In-situ testing of frequency labeling and aliasing of DP and measurement of signal cross-coupling at LWA1

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1 Introduction

For conducting VLBI experiments with LWA1 over baselines of thousands of kilometers, especially attempting to correlate with LOFAR stations, we require accurate frequency tagging at the highest precision possible with a GPS referenced clock. Also, some data conversion is required in order to match the LOFAR channelization with that of LWA1. The dataset collected here will aid in verification whether the conversion works as intended and provides a test dataset for future data analysis scripts to verify proper frequency tagging. In addition, possible aliasing artifacts in Jovian burst data from LWA1 was reported by Tracy Clarke. This document describes the work done in order to assess both the frequency accuracy and aliasing effects of the digital processor for beam-forming data at LWA1. A side-benefit of this work provides in-situ measurements of cross-talk between adjacent channels sharing the same RJ45 connector and Cat-7 cable connecting the output of the analog receiver with the digital processor input.

2 Setup

The setup consists mainly of the Novatech Model 408A 100 MHz quadrature signal generator (DDS) which is remote controllable through a RS232 interface. Control is implemented through a PC running Ubuntu Server and custom python scripts “singingBox.py” and “singingBoxExt.py” originally developed by Jayce Dowell and with features added for the purpose of the here described tests. The version of the employed “singingBoxExt.py” script is linked with this memo.

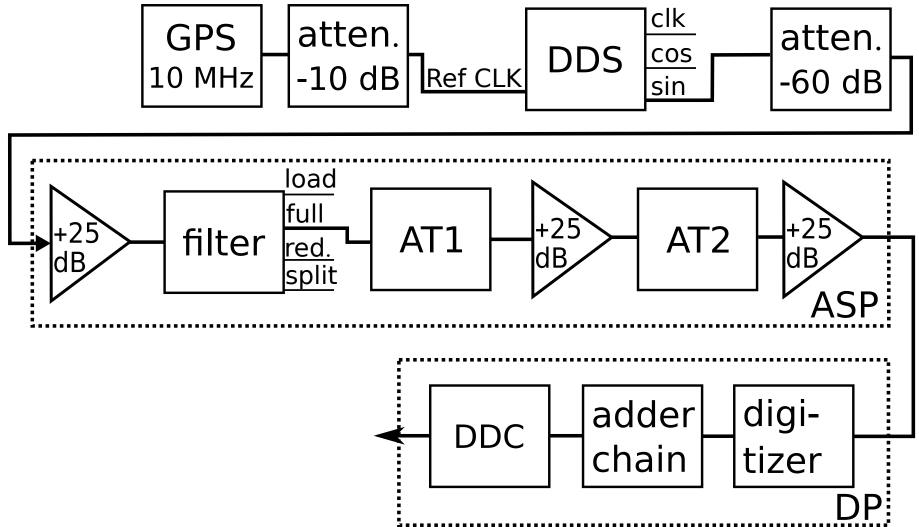

Figure 1: Block schedule of the setup including the key components involved inside the Analog Signal Processor (ASP) and Digital Processor (DP).

The DDS is operated using the 10 MHz output from the GPS reference which has to be attenuated by 10 dB to match the required power level of the DDS. The sine-wave output of the DDS is passed through a 60 dB attenuator on to the N-S polarization input of stand #108 on the analog signal processor (ASP) rack. The E-W polarization input of the same stand was terminated with a 50Ω load. Both polarization of stand #108 were disconnected for this purpose. In order to prevent the FEE power DC output to be passed onto the DDS output and to prevent the load resistor to burn-up, a DC block was attached at each input of stand #108. Figure 1 illustrates the key building blocks of the measurement setup.

In order to determine the injected power level, the injected signal from the DDS after the 60 dB attenuator was measured for various power settings. The nominal output of the DDS of +7 dBm was verified. The output power can be adjusted by applying a multiplicative factor to the maximum output power of the form $n/4096$ where n is an integer between 1 and 4096. Power levels are chosen to be at least 10 dB below the 1 dB compression point of the ASP and to be significantly below the clipping levels of DP that can occur at the digitizer, adder chain, and/or DDC/DRX. Determining whether clipping occurs at any stage is very tricky since no quantitative information is provided by DP about clipping occurring at the digitizer and in the adder chain. To avoid clipping in the digitizer, the power level was adjusted using the TBW mode. An input power level of around -22 dBm was deemed not to cause clipping at the digitizer. Clipping in the adder chain is avoided by recording just a single dipole signal. The DP gain bit levels from the DDC are adjusted accordingly in order to avoid clipping following the information provided by the LSL Commissioning script “drxFileCheck.py”.

