PROOF-OF-CONCEPT DEMONSTRATION OF A MILLIMETRE WAVE IMAGING SOUNDER FOR GEOSTATIONARY EARTH ORBIT

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Abstract

The proposed GEO Atmospheric Sounder (GAS) instrument is a mm-wave imaging sounder considered for future meteorological satellites. The instrument comprises a rotating sparse interferometer operating at several frequency bands of interest for temperature and humidity sounding. A 20-element demonstrator representing the central part of the 53 GHz interferometer has been developed. The demonstrator supports fully polarimetric imaging at 0.6 degree resolution. A proof of concept test campaign was executed during spring of 2010. Different arrangements of active and passive point sources and distributed sources were used to demonstrate the concept and to determine the imaging performance. The results of the demonstrator test campaign fulfilled all success criteria and the obtained performance parameters were found to agree well with model predictions.

INTRODUCTION

This paper presents the successful results of the proof-of-concept demonstration for the GEO Atmospheric Sounder (GAS) instrument that was completed last year. The GEO Atmospheric Sounder technology project consisted of two phases:

- In a first phase, an instrument concept was developed and its feasibility was analysed. Computer simulations were used to predict the performance of the instrument when operating in GEO. The defined instrument consists of a Y-shape structure that can rotate around an earth pointing axis at a rate of one degree per second and it produces images of the Earth from GEO at several frequencies in several bands.
- In a second phase, a demonstrator consisting of a 20-element rotating interferometer was developed and used to successfully demonstrate the instrument concept through imaging of different microwave sources, both outdoor (the sun and a neighbouring office building) and indoor (point sources and microwave absorbers).

INSTRUMENT OBJECTIVES

The instrument requirements were derived from the meteorological needs for nowcasting and short range forecasting in 2015 to 2020. A temporal update of 15 to 30 minutes is required and this implies that the instrument must be positioned in geostationary earth orbit. Temperature and humidity profiling in all weather conditions implies that the 53 GHz band and the 183 GHz bands must be included. For high altitude measurements, the 118 and 380 GHz bands have also been considered, see figure 1.

The requirement of a horizontal resolution of 30 km means that a 7 meter aperture is needed for the 53 GHz band and this is of course the biggest challenge of this project. Our solution is to apply interferometric techniques with arms carrying many small receivers that can be folded around the spacecraft during launch and then be deployed in orbit, see figure 2.

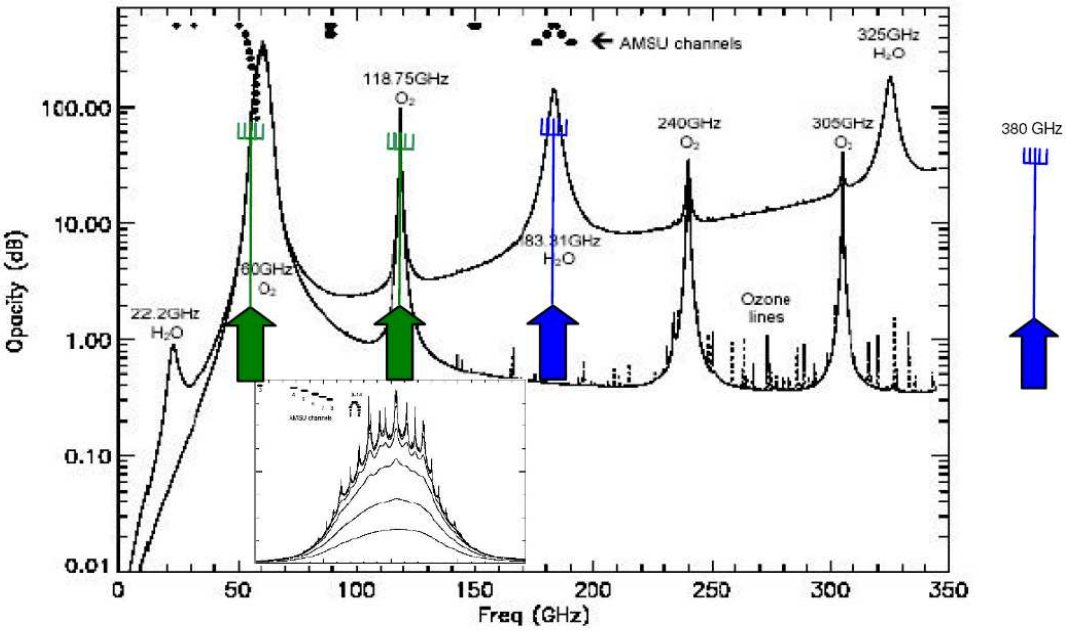

Figure 1: **Frequency bands considered are marked in green for oxygen lines and in blue for water vapour lines.**

