VLBI test observations with 8-bit quantization data

Jun Yang, Simon Casy, Michael Lindqvist @ *OSO, Sweden*

Aard Keimpema, Marjolein Verkouter @ *JIVE, the Netherlands*

1. VDIF data with 8-bit quantization

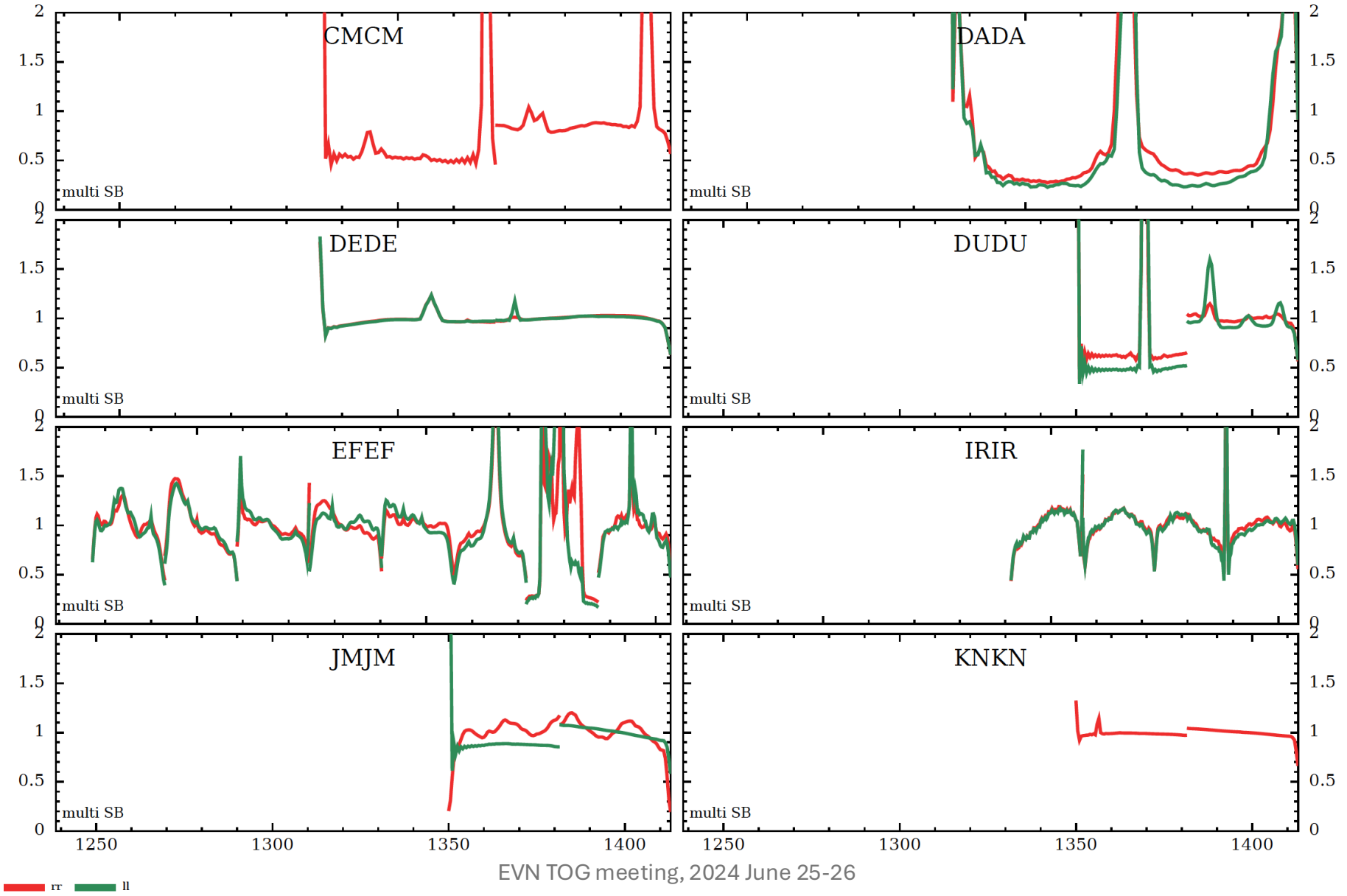
VDIF: VLBI Data Interchange Format

- Advantages
  - Theoretically, improve the quantization efficiency from 88 % (2 bits/4 levels) to 100% (8 bits/256 levels).
  - Increase system linearity and reliability in case of strong and varying RFIs.
    - More stable correlation amplitude on short timescales of <~10 sec.
    - More stable bandpass shapes during the observations.
- Disadvantages
  - Require more disk space, a factor of four higher.

