

VLBI Digital Backends

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MIT Haystack Observatory

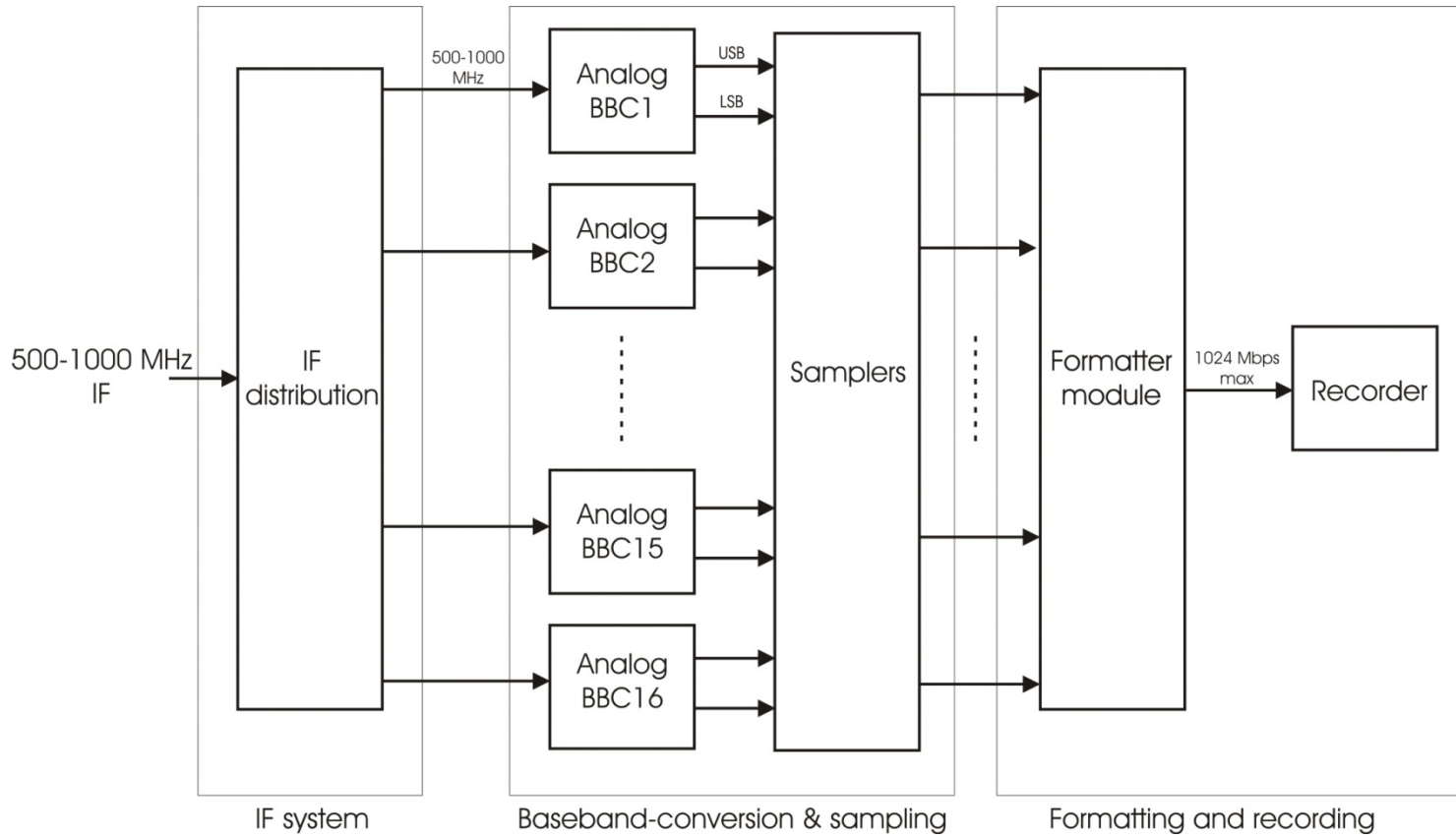
VLBI School
Helsinki, Finland
2 March 2013

Outline

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

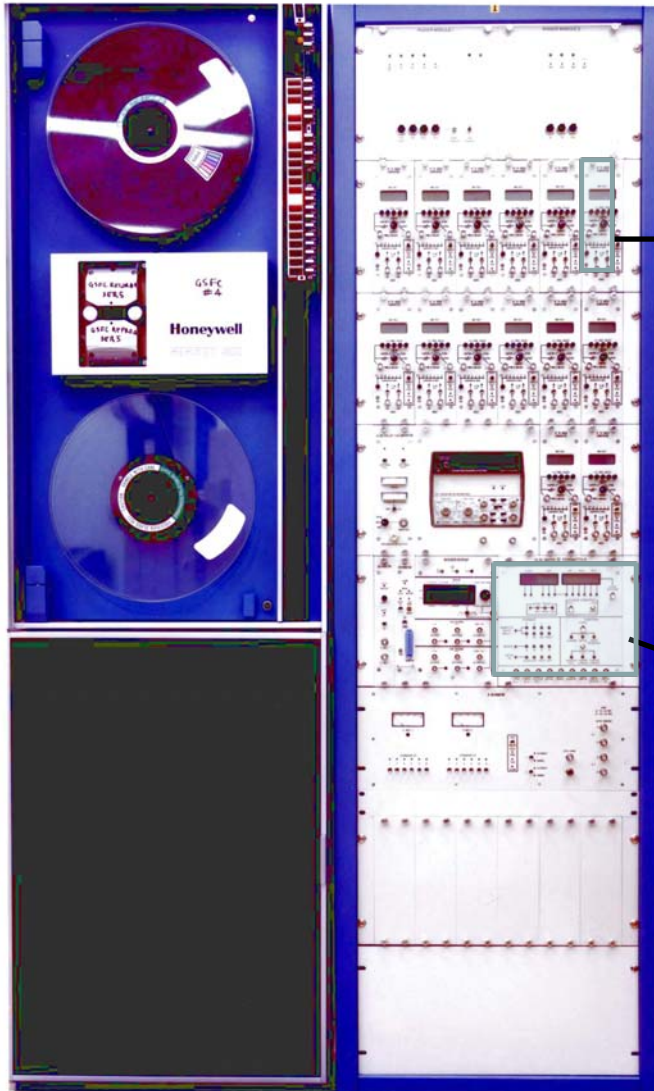
Rather an overwhelming case!

