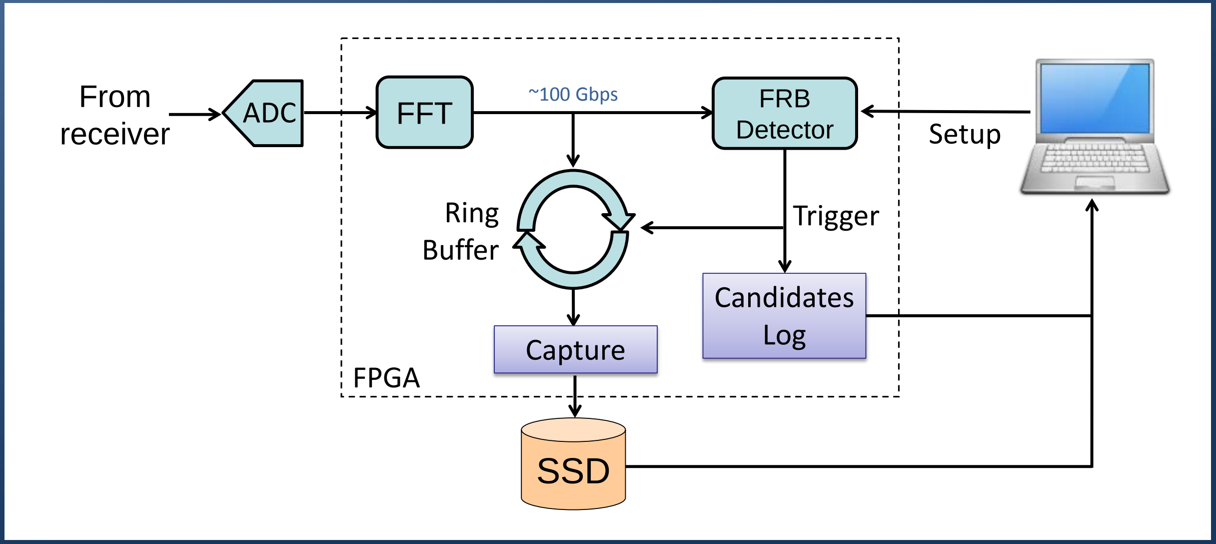




Fast Radio Burst (FRB) detection



- Most spectrometers integrates for seconds before dumping data to disk
- FRBs are undetectable for this type of back end
- Modern FPGAs allow cost-effective implementation of FRBs detectors
- FRBs surveys can be done in “commensal” mode, i.e. not requiring telescope time.



