GEOSTATIONARY ATMOSPHERIC SOUNDING BY FORMATION FLIGHT APERTURE SYNTHESIS

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***Abstract*—**

This paper introduces a multi-satellite approach to passive microwave interferometric radiometry applied to geostationary atmospheric sounding at 53 GHz. The concept applies satellite formation flight to the currently operational interferometric techniques to extend the achievable microwave aperture sizes, leading to unprecedented spatial resolution for microwave radiometers. The presented configurations are capable of synthesising 14.4 m aperture and larger using SMOS-sized satellites, and spatial resolution better than 16.7 km at 53 GHz from the geostationary orbit. Two instrument concepts are proposed: Single-Element Companion concept and Array Duplicate concept, both of which are scalable, where the achievable spatial resolution is extendible and constrained only by the number of satellites in the constellation. The performance of both concepts are simulated, and the results show that the interferometer is highly sensitive to uncertainties in inter-satellite position measurements, where measurement errors as small as 6 mm result in 6.3 K root mean square error in radiometric accuracy.

I. INTRODUCTION

While passive microwave sounders are highly versatile tool for meteorology and Earth observation, providing atmospheric temperature, humidity and precipitation measurements, their poor spatial resolution have bound these instruments to the low Earth orbit. In recent years the geostationary orbit has been in consideration as a desirable orbit for future atmospheric sounders, in order to achieve global and real-time observation. [1] Subsequently several interferometric techniques are currently being developed by NASA, ESA and China, with radiometer concepts GeoSTAR [2], GAS [3] and GIMS [4] respectively, that would for the first time enable radiometry from the geostationary orbit at 53 GHz for temperature sounding, and higher for humidity. Since these concepts are designed around a single satellite platform however, their achievable aperture size is fundamentally constrained by the satellite's physical size. To access any lower sounding frequencies, or to further improve the spatial resolution, we propose a multi-satellite approach to overcome this physical constraint. The proposed concept uses a set of interferometer antenna elements mounted on free-flying satellites. The signals from these elements are wirelessly transmitted to the relevant satellites where signal cross-correlation is performed. The concept's spatial resolution is determined by the longest inter-satellite separation distance, while the shape of the synthesised aperture is determined by the geometry of the constellation. The proposed formation geometries are capable of synthesising scalable, circular apertures for circular beams. These configurations and their performance are now described.

Comps	Aperture Diameter	Spatial Resolution	Mass
3	2.0 R = 8.0 m	30.1 km	868 kg
9	3.6 R = 14.4 m	16.7 km	1288 kg
18	5.0 R = 20.0 m	12.0 km	1918 kg
30	6.5 R = 26.2 m	9.2 km	2758 kg
45	8.0 R = 32.0 m	7.5 km	3808 kg

(a) Single-Element Companion

Sats	Aperture Diameter	Spatial Resolution	Mass
3	4.0 R = 16.0 m	15.0 km	1974 kg
6	7.2 R = 28.8 m	8.4 km	3948 kg
9	10.0 R = 40.0 m	6.0 km	5922 kg
12	13.1 R = 52.5 m	4.6 km	7896 kg
15	16.0 R = 64.0 m	3.8 km	9870 kg

(b) Array Duplicate

TABLE I: The scaling and system mass of the Single-Element Companion concept (a) and the Array Duplicate concept (b). The effective aperture with boom length R = 4 m on the central array. Total constellation mass is estimated with SMOS-sized central satellite at 658 kg and 70 kg companion microsatellites.

II. Multi-satellite Interferometry Concepts

Two suitable formation flight configurations are identified and contrasted for the radiometer concept, both synthesising circular apertures. The first type is the Single-Element Companion, where a single full-sized satellite is flown in formation with several “companion” satellites, while the second type is the Array Duplicate, where several full-sized satellites are flown in formation.

