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Crosstalk between antennas in the AAVS2 station

Executive Summary

This note is on analysis done to make a quantitative estimate of the magnitude of unwanted crosstalk between antennas in the AAVS2 station. The purpose of this work is to evaluate the magnitude of this spurious, so that its impact on the calibration of the station might be assessed. Specifically, it is of interest to know the magnitude of systematic errors in visibilities measured by intra-station baselines of varying lengths, as compared to that predicted using interferometer theory and models for global sky. That will inform the accuracy that might be expected in deriving antenna complex gains via forward modelling of the global sky.

The analysis here is at 110 MHz, roughly at the geometric centre of the SKA Low band. At this frequency, the conclusion is that coupling of receiver noise between antennas in the station may be expected to result in unwanted visibility component of magnitude up to 1 K on the shortest baselines, reducing to less than 100 mK beyond 20 m intra-station baselines. This is substantially smaller than the visibility amplitudes expected from galactic diffuse emission and the Sun. Thus even the shortest intra-station baseline visibilities might usefully participate in derivation of antenna gain solutions via forward modelling of global diffuse sky models, assuming that the embedded patterns are known to sufficient accuracy.

The result of the analysis is in Figs. 13 and 14 in page 9 of this note, where the 2D distribution of receiver noise crosstalk is depicted in the uv-plane in units of kelvin.

Background

"Cross talk" is a term that usually refers to non-ideal behaviour of an interferometer when the baseline is small and proximity of antennas corrupts visibility measurements. In SKA Low, we have a dense packing of antennas within stations, particularly at the longest wavelengths. Proximity between antennas in an interferometer pair results in

(a) Distortions in far-field beam patterns of the antennas. This is already well recognised in SKA Low stations and embedded element patterns are being computed for antennas, using EM analysis, taking into account parasitic effects of other antennas in the station. The embedded beam patterns are chromatic. Calibration of stations, particularly at the longest wavelengths where stations are densely populated, will have improved accuracy when embedded voltage beam patterns are used while transforming between visibilities and the celestial sphere.

(b) Response to uniform sky. This is an issue of greater import at frequencies where the stations have dense coverage and effective areas of antennas overlap. When the spacing between elements is small, the intra-station interferometers respond to uniform sky in a highly frequency dependent way, adding a component to the measured visibility that may not be included in standard computations that forward model sky to visibilities. The uniform component of the sky brightness results in a response that is baseline dependent. Provided the wide-field imaging algorithm transforms between the celestial sphere and u, v, w space visibilities, using correct 3D transforms, the uniform component of sky brightness will be correctly represented in the visibilities. Thus, assuming that the algorithms are precise, response to uniform sky need not be viewed as a spurious or unwanted component in visibilities.

(c) Coupling of receiver noise. Mutual coupling between antennas within stations causes space propagation of receiver noise between antennas. This results in a systematic additive error in intra-station correlations. This note makes a quantitative estimate of the crosstalk between antennas in the SKA Low station, from mutual coupling of receiver noise.

It may be noted here that these effects cannot be cancelled by traditional phase switching schemes that reject coupling between the arm electronics.

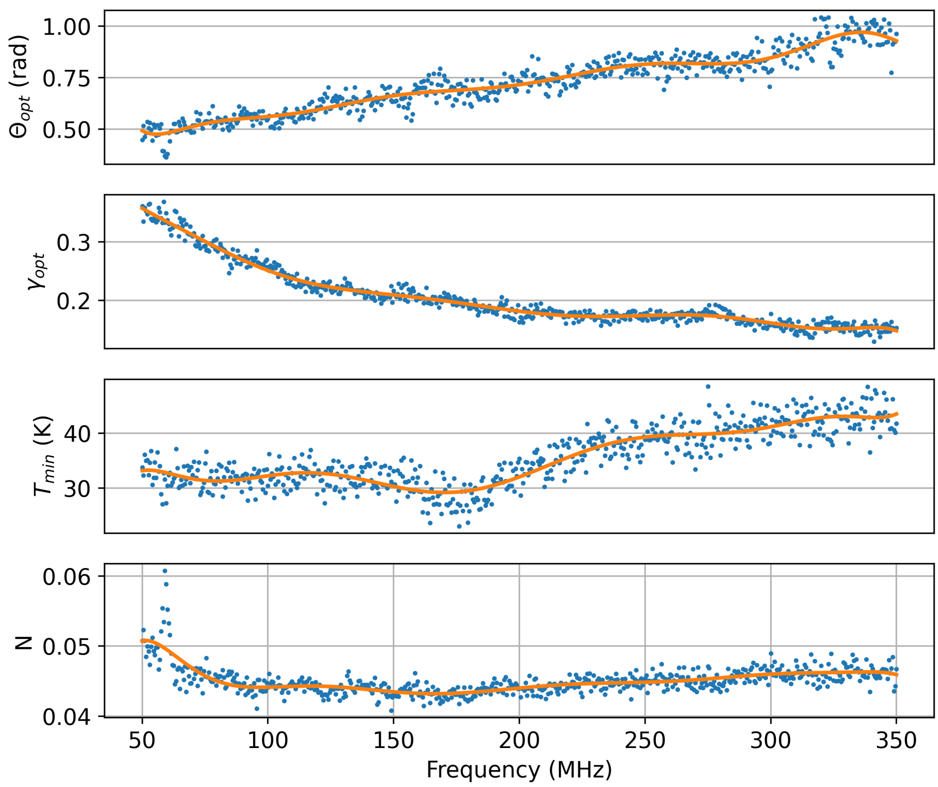
These problems are not new and have been recognised in practical interferometers. Imaging analysis pipelines of facilities like the VLA and ATCA provide an option to reject baselines that shadow. All baselines to the shadowed antenna are flagged. The MIRIAD cookbook has this to say: "If some data is shadowed, it is advisable to use an antenna diameter value greater than the physical antenna size (*e.g.,* 20% larger)". The reason why Fourier synthesis arrays advocate rejection of data on baselines involving the shadowed antenna is that its beam would differ from that of the rest of the array and hence visibilities on these baselines would be incompatible with imaging algorithms that assume identical beam patterns. Shadowing also results in crosstalk on the baseline between the shadowed antenna and the one in front. This may be due to leakage of receiver noise from one antenna to the other or due to emission from reflector panels; specifically, the slot antennas formed by gaps between panels. In this context, it is fitting that SKA-mid antennas have continuous surfaces without panel gaps.

