FINAL REPORT

<u>Passive Microwave Studies of Atmospheric Precipitation and State</u>

NASA Grant NAG5-7487

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Submitted by

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Passive Microwave Studies of

Atmospheric Precipitation and State

ABSTRACT

The principal contributions of this research on novel passive microwave spectral techniques are in the areas of: 1) global precipitation mapping using the opaque spectral bands on research and operational weather satellites, 2) development and analysis of extensive aircraft observational imaging data sets obtained using the MIT instrument NAST-M near 54 and 118 GHz over hurricanes and weather ranging from tropical to polar; simultaneous data from the 8500-channel infrared spectrometer NAST-I was obtained and analyzed separately, 3) estimation of hydrometeor diameters in cell tops using data from aircraft and spacecraft, 4) continued improvement of expressions for atmospheric transmittance at millimeter and sub-millimeter wavelengths, 5) development and airborne use of spectrometers operating near 183- and 425-GHz bands, appropriate to practical systems in geosynchronous orbit, and 6) preliminary studies of the design and performance of future geosynchronous microwave sounders for temperature and humidity profiles and for continuous monitoring of regional precipitation through most clouds.

This work was a natural extension of work under NASA Grant NAG5-2545 and its predecessors. This earlier work had developed improved airborne imaging microwave spectrometers and had shown their sensitivity to precipitation altitude and character. They also had prepared the foundations for precipitation estimation using the opaque microwave bands. The field demonstration and improvement of these capabilities was then a central part of the present research reported here, during which period the first AMSU data became available and several hurricanes were overflown by NAST-M, yielding unique data about their microwave signatures. This present work has in turn helped lay the foundation for future progress in incorporating the opaque microwave channels in systems for climatologically precise global precipitation mapping from current and future operational satellites. Extension of these techniques to global snowfall mapping, even over ice and snow, is one such opportunity signaled by this research.

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I. Introduction

This research program extended work under NASA Grant NAG5-10 and its continuation under NASA Grant NAG5-2545, both of which were directed toward different aspects of passive microwave remote sensing of the terrestrial atmosphere from aircraft and space. These efforts have been paralleled by separately funded but related MIT efforts directed toward improved definition and utilization of passive microwave imaging spectrometers on research aircraft (NAST), operational meteorological satellites (NOAA-15, -16, and -17), and research spacecraft (Aqua, geosynchronous microwave sounders).

Results from each of the six major elements of the recently completed program (NASA Grant NAG5-7487) are summarized below and are referenced to the literature: 1) precipitation mapping, 2) NAST-M aircraft observations, 3) retrievals of hydrometeor diameters, 4) atmospheric transmittance, 5) observations near 425 GHz, and 6) passive microwave geosynchronous satellite studies.

II. Precipitation Mapping using Opaque Millimeter-wave Bands

This program contributed to the development of new methods for retrieving precipitation rates (mm/h) using the opaque oxygen band resonances near 54 and 118 GHz, and the opaque water vapor resonance near 183 GHz. These new methods complement the traditional window-channel microwave methods used routinely by SSM/I, TRMM, and other polar satellite systems; these older methods work best over ocean and convective precipitation when there is no snow or ice below. The surface-blind character of the new opaque-channel methods promises to extend these precipitation retrieval capabilities over nearly all land below 2-km altitude, regardless of surface condition, and over intense snowfall, even when located over winter polar ice or snow.

These capabilities have been well documented in papers by Staelin and Chen (2000) and Chen and Staelin (2003; preprint). Abstracts of these papers appear here in Appendices A and B, respectively, and describe the method and some quantitative results. These papers compare individual 15- and 50-km footprints and precipitation retrievals to similarly averaged NEXRAD 3-GHz radar precipitation estimates that overlap within ~8 minutes in time. Figure 1 shows a scatter plot of the instantaneous differences in these retrievals at 50-km resolution. The principal remaining task is to extend these techniques to all global climate regimes and to calibrate against all other major precipitation measurement techniques to help minimize climatological bias differences between methods. At present the method appears to over estimate precipitation rates in the strongest convective storms, particularly in polar climates, and to underestimate the water equivalent of snowfall. The ability of the method to sense the morphology of storms in any climate appears to be very good, however, provided the rain rates of interest are above ~0.5 mm/h.

