EVLA Memo #166
Comparison of the Performance of the 3-bit and 8-bit Samplers at C (4–8 GHz), X (8–12 GHz) and Ku (12–18 GHz) Bands

E. Momjian and R. Perley
NRAO

March 27, 2013

Abstract

We present sensitivity measurements of the EVLA at C (4–8 GHz), X (8–12 GHz), and Ku (12–18 GHz) bands to assess the feasibility of using the 3-bit samplers with these receiver bands, to quantify the resulting sensitivity, and compare it to the sensitivity obtained using the 8-bit samplers. In spite of the higher noise in data obtained through the 3-bit samplers, our on-the-sky test results show that there is an overall gain in sensitivity when using the 3-bit samplers compared to that of the 8-bit for the same amount of on-source time. Depending on the amount of RFI contaminated bandwidth, the measured improvement in the continuum full-bandwidth sensitivity is ∼23%, ∼19% and ∼49%, for C, X, and Ku-bands, respectively.

1 Introduction

The EVLA antennas are equipped with two types of samplers, 3-bit and 8-bit. Per antenna, there are two 8-bit samplers per polarization, delivering 2×1 GHz dual polarization data streams. Each antenna also has four 3-bit samplers per polarization, delivering 4×2 GHz dual polarization data streams. Observations at the high frequency bands of the EVLA, namely K (18–26.5 GHz), Ka (26.5–40 GHz), and Q (40–50 GHz) bands, have shown that the 3-bit data were ∼15% noisier, per unit bandwidth, compared to data obtained through the 8-bit samplers. Therefore, the factor of four wider bandwidths of the 3-bit data in these three bands do not provide the expected improvement in continuum sensitivity compared to the 8-bit data.

Three other frequency bands – C, X, and Ku, have more bandwidth than can be covered by the 8-bit samplers, and hence are candidates for use of the 3-bit samplers. However, their narrower total bandwidth (4, 4, and 6 GHz, respectively), and the presence of significant RFI within each, may combine with the loss of sensitivity provided by the 3-bit samplers to render use of the 3-bit samplers less attractive. In addition, the RFI, if strong enough, could saturate the limited range of the 3-bit samplers.

To assess the feasibility of using the 3-bit samplers at C, X, and Ku bands, and to quantify the gain or loss in the sensitivity while using the 3-bit samplers instead of the more sensitive, but narrower bandwidth, 8-bit samplers, we have carried out on-the-sky test observations using these three receiver bands and both 3- and 8-bit samplers.

2 Observations

The EVLA observations at C, X, and Ku bands were carried out on February 25, 2013, in D-configuration for a total of 3 hours. The calibrator source 3C147 (J0542+4951) and a 1° off field

Receiver Band	Baseband Pairs & Frequency Ranges (MHz)		
	Setting 1	Setting 2	Setting 3
C (4–8 GHz)	A0C0: 4488–5512	A1C1: 3976–6024	B1D1: 3976–6024
	B0D0: 5488–6512	A2C2: 5976–8024	B2D2: 5976–8024
		B0D0: 5488–6512	A0C0: 5488–6512
X (8–12 GHz)	A0C0: 8488–9512	A1C1: 7976–10024	B1D1: 7976–10024
	B0D0: 10488–11512	A2C2: 9976–12024	B2D2: 9976–12024
		B0D0: 9488–10512	A0C0: 9488–10512
Ku (12–18 GHz)	A0C0: 12988–14012	A0C0: 14988–16012	A1C1: 11726–13774
	B0D0: 13988–15012	B0D0: 15988–17012	A2C2: 13726–15774
			B1D1: 15726–17774
			B2D2: 17726–18366

Table 1: Summary of the frequency setups per receiver band. The 8-bit data streams deliver 1 GHz wide baseband pairs (e.g., A0C0 and/or B0D0). The 3-bit data streams deliver 2 GHz wide baseband pairs (e.g., A1C1, A2C2, B1D1 and/or, B2D2). Resources can be configured to obtain certain 3-bit and 8-bit data simultaneously.

devoid of strong continuum sources (hereafter "blank field") were targeted in these observations. Each frequency band was observed using three different settings. Overall, the observations included nine settings in addition to a standard X-band reference pointing setting that was used to correct the antenna pointing offsets for the Ku-band observations. For the C and X-band observations, one setting had only 8-bit resources, while the other two had a mix of 3- and 8-bit instrument configurations. For the Ku-band observations, two settings had only 8-bit resources, while the third one had only 3-bit resources. Table 1 lists the samplers used in each setting, or instrument configuration, and the covered frequency ranges per receiver band. For illustration purposes, Figures 1, 2 and 3, show the three settings of C, X, and Ku bands, respectively.