Short-spacing interferometers have particularly suffered crosstalk. The problem is recognised and has been investigated in depth in interferometers like DASI and CBI, which have multiple reflector elements placed adjacent to each other for maximising sensitivity to CMB brightness temperature anisotropy. A strategy was to limit propagation of receiver noise out of the feed by placing isolators in-between, and to limit coupling of receiver noise between antennas by placing shrouds in-between. Separately, EM analysis was done to estimate the mutual coupling between adjacent apertures and characterise the effect. The visibilities in these short-baseline interferometers also have a significant component due to the brightness discontinuity at the horizon between sky and ground, which depends on the orientation of the baseline w.r.t. horizon.

SKALA4.1 receiver noise model

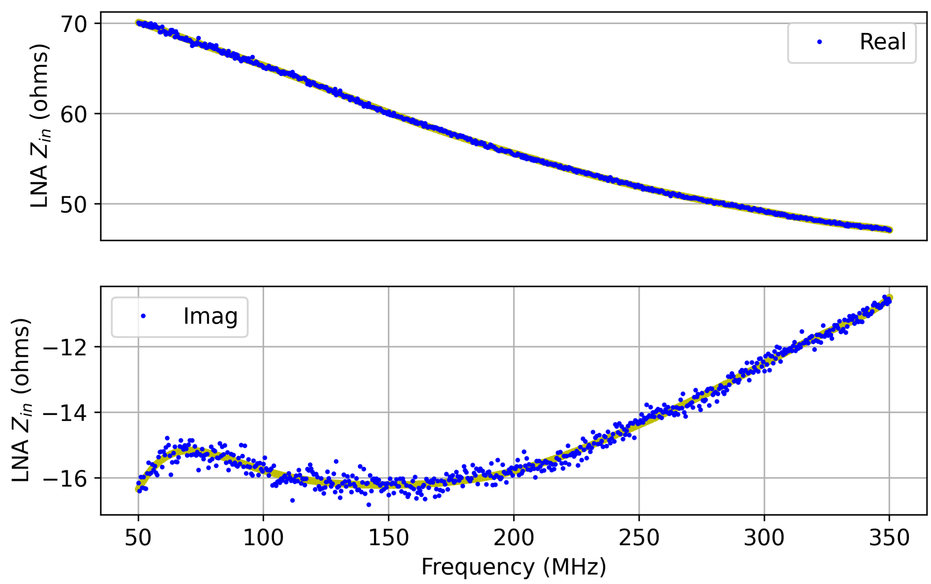
I use a measurement of the noise characteristics of the SKALA4.1 LNA module, provided to me by Daniel Ung, Curtin-CIRA. The parameters $\gamma_{opt}, \theta_{opt}$ give the magnitude and phase of the optimum source impedance, T_{min} is the minimum noise in kelvin and N is the Lange invariant. These are plotted in Fig. 1 below along with polynomial fits overlaid.

