Testing the VLBI system prior to the CONT11 campaign

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Revision history

Version	Date	Author	Updates
1.0	08-08-2011	PdV & SGE	First version

Contents

1 Introduction

CONT11 is a campaign of continuous VLBI sessions, scheduled to be observed in the second half of September 2011 (15-SEP-2011 00:00 UT through 29-SEP-2011 24:00 UT). The CONT11 campaign will be a continuation of the series of very successful continuous VLBI campaigns that were observed at irregular intervals since 1994. The most recent CONT campaigns were observed in roughly three-year intervals as CONT02 (October 2002), CONT05 (September 2005), and CONT08 (August 2008). With a tentative network size of fourteen stations (nine in the northern hemisphere and five in the southern hemisphere) the observation mode will depend on the station capabilities, media resources, e-transfer capacities, and correlator resources. Resource limitations may make it necessary to reduce the network size or length of the campaign.

2 Highlights on the CONT11 campaign

2.1 Goals

The plan for the CONT11 campaign is to acquire state-of-the-art VLBI data over a time period of about two weeks to demonstrate the highest accuracy of which the current VLBI system is capable. This will support high resolution Earth rotation studies, investigations of reference frame stability, and investigations of daily to sub-daily site motions, among other things. A number of scientific and technical goals are set for the campaign:

- **Science**: Analysis of the two weeks of continuous high frequency (sub-daily) Earth Orientation Parameters (EOP) will address the discrepancies seen between the theoretical models (ocean tidal and atmospheric) and the observations at the M2 and S1 frequencies as well as between long-term and short-term values of tidal amplitudes. The large network of CONT11, with the reasonably balanced geographical distribution between northern and southern hemisphere, is expected to provide an increased precision with respect to previous CONT campaigns and will thus allow further studies of high frequency EOP variations, analysis of ocean tide models, and tests of theoretical models. It is also expected that the precision of CONT11 will further the studies of ter-diurnal signals related to M3 and S3 tidal phenomena in the oceans and the atmosphere. For ionospheric research, the larger geographical coverage of CONT11 will allow the derivation of maps of total electron content (TEC) with an increased sensitivity to smaller scale features.

- **Technique improvement**: Continuous VLBI data allows comparison of estimates of troposphere zenith delay and gradients across experiment boundaries as a measure of the accuracy of the observations and analysis. Experience from previous CONT campaigns shows the importance of observing tropospheric parameters with several complementary instruments for the derivation of robust geodetic results in particular for reference frame investigations. Comparisons with GPS estimates and with Numerical Weather Models (NWM) will be of great importance. High-resolution NWM are being used for the derivation of mapping functions. CONT11 will be an excellent test bed to develop this approach further by investigating the inclusion of atmospheric turbulence models and/or NWM derived tropospheric gradients in the geodetic VLBI analysis.

- **Accuracy assessment**: Analysis of reference frame repeatability day to day can be made with CONT11 and compared with previous continuous VLBI series. In particular the rigorous combination of reference frame realizations can be investigated. Continuous VLBI sessions have proven to be a very important source of information for these investigations.
- **Comparisons**: All stations have IGS GPS systems relatively nearby that are considered Global Stations, three stations are co-located with an ILRS SLR system, and four stations are co-located with an IDS DORIS station. The continuous high accuracy allows investigation of daily and sub-daily site motions for comparison with external factors such as atmospheric effects and temperature distortions of the antennas or pedestals.

2.2 Observation Period

The fifteen days of continuous VLBI observation have been fixed as follows:

start of campaign:	Thursday September 15, 2011 @ 00:00:00 UT
end of campaign:	Thursday September 29, 2011 @ 23:59:59 UT

2.3 Network Resources

The following network resources will be used during the CONT11 campaign:

- Observation network: 14 stations alloted observing time for the 15 session days of the CONT11 campaign. The stations are enumerate in Table 1

Name	Code	Observatory name and location
BADARY	Bd	Badary Radio Astronomical Observatory, Russia
FORTLEZA	Ft	Space Radio Observatory of the Northeast (ROEN), Fortaleza, Brazil
HARTRAO	Hh	Hartebeesthoek Radio Astronomy Observatory, South Africa
HOBART12	Hb	Mt. Pleasant Radio Astronomy Observatory, Hobart, TAS, Australia
KOKEE	Kk	Kokee Park Geophysical Observatory, Kauai, HI, USA
NYALES20	Ny	Ny Ålesund Geodetic Observatory, Spitsbergen, Norway
ONSALA60	On	Onsala Space Observatory, Sweden
TIGOCONC	Tc	Transportable Integrated Geodetic Observatory (TIGO), Concepción, Chile
TSUKUB32	Ts	Tsukuba VLBI Station, Japan
WARK12M	Ww	Warkworth VLBI Station, New Zealand
WESTFORD	Wf	Westford Antenna, Haystack Observatory, MA, USA
WETTZELL	Wz	Fundamentalstation Wettzell, Germany
YEBES40M	Ys	Astronomical Center at Yebes, Spain
ZELENCHK	Zc	Radioastronomical Observatory Zelenchukskaya, Russia

Table 1: Scheduled participating stations in CONT11

The geographical distribution of these stations is depicted in the network map in Figure 1

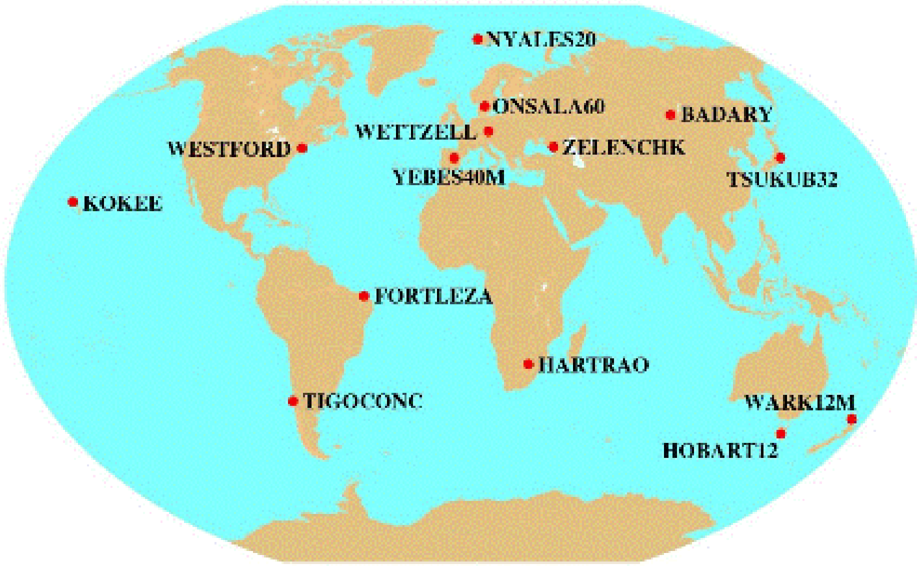

Figure 1: Scheduled participating stations in CONT11 campaing

2.3.1 CONT11 Network

- The CONT11 stations committed to a pre-campaign station checkout to ensure that the data acquired during the campaign are of the highest quality. Instructions and advice about what to check and how are handled by the Network Coordinator.
- Rapid disk return for the "R" type sessions during the CONT period so that IVS can keep up its commitment for two rapid-turnaround sessions each week.
- Simultaneous acquisition of high quality GPS data during the campaign so that the comparison analyses can be done. Coordination with the IGS community will be done to make sure that the stations can be expected to produce good data reliably.
- Simultaneous observing by co-located SLR systems at TIGO, HartRAO, and Wettzell.

2.4 Station testing

In order to make sure the stations are in good operating condition before CONT11, a set of tests is being developed under the direction of Brian Corey and Ed Himwich for each station to perform. These tests will be based on the similar tests that were done for previous CONT experiments, the last of which was the CONT08 campaign in 2008. The sixth Technical Operations Workshop (TOW), to be held at MIT Haystack Observatory in May 2011, will offer a troubleshooting class tailored to the CONT11 needs.

2.5 Correlator Resources

With a network size of fourteen stations, the CONT11 campaign can be viewed as a precursor of the observing mode of the next generation VLBI system (VLBI2010). In “VLBI2010 mode” networks of sixteen or more stations will observe continuously and transfer their data to a correlator facility for immediate correlation so that results become available within 24 hours of the end of observation. CONT11, of course, will have a lower data rate and a less stringent completion requirement than VLBI2010. It is expected that recording modules will store several campaign days of a given station in order to optimize the usage of media. Hence, for logistical ease, consistency of results, and to gain experience in VLBI2010-type load, correlation will be performed at a single correlator: the Washington Correlator will take on the large task of correlating the CONT11 data.

2.6 Expected Accuracies

The schedule will be a standard geodetic schedule which achieves simulated EOP results of at least as good as $35\mu''$ for pole position and $1.5\mu''$ for UT1. The recording mode will probably be the 2-bit sampled version of the R1 mode ($512Mb/s$ data rate) which was successfully used in the CONT08 campaign.

2.7 Schedules

The detailed observing schedule for CONT11 will be generated using the automatic scheduling algorithms of the NASA sked program. We will investigate the best combination of scheduling parameters, minimum SNR levels, source list, and flux models. The “best” schedule will be determined as a compromise between the optimum simulated formal errors, number of observations, number of scans per hour, sky coverage, and robustness. Gaps with no observational data will be avoided by scheduling the daily station checks at non-overlapping, staggered time periods that are convenient for the stations.

3 Yebes station testing

Yebes 40 meters radiotelescope is participating for the first time in a continuous campaign in geodetic VLBI. Tests at Yebes radiotelescope started on July 29th 2011 and lasted 2 weeks. The following sections show the testing carried out and their results. The station configuration is following the *setupys.prc* procedure file. Basically from BBC01 to BBC04 it is X-band, from BBC05 to BBC08 it is X-extended-band and from BBC09 to BBC14 it is S-band.

4 Testing phase cal tone amplitudes

The objective of this test is to measure the voltage amplitude of all the pcal tones in both sidebans of all 14 frequency channels. This will provide a coarse (in frequency) measure of gain vs. frequency from the front end all the way down to the samplers. Ideally the amplitude spectrum should be:

- flat to ± 10 from 10 kHz to 6 MHz
- down by ~ 30 at 7 MHz
- down by $55 - 60$ at 8 MHz.

We have used an FFT backend with 1638 channels in 10 MHz, and a spectral resolution of 6.1 KHz, to measure the phase cal power of the different tones at both bands of all BBCs. Figs. 2 to 15 show the baseband spectra with the phase cal on and off for BBCs and both bands. We have substracted a baseline to the spectra to get the total phase cal noise power over the noise. Values do not comply with the requirements since the power decreases less than 30% at 7 MHz and more than 60% at 8 MHz. S-band channels are plagued with RFI and some spur signals appear just over the phase cal tones frequencies or close to them (see figures 2 to 15).