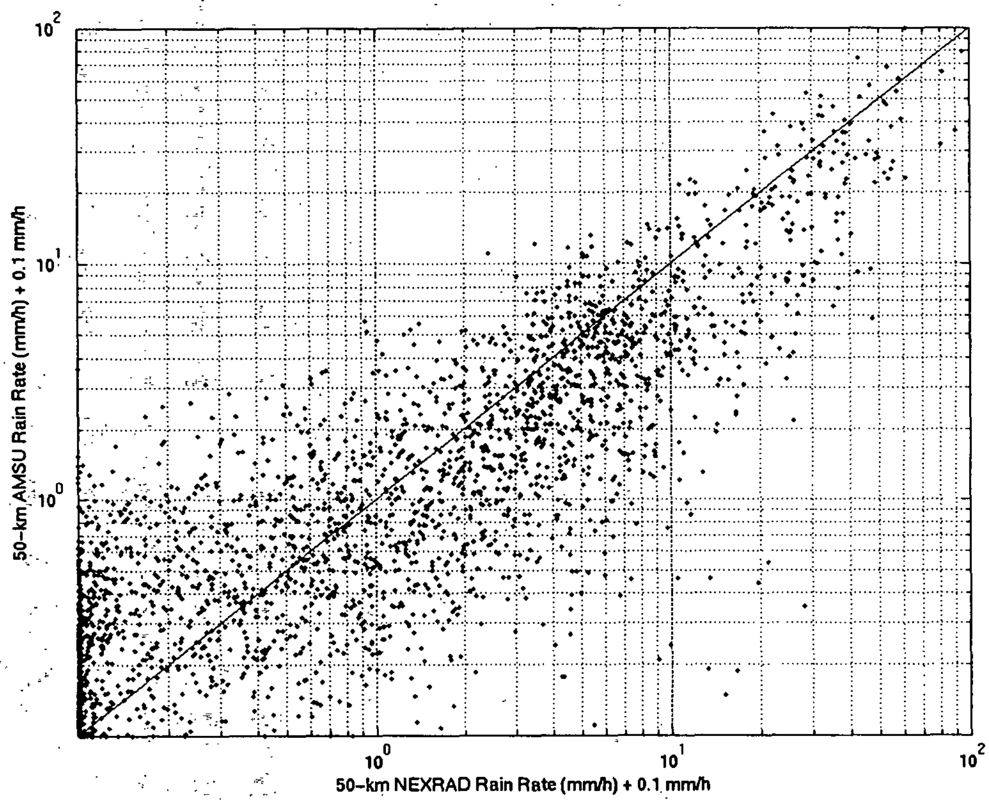

Figure 1. Comparison of AMSU and NEXRAD rain rate estimates at 50-km resolution

It was noticed that the rapid time variations of precipitation on a 15-km scale contribute to the observed discrepancies between AMSU and NEXRAD precipitation retrievals. To reduce these discrepancies algorithms were developed that aggregate footprints associated with single precipitation systems that may span large areas. Automated methods to define these larger regions were developed, and then precipitation retrievals were applied to those areas with a noticeable increase in agreement between radar and AMSU. This study was documented in part in the MEng. thesis of A. F. Loyola (1999), the abstract of which appears here in Appendix G.

III. Aircraft Observations using NAST-M

During this program several aircraft missions were undertaken with the MIT NAST-M microwave spectrometer flying on the NASA ER-2 or Proteus high-altitude aircraft. The NOAA Airborne Sounder Testbed - Microwave (NAST-M) system near 54- and 118-GHz was well documented by Blackwell et al. (2001). The basic early results are contained in the abstract of that paper, which appears here in Appendix C. Figure 2 presents images of the eye of Hurricane Bonnie on August 26, 1998 at 50.3 and 118.75±3.5 GHz. Much information is contained in such image combinations. For example, the cloud in the lower left corner of the 118-GHz image is not evident near 50.3 GHz because of the f^4 dependence of Rayleigh scattering. Similarly, the sensitivity of 50.3 GHz to water vapor reveals a significant dry spot (brightness temperature ≅ 240K) near the center of the eye near 16:29 UTC, presumably associated with dry air descending from aloft into the very center of the eye.