Fig. 1



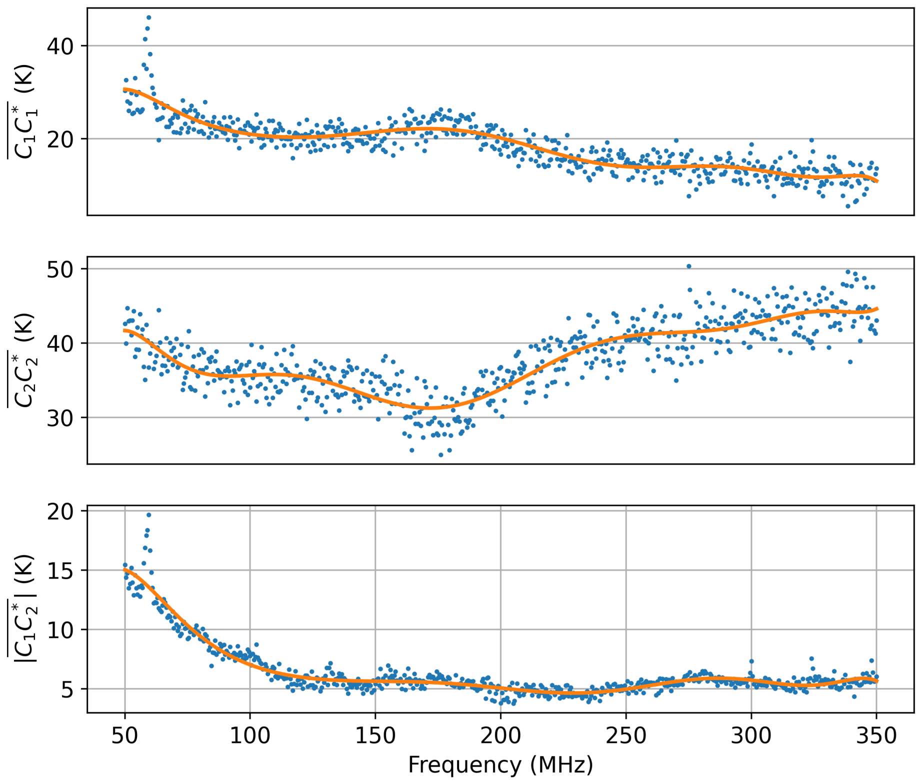
The input impedance of the LNA modules, from 2-port S-parameter measurements provided to me by Daniel Ung, are given in Fig. 2 below with polynomial fits overlaid.

Fig. 2



From the noise characteristics and input impedance of the LNA module, I computed the noise wave parameter $\overline{|C_1|^2}$ that denotes the average power in receiver noise flowing upstream from the input of the LNA module, $\overline{|C_2|^2}$ that denotes average power flowing downstream from the output of the LNA module and the magnitude of the average correlation $\overline{C_1 C_2^*}$. These are plotted below in Fig. 3, in units of kelvin, with polynomial fits overlaid. The noise temperatures at 110 MHz are well below sky temperature at this frequency.

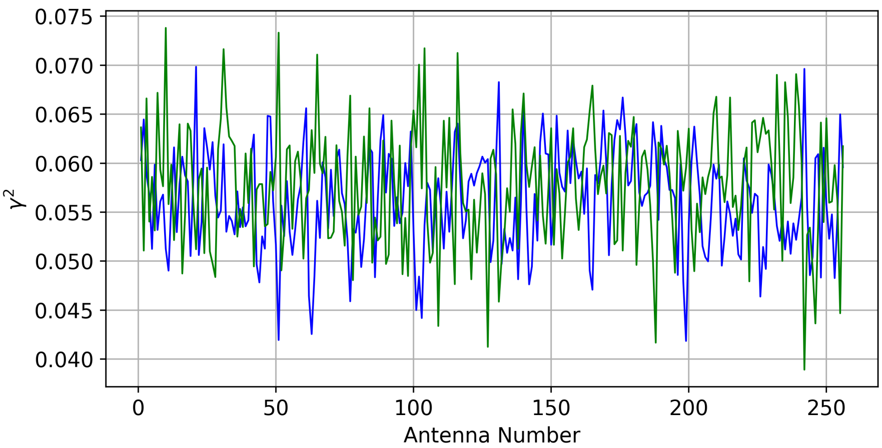
Fig. 3



The scattering parameters for the AAVS2 SKALA4.1 antennas, configured in the station, have been computed using FEKO by the EM groups at Curtin-CIRA and INAF. To compute crosstalk, I use the S11 and S21 values at 110 MHz along with noise parameters of the LNA module, which are derived at this frequency using the polynomial fits.

The magnitude of the reflection coefficient γ, from the S11 scattering parameter of the antennas, is plotted below in Fig. 4 versus antenna number.

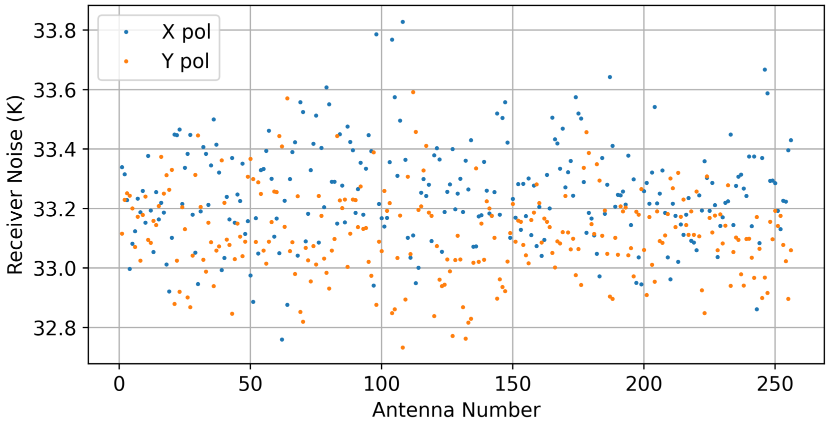
Fig. 4



The fraction γ^2 of power that is internally reflected is small and the reflection efficiency $(1-\gamma^2)$ is high, which means that only a small part of the noise wave C_1 suffers internal reflection; however, it implies that a significant fraction of the C_1 noise wave will be transmitted by the antenna to potentially couple to adjacent antennas and thereby result in crosstalk.