Analog backend system



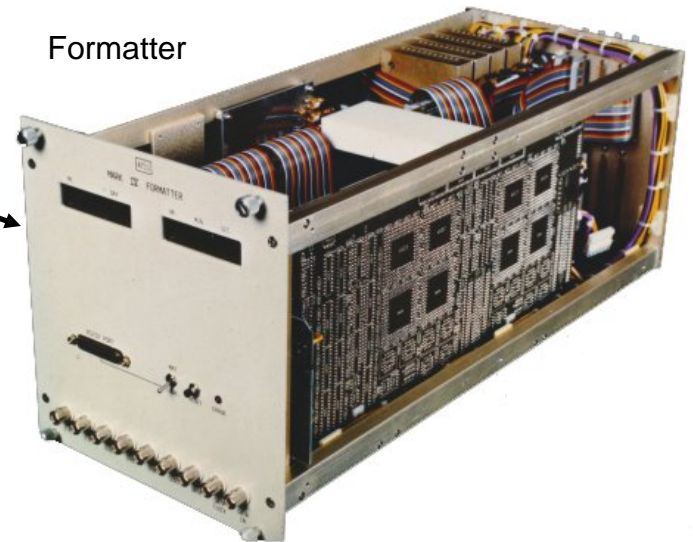
Traditional analog BBC in Mark 3 system

Mark 3 System

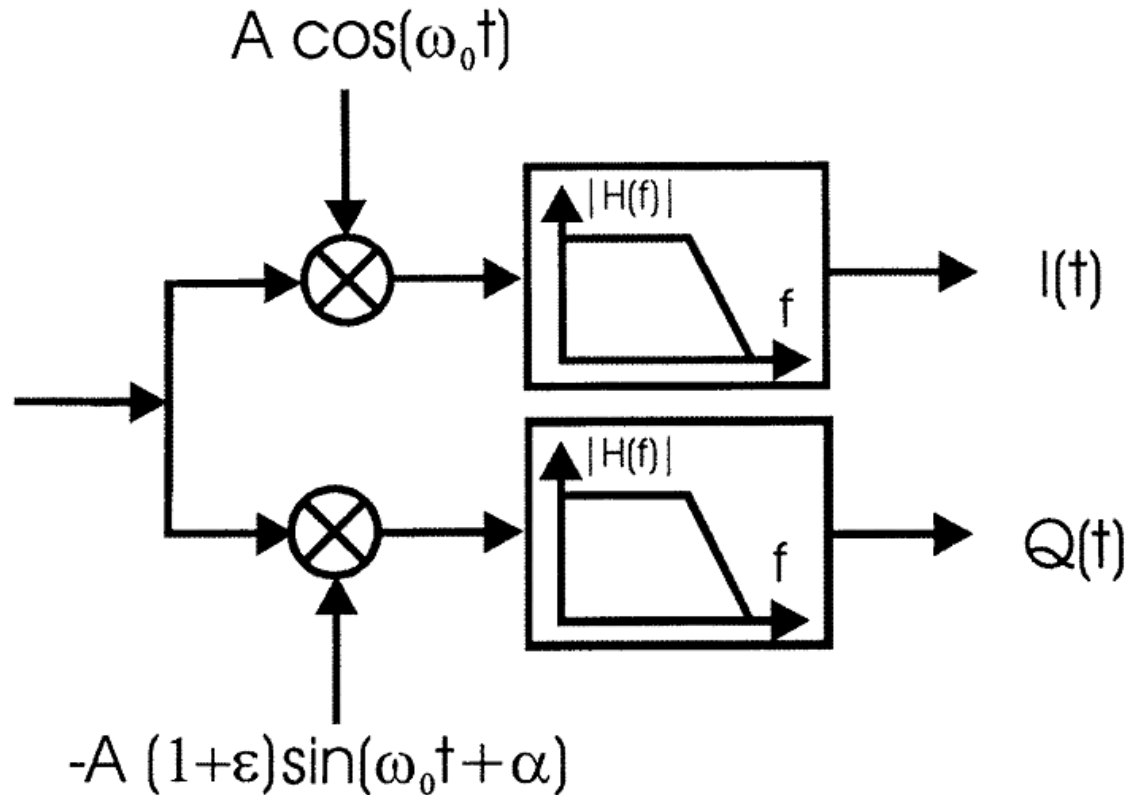


Mark 3 BBC

Formatter



Quadrature down-converter with gain and phase imbalance



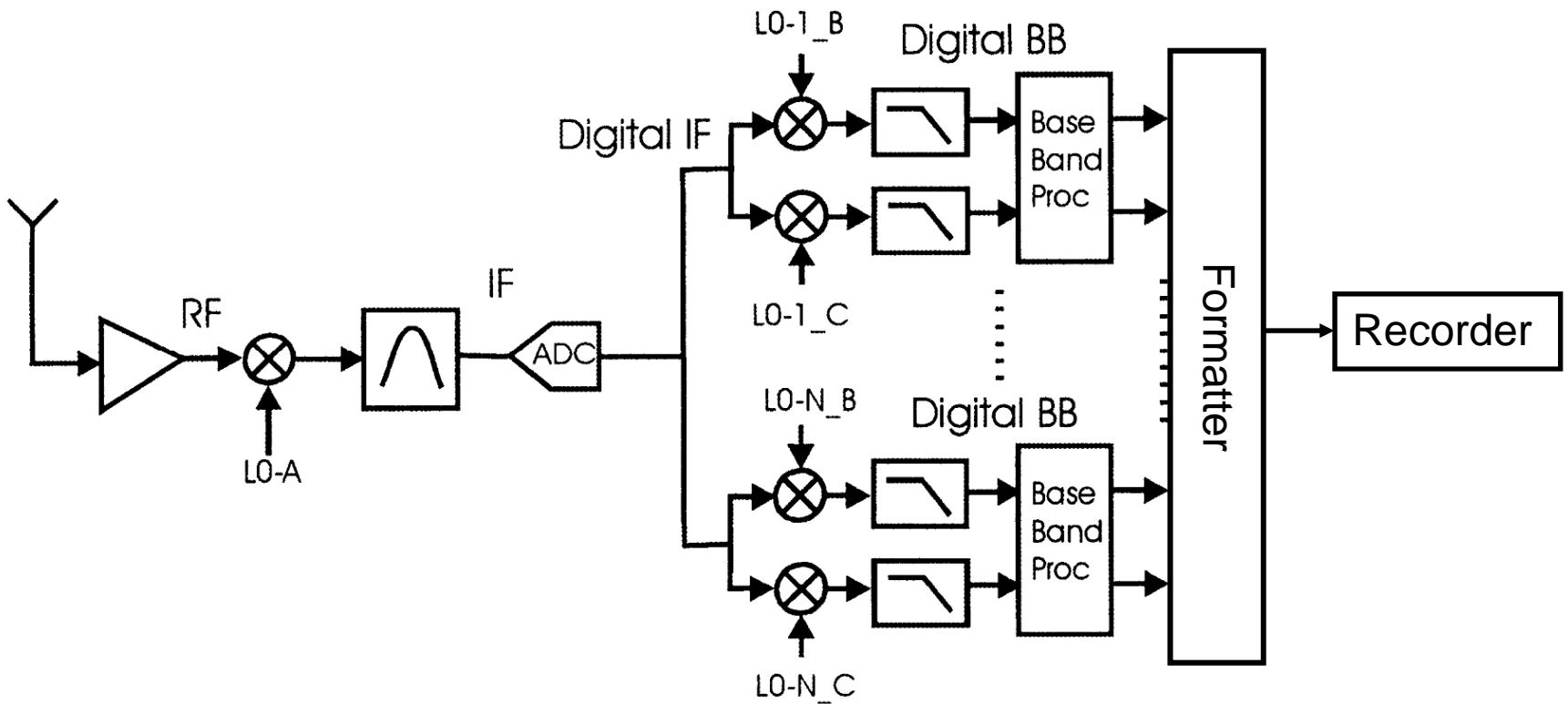
To achieve an imbalance-related spectral image 40dB below the desired spectral term, each imbalance term must be less than 1% of the desired term.

Why use digital backends?

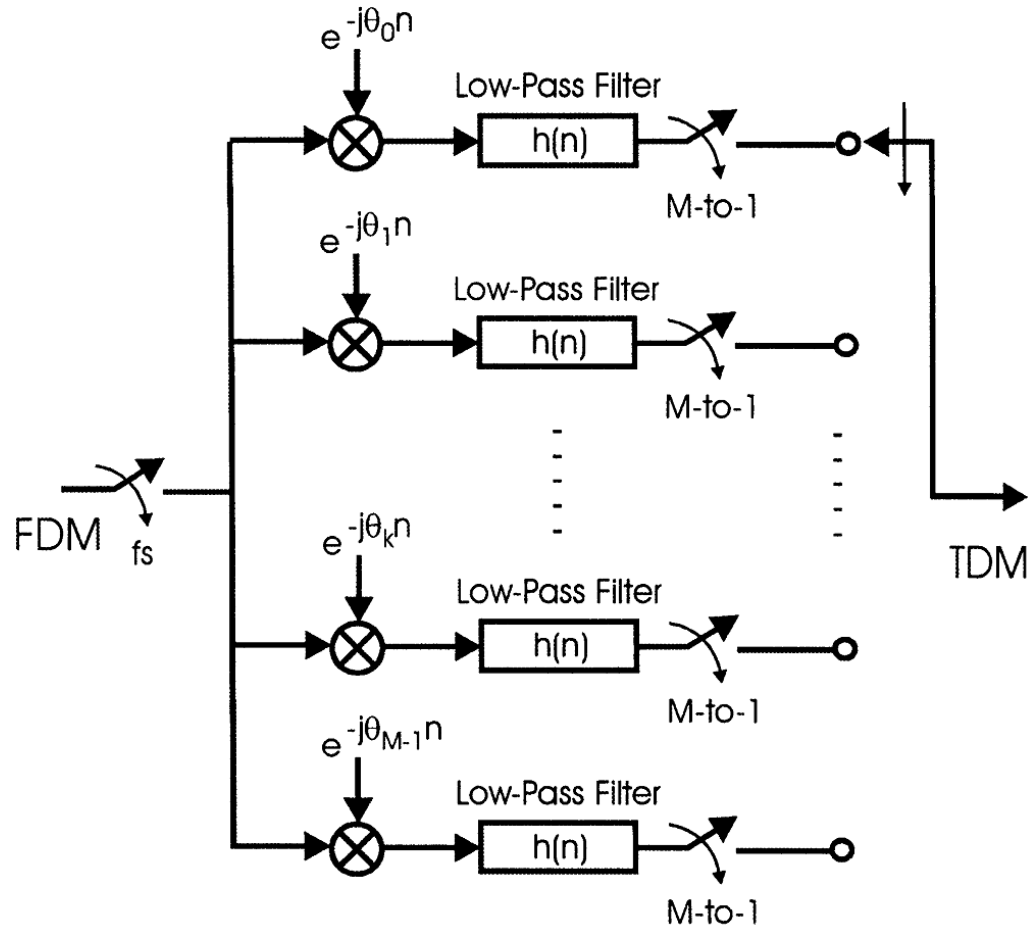
- Better performance
- Insensitive to environment (within limits)
- 100% stable
- 100% predictable
- 100% replicatable
- Easy to change/upgrade
- Easy to replicate
- Easily transferable to next-generation hardware
- Affordable cost

Rather an overwhelming case!

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

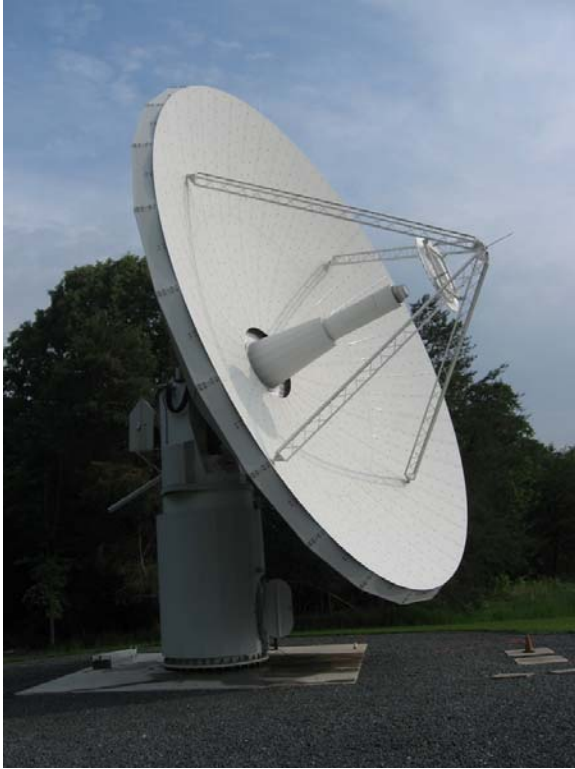


Conventional digital channelizer as a replica of analog prototype:
down converters, baseband filters, resamplers