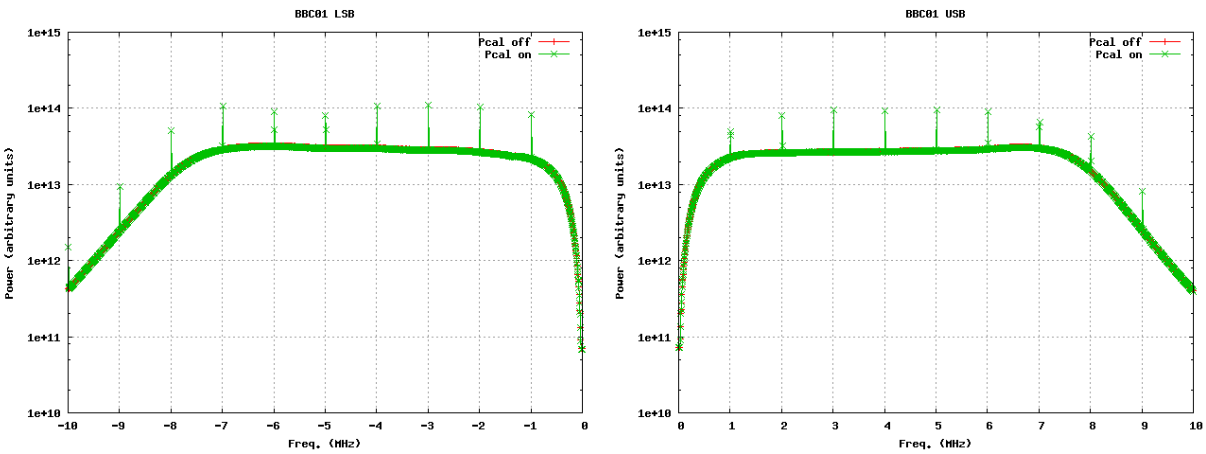

Figure 2: *BBC01 USB and LSB spectral band with phase cal on and off.*

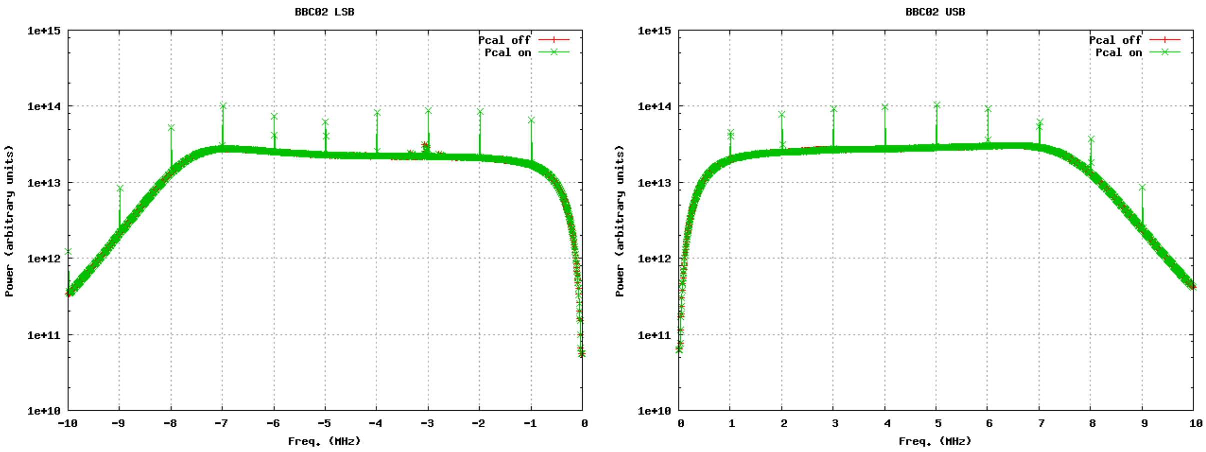

Figure 3: *BBC02 USB and LSB spectral band with phase cal on and off.*

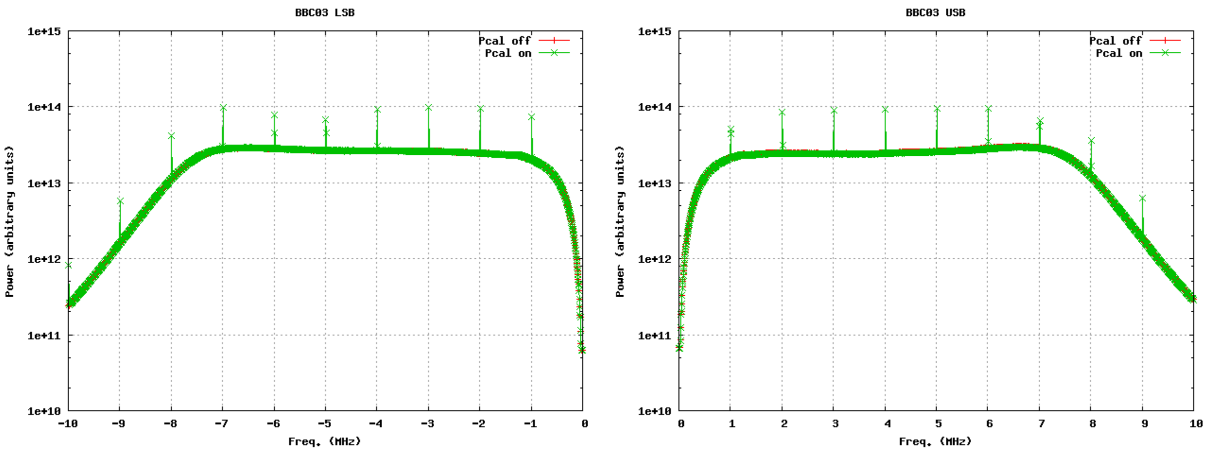

Figure 4: *BBC03 USB and LSB spectral band with phase cal on and off.*

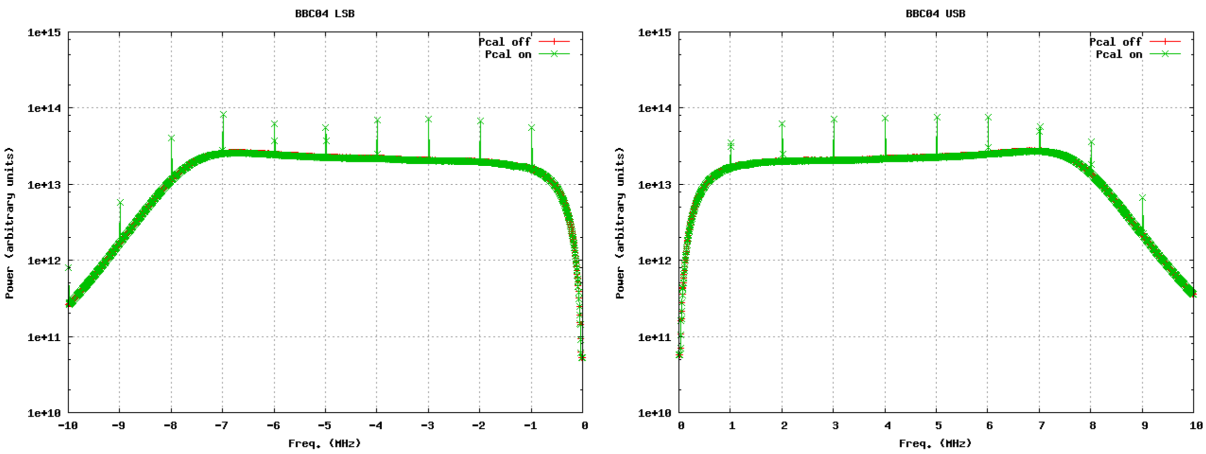

Figure 5: *BBC04 USB and LSB spectral band with phase cal on and off.*

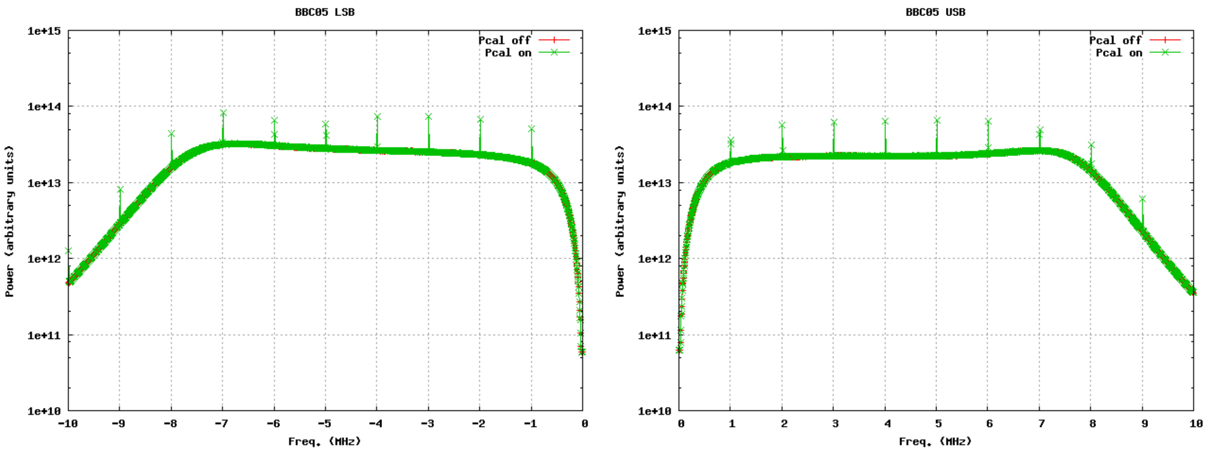

Figure 6: *BBC05 USB and LSB spectral band with phase cal on and off.*

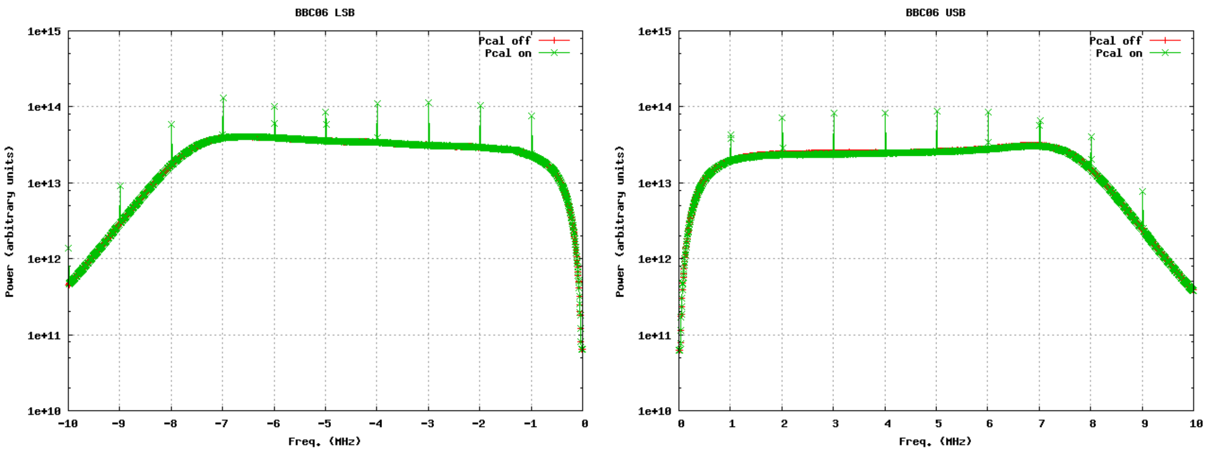

Figure 7: *BBC06 USB and LSB spectral band with phase cal on and off.*

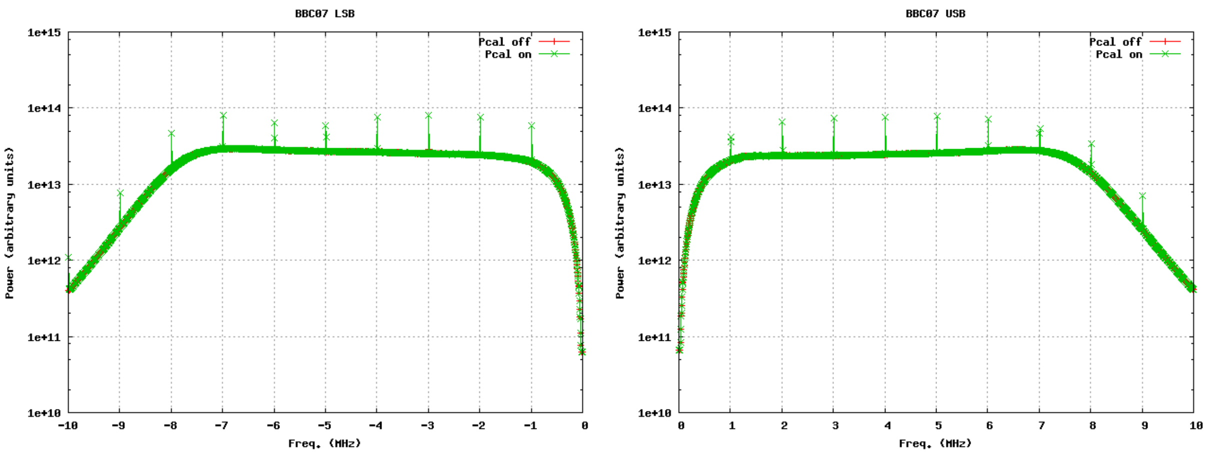

Figure 8: *BBC07 USB and LSB spectral band with phase cal on and off.*

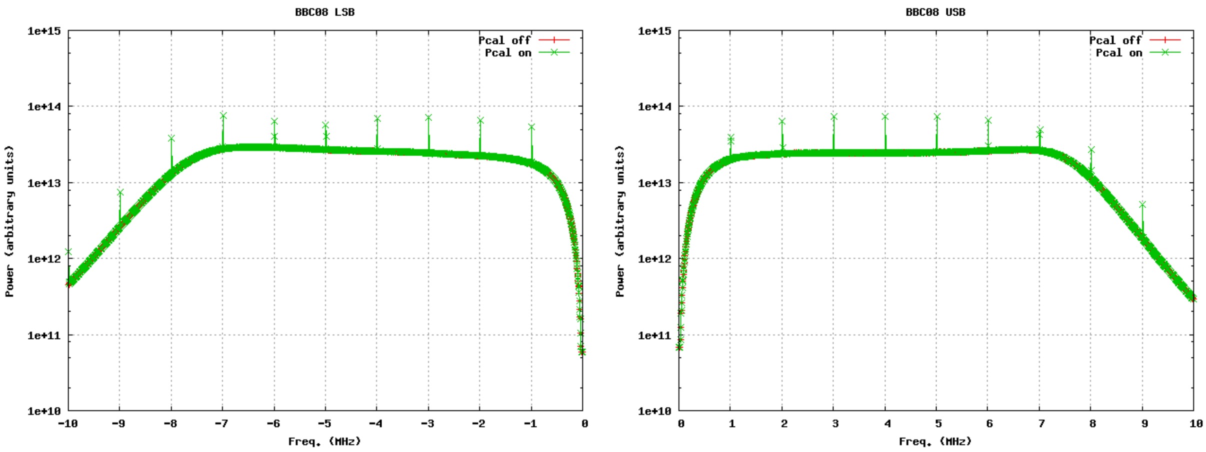

Figure 9: *BBC08 USB and LSB spectral band with phase cal on and off.*

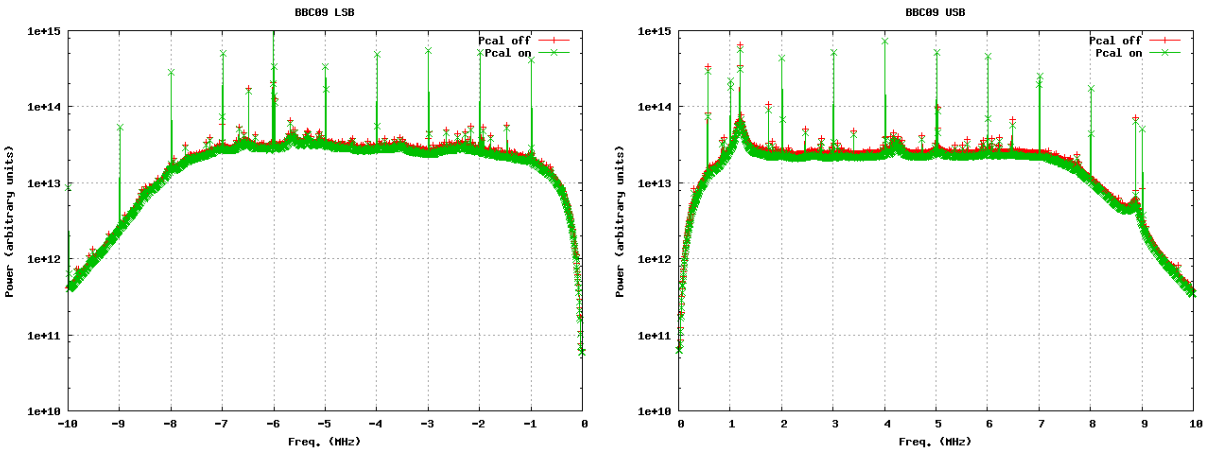

Figure 10: *BBC09 USB and LSB spectral band with phase cal on and off.*

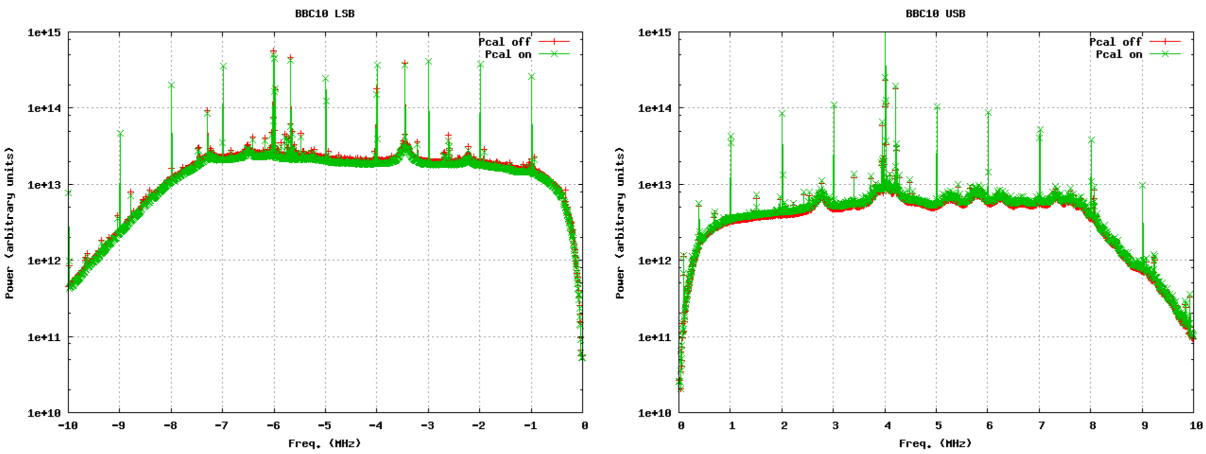

Figure 11: *BBC10 USB and LSB spectral band with phase cal on and off.*

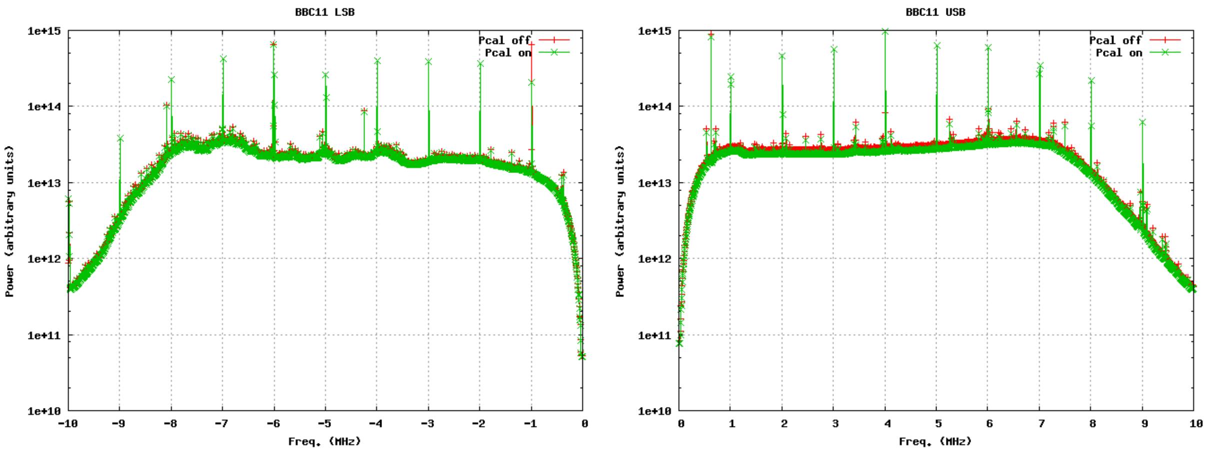

Figure 12: *BBC11 USB and LSB spectral band with phase cal on and off.*

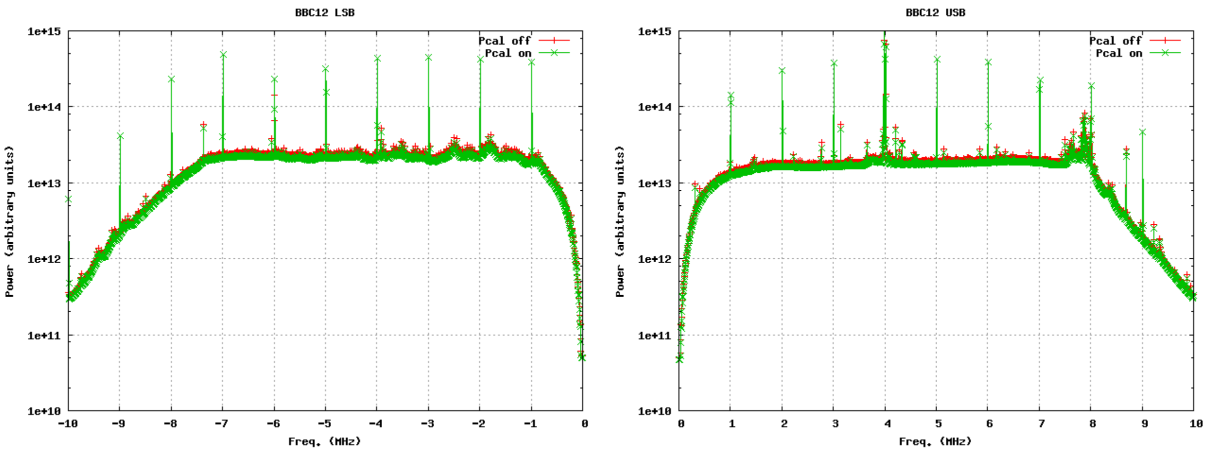

Figure 13: *BBC12 USB and LSB spectral band with phase cal on and off.*

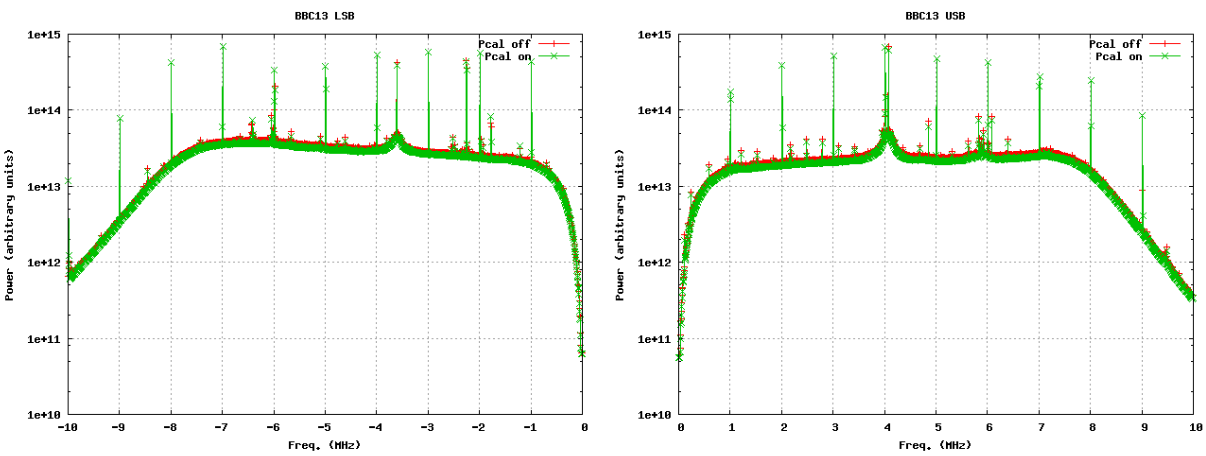

Figure 14: *BBC13 USB and LSB spectral band with phase cal on and off.*

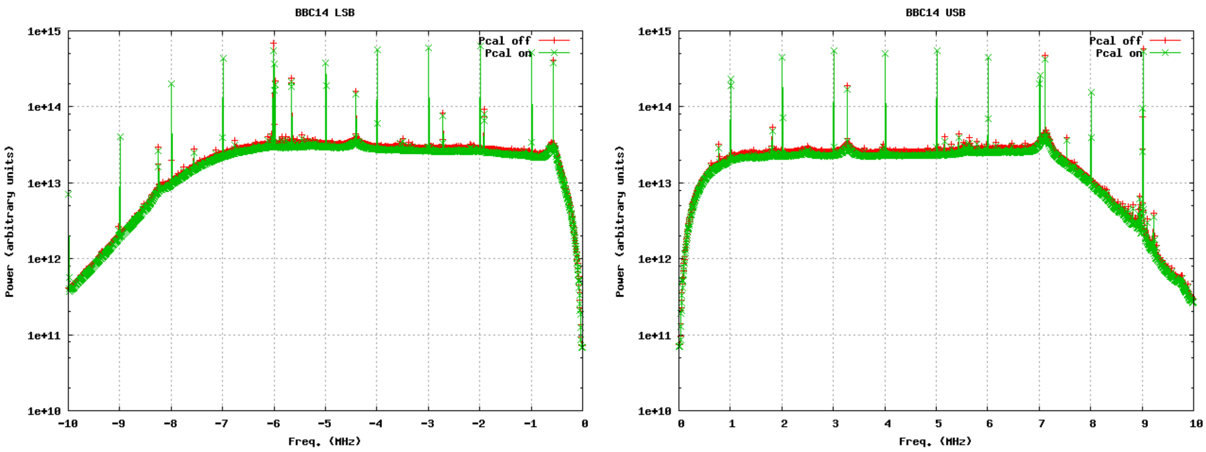

Figure 15: *BBC14 USB and LSB spectral band with phase cal on and off.*

Table 4 summarizes the amplitude of every phase cal tone at all BBCs and figure 16 shows the phase cal amplitudes plot in dB for both sidebands in all the BBCs. The LSB displays an awkward behaviour at the tone at 5 MHz, which we believe may come from a wrong measurement. Channels from BBC10 and BBC12 display different power amplitudes from the phase cal tone at 4 MHz. This is due to the presence of an RFI signal at 4 MHz that overlaps with the phase cal tone at 4 MHz (see Figs. 11 and 13)

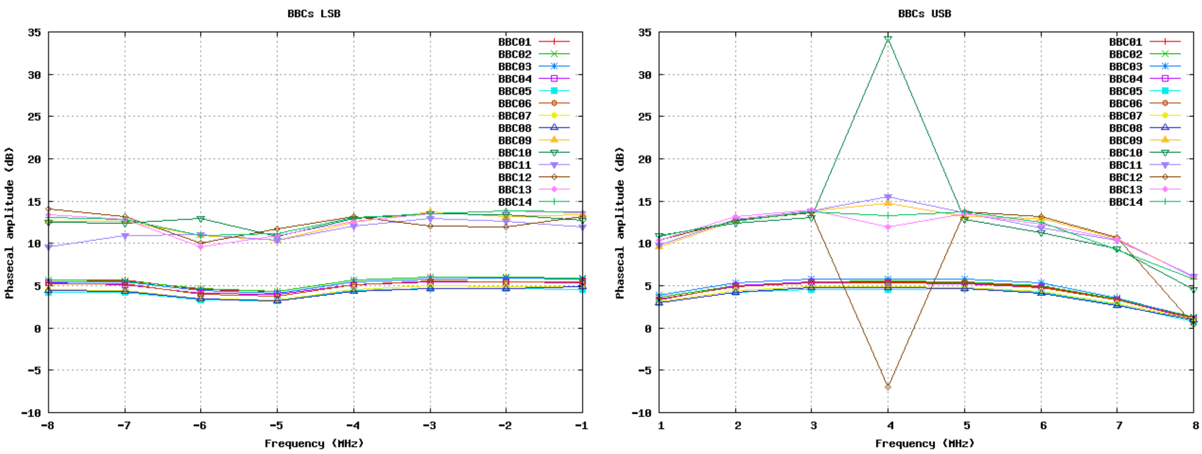

Figure 16: *Phasecal amplitudes (dB) for both sidebands in all BBCs.*

#BBC		Power phasecal (dB) Frequency channel							
		1	2	3	4	5	6	7	8
BBC01	USB	3.47	4.85	5.44	5.40	5.39	4.92	3.40	1.27
