QUASI-OPTICAL FEED-SYSTEMS
IN MILLIMETRE-WAVE AND SUBMILLIMETRE-WAVE RADIOMETRY

R. S. Donnan(1), **D. H. Martin**(2) **and M. R. Rayner**(3)

(1) Queen Mary, University of London, Department of Electronic Engineering, Mile End Rd, E1 4NS, UK
E-mail: robert.donnan@elec.qmul.ac.uk
(2) As in (1) above, but E-mail:- D.H.Martin@qmul.ac.uk
(3) As in (1) above, but E-mail:- mark.Rayner@elec.qmul.ac.uk

ABSTRACT

Antenna-pattern specifications for radiometric applications of millimetre-waves are typically highly demanding. Of key concern in the design of quasi-optical feed-systems for such radiometers is the need to minimise beam aberration. Numerical/computational electromagnetic software, though ultimately useful for performance verification, is not effective in initial design and optimisation. The paper outlines the analytical approaches of Fourier and Beam-mode Optics to design and optimisation, and the development of design criteria for minimising aberrations. The presentation of the paper will include examples drawn from the design of radiometric systems for use in remote-sensing of the Earth's atmosphere.

MILLIMETRE-WAVE AND SUBMILLIMETRE-WAVE RADIOMETER SYSTEMS

There are now major applications for millimetre-wave and submillimetre-wave radiometry in astronomy and observational cosmology and, especially, in remote-sensing of the Earth's atmosphere and oceans for climatological and meteorological purposes, or for studies of stratospheric chemistry.

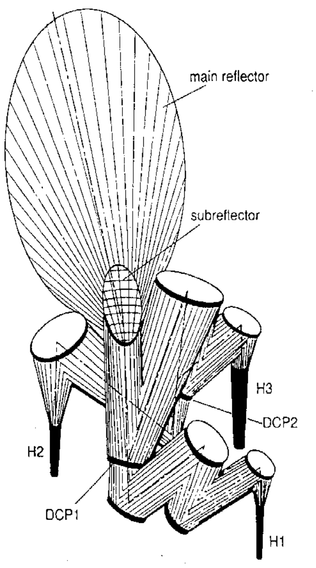
A measurement system of this type has a reflector-antenna that transforms the wide (high-gain) received signal-beams into beams of intermediate width (intermediate gain) that pass through a train of reflectors or lenses before being focussed into the low-gain waveguide-mounted feed-horns of the receivers. The beam-transport train provides an optical union between the steerable receive-antenna and the stationary receivers; if the receivers are at cryogenic temperatures the train provides an essential small-area optical link through the cryostat's thermal gradient. And in most such systems the beam-transport system will also be used to direct the signal beams through signal-conditioning components, for example, frequency-filters, frequency or polarisation multiplexers, local-oscillator diplexers, side-band separators, isolators or circulators.

These signal-conditioning components are optical in character - that is to say, the signal beams passing through them propagate in free-space, not in wave-guide - and they are planar in the sense that they are made up of plane metallic grids or gratings, or low-loss dielectric layers, in an appropriate sequence. They function well only if the signal-beams passing through them are sufficiently well-collimated. It is the role of the reflectors/lenses in the optical train to form and re-form the beams to this end, i.e. to correct the diffractive spreading of the beams that is an inescapable consequence of the modest electrical width of the beams in that part of the system. Such a "quasi-optical" network can have much wider bandwidth, and much lower throughput-loss, than an equivalent wave-guide network. Reflectors having quadratic surfaces (ellipsoids, hyperboloids or paraboloids) are to be preferred to dielectric lenses for the beam-forming components in high-performance systems since reflections at the surfaces of a lens will introduce beam distortions and loss of signal power.

The structures of such systems are clearly complex. The sketch of the AMSU-B radiometer [1] in Figure1 serves to illustrate that. Each of the many elements of the optical train of a radiometer (feedhorns, signal-conditioning components, and beam-reforming reflectors or lenses) will be involved in determining the form of the radiometer's antenna pattern. The specifications for the antenna pattern will usually be very demanding (requiring usually extremely high beam efficiency, and low throughput loss, over a wide frequency range, perhaps in each of the pixel-channels of an imaging system). To design a radiometer system of this kind therefore requires detailed understanding of electromagnetic propagation through complex structures.

Since the form of the antenna pattern of a radiometer is more simply determined by considering the system in transmission – reciprocity assures the identity of transmit and receive antenna patterns – the task is:

given the field over the aperture plane of a feed-horn, propagate the beam-field through the sequence of conic-section reflectors and planar components, through the main reflector-antenna, and into the far-field, to give the antenna pattern, maintaining throughout the full vector character of the beam fields.



