ANTENNA PERFORMANCE FOR A SYNTHETIC APERTURE MICROWAVE RADIOMETER IN GEOSYNCHRONOUS EARTH ORBIT

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ABSTRACT

Antenna array considerations are presented for an earth viewing microwave radiometer based on the radio astronomy technique of interferometric aperture synthesis. Measures of array performance are presented which can be incorporated into a numerical annealing process which searches for optimal antenna placements. A rotating ring of 48 small antennas is described which produces a high beam efficiency, low sidelobe antenna pattern with beamwidth ≅ 4 arc minutes. This antenna is capable of imaging the full earth disc from GEO with a 2 hours revisit time and a brightness temperature noise floor of ≤ 1.0 K. A similar quality phased array would require ≅ 123,000 elements.

INTRODUCTION

Traditional filled aperture antennas have been used exclusively by spaceborne microwave radiometers. Such antennas include horns, solid and mesh reflectors, and phased arrays. Maps of the brightness temperature measured by these radiometers are generated by steering the antenna beam either mechanically or electrically over the field of view of the resulting image. This approach has been used extensively in low earth orbit, but it presents several significant problems when applied to a geosynchronous system. The antenna size and mass required to produce useful images in the lower (1.4-37 GHz) microwave region are extremely significant. In addition, mechanically steering such a massive stucture across an image requires very large torques on the instrument platform and both electrical and mechanical steering allow very little time to dwell on each pixel in the image and increase the SNR to an acceptable level.

An alternative approach utilizes the aperture synthesis process by which radio astronomers have generated very large effective antennas by correlating an array of widely spaced antenna elements. An effective aperture is synthesized which is as large as the farthest spacing between elements in the sparse array of real antennas. The number of elements needed is greatly reduced below that of a conventional filled aperture phased array, thus reducing the required antenna size and mass. This aperture thinning reduces the available signal collecting area and, hence, reduces the image SNR. However aperture synthesis generates individual synthetic antenna beams simultaneously to each pixel in the image, thus increasing the available dwell time per pixel to compensate for the SNR reduction. In addition, this process is entirely electrical -there are no moving parts required for beam steering.

Extension of the radio astronomy heritage to an earth viewing system involves a number of significant issues which are discussed here. General array configurations are considered which can produce suitable synthetic antenna beams. The number and placement of antenna elements in the sparse array are examined. The performance of the synthetic antenna pattern is then computed, with particular attention paid to the resulting beam efficiency, which is a critical design parameter for an earth viewing microwave radiometer.

REVIEW OF APERTURE SYNTHESIS

Radio Astronomers have successfully used spatial interferometry to increase the resolution of their microwave radiometers for a number of years [Christiansen and Hogbom, 1985]. This technique involves the cross correlation of pairs of small antennas which are distributed in space. Each cross correlation samples a point on the visibility function, V(u,v), which is the Fourier transform of the brightness temperature distribution over the field of view of an individual antenna element (FOV). The relationship is described in an earth viewing coordinate system by:

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$$V(u,v) = \iint_{-\infty}^{\infty} T_B(x,y)\, e^{j2\pi(u\theta+v\phi)}\, dxdy \qquad (1)$$

where $u = Dx/\lambda$, $v = Dy/\lambda$, Dx and Dy are the relative coordinates of the antenna elements in the aperture plane, λ is the RF wavelength, $T_B(x,y)$ is the brightness temperature distribution to be imaged over the earth, $\theta = x/h$, $\phi = y/h$, and h is the altitude of the radiometer above the earth. This coordinate system is shown in figure 1. An inverse Fourier transform is then applied to the measurements, typically in software, to reconstruct the image. Each point in the inverse transform is equivalent to an independent antenna beam pointing at a particular spot in the FOV. All beams are present simultaneously provided the visibilty samples are made in parallel.

Measurements of the visibility function can be prescribed by the appropriate Nyquist sampling criteria [Papoulis, 1962]. The extent of the FOV determines the maximum allowable spacing between visibility samples and the maximum visibility sample determines the "low-pass filtering", or spatial resolution, of the image. In this context, undersampling will result in aliased responses in the image, which are analogous to grating lobes in the equivalent synthetic antenna pattern. Maximum visibility samples correspond to maximally separated antenna pairs. The resolution of an image is the same as would have resulted from a conventional antenna with an aperture diameter equal to that maximum separation. Most importantly, it is possible to satisfy the Nyquist criteria with a small number of small antennas distributed over a large region of space. The resulting imager is a Synthetic Aperture Interferometric Radiometer (SAIR).