EK056B

amplitude versus frequency
unique: 06:18:35.00/none/J2123+0535
Pol=RR,LL;Nsub=10;;Ch=*;
[Scalar avg'ed 0/06h18m05.00s->06h19m05.00s]

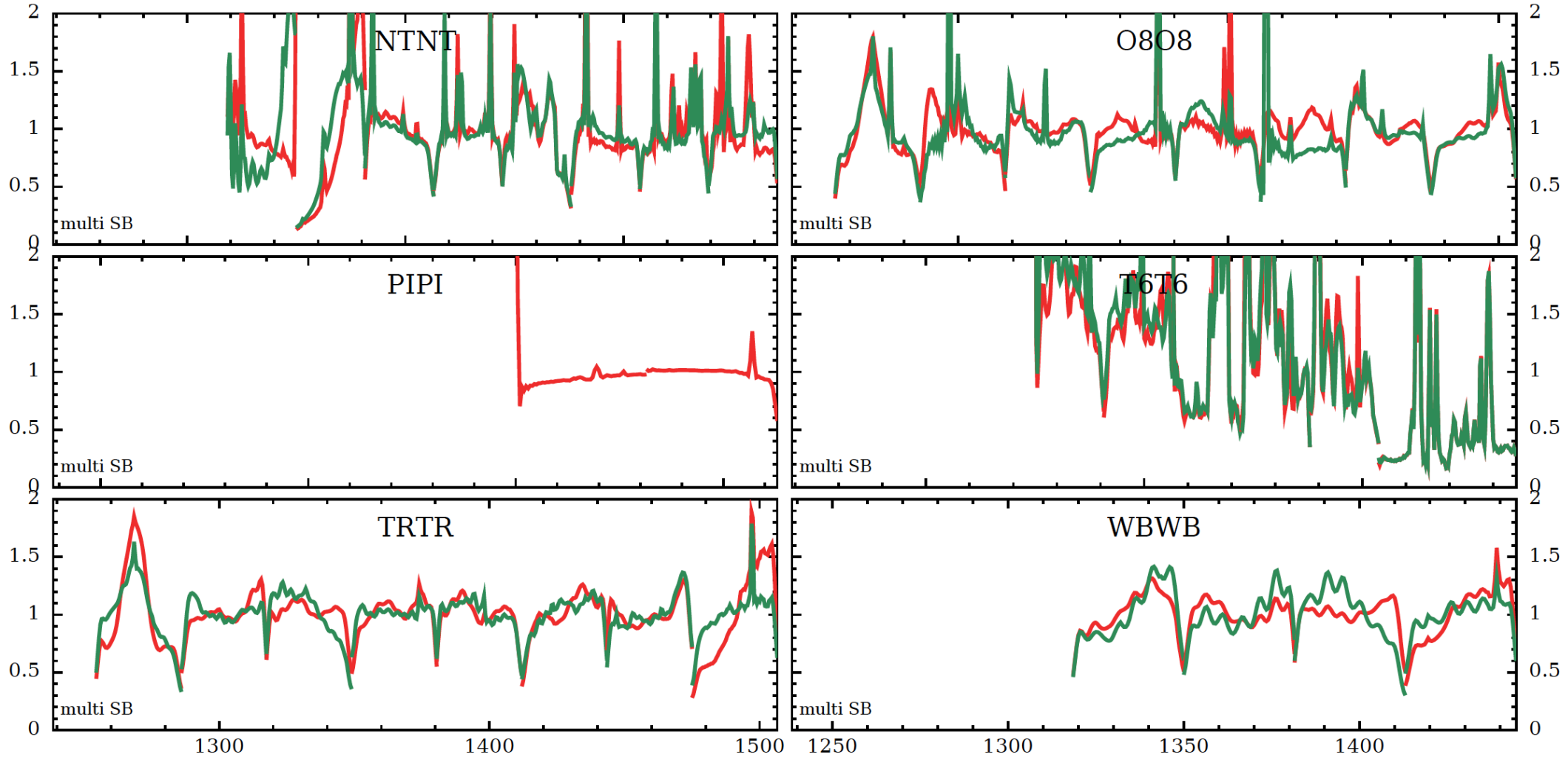
data: ek056b-pconv.ms [DATA]
jops@LOCALHOST 2024-06-10T15:42:20
page: 1/2



