SPARSE APERTURE INTERFEROMETRIC RADIOMETRY (SAIR) FOR THE REMOTE SENSING OF THE EARTH

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ABSTRACT

Traditional microwave radiometers generate images by steering a filled aperture antenna, either mechanically or electrically, across the field of view of the image. This procedure becomes increasingly impractical as spatial resolution requirements increase from low Earth and geosynchronous orbit. Spatial interferometry, as it has developed in radio astronomy, offers an attractive alternative. The physical antenna aperture can be significantly reduced without compromising its radiation pattern. Antenna beams pointing to all pixels in the image are generated simultaneously and in software. The design and performance results of a prototype airborne imager are presented, followed by some design considerations regarding a geosynchronous imager.

REVIEW OF TRADITIONAL FILLED APERTURE IMAGING

The most common antennas used with microwave radiometers are horns, reflectors, and phased arrays. For an imaging radiometer, the main lobe of the antenna pattern defines one pixel of the scene, and a complete image is generated by scanning the main lobe across the desired field of view (FOV). The spatial resolution of the resulting image is determined by the cross section, in wavelengths, of the antenna aperture.

Filled aperture imaging has been used successfully with radiometers in low earth orbit (LEO). However, its performance begins to degrade rapidly as the size of the antenna aperture is increased and the spatial resolution of the image is improved. Narrower antenna beams must be scanned slower in order to maintain adequate dwell time on each pixel in the image. For LEO applications, the forward motion of the satellite limits the available dwell time and a severe reduction in the FOV can result. For GEO applications, the result is a very long refresh time between new images. Another performance degradation involves the momentum generated by large moving structures in space. A mechanically steered microwave reflector in GEO, for example, may significantly compromise the pointing stability of other, e.g. optical and IR, sensors on the same platform. Possibly the most significant problem with filled aperture imagers is their physical size and mass. For example, a 6 GHz sea surface temperature imaging radiometer in GEO with 25 km resolution requires a 100 m antenna. A mesh or inflatable reflector technology is suggested, but even these approaches suffer the former drawbacks.

INTRODUCTION TO 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 in the visibility function, which is the Fourier transform of the brightness temperature distribution over the FOV. 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. The extent of the FOV determines the maximum allowable spacing between adjacent visibilty 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 filled aperture antenna with a cross section equal to that maximum separation. 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 Sparse Aperture Interferometric Radiometer (SAIR).

SAIR PERFORMANCE MEASURES

SAIR performance can be measured in a number of ways. The angular resolution of the image, in radians, is inversely proportional to the maximum number of wavelengths between pairs of antennas. The constant of proportionality varies with the transform window used, in a manner analogous to the aperture taper 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.

ELECTRONICALLY STEERED THINNED ARRAY RADIOMETER (ESTAR) PROTOTYPE

A one dimensional airborne prototype SAIR imager has been built and flown successfully. The sensor is described by Ruf, et al [1988] and a diagram is included here as Figure 1. This imager uses a minimum redundancy linear thinned array technique [Moffett, 1968] to sample the visibility function, hence its acronym, ESTAR. ESTAR operates at 1.4 GHz with a 30 MHz bandwidth for applications in soil moisture measurement. The thinned array consists of five line antennas with overlapping fan beam antenna patterns. The antennas are arranged in the thinned configuration described in Figure 1, and all ten possible pairs are cross correlated simultaneously. (An additional self correlation of one of the antennas provides the "zero'th" visibility sample.) ESTAR has had a number of shakedown flights on board a NASA P-3 aircraft out of Wallops Island, Virginia, USA during 1988. Initial imaging performance is very encouraging.

GEOSYNCHRONOUS SPARSE APERTURE CONSIDERATIONS

The GEO environment provides unique requirements for SAIR system designs. In contrast to airborne or LEO applications, there is no relative motion between the FOV and the sensor. This implies that a two dimensional aperture synthesis is appropriate. 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 2.8 wavelengths, as opposed to the standard half wavelength requirement for a full "two pi" steradian FOV.

The one dimensional ESTAR antenna configuration lends itself naturally to a two dimensional modification. The individual line antennas 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.