Interleaving spurious real-time subtraction

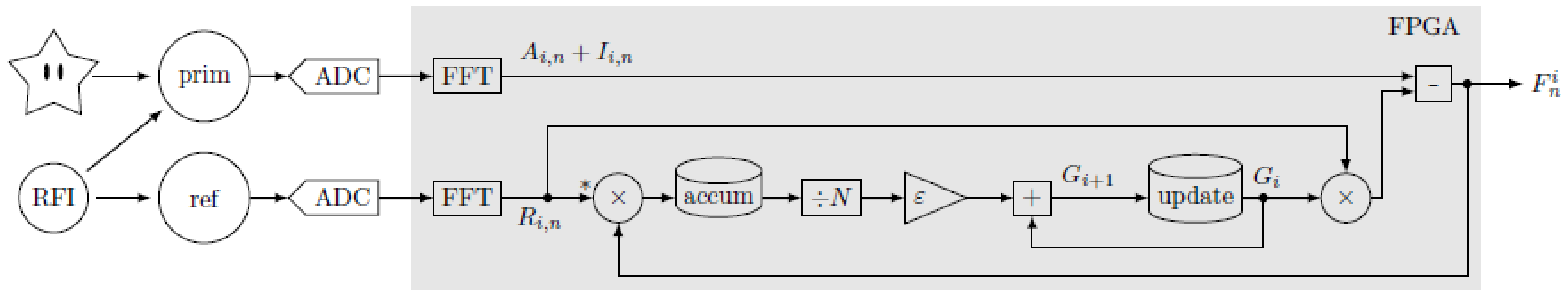
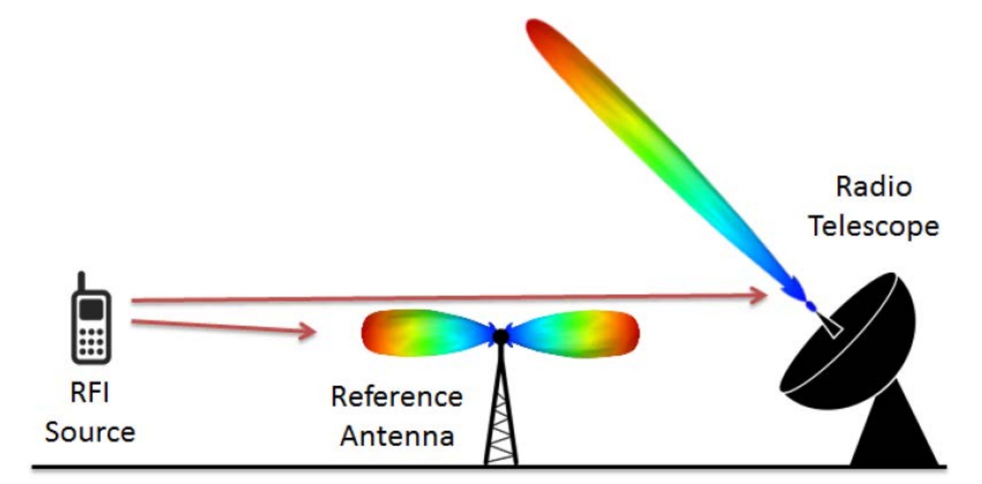


Figure 1: Schematic of the adaptive filter.