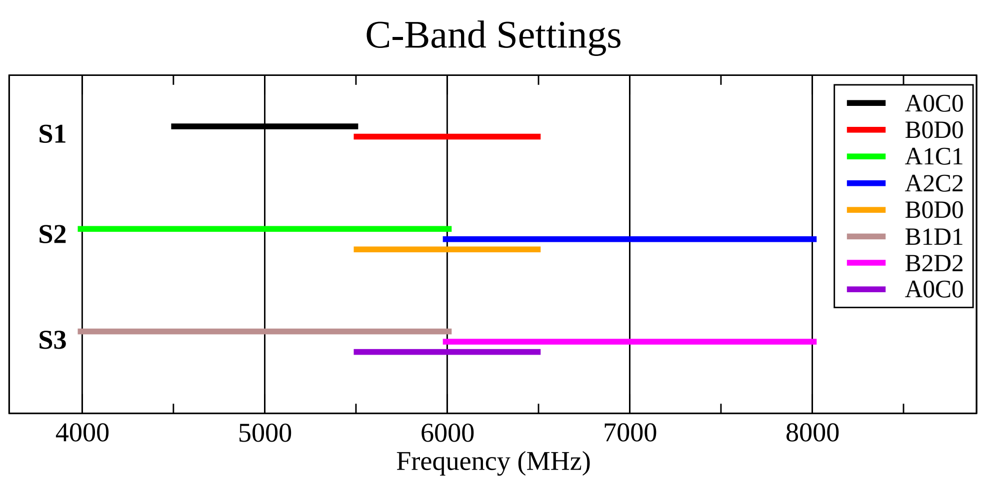

Figure 1: The three instrument configurations used for the C-band (4–8 GHz) observations. The indices (S1–S3) mark the individual settings and their respective baseband pairs and frequency ranges as listed in Table 1.

All the required 3- and 8-bit setup scans for each instrument configuration were utilized in the observations. The calibrator 3C147 and the blank field were observed in an identical, interleaved

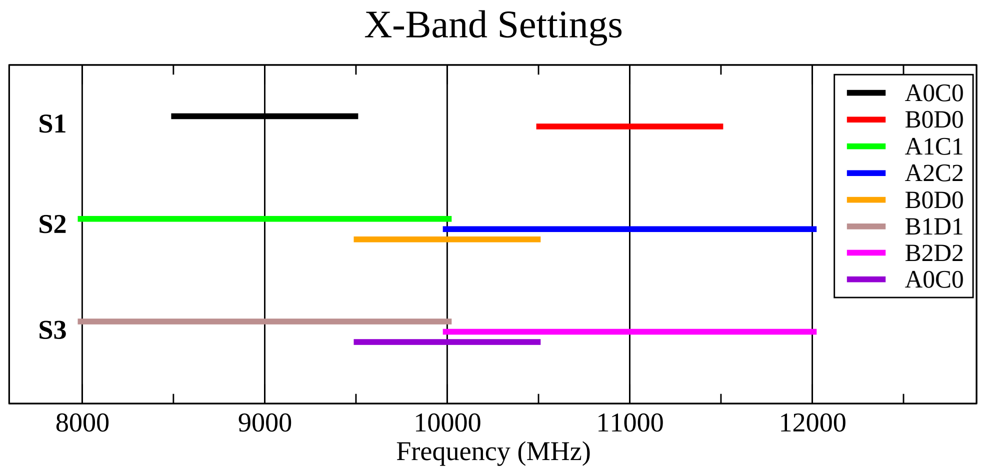

Figure 2: The three instrument configurations used for the X-band (8–12 GHz) observations. The indices (S1–S3) mark the individual settings and their respective baseband pairs and frequency ranges as listed in Table 1.