EK056B

amplitude versus frequency
unique: 06:18:35.00/none/J2123+0535
Pol=RR,LL;Nsub=10;;Ch=*;
[Scalar avg'ed 0/06h18m05.00s->06h19m05.00s]

data: ek056b-pconv.ms [DATA]
jops@LOCALHOST 2024-06-10T15:42:20
page: 2/2



2. Potential applications

- Future 4-Gbps e-VLBI observations at L band
  - No need to buy more disks.
  - Hard to effectively increase bandwidth at L band because of RFI.
  - Image sensitivity improvement => one more 30-m dish for the EVN
    - 10% in case of no RFI.
    - >10% in case of strong RFI.
- Narrow-band spectral line VLBI observations.
- FRB monitoring observations with VLBI backends.
  - 500-1000 hours per year at On, Tr, Wb, Ir et al.
- Simple option for stations to improve sensitivity at L band with more disks during the EVN sessions.
- Future SKA-VLBI observations at L band
  - 16 Gbps with ~512 MHz bandwidth at some stations: SKA-Mid, GMRT, FAST, Ef, On,…

3. Test observations with DDC E v126

- Backend: 2L2H DBBC3 with the firmware DDC E v126
- Experiment: PR327A (PRECISE project)
- Frequency setup for DBBC2 and DBBC3 at Onsala
  - Frequency: 1254-1510 MHz.
  - Dual polarization.
  - Data rate
    - DBBC2
      - 2048 Mbps (2 bits, 32 MHz x 8, 1 VDIF thread), LO=708 MHz.
    - DBBC3
      - 8096 Mbps (8 bits, 128 MHz x 4, 2 VDIF threads) , LO=0 MHz.

- Schedule VEX file with NRAO Sched
  - O8: DBBC2 backend.
  - ON: DBBC3 backend.
  - 2 bits for O8 and ON.
- Observation PRC and SNP files
  - SNP file from FS Drudg.
  - PRC file from FS Drudg and hands-on editing.
    - core3h01=$ => core3h01
    - fb_mode=vdif,,,256.0 => fb=mode=vdif_8000-8192-4-8
    - Adding the procedure sched_initi in the experimental PRC file
    - Inserting DBBC3 commands dbbc8bit in the procedure sched_initi
- Recording with JIVE5ab 3.1.0
  - Just do it. No special requirements.
    - 2024.115.19:48:27.22&setup01/fb=mode=vdif_8000-8192-4-8
    - 2024.115.19:48:27.22&setup01/fb_mode
    - ...
    - 2024.115.19:48:36.83/fb/!mode= 0 ;
    - 2024.115.19:48:36.83/fb_mode/vdif_8000-8192-4-8,,,,VDIF,32,256.,8000

```
dbbc3=dbbc8bit=on,1,u,1
!+1s
dbbc3=dbbc8bit=on,5,u,1
!+1s
dbbc3=dbbc8bit=on,9,u,1
!+1s
dbbc3=dbbc8bit=on,13,u,1
!+1s
```

- Available DiFX tools to check the 8-bit VDIF data
  - Print VDIF header: printVDIFheader
  - Check sample RMS and Mean m5bstate
  - Find the starting time: m5time
  - Make auto-corrlation spectra: m5spec
    - Sometimes, catched many warning messages of "**VDIF Validate** ..." due to a tiny time offset.
    - In the program format_vdif.c, we changed the threshold from 0.000001 to 0.5 ns at Onsala.

```
if(mjd_t != mjd_d || sec_t != sec_d || fabs((double)ns_t - ns_d) > 0.000001)
{
        fprintf(m5stdout, "VDIF validate[%lld]: %d %d %f : %d %d %lld\n", ms->framenum, mjd_d, sec_d, ns_d, mjd_t, sec_t, ns_t);

        return 0;
}
```

- Correlation at JIVE
  - VEX 2.0 file: Provided by JIVE Python Sched and tiny hands-on editing.
  - thread = &DS0: &thread0 : 0 : 2 : 256 Ms/sec : 8 : real : 8000;
    thread = &DS1: &thread1 : 1 : 2 : 256 Ms/sec : 8 : real : 8000;
  - An upgrade of SFXC was implemented by Aard Keimpema.