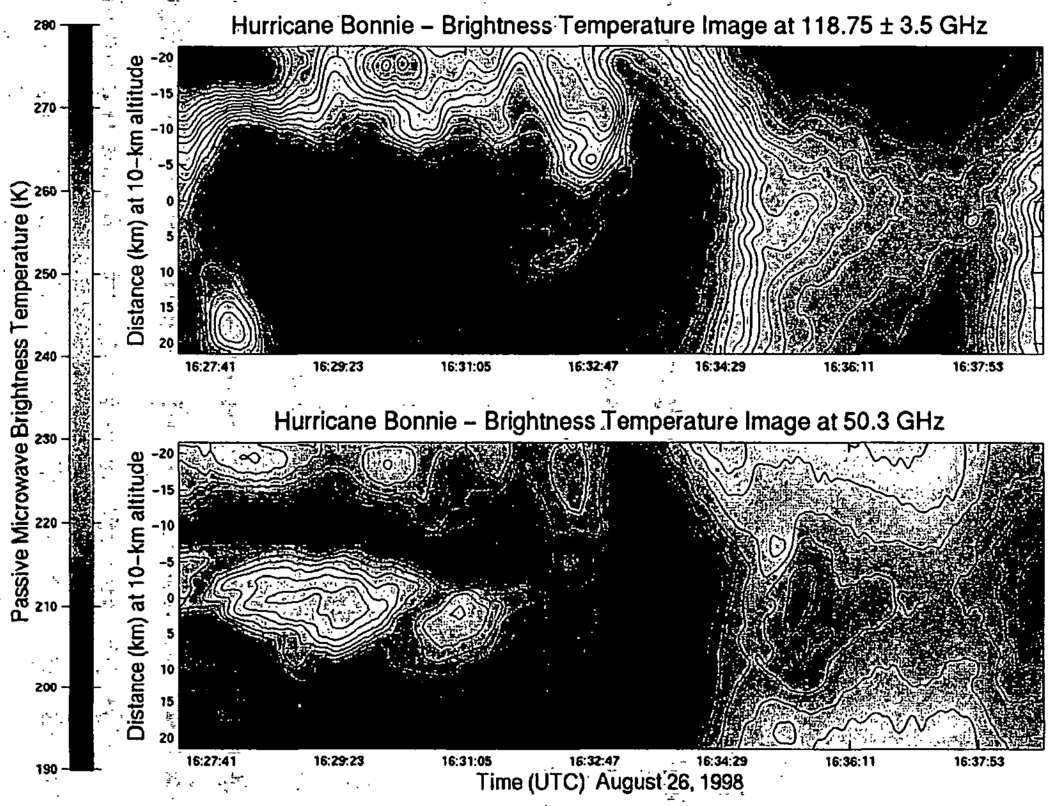

Figure 2. Brightness temperature images over the eye of Hurricane Bonnie, August 26, 1998, at window frequencies near 50.3 GHz and 118.75±3.5 GHz. The contour spacing is 5 K below 240 K and 4 K above. The x-y scales are equal at 10-km altitude, where the image size is approximately 40 x 140 km.

Since then 183-GHz and 425-GHz spectrometers have been added and (after termination of this grant) flown. The table below lists the missions flown during the grant and the number of days for which NAST-M flight images were obtained within the given time window. This flight data is currently available to the public on the web site <rseg.mit.edu>, although no permanent commitment to maintaining this site is intended.