Figure 1a shows the nine-companion configuration of the Single-Element Companion concept, whereby a single rotating Y-shaped central array identical in dimensions to the MIRAS instrument on board the SMOS mission [5] is accompanied by nine single antenna elements each on board identical formation-flying companion satellites, labelled A to I. Because all correlation can be performed in the central satellite, the companion satellites can be as small as a microsatellite. The size of the existing MIRAS instrument has been chosen as a baseline in order to adhere to currently feasible satellite structures. This configuration produces a circular effective aperture 3.6 times the length of the booms on the Y-shaped central array, synthesising 14.4 m effective aperture at MIRAS 4 m design. The effective aperture of this concept is scalable, as summarised in Table Ia where effective aperture, spatial resolution and estimated total constellation mass are listed for a given number of companion satellites.

Figure 1b shows the six-satellite configuration of the Array Duplicate concept, where six identical rotating arrays the size of SMOS, labelled a to f, fly in formation to produce a larger aperture of 7.2 times the boom length. As with the Single-Element Companion concept, this concept is also scalable by increasing the number of satellites, as summarised in Table Ib.

The expected spatial resolution and radiometric accuracy has been simulated at 53 GHz centre frequency from the geostationary orbit. With configuration shown in Figure 1a spatial resolution of 16.7 km is achieved, while Figure 1b shows 8.3 km. With an input image of modified GOES13 imagery data (Figure 1c), shown in Figure 1d is the recovered image by the configuration shown in Figure 1a, showing radiometric accuracy of 0.1 K ignoring fringe-washing and hardware imperfections.

The results show that the proposed interferometer is highly sensitive to the uncertainties in the measurement of satellites’ relative position. The results are summarised in Table II with measurement errors of 0.1 λ and 1 λ for both concepts. These are found from simulation results as shown in Figure 1e, the retrieved brightness temperature error of the Single-Element Companion concept with 1 λ measurement error, approximately 6 mm at 53 GHz. It is found however that the cause of these errors is the uncertainty in measurement, and not the physical deviation of the relative positions. Figure 1f shows better radiometric accuracy levels at 3.5 λ deviation, approximately 2 cm at 53 GHz, when the deviation is measured without uncertainties.

III. Conclusion

Two viable formation configurations have been found and explored for geostationary atmospheric sounding. The first configuration is the Single-Element Companion concept with a SMOS-sized rotating Y-shaped interferometer flying in formation with several formation-flying microsatellites, with total constellation mass of under two tonnes, achieving spatial resolution of 16.7 km and better at 53 GHz, with apertures of 14.4 m and larger. The second concept is the Array Duplicate concept with several SMOS-sized satellites flying in formation. Spatial resolution of 8.3 km and better can be achieved, with apertures of 28.8 m and larger, while total constellation mass may exceed five tonnes.

The arrays have been found highly sensitive to the uncertainties in the inter-satellite relative position measurement, meaning inter-satellite ranging with micron-level precision and accuracy is instrumental for the geostationary mission. It is also found that inter-satellite position may deviate by a few centimetres while maintaining array performance, as long as this deviation is measured to the required precision and accuracy.

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	Deviation	**RMS Error**	
Nominal	0 λ	0.79 K	0.12 K
Concept 1	0.1 λ	1.78 K	1.45 K
	1 λ	7.01 K	6.32 K
Concept 2	0.1 λ	0.90 K	0.42 K
	1 λ	5.90 K	5.32 K
Concept 1	3.5 λ	2.87 K	0.95 K
Concept 2	3.5 λ	3.35 K	1.18 K

TABLE II: Results on simulation trials on retrieved brightness temperature error induced by inter-satellite position uncertainty as a function of uncertainty magnitude. The two error values given are within the full field of view, and within Earth disc respectively. Strong error present at horizon due to the Gibbs phenomenon. The last two rows show the errors at 3.5λ deviation which are measured without uncertainties.

