Aperture Synthesis Concepts in Microwave Remote Sensing of the Earth

Calvin T. Swift, *Fellow, IEEE*, David M. LeVine, *Senior Member, IEEE*, and Christopher S. Ruf, *Member, IEEE*

***Abstract*—Aperture synthesis concepts have been used for many years in radio astronomy to achieve high image resolution at a reasonable cost. The time has come for earth remote sensing technology to consider some of these techniques to meet the cost challenges of large antennas in space for these and other applications. The electronically scanned thinned array radiometer is put forward as a viable alternative to improve spatial resolution by an order of magnitude over what is presently achieved by microwave imaging systems that are collecting data from earth orbit.**

Introduction

THE CONCEPT of aperture synthesis was advanced in the field of radio astronomy as a means to achieve the finest resolving power with an antenna array that uses a relatively small number of individual elements. The intent 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 that of the circle that encloses 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. The first meaningful microwave observations of the earth surface were not obtained until the electronically scanned microwave radiometer (ESMR) was launched on NIMBUS 5 in 1972. The ESMR operated at a single frequency (19.3 GHz) and utilized a phased array to scan cross-track about nadir to produce an image of the earth below it as the spacecraft advanced in orbit. Although its usefulness was somewhat limited across the board in geophysical applications due to the single frequency and the gross spatial resolution (50 km), the ESMR was soon used operationally by the Navy and Coast Guard to monitor the extent of sea ice in the north polar regions. Although much finer resolution is desirable, the fact is that only microwave satellite systems can provide an economical means to monitor the polar regions because of cloud cover, darkness, and the harsh environment. The ESMR was superseded by the scanning multichannel microwave radiometer (SMMR) and the special sensor microwave/imager (SSM/I). The SMMR was launched on both SeaSat I and NIMBUS 7 in 1978 and the SSM/I followed in 1987. Both of these radiometer systems added dual polarization and multiple frequencies and provided more usable data to a diverse science community. The SMMR spanned 6.6 GHz to 37 GHz, and SSM/I spanned 19 GHz to 85 GHz. For both instruments, the spatial resolution was of the same order as ESMR; i.e., the aperture size has remained fixed for the last 20 years. Although larger spacecraft antennas are technically feasible, the fact remains that the actual antennas used have not been greater than one meter in diameter.

As more geophysical users are getting accustomed to passive microwave 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 a similar 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 requirements. These and other issues have been addressed over the past four years, and has resulted in preliminary spacecraft studies and 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.

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C. T. Swift is with the Electrical and Computer Engineering Department, University of Massachusetts, Amherst, MA 01003.

D. M. Le Vine is with NASA Goddard Space Flight Center, Greenbelt, MD 20771.

C. S. Ruf is with the Jet Propulsion Laboratory, Microwave Observational Systems Section, Pasadena, CA 91109.

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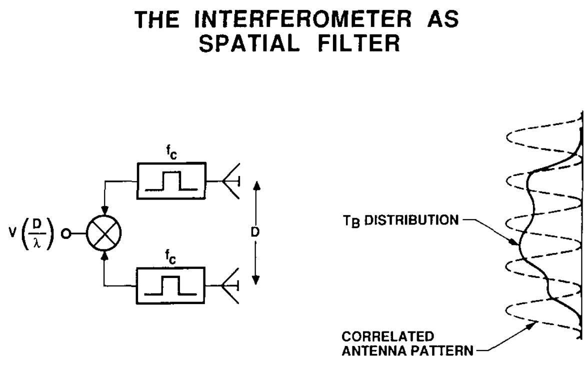

Fig. 1. Conceptual diagram of a two element imaging microwave interferometer.

Background

The interferometer shown in Fig. 1 is the basic building block of the aperture synthesis technique developed for earth observations. 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:

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

where λ is the electromagnetic wavelength θ is the incidence angle 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 $0<d<D$, then V can be defined as the Fourier transform of the thermal emission, or brightness temperature 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 integer half wavelengths are required for perfect reconstruction of the scene 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. The 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. An example is shown in Fig. 2. In this example, five elements are doing the work of eight. Although the savings are trivial in this case, we will show by illustration that the thinning geometrically increases as the size of the array increases. This is a desirable characteristic, since antennas become more expensive as the electrical size increases.

