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Sensitivity measurements of dipole groups under Phases I & II of the ORT Programmable Receiver

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1.0 Sensitivity of the Ooty Radio Telescope

Radio signals from celestial sources are extremely weak. To collect as much energy as possible from these sources in a short time, radio telescopes must have large collecting area and bandwidth. The radio power at the focus of the telescope produces electrical voltage fluctuations in the dipoles placed there. This input power to the telescope can be replaced by an equivalent resistor at the terminals kept at a particular temperature T_a. This temperature T_a, called the *antenna temperature*, is the physical temperature of the resistor that would feed the same amount of power at the input terminals of the antenna as the celestial radio source. Mathematically, we represent this concept as

$$\frac{1}{2}\ S\ A_{eff}\ \Delta\nu = k\ T_a\ \Delta\nu \tag{1}$$

where S is the flux density of the source, A_{eff} is the effective collecting area of the radio telescope, T_a is the antenna temperature and k is the Boltzmann constant. The $\frac{1}{2}$ appears because we consider only one polarisation. A higher value for T_a means larger input power at the terminals of the telescope. Since we have no control over the power radiated by the celestial source, it is easy to appreciate the fact that increasing the effective collecting area is the only way to increase T_a. This is the reason why radio telescopes are designed and built with ever increasing collecting areas. Even in the absence of radiation from a celestial source reaching the radio telescope, some power is available from the telescope. This is due to the thermal noise produced by the active and passive electronics, including the dipoles, cables, amplifiers and filters. This power can also be represented as an equivalent temperature called the system temperature, denoted by T_{sys}. The true equivalent temperature when looking at a celestial radio source is therefore $T_a + T_{sys}$.

The Ooty Radio Telescope (ORT) is an equatorial-mounted, steerable, offset-parabolic cylindrical reflector, the physical dimensions of which are 529 m in the North-South direction and 30 m in East-West(Swarup et al., 1971). The physical area is therefore 529 $m \times$ 30 m. However, not all the radiation falling on the reflecting surface is available at the focus. Only a fraction η of the power is available at the focus. This is equivalent to having a smaller reflecting surface of area ηA in which all the incident power is available at the focus. This quantity ηA is called the effective area, denoted by A_{eff}, where η is the aperture efficiency. The ORT has an effective area of 8700 m^2 (Swarup et al., 1971), giving an aperture efficiency of 55%. We can now compute the expected antenna temperature and when looking at a radio source of known flux density, and hence the system gain. Consider a radio source in the beam of the telescope with a flux density of 1000 Jy. Recalling eq. 1, we have

$$\frac{1}{2}\ \times\ 1000\ \times\ 10^{-26} \times\ 8700\ =\ 1.38\ \times\ 10^{-23}\ \times\ T_a$$

which gives

$$T_a\ =\ 3152\ K$$

The gain of the system is therefore 3.15 K/Jy. Since this is the output of all 1056 dipoles phased together, the gain per dipole is $T_a\ =\ 3\ mK/Jy$.

2.0 Summary of observations

Observations were made on 16^{th} and 17^{th} October 2011 to measure the sensitivity of a group of 4 and 24 dipoles, and to measure the usable 3-dB bandwidth in each case. The specifics of the observations are outlined in this section. Details are shown in Table 1.

Phases I & II of the ORT programmable receiver employ direct bandpass sampling of the RF signal. In Phase I, a group of 24 phased dipoles comprise one input channel to the digitiser. Therefore, each RF

Table 1: Details of the observations

S. No.	Date of observation	Target	Off-target	System
1	16-10-2011	Cygnus A	50^o away North	Phase II - 4 dipoles - S11
2	17-10-2011	Sun	-2 h away in RA	Phase II - 4 dipoles - S11
3	17-10-2011	Cygnus A	-2 h away in RA	Phase I - 24 dipoles - S03
4	17-10-2011	Sun	-2 h away in RA	Phase I - 24 dipoles - S03