AMSU-B [1] is a millimetre-wave radiometer, developed at BAe Space Systems for the UK Meteorological Office. It is currently operating on a NOAA satellite in sun-synchronous polar orbit. It is downward-looking and sweeps a swathe on the Earth, providing complete global coverage every 24 hours with 10km pixel diameter on the surface. The dual-reflector main antenna is followed by an optical demultiplexer that splits the incoming signals into three frequency bands, each transmitted to a receiver feed-horn. Two of the bands, at 89 and 150 GHz, are atmospheric windows, and the signals in these channels reveal near-surface conditions. The third band, 175 - 192 GHz, spans a pressure-broadened water-vapour line and measurements at six frequencies within this band serve to determine water-vapour concentrations at six vertical heights in the atmosphere.

The sketch illustrates the dual-reflector and optical demultiplexer of the AMSU-B radiometer. H1, H2, and H3 are the receiver feed-horns for the three frequency bands. DCP1 and DCP2 are dichroic plates that separate the bands. The optical trains include six off-axis ellipsoidal reflectors and two plane reflectors. (The lines joining the several components indicate the routes of the beams through the optical system but are not ray paths).

Fig. 1

There are numerical/computational software codes that can be addressed to such a task but they are not appropriate for designing a system as complex as this; they do not formulate design precepts and would be too demanding in computing time to facilitate optimisation. Procedures that are analytic in character are required for this. Once a system has been designed and optimised, there will come a point for using computational procedures for verification of performance characteristics, since details of the beam-fields might be more precisely maintained in that process than in analytic procedures that might involve a measure of approximation.

The design methods of classical optics are not applicable here. For one thing, at these wavelengths, the size of the optical train would be excessively large if each reflector in the train were in the far-field of the one before it. In fact reflectors have usually to be placed in the transition region between the near and far fields of the signal beams incident upon them. Also, apertures and stops will not usually be used to define the signal beams through the beam-transporting system since that would give rise to edge-diffraction which would seriously degrade beam-efficiencies; the signal beams will be formed by the receivers' feed-horns, and the diameters of the reflectors will be made sufficiently large for there to be a very low level of field amplitude at the rims (such diameters are usually feasible within the beam-transport and signal-conditioning system where the beam-widths there are not great).

BASE-LINE DESIGN: FOURIER OPTICS AND BEAM-MODE OPTICS

If a system is to reach demanding performance specifications (such as very high beam-efficiency, or low cross-talk between pixels in an imaging system) it will usually be necessary that the reflectors and signal-conditioning components be **non-aberrating**. A non-aberrating reflector increments the phase of the field of the emerging beam by an amount that varies quadratically with off-axis distance thus simulating the optical function of an ideal thin lens (phase increments having a dependence on off-axis distance of higher-order than quadratic would result in aberration of the reflected beam).

Ellipsoidal and hyperboloidal reflectors can be almost non-aberrating provided their dimensions are chosen appropriately with respect to those of the incident beam. This might seem unsurprising, given the geometry, for cases in which the reflector is in the far field of the incident beam. It can also be so when the reflector is in the near-to-far field transition region of the incident beam, however, and that is important because it implies that the dimensions required for low aberration need not be excessive. It is necessary that the dimensional bounds on reflectors and components that will ensure that aberrations are of negligible magnitude be well understood (see below).

If the value of the quadratic phase increment of a non-aberrating reflector is written ($\boldsymbol{kr^2/2f}$), the constant $\boldsymbol{f}$ is the "focal length" of the reflector. Similarly, a planar signal-conditioning component will be non-aberrating (with infinite focal length) if the division of complex amplitude into transmitted and reflected beams is uniform over the cross-section.

A system of non-aberrating components can be analysed by the methods of **Fourier Optics and Beam-mode Optics** [2], which are well suited to the task identified above:

> propagating the beam-field from the aperture plane of the feed-horn, through the sequence of conic-section reflectors and planar components, through the main reflector-antenna, and into the far-field, to determine the antenna pattern, maintaining throughout the full vector character of the beam fields.

The basic design precept provided by Fourier Optics is the fact that the field distribution in the back focal plane of a non-aberrating reflector is a Fourier transform of the field in its front focal plane. It follows, furthermore, that an afocal pair of reflectors, i.e. two reflectors in tandem separated by the sum of their focal lengths, will have the property that the field in the back focal plane of the second reflector is a *coherent image* of the field in the front focal plane of the first reflector, with magnification equal to the ratio of the focal lengths of the reflectors. This property is of special utility for beam-transport systems. It is independent of signal frequency (pertinent when large bandwidths are required). It means that an afocal pair in a beam-transport system will allow a free choice of beam widths for the signal-conditioning components and will deliver a field to the input of the main, high gain, antenna that has the same advantageous form as the field in the aperture of a receiver feed-horn.

