The STEAMR Instrument: Optical Design, Development & Testing

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***Abstract*—The STEAMR instrument is a Swedish national contribution to the ESA PREMIER mission, which is a candidate for the upcoming Earth Core Explorer mission. The STEAMR instrument is envisaged as a multi-beam limb sounding satellite, which will utilise 14 simultaneously observing beams in two 12 GHz wide bands from 323 to 357 GHz. To maximize spatial sampling in the elevation direction the observing beams have an elliptical geometry, which defines the incoming beams as being astigmatic. In this paper we present an antenna optics scheme which corrects for this inherent astigmatism, thereby ensuring optimum imaging of the incoming to the circularly symmetric receiver feed horns. Furthermore, the design, synthesis and electromagnetic verification of a prototype focal plane array for the STEAMR instrument is also reported.**

I. Introduction

The STEAMR instrument is a Swedish national contribution to the upcoming ESA PREMIER mission, which is a candidate for the Earth Core Explorer mission [1]. The aim of the PREMIER mission (Process Exploration through Measurement of Infrared and millimetre-wave Emitted Radiation) will be to advance current understanding of the processes that link trace gases, radiation and chemistry in the upper troposphere and lower stratosphere. The composition and dynamics of the atmosphere at this boundary have an important impact on chemical exchanges and the Earth's radiative balance.

The STEAMR instrument is envisaged as a passive multi-beam limb sounder which will observe over a nominal altitude range of 6-28 km and azimuthal range of 10 km in a push-broom beam pattern configuration - c.f. Fig. 1. In order to maximise spatial sampling the 14 observing beams are separated into two groups of seven, polarised at ±45°. The minimum beam sampling rate of the observing beams is approximately 18 dB in terms of amplitude radius. The elliptical geometry of the observing beams defines the incident beam patterns as astigmatic. Here we define astigmatic in terms of a skew Gaussian beam treatment, wherein the beams are treated with independently propagating Gaussian beam parameters in the orthogonal azimuth and elevation directions. Correction of this astigmatism is necessary in order to achieve optimum imaging between the primary reflector and the feed horns. Concurrent with this requirement for anastigmatic imaging is the requirement for maximal power throughput of the individual beams. This requirement necessitates the use of a focal plane array (FPA) unit, whose function is to intercept the individual beams at the output focal plane of the complete antenna optics.

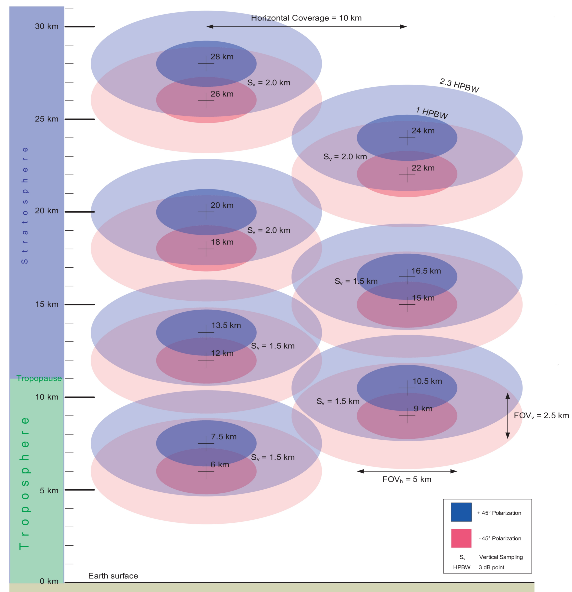

Fig. 1: Limb view geometry of the STEAMR antenna [1].

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II. Antenna Optics Scheme

The antenna optical scheme is treated in three distinct sections. The primary and secondary reflectors, M1 and M2, form an off-axis Ritchey-Chrétien telescope. This particular telescope design is chosen for its larger field of view over classical Cassegrain or Gregorian designs, thereby providing the best possible imaging requirements for the widely spread multiple observations beams [2]. The aperture of the M1 reflector is elliptical, thus defining the output beam pattern geometry. The observing requirements for STEAMR, as is typical in millimetre wave radiometer antennas, places a higher priority on beam efficiency over antenna pattern resolution [3], [4], and as such the edge taper of the primary aperture is 25 dB in terms of 1-D fundamental Gaussian beam illumination. The subsequent four relay reflectors, referred to as M3, M4, M5 and M6, comprise the beam forming network which is designed to correct the inherent beam astigmatism. This anastigmatic correction is achieved through treating the incoming beams as skew Gaussian, with independently evolving beam parameters in the azimuth and elevation directions such that