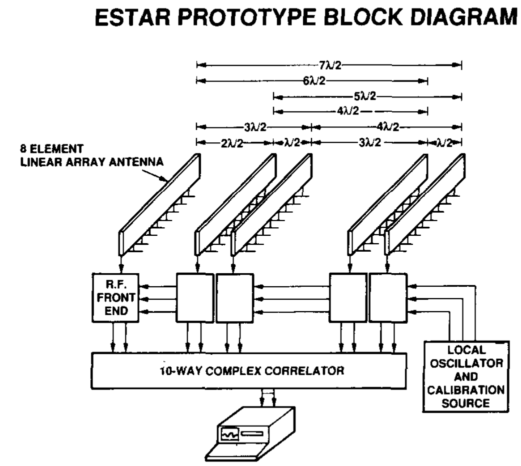

Fig. 2. Example of thinned array antenna with five elements performing as a filled array of light elements.

The thinned array concept offers interesting cost benefit trade-offs. We have already indicated that one trade-off is the exchange of antenna complexity for system complexity. In the example cited, five receivers and fifteen correlations are utilized to image the scene. This particular trade-off option of thinned arrays has become attractive as a result of advances that have occurred over the past several years in microwave and computer technology. However we should note that the system complexity is considerable as the array thinning becomes more significant. The other trade-off relates to signal-to-noise considerations. The figure of merit of a single total power radiometer is determined by ΔT, the measurement standard deviation, as given by the following formula:

$$\Delta T=\frac{T_{sys}}{\sqrt{B\tau}} \qquad (2)$$

where T_{sys} is the system noise temperature, B is the system bandwidth, and τ is the post-detection integration time. Because of the type of processing used in aperture synthesis, The ΔT of the thinned array additionally depends upon the size of the array and the degree of thinning, which generally leads to a significant degradation over what can be achieved with a total power radiometer in a "stare" mode. Such a trade-off is discussed in [4].

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 Fig. 3. The system uses five "stick" antennas consisting of a linear array of eight dipoles, which behaves as a 64 element filled array that projects a number of beams in the synthe-

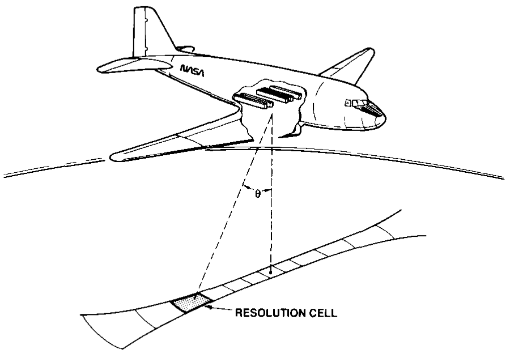

Fig. 3. Configuration of five element array used for the aircraft prototype instruments.

sized 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 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 with r_n redundant visibility measurements [5]:

$$\Delta T = T_{sys}\left(\frac{\sum_{n=1}^{N} 1/r_n}{B\tau}\right)^{1/2} \tag{3}$$

where T_{sys} is the system noise temperature, B is the predetection bandwidth, and τ is the post detection integration time. The system parameters are such that the 5 element ESTAR constructed at the University of Massachusetts achieves a theoretical ΔT of better than 0.5 K, 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 map has recently been published [6], 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 aircraft ESTAR has a measured ΔT of 0.53 K, compared with a theoretical value of 0.32 K. The present limitation is not noise performance, but rather processing errors associated with inverting the visibility functions. These problems can be partially traced to limitations in the antenna performance, which tends 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 compaigns 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 measurements could be made using an array of stick antennas, similar to the design of the aircraft prototypes, but operating at three frequencies; namely, 1.4 GHz, 2.65 GHz, and 5.0 GHz. The L-band frequency would provide the primary channel for determining soil moisture, with the S-band and C-band frequencies providing ancillary information to provide corrections for effects due to the vegetation canopy and possibly to estimate soil moisture profile. Over water, the L- and S-band channels together provide an estimate of ocean salinity [7], [8] with the C-band channel providing ancillary information, such as sea surface temperature and surface wind speed.