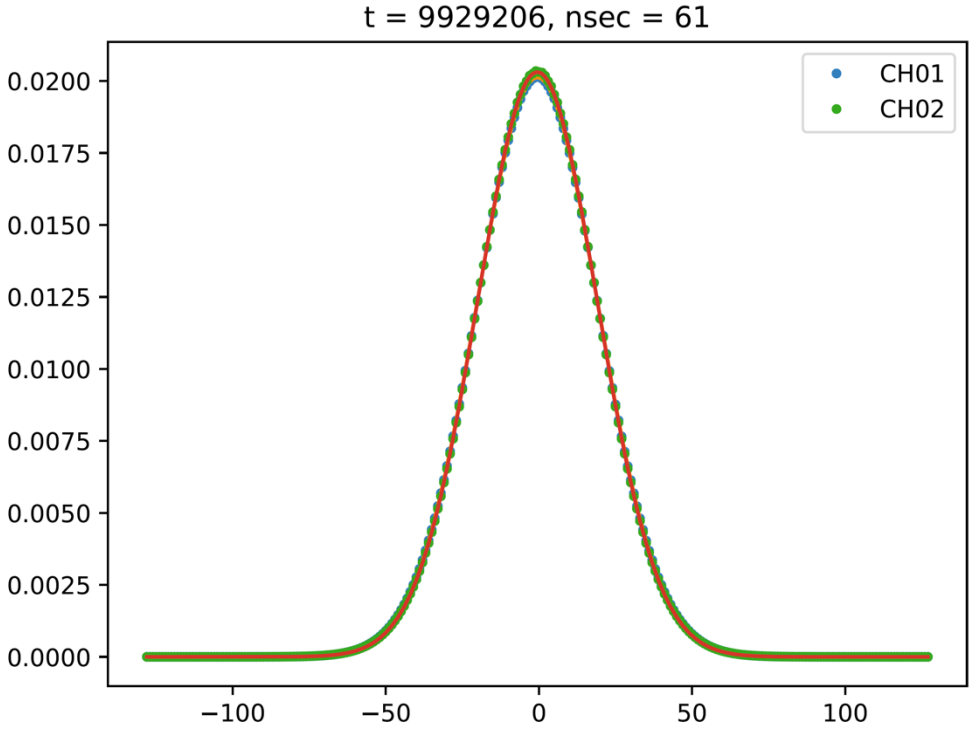
- VDIF data format
  - The output 8-bit VDIF data from DDC E v126 follows the format of two's complement instead of offset binary.
- Fringe-test results of 60-s scan No.123
  - Stations: Ef, Mc and Onsala.
  - Webpage: https://services.jive.nl/ftp_fringes/PR327A/scan123/index.html

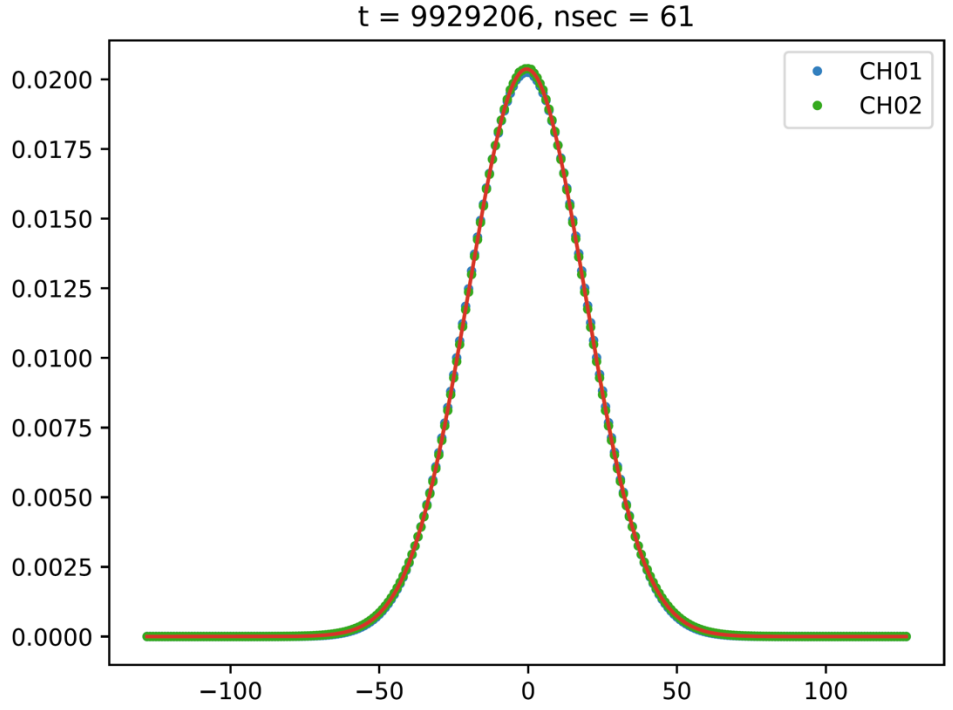
Bright fringes to DBBC3 (On) and DBBC2 (O8)