	LSB	5.91	6.00	5.96	5.65	2.47	4.57	5.69	5.70
BBC02	USB	3.60	5.04	5.42	5.52	5.49	4.96	3.43	1.30
	LSB	5.94	6.03	5.95	5.65	2.49	4.69	5.57	5.71
BBC03	USB	3.80	5.38	5.76	5.75	5.82	5.31	3.58	1.22
	LSB	5.73	5.86	5.78	5.41	2.31	4.45	5.44	5.49
BBC04	USB	3.31	4.94	5.41	5.30	5.24	4.78	3.27	1.06
	LSB	5.45	5.42	5.44	5.11	2.21	4.11	5.15	5.30
BBC05	USB	2.98	4.17	4.50	4.53	4.68	4.25	2.71	0.79
	LSB	4.58	4.60	4.63	4.46	1.72	3.28	4.70	4.24
BBC06	USB	3.47	4.91	5.37	5.33	5.32	4.82	3.28	1.14
	LSB	5.35	5.49	5.59	5.09	2.11	4.04	5.22	5.19
BBC07	USB	3.07	4.38	4.84	4.84	4.80	4.29	2.88	1.04
	LSB	4.86	4.91	5.04	4.54	1.82	3.47	4.43	4.54
BBC08	USB	2.97	4.20	4.72	4.80	4.64	4.06	2.63	0.93
	LSB	4.84	4.66	4.65	4.31	1.76	3.43	4.32	4.48
BBC09	USB	9.56	12.77	13.89	14.71	13.21	12.95	10.61	6.03
	LSB	13.43	13.18	13.67	12.48	7.54	10.93	12.64	12.62
BBC10	USB	10.92	12.33	13.10	34.22	12.78	11.22	9.37	4.50
	LSB	12.69	13.36	13.54	12.93	7.81	12.90	12.34	12.52
BBC11	USB	9.79	12.85	13.82	15.48	13.59	11.87	10.34	6.07
	LSB	11.89	12.62	12.98	12.08	12.08	7.29	10.99	10.89
BBC12	USB	10.36	12.69	13.63	-6.92	13.77	13.18	10.74	0.45
	LSB	13.19	11.89	12.06	13.22	8.63	10.00	13.20	14.03
BBC13	USB	10.42	13.20	13.94	11.88	13.47	12.30	10.43	5.96
	LSB	13.59	13.84	13.47	12.56	7.93	9.60	12.81	13.34
BBC14	USB	10.82	12.58	13.78	13.25	13.76	12.46	9.24	5.73
	LSB	13.72	13.83	13.49	13.10	8.00	10.90	12.88	13.09

Table 2: Phase cal tone amplitudes

5 Testing the phasecal total power

The objective of this test is to measure the fractional contribution by the phase cal to the total system power in both sidebands of all 14 frequency channels. SNAP procedure `pcalpowera` measures the fractional contribution of all 14 frequency channels by switching on and off the phase cal several times. The data analysis script `pcalpower` produces the results. The requested performance is that phase cal should contribute $1-2\%$ of total system power.

Phase cal total power contribution at X standard and expanded band is between $1-2\%$. S band resulted up to 15% of total power. We inserted 6 dB attenuators in the phase cal signal path and the current power contribution is 3%. S band channels are more noisy due to high RFI. BBC10 measurements are not reliable.

Results are summarized in table 3.

Channel ID	Diff	±	Power (%)	± (%)	Comment
1l	0.99	0.09	1.81	0.16	
1u	1.19	0.10	1.96	0.16	
2u	0.74	0.07	1.94	0.17	
