VLBI Digital Backends

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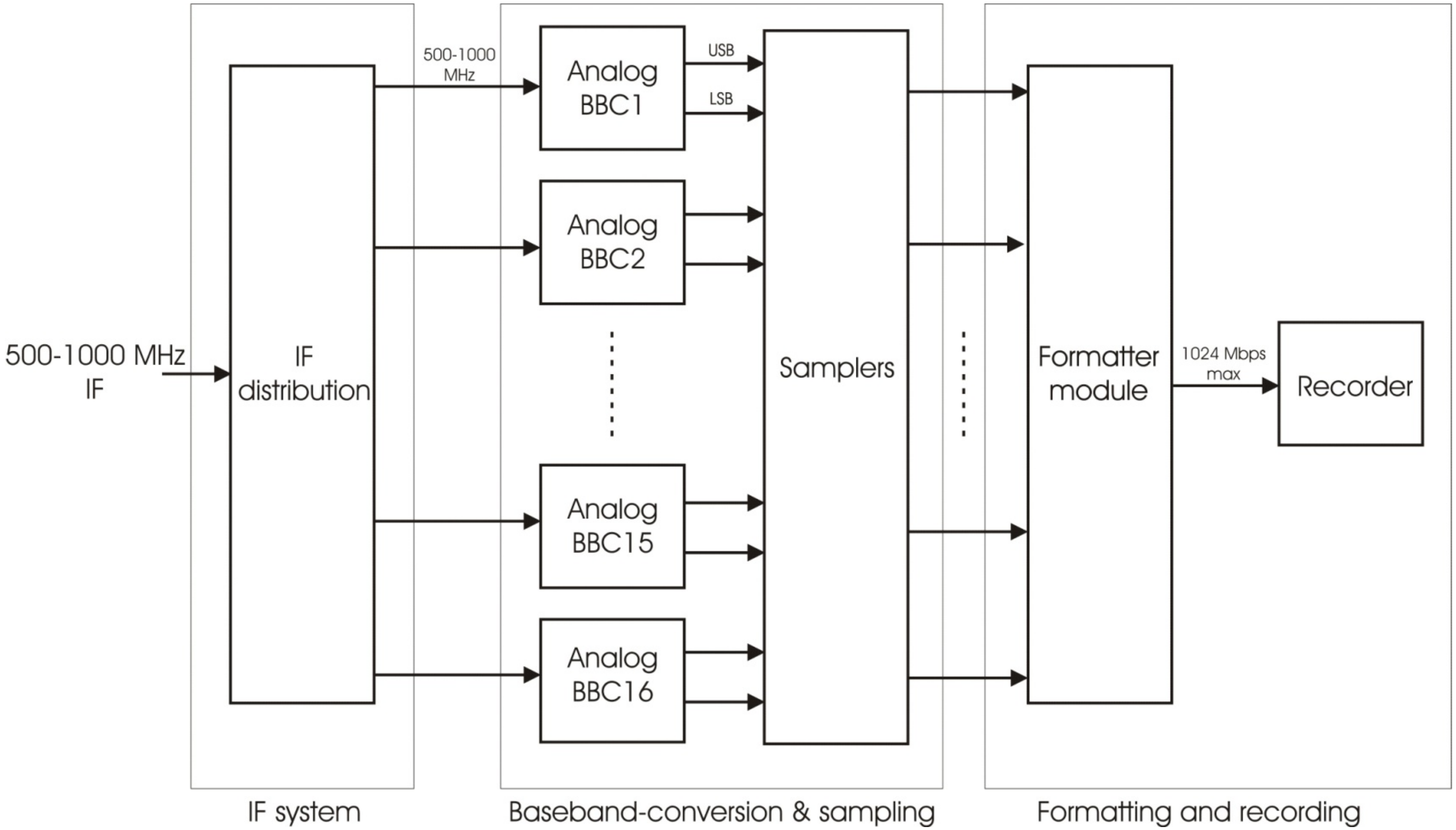
Outline

- Traditional VLBI backend architecture
- Digital realization of traditional VLBI backend
- DBBC channelization
- 100% stable
- 100% predictable
- 100% replicatible
- Easy to change/upgrade
- Easy to replicate
- Easily transferable to next-generation hardware
- Affordable cost

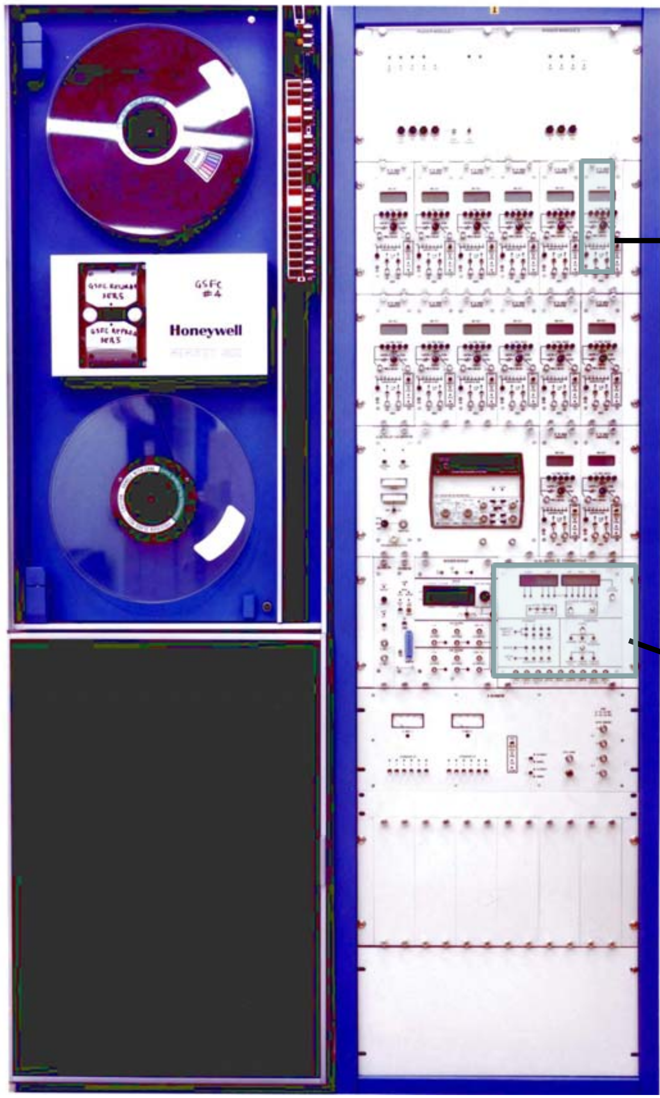
Rather an overwhelming case!