channel corresponds to one half-module. Each pillar takes 10 half-modules in Phase I. There are four pillars in Phase-I, spaced five modules apart. These pillars are located under S08, S03, N03 and N08. The RF inputs to the 10-channel digitiser can be tapped before the digitiser for measurements in the field. In Phase II, a 4-dipole group forms a single channel RF input to the digitiser. Twelve such groups comprise the 12 RF inputs to the digitiser. Each digitiser, therefore, takes in one full module. There is a pillar for each module in Phase-II; however at present not all of them have been installed. The measurements of 16^{th} and 17^{th} Oct 2011 were made at the pillars under modules S03(Phase-I) and S11(Phase-II). For each of the four measurements shown in Table 1, the telescope was pointed at the target and allowed to track. The power levels on the target and off-target were recorded for each RF channel by disconnecting the input to the digitiser and connecting the same to the RF input of the spectrum analyser.

3.0 Results from measurements

The ratio of on-source to off-source RF power is

$$a = \frac{T_a + T_{sys}}{T_{sys}}$$

This ratio can be obtained from the deflection measurements by inverting

$$D = 10\ log_{10}(a).$$

where

$$D = P_{on} - P_{off}$$

If the flux of the source is known, the sensitivity of the system per polarisation is

$$g = \frac{(a-1)T_{sys}}{\frac{1}{2}S} \quad K/Jy$$

The plots of the sensitivities across the band for the different observations are given here. In Figure 1, the sensitivity of each of the 4-dipole groups of the Phase-II system at S11 is shown across the RF band. The target was Cygnus-A, whose flux density of 6350 Jy at 327 MHz was estimated from its low frequency spectral index(data from NASA Extragalactic Database). The telescope was allowed to track the source while the power on the source was measured. The telescope was pointed 50^o away North for measuring off-source power. Both on-source and off-source spectra were recorded in the spectrum analyser. The peak sensitivity is attained at 327 MHz. The sensitivity drops by 3 dB at about 13 MHz on either side of 327 MHz. Hence, the 3-dB bandwidth is about 25-26 MHz. The peak sensitivity(at 327 MHz) for all 4-dipole groups in given in Table 2. The mean peak sensitivity of all the 4-dipole groups in S11 is 35.1 mK/Jy.

Sensitivities of the half-modules of the Phase-I system at S03 pillar were also measured. The observing procedure was identical to the one followed for the Phase-II system at S11. However, here instead of a group of four dipoles, each RF channel is a phased sum of twenty-four dipoles, or a half-module. The sensitivity is expected to scale by a factor of 6. The sensitivities of the half-modules of the Phase-I system from S1 to S5 are shown in Figure 2. As an example, the sensitivity as a function of bandwidth is shown for the two half-modules of S4. Overlays from all half-modules is shown for comparison of the different sensitivities.

The Phase-I mean peak sensitivity of 75 mK/Jy is close to the expected sensitivity of 72 mK/Jy (24 dipoles of 3 mK/Jy each). However, the Phase-II 4-dipole sensitivity does not scale as expected: while we

Table 2: Peak sensitivity of the Phase-II 4-dipole groups in S11

S. No.	Dipole group	Peak sensitivity - K/Jy
1	1 to 4	4.01×10^{-2}
2	5 to 8	4.18×10^{-2}
3	9 to 12	2.25×10^{-2}
4	13 to 16	1.06×10^{-2}
5	17 to 20	4.62×10^{-2}
6	21 to 24	4.04×10^{-2}
7	25 to 28	3.55×10^{-2}
8	29 to 32	4.71×10^{-2}
9	33 to 36	3.76×10^{-2}
10	37 to 40	3.88×10^{-2}
11	41 to 44	3.28×10^{-2}
12	45 to 48	2.78×10^{-2}