3u	0.74	0.08	1.80	0.19	
4u	0.65	0.08	1.68	0.21	
5u	0.76	0.11	1.53	0.21	
6u	0.75	0.12	1.37	0.22	
7u	0.72	0.10	1.57	0.21	
8l	0.55	0.09	1.35	0.21	
8u	0.53	0.08	1.44	0.21	
9u	10.50	0.09	3.16	0.03	
au	-57.28	16.46	-3.41	0.96	
bu	10.82	0.14	3.48	0.05	
cu	12.14	0.39	3.54	0.12	noisy
du	8.45	0.17	3.13	0.07	noisy
eu	9.40	0.10	3.69	0.04	noisy
ia	0.62	0.07	1.60	0.19	
ib	5.54	0.63	1.79	0.20	

Table 3: *Phase cal power contribution in % and difference between power on and off. Channels are considered noisy when the measured values show a high dispersion.*

6 Testing phase cal spurious signals

The objective of this test was to look for evidence of spurious phase cal signals at all phase cal tone frequencies in both sidebands of all 14 frequency channels. The method proposed is to switch off the pcal pulses and to unlock them from the reference signal and use the decoder to extract the amplitude and phase of the detected signals at the frequency the tones should appear.

The desired performance is that spurious signals should be >50 dB below the pcal signals. However, due to the nature of the decoder it is not possible to detect spurs weaker than -30 dBc.

Since no decoder is available two alternatives were possible: examination of spectra (see figs 2 to 15) and recording data in two different scenarios and comparing them. X standard band and x expanded band show a good behaviour but S band is plagued with RFI signals, of which some of them appear at the frequency of the pcal tones.

7 Testing the BBC image rejection

The objetive of this test is to measure the image rejection at the pcal frequencies in both sidebands in all 14 BBCs.

We generated a signal of 746 MHz and a RF level of -15dBm with a signal generator device, that was injected in the VLBA using the alternate IF inputs. All BBCs were tuned to 750.00 MHz and hence the image signal should appear at 4 MHz in the LSB of each BBC. We measured the rejection level by substracting the image signal from the band signal with a spectrum analyzer.

The image rejection in the USB band was measured in a similar way, but injecting a test signal of 756 MHz signal and keeping all BBCs at 750.00 MHz.

Table 7 shows the value in dB of the image rejection in both sidebands for all BBCs. All values (except BBC03 USB) comply with the requested performance (>25 dB).