From balancing all these factors the following settings were found to achieve these requirements. The DDS output power was set to -18 dBm, injecting a signal power of -78 dBm into ASP. The ASP full bandwidth filter was selected and the attenuators AT1 and AT2 were both set to 14 dB for both stand #108 inputs. In order to avoid cross-contamination from the remaining ASP inputs, the FEE power was turned off and all other inputs were terminated using the ASP filter in the off setting, terminating those inputs with a 50Ω load. The signal output was recorded in beam-forming mode using custom beam forming only selecting stand #108. The DP gain setting was 1.

3 Measurements

Measurements were conducted on February 11 and 12, 2014. Most of the time was spent on finding the right power output and attenuation settings in order not to clip at the DP. The signal power injected in DP was about -31 dBm by setting the output power of the DDS to -18 dBm (I/Q power integer value of 82). A successful 10 min recording of the dual-polarization single dipole data was performed with the center frequencies set to 47.8515625 and 66.9921875 MHz and using 19.6 MHz bandwidth each to match the frequency tunings of a previous VLBI experiment with LOFAR (also see Fig. 2).

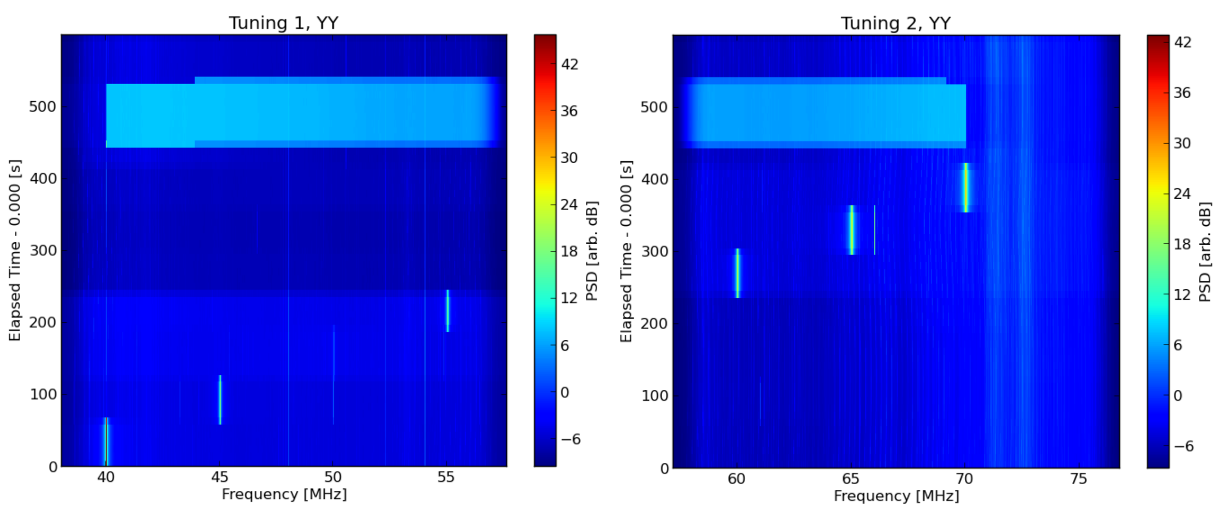

Figure 2: Overview of the tunings with injected signals from the DDS. Injected signals step from 40 – 70 MHz in 5 MHz jumps, afterwards the sweep signal from 40 – 70 MHz can be seen as a broad signal across the band. Each tuning has 4096 channels, time steps are 10 s integrations each. Differences seen in output power between the individual frequency tunings is an effect of the channelization and visualization and is not due to a change in power of the injected signal.

The DDS was set to output the following sequence of signals:

1. 1 min – 40 MHz
2. 1 min – 45 MHz
3. 1 min – 50 MHz
4. 1 min – 55 MHz
5. 1 min – 60 MHz
6. 1 min – 65 MHz
7. 1 min – 70 MHz
8. 0.5 min – no signal
9. 1.5 min – sweeping between 40 and 70 MHz at a speed of 30 MHz/s
10. 1.0 min – no signal

The collected data did not have reported clipping from the DDC. The file tag of this dataset is 056700_000201019 and can be downloaded from `http://lda10g.alliance.unm.edu/data1/DG001/056700_000201019`.