Vex file -- Scan name = No0123, total averaging time = 60.0 sec
Timerange: 2024-04-24 22:06:46-22:07:46

pr327a	Auto correlations (BBC number)				Cross correlations (SNR, lag offset)					
	Ef	Mc	O8	On	Ef-Mc	Ef-O8	Ef-On	Mc-O8	Mc-On	O8-On
1286.00MHz, LSB, RCP-RCP	1		1	1		193.6AP offset: 0	165.0AP offset: 0			65925.8AP offset: 0
1286.00MHz, LSB, RCP-LCP	Cross hands					13.2AP offset: 0	12.3AP offset: -1			10643.3AP offset: -4
1286.00MHz, LSB, LCP-LCP	9		9	9		177.4AP offset: -1	230.6AP offset: -1			88773.8AP offset: 0
1286.00MHz, LSB, LCP-RCP	Cross hands					8.9AP offset: 1	8.9AP offset: 0			9250.1AP offset: 3
1286.00MHz, USB, RCP-RCP	1		1	1		204.1AP offset: 0	199.4AP offset: -1			96361.1AP offset: 0
1286.00MHz, USB, RCP-LCP	Cross hands					7.6AP offset: 0	10.7AP offset: 0			41925.6AP offset: 20
1286.00MHz, USB, LCP-LCP	9		9	9		197.5AP offset: 0	208.9AP offset: 0			95918.6AP offset: 0
1286.00MHz, USB, LCP-RCP	Cross hands					19.1AP offset: 0	19.6AP offset: 0			43516.3AP offset: -17
1350.00MHz, LSB, RCP-RCP	2		2	1		218.7AP offset: 1	218.6AP offset: 1			61203.1AP offset: -1
1350.00MHz, LSB, RCP-LCP	Cross hands					13.4AP offset: 1	14.9AP offset: 0			9890.6AP offset: 0
1350.00MHz, LSB, LCP-LCP	10		10	9		329.8AP offset: 0	203.2AP offset: 0			57127.8AP offset: 1
1350.00MHz, LSB, LCP-RCP	Cross hands					22.9AP offset: 0	12.7AP offset: 1			10704.8AP offset: 0
1350.00MHz, USB, RCP-RCP	2	1	2	1	336.4AP offset: 0	340.0AP offset: 0	249.5AP offset: 0	49.1AP offset: 0	46.3AP offset: 0	57770.6AP offset: -1
1350.00MHz, USB, RCP-LCP	Cross hands				10.0AP offset: 0	9.8AP offset: -1	12.9AP offset: 0	4.0AP offset: -35	3.6AP offset: 64	8586.9AP offset: -1
1350.00MHz, USB, LCP-LCP	10	9	10	9	213.3AP offset: 1	347.6AP offset: 0	341.2AP offset: 0	40.6AP offset: -1	40.7AP offset: 0	59058.3AP offset: 1
1350.00MHz, USB, LCP-RCP	Cross hands				17.4AP offset: 0	24.0AP offset: -1	29.1AP offset: 0	4.5AP offset: 28	3.6AP offset: 46	8453.7AP offset: 1
1414.00MHz, LSB, RCP-RCP	3	1	3	5	255.8AP offset: 1	342.0AP offset: 1	326.7AP offset: 0	66.7AP offset: 0	45.2AP offset: 0	62232.5AP offset: 0