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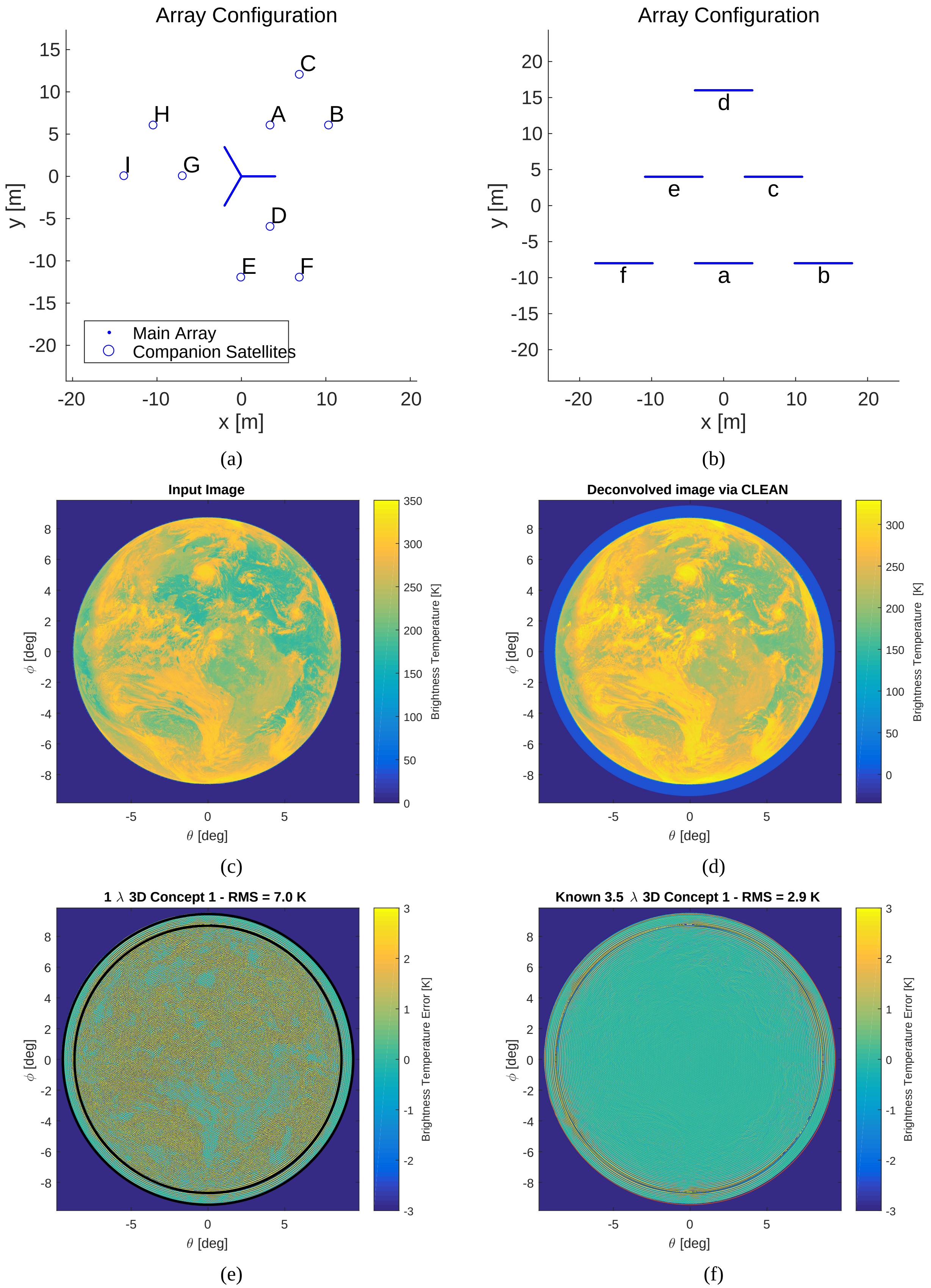

Fig. 1: Constellation layout for the Single-Element Companion concept where SMOS-sized central array flies in formation with nine microsatellites, labelled A to I (a). Array Duplicate concept where six SMOS-sized array fly in formation, labelled a to f (b). Input image of the Earth from GEO (c), the image reconstructed by the Single-Element Companion interferometer at 53 GHz (d). (e) shows the retrieved brightness temperature error when the inter-satellite position measurement is uncertain at one wavelength (6 mm at 53 GHz), and (f) shows the error when the deviation is large at 3.5 wavelengths, but is measured without uncertainty.