I used the complex S11 parameters of the antennas to compute the source impedance as seen by the LNA modules when connected to the X and Y polarisations of different antennas. The optimum impedance of the LNA module at 110 MHz has value 72+j20 ohms, which has a magnitude of 74 ohms. The average impedance of the SKALA4.1 antenna, as computed using S11 parameters from the FEKO modelling, is 80+j8 ohms, which has a magnitude of 80 ohms. The closeness between the antenna impedance and optimum impedance of the LNA module means that the LNA noise figure is close to optimum. The predicted values for the receiver noise, computed from the S11 scattering parameters of the antennas and the noise wave parameters of the LNA module, is given in Fig. 5 below versus antenna number.

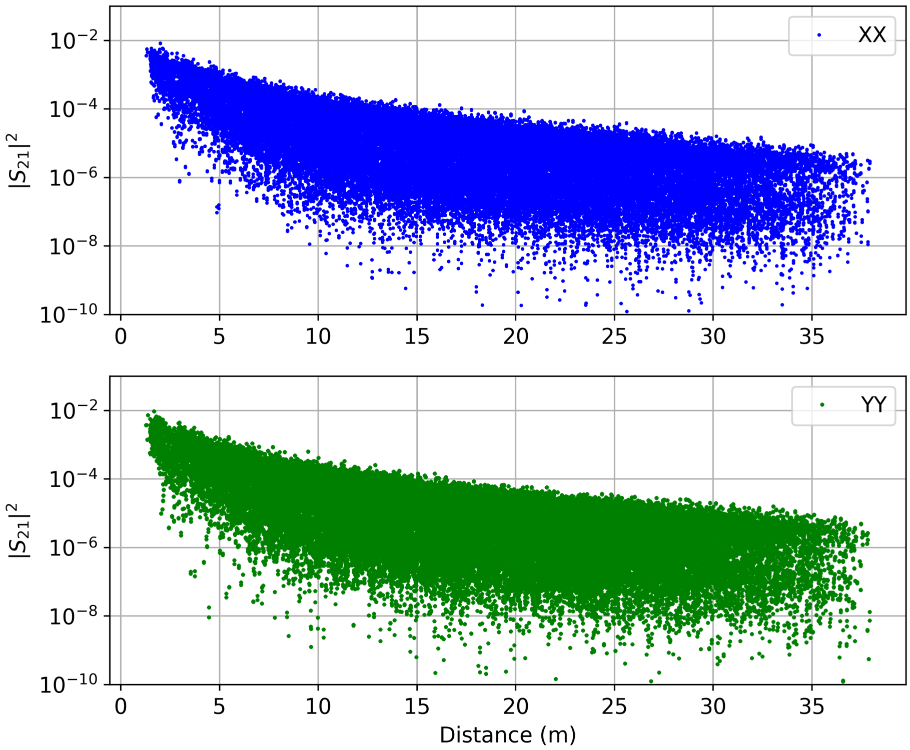
Fig. 5



Additionally, at 110 MHz, the LNA module has an input impedance of 64-j16 ohms, which is nicely conjugate matched to the antenna impedance of 80+j8 ohms, thus providing high antenna efficiency.

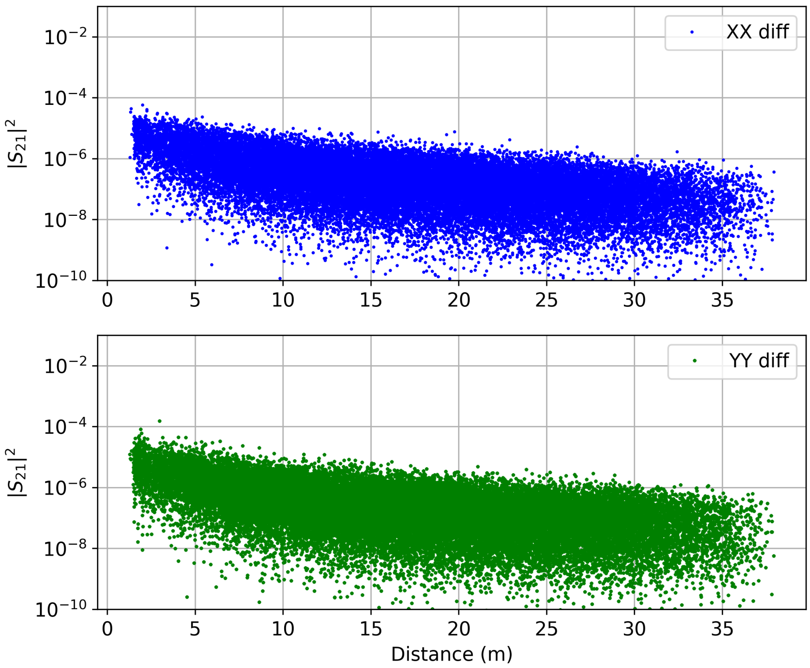
I used the S21 scattering parameter, along with the noise wave correlation $\overline{C_1 C_2^*}$, to estimate the magnitude of cross talk. Shown below in Fig. 6 is the magnitude of the coupling S21, in XX and YY polarisation products, versus length of the intra-station baseline. Less than 1% receiver noise couples between the closest antennas and the coupling is substantially smaller at longer spacings.

