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Passive Measurement and Interpretation of Polarized Microwave Brightness Temperatures

A.J. Gasiewski (principal investigator)
D.B. Kunkee (graduate student)
J.R. Piepmeier (graduate student)

Covering the period from

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Submitted by:

Professor Albin J. Gasiewski
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332-0250
(404) 894-2934 (O) (404) 853-9171 (F)
ag14@prism.gatech.edu

NASA Technical Officers:

Dr. Donna Blake
Code YS
NASA Headquarters
Washington, D.C. 20546
(202) 554-6472 (O)
(202) 554-6499 (F)

Dr. Ramesh Kakar
Code EET, B200
NASA Headquarters
Washington, D.C. 20546
(202) 358-0274 (O)
(202) 358-2771 (F)

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INTRODUCTION

The goal of this project is to develop satellite-based observational techniques for measuring both oceanic and atmospheric variables using passive polarimetric radiometry. Polarimetric radiometry offers a potential alternative to radar scatterometry in observing global ocean surface wind direction from satellites. Polarimetric radiometry might also provide a means of detecting cell-top ice in convective storms by virtue of the polarizing properties of oriented ice particles, and thus facilitate estimation of the phase of the storm.

The project focuses on the development of polarimetric microwave radiometers using digital cross-correlators for obtaining precise measurements of all four Stokes' parameters. As part of the project a unique four-band polarimetric imaging radiometer, the Polar Scanning Radiometer (PSR), is being designed for use on the NASA DC-8 aircraft. In addition to providing an aircraft-based demonstration of digital correlation technology the PSR will significantly enhance the microwave imaging capability of the existing suite of DC-8 instruments. During the first grant year excellent progress has been made in the following areas: (1) demonstrating digital correlation radiometry, (2) fabricating aircraft-qualified correlators for use in the PSR, and (3) modeling observed SSM/I brightness signatures of ocean wind direction.

The development of the PSR is supported both by this project's grant (NAGW-4191) and a grant from the U.S. Office of Naval Research (ONR grant # N00014-95-1-0426). Specific tasks funded under NASA support are related to the development of the PSR digital correlator hardware, the integration of an 89-GHz radiometer into the PSR, and the modeling and analysis of polarimetric microwave imagery over the ocean. Other PSR-related including most major hardware development tasks, are funded by the ONR.

SUMMARY OF ACTIVITIES

Activities sponsored by this grant at Georgia Tech during the period from August 1, 1994 through July 31, 1995 include (1) the demonstration of a prototype digital correlator for passive polarimetric radiometry, (2) the development of aircraft-qualified digital correlator hardware for in-flight demonstration of polarimetric radiometry on the Polar Scanning Radiometer (PSR), and (3) the development of a new *non-stationary* ocean surface model for the prediction of upwelling polarimetric brightness temperatures.

A. Digital Correlator Development

Several hardware techniques have been demonstrated for measuring the third and fourth Stokes' parameters (e.g., [Dzura et al., 1992; Swift and Helvisi, 1994; Johnson et al., 1993]). In each of these techniques a correlation of the orthogonally-polarized field components received by a dual-linearly polarized antenna is performed. Two classes exist: adding correlators and multiplying correlators. In the adding correlator the orthogonally-polarized signals are added then detected using a square-law detector. That is, if v_A and v_B are complex signals for antenna polarizations A and B, then the detector output is proportional to $|v_A+v_B|^2$. The correlation signal, which is the cross term in the squared-sum, is obtained by subtracting independent measurements of $|v_A|^2$ and $|v_B|^2$. While the required hardware for this technique is simple, the calibration is not straightforward since the cross-correlation signal is computed as the difference between large noisy signals.

Multiplying correlators, in contrast, eliminate the need to subtract independent measurements of $|v_A|^2$ and $|v_B|^2$. If implemented using analog hardware, however, they are subject to drift. Although analog multiplying correlators can be stabilized it is possible to eliminate many of the problems caused by drift and to obtain large bandwidths (several hundred MHz) by digital sampling and correlation. An added advantage of such a digital correlator over an analog correlator is simplicity in calibration. With the digital correlator only two unknown gain and offset parameters per channel (a total of four system parameters) require estimation. These four parameters can be measured during operation using conventional unpolarized hot-and-cold blackbody standards.