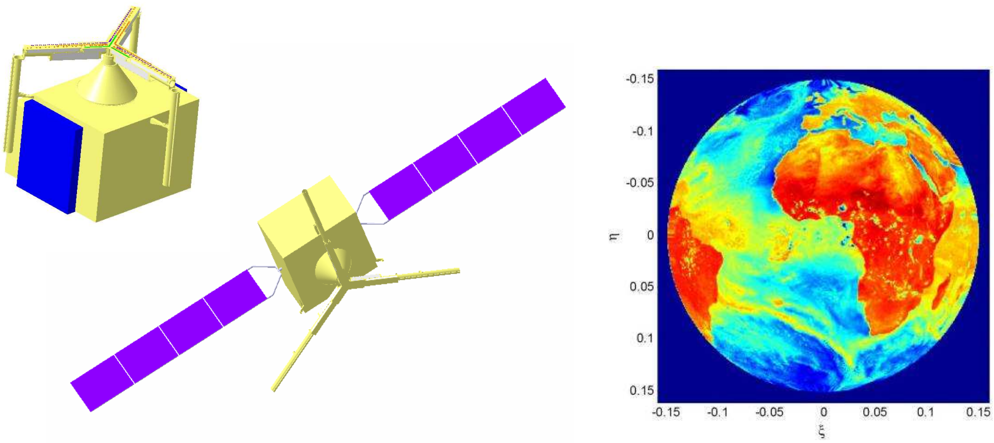

Figure 2: **The instrument in stowed and deployed configuration and a simulated image of the Earth.**

In addition, we propose to slowly rotate the interferometer around an earth pointing axis, which allows the elements to be sparsely distributed on longer arms instead of the densely packed arrays that are required for a stationary interferometer. Already after half a rotation cycle, achieved after 3 minutes, a dense grid of measurements is obtained that allows a high resolution image to be formed. The use of rotation with longer arms thus enables us to meet the requirement of 30 km resolution.

DEMONSTRATOR

The demonstrator consists of the central part of the Y-shape array (figure 3). It has 20 dual-polarised receivers that are connected to a central cross correlation unit and it is mounted on a rotational drive that provides a rotation of one degree per second. In comparison to the GEO instrument, the demonstrator contains only one frequency band, it has fewer elements, shorter arms, and thus coarser resolution, but otherwise it is a fully operational interferometer system.