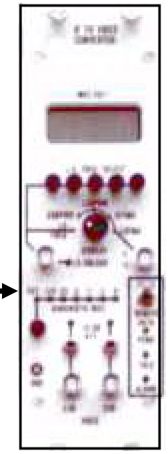
Analog backend system



Traditional analog BBC in Mark 3 system

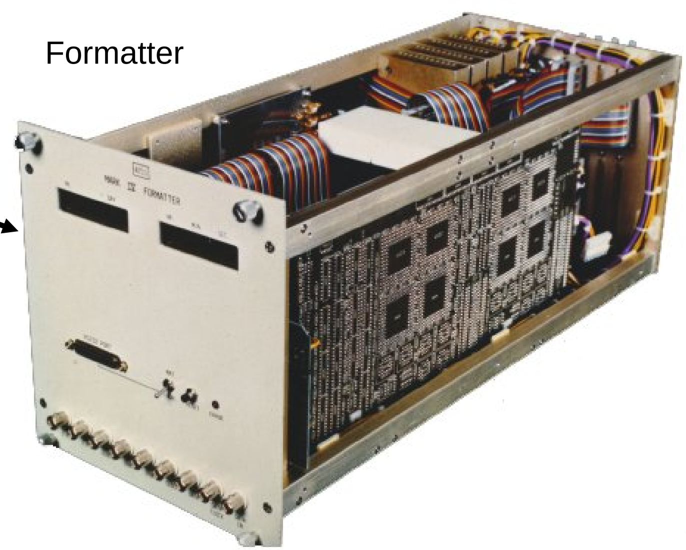
Mark 3 System



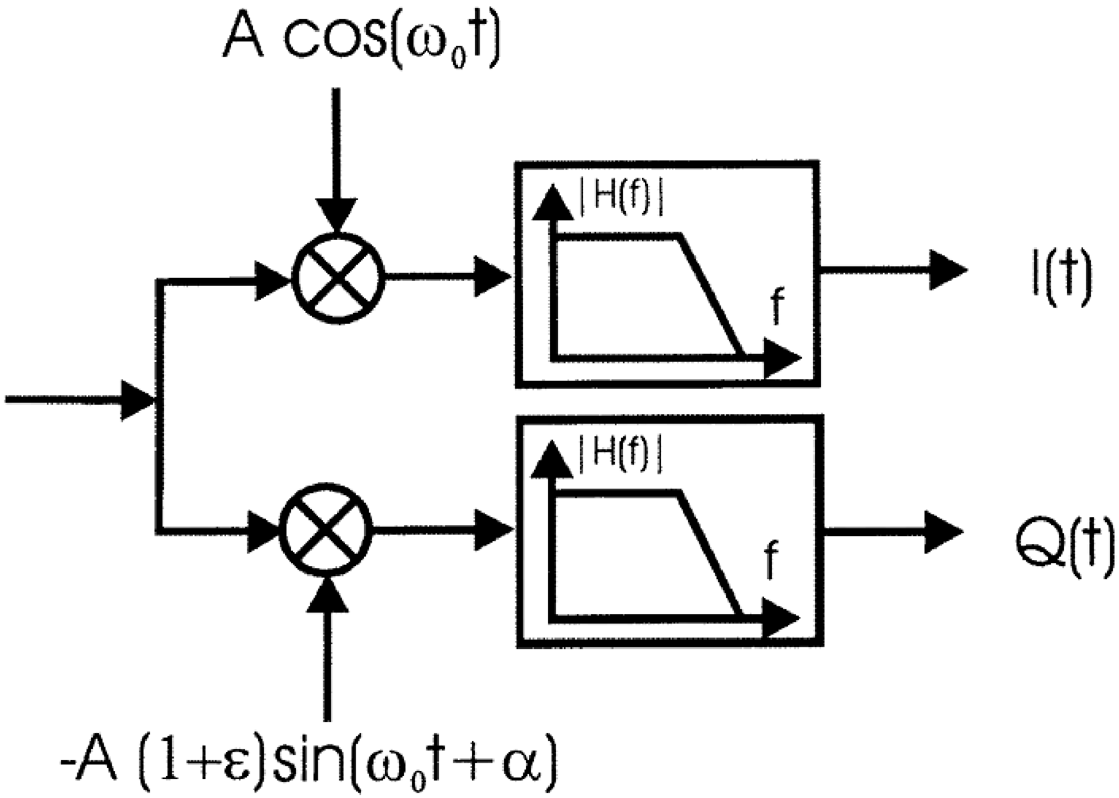


Mark 3 BBC

Formatter



Quadrature down-converter with gain and phase imbalance



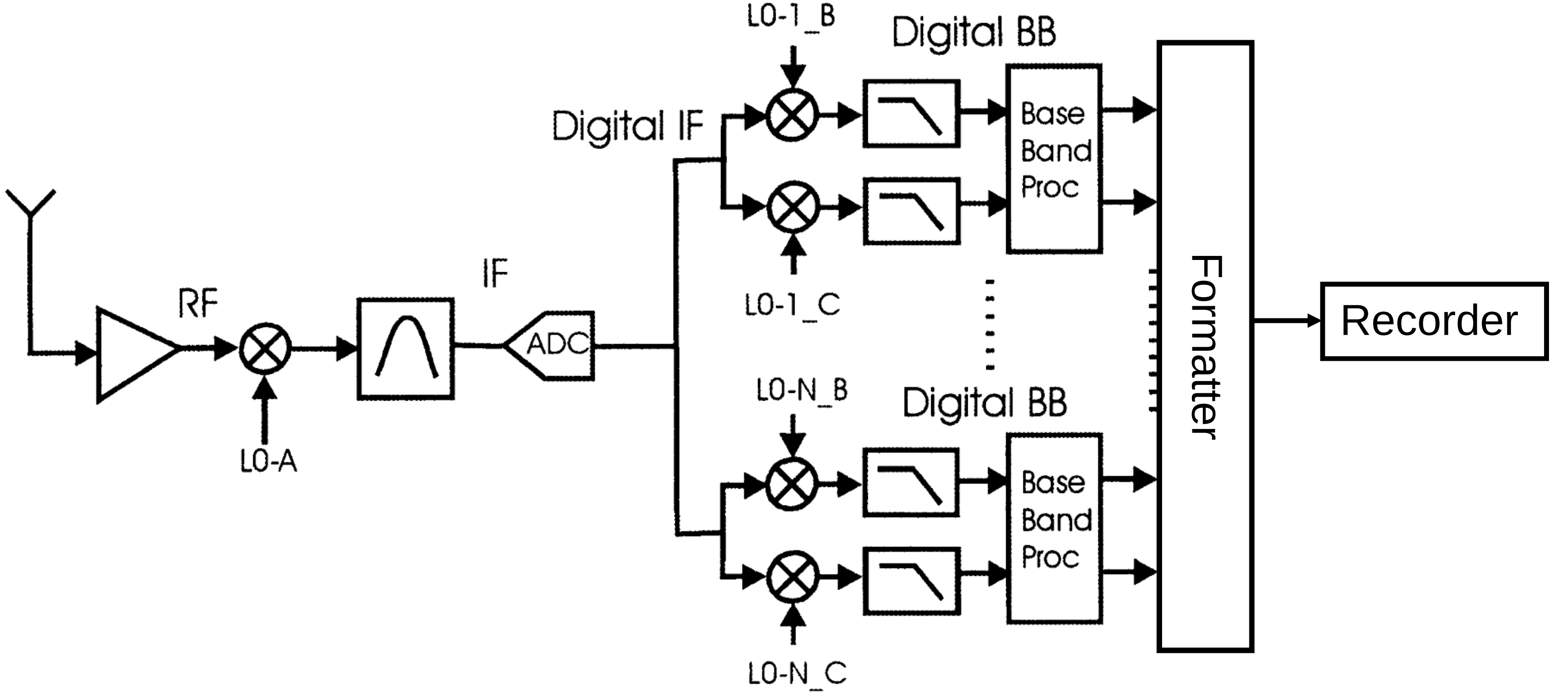
To achieve an imbalance-related spectral image 40dB below the desired spectral term, each imbalance term must be less than 1% of the desired term.

Why use digital backends?

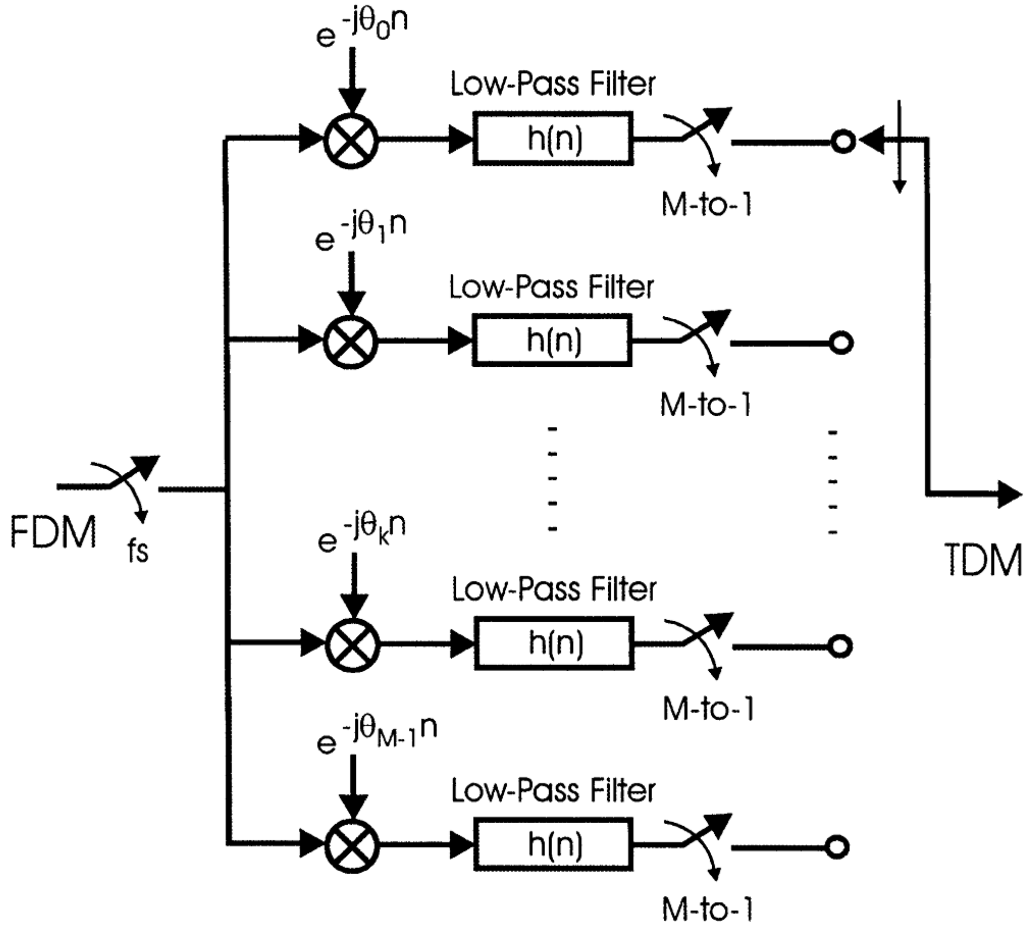
- Better performance
- Insensitive to environment (within limits)
- 100% stable
- 100% predictable
- 100% replicatible
- Easy to change/upgrade
- Easy to replicate
- Easily transferable to next-generation hardware
- Affordable cost

Rather an overwhelming case!

Typical traditional VLBI channelization: A-to-D conversion at IF followed by DDCs and lo-pass filters, formatter and recorder



Conventional digital channelizer as a replica of analog prototype: down converters, baseband filters, resamplers

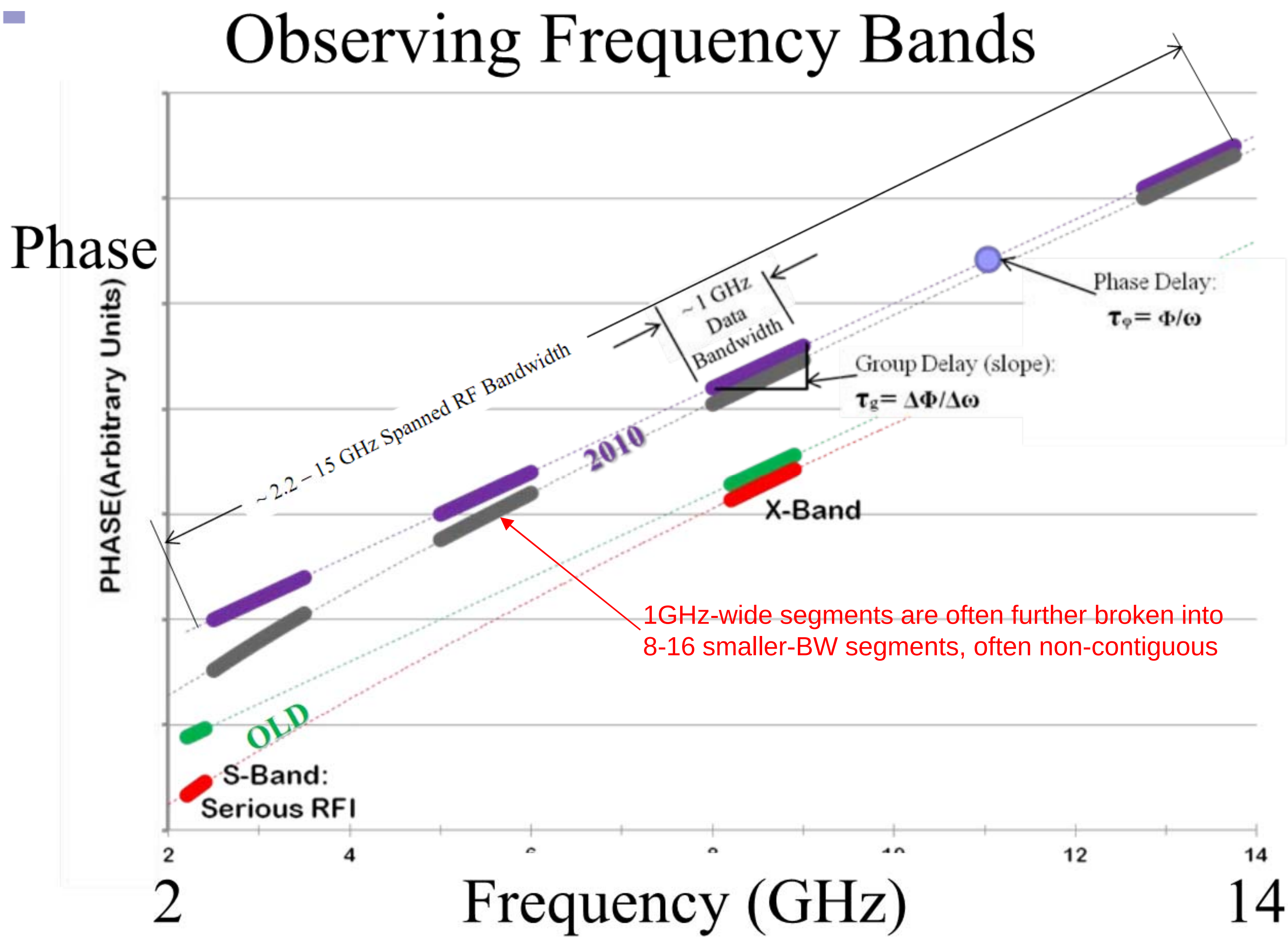


This model is still useful for some types of VLBI observations, particularly for astronomy