A demonstration of digital correlation radiometry and its advantages over analog correlation radiometry with regard to calibration was performed using a 200-MHz bandwidth emitter-coupled logic (ECL) correlator viewing a polarized calibration load. The demonstration used an existing dual-channel 92-GHz radiometer interfaced to custom 1.6-bit (three level) correlators using 24-bit accumulators. The intermediate frequency (IF) input signal was sampled at a rate of 400 Ms/sec. The correlator equipment (illustrated schematically in Fig. 1) was trained on the polarized calibration load described by Gasiewski and Kunkee [1993]. Rotation of the polarized load resulted in brightness temperature variations in all three measured Stokes' parameters T_A, T_B, and T_U. The data represent the first demonstration of digital correlation radiometry for passive polarimetric measurements.

As can be seen in Fig. 2, the T_U variations are in phase quadrature with those of T_A and T_B, and the amplitude of the T_U variations are nearly equal to the amplitude of the T_A and T_B variations. These forementioned features are anticipated consequences of the Stokes' parameter rotational transform [e.g., Chandrasekhar, 1960; Tsang et al., 1985]. It is important to note that only conventional hot-and-cold blackbody standards were used to calibrate the digital correlation radiometer. Thus, the digital technique is expected to be immediately applicable to spaceborne implementations which require a minimum of calibration hardware. Furthermore, the anticipated results were achieved using a relatively noisy 92-GHz dual-channel radiometer with receiver temperatures of approximately 1600 and 2300 K. Improved results can be expected using modern low-noise receivers.

B. PSR Digital Correlator Development

To facilitate application in an aircraft environment, the prototype correlator has since been simplified, made more mechnically robust, and considerably increased in bandwidth. In order to achieve the desired wide bandwidth needed for precision measurements of the three Stokes' parameters (at least 500 MHz for channels near 37 and 89 GHz) the sample rate of the correlators was increased from 400 Ms/sec to 1000 Ms/sec. This task was successfully accomplished by adhering to standard microwave circuit design and layout principles. The correlator design was simultaneously simplified by the use of high-speed ECL components in only those portions of the circuitry that are required to operate at the main clock rate of 1000 MHz. Circuit boards for eight correlators were subsequently etched, then assembled. Surface-mount components were used to maximize reliability of the boards under mechanical and thermal stress. A circuit layout for the improved correlator card is shown in Fig. 3.

The eight correlator cards along with appropriate clock and computer interface hardware will be incorporated into the PSR in August, 1995. Initial operation of the PSR using the correlator hardware is expected during the fall of 1995.[1] Data flights of the PSR on the NASA DC-8 are currently under negotiation, but are expected to be scheduled for the spring or summer of 1996. In addition to the correlator hardware a low-noise dual-channel 37-GHz radiometer has been purchased under this grant to facilitate polarimetric radiometer experiments. This receiver will be installed in the PSR along with the correlator hardware.

C. Non-stationary Ocean Surface Modeling

Efforts to model ocean wind direction signatures observed using the DMSP Special Sensor Microwave/Imager (SSM/I) have been similarly successful. A new non-stationary ocean surface model was combined with a simple geometrical optics electromagnetic emission and scattering model to predict the upwelling thermal emission from the ocean surface [Kunkee and Gasiewski, 1995a, 1995b]. The non-stationary model is based on a Monte Carlo surface simulator that uses a random spectral generator for the ocean surface, but includes an algorithm that prescribes a known phase distribution to the short gravity and capillary wave components. Using the above algorithm, asymmetric waves typical of a real wind-driven ocean surface are constructed. The asymmetric wave/geometrical optics (AWGO) model also includes the effects of multiple geometric scattering and shadowing, both of which are important effects at incidence angles near and beyond that of the SSM/I instrument (53 degrees and higher).

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[1] An intensive design and fabrication effort was started in January 1995 with the goal of flying the PSR on the NASA DC-8 during the MACAWS. While this goal was not met, the fabrication of the PSR progressed at a rapid rate. Laboratory operation of the PSR is now expected for October, 1995.

As seen in Fig. 4, the model is well corroborated by SSM/I 19 and 37 GHz oceanic wind direction signatures at both moderate (~7 m/sec) and high (~12 m/sec) wind speeds [Wentz, 1991; Wentz, 1992]. The fact that the AWGO model successfully explains the brightness temperature signatures of wind direction without a diffraction-based electromagnetic model suggests that the thermal emission mechanism for the ocean surface is primarily the result of broadband specular scattering and emission. Such broadband signatures were noted in 10, 37, and 92 GHz aircraft data observed during constant-angle bank turns during TOGA/COARE [Kunkee and Gasiewski, 1994], albeit at relatively low wind speeds. The broadband nature of the wind direction signature in radiometry thus contrasts with that of radar scatterometry in which the wind direction signatures are predominantly the result of Bragg backscattering from capillary wavelets. The model further shows that the amplitude and harmonic content of the passive wind-direction signatures are heavily influenced by the presence and extent of ocean wave asymmetry and ocean foam. The AWGO model is the first physcially-based thermal emission model to be successfully corroborated using the SSM/I satellite data.