Fig. 6



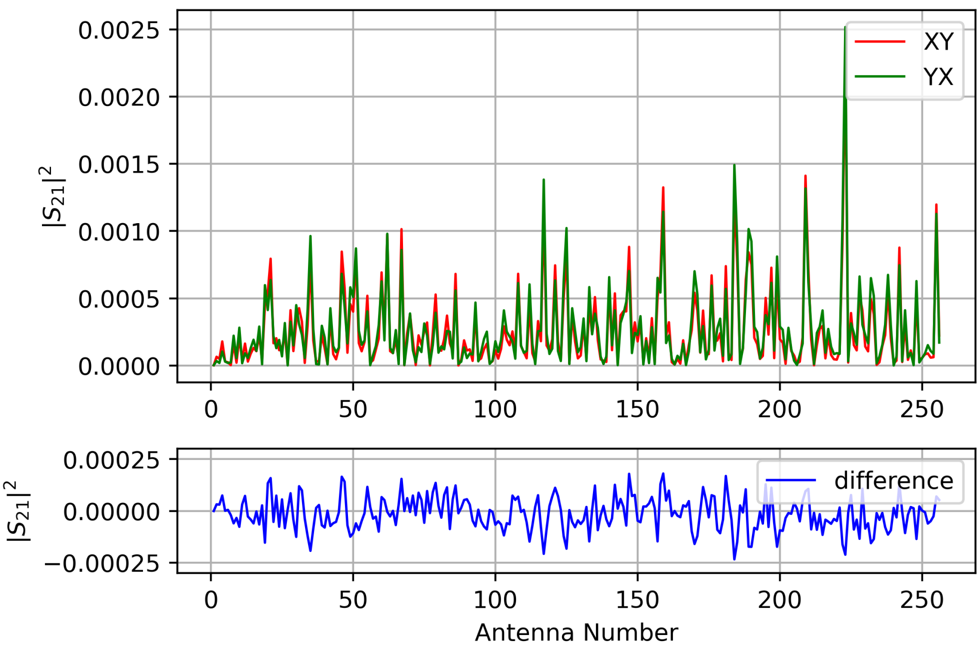
A measure of the computational error in the above coupling is the difference in the S21 scattering parameter going from antenna ‘a’ to ‘b’, compared to that going from ‘b’ to ‘a’, for any pair of antennas ‘a’ and ‘b’. Differences in these reciprocal scattering terms are plotted below in Fig. 7, separately for the X and Y polarisations. For the closely spaced antennas where the coupling is strongest, it appears that the accuracy of the computation is better than 1%.

Fig. 7



Shown below in Fig. 8 are magnitudes of the S21 coupling between the X and Y polarisations on individual antennas, versus antenna number. Here also the differences between reciprocal scattering parameters have been computed and plotted in the lower panel.