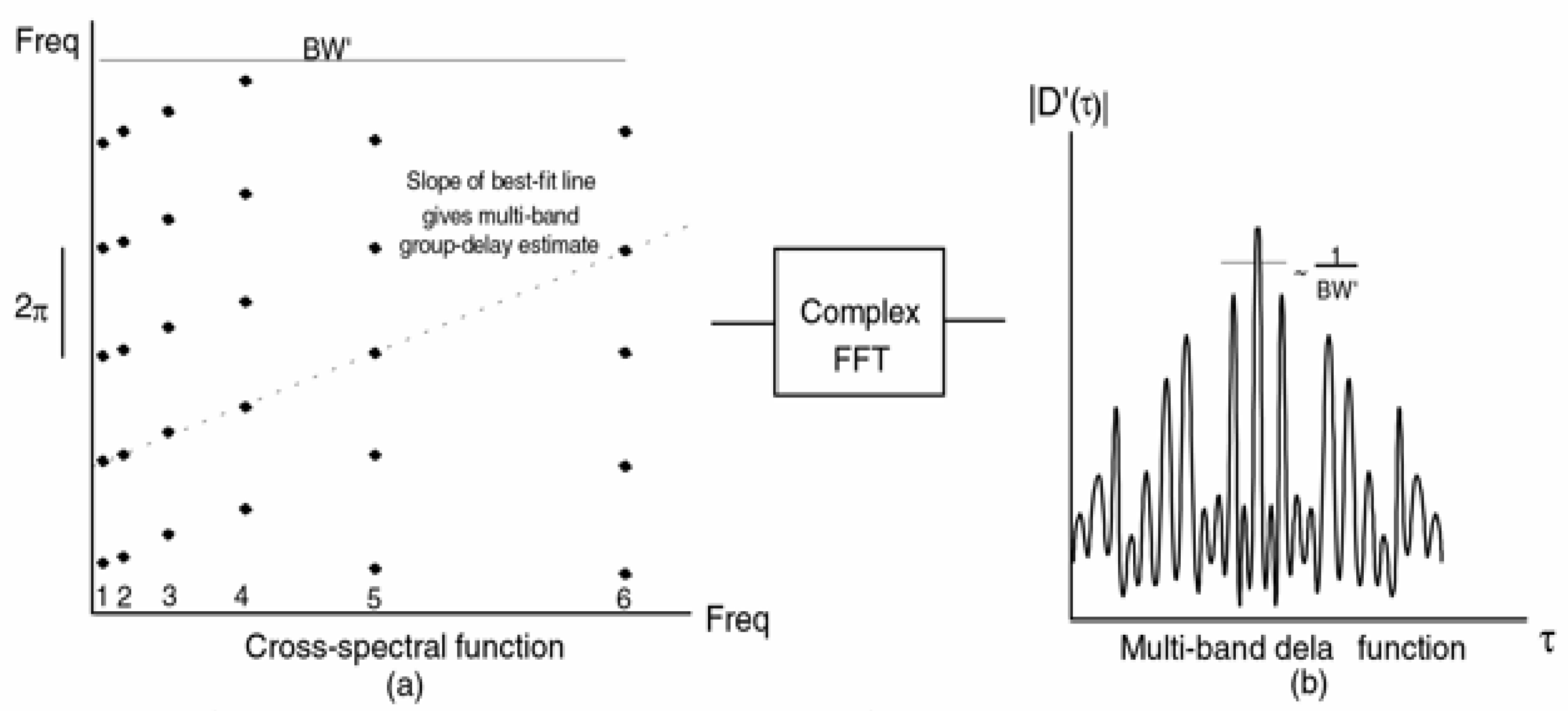
VLBI2010

Goal of VLBI2010 is ~4 psec group-delay precision
for single ~30-sec observation

VLBI2010 Observing Bands



How geodetic-VLBI group delays are determined



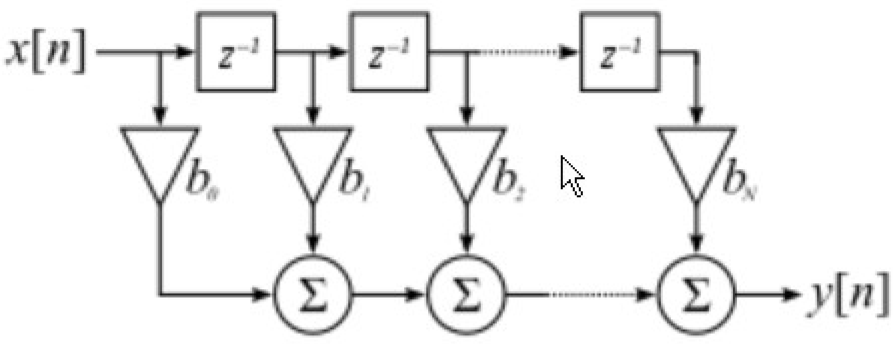
Frequency-channel spacings are chosen to be as non-redundant as possible to maximum the amplitude of main peak of delay function compared to sidelobes; an ARSAC array of frequency spacings is ideal, but not always achieveable.

Output of linear time-invariant system

The output *y* of a linear time invariant system is determined by convolving its input signal *x* with its impulse response *g (often called 'h')*.

$$(f * g)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau$$
$$= \int_{-\infty}^{\infty} f(t-\tau)\, g(\tau)\, d\tau.$$

Traditional FIR filter approximates a convolution with a time-limited impulse function



$$y[n] = b_0 x[n] + b_1 x[n-1] + \cdots + b_N x[n-N]$$
$$= \sum_{i=0}^{N} b_i x[n-i]$$

where:

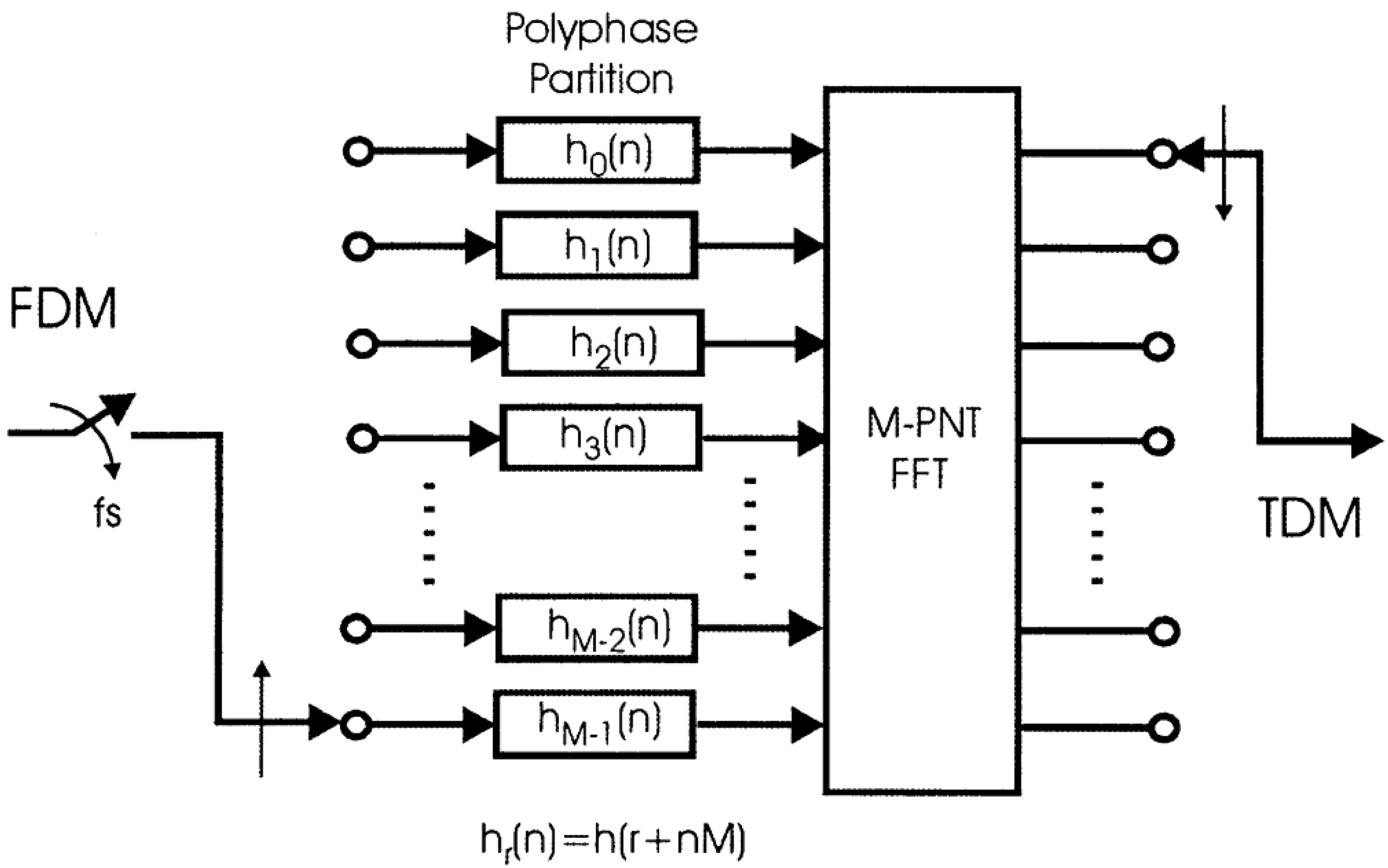
- $x[n]$ is the input signal,
- $y[n]$ is the output signal,
- b_i are the *filter coefficients*, also known as *tap weights*, that make up the impulse response,
- N is the filter order; an Nth-order filter has $(N+1)$ terms on the right-hand side. The $x[n-i]$ in these terms are commonly referred to as *taps*, based on the structure of a tapped delay line that in many implementations or block diagrams provides the delayed inputs to the multiplication operations. One may speak of a *5th order/6-tap filter*, for instance.

Equivalency Theorem

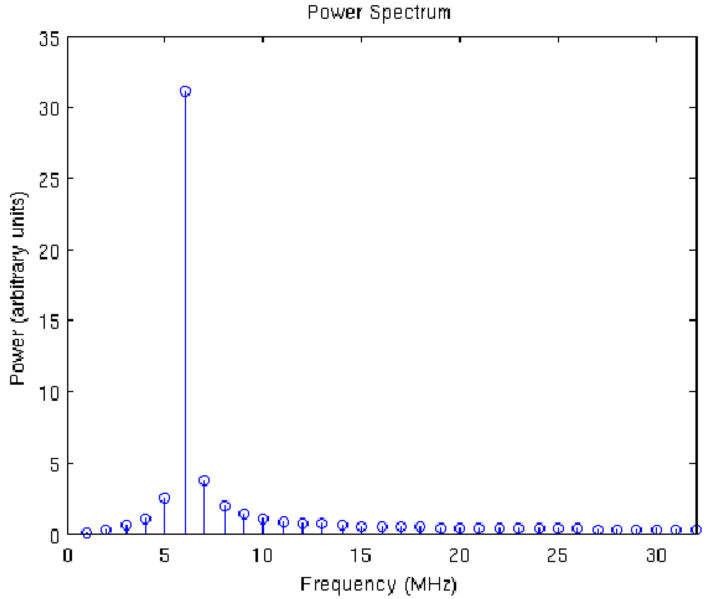
“The operations of down conversion followed by a low-pass filter are totally equivalent to the operations of a bandpass filter followed by a down conversion.”