4 Frequency Labels

The time series data was processed using hdfWaterfall.py using an integration time of 14 s with 2^{28} spectral channels, corresponding to a frequency resolution of 73 mHz. The floating point accuracy of the hdf5 frequency tags generated by hdfWaterfall is not sufficient. Thus, the actual values were calculated separately using the full precision center frequency known for each tuning and a channel width of exactly $19.6 \cdot 10^6\,\mathrm{Hz}/2^{28} = 0.07301569\,\mathrm{Hz}$. The corresponding channels around each of the injected tone frequencies were extracted to determine how well they correspond with each other. Figure 3 plots the recorded signal of all 7 tones injected. This shows that the tuning accuracy of the system matches at least that of the maximum resolution the data was Fourier transformed. In the case of 50.0 and 65.0 MHz, the channel edges fell almost exactly on the injected frequency values thus the recorded power is split between two channels as can be seen in Figure 3.

Olaf Wucknitz (MPIfR), who has been performing the correlations at low frequencies for the LWA1-LOFAR experiment used the here described dataset to verify the tuning accuracy of DP as well. He took 14 s of data at a time and transformed it with 2^{28} (268 Mio.) channels, similar to what was done with "hdfWaterfall.py" described above. With this he was able to verify a tuning accuracy down to the spectral resolution of 73 mHz. In order to push the limits further he fit the according sinc function to the individual spectra. In all cases he obtained very small variations from the nominal values of $< 50\mu$Hz. In more conservative terms, a tuning accuracy of at least 1 mHz is confirmed. A waterfall plot of both tunings using 10 s integration time and 4096 channels is shown in the previous section (Fig. 2).

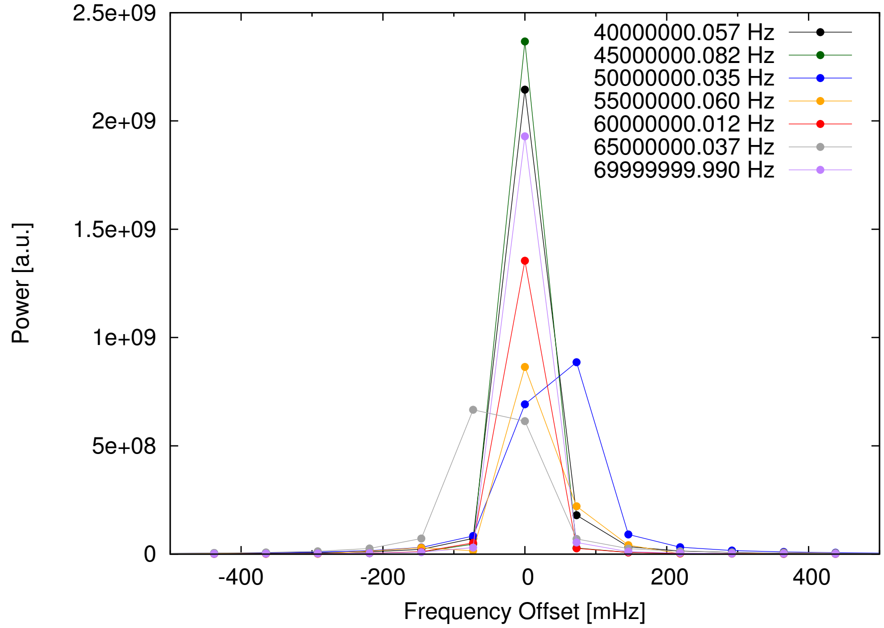

Figure 3: Comparing the tuning accuracy of the recorded DRX output for seven different tones injected between 40.0 and 70.0 MHz in 5 MHz steps. The legend provides the 0 value corresponding to the center frequency of that particular FFT bin.