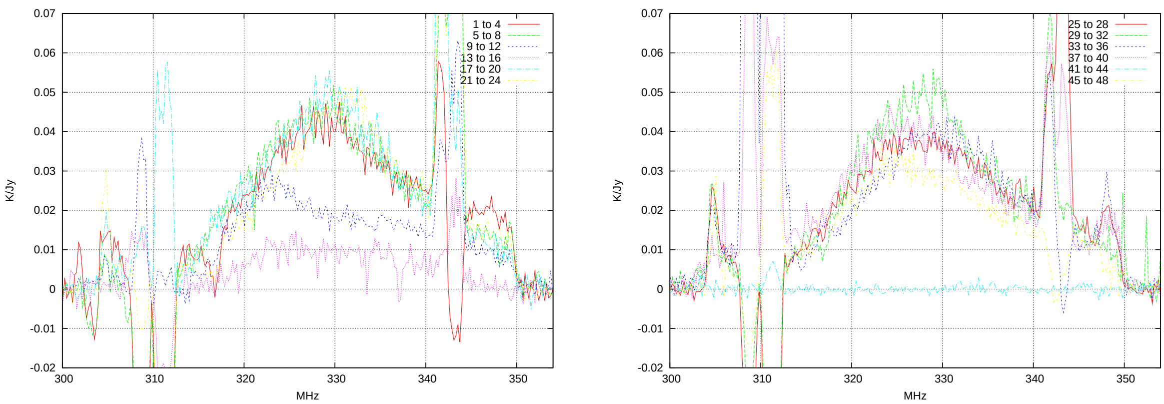

Figure 1: Sensitivities of the Phase-II 4-dipole groups for dipoles 1 to 48 at module S11 on Cygnus A

expect a mean peak sensitivity of 12 mK/Jy, we obtain a larger value of 35.1 mK/Jy as already stated above. The reason for this discrepancy is not clear, although it is possible that it could arise from the fact that much more sky-radiation could enter through the half-radian Phase-I fan-beam, especially since Cygnus A is near the Galactic Plane. The mean sensitivities of Phase-I and Phase-II systems, measured respectively at S03 and S11, are shown in Fig. 3. Their 3-dB bandwidths are also shown in the figure: for the Phase-I system it is approximately 314 MHz to 343 MHz, and for the Phase-II system it is 319 MHz to 340 MHz.

The deflection measurements for the Phase-I and Phase-II systems were subsequently repeated for the Sun. Since the flux density of the Sun is not known reasonably well at any given time, these observations were not used for measuring the sensitivities. However, by using arbitrary flux units, the shape of the sensitive RF band can be ascertained. The observing procedure is identical to that followed earlier for Cygnus A. The recorded spectra were analysed to obtain the deflection band shapes. These plots are given in Figure 5. We note that the deflection band shapes do not represent the true sensitive band shapes of the RF channels. The radio flux from the Sun has likely saturated the system. Similar deflection plots for the Phase-I system at S03 obtained from observing the Sun are show in Figure 6.

Table 3: Peak sensitivity of the Phase-I half-modules in S03

S. No.	Dipole group	Peak sensitivity - K/Jy
1	S1 north	4.83×10^{-2}
2	S1 south	1.07×10^{-2}
3	S2 north	6.77×10^{-2}
4	S2 south	9.42×10^{-2}
5	S3 north	4.32×10^{-2}
6	S3 south	2.53×10^{-2}
7	S4 north	8.21×10^{-2}
8	S4 south	8.54×10^{-2}
9	S5 north	9.82×10^{-2}
10	S5 south	8.30×10^{-2}