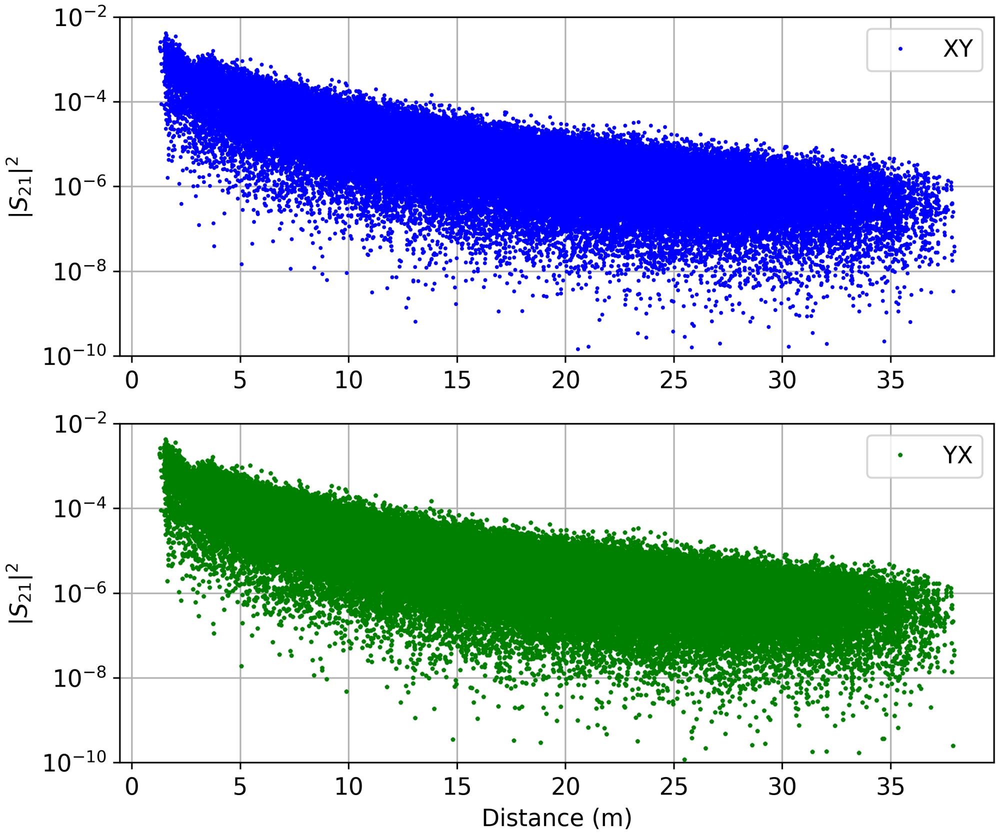
Fig. 8



The EM simulations indicate extremely low cross polar coupling between the X and Y polarisation feeds of individual antennas.

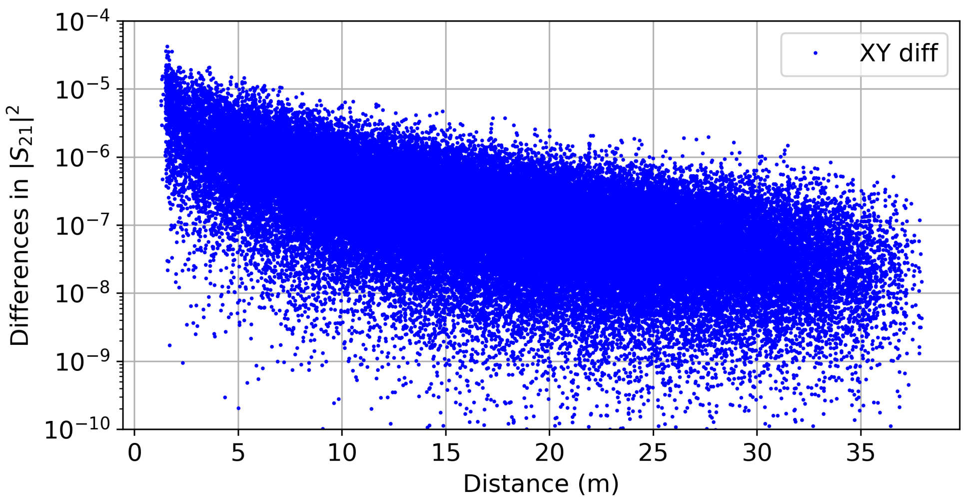
In Fig. 9 below are displayed magnitudes of the cross polar coupling between X and Y polarisation terminals of antenna pairs, from the S21 scattering parameters. The coupling between cross hand polarisation feeds XY is below 1% and somewhat less than that between parallel hand polarisations XX and YY.

Fig. 9



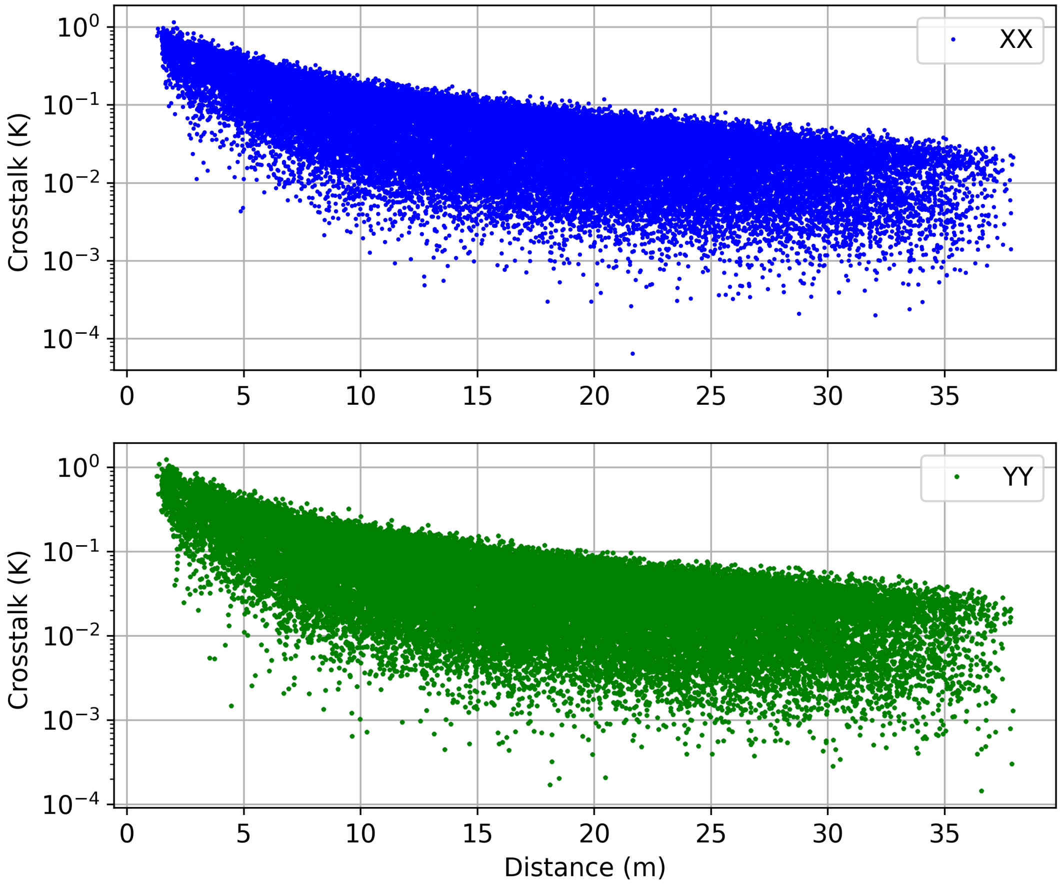
Here too we may compare the reciprocal S21 values: X polarisation of antenna ‘a’ to Y polarisation of antenna ‘b’, compared with the coupling from Y polarisation of antenna ‘b’ to X polarisation of antenna ‘a’. These differences are shown below in Fig. 10, versus baseline length, indicating once again that the numerical computational errors associated with the coupling coefficients may be 1%.