Spurious real-time subtraction

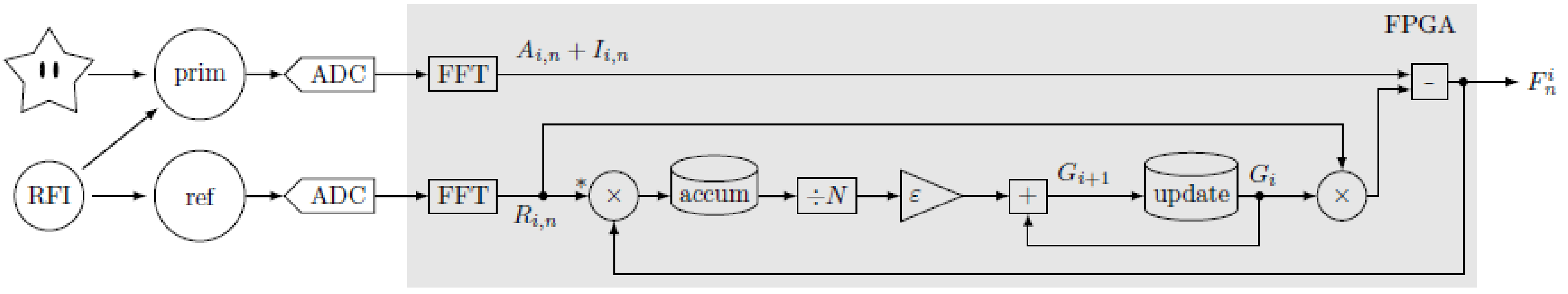
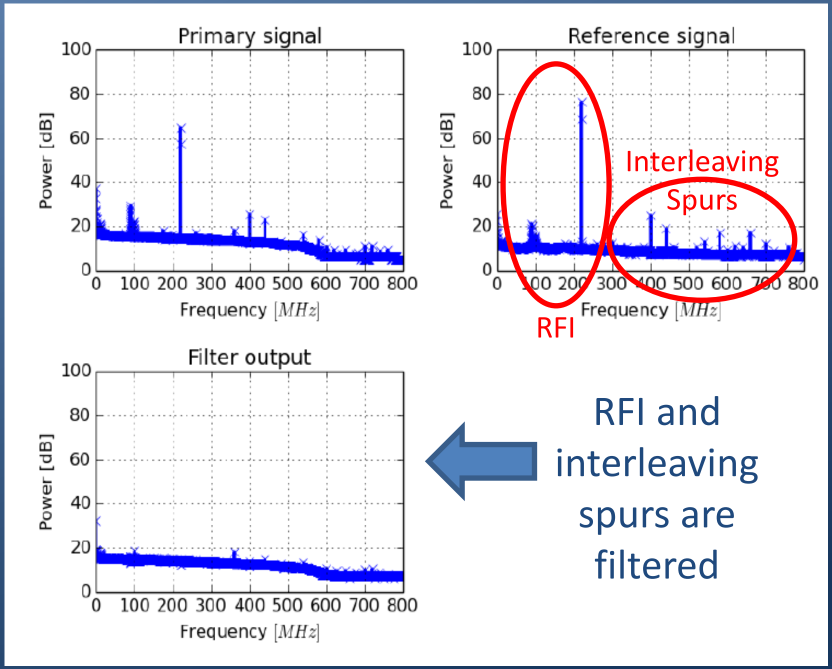
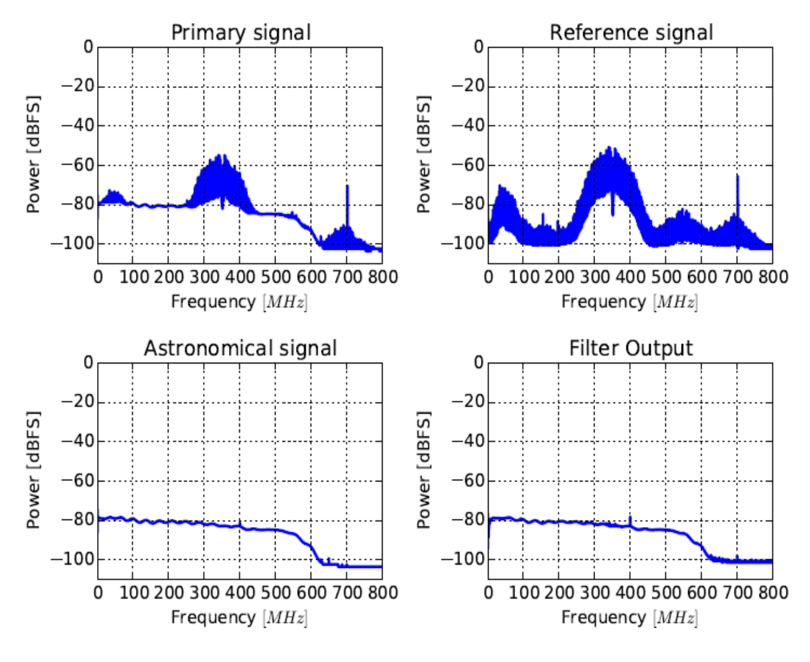


Figure 1: Schematic of the adaptive filter.