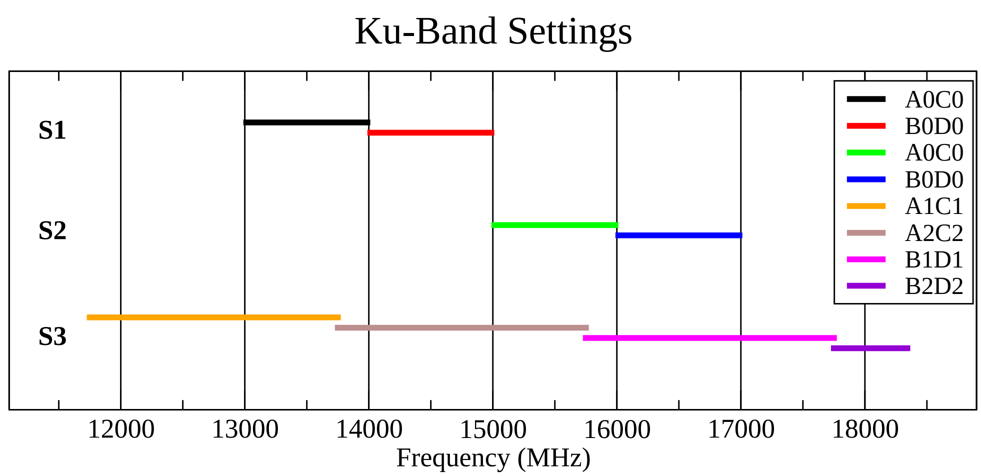

Figure 3: The three instrument configurations used for the Ku-band (12–18 GHz) observations. The indices (S1–S3) mark the individual settings and their respective baseband pairs and frequency ranges as listed in Table 1.

scan sequence in each of the three settings of each receiver band.

The WIDAR correlator was configured to deliver 8 adjacent sub-bands for each 8-bit baseband pair, and 16 adjacent sub-bands for each 3-bit baseband pair. Each sub-band had a bandwidth of 128 MHz, 64 spectral channels, and full polarization (RR, LL, RL, LR) products. The resulting spectral resolution was 2 MHz. The correlator integration time was set to 3 seconds.

3 Data Reduction and Analysis

Data reduction and analysis were carried out in AIPS. The data of each instrument configuration were loaded separately using BDF2AIPS. A 3-channel Hanning-smoothing was applied in all the data reduction and analysis steps to reduce the Gibbs ringing phenomenon introduced by strong

RFI features in the observed frequency bands.

The flux density scale was set using the Perley and Butler (2013) coefficients for 3C147. After applying *a priori* flagging and excising integrations affected by interference, antenna based delay, complex gain and bandpass calibration solutions were obtained using the data of the calibrator source 3C147 per sub-band and polarization (i.e., R and L) separately. These solutions were then applied on the visibilities of the blank field, and RR and LL spectra were generated to visually inspect its data in order to further ensure the exclusion of spectral channels that were affected by RFI from subsequent analysis.

Using the AIPS task UVHGM, the RMS noise values for Stokes I were measured by fitting Gaussian profiles on the histogram distributions of the blank field's real part of the visibilities. For this, we used channels from each sub-band that were not visibly contaminated by RFI. We have also excluded antennas with misbehaving samplers.

Multiple background continuum sources in the blank field contribute a total of $S \sim 5$ mJy to our measurements at C-band, as determined through imaging. A correction was made to account for these background sources as follows:

$$\mathrm{RMS} = \sqrt{(\mathrm{RMS}_h)^2 - (S)^2}, \tag{1}$$

where RMS_h is the noise values obtained through the histogram fittings.

The background continuum sources contribute less than 0.5 mJy to our measurements at both X and Ku bands. Therefore, the correction noted in Equation 1 was not performed for the RMS noise values measured in these two bands.

The RMS noise values were then converted to RMS values per 1 MHz per 1 hr on-source time for a single baseline using the following equation:

$$\mathrm{RMS}_{(\mathrm{1hr,1MHz})} = \mathrm{RMS} \times \sqrt{\frac{\tau\ \beta}{3600\ \mathrm{s} \times 1\ \mathrm{MHz}}} \tag{2}$$

where τ is the correlator integration time in seconds (3 s in these observations), and β is the noise equivalent spectral channel width in MHz due to the application of a 3-channel Hanning-smoothing ($\beta = \kappa_{hs}^2 \times 2\,\mathrm{MHz}$ in these observations, with κ_{hs} being the improvement in the signal-to-noise due to the application of a 3-channel Hanning-smoothing, which is 1.633[1]).

