TERRESTRIAL SENSING WITH SYNTHETIC APERTURE RADIOMETERS

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ABSTRACT

Aperture synthesis concepts have been used for many years in Radio Astronomy to achieve high image resolution at a reasonable cost. The time is approaching for earth remote sensing technology to borrow some of these techniques to meet the cost challenges of large antennas in space.

INTRODUCTION

The concept of aperture synthesis was advanced in the field of radio astronomy. The intent of the radio astronomy community has been to achieve the finest resolving power with an array antenna that uses a relatively small number of individual elements. The strategy of this technique is to achieve the best resolution for a fixed amount of dollars available. A prime example is the Very Large Array (1) which uses a "Y" configuration of elements to achieve the resolution of a filled array whose diameter is equal to the maximum linear dimension of the "Y". Because of phase fidelity offered by microwave components, antenna complexity can be transformed to signal processing complexity to obtain resolution which would not otherwise be achieved. Indeed, radio telescopes utilizing aperture synthesis and Very Long Baseline interferometry rival and even exceed resolution achieved by some of the best earth-based optical telescopes.

Space-based microwave observations for applications to earth science is a much younger discipline than is radio astronomy. As more geophysical users are getting accustomed to satellite data, a demand is developing for both better spatial resolution and for the addition of frequencies as low as 1.4 GHz. Both of these demands now place the technologist in the same quandary that radio astronomers were faced with 40 years ago; large, mechanically scanned filled apertures are just too costly to place into orbit. The ground rules for earth observations are; however, somewhat different than those for radio astronomy. The spacecraft moves along at 6.5 km/s, so that processing must be done more rapidly. The earth is an extended source, whereas astronomical sources are embedded in a cold cosmic background which influences signal-to-noise ratios and sampling density. These and other issues have been addressed over the past four years, and have resulted in the development of an airborne demonstration instrument called the Electronically Scanned Thinned Array Radiometer, or the ESTAR. Some of this work was done in collaboration with Carl A. Wiley before he passed away.

BACKGROUND

The interferometer comprised of two antenna elements spaced a distance d apart is the basic building block of the aperture synthesis technique. If the outputs of the two isotropic antenna elements are multiplied together, it can be shown (see (2), for example) that the equivalent measurement is described by the following formula:

$$V = \int_{1}^{1} T_B(x) exp[-j(2\pi d/\lambda)x]dx \qquad (1)$$

where λ is the electromagnetic wavelength and d is the spacing between elements. We have chosen to call this expression V to conform with the nomenclature ("visibility" function) that is commonly used in the radio astronomy literature. If we sequentially measure the visibility function for $O < d < D$, then V can be defined as the Fourier transform of the thermal emission, or brightness temperature T_B of the scene. The scene can then be reconstructed by performing the Fourier inverse. The resolution of the measurement is then determined by the total baseline D, and not the dimension of the antenna elements. Furthermore, only discrete samples with d equal to an integer half wavelength are required for perfect reconstruction with spatial resolution determined by D.

Unfortunately, such a scheme is not practical from low earth orbit because the forward motion of the spacecraft limits the time on target. A practical system will require simultaneous sampling of all integer half wavelengths distributed over the baseline. This dilemma has led to the concept of thinned array radiometry as proposed by Moffett (3). The objective is to appropriately distribute a small number of elements over a baseline, perform power divisions of each output, and then perform the cross-correlations to generate the complete set of visibility functions.

THE AIRCRAFT ESTAR

In order to demonstrate the utility of a thinned array radiometer for earth observations, an airborne L-Band prototype was constructed at the University of Massachusetts, and flown several times on a NASA P-3 aircraft. A conceptual diagram is shown in Figure 1. The system uses five "stick" antennas consisting of a linear array of 8 dipoles, which behaves as a 64 element filled array that projects a total of 8 beams in the synthesized direction. This is a hybrid system that respectively utilizes a "real" aperture along the aircraft direction of motion, and "synthetic" aperture in the cross-track direction. An image of the scene is therefore developed by means of a pushbroom scan. The performance ΔT of this particular configuration has been studied in some depth, and is given by the following formula for a hybrid system composed of N elements, and r_n redundant half-wavelength spacings:

$$\Delta T = T_{sys}\left(\frac{\Sigma_{n=o}^{n} 1/r_n}{B\tau}\right)^{1/2} \qquad (2)$$

where T_{sys} is the system noise temperature, B is the system Bandwidth, and τ is the post-detection integration time.

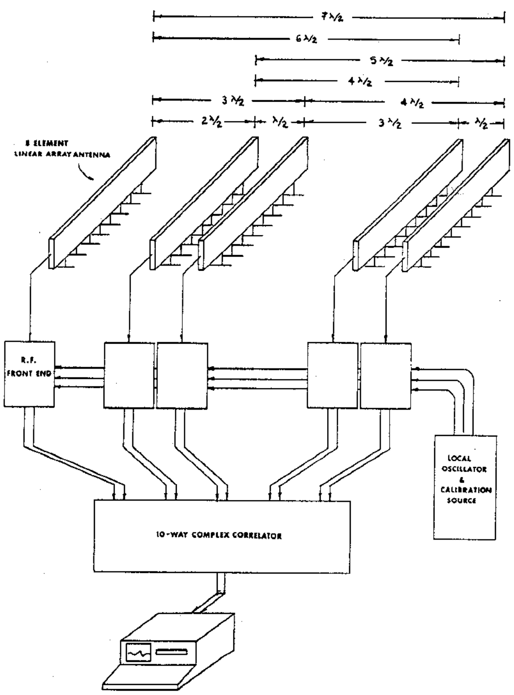

Fig. 1 Block diagram of the ESTAR system.

The system parameters are such that the 5 element ESTAR constructed at the University of Massachusetts achieves a theoretical ΔT of better that 0.5K, which is more than adequate for its prime application of measuring soil moisture.

The ESTAR was first test flown in June 1988 on a P-3 aircraft flown out of Wallops Island, VA. This first test flight was a mapping mission designed to determine whether or not aperture synthesis concepts would actually work when applied to earth observations. To this end, lines were flown from the Atlantic Ocean, over the Virginia eastern shore, and over the Chesapeake Bay. The purpose was to achieve a wide dynamic range of brightness temperatures to discriminate land from water, and then to detect more subtle changes associated with variations in soil moisture over the eastern shore. The flight was highly successful, considering the limited objectives of the mission. The L-Band brightness map has recently been published (4), which clearly indicates a response to soil moisture in addition to detection of land-water boundaries. Subsequent analyses have also indicated that the ESTAR responds to more subtle signatures associated with differences in the emissivity of ocean and bay water due to differences in salinity.

FUTURE DEVELOPMENTS

The present ESTAR performs brightness temperature measurements to within 50% of the ΔT calculated from the theoretical value. The present limitation is not due to noise, but rather processing errors associated with inverting the visibility functions. These problems can be traced to limitations in the antenna, which tend to scramble the received polarization components. Work is underway to develop a new antenna array which will have better linear polarization characteristics. In the meantime, the sensor has participated in several field campaigns with the understanding that the system has its limitations.

Parallel with this activity, we are developing the next generation airborne sensor. The new system will use seven slotted waveguide stick antennas that are 75% longer, and it will take advantage of a new chip to perform the correlations in a much more straightforward manner. Only two additional receivers will be added, yet the number of usable beams and swath will be doubled. Further down the line, some system studies are being done by the NASA Jet Propulsion Laboratory for future spacecraft applications. The objective will be to collect soil moisture data over a 90 degree swath with a spatial resolution of 10 km.

<u>References:</u>

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