A preliminary study indicates that an orbit at 450 km would provide coverage of better than 95% of the earth every three days. A 10 km resolution cell at nadir will require stick antennas approximately 9.5 m long at L-band. The S- and C-band sticks would be proportionately shorter because of the higher operating frequencies. An instrument which can meet the measurement requirements is illustrated in Fig. 4. This particular radiometer concept consists of an array of slotted waveguide stick antennas approximately 45 wavelengths long. The sticks are oriented so that their long axis is parallel to the direction of motion; i.e., along-track. As in the aircraft ESTAR, the antennas themselves provide the specified resolution along-track, and aperture synthesis is used to "manufacture" resolution in the cross-track dimension. If the cross-track resolution were to be achieved using a conventional phased array antenna, approximately 100 individual sticks would be necessary at each frequency, and it would be difficult to accommodate such a large amount of mass within the shroud of a Delta-II class of launch vehicles. However, if aperture synthesis is used, only 14 sticks are required for each channel, and adequate empty space is available within the L-band array to nest in the higher frequencies.

ESTAR IN LEO

FIRST CUT INSTRUMENT DESIGN

OVERVIEW:

- **THREE CHANNELS (1.41, 2.65, 5.00 GHz)**
- **14 SLOTTED WAVEGUIDE ANTENNA ELEMENTS PER CHANNEL**
- **APERTURE SIZE = 44.8λ x 44.8λ AT ALL FREQUENCIES**

ANTENNA ARRAY ELEMENTS:

FREQUENCY (GHz)	1.41	2.65	5.00
LENGTH (cm)	950.8	505.9	268.1
CROSS SECTION		STANDARD WAVEGUIDE	
WEIGHT* (kg/ELEMENT)	6.6	1.5	0.5

*** PRELIMINARY BASED ON EXISTING GRAPHITE/EPOXY COMPOSITE DESIGN**

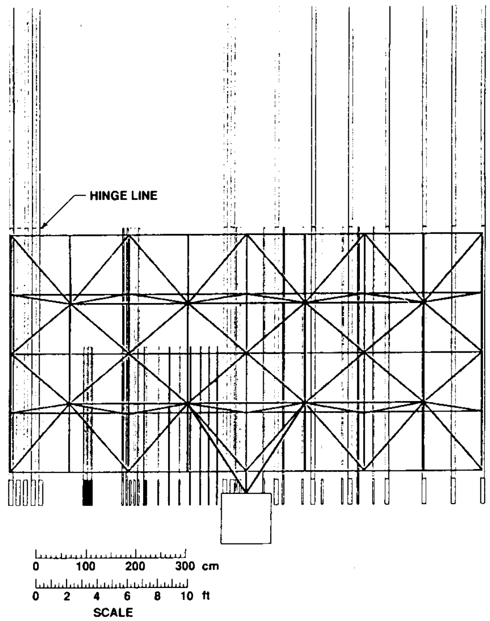

Fig. 4. Thinned array configuration for spacecraft applications.

In the proposed instrument, the sticks would be made of standard waveguide and the entire structure would be folded, accordion style, to fit into the shroud of a Delta-II class launch vehicle. The shroud could accommodate all the sticks without folds except at L-band, and these would have to be folded once near their midpoint (indicated by the hinge line, Fig. 4). The deployment and support structure is composed of tubular truss similar to structures which have been successfully designed in the past. Assuming existing composite graphite/epoxy designs, each waveguide element would weigh about 6.6 kg (L-band) and 1.5 kg (S-band) and 0.5 kg (C-band) for a total of about 525 kg for the antenna. Estimates of the total weight of the instrument, supporting structure and spacecraft are well below the capacity of a Delta-II class launch vehicle.

Such an array would provide resolution at nadir of about 10 km. Assuming an integration time of 1 s, a bandwidth of 10 MHz and a system noise temperature of 500 K, one would achieve a sensitivity of better than 1 K, which is adequate for the soil moisture measurement. The sensitivity needed for the salinity measurement (about 0.25 K) could be obtained by averaging over adjacent pixels. This will reduce resolution but this is acceptable over the oceans. Reducing the resolution to 50 km permits averaging over 25 pixels and will yield a sensitivity of $1/\sqrt{25} = 0.2$ K.

Acknowledgment

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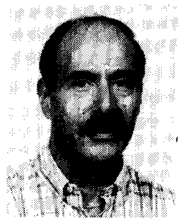
Calvin T. Swift (M'67–SM'69–F'83) was born in Prince William County, VA. He received the S.B. degree from the Massachusetts Institute of Technology, Cambridge, in 1959, the M.S. degree from Virginia Polytechnic Institute, Blacksburg, in 1965, and the Ph.D. degree from the College of William and Mary, Williamsburg, VA, in 1969.