The AWGO model also has also been used to predict the upwelling thermal signature expected for the third Stokes' parameter (Fig. 5). As expected from laboratory wave tank measurements [Gasiewski and Kunkee, 1994; Johnson et al., 1993] the signature for T_U is quadrature-phased with respect to the either of the signatures for T_v and T_h. This quadrature phasing is also seen in the AWGO simulations over wind-driven ocean surfaces. Thus, the orthogonal nature of T_U measurements are expected to facilitate passive wind direction retrieval by removing directional ambiguities in the retrieved wind direction. Moreover, the AWGO model shows that T_U is not as strongly influenced as T_v or T_h by either the degree of water wave asymmetry or the amount of foam coverage on the surface. Finally, T_U is a zero-mean signal, and thus (in contrast to T_v and T_h) does not need to have a large drifting baseline removed prior to interpretation.

D. Interaction with the NASA Marshall Space Flight Center

As originally proposed, this grant was intended to support the development and acquisition of microwave hardware necessary for Georgia Tech to upgrade the NASA Marshall Space Flight Center's Advanced Microwave Precipitation Radiometer (AMPR). Under this plan the AMPR would have been modified to provide fully polarimetric measurement capabilities over the full swath of the instrument. After discussions with both NASA/MSFC and NASA/Headquarters in October 1994 (during the first year of this grant) it was decided that a more suitable instrument for polarimetric observations and retrieval technique development would be the PSR. Thus, in December 1994 a decision was made by Georgia Tech and NASA/MSFC to leave the AMPR in its current (non-polarimetric) configuration and to redirect the polarimetric radiometer development effort toward the PSR.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of laboratory measurements of thermal emission over water waves [Gasiewski and Kunkee, 1994; Johnson et al., 1993] and SSM/I satellite measurements over the ocean [Wentz, 1991; 1992] it appears that it is possible to perform satellite-based measurements of ocean surface wind direction using polarimetric radiometry. Moreover, the addition of a cross-correlation channel to measure T_U will provide independent and unique information on the direction of surface wind. In order to develop practical retrieval techniques for passive measurement of wind direction it is important that the model function for thermal emission from a striated ocean be more fully developed. This task can be accomplished through (1) collection of in-situ ocean thermal emission data for a variety of conditions from aircraft, and (2) extensions to the AWGO model to incorporate diffraction from Bragg wavelets.

A. Airborne Passive Polarimetric Measurements using the PSR

When completed, the PSR will allow passive polarimetric observations of the ocean surface from the NASA DC-8 aircraft over a wide range of incidence angles. The gimbal mount scanning mechanism will allow the four PSR radiometers (at frequencies of 10.7, 18.6, 37.0, and 89.0 GHz) to be trained on the surface at elevation angles from nadir up to 70 degrees, and over 360 degrees in azimuthal angle.[2] Thus, two-look algorithms for ocean wind direction sensing will be able to be thoroughly tested prior to space instrument definition. A variety of scan modes will be available: cross-track, along-track, spotlight, and conical. In the conical mode, incidence angles from zero to 70 degrees will be selectable in-flight via software.

The four PSR channels will be useful for broadband imaging of the ocean surface at a variety of observations angles. The broadband nature of the PSR channel set will greatly facilitate the collection of a data set for corroborating a thermal emission model function of the ocean surface. The PSR channels will also coincide with critical channels used by the SSM/I, SSM/I-S, and TRMM

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[2] The elevation angle of the forward view is limited to 53 degrees due to occultation caused by the aircraft faring.

instruments. Thus, the PSR is expected to be a valuable underflight instrument for calibration and validation studies involving these sensors. At this time, the 10.7, 18.6, and 37.0 GHz radiometers have been purchased and are being installed into the PSR scanhead. In order to complete the complement of channels it is recommended that purchase of the 89-GHz receiver and feedhorn be completed in the second grant year.