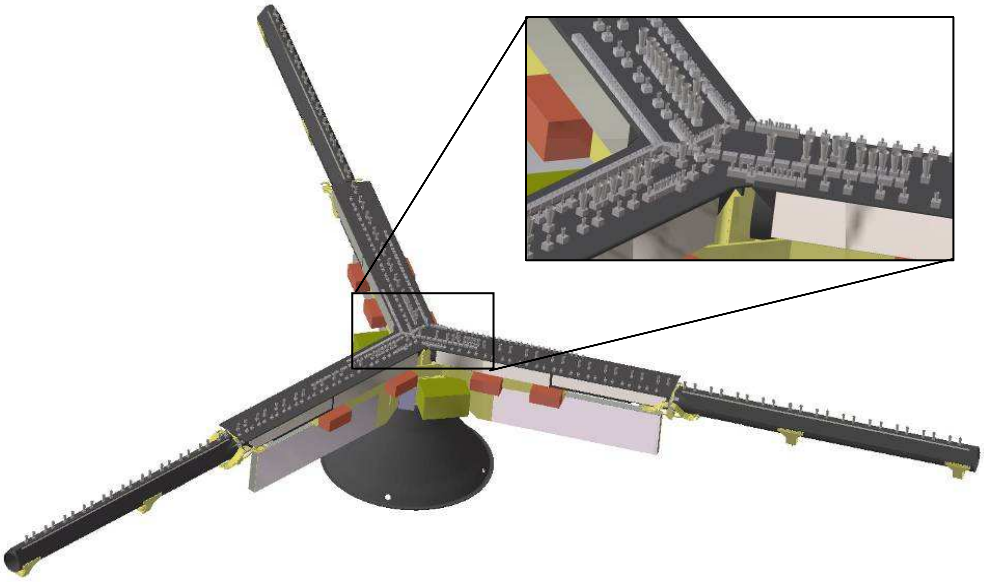

Figure 3: **The instrument and a blow-up of the central part.**

The demonstrator is shown in figure 4 below. The characteristics of the demonstrator are shown side by side with the corresponding GEO instrument parameters in table 1.

Figure 4: **The demonstrator with its 20 antenna elements and rotating structure.**

The layout of the receiver elements is sparse but contains a few densely positioned antennas in order to avoid ambiguities in the image, see figure 5. The sparseness of the array creates space in the centre such that arrays at other frequency bands, for example 183 GHz, can be easily interlaced. All distances between neighbouring elements are redundant, meaning that there are at least two of each distance, which allows relative calibration of phase and amplitude.

Parameter	Demonstrator	GEO instrument
Frequency band	49-53 GHz	50-56, 118, 183, 380 GHz
Number of elements	21	100-140 per band
Dual polarisation	Yes	Yes
Length of arms	0.4 m	3.7 m
Image Resolution	<10 mrad	<0.9 mrad (30 km)
Relative accuracy	< 2K	< 0.5K

Table 1: **Characteristics of the demonstrator in comparison to the GEO instrument.**

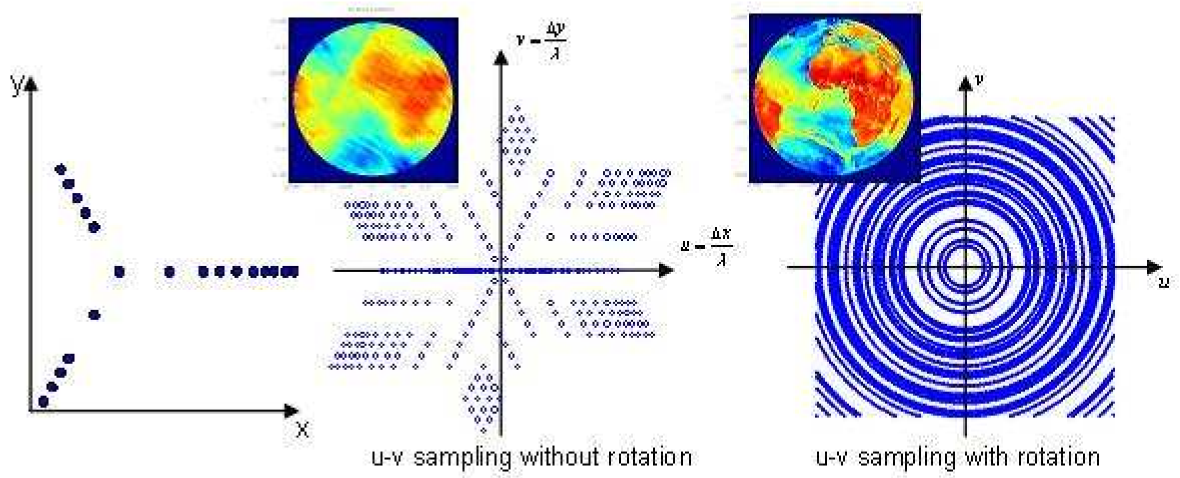

Figure 5: **The layout of the elements and the resulting visibility function sampling in the u-v plane.**

The visibility sampling grid without rotation is not dense enough to allow unambiguous image retrieval. However, when this grid is rotated it results in a very dense sampling that enables accurate imaging. The use of the rotation thus adds a degree of freedom to the design space such that spatial and temporal resolution can be traded against each other.