4 Results

4.1 C-Band (4–8 GHz)

Figure 4 shows the RMS noise values of Stokes I in the EVLA C-band frequency range $4 - 8$ GHz per 1 MHz and per 1 hr on-source time for a single baseline. The various curves represent the RMS noise values of the different 8-bit and 3-bit settings and their respective baseband pairs as illustrated in Figure 1 and listed in Table 1. No measurements were possible between 4.0 and 4.2 GHz due to severe RFI (satellite downlinks). Figure 4 clearly shows that the 3-bit data are less sensitive than those of the 8-bit. Numerical comparison of the RMS noise values between the 3-bit and 8-bit results was made at each common frequency value. The results show that the 3-bit data are noisier than the 8-bit data by $12.6\% \pm 4.2\%$. We note that the increase in the RMS noise at the higher frequency edges of the 3-bit basebands is very likely due to the anti-aliasing filters.

[1] The improvement in signal-to-noise due to a 3-channel Hanning-smoothing is $1/\sqrt{0.25^2 + 0.5^2 + 0.25^2}$=1.633

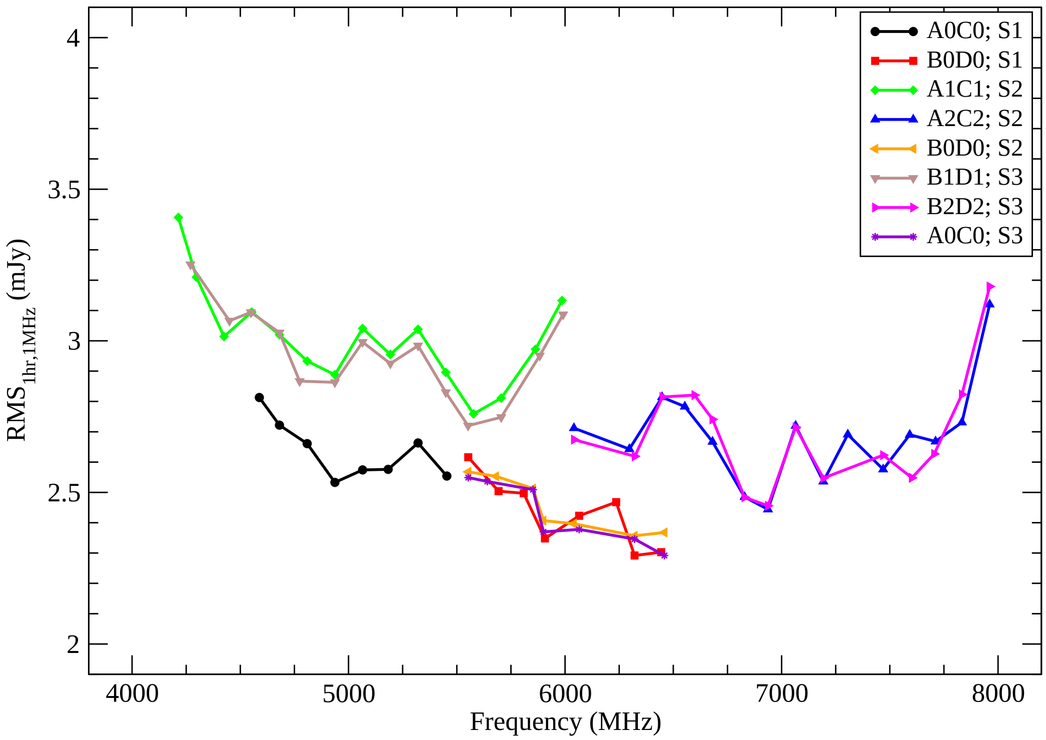

Figure 4: The RMS noise values of Stokes I per 1 MHz per 1 hr on-source time for a single baseline in the EVLA C-band frequency range $4 - 8$ GHz. The various curves represent the RMS noise values of the different settings and their respective baseband pairs as illustrated in Figure 1 and listed in Table 1. No measurements were made below 4.2 GHz due to RFI.