1414.00MHz, LSB, RCP-LCP	Cross hands				5.8AP offset: -10	15.5AP offset: 0	12.1AP offset: 0	5.2AP offset: 0	6.6AP offset: 0	8789.0AP offset: 0
1414.00MHz, LSB, LCP-LCP	11	9	11	13	329.7AP offset: -1	278.7AP offset: 0	303.5AP offset: -1	63.9AP offset: 0	73.0AP offset: 0	86733.3AP offset: 0
1414.00MHz, LSB, LCP-RCP	Cross hands				26.5AP offset: -1	19.3AP offset: 1	20.9AP offset: 0	3.9AP offset: 13	5.0AP offset: -52	6623.2AP offset: 0
1414.00MHz, USB, RCP-RCP	3	2	3	5	192.5AP offset: 0	248.8AP offset: 0	216.1AP offset: -1	53.4AP offset: 0	59.5AP offset: 0	63226.4AP offset: -1
1414.00MHz, USB, RCP-LCP	Cross hands				7.5AP offset: -1	7.2AP offset: 0	6.5AP offset: 12	4.7AP offset: -12	5.1AP offset: 4	5938.7AP offset: 1
1414.00MHz, USB, LCP-LCP	11	10	11	13	166.5AP offset: 1	200.5AP offset: 1	201.8AP offset: 1	55.5AP offset: 0	58.6AP offset: 0	81093.3AP offset: 0
1414.00MHz, USB, LCP-RCP	Cross hands				16.2AP offset: 0	13.6AP offset: 1	20.7AP offset: 0	4.8AP offset: 9	4.9AP offset: -63	5845.0AP offset: -1
1478.00MHz, LSB, RCP-RCP	4	2	4	5	44.4AP offset: 0	130.4AP offset: 0	123.5AP offset: 1	18.7AP offset: 0	13.6AP offset: 0	81730.3AP offset: 0
1478.00MHz, LSB, RCP-LCP	Cross hands				4.0AP offset: -34	7.5AP offset: 0	5.5AP offset: 39	4.3AP offset: -57	4.9AP offset: -51	4855.7AP offset: 0
1478.00MHz, LSB, LCP-LCP	12	10	12	13	35.7AP offset: 0	119.6AP offset: 0	118.8AP offset: 0	15.9AP offset: 0	14.3AP offset: 0	52197.3AP offset: 1
1478.00MHz, LSB, LCP-RCP	Cross hands				3.9AP offset: -27	6.6AP offset: 1	4.9AP offset: -5	4.4AP offset: 68	3.7AP offset: 65	3313.7AP offset: 1
1478.00MHz, USB, RCP-RCP	4		4	5		165.5AP offset: 0	120.2AP offset: -1			41536.7AP offset: 0
1478.00MHz, USB, RCP-LCP	Cross hands					23.4AP offset: 1	13.1AP offset: 0			5424.1AP offset: 0
1478.00MHz, USB, LCP-LCP	12		12	13		229.8AP offset: 1	161.0AP offset: 1			43556.0AP offset: 0
1478.00MHz, USB, LCP-RCP	Cross hands					28.7AP offset: 0	21.4AP offset: 1			6244.1AP offset: 0