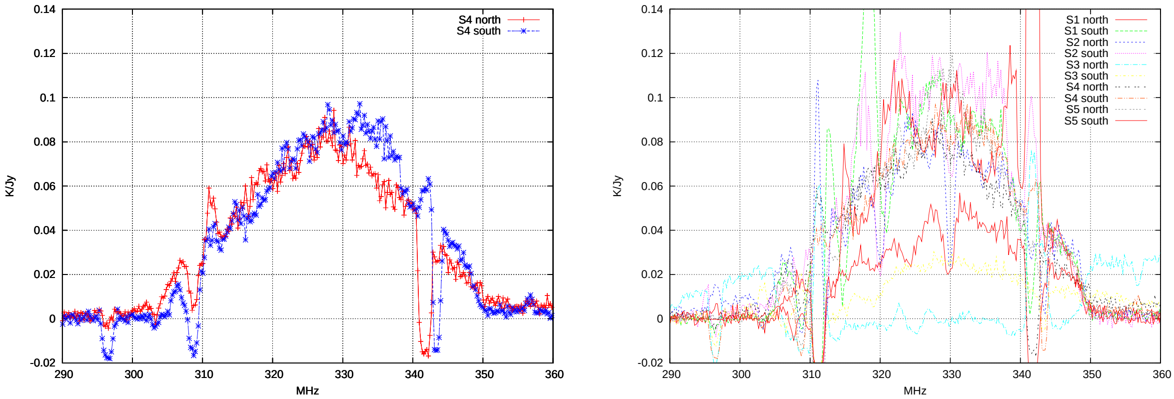

Figure 2: Sensitivities of Phase-I half-modules at S3 pillar on Cygnus A

3.0 Television Interference Lines

Television transmission lines appear in the RF band of Phase I & II because of the increased bandwidth. These lines appear at 311 MHz and 343.25 MHz. The strength of these lines varies with the time of the day and telescope pointing. Shown below in Figure 4 are plots of these lines.

4.0 References

G. Swarup et al., *Large Steerable Radio Telescope at Ootacamund, India*, Nature Physical Sciences, 1971, 230, 181.

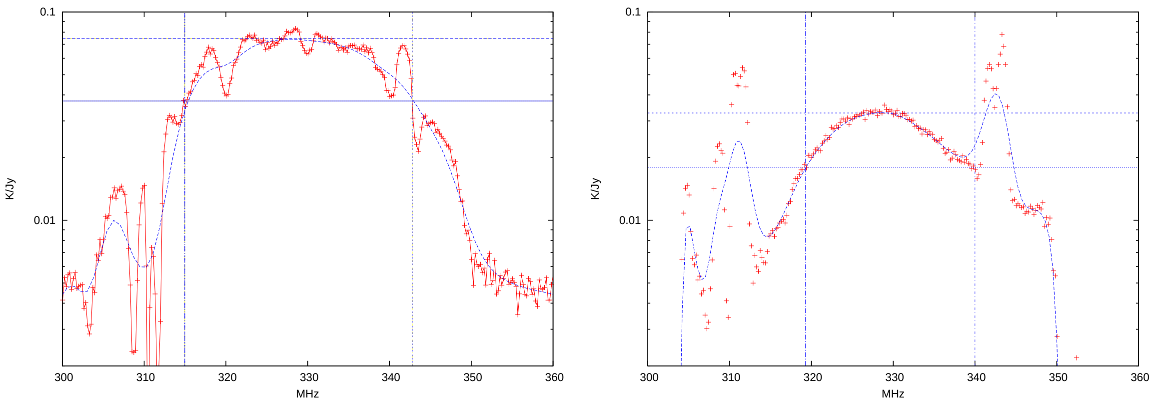

Figure 3: Mean sensitivities across the band for the Phase-I and Phase-II systems at S03 and S11 respectively

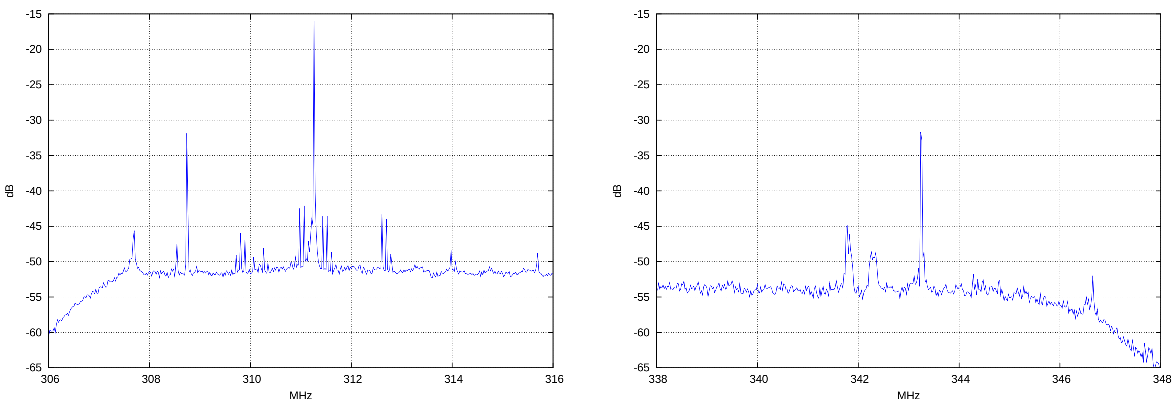

Figure 4: Magnified views of the television interference lines at 311 MHz and 343.25 MHz