Due to its wide altitude range (500 m to 12 km) and exceptional attitudinal stability the DC-8 is an excellent platform for ocean surface emission studies. However, the PSR channel set and polarimetric capabilities can also be used for studies of atmospheric convection. In the latter case it is desirable to obtain platform altitudes up to 20 km in order to observe the highest cell tops. Such altitudes can be obtained by the NASA ER-2 high-altitude aircraft. Thus, in the second grant year it is recommended that integration of the PSR on the NASA ER-2 be considered. Since the PSR has yet to be deployed even on the DC-8 , however, only a mechanical and cost feasibility study of ER-2 integration is suggested at this time.

B. Incorporation of Diffraction into the AWGO Model

Without the incorporation of any diffraction from short water waves the AWGO model has successfully explained much of the variance in Wentz' 19 and 37 GHz SSM/I wind direction data at 7.9 and 12 m/sec. This fact suggests that much of the wind-direction signature is caused by geometrical optics reflection and emission from essentially flat ocean facets; the signature is a result of the anisotropic tilt distribution of these facets and of nonuniform foam distribution. At wind speeds below approximately 5 m/sec (for which foam is not present), however, the AWGO model fails to adequately reproduce the SSM/I data, suggesting that anisotropic facet tilt is not the only cause of the signatures. At low wind speeds it is suggested that resonant thermal emission from capillary wavelets is the dominant signature-producing mechanism. Capillary wavelets occur primarily on the lee side of waves, thus, a non-stationary model of the ocean surface is necessary to model the effects of capillary waves. Accordingly, it is recommended that the AWGO model be modified to incorporate short-wavelength capillary waves, the emission from which would be computed using a diffraction-based electromagnetic model, for example, the small perturbation method. The resulting two-scale asymmetric wave model (TSAW) model will be unique in its incorporation of non-stationary surface behavior in a physically-based manner. Such a model will be valuable for spaceborne wind vector sensor design.

C. Ground-based Polarimetric Imaging of Thunderstorms

During ground-based testing of the PSR the polarimetric emission characteristics of thunderstorms will be studied by obtaining scanned images of the downwelling polarized brightness temperature from precipitating clouds. Such observations will be used to investigate correlations between oriented ice particles and thunderstorm electrification. To support this investigation, a the PSR will be configured to obtain 32x32 pixel images with approximately 2 degree angular interpixel spacing. An imaging time of ten seconds per frame should yield brightness temperature resolutions of approximately 0.5-1 K per pixel while capturing significant thunderstorm evolution. Upon integration into either the NASA DC-8 or ER-2 aircraft, the PSR will be particularly useful for studying upwelling polarized emission from electrified thunderstorm anvils and other cloud forms over water backgrounds.

Of particular interest is the relationship between polarimetric emission and the presence of thunderstorm electrification. Alignment of anvil ice by charged cell tops has been observed to cause rapid changes in satellite downlink depolarization [Cox and Arnold, 1979]. The same alignment mechanism is expected to cause similar rapid changes in polarimetric thermal emission. Such sudden changes will be of key interest in the ground-based PSR sky imaging experiments. If the initial PSR imagery shows a significant level of rapidly changing polarization then the imaging experiments will be repeated along with a quantitative characterization of the intercloud electric field using, e.g., a ground-based field-mill probe. The results of passive radiometer imaging and coincident electric field measurements could provide an improved understanding of propagation through regions of oriented atmospheric ice particles, particularly thunderstorm anvils. Variability in the absorption and scattering properties of thunderstorm anvil ice are a major source of uncertainty in radiative transfer modeling over convective storms [Gasiewski and Staelin, 1990]. This uncertainty becomes progressively worse at frequencies above 30 GHz.