He was employed as a Research Engineer by North American Aviation (now Rockwell International), Downey, CA, from 1959–1962 where he worked on a variety of defense and space-related problems. In 1962 he was employed by NASA Langley Research Center, Hampton, VA, where he initially conducted research on plasma-covered antennas. After 1970, he was involved in microwave remote sensing of the Earth, and assumed leadership responsibility of a microwave radiometer group at Langley. While at Langley, he held part time teaching appointments with local universities, and was the organizer of a short course sponsored by the George Washington University, Washington, D.C.. Since 1981, he has been Professor of Electrical and Computer Engineering at the University of Massachusetts, Amherst.

Dr. Swift is Chairman of U.S. Commission F (Radio and Non-Ionized Media) of the International Union of Radio Science (URSI). He served the IEEE Antennas and Propagation Society (AP-S) as Technical Program Chairman of the International AP-S/URSI Symposium held in Williamsburg in 1972, and was twice elected a member of the AP-S Administrative Committee (AdCom); serving as Meetings Chairman, Secretary-Treasurer, Membership Chairman and Chairman of Long Range Planning. He was twice elected to the Administrative Committee of the IEEE Geoscience and Remote Sensing Society (GRS-S) and was president of the Society in 1985. He was Vice-Chairman of U.S. Commission F of URSI prior to his election to chairman. He has served as a Reviewer for many journals and was Guest Editor for the AP-S/JOE (*Journal of Oceanic Engineering*) Special Joint Issue on Radio Oceanography. He is a past Editor of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING and a former Associate Editor of JOE. In 1984, he was awarded a Contennial medal from the IEEE. He has published in the areas of antennas, wave propagation, plasmas, and microwave remote sensing.



David M. Le Vine (M'70–SM'79) received the B.S. and M.S. degrees in electrical engineering, the M.S. degree in physics, and the Ph.D. degree in electrical engineering, all from the University of Michigan, Ann Arbor, in 1963, 1965, 1966, and 1968, respectively.

He has been employed as an Electronics Engineer at the Harry Diamond Laboratory, Department of the Army and as a Research Engineer at the Radiation Laboratory, University of Michigan. He left the University of Michigan to become Assistant Professor in the Department of Electrical Engineering at the University of Maryland. He is currently a member of the Microwave Sensors Branch at NASA's Goddard Space Flight Center where his research has focused on the development of techniques for microwave sensing of the environment from space.

Dr. Le Vine is a member of the International Union of Radio Science (URSI, Commissions B, E and F), the American Geophysical Union and the Institute of Electrical and Electronics Engineers (IEEE). In IEEE he is affiliated with the Antennas and Propagation Society and the Geoscience and Remote Sensing Society. He was President of the local (Washington, D.C.) section of the Antennas and Propagation Society. He currently serves as a visitor for ABET. Dr. Le Vine has been elected to Eta Kappa Nu, Tau Beta Pi, and Phi Kappa Phi. He was a University of Michigan Fellow and NASA/ASEE Faculty Fellow, and is the recipient of several service awards from the Goddard Space Flight Center.

Christopher S. Ruf (S'85–M'87) received the B.A. degree in physics from Reed College, Portland OR, in 1982 and the Ph.D. degree in electrical and computer engineering from the University of Massachusetts, Amherst in 1987.

He worked as a Research Assistant for the Microwave Remote Sensing Laboratory at UMass from 1983 to 1987, involved with microwave radar and radiometer instrumentation and geophysical parameter retrieval. He continued at UMass during 1987–1988 as a Visiting Professor and Research Engineer. He is currently a member of the Technical Staff at the Jet Propulsion Laboratory, Pasadena, CA in the Microwave Observational Systems Section. He is involved with the TOPEX/Poseidon Microwave Radiometer program as instrument scientist, science verification system team leader, and algorithm development team member. His other research activities involve synthetic aperture microwave radiometry, remote sensing of atmospheric water vapor, and design studies for the Geosynchronous Microwave Precipitation Radiometer.

Dr. Ruf is Associate Editor of *Radio Science* and is a member of the American Geophysical Union.