Wozencraft and Jacobs, *Principles of Communications Engineering*, 1967

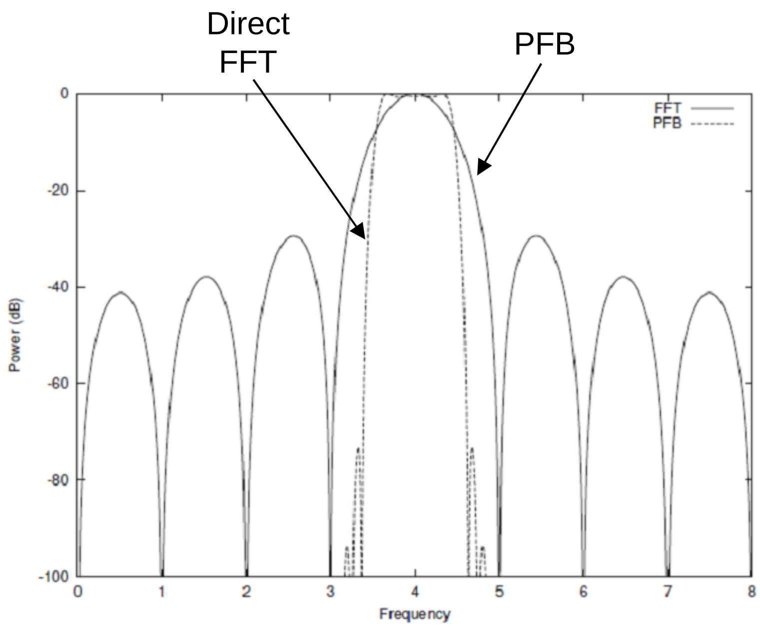
Polyphase channelizer:
resampler, all-pass partition, FFT