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

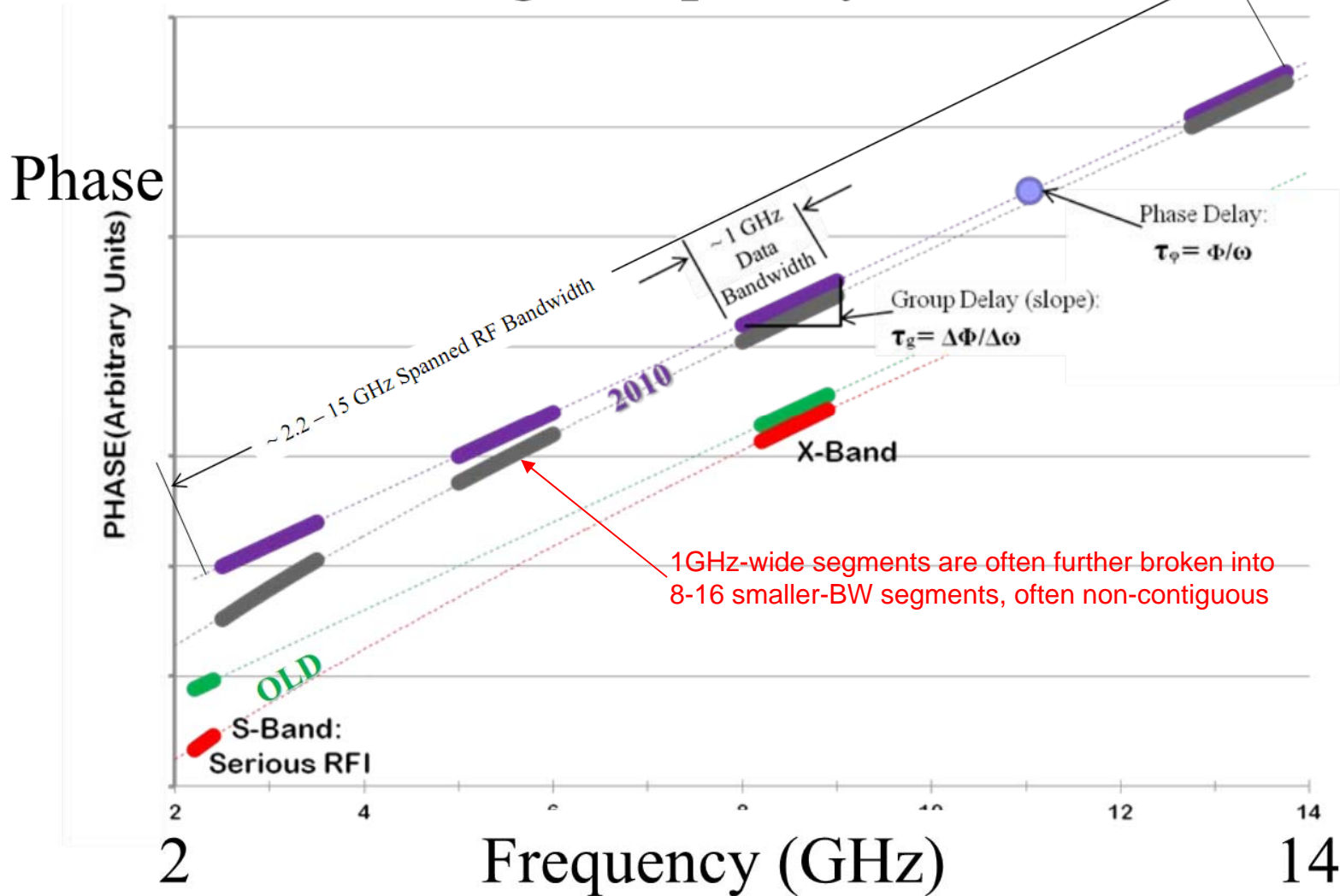
VLBI2010



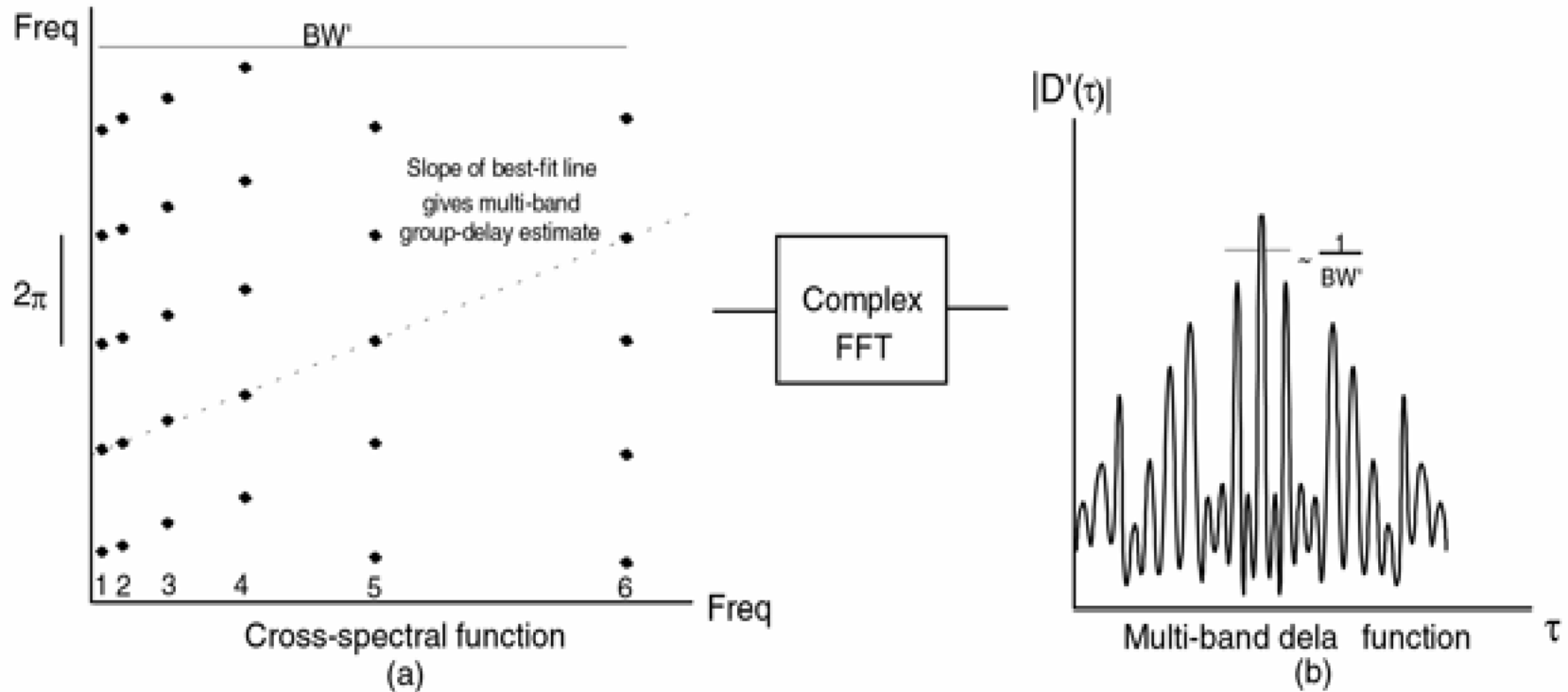
Goal of VLBI2010 is ~ 4 psec group-delay precision
for single ~ 30 -sec observation

VLBI2010 Observing Bands

Observing Frequency Bands



How geodetic-VLBI group delays are determined



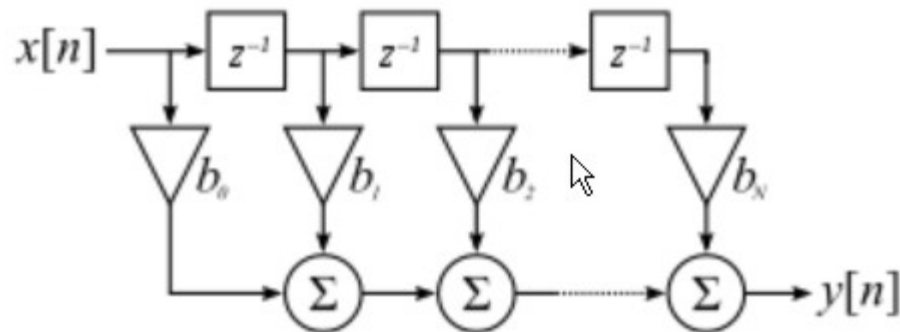
Frequency-channel spacings are chosen to be as non-redundant as possible to maximum the amplitude of main peak of delay function compared to sidelobes; an ARSAC array of frequency spacings is ideal, but not always achievable.

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').

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

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



$$y[n] = b_0x[n] + b_1x[n - 1] + \dots + b_Nx[n - N]$$
$$= \sum_{i=0}^N b_i x[n - i]$$

where:

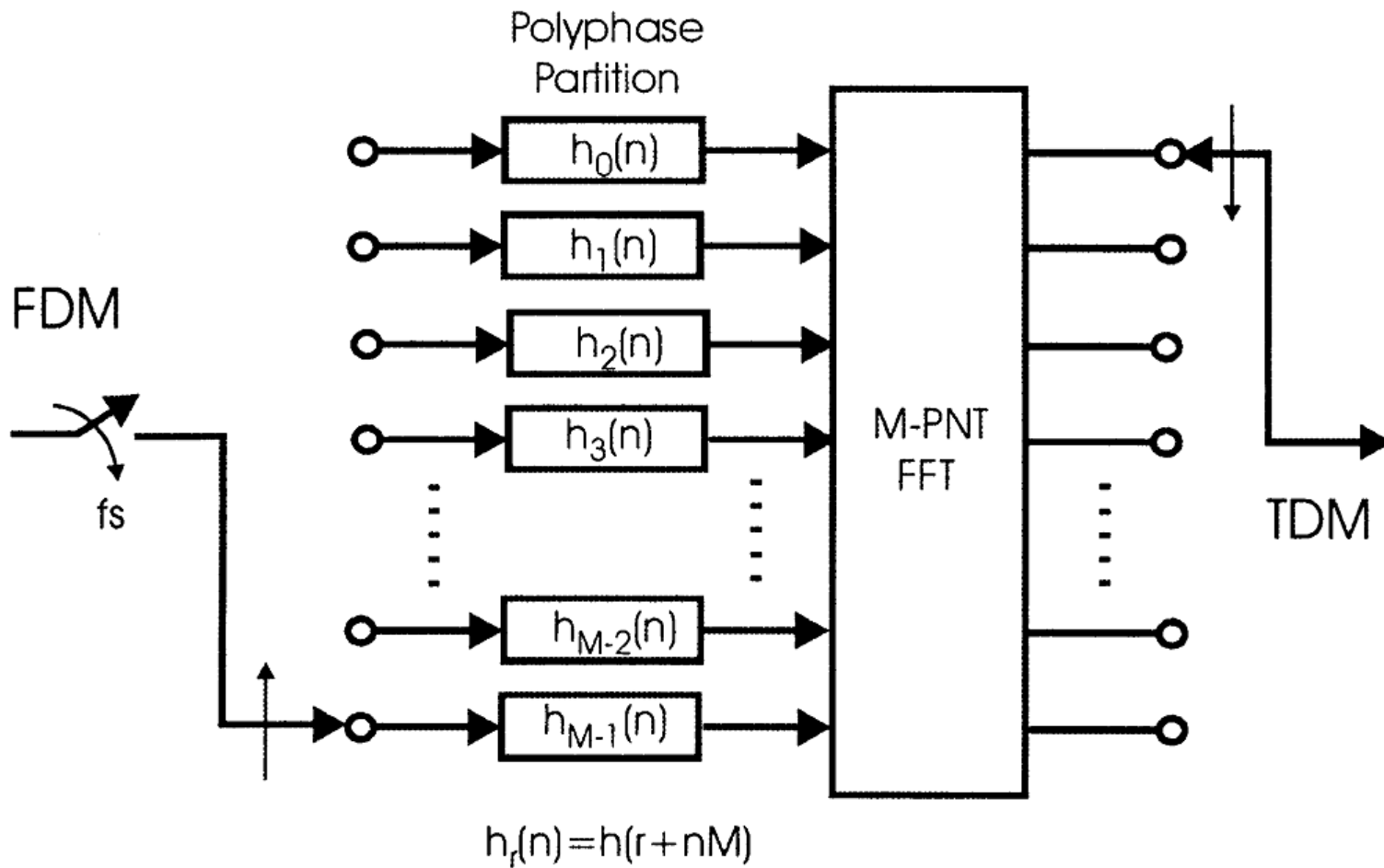
- $x[n]$ is the input signal,
- $y[n]$ is the output signal,
- b_i are the *filter coefficients*, also known as *tap weights*, that make up the impulse response,
- N is the filter order; an N th-order filter has $(N + 1)$ terms on the right-hand side. The $x[n - i]$ in these terms are commonly referred 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

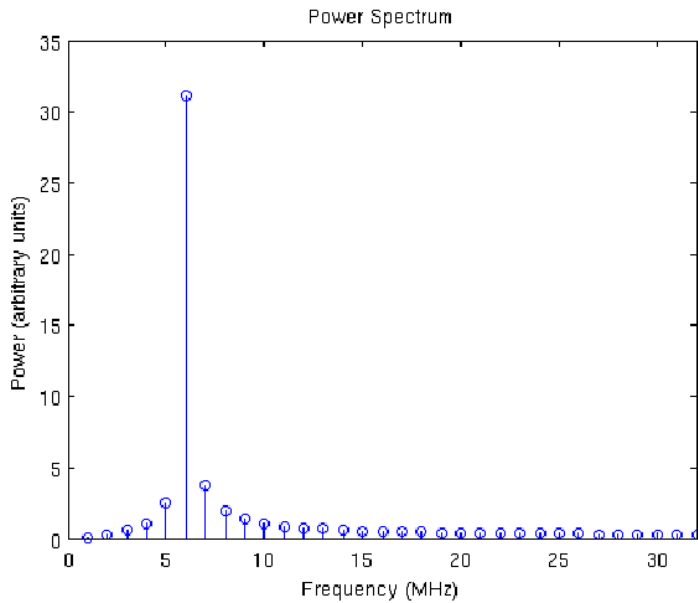
“The operations of down conversion followed by a low-pass filter are totally equivalent to the operations of a bandpass filter followed by a down conversion.”