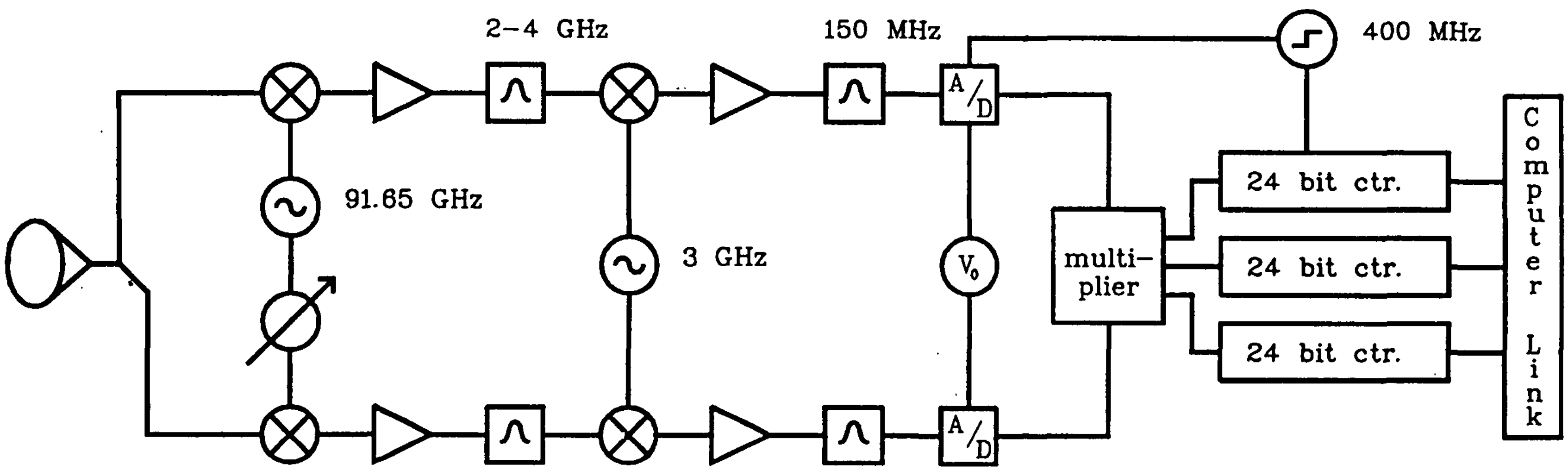

Figure 1. Block diagram of the prototype digital correlator hardware. The feedhorn antenna (left) is directed toward a polarized calibration standard.