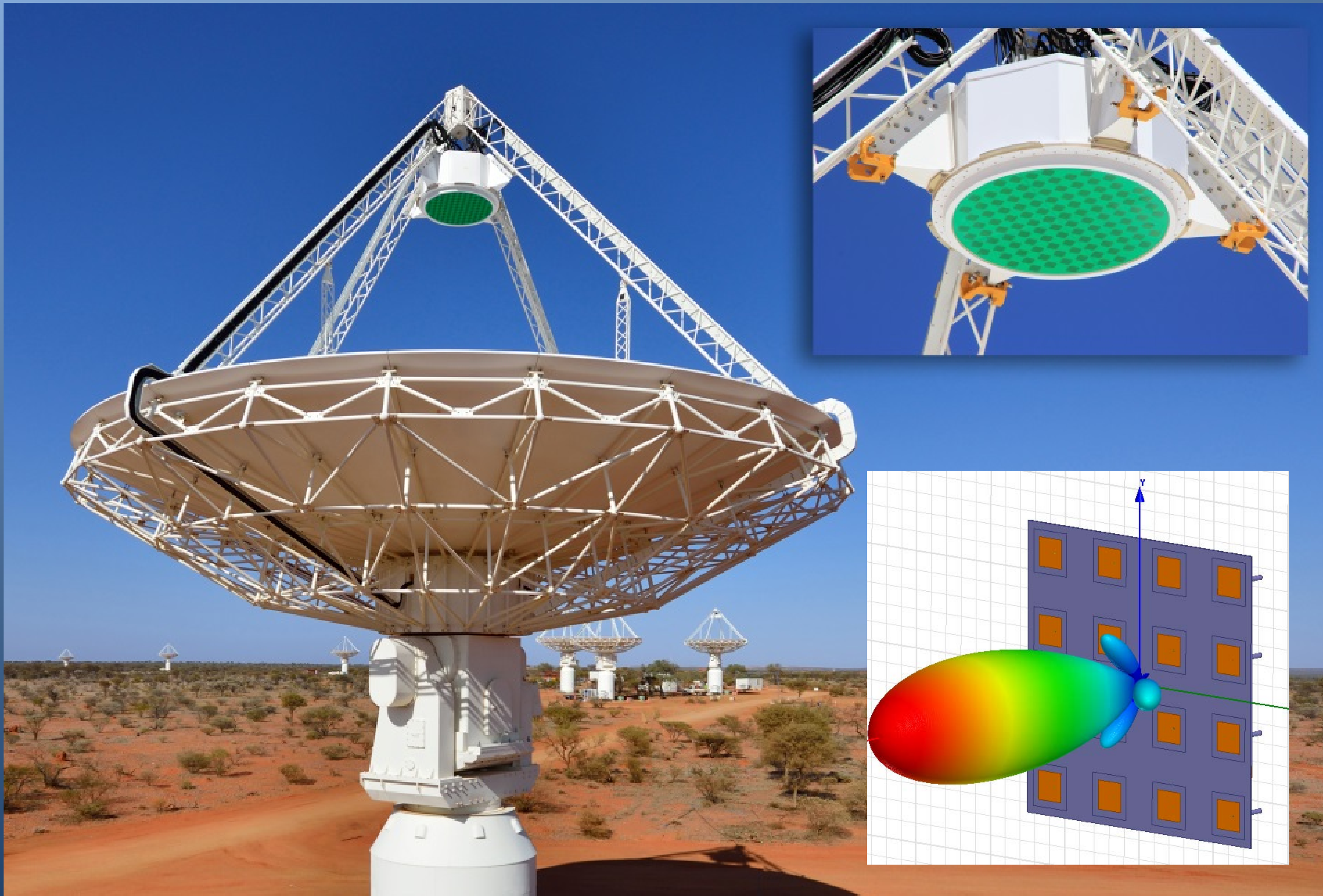


Carrier like RFI (pure tone)