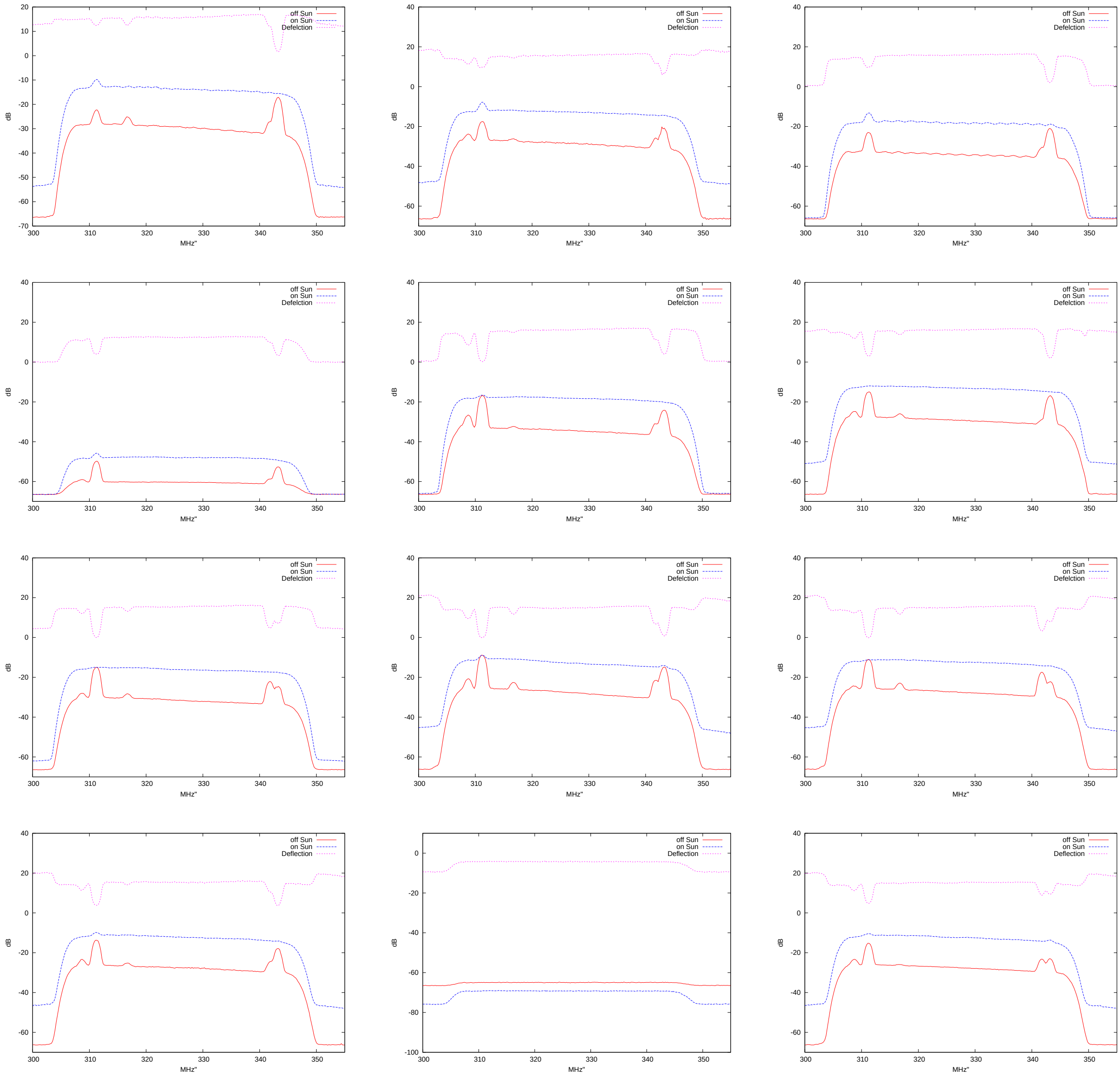

Figure 5: Deflections of Phase-II 4-dipole groups at S11 pillar measured on Sun