SAIR PERFORMANCE MEASURES

SAIR performance can be measured in a number of ways. The angular resolution of the image is inversely proportional to the maximum number of wavelengths between pairs of antennas. The constant of proportionality varies with the Fourier transform window used, in a manner analogous to the tapered electric field distribution used on filled apertures. In both cases, the taper reduces sidelobes at the expense of resolution. The physical aperture required of a SAIR imager is determined by the efficiency with which the various pairs of antennas sample the visibility function. This performance measure is a key design parameter in SAIR systems analysis. The method by which visibility samples are made is another performance measure. "Snapshot" sampling implies that a complete sampling (complete in the sense of Nyquist) is possible by cross correlating all possible pairs of antennas instantaneously. Other sampling schemes could, for example, require relative motion between the antennas and the FOV. This is typically the sampling used in radio astronomy, which allows the earth's rotation to change the antenna spacings relative to a point in space. The beam efficiency of the synthesized antenna pattern is of particular importance in earth remote sensing applications. Beam efficiency is the percentage of power received by the antenna which originates in the main lobe of its pattern. The remainder of the power originates over the pattern's integrated sidelobes and is typically viewed as noise on each pixel in the image. When imaging the earth, the FOV away from a pixel is often radiometrically bright and this noise can be very significant.

GEOSYNCHRONOUS CONSIDERATIONS

The GEO environment provides unique design constraints on a SAIR antenna. In contrast to airborne or LEO applications, there is no relative motion between the FOV and the sensor. Relative motion suggests a hybrid imaging mode, with a real aperture in the direction of motion and a one dimensional synthetic aperture cross track [Ruf et al, 1988]. Without relative motion, a pure two dimensional aperture synthesis mode is more natural. Again because of the lack of relative motion, snapshot sampling of the visibility function is no longer necessary. The visibility function can be built up serially in time using a number of different sampling schemes. Typical science requirements call for image refresh times on the order of once per hour. The solid angle subtended by the earth from GEO specifies the maximum allowable spacing between samples of the visibilty function. This corresponds to spacings between closest pairs of antennas of approximately 2.8λ, as opposed to the standard half wavelength requirement for a full 2π steradian FOV. The individual array elements here would correspondingly have antenna main beams matched to the earth's solid angle. This is provided by array elements with real aperture diameters of 2.8λ.

The one dimensional hybrid imager mentioned above consists of a line of fan beam antenna elements, configured in a thinned array which satisfies Nyquist sampling of the one dimensional visibility function along the coincident main beams of the individual antenna elements. This configuration lends itself naturally to a two dimensional modification. The individual antenna elements can be replaced by smaller flood beam antennas with individual main beams covering the full earth solid angle. These antennas would be arranged in the same thinned linear configuration, and the line would rotate about its center. A complete image would result every half rotation. A SAIR imager of this type could image with 10 km resolution using only 70 individual elements. This is as opposed to a filled aperture phased array which would require 1,592,000 individual elements. However, a system level SNR analysis of this approach indicates that rotation rates below approximately 1 rev/day produce unacceptably noisey images. Thus, while diurnal variations could be mapped, shorter term changes would be undersampled.

SAIR RING ARRAYS

For image refresh time requirements approaching one hour, a sampling scheme based on the ring array [Cornwell, 1988] is a promising alternative. Flood beam antennas similar to those used in the rotating linear array are arranged on the perimeter of a ring. All possible pairs of antennas are cross correlated simultaneously. The diameter of the ring determines the spatial resolution of the image and the distribution of antennas around the ring determines the sampling characteristics. A schematic example of such an imager is shown in figure 2.

Cornwell describes a scheme for determining the positions of the antennas along the ring perimeter. It involves the optimization of some measure of the quality of a particular array configuration by a numerical annealing process [Kirkpatrick et al, 1983.]. Perturbations on the element locations in a given array are accepted if either the optimization measure improves or a variable random test is satisfied (regardless of the measure of the perturbed array). The random test is at first easier to pass, then becomes progressively less so as the optimization measure improves and as this iterative process progresses. Numerical annealing allows the system to escape from locally optimal measures and eventually settle at the global optimum.

The beam efficiency requirements on an earth viewing microwave radiometer (typically 90-95%) allow for very few gaps in the set of visibility function points sampled. These gaps tend to raise the sidelobe levels in the synthesized antenna pattern and, hence, reduce the beam efficiency. The ring arrays annealed by Cornwell are designed to maximize the distances between sample points in visibility space. This results in a sample space with many small gaps but few large regions without any samples. The gaps can be filled in by rotating the ring about its center. Only a small angular rotation is needed to completely sample the region of visibility space bounded by the correlation of diametrically opposite points on the ring.