Comparison of DFT vs PFB response

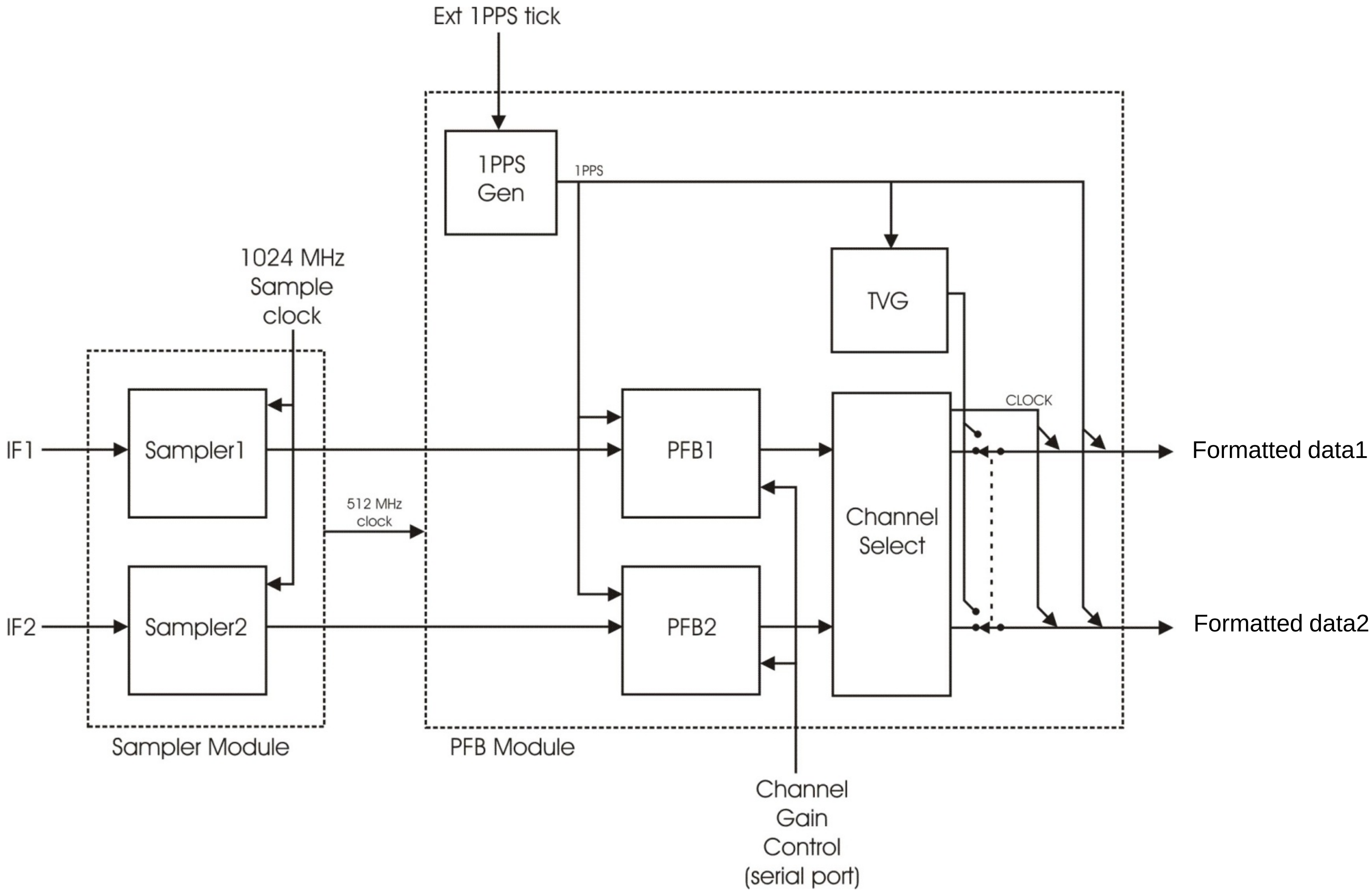


DFT leakage from tone at 5.1MHz, sampled at 128MHz

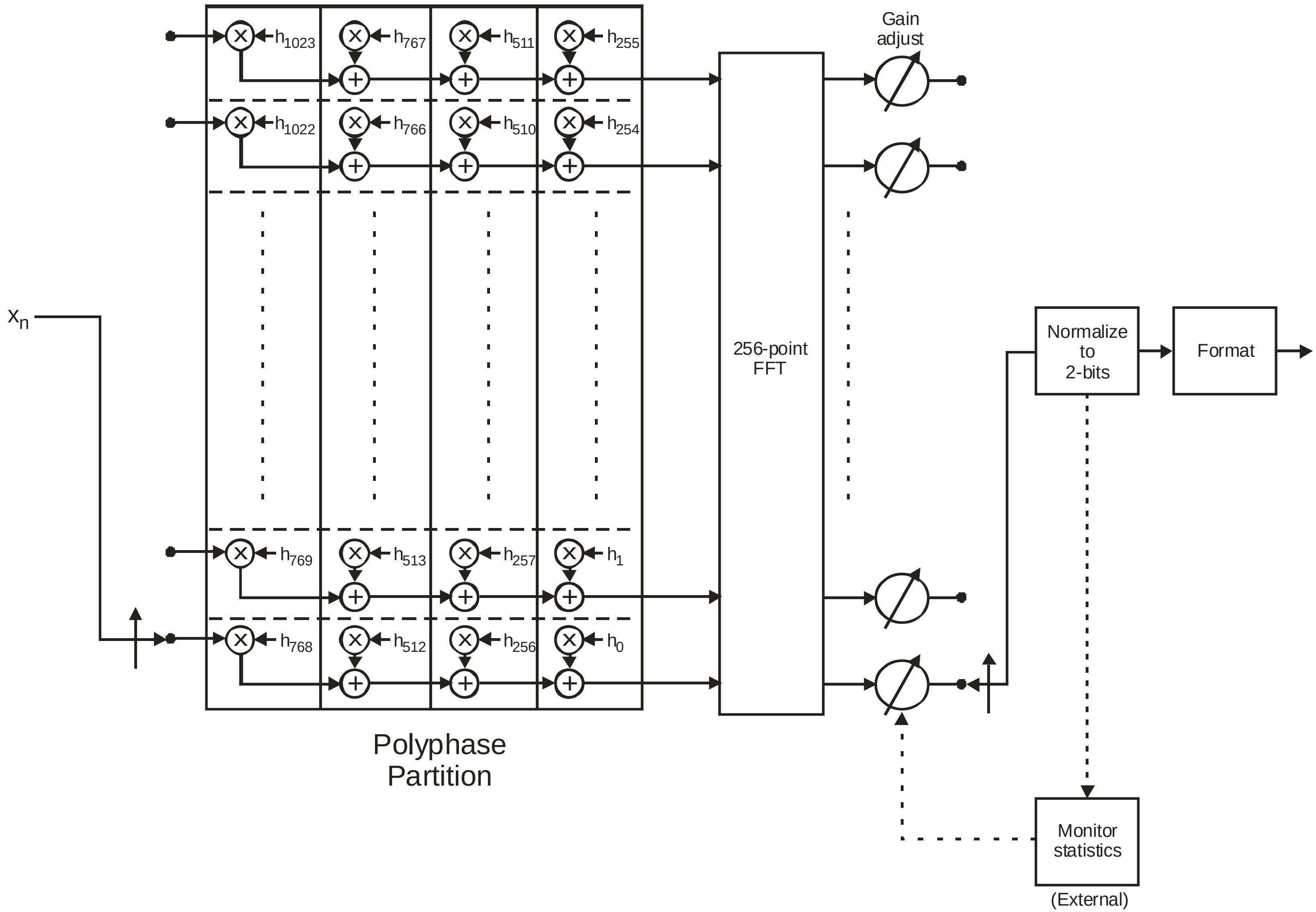


Comparison of single-bin frequency response of PFB with direct FFT

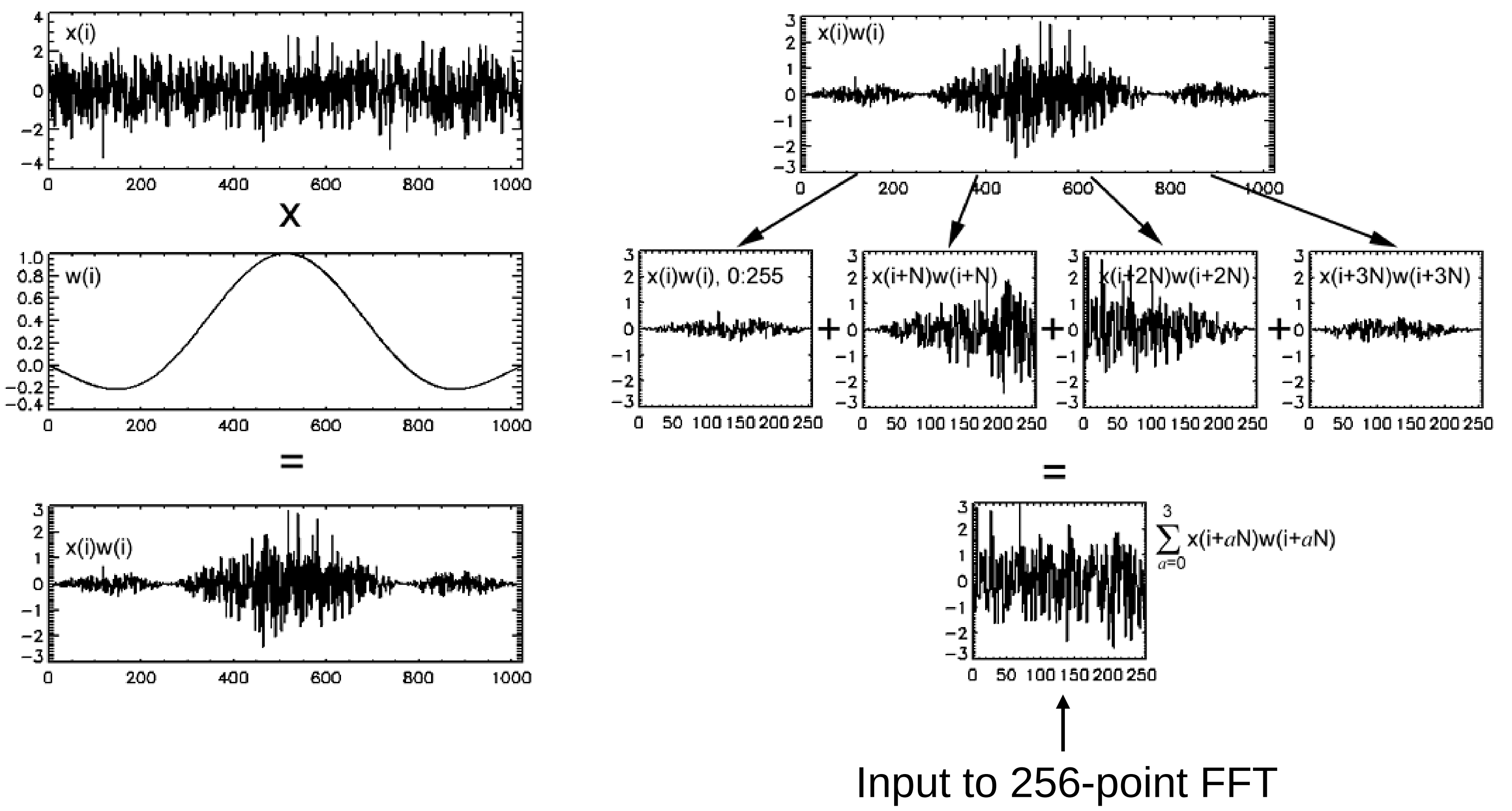
General block diagram of a PFB unit



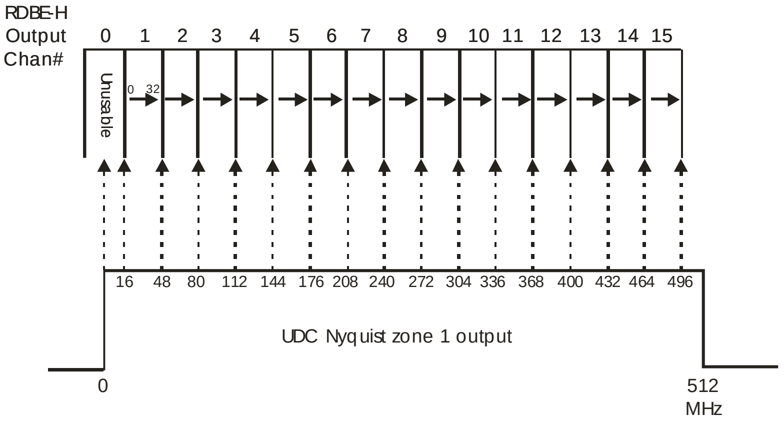
Polyphase channelizer
(time series of length 1024; split into 4 blocks of 256 each)

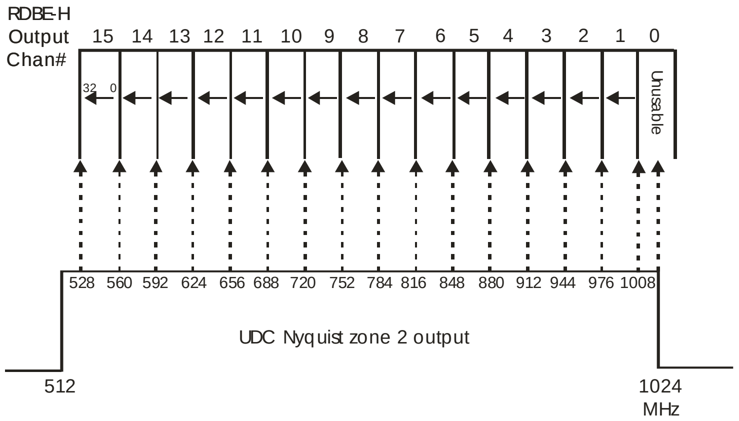


PFB implementation on CASPER ROACH board



Relationship between RDBE-H analog input IF and digital output channels for cases of input Nyquist-zones 1 (top) and 2 (bottom)



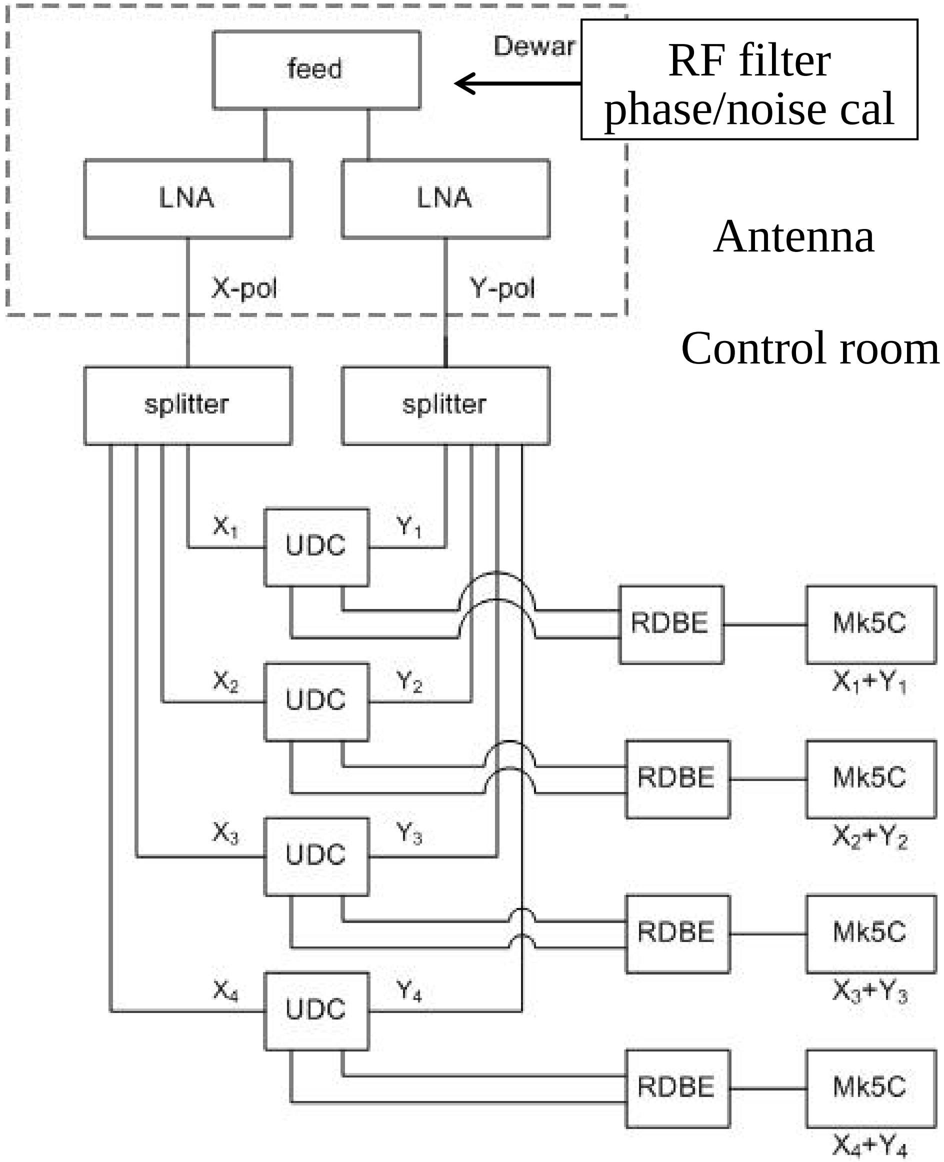


Examples of available DBEs

- ROACH-base DBEs (Haystack/NRAO)
- DBBC series (INAF/EVN)
- CDAS-DDC and CDAS-PFB (SHAO)
- ADS3000+ (NICT, JAXA/ISAS)
- BRAS (IAA)
- JPL DBE (JPL)
- XCube (XCube)

Full list and comparison at
http://ivs.nict.go.jp/mirror/technology/vlbi2010-docs/dbe_comparison_130121.pdf

RDBE Usage in VLBI2010 Prototype System



Feed and LNAs cooled to ~20K

Both senses of linear polarization used

Odd channels from each pol'n for one band output to each Mk5C.

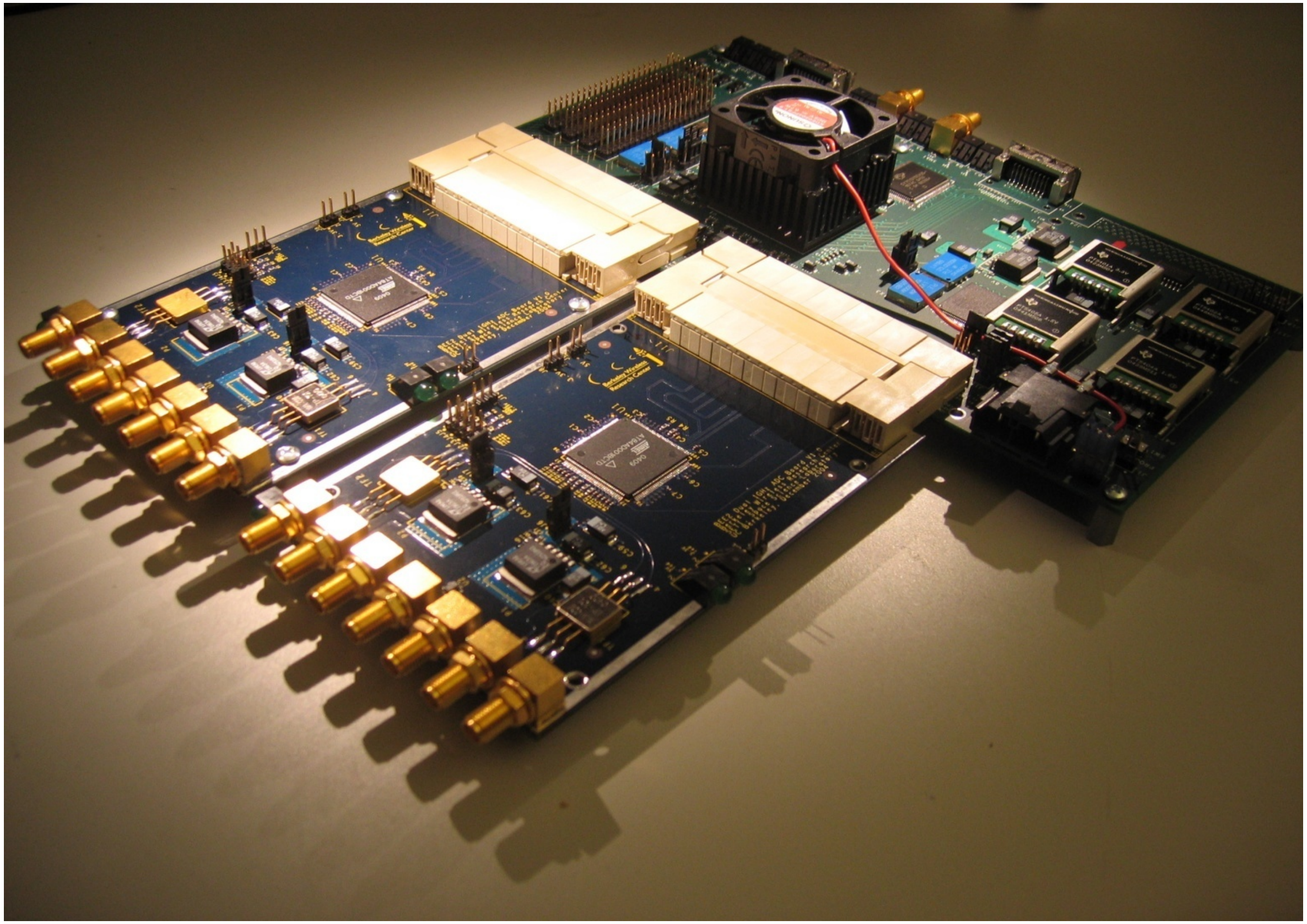
2 Gigabits/sec recorded on each Mk5C.