To determine the field distributions at arbitrary planes in a beam-transport system **Beam-mode analysis** [2] is required. This provides a concise scheme, based on ABCD transfer matrices, for tracing the changing form of a beam as it propagates through a system. It is necessary to determine in particular the field distributions at reflectors and components in order to ensure that the diameters of the reflectors and components are large enough to avoid significant truncation of the beams.

MINIMISING ABERRATIONS

There is a further task to be undertaken in parallel with the analyses referred to above, namely quantification of the dimensional bounds on reflectors and components that will ensure that aberrations are of negligible magnitude. These bounds must be imposed on the design.

An ellipsoidal reflector (an off-axis portion of the inner surface of an ellipse of rotation, of major axis $2\boldsymbol{a}$ and interfocal distance $2\boldsymbol{c}$), has a focal length, $\boldsymbol{f}$, given by $(\boldsymbol{a}^2 - \boldsymbol{c}^2)/(1+\cos\alpha)$ where α is the angle between the axes of the incident and reflected beams. To uniquely determine $\boldsymbol{a}$ and $\boldsymbol{c}$ it is necessary to specify not only $\boldsymbol{f}$ and α but also the distance from the geometric focus of the ellipsoid to the centre of the reflector. If aberration is to be kept low, this distance must be set equal to the radius of curvature of the phase-fronts in the incident beam-modes at the reflector.

Analysis of the reflection of a fundamental Gaussian beam-mode incident on an ellipsoidal reflector having the geometrical parameters chosen in this way, shows [3] that the reflected beam is mainly a co-polar fundamental Gaussian beam-mode with an admixture of higher-order beam-modes, co- and cross-polar – i.e. aberration. Provided $(kw_m)^{-1}$ and (w_m/f) are both small, where w_m is the beam-width parameter at the reflector, the fraction of signal power carried by the aberration components is small, at the level of a few times $(1/8)(\tan^2\alpha/2)(w_m/f)^2$. For example, for $(w_m/f) = 1/4$ and $\alpha = \pi/2$, this loss is at the –20 dB level. Setting α to 20 degrees reduces this to the –30 dB level.

Aberrations can be assessed by analysis [3] or, as here, by physical optics computations, allowing a wide range of configurations to be examined (including off-centre beams such as those involved in imaging arrays). The cumulative aberration for two or more reflectors in tandem can also be determined in these ways. It is also necessary to ensure that aberrations at planar signal-conditioning components be sufficiently small; the presentation of the paper will illustrate that.

As an example of a physical optics computation of the aberration produced in an afocal pair of reflectors, Figure 2 shows the output field produced when a Gaussian beam-mode is incident on an afocal pair of ellipsoidal reflectors having focal lengths 50 and 177 mm, the beam-waist parameter of the incident beam is 3.22 mm (these values are appropriate to the afocal pair in the 183 GHz channel of AMSU-B [1]). The ellipsoid parameters chosen for the reflectors in this computation were such that the beam is turned through 90 degrees at each reflector. The beam-waist of the incident beam is in the front focal plane of the first reflector; the computed fields shown in the Figure 2 are the co-polar (2a) and cross-polar (2b) fields in the back focal plane of the second reflector.

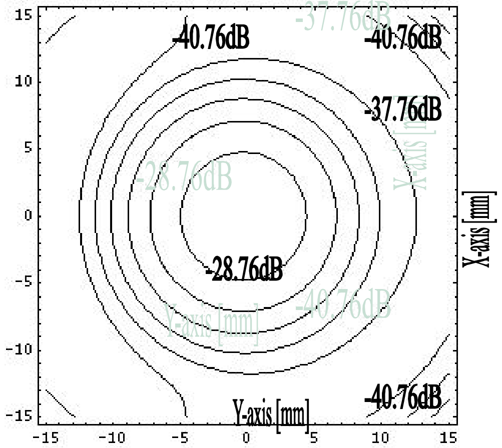


Fig. 2a: Co-polar field plot at the focal plane of Mirror 2

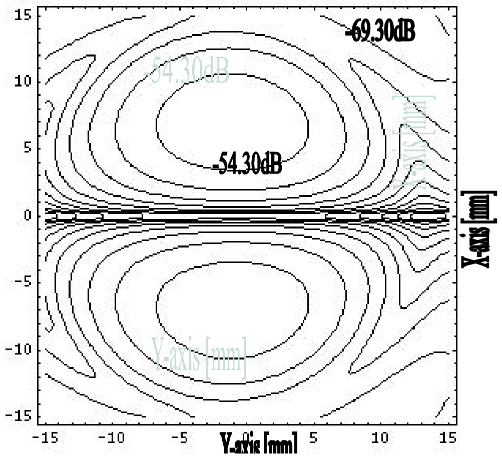


Fig. 2b: Cross-polar field plot at the focal plane of Mirror 2

The presentation of the paper will include illustrative examples of all the steps involved in the design and optimisation procedures described above. The final phase in performance verification applies diffracted

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