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

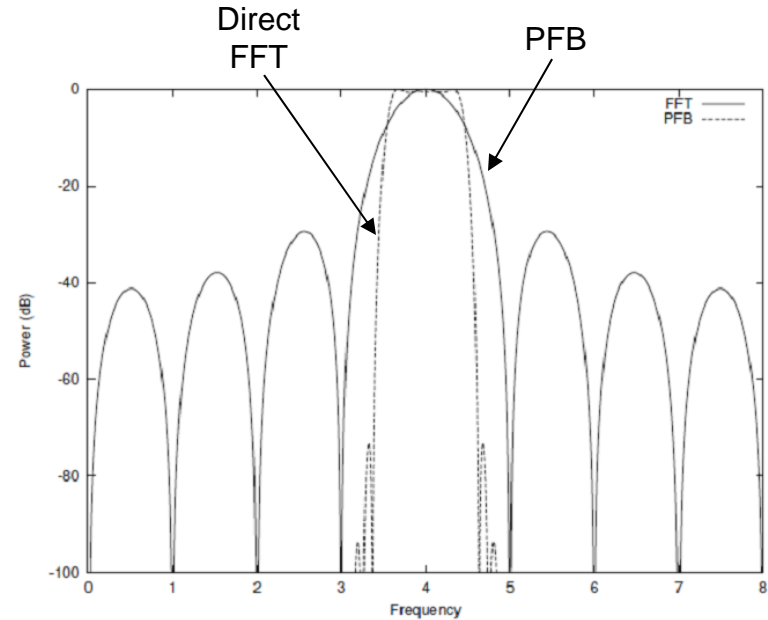
Polyphase channelizer:
resampler, all-pass partition, FFT



Comparison of DFT vs PFB response

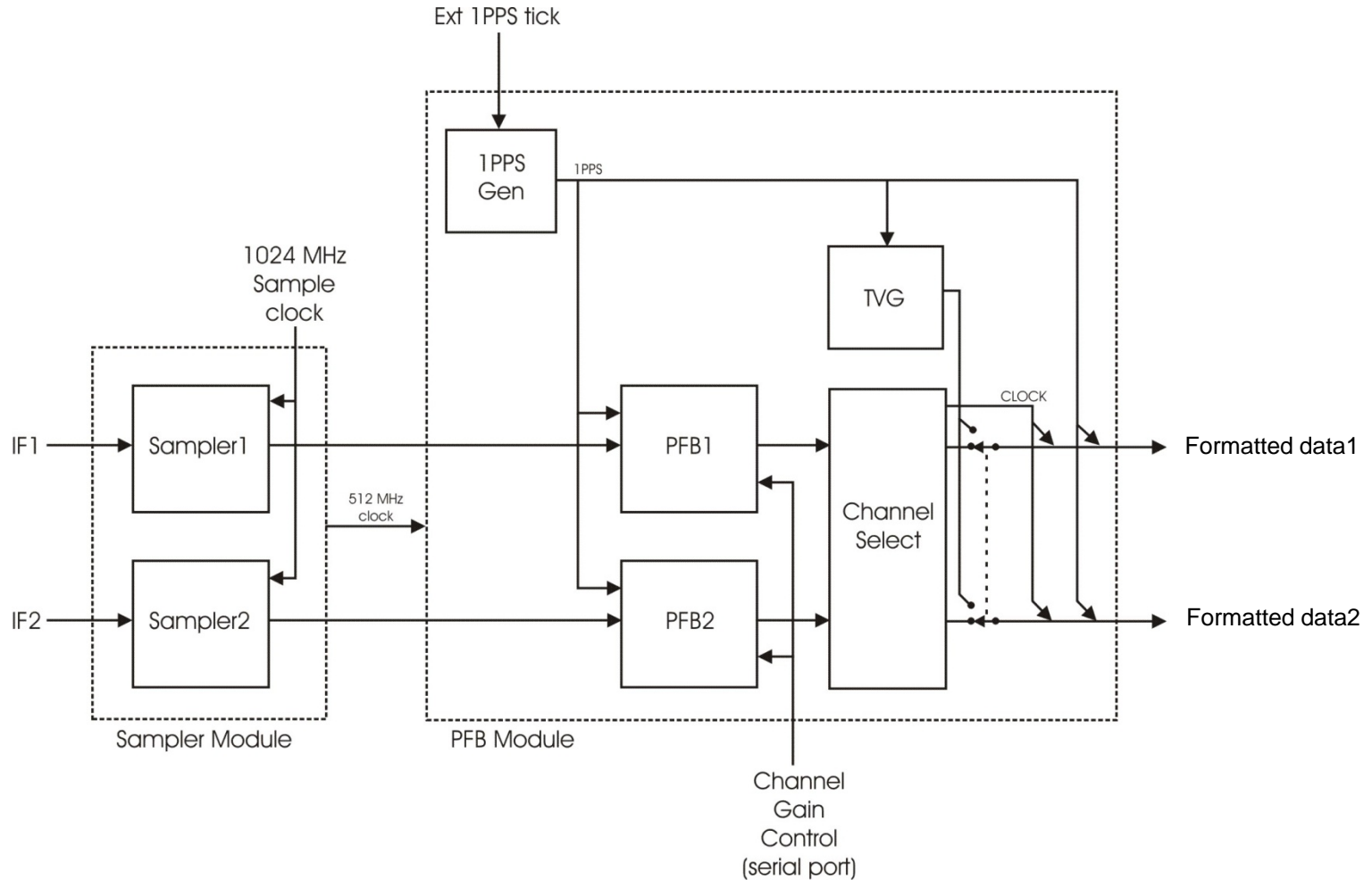


DFT leakage from tone at 5.1MHz,
sampled at 128MHz



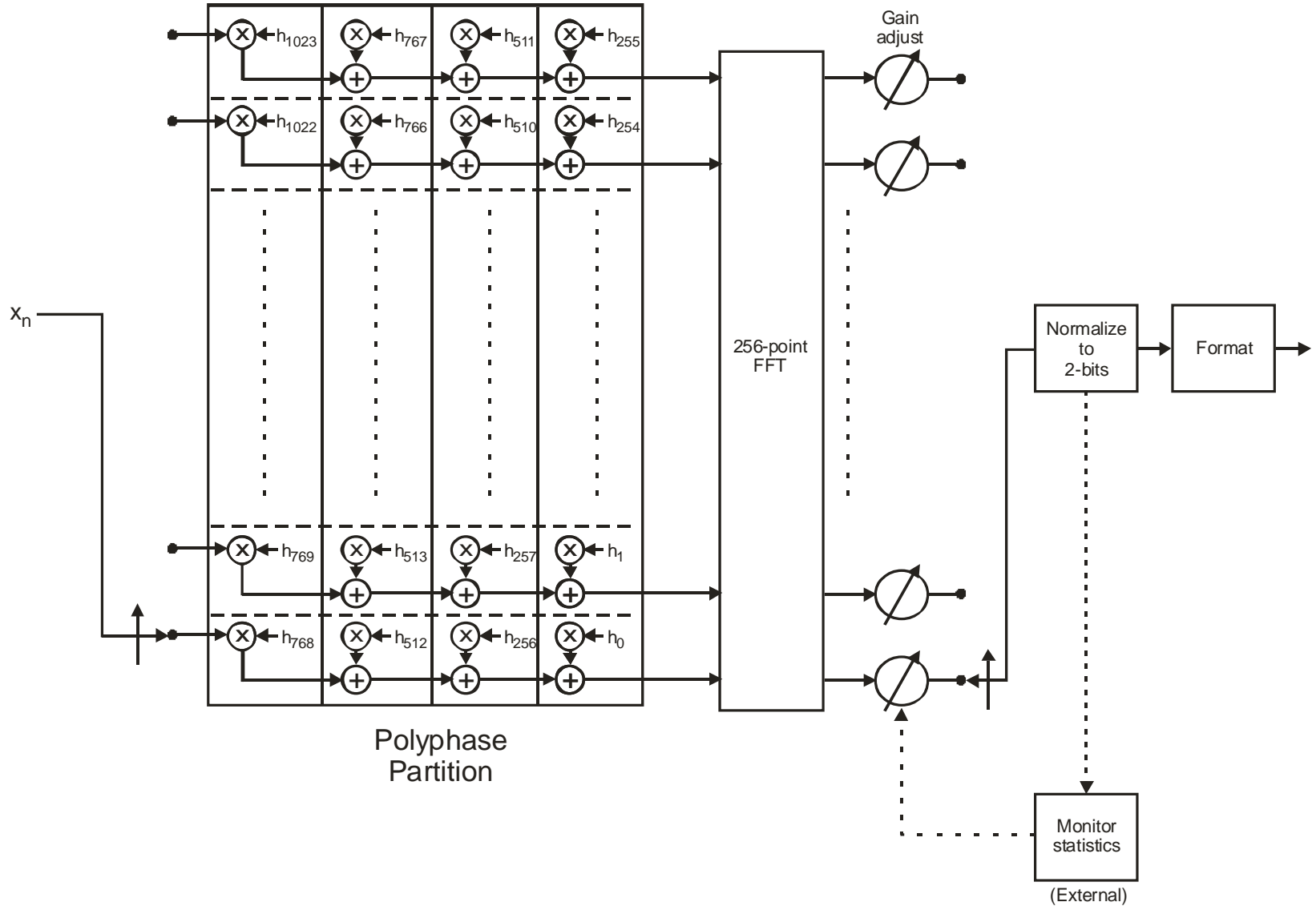
Comparison of single-bin frequency
response of PFB with direct FFT

General block diagram of a PFB unit

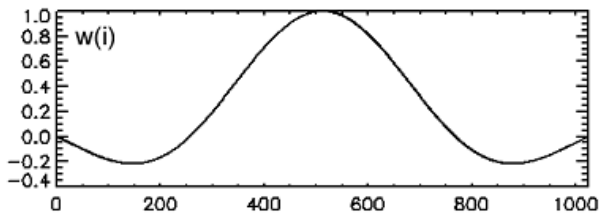
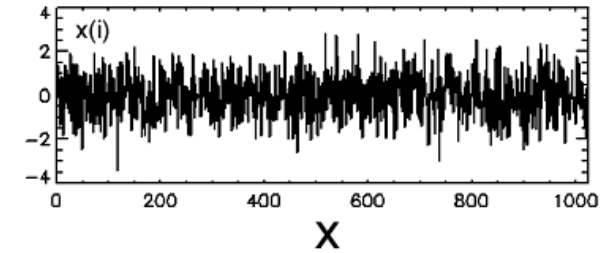