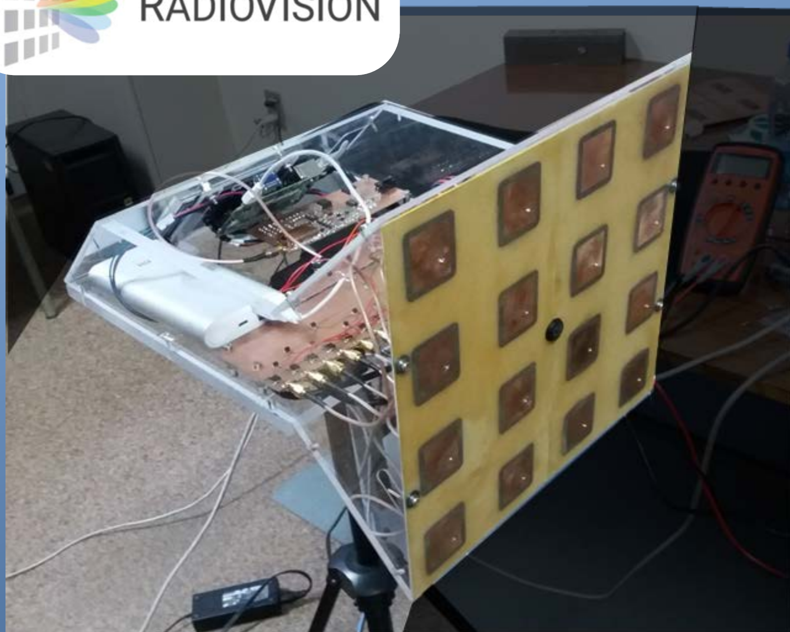


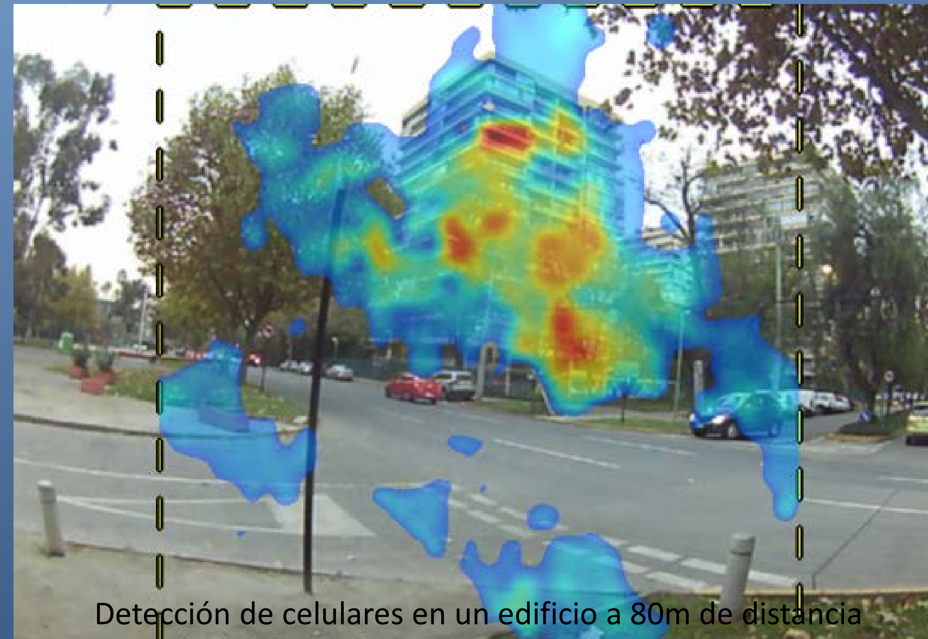
Wideband + carrier RFI

Phased Array Feeds



RADIOVISION

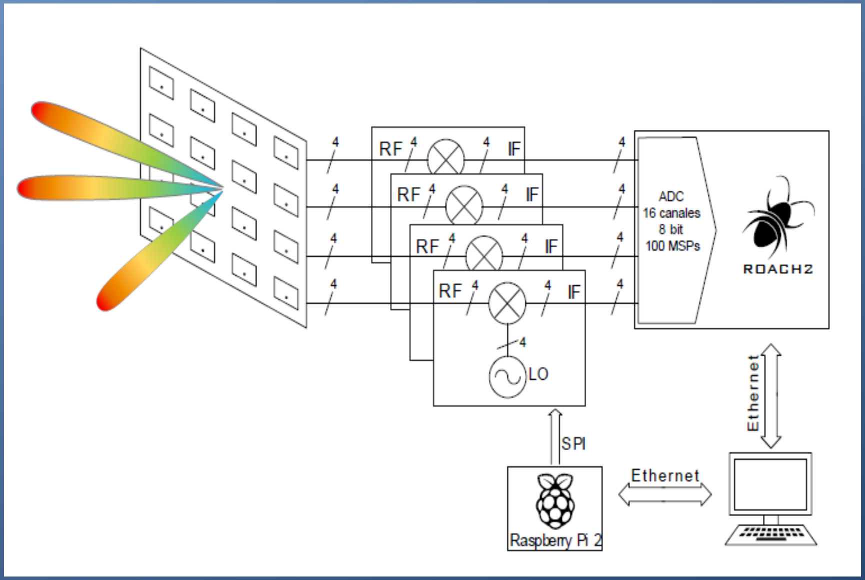




Phased Arrays

Applications beyond astronomy:

Adaptive Smart Antenna



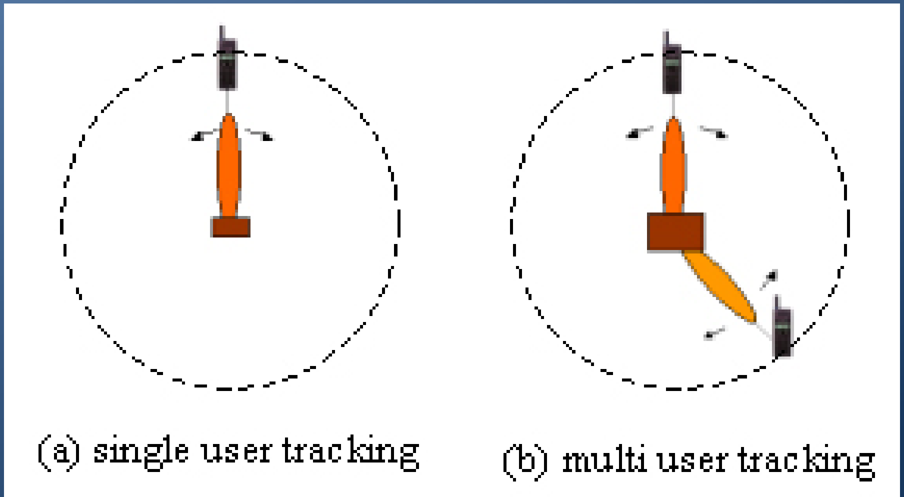
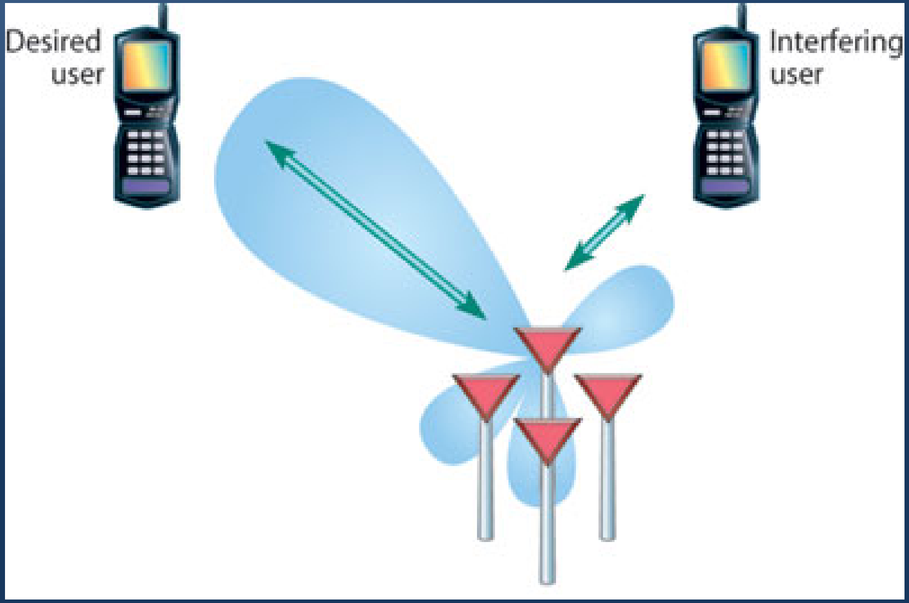


Figure 3: Adaptive Array Smart Antennas



Conclusions

FPGA capability of processing hundreds of Gbps in real time is changing the business of receiver and back-end design

- ✓ >40 dB **digital sideband separation** demonstrated at ALMA B3 (3mm) and B9 (1.2mm) wavelengths. 20-30 dB better than current analog technology
- ✓ **Digital polarization synthesis demonstrated**. Mostly useful for small fields point-like observations.
- ✓ RFI and ADC **artifacts can be removed** in real time.
- ✓ FRBs and other **short-time domain detectors become practical**
- ✓ Very promising applications outside astronomy

Direct RF Digital Signal Processing is now a reality, its full potential is still to be seen.

Domo arigato

http://www.das.uchile.cl/lab_mwl/