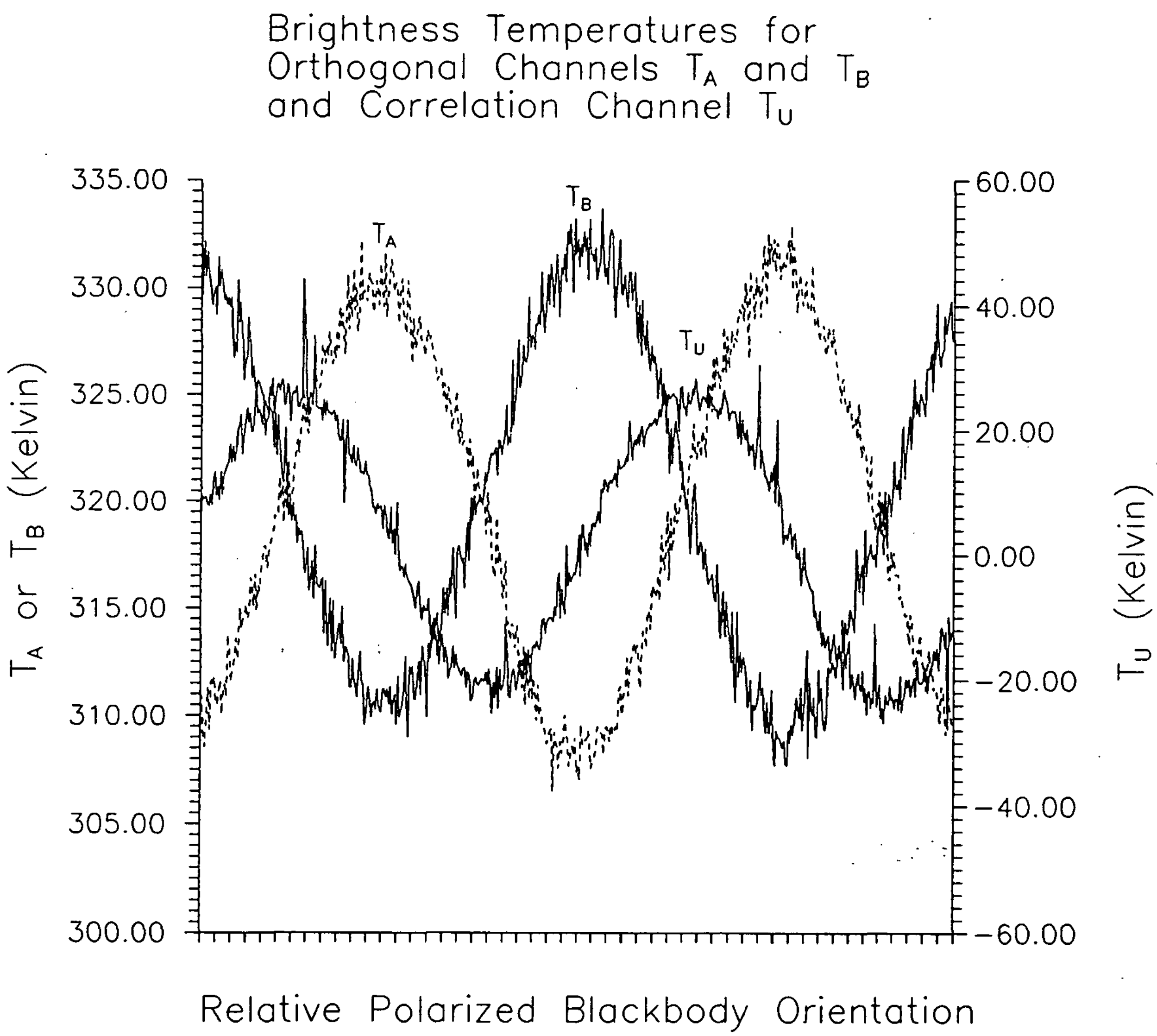

Figure 2. Variations in the first three Stokes' parameters as a function of the rotational angle of a polarize calibration load. As expected, T_A and T_B are in phase quadrature with T_U, and the amplitude of T_U is equal to the amplitudes of T_A and T_B.