HARDWARE DESIGN

The demonstrator contains 20 dual-polarised horn antennas. The design is optimized for high gain and for high isolation between neighbouring antennas. The horn antenna couples electromagnetically to mictrostrip probes which are directly connected to an integrated circuit that contains amplification and down-conversion to a frequency band between 100 and 200 MHz. The compact front-end module shown in figure 6 thus contains a complete single side band 53 GHz receiver.

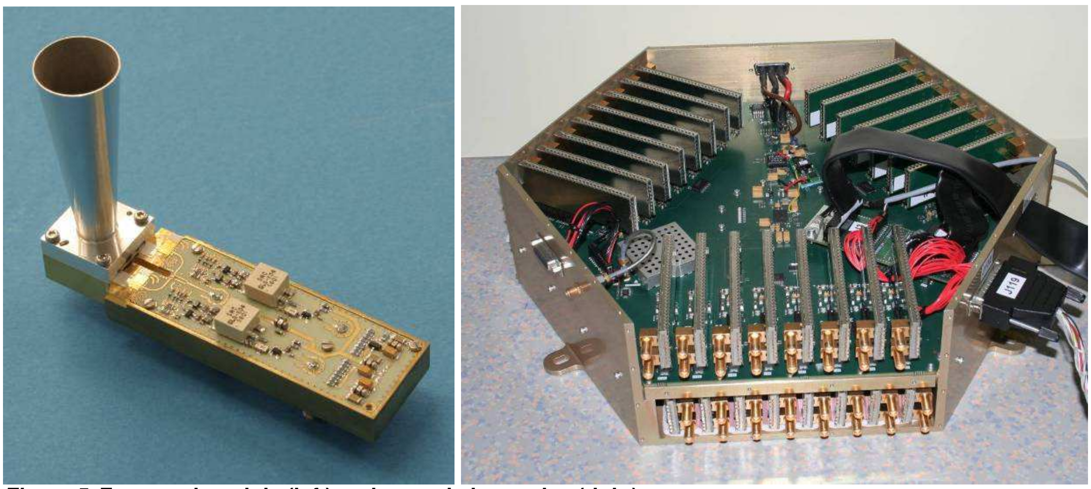

Figure 5: **Front-end module (left) and central electronics (right).**

TEST CAMPAIGN

The test campaign included both outdoor and indoor measurements. Measurements of the sun were used to demonstrate the capability to achieve high beam efficiency with low side lobe levels for point sources. A complete transition of the sun through the field-of-view was measured. A number of images are superimposed in figure 6.

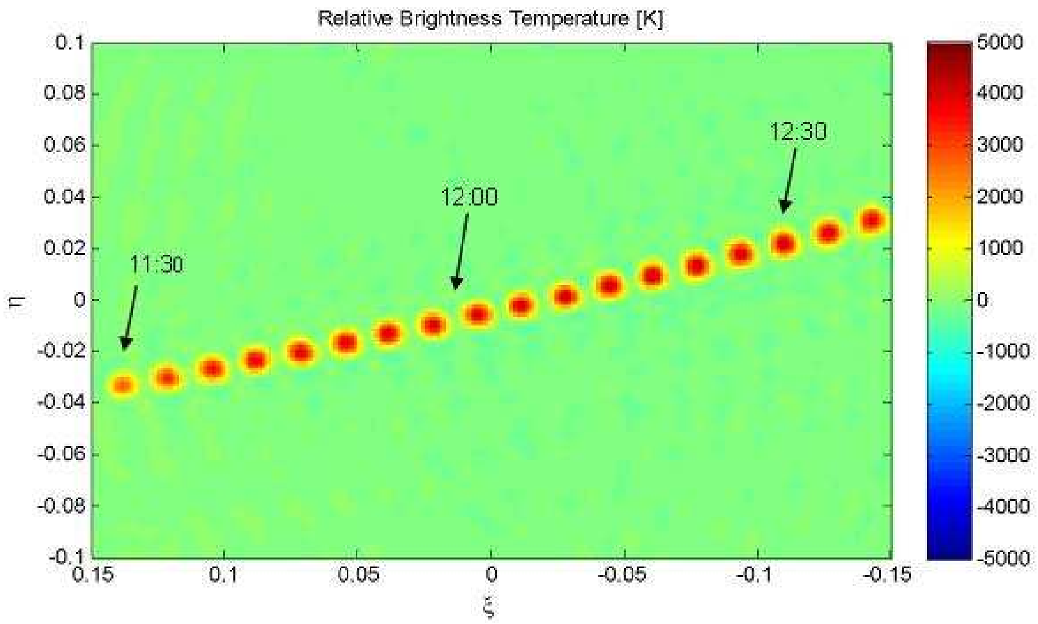

Figure 6: **Superimposed images of the sun at different times during transition through the field of view.**