4.2 X-Band (8–12 GHz)

Figure 5 shows the RMS noise values of Stokes I in the EVLA X-band frequency range $8 - 12$ GHz per 1 MHz and per 1 hr on-source time for a single baseline. The various curves represent the RMS noise values of the different 8-bit and 3-bit settings and their respective baseband pairs as illustrated in Figure 2 and listed in Table 1. No measurements were possible between 11.7 and 12.0 GHz due to severe RFI (transmission from geostationary satellites). Figure 5 clearly shows that the 3-bit data are less sensitive than those of the 8-bit. Numerical comparison of the RMS noise values between the 3-bit and 8-bit results was made at each common frequency value. The results show that the 3-bit data are noisier than the 8-bit data by $15.6\% \pm 3.2\%$. We note that the increase in the RMS noise at the lower frequency edges of the 3-bit basebands is very likely due to the anti-aliasing filters.

4.3 Ku-Band (12–18 GHz)

Figure 6 shows the RMS noise values of Stokes I in the EVLA Ku-band frequency range $12-18$ GHz per 1 MHz and per 1 hr on-source time for a single baseline. The various curves represent the RMS noise values of the different 8-bit and 3-bit settings and their respective baseband pairs as illustrated in Figure 3 and listed in Table 1. No measurements were possible between 12.0 and 12.7 GHz due to

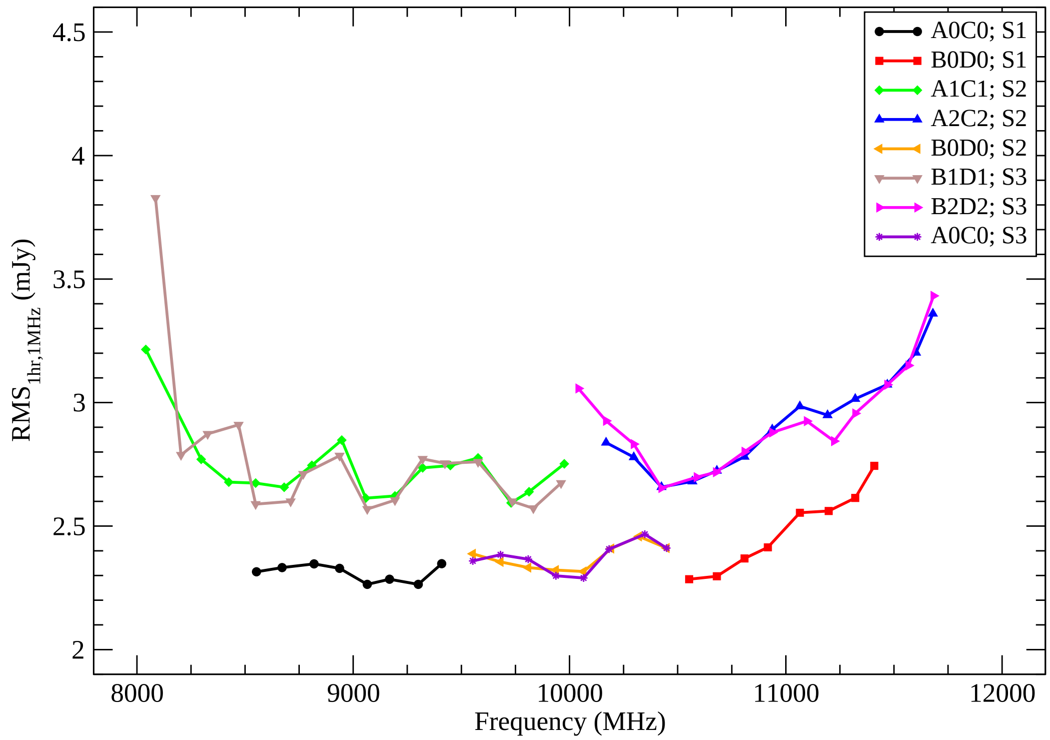

Figure 5: The RMS noise values of Stokes I per 1 MHz per 1 hr on-source time for a single baseline in the EVLA X-band frequency range $8 - 12$ GHz. The various curves represent the RMS noise values of the different settings and their respective baseband pairs as illustrated in Figure 2 and listed in Table 1. No measurements were made above 11.7 GHz due to RFI.

severe RFI (transmission from geostationary satellites). Figure 6 clearly shows that the 3-bit data are less sensitive than those of the 8-bit. Numerical comparison of the RMS noise values between the 3-bit and 8-bit results was made at each common frequency value. The results show that the 3-bit data are noisier than the 8-bit data by $10.3\% \pm 6.2\%$. We note that the increase in the RMS noise at the higher frequency edges of the 2 GHz wide 3-bit basebands is very likely due to the anti-aliasing filters.