#BBC	Image rejection (dB)	
	LSB	USB
BBC01	28	25
BBC02	35.2	31
BBC03	32.8	24
BBC04	37	32
BBC05	38	25
BBC06	30	26
BBC07	36	35
BBC08	32	32
BBC09	36	26
BBC10	38	31
BBC11	33	38
BBC12	37	27
BBC13	40	48
BBC14	31.5	27

Table 4: *Image rejection (dB) in both sidebands for all the BBCs*

8 Testing sample statistics

The objective of this test is to measure the distribution of the de 2-bit data samples on the four possible states: large negative (–), small negative (-), small positive (+), and large positive (++).

Ideally the distribution for white noise should be 18%/32%/32%/18% for these four states –/-/+/++, respectively. A deviation of $\pm3\%$ is tolerated. We include here data from past correlation experiments and data obtained from the mark5B recorder.

All NMEs from the EVN VLBI observations provide these numbers and the values have always comply as expected. We include some data from NME N11M2 (June 2011) in table 5.

Channel ID	Band	–	-+	+-	++	Invalid	Avg sign bit	Avg mag bit
16	6640.52MHz, LSB, Rcp	19.56	30.22	30.3	19.41	0.513	49.97	49.88
18	6640.52MHz, LSB, Lcp	15.8	33.89	34.48	15.31	0.513	50.05	49.45
0	6640.52MHz, USB, Rcp	18.91	30.83	30.81	18.94	0.513	50.01	50.03
2	6640.52MHz, USB, Lcp	17.63	32.37	32.28	17.21	0.513	49.75	49.83
20	6656.52MHz, LSB, Rcp	18.43	31.64	32.04	17.38	0.513	49.67	49.27
22	6656.52MHz, LSB, Lcp	15.4	34.61	34.43	15.04	0.513	49.73	49.91
4	6656.52MHz, USB, Rcp	18.4	31.91	30.92	18.25	0.513	49.43	50.42
6	6656.52MHz, USB, Lcp	16.58	33.49	32.92	16.5	0.513	49.67	50.25
26	6672.52MHz, LSB, Rcp	17.91	31.87	32.12	17.59	0.513	49.97	49.71
28	6672.52MHz, LSB, Lcp	20.25	29.38	29.66	20.2	0.513	50.12	49.84
8	6672.52MHz, USB, Rcp	17.23	33.08	32.2	16.98	0.513	49.43	50.32
10	6672.52MHz, USB, Lcp	18.26	31.71	31.49	18.02	0.513	49.77	49.99
30	6688.52MHz, LSB, Rcp	17.89	32.14	31.99	17.46	0.513	49.71	49.86
31	6688.52MHz, LSB, Lcp	17.27	32.55	32.65	17.02	0.513	49.92	49.83
10	6688.52MHz, USB, Rcp	18.02	32.29	31.5	17.68	0.513	49.43	50.23
12	6688.52MHz, USB, Lcp	17.17	32.7	32.31	17.32	0.513	49.88	50.27

Table 5: *2-bit sampler statistics for astronomy experiment N11M2 in %.*

We have also got this information from Haystack observatory for experiment RD1102, which is summarized in table 6.

Channel ID	Band	++	+-	-+	–	Bias	Level
0	X1U	19.16	30.86	30.83	19.15	50.01	61.69
2	X1L	19.67	30.41	30.47	19.45	50.08	60.88
4	X2U	17.79	32.44	32.42	17.35	50.23	64.86
6	X3U	18.45	32.15	31.09	18.32	50.60	63.24
8	X4U	16.82	33.57	32.93	16.68	50.40	66.50
10	X5U	17.16	33.43	32.62	16.79	50.59	66.05
12	X6U	18.57	31.57	31.46	18.40	50.14	63.03
14	X7U	18.10	32.41	31.71	17.78	50.52	64.12
1	X8U	17.42	32.65	32.32	17.61	50.06	64.97
3	X8L	17.63	32.40	32.57	17.40	50.03	64.98
5	S1U	18.24	32.09	31.49	18.18	50.33	63.58
7	S2U	20.50	29.75	30.03	19.72	50.26	59.78
9	S3U	21.08	29.27	28.40	21.24	50.36	57.67
11	S4U	15.61	33.33	33.73	17.34	48.94	67.05
13	S5U	18.96	31.54	31.38	18.12	50.50	62.92
15	S6U	19.13	31.45	30.79	18.63	50.58	62.24

Table 6: *2-bit sampler statistics for geodetic experiment RD1102 in %. The bias is the fraction in the two negative states, and the level is the fraction in the two low-magnitude states.*

For Mark5B it is also possible to record an experiment on the disk and later use script 'bstate' to get the statistics. This is a very convenient procedure because it allows to play with the attenuation and tune it to get optimum results. Table 7 summarizes the results.

We conclude that statistics show a correct behaviour of the samplers and levels of the signals.

Channel ID	++	+-	-+	–	++	+-	-+	–	gfact
		Power				(%)			
0	97588	156181	152585	93646	19.5	30.5	31.2	18.7	0.96
1	89648	161016	161518	87818	17.9	32.3	32.2	17.6	1.02
2	91464	161511	155202	91823	18.3	31.0	32.3	18.4	0.99
3	85482	169896	163827	80795	17.1	32.8	34.0	16.2	1.06
4	86917	166942	162468	83673	17.4	32.5	33.4	16.7	1.05
5	92036	159012	159016	89936	18.4	31.8	31.8	18.0	1.00
6	90605	161836	158153	89406	18.1	31.6	32.4	17.9	1.01
7	88173	165771	161504	84552	17.6	32.3	33.2	16.9	1.04
8	98213	152941	152101	96745	19.6	30.4	30.6	19.3	0.94
9	88475	164294	163449	83782	17.7	32.7	32.9	16.8	1.04
10	89331	160224	158326	92119	17.9	31.7	32.0	18.4	1.00
11	110354	137123	144330	108193	22.1	28.9	27.4	21.6	0.85
12	108338	148793	140977	101892	21.7	28.2	29.8	20.4	0.89
13	83593	169446	165629	81332	16.7	33.1	33.9	16.3	1.07
14	94275	158794	156961	89970	18.9	31.4	31.8	18.0	0.99
15	96971	157725	152346	92958	19.4	30.5	31.5	18.6	0.96

Table 7: *2-bit sampler statistics obtained using utility 'bstate' for 200 sampler from the Yebes Mark5B recorder. The statistics are grouped in arbirtray values (first block of columns) and in % (second block of columns)*

9 Measuring the baseband spectra

The objective of this test is to mesure the analog power of the BBCs to look for distortions or RFI. We have used an FFT backend with 1638 channels in 10 MHz and a resolution of 6.1 KHz. The results are grouped by bands in figures 17, 18 and 19. The total power has no sense but the relative amplitude in dB is correct. All BBCs were set to a total bandwidth of 8 MHz.

The figures show that BBCs show a good behaviour but do not comply with the required values: flat to <1 dB from 10 kHz to 6.4 MHz, down by 3 dB at 7.2 MHz and down by 8 dB at 8 MHz. We see strong RFI in the S band spectra. Most of this RFI comes from the servo system of the 40 m radiotelescope and it is very difficult to mitigate.

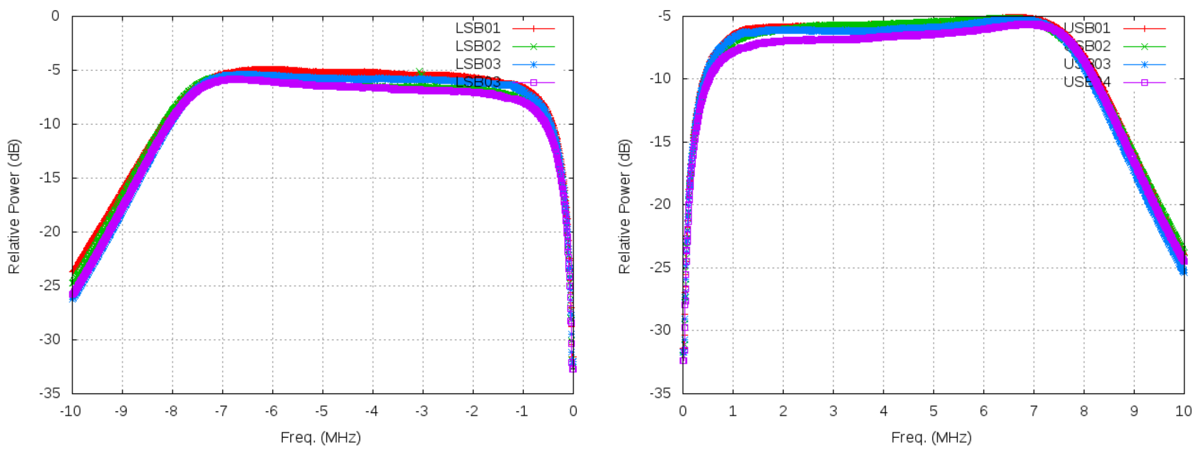

Figure 17: *Baseband spectra for BBCs 01 to 04. Left: LSB, Right: USB*

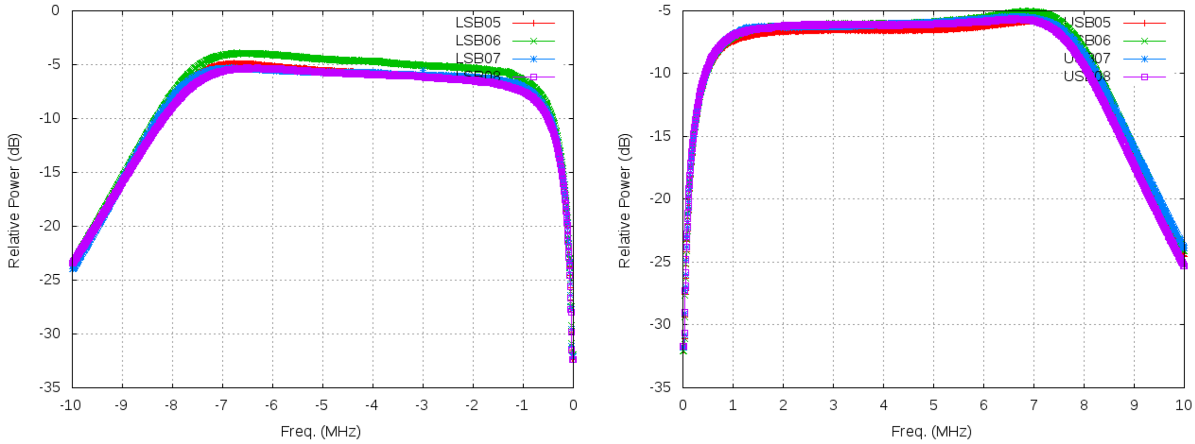

Figure 18: *Baseband spectra for BBCs 05 to 08. Left: LSB, Right: USB*

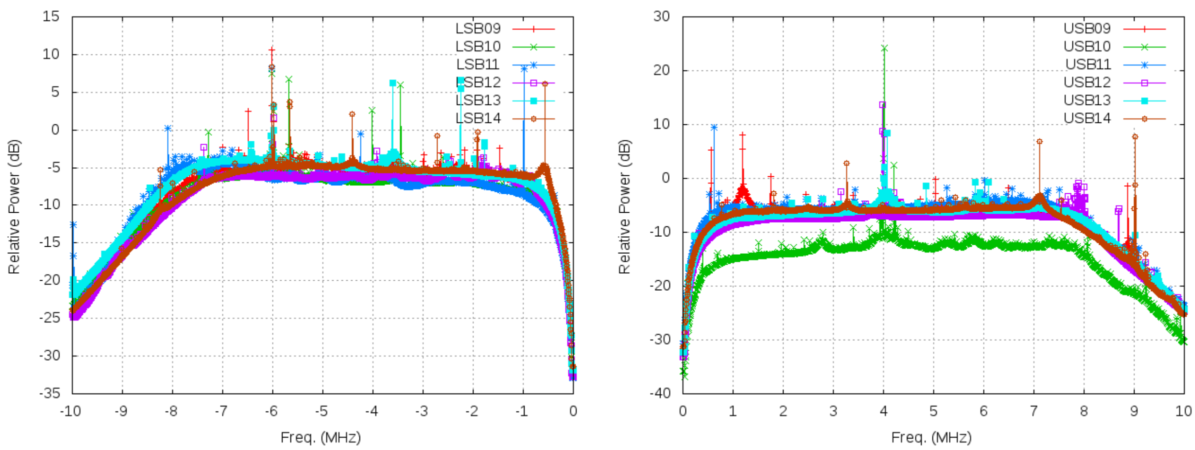

Figure 19: *Baseband spectra for BBCs 09 to 14. Left: LSB, Right: USB*

10 VC/BBC LO phase jitter

The objective of this test is to measure the LO phase noise in each of the 14 BBCs.