5 Aliasing

The ARX and DP settings were unchanged over that what is described in Section 2 and used for the frequency label analysis. In order to test aliasing the section of the dataset that includes the recording of a signal sweeping between 40 and 70 MHz at a speed of 30 MHz/s was processed using hdfWaterfall.py using an integration time of 200 μs with 2048 channels and 800 μs with 1024 channels. In Figure 4 the 1024 channel waterfall plot is shown for both tunings. The clearly visible 'V'-shaped signal sweeping back and forth across the tuning is the generated sweep signal from the DDS. The weaker, inverted signal sweeping across the band is most likely an aliased version of the original tone. The two signals cross in both tunings at a distinct frequency, 49.0 and 65.34 MHz. The DP is using a sample frequency of 196.0 MHz. The frequencies at which the aliased signals cross with the original signal are an integer fraction of the DP sample frequency 4 (49.0 MHz) and 3 (64.33 MHz) respectively. This confirms that the original injected signal is aliased by DP. The aliased signal was found to be lower by about 26 – 36 dB over that of the original sweep tone. In LWA engineering memo DRX0003 authored by Robert Navarro the out-of-band frequencies are suppressed by $\sim$50 dB which makes aliasing by DP of signals from outside the observing band negelibile and only in-band signals need to be considered.

The "off" channel that was recorded in the other polarization had no signal injected. Thus, all the signal that is observed is introduced due to cross-talk with the adjacent channel. The cross-talk is discussed in Section 6. The observed signal in the "off" channel is visualized in Figure 5. The frequency sweep and its alias injected into the N-S polarization are clearly visible albeit weak.

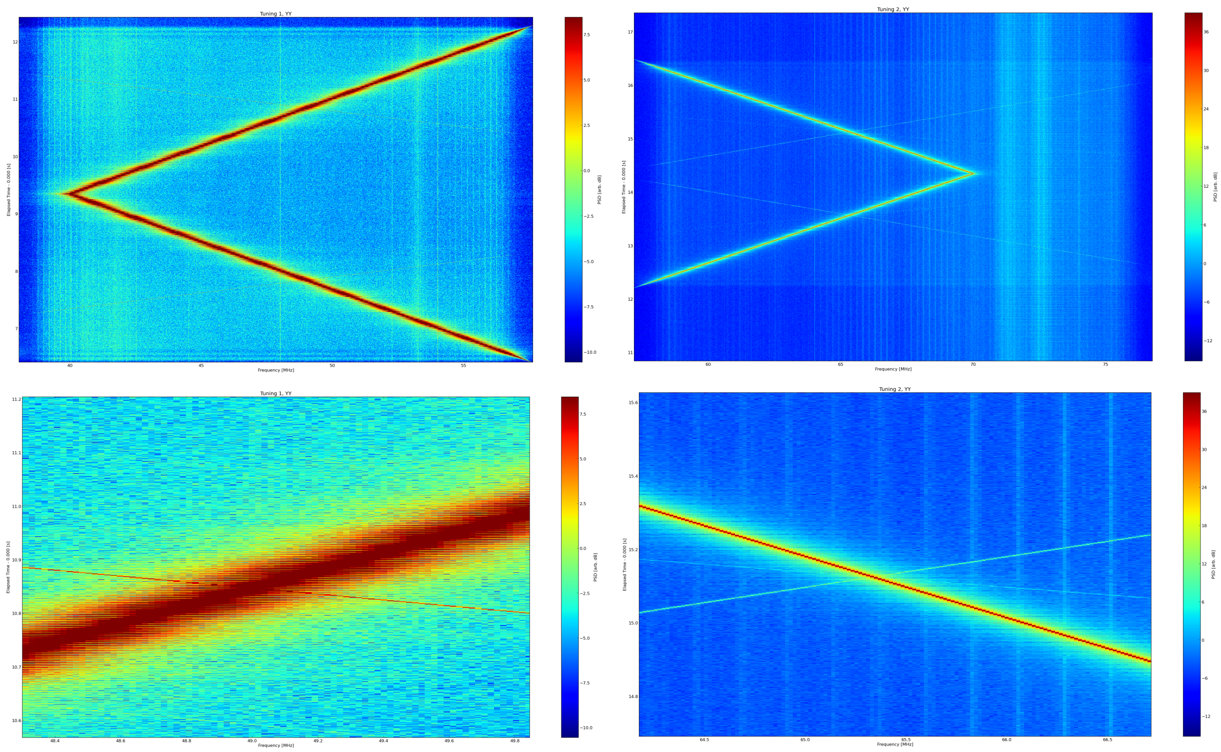

Figure 4: Waterfall plots of the frequency sweep for low (left) and high (right) tunings. Below are zoomed versions showing the aliased signal crossing the sweep tone. At the low tuning the aliased signal crosses at 49.0 MHz, at the high tuning at 65.34 MHz.