Total data rate: 8 Gbps

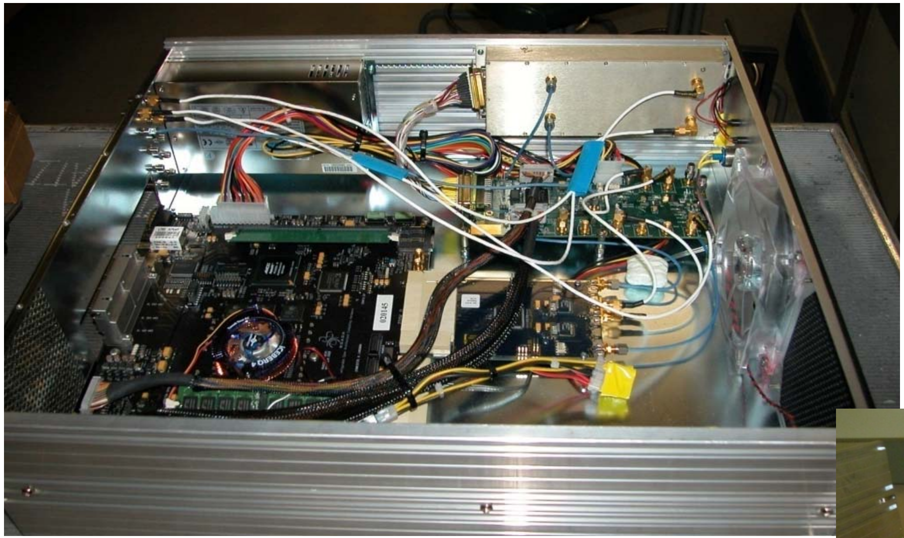
PFB Design Criteria for VLBI

- PFBs designed for VLBI must be more accountable than PFBs designed for general use
  - Synchronization to external 1pps
  - Strict timing accountability; sample time-tags must be tracked accurately from A/D through to output
  - Timing of parallel samples across all channels must be exactly the same
  - For geodesy, and particularly VLBI2010, out-of-band specifications for each channel is very demanding (typically >~70dB suppression)

CASPER ROACH board w/two sampler boards

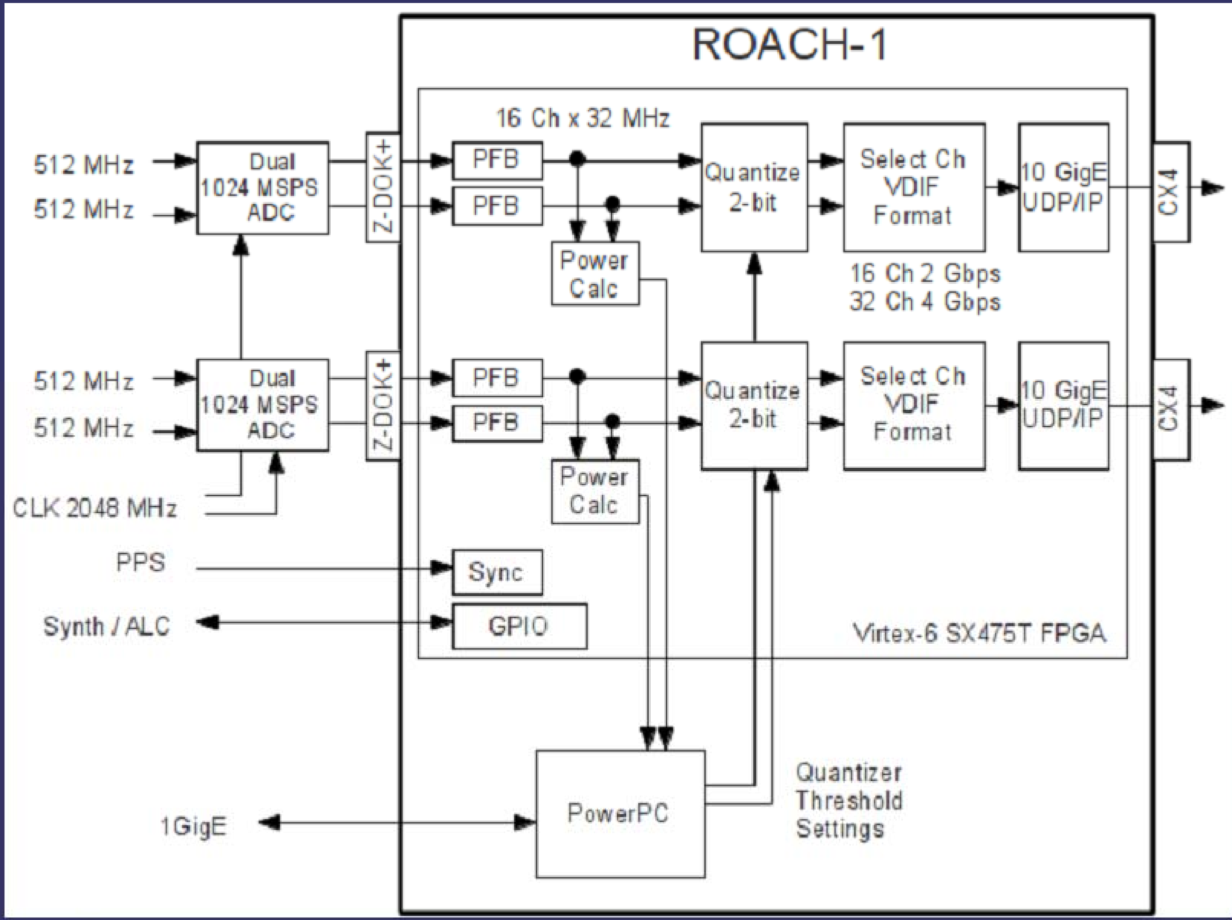


RDBE housed in 3U ‘ROACH Hotel’



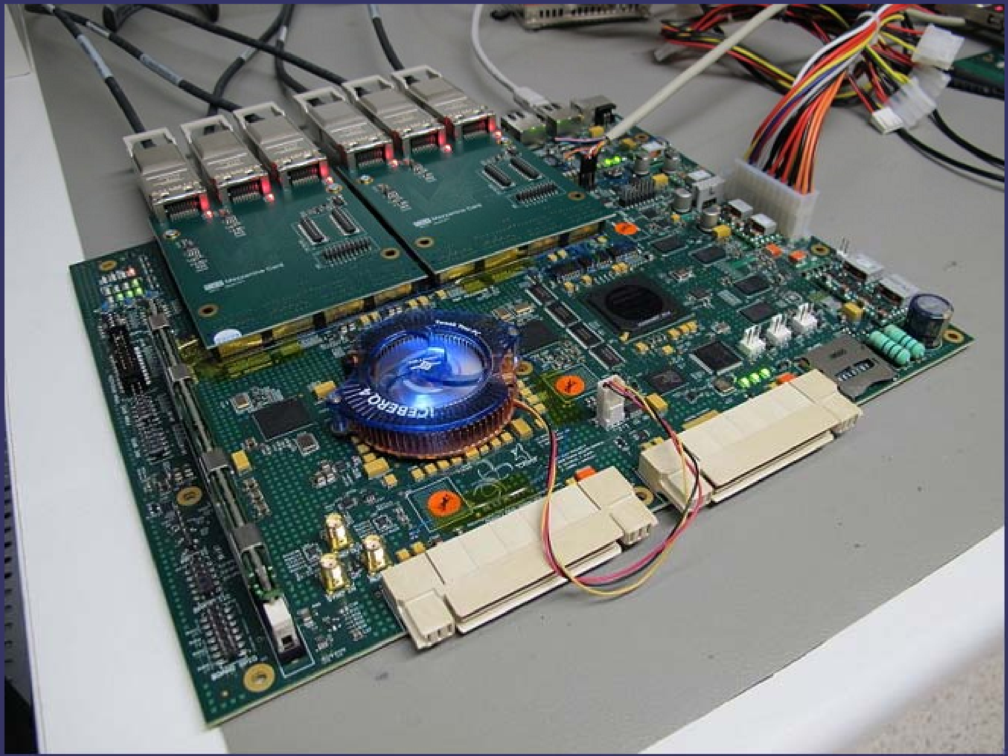
RDBE-Q

- Four 512 MHz IF bands
- Flexible 2 / 4 / 8 Gbps data storage rate
- VDIF output packets
- single N point complex FFT to compute two N point real FFT



Roach 2 with ADC1x5000-8

- Virtex-6 SX475T FPGA three times DSP resource
- Two Z-DOK+ 8-bit dual 2.5GSPS in two-channel mode
- CX4 or SFP+ mezzanine board for eight 10 GbE links



https://casper.berkeley.edu/wiki/ADC1x5000-8

MIT HAYSTACK OBSERVATORY

NASA

DBE Intercomparison Testing

- Intercomparison testing sessions at Haystack Observatory in 2009 and 2012
- Goal is to test correct operation and interoperability; much easier and more accurately than trying to do so using VLBI observations
- 2012 testing included
  - DBBC/PFB (INAF/EVN)
  - ADS3000+ (NICT, JAXA/ISAS)
  - CDAS-DDC and CDAS-PFB (SHAO)
  - RDBEH (Haystack/NRAO/CASPER)

Full list and comparison at
http://ivs.nict.go.jp/mirror/technology/vlbi2010-docs/dbe_comparison_130121.pdf

Test Objectives

- Test compatibility with laboratory interfaces, command/control functionality, data-format compatibility
- Single-baseline cross-corr test of each unit paired with RDBEH unit; all station auto-correlations
- Simultaneous 4-station zero-baseline cross-corr of all station pairs; all station auto-correlations
- 2012 testing included
  - DBBC (INAF/EVN), both DDC and PFB capability; record on Mark 5C
  - CDAS-DDC and CDAS-PFB (SHAO); record on Mark 5B+
  - ADS3000+ (NICT, JAXA/ISAS); record on K5
  - Haystack RDBEH; record on Mark 5C