A test tone of 749.99 MHz from a signal generator locked to the 5 MHz of the maser was injected in the external inputs A and B of the IF. The phase cal was turned off to avoid potential interference in the measurement. All BBBC LOs were tuned to a fixed frequency of 750 MHz. The 10 KHz mixed signal was injected into an HP scope locked to the 5 MHz from the maser. The resulting sinusoid was leaving a trace on the screen for some seconds. We estimated the peak to peak jitter of the sinusoid at 0, that is, when it crosses the X axis. The result is summarized in table 10. Conversion from delay (μs) to degrees is done by multiplying by 360 deg divided by 100 μs (the period of the 10 KHz signal). The conversion factor is 3.6 deg/μs.

Measurement values for the phase jitter are shown in table 10. We include the peak to peak measurement and the RMS which is obtained approximately by dividing these values by 3. The desired performance for the VLBA BBC local oscillator RMS phase noise should be $< 2deg$ which is fulfilled in all cases.

#BBC	Peak to peak phase noise (deg)	RMS phase noise (deg)
BBC01	4.09	1.36
BBC02	3.87	1.29
BBC03	3.87	1.29
BBC04	3.6	1.2
BBC05	4.76	1.59
BBC06	3.87	1.29
BBC07	3.14	1.05
BBC08	3.14	1.05
BBC09	3.14	1.05
BBC10	4.09	1.36
BBC11	5.4	1.8
BBC12	3.6	1.2
BBC13	3.33	1.11
BBC14	4.09	1.36

Table 8: *Peak to peak and RMS phase noise for all BBC LOs when tuned at 749.99 MHz.*

11 Testing orientation-dependent effects

The objective of this test is to look for variations in the phase cal phase and cable cal that depend on the orientation of the antenna. Sudden changes could indicate a cable or connector problem. These measurements were done while moving the antenna 360 degrees in azimuth and 85 degrees in elevation.

The phase cal amplitude and phase was obtained by recording data in the Mark5B and extracting small files with 1 s data every 10 seconds. Since the movement of the antenna is rather fast (1 deg/s in elevation and 3 degs/s in azimuth) there are very few values during the slewing of the antenna. The phase cal data was extracted for tone 4010 KHz for all files using utility `bpcal`. The results for BBCs 1, 4, 5, 8, 9 and 14 are in figs. 21, 22 and **??**.

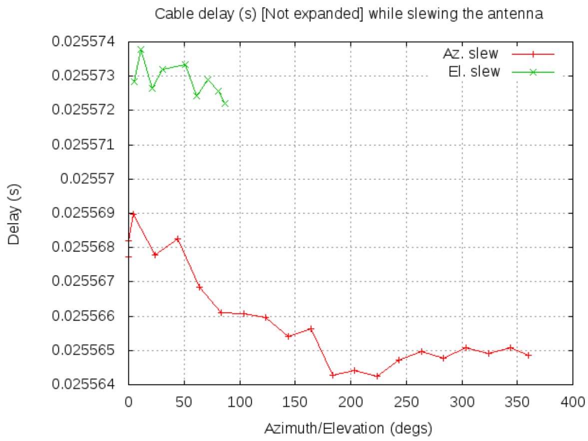

Figure 20: *Cable delay while slewing the antenna first in elevation from 5 to 87 degrees and later in azimuth from 360 to 0 degrees.*

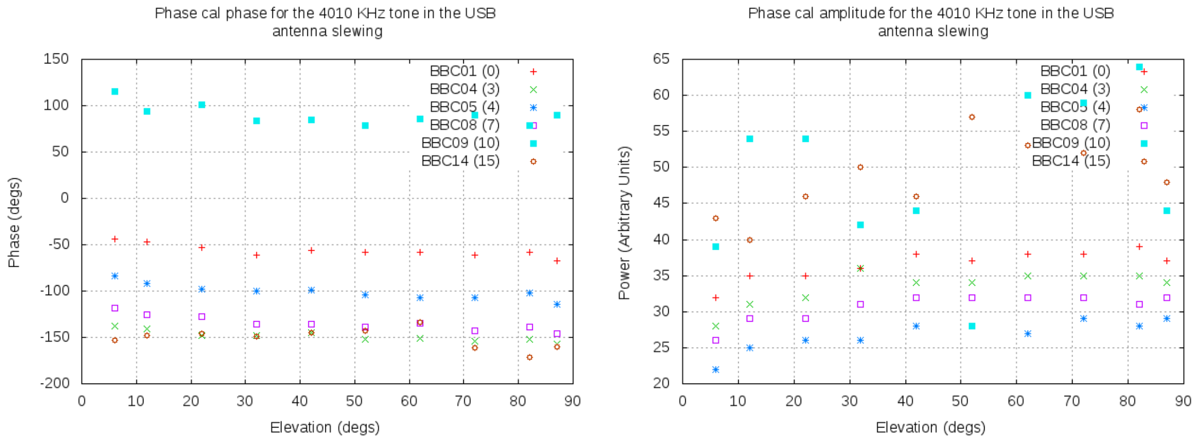

Figure 21: *Phase cal amplitude and phase while the antenna slews in elevation from 5 to 87 degrees*

12 Diurnal behavior

The objective of this test is to measure the temporal stability of the VLBI system over 24 hours, exclusive of the maser, on time scales of minutes and longer, without moving the antenna. We

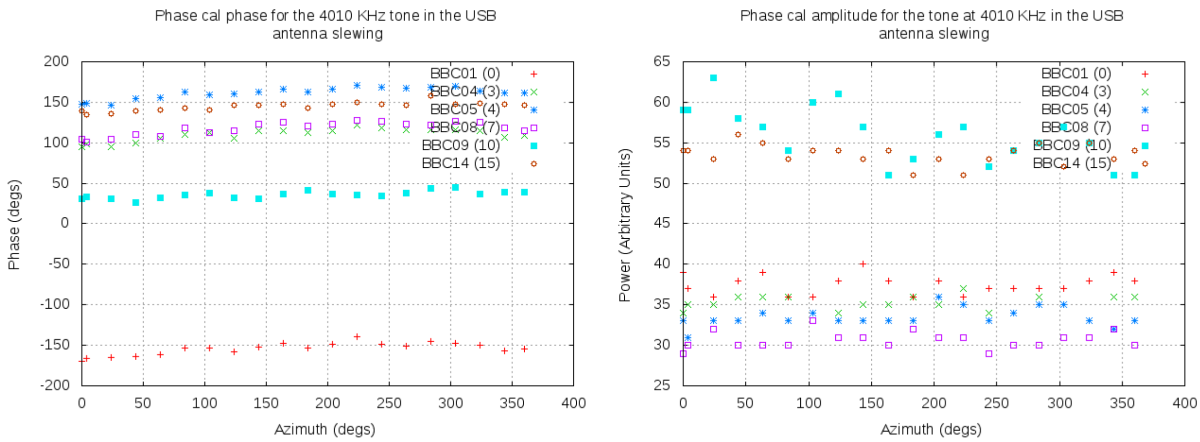

Figure 22: *Phase cal amplitude and phase while the antenna slews in azimuth from 360 to 0 degrees*

run systests procedure `overnite` for at least 24 hours, with the antenna parked at the zenith. This test was performed during 22.5 hours due to previous scheduled holography observations.

The default procedure monitors the following parameters:

- cable cal
- system temperatures in all channels (caltsys)
- receiver monitor points (usually rxall)
- fmout-gps or gps-fmout
- wx

The desired performance is that variations in phase cal phases and cable cal should be gradual, generally consistent among themselves, and dominated by temperature dependence. Variations in system temperatures and phase cal amplitudes should be explainable by changes in weather conditions (e.g., rain), RFI, and, in the case of phase cal, spurious signals. Temperature variations of the receiver box, LO, and phase cal antenna unit should stay within acceptable bounds (approximately 5, 5, and 2 deg C, respectively). Gps-fmout readings should be stable to <0.2 microsec, peak-to-peak. Weather data should behave reasonably.

Results are shown in figures 23, 24.

All values show smooth variations. Tsys for IFC should be discarded since the continuum detectors were saturated by the expanded X band 750 MHz local oscillator whose first harmonic at 900 MHz leaks, spoiling the Tsys measurements.

13 Short-term variations

The objective of this test is to measure the temporal stability of the VLBI system during 15 minutes while the antenna is stowed. The parameters to measure are phase cal amplitude and phase for BBCs 1, 4, 5, 8 9 and 14 and the cable cal.

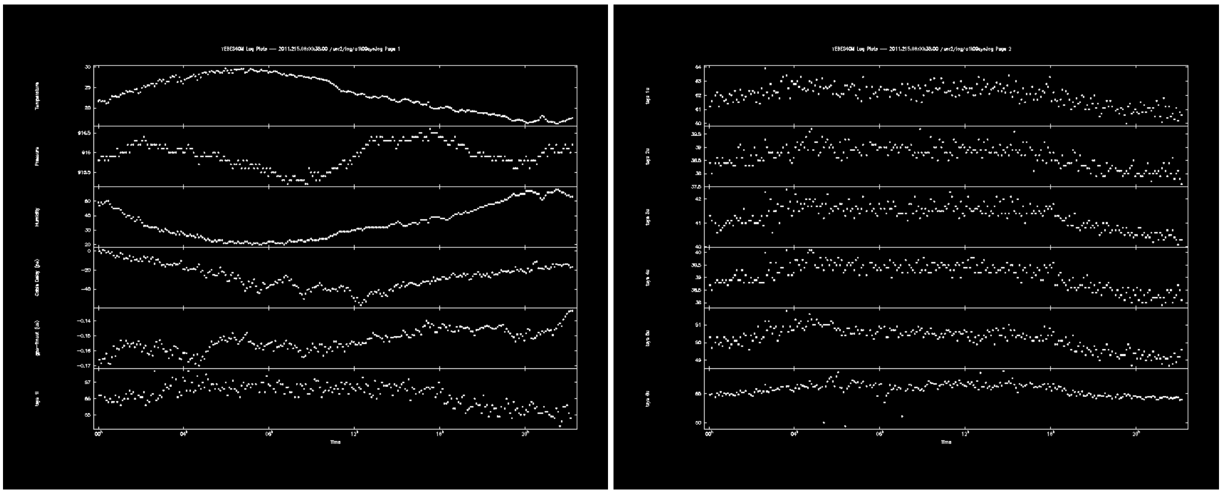

Figure 23: *On the left from top to bottom variations of temperature, pressure, humidity, cable delay, gps-fmout and tsys 1l over 22.5 hours. On the right from top to bottom variations of tsys 1u, tsys 2u, tsys 3u, tsys 4u, tsys 5u and tsys 6u over 22.5 hours.*