Looking into polarization, the data was also processed calculating full stokes parameters. As expected in Stokes I the sweep and alias are both visible, however the aliased signal is significantly less pronounced than looking at the XX/YY products. In Stokes Q, U and V the aliased signal is visible at the same power level as the original signal. Based on the structure seen in plots (Fig. 6 of Jupiter S-bursts by Tracy Clarke) it is conceivable that aliasing is responsible for the mirror images seen in the waterfall plots of such bursts. However, the power of the aliased signal should be significantly lower than the original signal (26 – 36 dB). Imagining a continuation of the structure of the original burst signal around 22.6 MHz in Fig. 6 with that of the first alias around 26.5 MHz, they would cross around 24.5 MHz, which is 1/8 of the sample rate of DP. The second set would cross at 28.0 MHz (1/7 of the sample rate of DP).

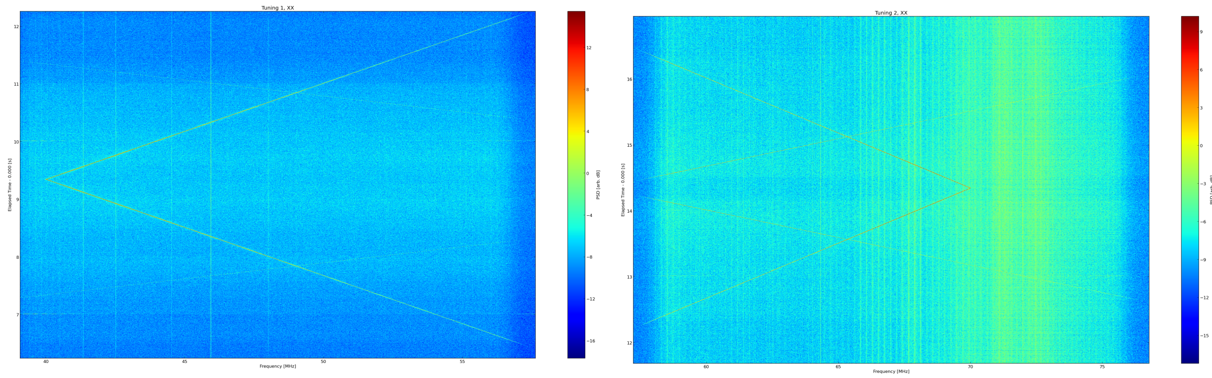

Figure 5: Waterfall plots of the E-W polarization with the ASP input terminated and the frequency sweep visible due to cross-talk. Low (left) and high (right) frequency tunings are shown.

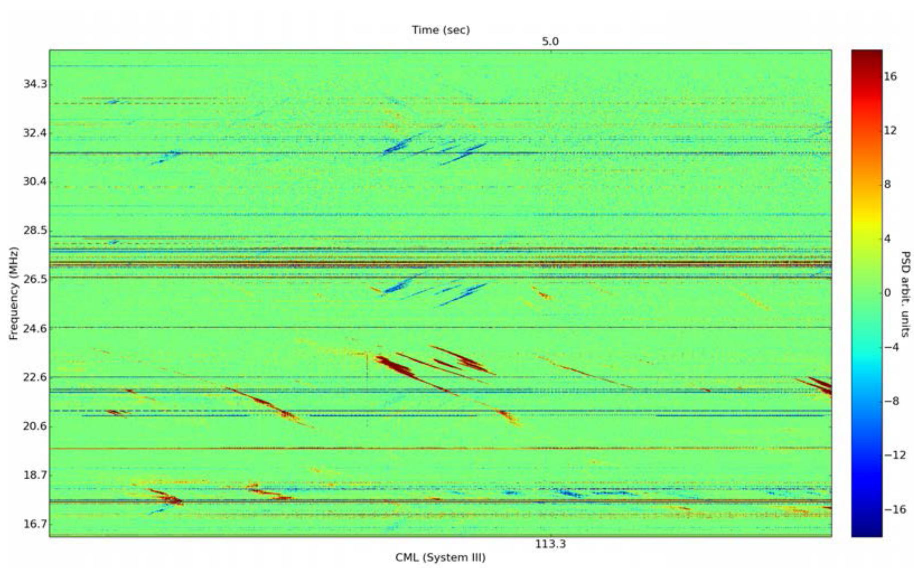

Figure 6: Waterfall plot of Jupiter S-bursts observed and plot provided by Tracy Clarke.