5 Discussion

The 8-bit samplers of the EVLA deliver a total instantaneous bandwidth of 2 GHz, while the 3-bit samplers can deliver up to 8 GHz of instantaneous bandwidth. However, considering the receivers' frequency coverage, the 3-bit samplers can be used to deliver only 4 GHz of instantaneous bandwidth at C and X-bands, and 6 GHz of bandwidth at Ku-band. At best, this predicts a 41% (for C and X-bands) and a 73% (for Ku-band) better continuum sensitivity when compared to data obtained with the 8-bit samplers. These are "at best" predictions because the overall efficiency of the system (samplers and correlator) is different for 8- and 3-bit data. Based on careful simulations, the overall efficiencies are $\sim$93.6% and $\sim$90.1%, for the 8-bit and the 3-bit, respectively (Carlson, B. 2001, NRC-EVLA Memo #011; Carlson, B., private communication), suggesting that the 3-bit

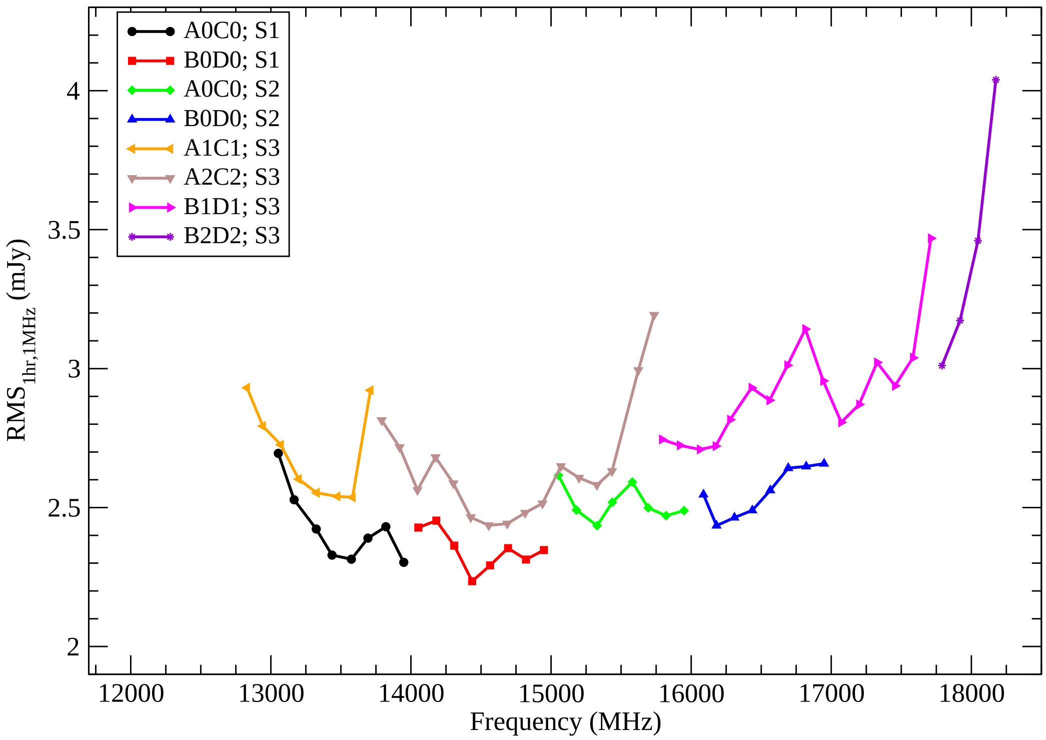

Figure 6: The RMS noise values of Stokes I per 1 MHz per 1 hr on-source time for a single baseline in the EVLA Ku-band frequency range $12 - 18$ GHz. The various curves represent the RMS noise values values of the different settings and their respective baseband pairs as illustrated in Figure 3 and listed in Table 1. No measurements were made below 12.7 GHz due to RFI.

data would nominally be ∼4% noisier than 8-bit data per unit bandwidth.