Polyphase channelizer

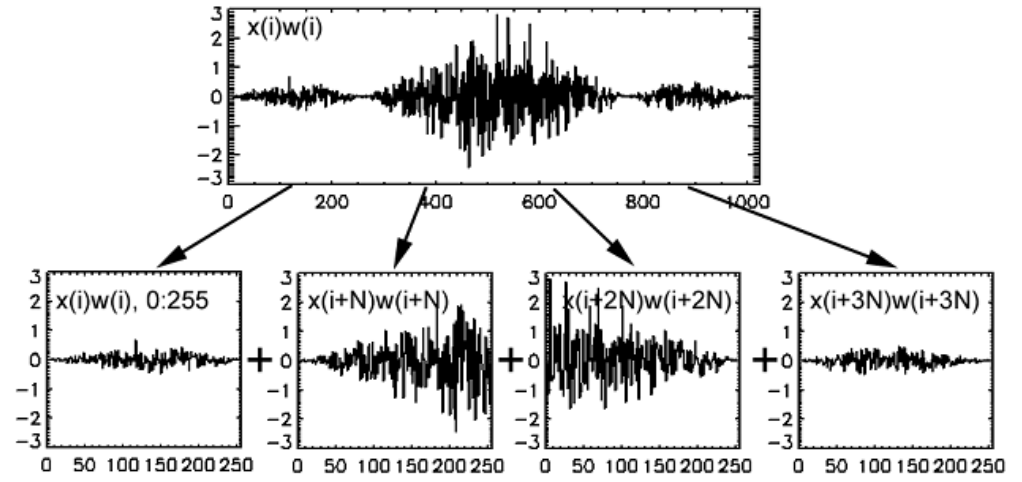
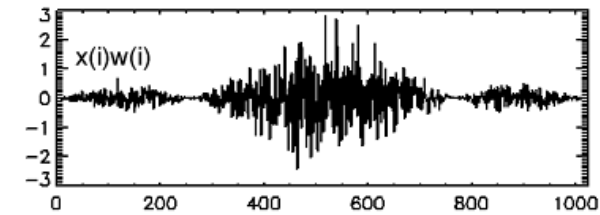
(time series of length 1024; split into 4 blocks of 256 each)



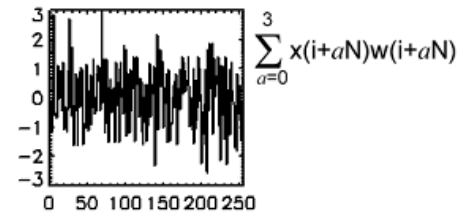
PFB implementation on CASPER ROACH board



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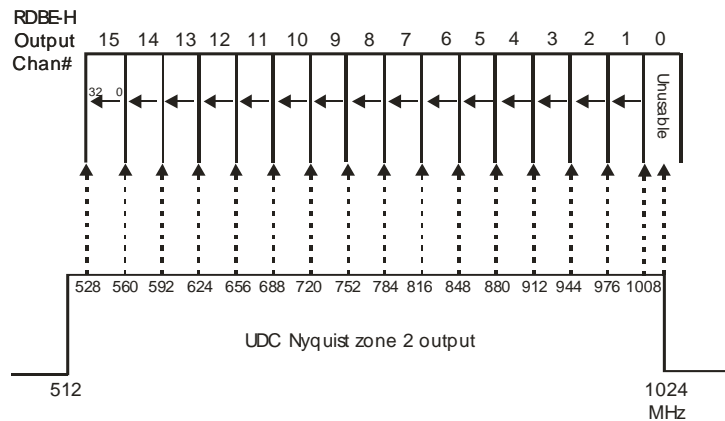
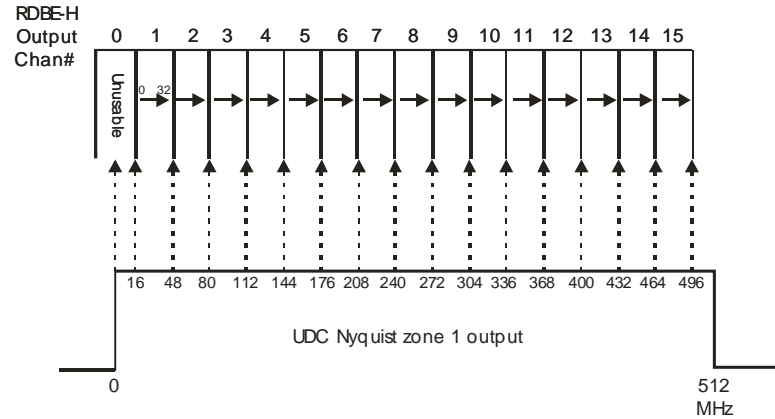


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Input to 256-point FFT

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



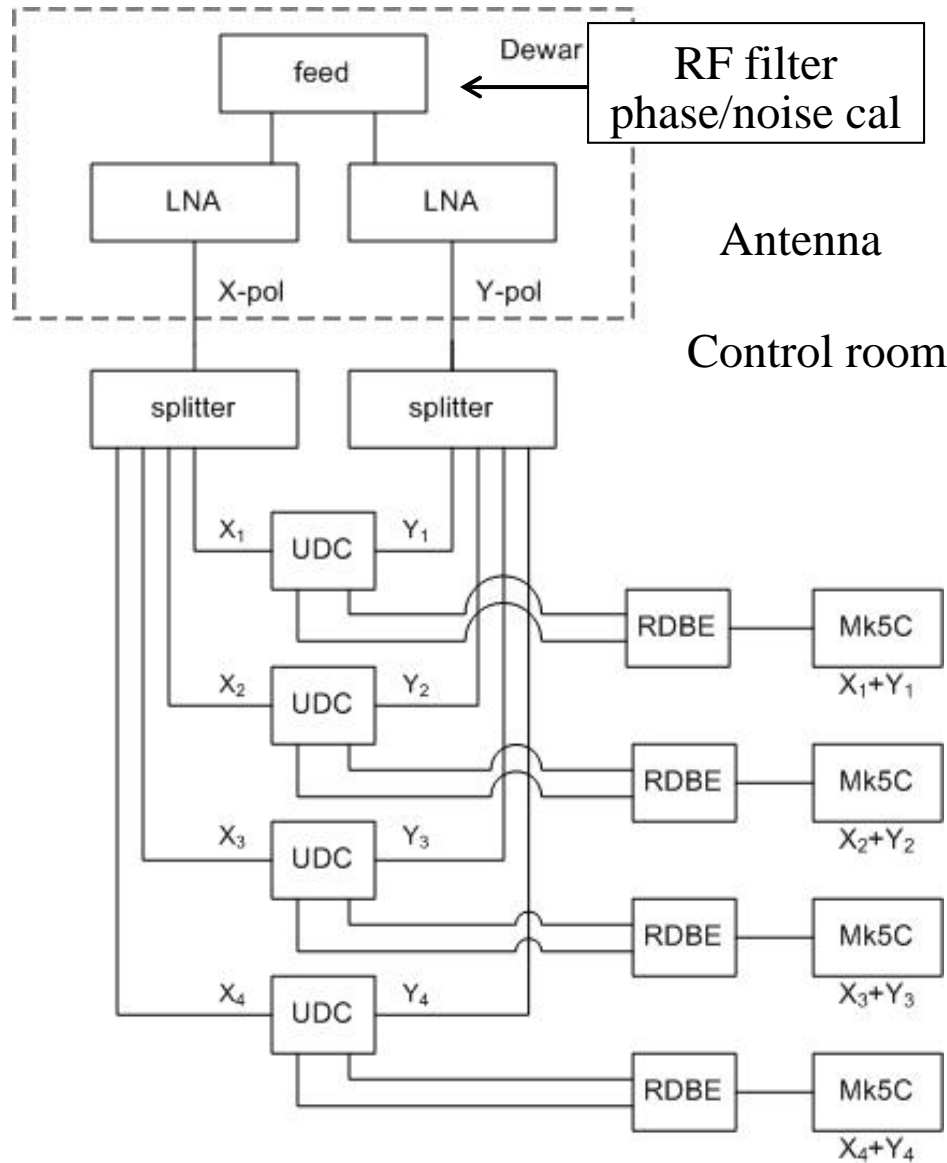
Examples of available DBEs

- 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 $\sim 20\text{K}$

Both senses of linear polarization used

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

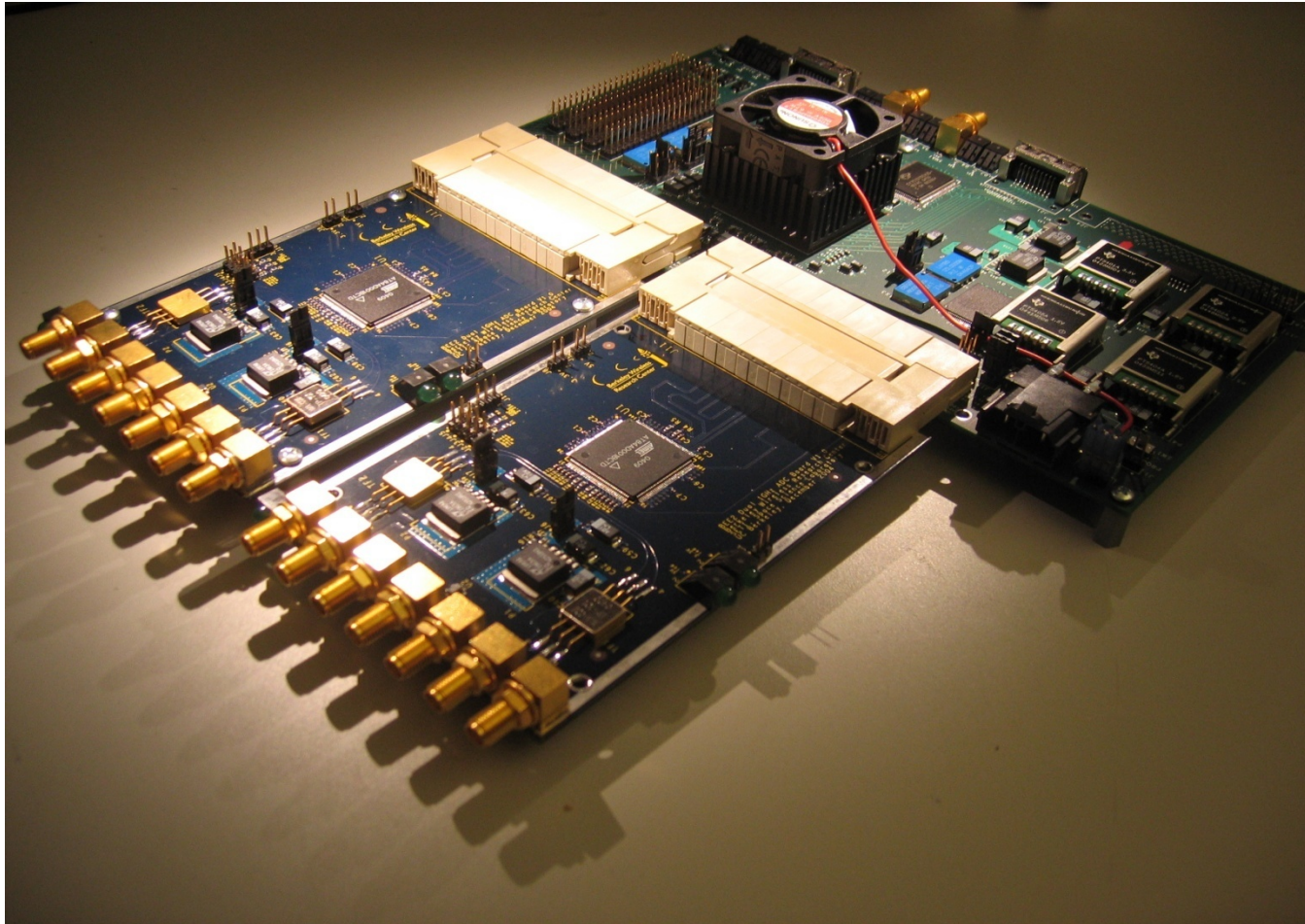
2 Gigabits/sec recorded on each Mk5C.