As part of the outdoor tests, the demonstrator was pointed against the building shown in figure 7 and thirty minutes of data was recorded. The resulting image shows the sharp contours of the building against the sky background and also some window details. The image estimate is updated every second of processing and new measurements are assimilated as soon as they become available. The image in figure 7 shows the result after 30 minutes of data assimilation.

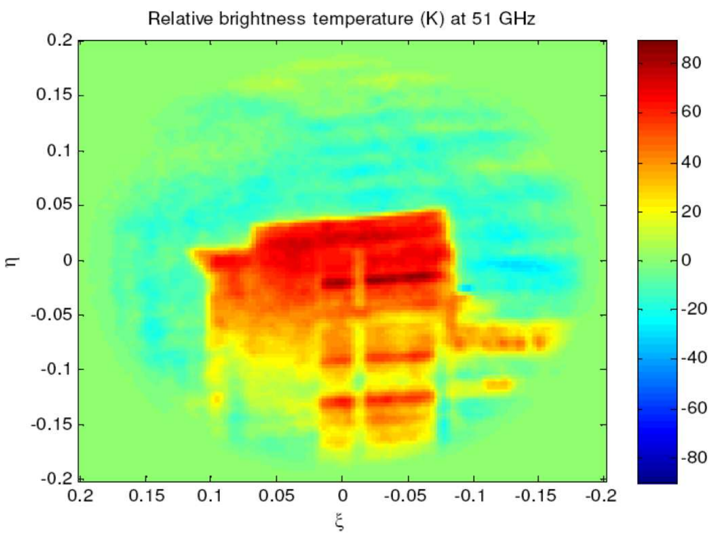

Figure 7: **Outdoor imaging of a building against a sky background.**

Two active point sources with linear polarisation were used to demonstrate image resolution and polarisation isolation. Both point sources were active during this measurement and images were generated for the two polarisation directions. The results agree very well with the expected performance with one point source visible in each image. The polarisation isolation is better than 20 dB and it was concluded that the visible co-polar sidelobes are due to reflections in the indoor test-range since they are not present in the outdoor images of the sun.