Fig. 10



Combining the noise waves with the scattering parameters between antennas, the crosstalk magnitude may be expressed in units of kelvin. The crosstalk in the intra-station XX and YY polarisations is shown below in Fig. 11.

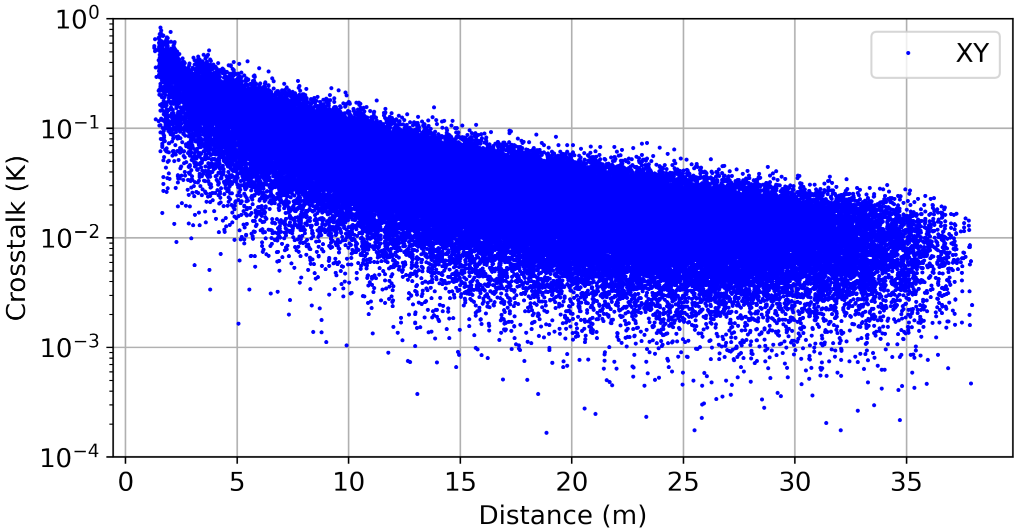
Fig. 11



The magnitude of crosstalk is at most 1 K between the closest antennas, and reduces substantially with increasing spacings.

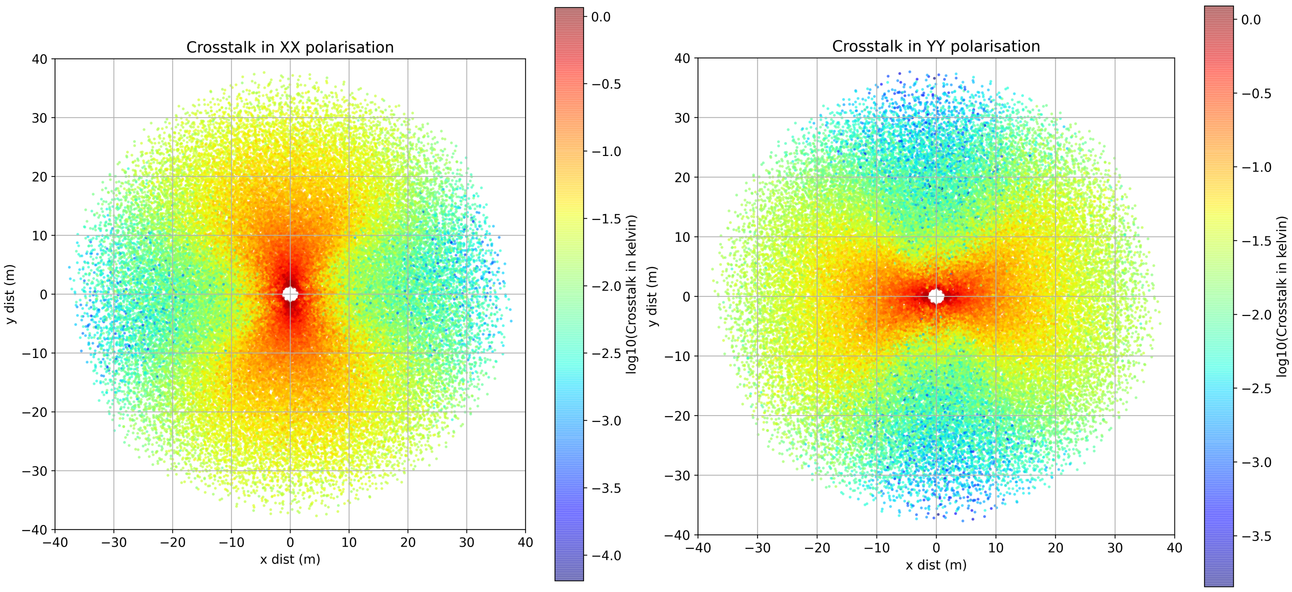
The cross talk in the intra-station XY and YX products is shown below in Fig. 12; the magnitude of coupling results in crosstalk somewhat less than 1 K between closely spaced antennas.