- Sample distribution
  - IF AGC target value: 18000 instead of 35000 (for 0.5 GHz input signal).
  - BBC AGC target value (power): 24000 (sample RMS ~6 from m5bstate).
  - Switching off 80 Hz Cont-Cal signal, IF and BBC and AGC during scans.
  - Following Gaussian distribution in the range of –127 to +127
    - Voltage sample Mean ~0.1 and RMS ~20.
    - Consistent with DiFX m5bstate output since it has a scale factor (3.3).

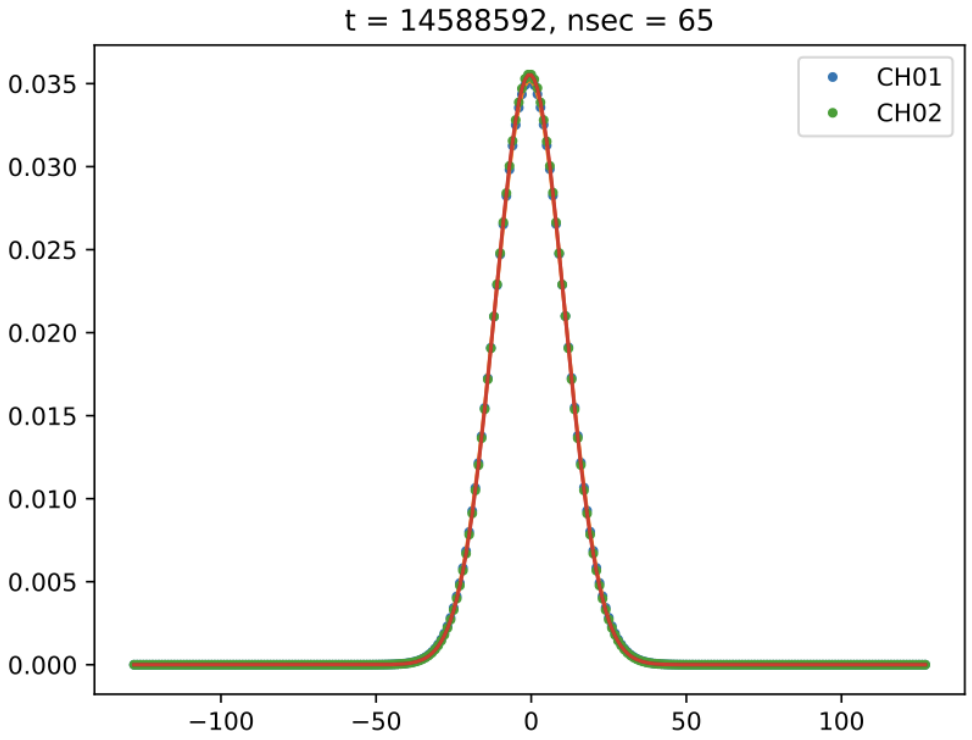


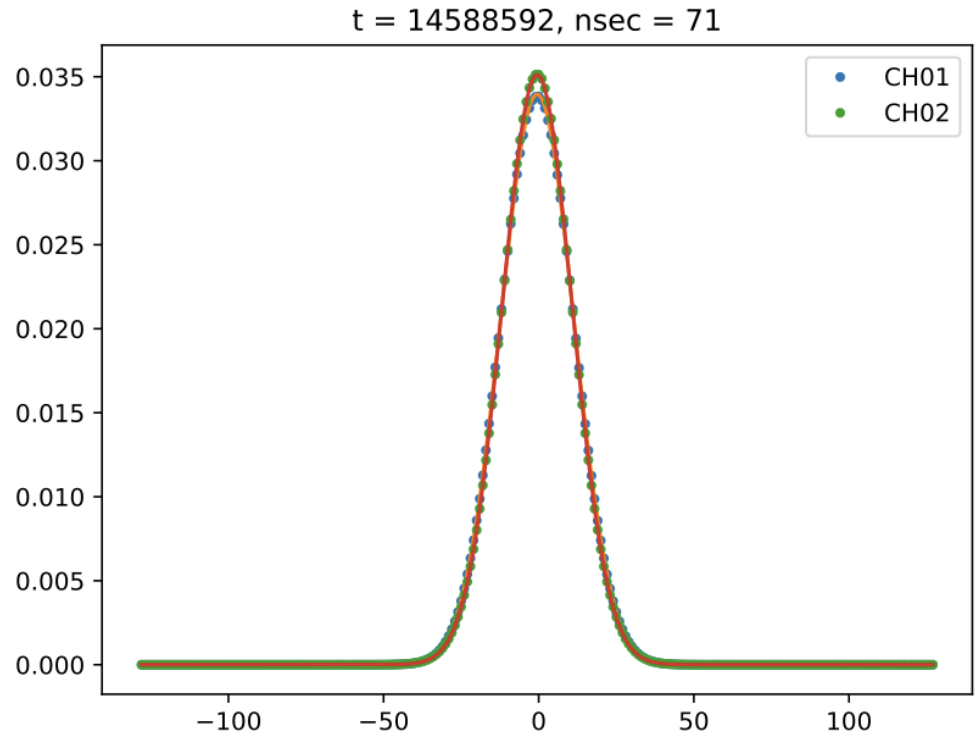


4. Test observations with DDC E&U v127

- Firmware changes: outputs the standard VDIF data, i.e. offset binary format.
  - It begins with all 0's for the most-negative sampled value to all 1's for the most-positive sampled value. For example, 2 bit/sample coding is (in order from most negative to most positive) 00, 01, 10, 11, and nominal unpack values might be -3.336, -1, 1, 3.336.
- Experiment: PR335A (PRECISE project)
- Frequency setup for DBBC2 and DBBC3 at Onsala
  - Frequency: 1254-1510 MHz.
  - Dual polarization.
  - Data rate
    - O8: DBBC2
      - 2048 Mbps (2 bits, 32 MHz x 8, 1 VDIF thread), LO=708 MHz.
    - ON: DBBC3 DDC E v127 in the 1st part
      - 8096 Mbps (8 bits, 128 MHz x 4, 2 VDIF threads) , LO=0 MHz.
    - ON: DBBC3 DDC U v127 in the 2nd part
      - 8096 Mbps (8 bits, 64 MHz x 8, 4 VDIF threads) , LO=0 MHz.
- Correlation results: https://services.jive.eu/ftp_fringes/PR335/index.html