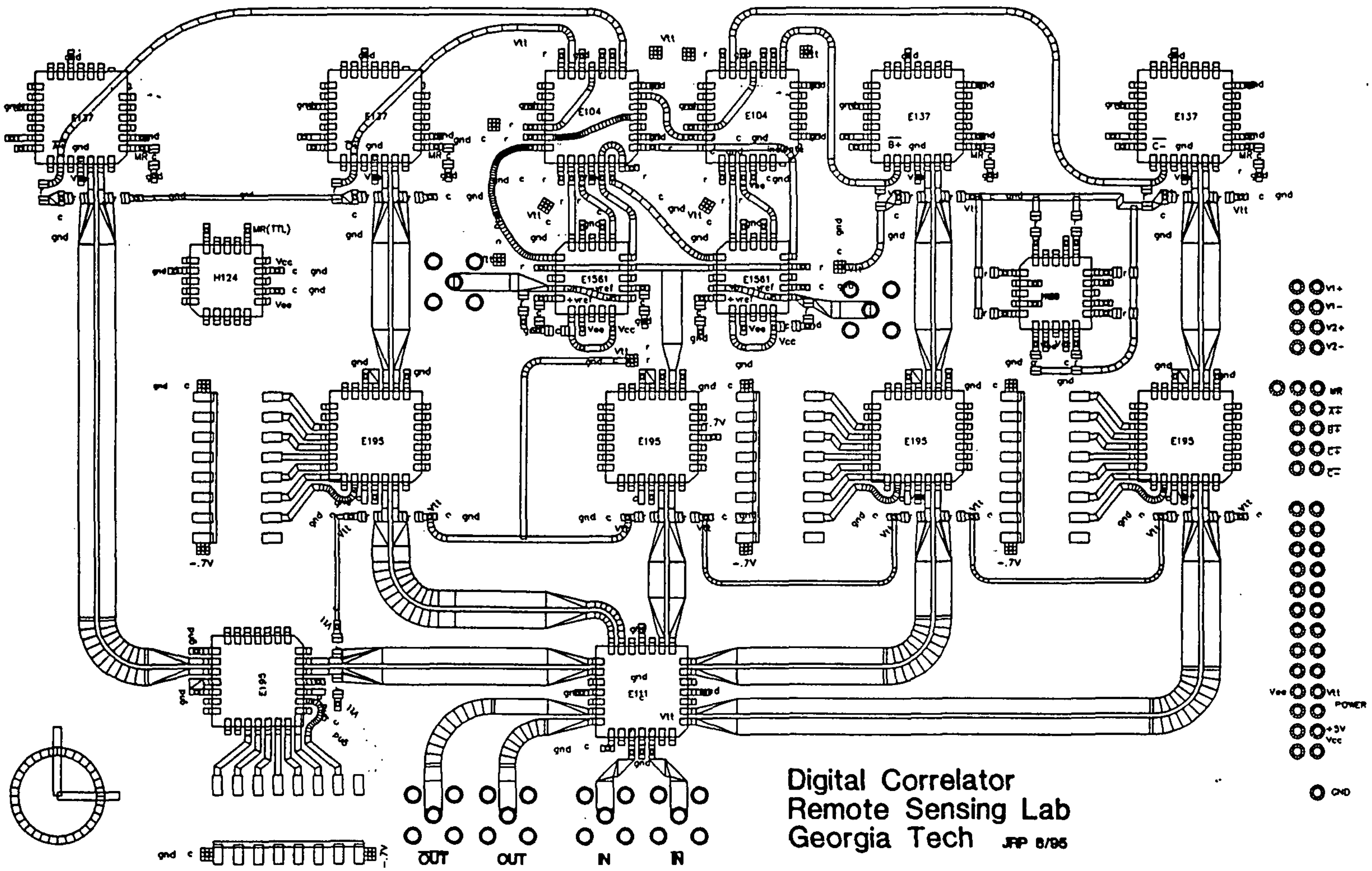

Figure 3. Circuit layout for the 1000 Ms/sec digital correlator to be used in the PSR.

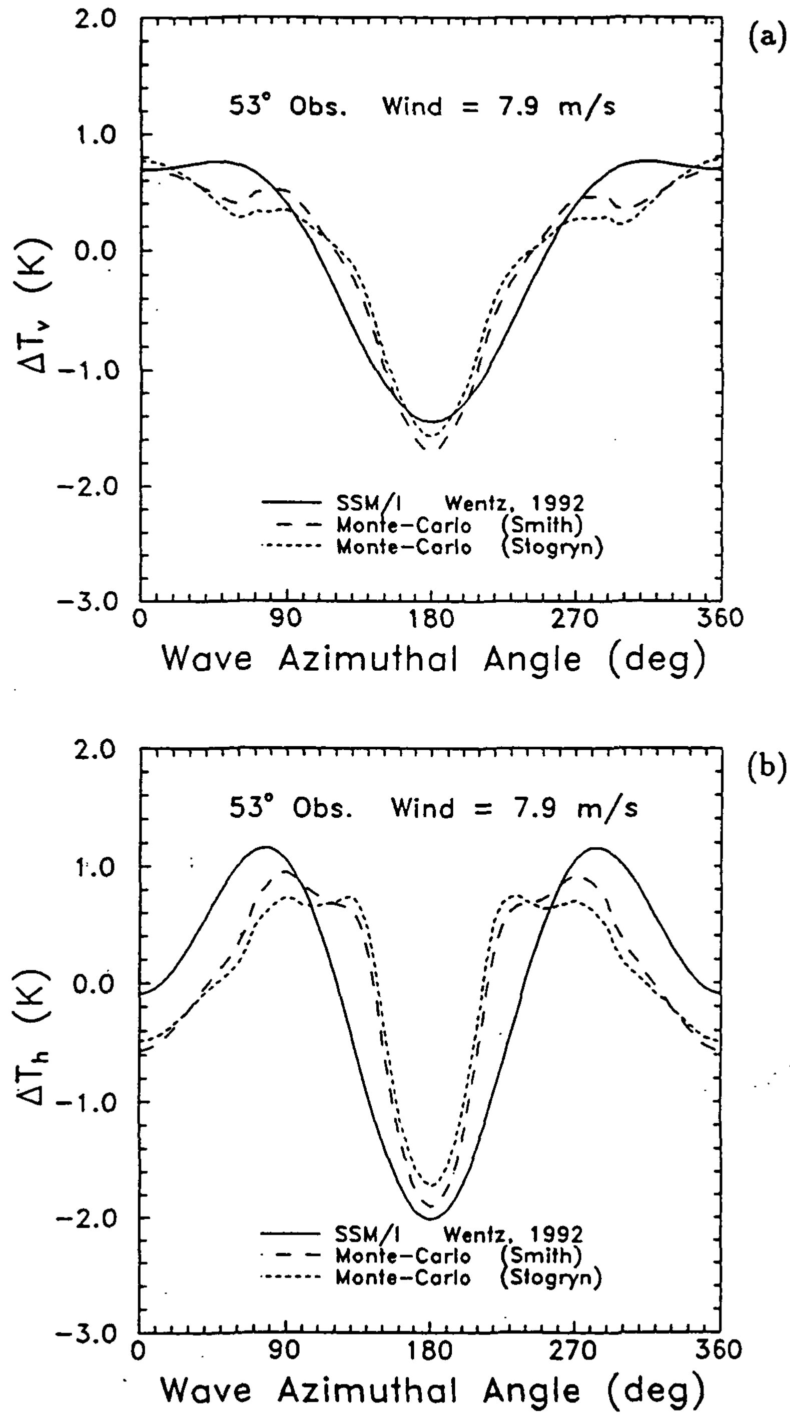

Figure 4. Comparisons of measured SSM/I brightness temperature variations at 37 GHz as a function of ocean wind direction with AWGO model calculations: (a) T_v, (b) T_h.