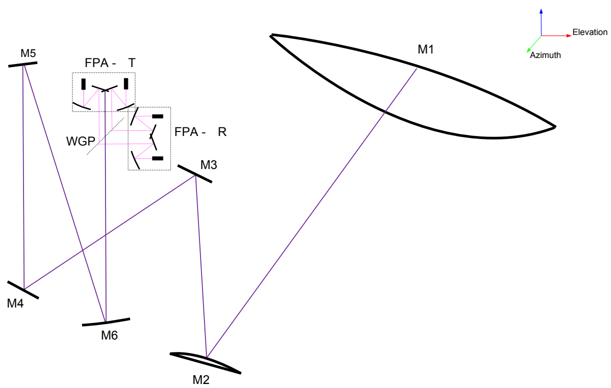


Fig. 2: Simplified ray-trace model of the STEAMR antenna optics, listing the component reflectors including FPAs, where the subscripts T and R refer to transmission and reflection through the wire grid polariser (WGP)

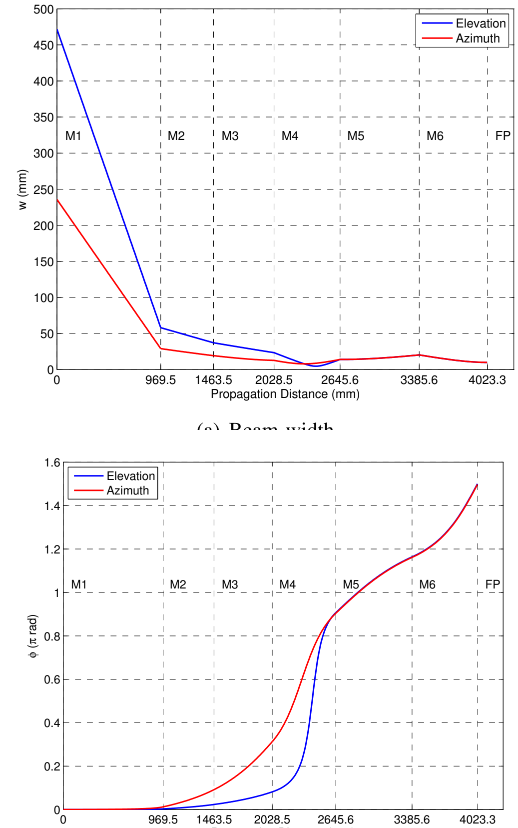
The anastigmatic imaging solution is then achieved through manipulation of the *ABCD* matrix description of the system. To provide the required degrees of freedom for this anastigmatic solution, the reflectors must be biconic, with independent lengths in the orthogonal azimuth and elevation plane order for the beams at the output focal plane of the an optics to maintain the maximum achievable mutual separ the output focal plane must be located at a phase sh $n + \pi/2$ radians with respect to the primary aperture matrix solution must also ensure a waist at both the c focal plane and the telescope aperture, with the ortho beam widths matched to the primary aperture rim in to provide the required edge taper for the two ortho directions.

As can be seen in Fig. 3 the combination of biconic r tors M3 and M4 produce the required matching of amp and phase shift at the plane of the M5 reflector, beyond the beams evolve equivalently for the two orthogonal tions, thereby forming a circularly symmetric, anastig beam. A complete description of this anastigmatic im solution is given in [5].

The physical interpretation of this imaging system rec the use of so-called astigmatic off-axis reflectors [6]. reflectors are a special case of biconic reflectors whose orthogonal geometries are defined as off-axis conics, with conic parameters defined in the standard manner for off-axis quasioptical reflectors. With this definition a complete model of the STEAMR antenna optics scheme has been implemented in the GRASP physical optics software package for numerical electromagnetic analysis.

III. Focal Plane Array

The STEAMR FPA, as shown in Fig. 2, is composed of two imaging arrays FPA-T and FPA-R, were T and R refer respectively to transmission and reflection at the wire grid polariser (WGP). The WGP separates the incident 14 beams into the two groups of seven. The optical path for each pixel in both arrays is equivalent, with the complete phase shift between the apertures of the primary reflector and the feed horns being 2π radians, thereby ensuring frequency independent coupling. This FPA has been developed on the heritage of two similar array units [7] and [8], which utilise monolithically machined facet reflector arrays to couple multiple beams at an antenna focal plane to their corresponding receiver elements. This type of reflector array has been selected for two chief reasons. Firstly, the output focal plane, being a Fourier transform of the antenna farfield, ensures that the beams experience their maximum mutual separation. However, to place feed horns



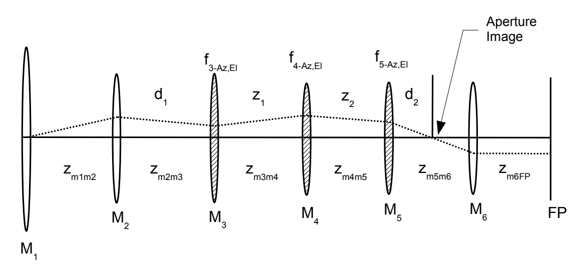
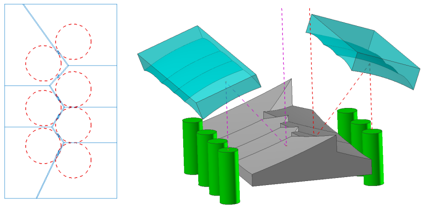


Fig. 4: Thin lens representation of the STEAMR antenna optics from the primary aperture (M1) through to the output focal plane (FP). The anastigmatic network, i.e. M3, M4 and M5 are shown as hatched filled lenses.