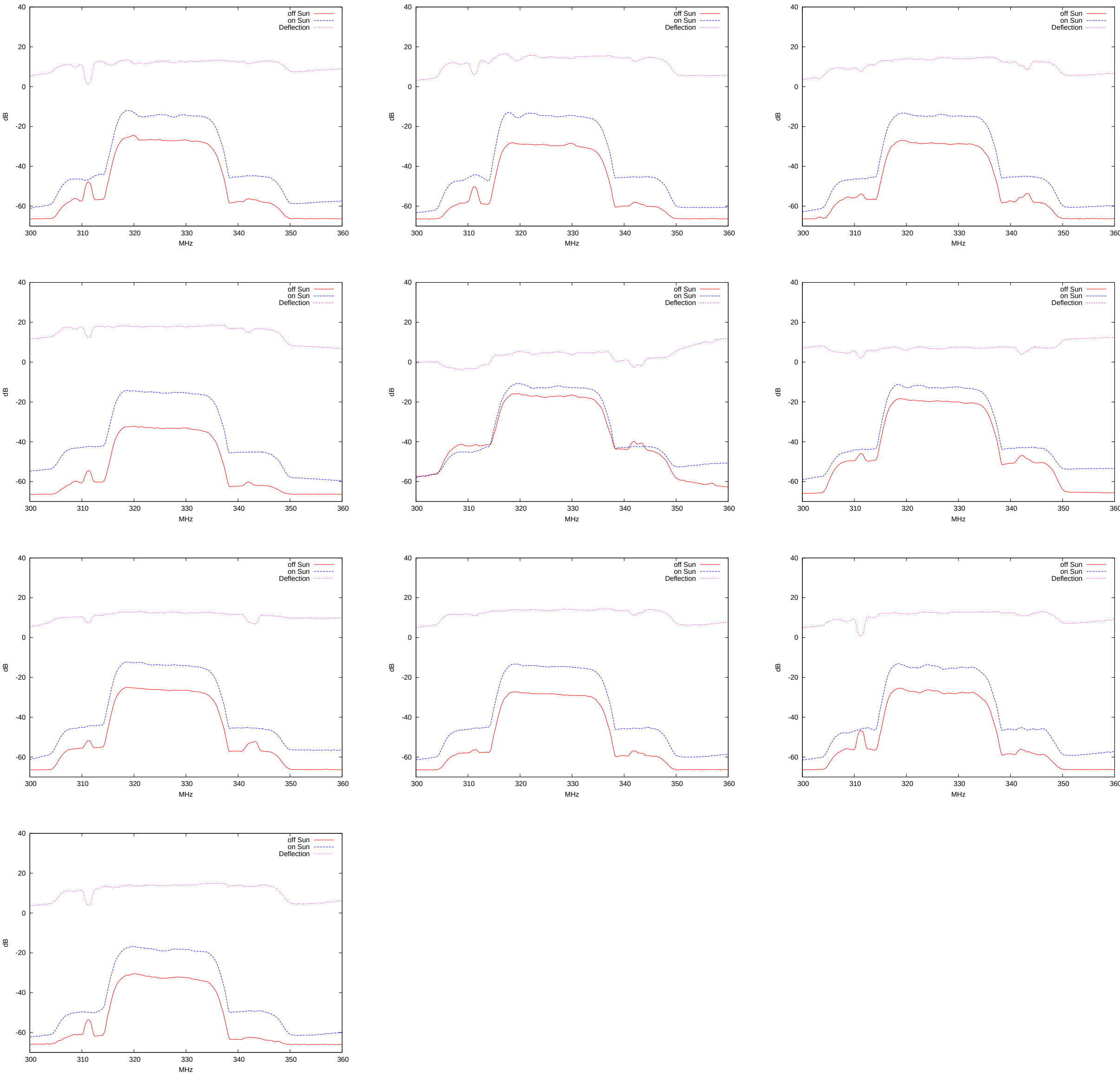

Figure 6: Deflections of Phase-I half-modules at S03 pillar measured on Sun