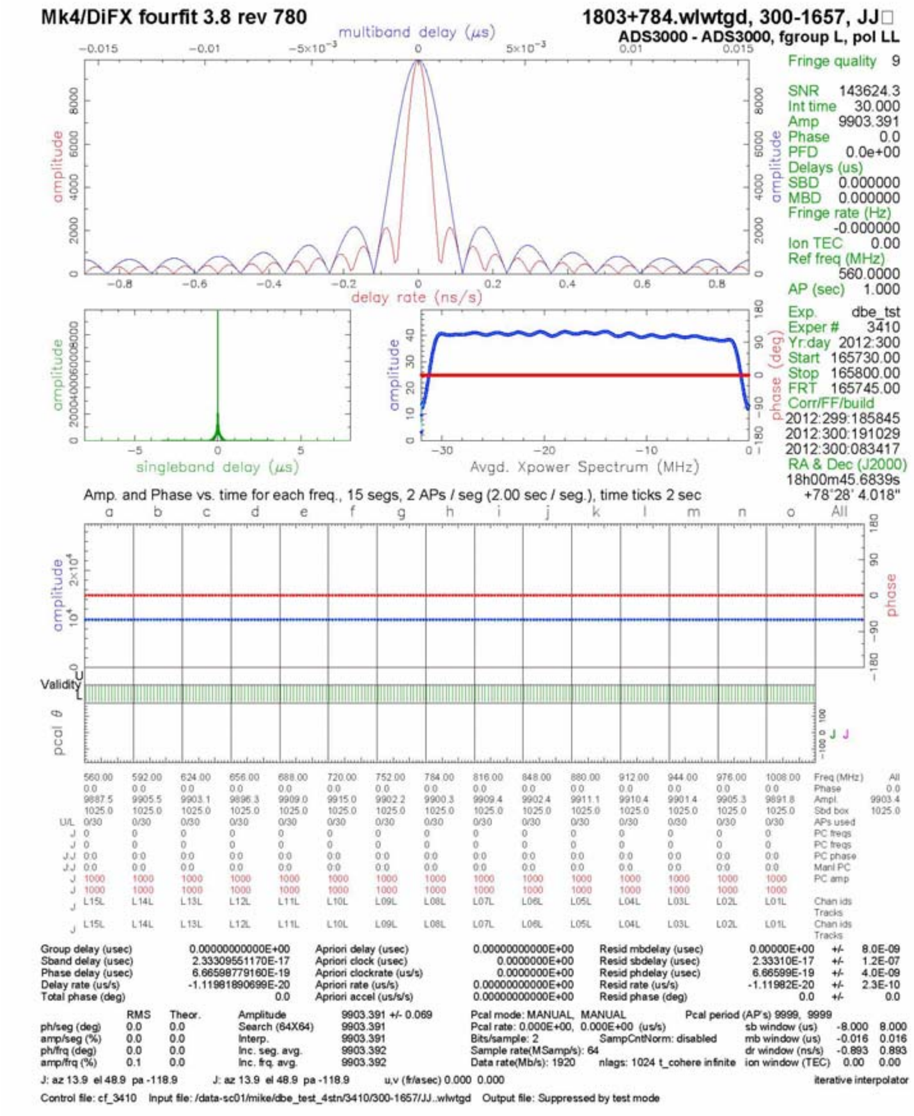
Test Environment

- All units supplied with common 5/10MHz ref signal
- All units synchronized to common 1pps
- All units set to identical UT times
- All units supplied with identical 100MHz-to-2GHz broadband noise signal
- IF level set appropriately for each unit under test
- All units equipped with 512MHz-wide 2^{nd} Nyquist zone filters; 1024 Msample/sec sampling rate used for all units

Autocorrelation testing

- Each unit recorded ~30 seconds of data
- Auto-corr processing done on DiFX correlator
- Results of all stations were nominal

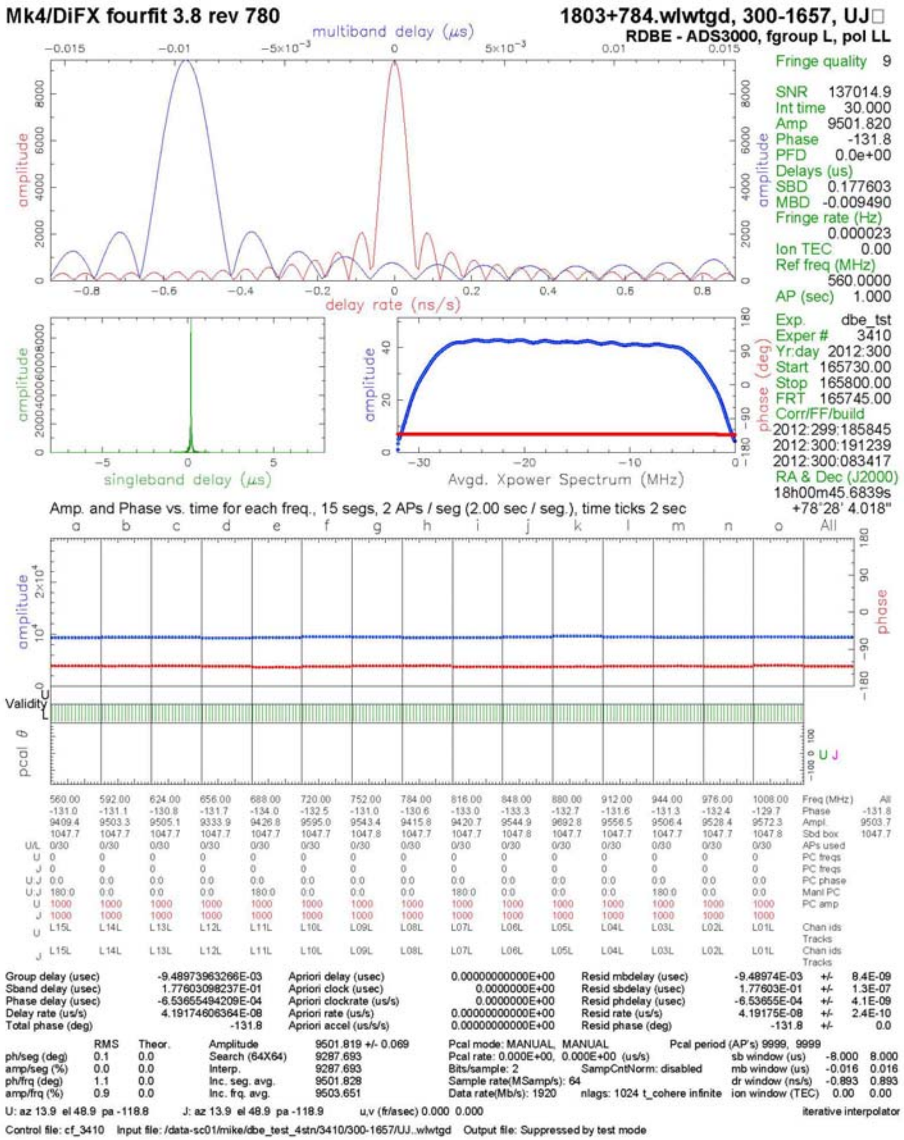
Typical frnge output for auto-correlation test



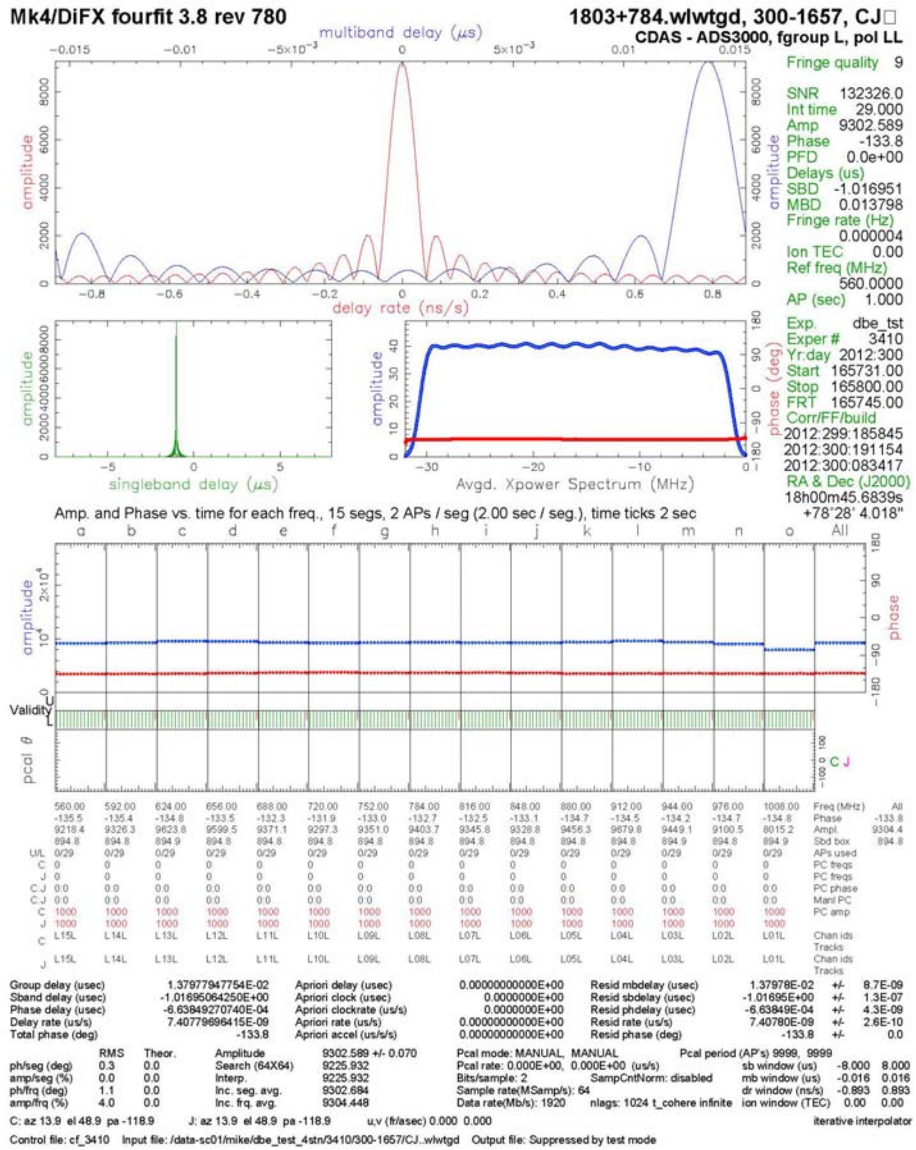
Cross-correlation testing

- Each unit under test recorded ~30 seconds of data simultaneously with Mark 6 on RDBEH
- Processing done on DiFX correlator
- Results of all stations were nominal