Total data rate: 8 Gbps

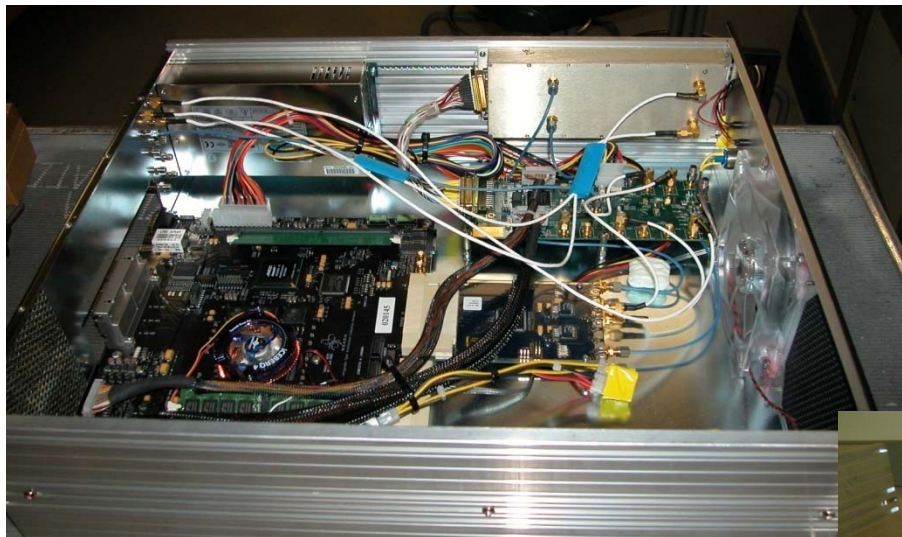
PFB Design Criteria for VLBI

- 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 $>\sim 70\text{dB}$ suppression)

CASPER ROACH board w/two sampler boards

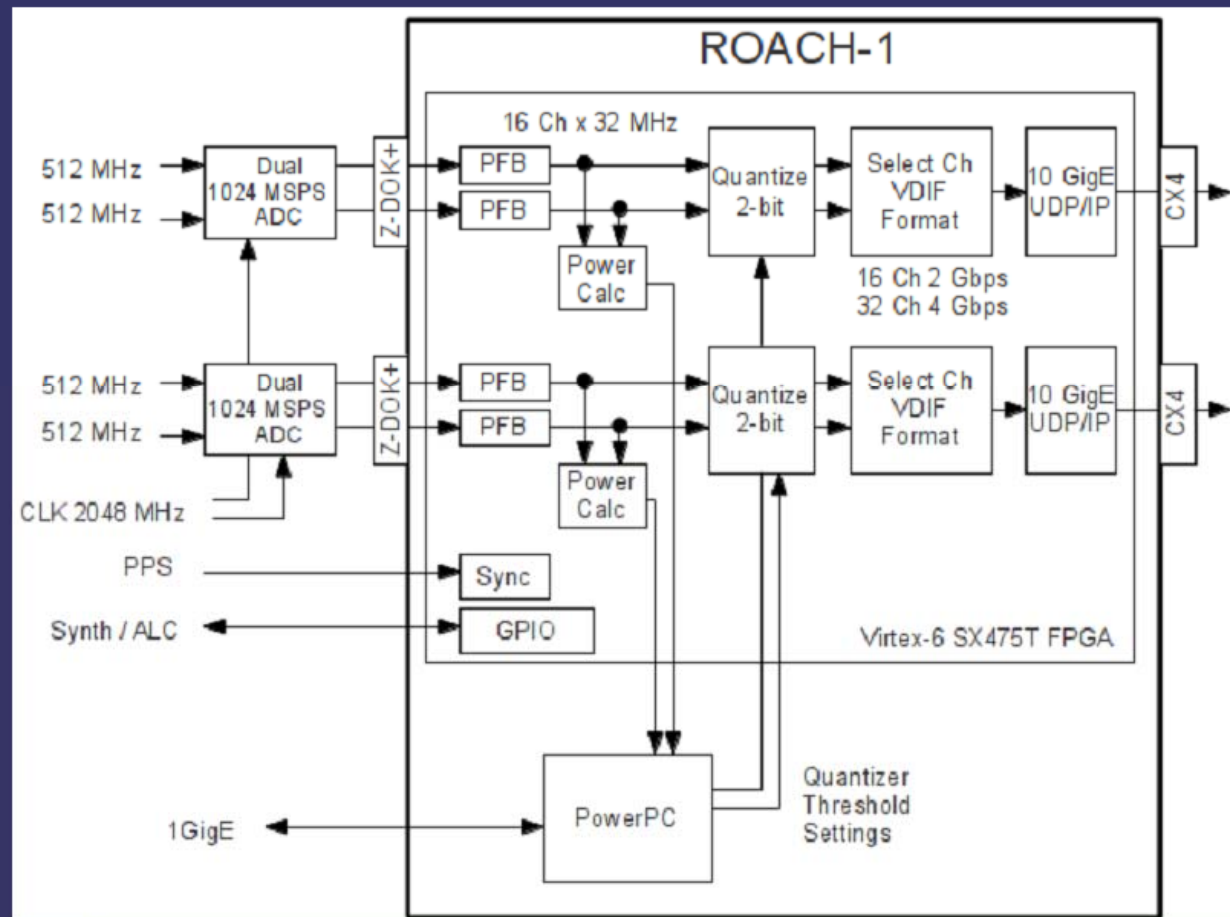


RDBE housed in 3U 'ROACH Hotel'



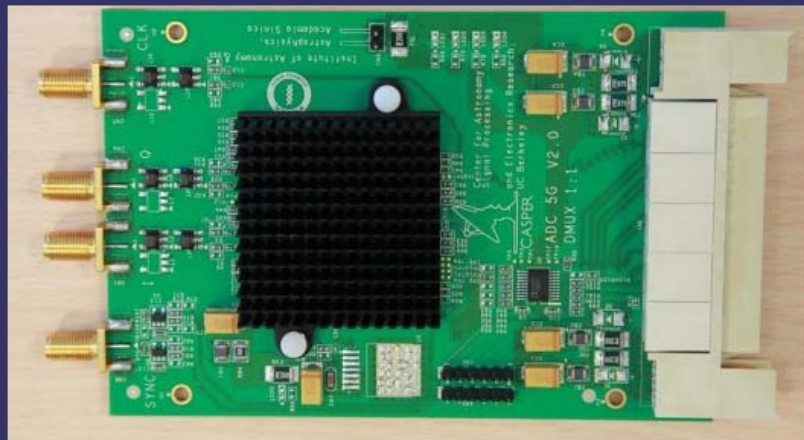
RDBE-Q

- 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



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

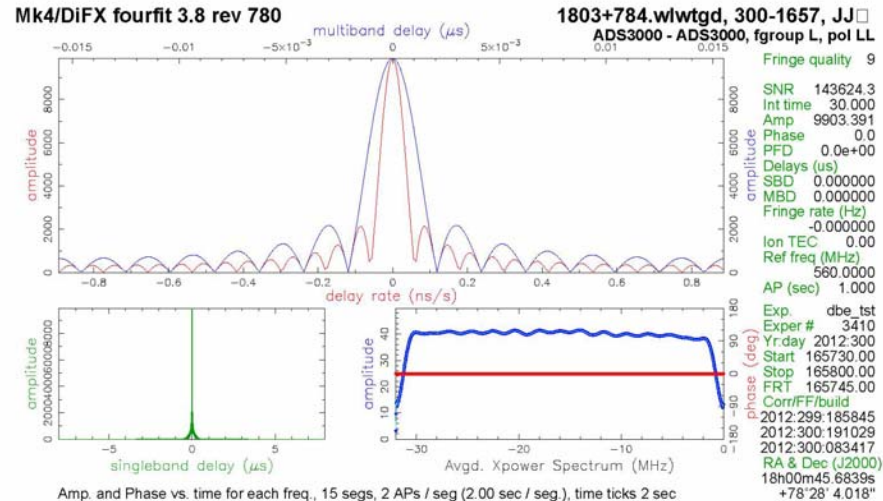
Test Environment

- 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 2nd 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 fringe output for auto-correlation test



a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	All							
560.00	592.00	624.00	656.00	688.00	720.00	752.00	784.00	816.00	848.00	880.00	912.00	944.00	976.00	1008.00	Freq (MHz)							
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Phase							
9897.5	9905.5	9903.1	9896.3	9909.0	9915.0	9902.2	9900.3	9909.4	9902.4	9911.1	9910.4	9901.4	9905.3	9901.8	Amp							
1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	1025.0	Sbd box							
UL 0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	0930	APs used							
J 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PC flags							
J 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PC flags							
J 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PC phase							
J 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Man PC							
J 1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	PC amp							
J 1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	Chan ids							
J 115L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L	Chan ids							
J 115L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L	Tracks							
Group delay (usec)	0.000000000E+00	Apriori delay (usec)	0.000000000E+00	Resid mbdelay (usec)	0.00000E+00	+	-	8.0E-09	Stand delay (usec)	2.33309551170E-17	Apriori clock (usec)	0.000000000E+00	Resid sbdelay (usec)	2.33310E-17	+	-	1.2E-07					
Phase delay (usec)	6.66598779160E-19	Apriori clockrate (us/s)	0.000000000E+00	Resid phdelay (usec)	6.66599E-19	+	-	4.0E-09	Delay rate (us/s)	-1.11981890699E-20	Apriori rate (us/s)	0.00000000000E+00	Resid rate (us/s)	-1.11982E-20	+	-	2.3E-10					
Total phase (deg)	0.0	Apriori accel (us/s/s)	0.00000000000E+00	Resid phase (deg)	0.0	+	-	0.0														
ph/seg (deg)	0.0	RMS	0.0	Theor.	Amplitude	9903.391	+-	0.089	Pcal mode: MANUAL	MANUAL	Pcal period (AP's)	9999	9999	ph/seg (%)	0.0	0.0	Search (84X64)	9903.391	Pcal rate: 0.000E+00, 0.000E+00 (us/s)	sb window (us)	-8.000	8.000
amp/seg (%)	0.0	0.0	Interp.	9903.391	Bits/sample: 2	SampCntNorm: disabled	mb window (us)	-0.018	0.016													
ph/frq (deg)	0.0	0.0	Inc. seg. avg.	9903.392	Sample rate/MSample/s): 64	dr window (ns/s)	-0.893	0.893														
amp/frq (%)	0.1	0.0	Inc. frq. avg.	9903.392	Data rate(Mb/s): 1920	nlags: 1024 t_coherence infinite	ion window (TEC)	0.00	0.00													