The corresponding aliasing frequency for DP can be estimated in the following way:

$$f_a = |f_s \cdot n - f_t| \, , \tag{1}$$

where the aliasing frequency is f_a, f_s is the sample frequency, and f_t is the frequency of the signal that is aliased. The integer factor n needs to be chosen to be closest to to the aliased signal f_t. Thus, in the case of DP n is always 1. The effective Nyquist frequency of the DP beam forming mode depends on the chosen tuning and bandwidth setting due to filtering of the original sampling frequency. For the full bandwidth filter (19.6 MHz) it corresponds to the integer fraction of the DP 196 MHz sample frequency that provides a value closest to the chosen center frequency. For example in the case of the Jupiter burst, the Nyquist frequency for a tuning of 25.5 MHz is 24.5 MHz (1/8) with a sample rate of 49 MHz. Thus, the alias of a signal at frequency 22.6 MHz would appear at a frequency of 26.4 MHz. This is the case for the first reflection shown in Fig. 6. The second reflection is most likely related to aliasing on a Nyquist frequency of 1/7 of the sample rate (28 MHz). It shall be noted that this way of determining the aliasing frequency did not produce accurate results, deviations of up to one MHz were noticed. Without a detailed understanding of the internal workings of DP it is not possible to determine the reason for this deviation.

6 Cross-talk

The DDS allows in-situ measurement of cross-talk between neighboring channels of stand #108 E-W polarization which corresponds to ARX board 129 channel 3. Channel 4 on this board corresponds to N-S polarization, channels 1 and 2 belong to stand #35 (outrigger #5) and channels 5 and 6 belong to stand #99. All four signals of stand #108 and #35 pass through the LEDA splitter box on the same cable and then on to DP. In order to test cross-talk within the LEDA splitter box through which the signals of stand #108 and #35 pass, stands #203 and #258 are tested as well, which are connected to the input next to that of stands #108 and #35 but pass through ARX board 137. Stand #50 was also included in the cross-talk check, since it does not pass through the splitter box and is connected to ARX board 134.

The observed injected power value at 55 MHz for stand #108 N-S was 55.5 dB/RBW. The observed values and the dB attenuation value for the discussed stands are listed in Table 1. This corresponds to an injected power of -22 dBm at the digitizer and -78 dBm at the ARX input. Summarizing, the attenuation between all channels is at least 30 dB with the exception of signal paths that share the same Cat-7 cable, those have a signal separation of between 12 and 29 dB. Especially, cross-talk is high between the E-W polarization of stand #108 and both polarizations on stand #35. Previous lab tests of cross-talk using the ARX prototype board are described in LWA Engineering Memo ARX0014 authored by Craig & Ellingson (2008). For a -50 dBm tone injected the cross-talk was measured and an attenuation of (channel-to-channel cross-coupling) of -64.5 dB was determined.

Table 1: Cross-talk values for selected channels.

Stand	Pol.	Channel	ARX	Power (dB/RBW)	Attenuation (dB)
108	N-S	4	129	55.5	–
108	E-W	3	129	26.2	-29.3
35	E-W	1	129	39.6	-15.9
35	N-S	2	129	43.3	-12.2
99	E-W	5	129	18.7	-36.8
99	N-S	6	129	20.9	-34.6
203	E-W	5	137	24.4	-31.1
203	N-S	6	137	25.8	-29.7
258	E-W	7	137	17.5	-38.0
258	N-S	8	137	28.6	-26.9
50	N-S	13	134	8.7	-46.8
50	E-W	14	134	11.9	-43.6

More recently, LEDA related VNA measurements of the RJ45 connector and Cat7 cables reported by Danny Price in October 2013 determined a cross-coupling due to the cabling of as high as -30 dB, which is consistent with the here reported measurements.

7 Summary

- Injection of a remote controllable signal into the input of a single LWA1 stand resulted in the verification and determination of an absolute frequency accuracy of better than 73 mHz.
- Using the signal generator to output a frequency sweep signal aliasing of DP was investigated. Signal aliasing is determined to be present with its power reduced by -26 – -36 dB over the injected signal. Aliasing can thus be a concern for strong bursts, such as in Jupiter emission, or solar bursts or from radio frequency interference.
- Cross-coupling of signal paths was investigated using an injected tone of 55 MHz. Cross-talk was found to be less than 30 dB for channels on the same ARX board. Separation between different ARX boards not passing through the splitters a signal separation of at least 40 dB was determined. Signal paths sharing the same aggregate output cable from ASP have a signal separation of only 12-29 dB.

Document Version History

- v1. February 18, 2014
- v2. March 3, 2014