(a) (b)

Fig. 5: FPA M7 facet reflector geometry (a), showing individual beam footprints for the 18 dB radius at the central frequency (340 GHz). A 3D CAD model of the complete FPA optics is shown in (b).

directly at this plane is undesirable. The maximum separation between the beams is insufficient to allow for feed horns of the desired directivity to occupy the focal plane and would overlap. If lower gain feeds were located here, this would alter the edge taper on the primary aperture and subsequently the beam field of view. Furthermore, locating the feeds at this plane would imply frequency dependent coupling between the feed and primary reflector apertures.

The maximum mutual separation between the focal plane beams in terms of Gaussian beam amplitude is 18 dB determines the maximum reflector truncation - c.f. Fig. 5(a). This is significantly lower than is desired for such an optical system where optimal power throughput is required. Typical truncation for such a system would be of the order of 35 dB [9]. This truncation leads to both reduction in power throughput per beam and introduces losses through diffraction and scattering. These issues were alleviated in two ways. The geometry of the reflector facets has been optimised for maximum area per beam, resulting in the complex 'saw-tooth' structure shown in Fig. 5(b). The feed horns have also been optimised for highly centralised aperture field distribution and low side lobes [10]. A full treatment of the design, analysis and electromagnetic measurement of a breadboard model of the STEAMR FPA is given by [11] and [12].

A breadboard model of the FPA was synthesized in conjunction with industrial partners, which can be seen in Fig. 10. High density CMM measurements, shown in Fig. 6, revealed that conformance of the breadboard facet reflector to stringent tolerance requirements was very high, with a maximum measured surface roughness RMS of $0.294\mu m$.

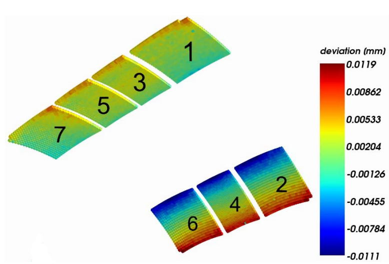


Fig. 6: Deviation distribution of the CMM measured FPA reflector surfaces from nominal surface for the facets of the FPA base plate.

IV. Electromagnetic Simulations

The complete STEAMR antenna optics model was numerically analysed using the antenna design software GRASP, with Physical Optics (PO) and Physical Theory of Diffraction (PTD) approximations being used for the major reflectors, and the Method of Moments (MoM) approximation to account for the complex geometries of the FPA reflectors [12]. From these data we can confidently draw conclusions of the performance of the antenna optics model.

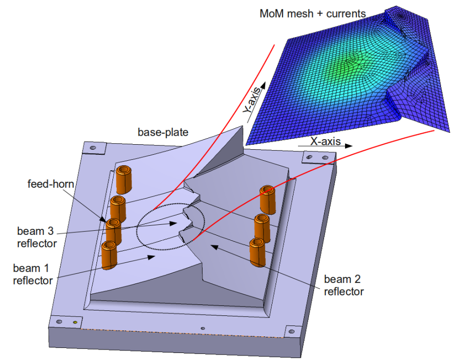
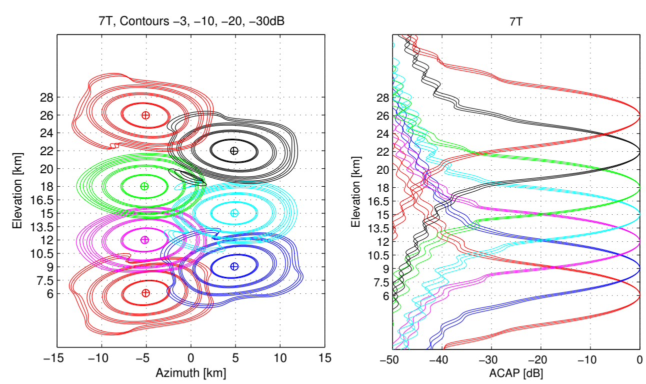


Fig. 7: CAD model of FPA baseplate, with example of MoM mesh and calculated current surface field.