Table 1. NAST-M Flight Missions during program

1.	CLOUDIOP	(11-21 March 2000; 7 days)
2.	WVIOP	(30 September - 6 October, 2000; 4 days)
3.	AFWEX	(27 November - 8 December, 2000; 6 days)
4.	TRACEP	(17 February - 26 March, 2001; 12 days)
5.	CLAMS	(9 July - 2 August, 2001; 10 days)

Both temperature and humidity profile retrievals have been performed with this data, the latter involving joint interpretation of 183-GHz data obtained on the same aircraft using the NASA GSFC MIR imaging spectrometer (data provided by James Wang, personal communication). The temperature profile studies were documented in the S.M. thesis of R. V. Leslie (2000), the abstract of which appears here in Appendix D, and the humidity profile retrievals were documented in the S.M. thesis of J. B. Hancock (2001), the abstract of which appears here in Appendix F. The flight data analysis of the latter is incomplete and awaits re-evaluation.

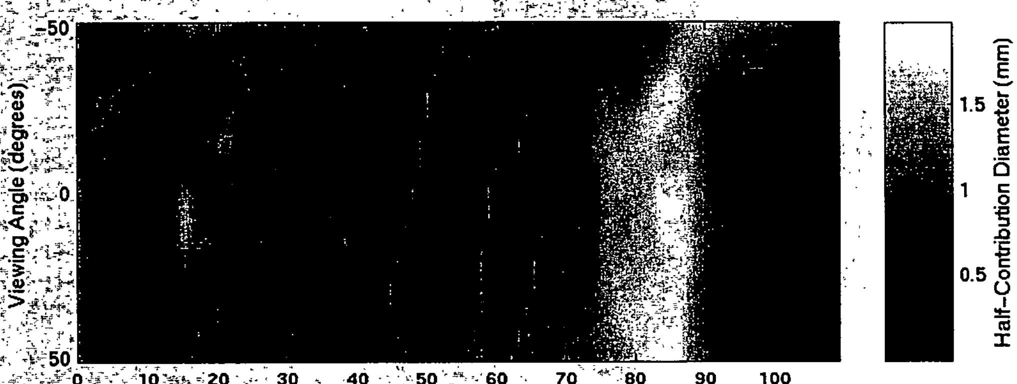

Figure 3. Retrieval of particle size index for Hurricane Bonnie on August 23, 1998, using NAST-M 54/118-GHz spectral data

IV. Retrievals of Hydrometeor Diameters

Hydrometeor diameters can be retrieved by comparing the albedos of cloud tops observed at microwave frequencies offset by factors of ~2 or more. This capability and method were documented in a paper by Blackwell et al. (2001), the abstract of which appears here in Appendix C, and in the ScD. thesis of Blackwell (2002), the abstract of which appears here in Appendix E. A retrieval of "particle size index" appears here in Figure 3 for Hurricane Bonnie on August 23, 1998, where the largest values are near 1.8 mm. This index represents that particle diameter for which half the mass is lodged in larger particles, assuming exponentially distributed diameters. Note that the larger particles are concentrated toward the inner edge of the hurricane eyewall, where the convective strength is expected to be greater. This capability appears extensible to 54/183 GHz spectral soundings as well, provided the spatial resolution is sufficient.

V. Studies of Atmospheric Transmittance

A new algorithm was developed for solving the radiative transfer equation in a planar-stratified atmosphere with multiple scattering (Rosenkranz, 2002). The basis of the algorithm is numerical integration of an ensemble of trial functions which are constructed so as to satisfy the boundary conditions at the top of the atmosphere. The boundary conditions at the surface are imposed after integration. The algorithm is very efficient because it requires solution, only once, of a set of linear equations of rank equal to half the number of radiation streams. It has been implemented in Fortran and Matlab for use in simulating brightness temperatures from precipitation, as would be measured by NAST-M.