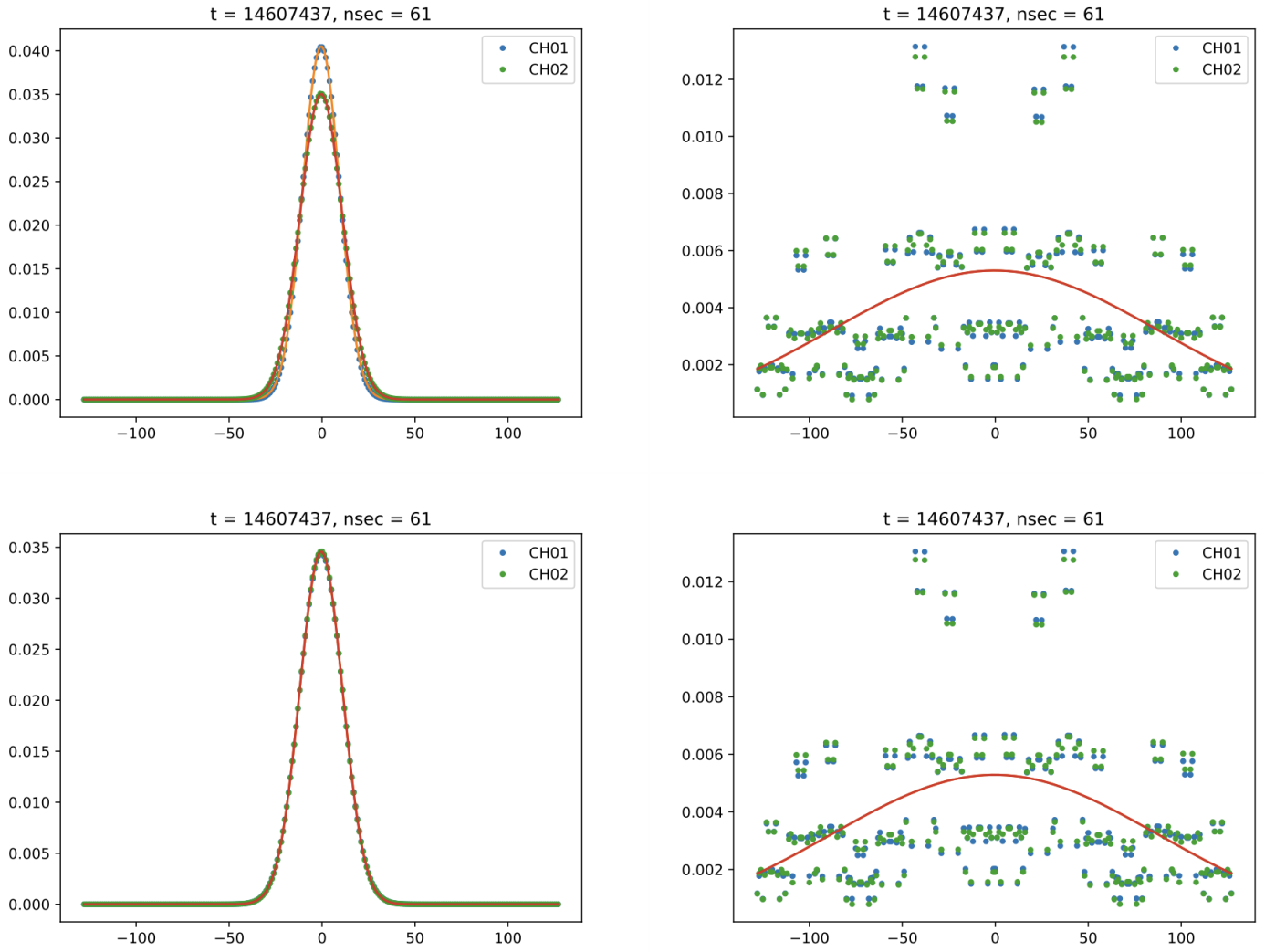
- Fringes to both DBBC2 and DBBC3 with comparable SNR!
- DDC E v127
  - Calibrator scan: No. 24
  - Sample distribution between -127 and +127
    - BBC AGC target level: 8000.
    - Following Gaussian distribution: RMS ~11.5 (~3.5 from m5bstate), Mean ~0.
    - Fringes were seen in all 128 MHz subbands.





- DDC U v127
  - Calibrator scan: No. 111
  - BBC AGC target level: 8000
  - Sample distribution in the lower two 64 MHz subbands
    - Following Gaussian distribution
    - RMS ~11.5
    - Mean ~0
    - High-SNR fringes
  - Sample distribution in the upper two 64 MHz subbands
    - 8-bit header, 2-bit meta data
    - Strange distribution.
    - A bug in the control software.
    - Fixed rapidly by Sven Dornbusch.

8-bit mode: Support 4 x 128 MHz filters per Core3H board



5. Summary and outlook

- VLBI test observations with 8-bit VDIF data went successfully
  - DBBC3 backends do output sensible 8-bit VDIF data, in particular using the new firmware DDC E/U v127.
  - The upgraded SFXC fully supports the correlation of 8-bit VDIF data.
- Follow-up thoughts
  - A few more test observations with DDC E/U v127.
  - Justify 10% sensitivity improvement with more stations and careful setups.

- Required supports for future hands-off observations
  - NRAO Sched
    - Tiny change: adding the option of 8 bit VDIF data format.
  - FS
    - Drudg
      - Supporting VEX 2.0
    - SNAP commands
      - core3h_mode
      - fb_mode
  - JIVE5ab and SFXC
    - Done?
  - DBBC3 firmware DDC
    - Improve the bandpass shape of 32 MHz filters
      - Minimize bandpass mismatch on the baselines of DBBC3-DBBC2 .
- Thank Gino and Sven for helpful email discussion!