J: az 13.9 el 48.9 pa -118.9 J: az 13.9 el 48.9 pa -118.9 uv (fr/sec) 0.000 0.000
 Iterative interpolator
 Control file: cf_3410 Input file: /data-sc01/mike/lbe/test_4str/3410/300-1657/JJ.wlwtgd Output file: Suppressed by test mode

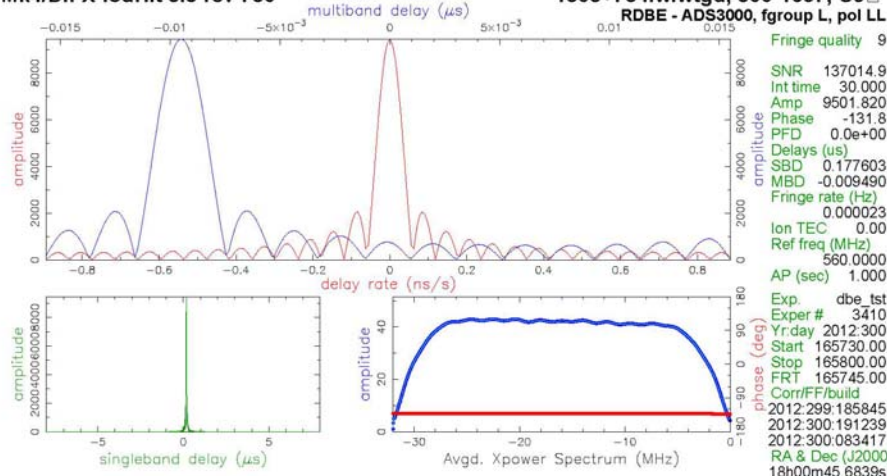
Cross-correlation testing

- 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

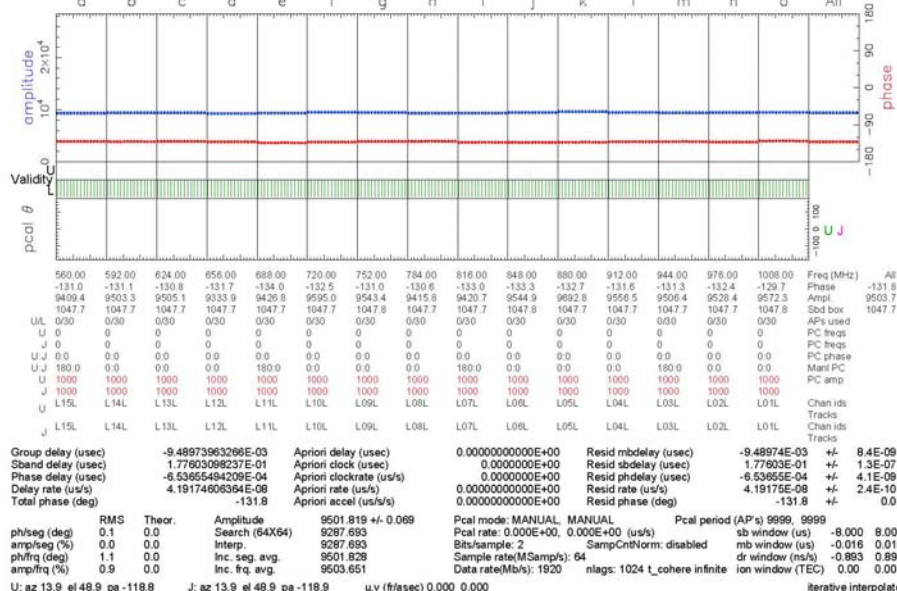
Mk4/DiFX fourfit 3.8 rev 780

1803+784.wlwtgd, 300-1657, UJ
RDBE - ADS3000, fgroup L, pol LL



Fringe quality 9
SNR 137014.9
Int time 30.000
Amp 9501.820
Phase -131.8
PFD 0.0e+00
Delays (us)
SBD 0.177603
MBD -0.009490
Fringe rate (Hz)
0.000023
Ion TEC 0.00
Ref freq (MHz)
560.0000
AP (sec) 1.000
Exp. dbe tst
Exper # 3410
Yr.day 2012.300
Start 165730.00
Stop 165800.00
FRT 165745.00
Corr/FF/build
2012:299:185845
2012:300:191239
2012:300:083417
RA & Dec (J2000)
18h00m45.6839s
+78°28' 4.018"

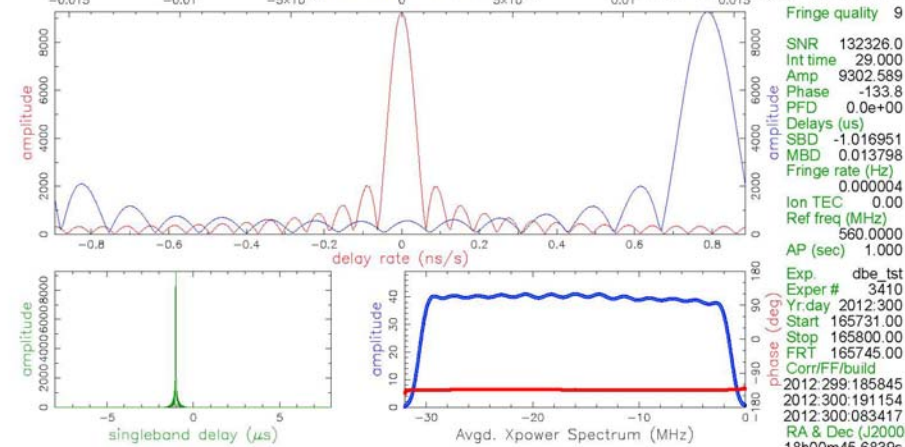
Amp. and Phase vs. time for each freq., 15 segs, 2 APs / seg (2.00 sec / seg), time ticks 2 sec



U: az 13.9 el 48.9 pa -118.8 J: az 13.9 el 48.9 pa -118.9 u,v (fr/sec) 0.000 0.000
Control file: cf_3410 Input file: /data-sco1/mike/dbe_test_4stn/3410/300-1657/UJ.wlwtgd Output file: Suppressed by test mode

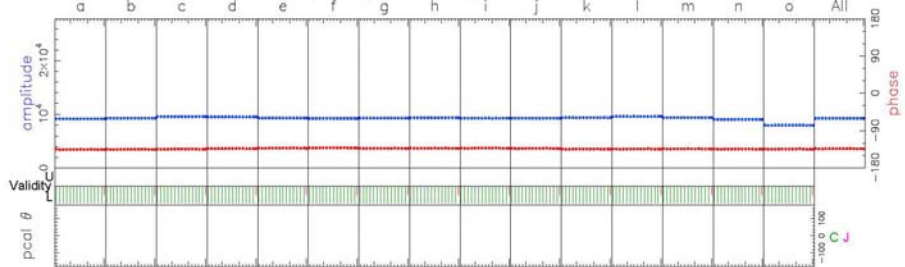
CDAS/PFB-to-ADS3000+ cross-corr results

Mk4/DIFX fourfit 3.8 rev 780 1803+784.wlwtgd, 300-1657, CJ
 CDAS - ADS3000, fgroup L, pol LL



Fringe quality 9
 SNR 132326.0
 Int time 29.000
 Amp 9302.589
 Phase -133.8
 PFD 0.0e+00
 Delays (us)
 SBD -1.016951
 MBD 0.013798
 Fringe rate (Hz)
 0.000004
 Ion TEC 0.00
 Ref freq (MHz)
 560.0000
 AP (sec) 1.000
 Exp dbe Ist
 Exper # 3410
 Yr.day 2012.300
 Start 165731.00
 Stop 165800.00
 FRIT 165745.00
 Corr/FF/build
 2012.299.185845
 2012.300.191154
 2012.300.083417
 RA & Dec (J2000)
 18h00m45.6839s
 +78°28' 4.018"

Amp. and Phase vs. time for each freq., 15 segs, 2 APs / seg (2.00 sec / seg.), time ticks 2 sec



Segment	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	All
590.00	592.00	624.00	656.00	688.00	720.00	752.00	784.00	816.00	848.00	880.00	912.00	944.00	976.00	1008.00		Freq (MHz)
135.5	-135.4	-134.9	-133.5	-132.3	-131.9	-133.0	-132.7	-132.5	-133.1	-134.7	-134.5	-134.7	-134.7	-134.7		Phase
9219.4	9326.3	9623.8	9599.5	9371.1	9297.3	9351.0	9403.7	9345.8	9328.8	9456.3	9679.8	9449.1	9100.5	8015.2		Ampl.
894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.8	894.9	894.8	894.8		Sbd box
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		APs used
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		PC frags
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		PC frags
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		PC phase
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		Mani PC
1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		PC amp
1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		PC amp
L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L		Chan ids
L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L		Tracks
L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L		Tracks

Group delay (usec) 1.37977947754E-02 Apriori delay (usec) 0.00000000000E+00 Resid mbdelay (usec) 1.37978E-02 +/- 8.7E-09
 Sband delay (usec) -1.01695064250E+00 Apriori clock (usec) 0.00000000E+00 Resid sbdelay (usec) -1.01695E+00 +/- 1.3E-07
 Phase delay (usec) -6.63949270740E-04 Apriori clockrate (us/s) 0.00000000E+00 Resid phdelay (usec) -6.63949E-04 +/- 4.3E-09
 Delay rate (us/s) 7.40779696415E-09 Apriori rate (us/s) 0.00000000000E+00 Resid rate (us/s) 7.40780E-09 +/- 2.6E-10
 Total phase (deg) -133.8 Apriori accel (us/s/s) 0.00000000000E+00 Resid phase (deg) -133.8 +/- 0.0