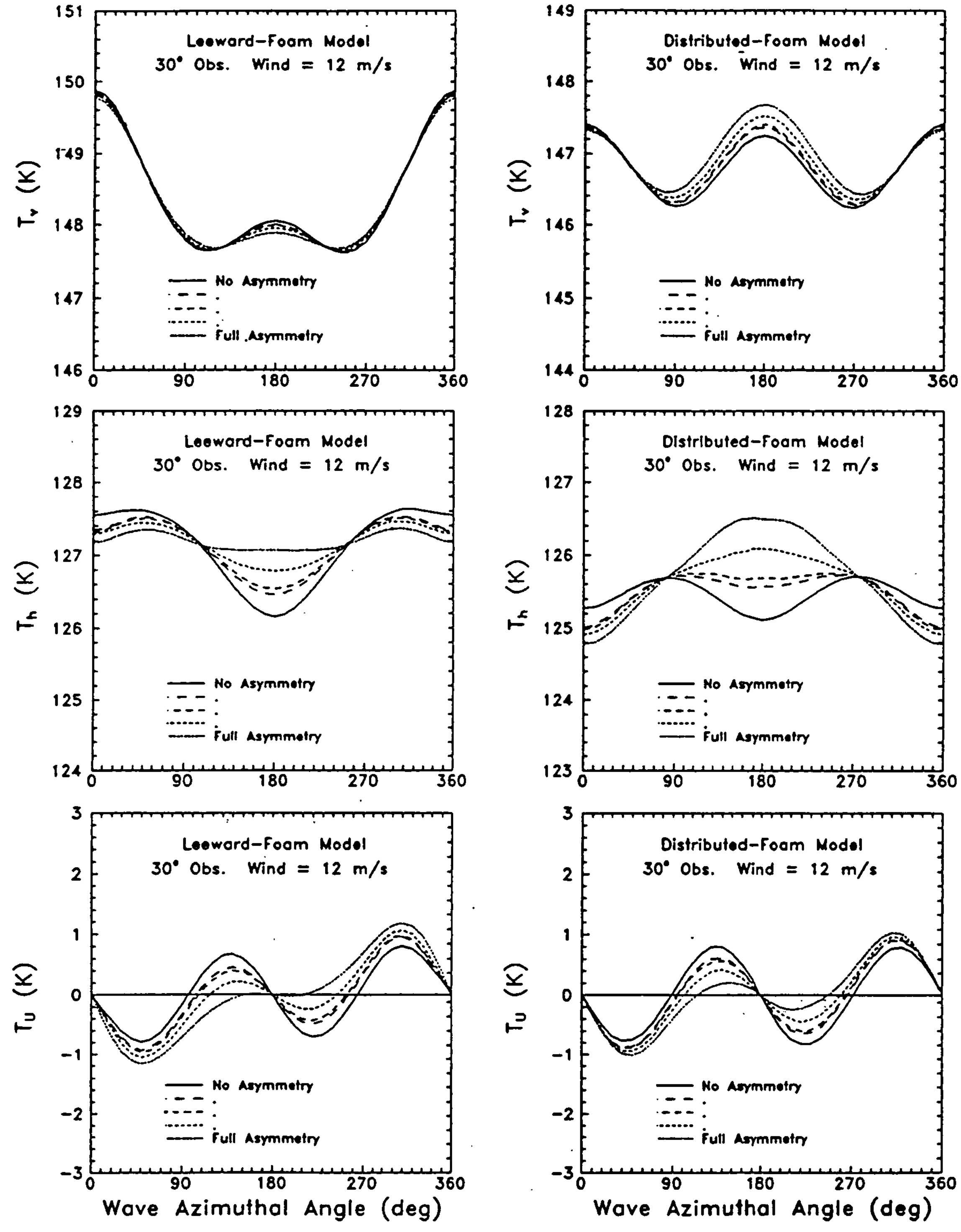

Figure 5. Predicted 19 GHz SSM/I brightness temperature variations for T_v, T_h, and T_U versus ocean surface wind direction using the AWGO model. The two columns of plots are for two different surface foam coverage models, while the individual curves are for different degrees of ocean wave asymmetry. Only a moderate dependence on foam coverage and wave asymmetry is seen for T_U.

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