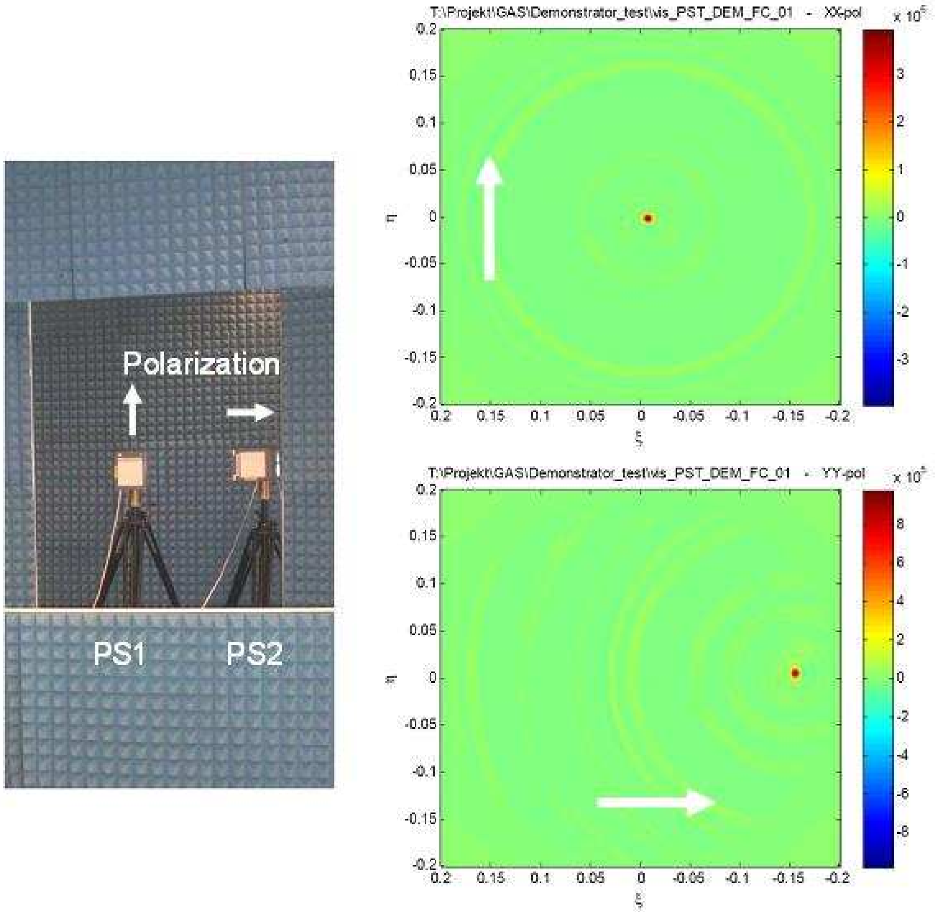

Figure 8: **Simultaneous imaging of two point sources with different polarisation directions.**

The brightness temperature linearity and stability across the image was demonstrated using a heated plate covered with absorber. The plate was heated to different temperature and it was also moved across the image, see figure 9.

The image noise level was calculated from the difference of two images of a stable scene, after thirty minutes of integration for each image. The measured noise level agrees well with our theoretical model with independently characterised parameters applied. The theory assumes a Gaussian distribution of visibility sample points, which is a quite rough approximation in this case, and this is the main reason for deviation between measurement and theory. The theoretical model is defined as:

$$\sigma_T(\theta) \approx \frac{4\pi}{G(\theta)\eta_c} \frac{T_{sys}\pi\rho_0^2}{\sqrt{2N_{corr}B\tau_{image}}} \qquad \textit{Equation (1)}$$

with parameters as defined in table 2 below.