The lower overall efficiency of the system for 3-bit data (as reflected through simulations), the underperformance of the EVLA 3-bit samplers, and the presence of RFI within these three bands, will effectively reduce the actual improvement in continuum sensitivity when the wide-band system is employed. In the following, we discuss the expected improvement in the sensitivity when using the 3-bit samplers at C, X, and Ku bands in light of their receivers' respective frequency spans and the RFI.

5.1 C-band (4–8 GHz)

At this band, a fraction of the 4 GHz total bandwidth is affected by severe RFI. The known major RFI sources are listed below:

- Satellite downlinks operating between 4.0 and 4.2 GHz. This RFI is continuous, and would most likely result in astronomically useless data spanning 200 MHz of frequency. To our knowledge, all of these transmitters are located in the geostationary belt, so their impact is much stronger on observations within a few degrees of −4.5 declination. Note that in the longer configurations, rapid fringe winding may allow useful data within this frequency range.

- Various microwave links between 6 and 7 GHz. There are several of these with widths of 10–30 MHz, and all broadcast continually. They will result in severely affecting a total of $\sim$ 130 MHz in the above noted frequency range.
- Geo-Stationary Orbit (GSO) and Mobile satellite Services downlinks operating between 7.25 and 7.85 GHz. These are continuous signals, but do not fully span the 600 MHz frequency range. RFI sweeps conducted by the VLA indicate no more than about 50 MHz is lost due to these broadcasts.

Therefore, of the 4 GHz nominal frequency span of the C-band receivers of the EVLA, up to 400 MHz may be severely affected by RFI. The loss of a fraction of the total bandwidth to RFI combined with the less sensitive nature of the 3-bit samplers (see §4.1), and assuming equal amount of on-source integration times, will result in a net gain in the sensitivity of $\sim$23% for the 3-bit samplers compared to observations carried out with the 8-bit samplers (assuming up to 1.9 GHz of usable bandwidth due to RFI). We note that some non-linear effects can be expected when the antennas are pointing to within a few degrees of the GSO satellites. The extent of such effects are currently not quantified.

5.2 X-band (8–12 GHz)

This band is also affected by RFI. Known major sources include:

- RFI in the frequency range 9.3–9.5 GHz. Of this 200 MHz, RFI sweeps conducted by the VLA indicate no more than about 60 MHz is lost.
- Various satellite transmissions along the GSO path severely affecting the frequency range 11.7–12.0 GHz. This would most likely result in astronomically useless data spanning 300 MHz of frequency. However, long spacings (e.g., observations in A-configuration) may provide enough fringe winding to permit useful observations – this has yet to be shown.

Therefore, of the 4 GHz nominal frequency span of the X-band receivers of the EVLA, 300 to 360 MHz may be severely affected by RFI. The loss of a fraction of the total bandwidth to RFI combined with the less sensitive nature of the 3-bit samplers (see §4.2), and assuming equal amount of on-source integration times, will result in a net gain in the sensitivity of $\sim$19% for the 3-bit samplers compared to observations carried out with the 8-bit samplers (up to 2 GHz of bandwidth). We note that some non-linear effects can be expected when the antennas are pointing to within a few degrees of the GSO satellites. The extent of such effects are currently not quantified.

5.2.1 X-band Imaging

We have also imaged 8-bit and 3-bit X-band data of the blank field from these test observations. The images were made using the data of the two 1 GHz baseband pairs form the 8-bit samplers (Setting 1 in Table 1), and the data of the two 2 GHz baseband pairs form the 3-bit samplers (from Setting 2 in Table 1; the accompanying 8-bit data from B0D0 were discarded). The RFI at X-band was primarily due to the satellite transmissions between 11.7–12.0 GHz, and the data at this frequency range were edited out. The RMS noise measured in the resulting two images showed that the 3-bit data were more sensitive by 19.2% than the 8-bit data for the same amount of on-source time. This is in excellent agreement with the expected improvement in the RMS noise as presented in §5.2.

5.3 Ku-band (12–18 GHz)

This band is also affected by severe RFI. Of these:

- Various satellite transmissions along the GSO path severely affecting the frequency range 12.0–12.7 GHz. This would most likely result in astronomically useless data spanning 700 MHz of frequency. However, long spacings (e.g., observations in A-configuration) may provide enough fringe winding to permit useful observations – this has yet to be shown.