For refresh time requirements of less than one hour, rotating one dimensional imagers will typically produce images with inadequate signal-to-noise ratios because of the limited integration time available for each visibility sample. A sampling scheme based on the ring array [Cornwell, 1988] is an attractive alternative. Flood beam antennas similar to those used in the rotating linear array are arranged in 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. The antenna positions can be determined by a numerical annealing process which pseudo-randomly maximizes some measure of the ring's performance as a SAIR imager. Figure 2 describes the antenna locations in a 48 element annealed ring which can measure most, but not all, of the necessary visibility samples in snapshot mode. Figure 3 plots the resulting synthesized antenna pattern. The ring is assumed to have a diameter of 122.6 wavelengths, resulting in a HPBW of 0.3 degrees, and a quadratic radial aperture taper has been used. If this ring is allowed to rotate for 35 degrees, the missing visibility samples can be measured, resulting in the antenna pattern shown in Figure 4. This annealing process is a significant area for further research with two dimensional SAIR imagers.

ACKNOWLEDGEMENTS

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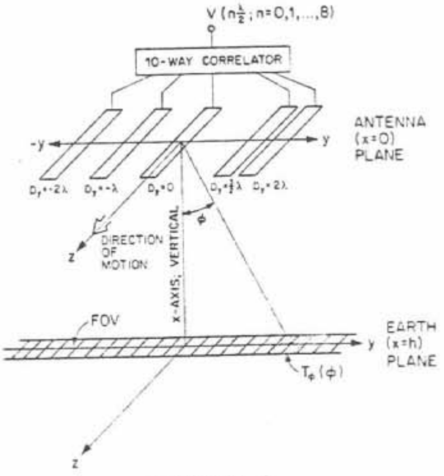

FIGURE 1

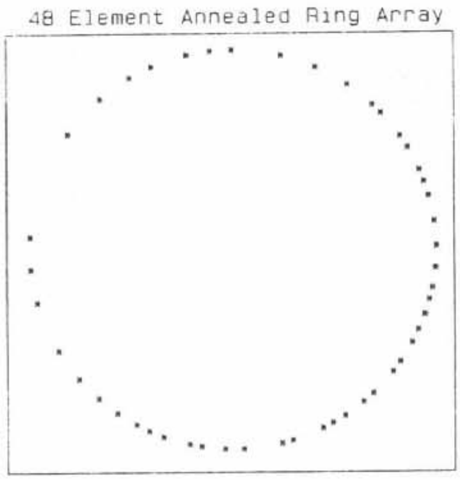

FIGURE 2

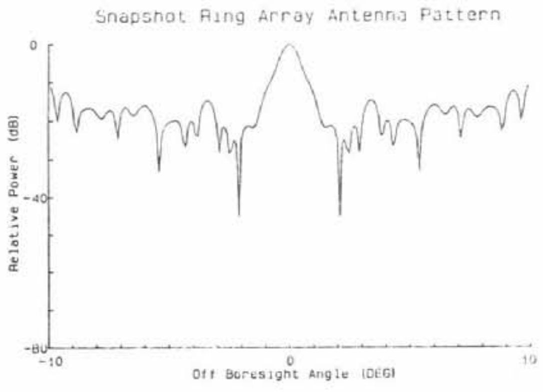

FIGURE 3

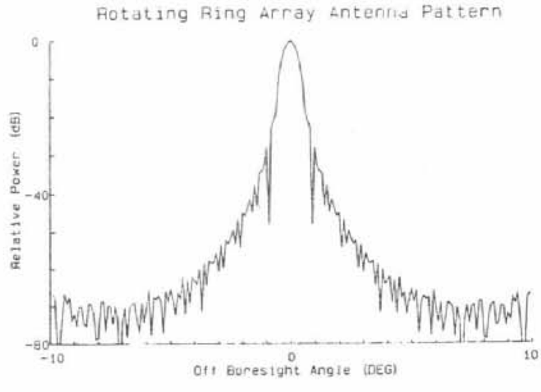

FIGURE 4