Farfield beam pattern simulations reveal that overall the beams exhibit the desired elliptical patterns (Fig. 8(a)), with the outermost beams in the upper and lower ranges displaying a minor degree of rotation in the positive and negative elevation directions respectively, with the centrally located beams displaying the highest conformity with desired patterns in Fig. 1. Furthermore, at the -30 dB amplitude level there exist some asymmetrical sidelobes, once again for the beams at the extremities. Specific antenna performance requirements



(a) (b)

Fig. 8: Farfield contour plots for one set of seven beams from FPA-T, with contour levels spaced at -3, -10, -20 and -30 dB for frequencies 323, 340 and 357 GHz (a), and ACAPs for the same beams three contours per beam for frequencies 323, 340 and 357 GHz (b).

necessitate that the azimuthally collapsed antenna patterns (ACAPs) first sidelobe amplitudes be $\leq$-30 dB. The ACAPs are generated through numerically integrating the individual beams across the azimuth direction. ACAPs for the T beam set in Fig. 8(b) show that this requirement is fulfilled, with the R beam set performing equivalently. The full width half maximum (FWHM) requirement in elevation is $\leq$3 km, which is met by all beams. Beam pointing in the elevation direction is also critical for accurate observations, and the residual pointing offsets from the nominal values reveal good performance with maximum offsets of the order of < 100 m. Complete power throughput for all beams across the frequency band is $> 98\%$.

V. Beam Pattern Measurements

The farfield beam patterns of the FPA feed horns have been measured using a submillimetre optical test bench and compared with theoretical predictions - c.f. Fig. **??**. These measurements reveal strong agreement with predictions. Minor disparities in the cross-polar measurements are here attributed to measurement misalignment, with peak measured cross-polar amplitude being under -30 dB across the frequency band.

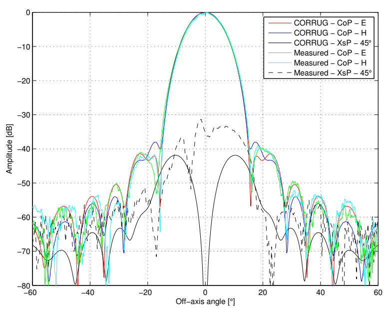


Fig. 9: Measured and simulated copolar and crosspolar amplitude patterns for the STEAMR FPA feed horn at 340 GHz.

A breadboard model of the STEAMR FPA has been synthesised and its optical performance quantified through near field beam pattern measurements. Comparisons between MoM simulations and beam pattern measurements for the three pixels with highest beam truncation reveal excellent performance of the FPA, with power coupling coefficients integrated between simulations and measurements being $> 98\%$ for all beams tested over the complete bandwidths [11].

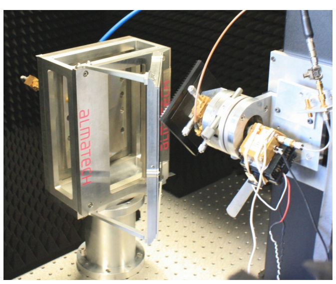
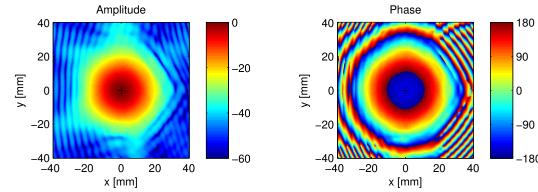
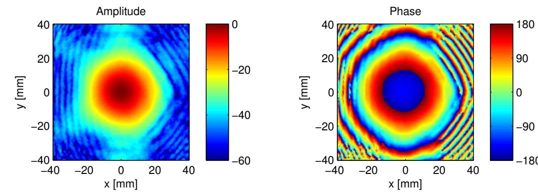


Fig. 10: Optical test bench for STEAMR FPA breadboard, showing arrangement for near field beam pattern measurement.



(a)



(b)

Fig. 11: Sample copolar amplitude and phase patterns for single FPA pixel from MoM simulations (a) and near field beam pattern measurements (b).

VI. Conclusions

A complete antenna optics scheme for the STEAMR instrument has been presented, whose optical performance meets the imaging requirements of the proposed instrument. The inherent astigmatism of the farfield beams has been corrected optically, thus ensuring optimum imaging. The design for a breadboard FPA, which couples the individual beams from the focal plane to the corresponding feed horns has also been presented as part of the complete optics scheme. This FPA has been synthesised and the results of electromagnetic testing have already shown excellent conformity with theoretical predictions. The complete antenna optics scheme has been modeled in the GRASP software package, and resultant simulations the observing beams conform well within predefined requirements for the antenna.

Acknowledgment

These research activities were supported by the Swiss National Science Foundation under Grant 200021-130517 and the ESA PRODEX project number C4000100544.

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