- Transmission from various mapping satellites between 13.4 and 13.75 GHz. This RFI is intermittent, and does not fully span the 350 MHz frequency range. RFI sweeps conducted by the VLA indicate no more than about 20 MHz is lost due to these broadcasts.

Therefore, of the 6 GHz nominal frequency span of the Ku-band receivers of the EVLA, up to 720 MHz may be severely affected by RFI. The loss of a fraction of the total bandwidth to RFI combined with the less sensitive nature of the 3-bit samplers (see §4.3), and assuming equal amount of on-source integration times, will result in a net gain in the sensitivity of $\sim$49% for the 3-bit samplers compared to observations carried out with the 8-bit samplers (up to 2 GHz of bandwidth). We note that some non-linear effects can be expected when the antennas are pointing to within a few degrees of the GSO satellites. The extent of such effects are currently not quantified.

5.4 3-bit Samplers: Hittite vs. Teledyne

In addition to comparing the overall performance of the 3-bit and the 8-bit samplers, we have carried out a comparison on the performance of the two types of the 3-bit samplers that the EVLA antennas are equipped with, namely the Hittite samplers and the Teledyne samplers.

Currently four EVLA antennas, ea02, ea03, ea16, and ea25, are equipped with the Hittite 3-bit samplers on the baseband pair A1C1, while the rest of the samplers on these antennas and on all the other EVLA antennas are Teledyne. We measured the RMS noise as described in §3 using sub-bands that are free of RFI in data from the baseband pair A1C1. The measurements were made using three of the antennas with the Hittite samplers (ea02, ea03, ea16). We excluded ea25 from this analysis because it is known to be problematic. We then measured the RMS noise at the same frequencies using all the other EVLA antennas, i.e., those that have Teledyne samplers in A1C1.

While the comparison at C-band did not show any significant difference in the measured RMS noise values, both the X and Ku-band data showed that the Hittite samplers are $\sim$9–10% more sensitive. While the C-band data seem to be affected by a problem that currently remains unknown, the X and Ku-band results are consistent with the expected performance of the Hittite 3-bit samplers.

6 Conclusions

We presented RMS noise measurements of the EVLA at C (4–8 GHz), X (8-12 GHz), and Ku (12–18 GHz) bands to assess the feasibility of using the 3-bit samplers with these receiver bands, and to quantify the overall gain in the sensitivity by using the 3-bit samplers instead of the 8-bit samplers. Considering the receivers' frequency coverage, the 3-bit samplers can be used to deliver only 4 GHz of instantaneous bandwidth at C and X-bands, and 6 GHz of bandwidth at Ku-band.

In spite of the higher noise in data obtained through the 3-bit samplers, our on-the-sky test results show that there is an overall gain in sensitivity when using these samplers compared to that of the 8-bit for the same amount of on-source time. Depending on the amount of RFI contaminated bandwidth, the measured improvement in the continuum full-bandwidth sensitivity is ∼23%, ∼19% and ∼49%, for C, X, and Ku-bands, respectively. RFI remains a major concern in these bands, especially that of GSO satellites that can potentially saturate the limited range of the 3-bit samplers if the observations were within a few degrees of −4.5 declination.

The results also showed what is likely to be the effect of the anti-aliasing filters. Considering that there are four 3-bit baseband pairs, but only two (C and X bands) or three (Ku-band) pairs are needed to cover the nominal frequency ranges of these three receivers, the effect of the increased noise due to the anti-aliasing filters can be eliminated by using one more baseband pair and slightly overlapping the frequency tunings. This will ensure the use of the more sensitive parts of each baseband pair while effectively covering the full frequency span of each receiver band.

We have also compared the performance of the two types of the EVLA 3-bit samplers: Hittites and Teledynes. The results show that the Hittite samplers deliver 9–10% more sensitive data than the Teledyne samplers. If the EVLA antennas were to be equipped with Hittite or comparable 3-bit samplers, the resulting sensitivity would be very close or within only a few percent of the value that the EVLA and its WIDAR correlator would have nominally delivered.

7 Acknowledgements

We would like to thank K. Sowinski, M. Rupen, K. Morris, J. Jackson, and B. Carlson for helpful discussions.