A 48 element ring annealing was generated which attempted to optimize the rotation characteristic noted above. The annealing measure used was the angular rotation needed to fill in all gaps in the visibility sample space. This measure was minimized. Once the measure passed below 30°, however, the diameter of the ring was increased by 10% and the annealing continued. A 30° rotation was determined capable of allowing adequate SNR for a one hour image refresh time, and maximizing the ring diameter would also maximize the resolving power of the imager. The resulting array configuration is shown in figure 3. The synthetic antenna patterns provided by this array with a diameter of 122.5λ and using a quadratic radial aperture taper are shown in figures 4 and 5. Figure 4 shows the pattern without angular rotation, figure 5 with enough rotation to complete the visibility sampling. Note that the absence of visibility gaps has driven the far sidelobes down to the -70 dB level.

The efficiency with which angular rotation fills in visibility gaps is demonstrated in figure 6. The percentage of visibility samples which are missing is shown as a function of rotation angle for a family of ring diameters. Note that the largest portion of gap filling occurs very rapidly. Note, also, that a ring with approximately twice the diameter (i.e. twice the resolution) can still generate a 99% visibilty sampling within a 50° rotation and a ring with approximately four times the resolution samples 95% of the visibility function after the same 50° rotation. This new degree of freedom in SAIR system design tradeoffs -resolution vs. beam efficiency vs. image refresh time- is a significant area for future research.

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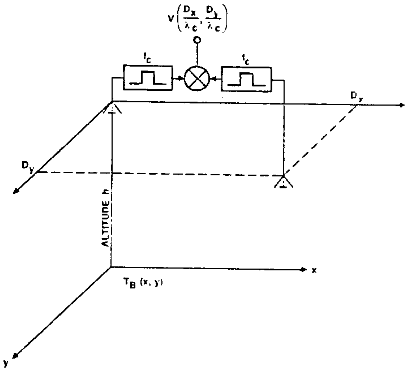

$$V\left(\frac{D_x}{\lambda},\frac{D_y}{\lambda}\right)=\iint_{-\infty}^{\infty} T_B(x,y)\,e^{j2\pi\left(\frac{D_x}{\lambda}\frac{x}{h}+\frac{D_y}{\lambda}\frac{y}{h}\right)}\,dxdy$$

Figure 1.

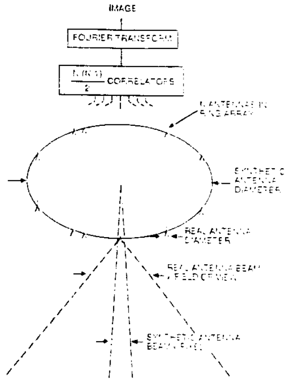

Figure 2.

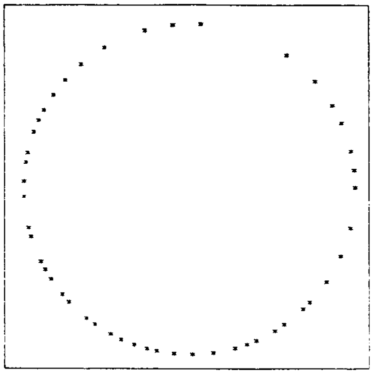

Figure 3.

UV-PLANE COVERAGE ANTENNA PATTERN

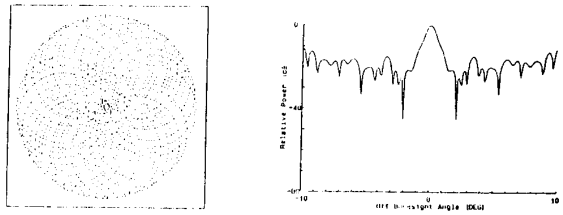

Figure 4.

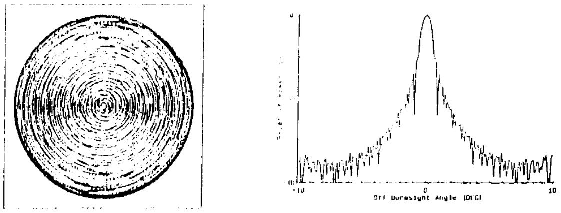

Figure 5.

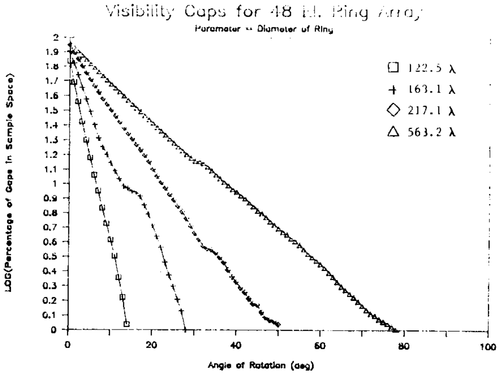

Figure 6.