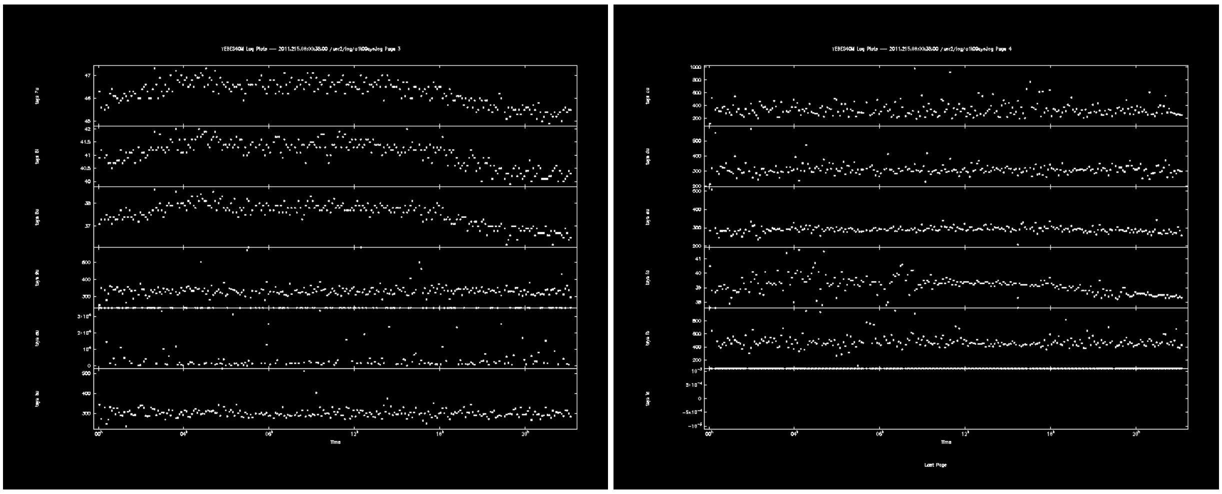

Figure 24: *On the left from top to bottom variations of tsys 7u, tsys 8l, tsys 8u, tsys 9u, tsys au and tsys bu over 22.5 hours. On the right from top to bottom variations of tsys cu, tsys du, tsys eu, tsys ia, tsys ib and tsys ic over 24 hours.*

The phase cal amplitudes and phases was measured by recording during 11 minutes data on the Mark5B. Later we extracted 1 second of data every 10 seconds and used utility "bpcal" to extract the amplitude and phase of tone 4010 KHz from all 66 files generated by the extraction. The extraction was done using command `disk2file` as shown below:

```
disk2file=,/home/data/test01.m5b,11h00m06.00s,11h00m07.00s,
!+5s
disk2file=,/home/data/test02.m5b,11h00m16.00s,11h00m17.00s,
!+5s
disk2file=,/home/data/test03.m5b,11h00m26.00s,11h00m27.00s,
.....
```

The results are summarized in figs. 25 and 26. The behaviour is smooth and the required performance is fulfilled.

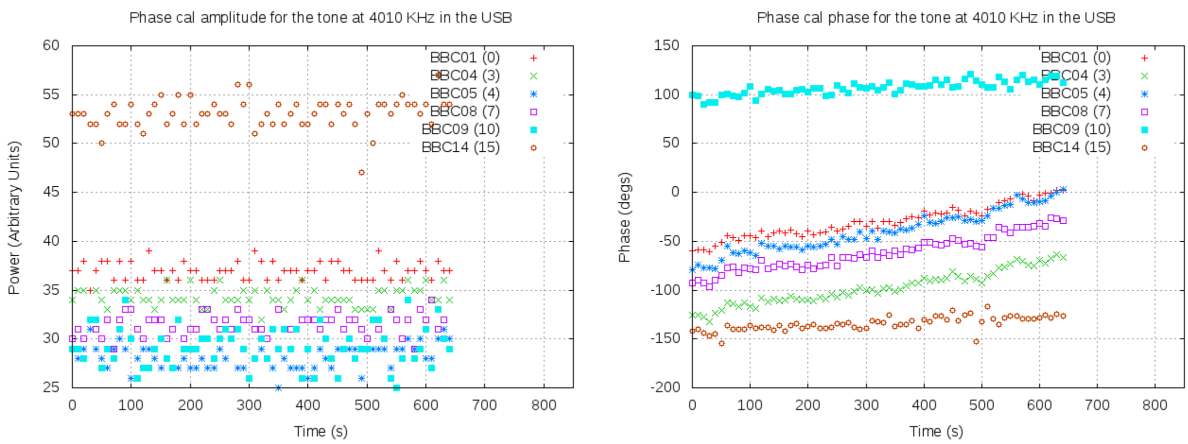

Figure 25: *Phase cal amplitude (left) and phase (right) variation during 11 minutes with the antenna in stow position for tone 4010 KHz. The number between parenthesis is the channel id used to extract the data. Two BBCs per band (X standard, X expanded and S band) were used.*

14 Testing the cable cal

The objective of this test is to measure the cable that is part of the phase/delay system.

We have measured the cable every 5 seconds during 28 minutes with the antenna in stow position. Table 9 summarizes the average value and the standard deviation of the measurements. If the measurements lasted for more time an Allan variance should replace the standard deviation, since the cable length drifts with time. We have also inserted a cable of known length which allows us to calibrate the cable. The inserted cable is 34 cm long and it ammounts a delay of 1.68 ns, measured with a vector analyzer in the lab. The measurements performed by the counter should be converted to real time units by dividing by the expansion factor $2\,10^5$. However since the signal goes through the cable back and forth, in order to estimate the contribution of the cable we should divide by $4\,10^5$.

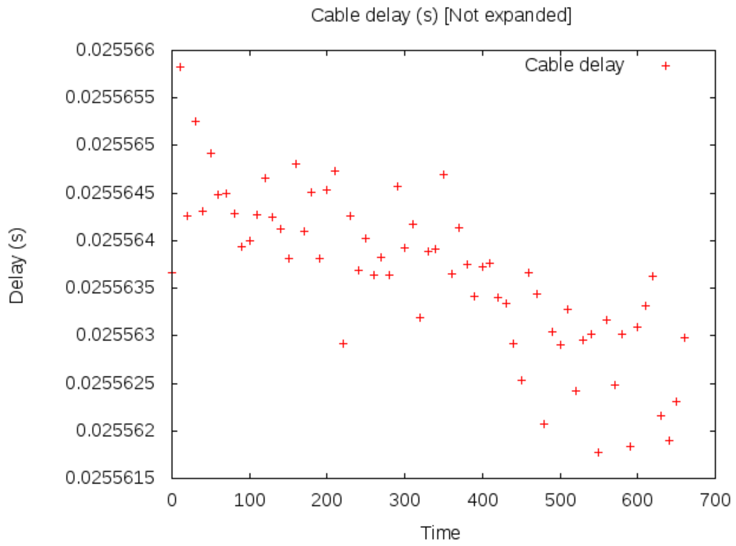

Figure 26: *Cable variations during 11 minutes with the antenna in stow position.*

Data (s)		Delay (μs)	
Average	σ	Average	σ
0.0255587	5.25023e-07	0.1277	$2.65\,10^{-6}$

Table 9: *Average and standard deviation for the cable values during 28 minutes with the antenna in stow position. Two last columns are converted to real delay time by dividing by* $2\,10^5$. Take into account that the signalk travels twice through the cable.

The cable is stable on the order of 1 μseconds (2.6 ps) which complies with the requirement.

The measured delay with the cable inserted is: 0.02624 s. Hence the delay due to the cable is the difference between this value and that one without the cable: 0.00068224 s, which corresponds to 1.71 ns once we apply the expansion factor and divide by 2 since the signal traverses the cable twice. This value is almost identical to 1.68 ns, the delay estimated at the lab. Hence we can conclude that the cable is correctly calibrated.

15 Power supplies

The objective of this test is to check that the power supplies have the proper DC level and for excesive ripple or noise.

All DC supply voltages were checked with a multimeter connected to the front face plugs. Two of the three power supplies of 5 V were within 0.1 V of the proper level. None of the 15 V power supplies were within the 0.2 V proper level.

Power supplies ID	Theoretical DC level (V)	Measured DC level (V)
P101-P537	15	15.69
P106-P540	5	5.28
P105-P539	5	5.08
P101-P538	15	15.58
P101-P536	15	15.34
P103-P530	5	5.11

Table 10: *DC supply voltages*

We could measure the ripple and noise in only four of the six power supplies due to an earthing problem in two of them. We checked with an oscilloscope the low frequency peak to peak ripple. None of the sources showed a performance below 10 mV, and only two displayed total noise below the 100 mV peak to peak. All results may be found in table 11.

Power supplies ID	Total noise pk-pk (mV)	Low-frequency ripple pk-pk (mV)
P101-P537	76	30
P106-P540	320	63
P105-P539	104	43
P101-P538	80	33
P101-P536	Earthing problem	
P103-P530	Earthing problem	

Table 11: *Total noise and low-frequency ripple voltages*

16 Testing the meteorological sensors

The objective is to check the accuracy and short-term stability of the barometer and thermometer. The required performance is summarized below:

- The temperature readings should be stable to +-0.1 deg C over a few minutes.
- The pressure readings should be stable to +-0.1 mb over a few minutes.

Additionaly it is required to record the pressure offset relative to a local authority.

Results obtained comply with the requirements. Temperature and pressure as provided by the SEAC-EMC weather station at Yebes are updated every 1 minute. We recorded data for 10 minutes in a unstable day. The results are summarized below:

Temp (C)		Pressure (hPa)		Humidity	
Average	RMS	Average	RMS	Average	RMS
21.24	0.08	911.33	0.06	49.1	0.54

Table 12: *Average and standard deviation for the temperature, pressure and humidity during 10 minutes on a day with unstable weather.*

Pressure values were compared three times with a difference of 12 consecutive hours with values from a radiosonde balloon released from Barajas-Madrid airport, at an approximate distance of 45 km. The data from the ballon are recorded with a regular time period. This period does not match with a uniform height from the surface of the Earth since the balloon rises in a irregular way subject to changing weather conditions. In order to compare the pressure from the ballon with that from Yebes we did a linear interpolation of two values of height as shown in table 13 below. We have tried to use the same reference system for Yebes and Barajas, although we do not know exactly the site from which the ballon is released. Yebes is at an altitude of 990 m according to the WGS84 ellipsoid, but at an altitude of 930 m if using the same system as Barajas (ED50). The data are public and can be retrieved from the following web page (http://weather.uwyo.edu/upperair/sounding.html). Barajas altitude is 633 m.

The pressure values differ a maximum of 0.5 hPa which corresponds to an error of 5 meters approximately. We conclude that the pressure probe at Yebes is probabñy working correctly.

Date & Time	Balloon data						Yebes data
	Height (m)	Press (hPa)	Height (m)	Press. (hPa)	Yebes Height (m)	Interpol. Press. (hPa)	Press (hPa)
03/08/2011 00:00	820	925	1009	905	930	**913.3**	**913.8**
03/08/2011 12:00	842	925	1570	850	930	**915.9**	**916.2**
03/08/2011 00:00	840	925	1247	883	930	**915.7**	**916.1**

Table 13: *Height and pressure values from a ballon released from Barajas airport. The interpolated pressure for a height of 930 m and the pressure by the Yebes weather station appear in boldface. The real Yebes height is 990 m in the WGS84 ellipsoid, but in order to compare with the ballon data we need to use the same reference system (ED50).*

17 Testing the pointing offsets

The objective of this test is to verify that the antenna pointing is accurate. We have used our own control system, strategy and data anaylsis software to generate a pointing model. Six different sources were observed during 24 hours at X band. Since X and S band are observed simmultaneously using a dichoric mirror, the same pointing model applies for both bands. This model was obtained on July 11th 2011 with the subreflector in a fixed position at all elevations and was applied on July 12th. Table 14 contains a summary of the parameters for the pointing model together with the standard deviation of the appplied model relative to the data.