RMS Theor. Amplitude 9302.589 +/- 0.070 Pcal mode: MANUAL, MANUAL Pcal period (APs) 9999, 9999
 amp/seg (%) 0.0 0.0 Search (64X64) 9225.932 Pcal rate: 0.000E+00, 0.000E+00 (us/s) sb window (us) -8.000 8.000
 ph/seg (deg) 1.1 0.0 Interp. 9225.932 Bits/sample: 2 SampCntNorm: disabled mb window (us) -0.016 0.016
 amp/frq (deg) 4.0 0.0 Inc. seg avg 9302.584 Sample rate (MSamp/s): 64 Data rate (Mbps): 1920 nlags: 1024 t_coherence infinite d window (ns/s) -0.893 0.893
 amp/frq (deg) 4.0 0.0 Inc. frq avg 9304.448 Data rate (Mbps): 1920 nlags: 1024 t_coherence infinite ion window (TEC) 0.00 0.00

C: az 13.9 el 48.9 pa -118.9 J: az 13.9 el 48.9 pa -118.9 uv (/frsec) 0.000 0.000 iterative interpolator

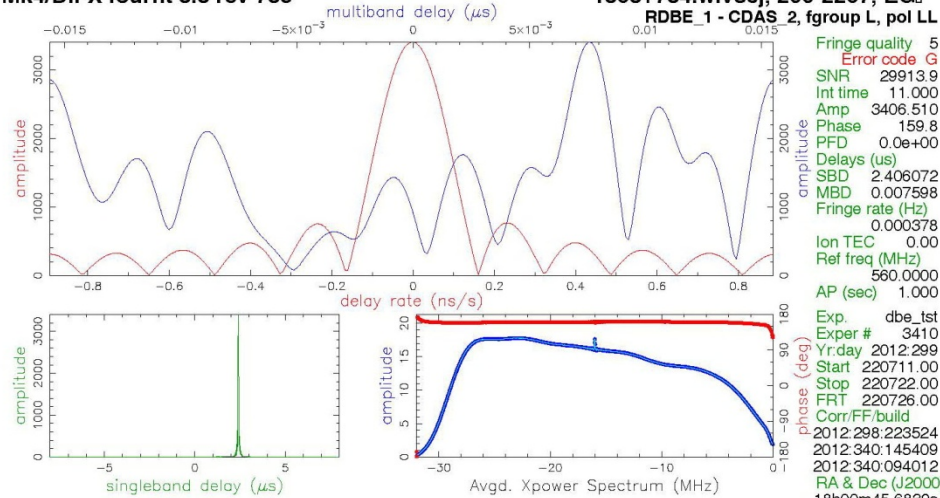
Control file: cf_3410 Input file: /data-sc01/mike/dbe_test_4str/3410/300-1657/CJ.wlwtgd Output file: Suppressed by test mode

RDBEH-to-CDAS/DDC cross-corr results

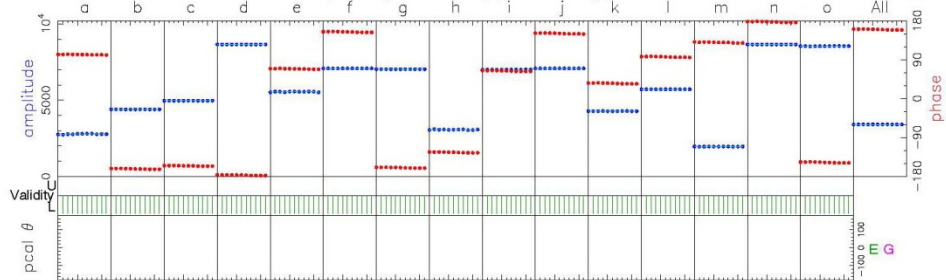
Mk4/DiFX fourfit 3.8 rev 785

1803+784.wlvscj, 299-2207, EG

RDBE_1 - CDAS_2, fgroup L, pol LL



Amp. and Phase vs. time for each freq., 11 segs, 1 APs / seg (1.00 sec / seg.), time ticks 1 sec



	560.00	592.00	624.00	656.00	688.00	720.00	752.00	784.00	816.00	848.00	880.00	912.00	944.00	976.00	1008.00	Freq (MHz)
UL	101.5	-162.8	-155.8	-177.3	89.6	154.0	-124.6	83.9	150.5	35.1	96.2	129.7	177.0	-147.9	159.8	All
EL	1772.6	-4401.9	-4365.4	8690.2	5549.3	7094.4	7037.2	2360.6	7005.9	7089.2	4261.3	5711.9	1353.9	6857.4	8550.4	Phase
EL	1332.9	1332.9	1335.0	1332.9	1332.9	1333.0	1333.3	1331.4	1332.9	1333.0	1333.5	1332.5	1332.7	1332.8	1333.3	Ampl
UL	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	0/11	APs used
EL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PC Ineqs
EL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PC Ineqs
EL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	PC phase
EL	0.180	0.0	0.0	0.0	0.180	0.0	0.0	0.180	0.0	0.0	0.0	0.180	0.0	0.0	0.0	Manl PC
G	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	PC amp
G	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	PC amp
m	L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L	Chan ids
G	L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L	Tracks
G	L15L	L14L	L13L	L12L	L11L	L10L	L09L	L08L	L07L	L06L	L05L	L04L	L03L	L02L	L01L	Chan ids

Group delay (usec) 7.59773314834E-03 Apriori delay (usec) 0.0000000000E+00 Resid mbdelay (usec) 7.59773E-03 +/- 3.9E-08

Sband delay (usec) 2.40607191018E+00 Apriori clock (usec) 0.0000000E+00 Resid sbdelay (usec) 2.40607E+00 +/- 5.8E-07

Phase delay (usec) 7.92646495179E-04 Apriori clockrate (us/s) 0.0000000E+00 Resid phdelay (usec) 7.92646E-04 +/- 1.9E-08

Delay rate (us/s) 6.75165790423E-07 Apriori rate (us/s) 0.0000000000E+00 Resid rate (us/s) 6.75166E-07 +/- 3.0E-09

Total phase (deg) 159.8 Apriori accel (us/s/s) 0.0000000000E+00 Resid phase (deg) 159.8 +/- 0.0

RMS Theor. Amplitude 3406.510 +/- 0.114 Pcal mode: MANUAL, MANUAL Pcal period (AP's) 9999, 9999

ph/seg (deg) 0.8 0.0 Search (32X64) 3335.790 Pcal rate: 0.000E+00, 0.000E+00 (us/s) sb window (us) -8.000 8.000

amp/seg (%) 0.0 0.0 Interp. 3335.790 Bits/sample: 2 SampCntNorm: disabled mb window (us) -0.016 0.016

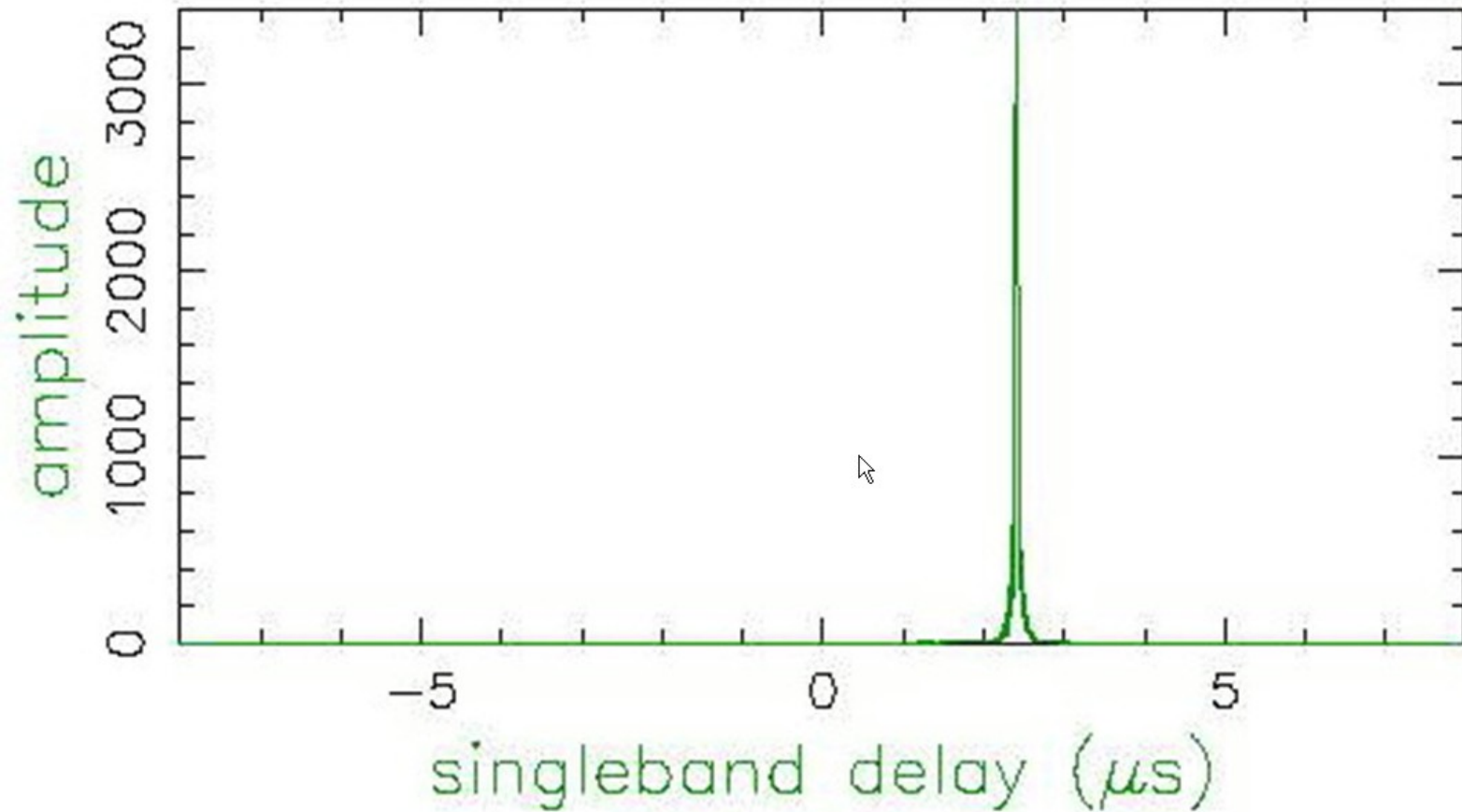
ph/frq (deg) 40.7 0.0 Inc. seg. avg. 3406.724 Sample rate(MSample/s): 64 ch window (ms) -0.893 0.893

amp/frq (%) 93.3 0.0 Inc. frq. avg. 5785.000 Data rate(Mb/s): 1920 nlags: 1024 L_coher infinite ion window (TEC) 0.00 0.00

E: az 352.1 el 52.8 pa 149.8 G: az 352.1 el 52.8 pa 149.8 uv (fr/asec) 0.000 0.000 iterative interpolator

Control file: cf_3410 Input file: /data-sc01/mike/dbe_test_master/3410/299-2207/EG.wlvscj Output file: Suppressed by test mode

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?