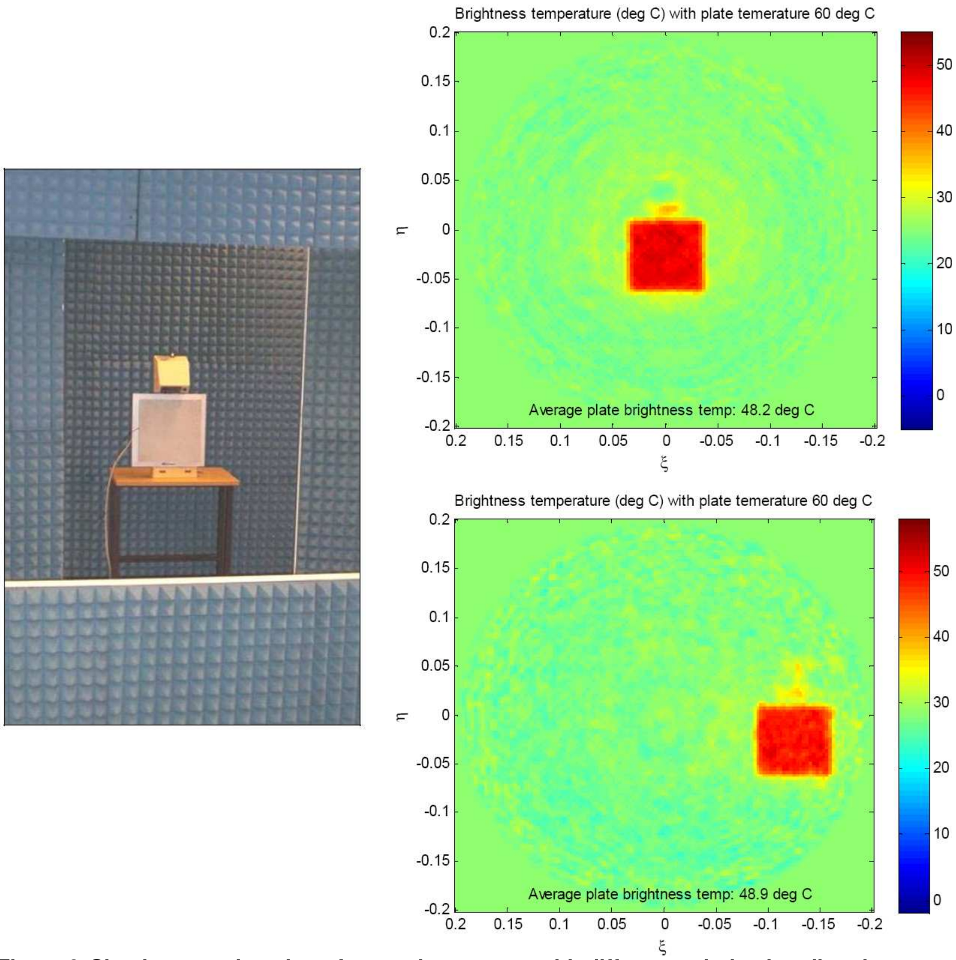

Figure 9: **Simultaneous imaging of two point sources with different polarisation directions.**

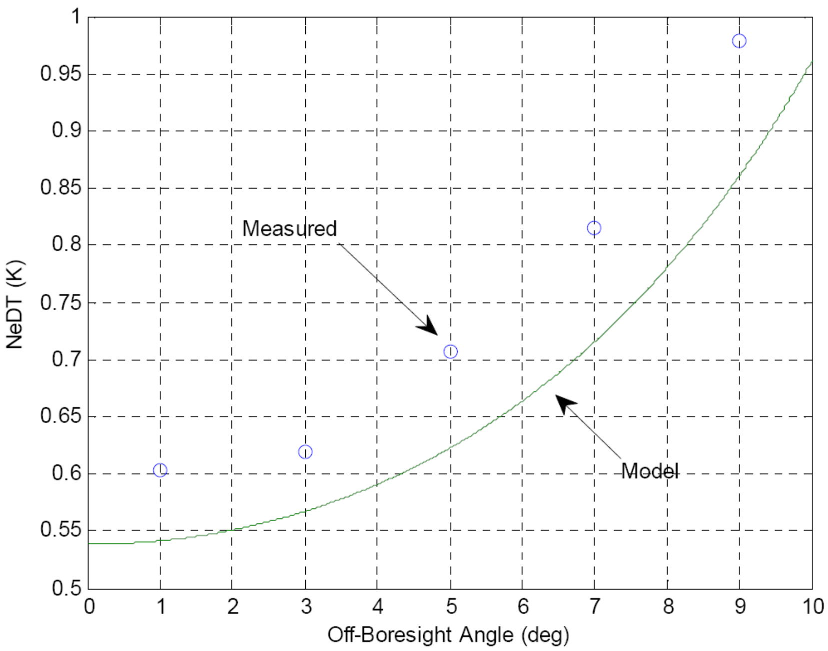

Figure 10: **Comparison of measured sensitivity and the theoretical model given in equation (1) with parameters as specified in table 2.**

Parameter	Value
Peak antenna gain	18.9 dBi
Antenna 3-dB beamwidth	21.8 deg
Correlation efficency, η	0.81
System noise temperature, $Tsys$	1800 K
Number of correlators, $Ncorr$	380
Bandwidth, B	95 MHz
Integration time, τ	1440 s

Table2: **Parameters and values used in equation (1) to obtain the result shown in figure 10.**

ACKNOWLEDGEMENT

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CONCLUSION

A novel GEO microwave imaging instrument concept has been developed and demonstrated. The concept enables optimization of the image resolution with a limited number of receiver elements by integration over time during rotation of a sparse interferometer array.

The demonstration campaign achieved to meet all success criteria that were defined at the start of the activity in terms of resolution, beam efficiency, brightness temperature accuracy, and polarisation isolation. These performance success criteria were:

- Image resolution: <10 mrad
- Image beam efficiency: >95%
- Relative accuracy of brightness temperature: <2K
- Image polarization isolation: >10 dB (goal: 20 dB)

This means that the concept is successfully demonstrated and we have also shown that the performance parameters can be accurately predicted with theoretical models.