Fig. 12



The crosstalk is not just dependent on baseline length, but also dependent on the relative orientations of the pair of antennas, which depends on the position angle of the baseline in the u,v-plane. Below in Fig. 13 are 2D distributions of the magnitude of crosstalk in the XX polarisation, and separately in the YY polarisation.

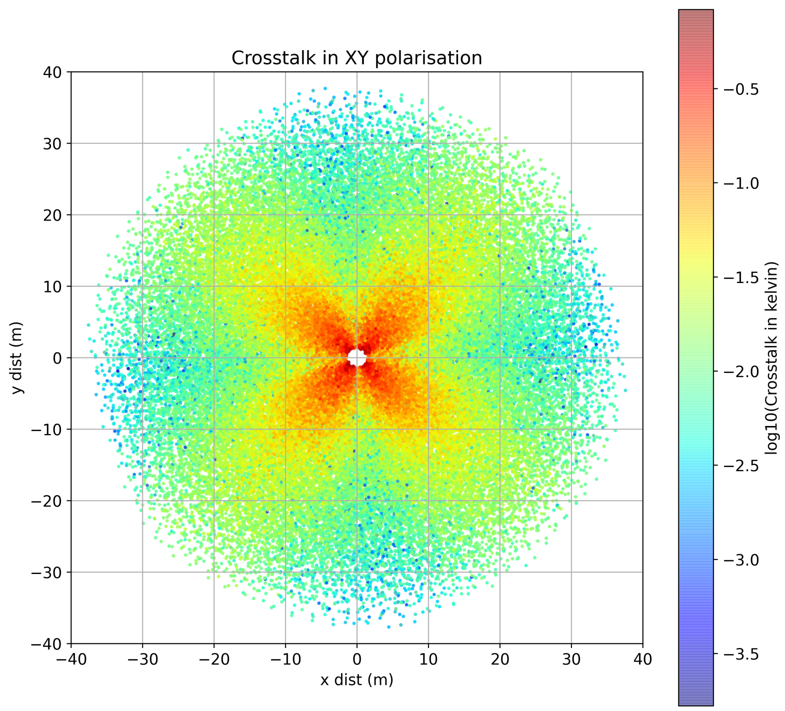
Fig. 13



As expected, crosstalk in XX and YY polarisation is a maximum in baselines where the antennas are separated in NS and EW respectively. Crosstalk is a maximum between dipoles that are parallel to each other, and a minimum when the dipoles are perpendicular to each other.

The 2D distribution of crosstalk in XY products of the intra-station correlations is shown below in Fig. 14. The crosstalk in XY products is a minimum in baselines oriented EW and NS, since in both these configurations the dipole pairs providing the XY correlation are perpendicular to each other.

Fig. 14



End Note

There are two inputs to the computations in this note:

A. Characteristics of the noise in the receiver and the 2-port scattering parameters of the receiver. These are based on laboratory measurements on a single amplifier module and it has been assumed in this note that amplifiers across the array and polarisations would have identical characteristics.

B. Scattering parameters of the AAVS2 array of antennas. This is based on EM modelling and assuming 50 ohm terminations at the antenna terminals.

The EM simulations are certainly reliable - I've seen that the observed total power versus LST matches predictions made using the chromatic beam patterns from EM simulations to within 3%. There is expected to be a difference between modelling and real world because the modelling was done assuming 50 ohm terminations at antenna terminals whereas in practice they would be terminated with LNA modules that are closer to 66 ohms.

The measurements on the LNA module are representative; however, I would be surprised if the production units have parameters off by more than 25%.

In spite of these uncertainties in the inputs to the computations, I expect that the result that the crosstalk is substantially smaller than visibility amplitudes from diffuse sky is robust.