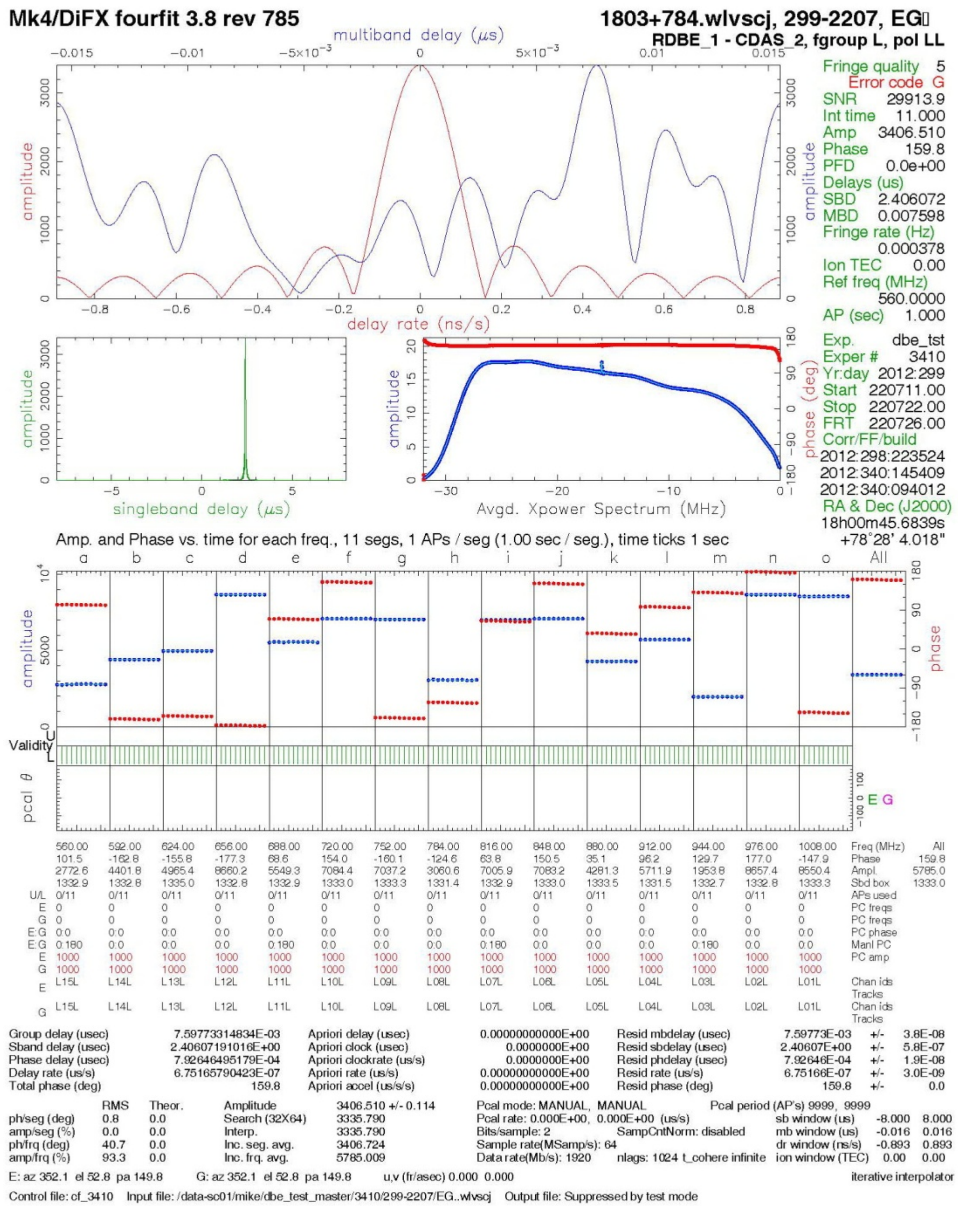
RDBE-to-ADS300+ cross-corr results



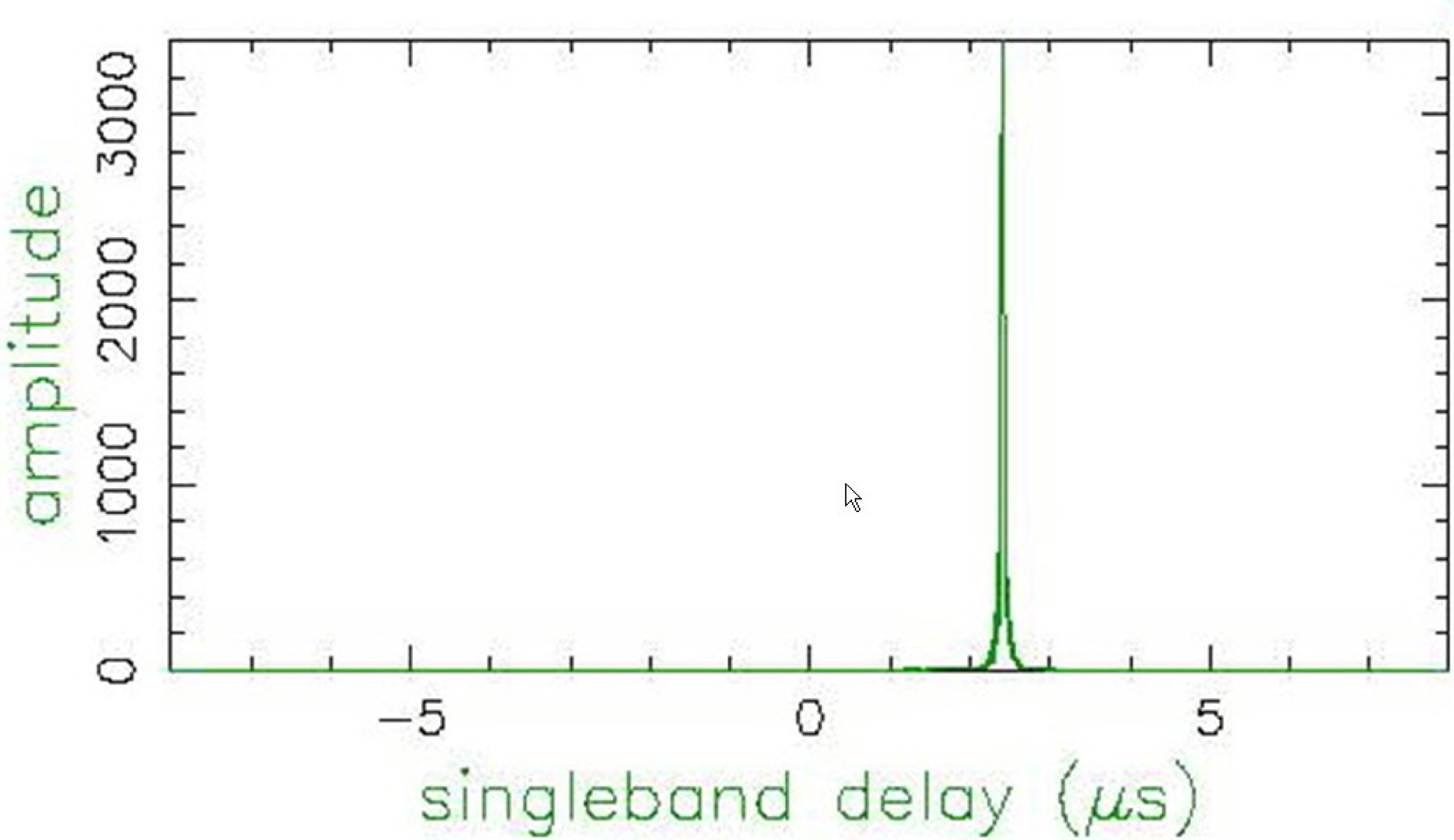
CDAS/PFB-to-ADS3000+ cross-corr results



RDBEH-to-CDAS/DDC cross-corr results



RDBEH-to-CDAS/DDC cross-corr results (single-band delay function)



Comparison of channel-by-channel delays between pairs of test units

Scan	299-2207	300-1657	300-1657	300-1657	300-1657	300-1657	300-1657	
DBEs	RDBE to CDAS-DDC	RDBE to ADS3000	DBBC to CDAS-PFB	DBBC to ADS3000	CDAS-PFB to ADS3000	RDBE to DBBC	RDBE to CDAS-PFB	
Baseline	EG	UJ	EC	EJ	CJ	UE	UC	
SBDs (usec)								
a	2.405219	0.177372	0.776232	-0.240674	-1.017162	0.418344	1.194596	
b	2.404540	0.177720	0.777008	-0.240094	-1.016917	0.417110	1.194683	
c	2.422108	0.177591	0.777252	-0.239392	-1.016447	0.417071	1.194092	
d	2.404854	0.177558	0.777240	-0.240202	-1.017235	0.418059	1.195042	
e	2.405596	0.177662	0.777416	-0.239728	-1.017061	0.416874	1.194499	
f	2.406212	0.177384	0.776602	-0.240056	-1.016962	0.417346	1.194727	
g	2.408823	0.177836	0.777029	-0.240133	-1.017103	0.417977	1.194546	
h	2.393550	0.177433	0.777416	-0.240021	-1.016957	0.417581	1.194711	
i	2.405527	0.177388	0.777294	-0.239621	-1.016944	0.416646	1.194184	
j	2.406153	0.177790	0.776652	-0.239963	-1.016883	0.417535	1.194738	
k	2.409979	0.177269	0.776622	-0.240552	-1.017041	0.418177	1.194369	
l	2.394683	0.177703	0.777330	-0.239977	-1.017154	0.417429	1.195040	
m	2.404141	0.177586	0.776953	-0.240048	-1.016785	0.417443	1.194282	
n	2.404928	0.177432	0.776098	-0.241074	-1.017016	0.418379	1.194888	
o	2.408890	0.178279	0.775322	-0.239794	-1.016611	0.418252	1.194718	
Avg (usec)	2.405680	0.177600	0.776831	-0.240089	-1.016952	0.417615	1.194608	
Std dev (nsec)	6.449140	0.252557	0.590345	0.422538	0.209942	0.557291	0.285115	
Max-min (nsec)	28.558000	1.010000	2.094000	1.682000	0.788000	1.733000	0.950000	

Current and future PFB capabilities

- Most all PFB units support at least one 512MHz IF to create 16 32MHz-wide channels
- All units support real output; some also support complex output
- Some existing units process as many as 4 or 8 simultaneous IF inputs, some to 1024MHz or 2048MHz BW
- Aggregate output rate range from 2Gbps to 8Gbps or more; future will demand higher rates, at least up to 64Gbps (though not necessarily in a single box)
- Many units produce VDIF-format data; all are moving in that direction

DBBC Evolution

DBBC1 2004 - 2008

in: 4 x IF-512MHz

out: **DDC** 16xbbc(1-2-4-8-16MHz)@32MHz

0.512/1.024Gbps

DBBC2 2007 – to date

in: 4 x IF-512/1024MHz

out: **DDC** 16xbbc(1-2-4-8-16MHz)@32MHz

PFB 4 x 16 x 32MHz@64MHz

4.096/8.192Gbps

DBBC2010 2009 – to date

in: 8 x IF – 512/1024MHz

out: **PFB** / **DSC** **16.384/32.768Gbps**

More information

- PFB theory and technique
  - Chennamanagalam, Jayanth, “The Polyphase Filter Bank Technique, CASPER Memo 42, 2011, https://casper.berkeley.edu/wiki/The_Polyphase_Filter_Bank_Technique
  - Harris, Frederic et al, “Digital Receiver and Transmitters Using Polyphase Filter Banks for Wireless Communications”, IEEE Trans on Microwave & Techniques, 51, 4, 2003, (available from IEEE for fee, as well as free from several obscure sources – easy to find)
- Digital backend comparison
  - Petrachenko, W., “VLBI2010 Receiver Back End Comparison”, 2013, http://ivs.nict.go.jp/mirror/technology/vlbi2010-docs/dbe_comparison_130121.pdf
- DBE Intercomparison testing
  - Whitney et al, “VLBI Digital-Backend Intercomparison Test Report”, Dec 2012, http://www.haystack.mit.edu/workshop/ivtw/2012.12.17_DBE_testing_memo_final.pdf

Thanks for your attention

Questions?