Parameter	Model
P_1 ($''$)	2521
P_2 ($''$)	76
P_3 ($''$)	3
P_4 ($''$)	2
P_5 ($''$)	0
P_7 ($''$)	-1119
P_8 ($''$)	70
P_9 ($''$)	614
$< \sigma(P) >$ ($''$)	9
σ(dev) ($''$)	20

Table 14: *X band pointing model with subreflector at a fixed Z axis position at all elevations. The parameter residual fit is 9" and the sandard deviation 20". The HPBW at X band is 230" aproximately and hence the error is below 10% of the HPBW.*

Figures 27 and 28 summarize the fits on top of the data. The errors are from the previous pointing model in which the subreflector moved along the Z axis as a function of elevation.

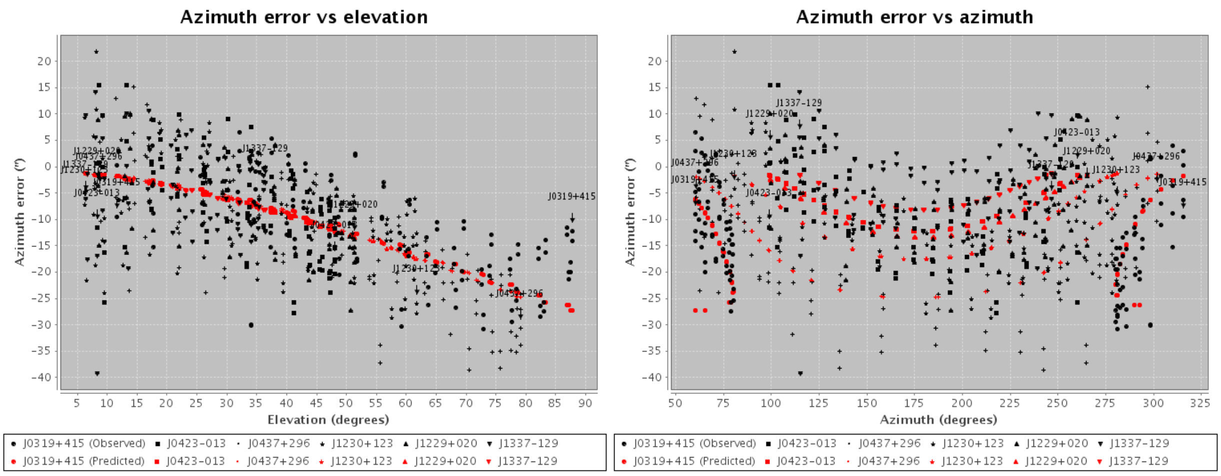

Figure 27: *Left: Azimuth error versus azimuth at X band. Right: Azimuth error versus elevation at X band*

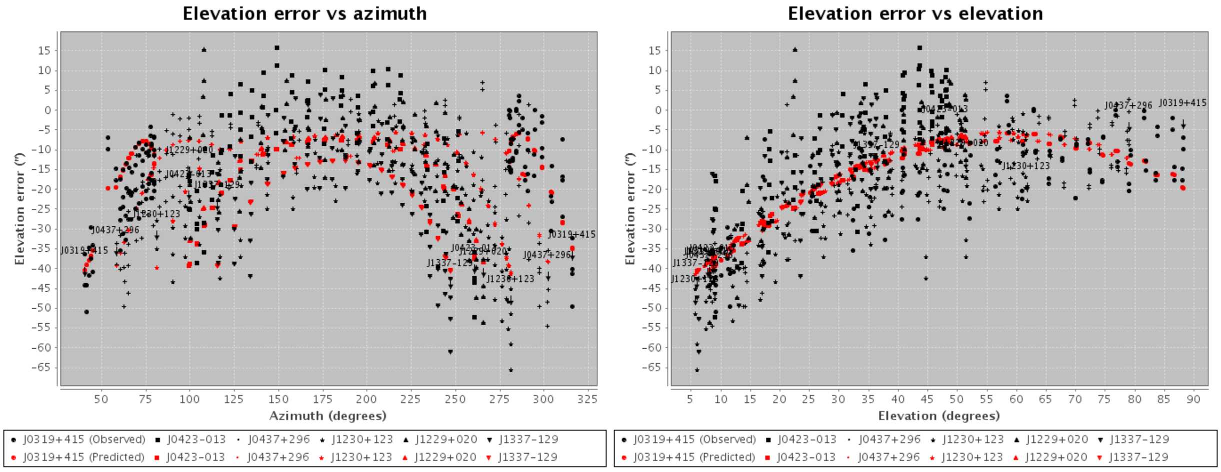

Figure 28: *Left: Elevation error versus azimuth at X band. Right: Elevation error versus elevation at X band*

18 SEFD measurements

The objective of this test is to measure the SEFD, channel by channel with the CONT11 configuration. The test provides the SEFD, the antenna gain curve as a function of elevation, and noise diode variations as a function of frequency. Fig. 30 shows the SEFD determined from onoff observations on 3C123 as a function of frequency for S and X band for a short elevation range (22 to 30 degrees). BBCs11 and 12 show strong variations that possibly arise from RFI in the band where the detectors are. The SFED average value is 200 Jy for X band and 1100 Jy at S band. The dependency curve of the SEFD as function of frequency is not flat and requires some tuning in the cal values of the RXG file.

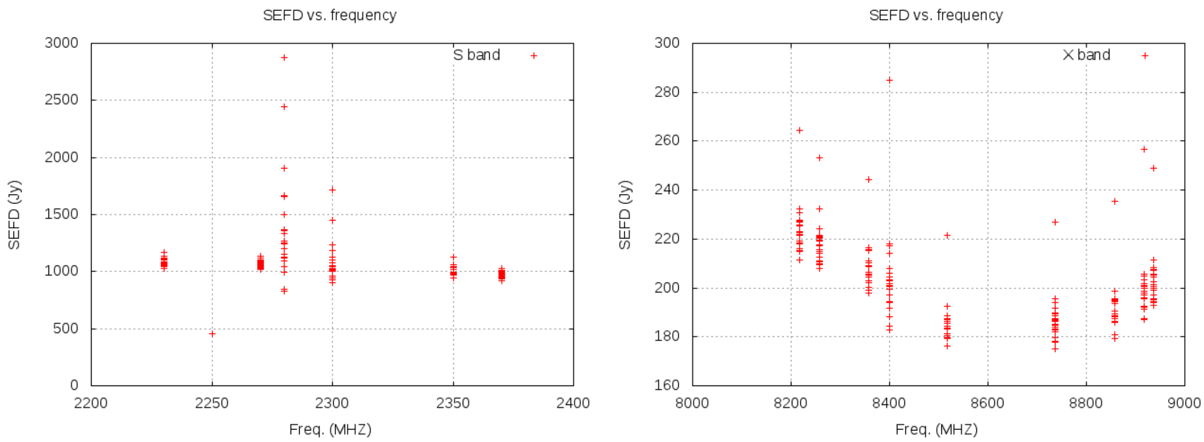

Figure 29: *SEFD versus frequency. Left: S band, Right: X band*

The gain curve at S and X band was measured performing ”ONOFF” cycles on 3C123 and 3C274 for a long time.

S band results, both for the Kelvin/Jansky relation and the gain curve have been obtained from individual channels 8 MHz wide at 2230, 2250, 2270, 2300, 2350 and 2370 MHz. Channel

2250 MHz shows a lot of dispersion ariusing from strong RFI in the band. Measurements from the total IF detectors were also discarded for the same reason. The strong RFI spoiled the measurements. The maximum K/Jy ratio is 0.315 at 60 degrees elevation.

At X band we had to suppress the data from channel 6 at 8857 MHz because the detector also showed a big dispersion.

There is a discrepancy between the 3C123 and 3C274 curves at all x bands and at all elevations. The K/Jy ratio is larger for 3C123 and can be corrected by decreasing 3C274 flux or increasing 3C123 flux. We have investigated this issue by comparing the assumed fluxes with those from VLBA pointing on the same date. The results are in table 15. Our conclusion is that 3C123 flux should be increased by 7% to get a gain curve which matches that of 3C274 whose flux seems to be correct.

Source	X (VLBA) [Jy]	S (VLBA) [Jy]	X (Ys) [Jy]	S (Ys) [Jy]
3C274	42.7	136.2	43	135.8
3C123	9.8	32.1	9.1	31

Table 15: *Fluxes for sources 3C123 and 3C274 according to measurements at the VLBA on August 18th and assumed in the RXG control file (Ys columns).*

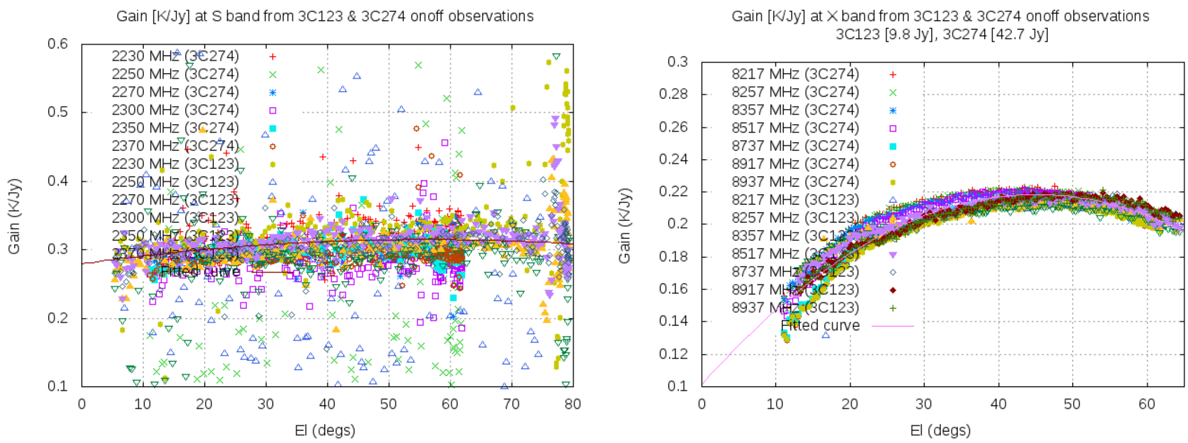

Figure 30: *Gain [K/Jy] Left: S band, Right: X band (3C123 flux was increased by 7% to match that from VLBA observations on the same date)*

TCal as a function of frequency was corrected according to the previous measurements. The gain curve and the K/Jy ratio were also updated for both frequencies. Results are in table 16. These values are valid for geodetic observations for which the subreflector position remains fixed in the Z axis and moves along the Y axis.

SEFD		Gain [K/Jy]	
S	X	S	X
1000	210	0.315	0.223

Table 16: *SEFD and maximum gain at S and X bands. 3C123 flux was corrected*

References

[IVS] http://ivscc.gsfc.nasa.gov/program/cont11/

[Smythe D.] D. Smythe. ”VSI Interface Board for the Mark4 Formatter”. MIT-Haystack Mark5 Memo 16, 2004.

[Smythe D.] D. Smythe. ”Mark5B File Utility Programs”. MIT-Haystack Mark5 Memo 73, 2008.