VI. Aircraft Observations near 425 GHz

During much of this program the NAST-M system was improved and, under separate funding, hardware for 425-GHz spectral imaging was obtained. The laboratory testing and evaluation of this system was jointly supported under this program, and the first flight tests occurred shortly after its conclusion. They yielded the first good images of convective storms at three wavelengths near 425 GHz, together with good correlative spectral image data near 54, 118, and 183 GHz, see Figure 4. The great interest in this data arises largely from the fact that if this frequency can successfully penetrate most clouds and upper humidity, then geosynchronous sounders of atmospheric temperature, humidity, and precipitation become much more economic because of the much lower cost, size, and weight of the 2-3 meter antenna that probably would be used for this purpose.

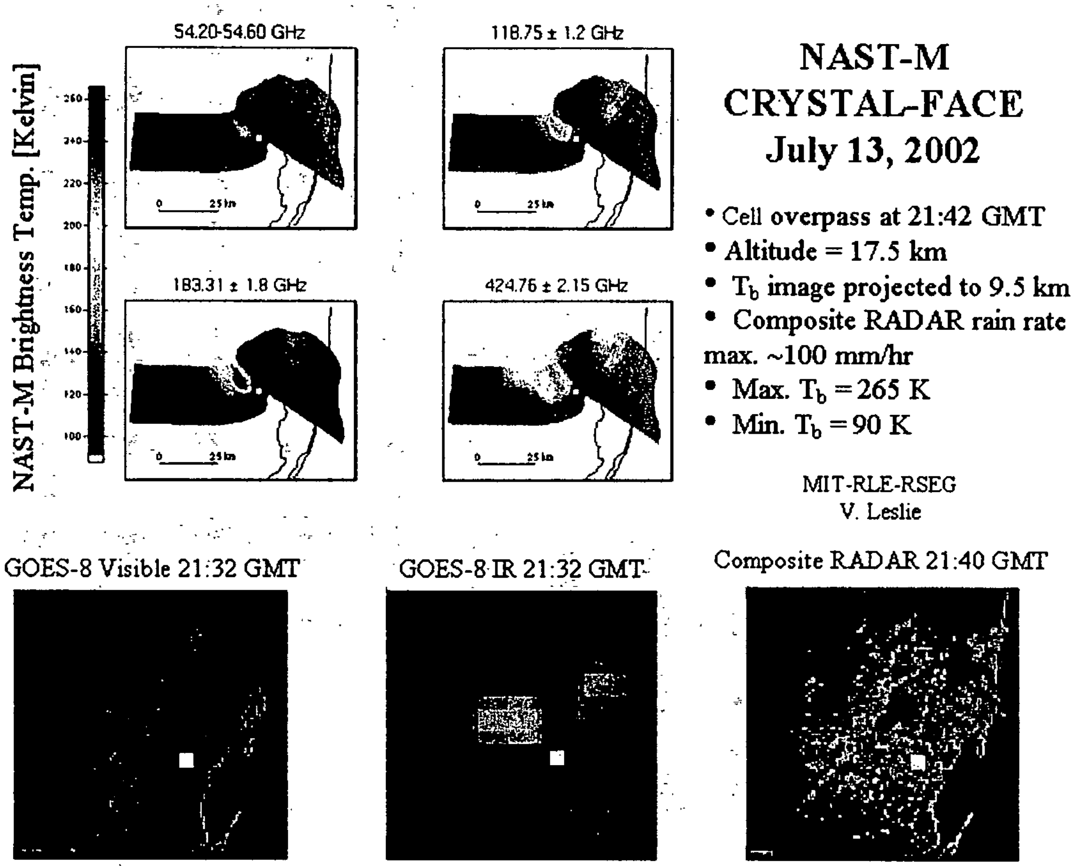

Fig.4 NAST-M brightness temperature images of a convective cell near 54.4, 118.75±1.2, 183.3±1.8, and 424.8±2.2 GHz; NEXRAD and GOES visible and IR images provide a reference.

VII. Geosynchronous Passive Microwave Satellite Studies

During this period numerous approaches to geosynchronous sounding of the atmospheric temperature, humidity, and precipitation profiles were explored. The concepts developed were documented in a paper "MW/Sub-mm sounding from geostationary orbit" by B. Bizzarri, A. J. Gasiewski, and D. H Staelin; it was submitted to URSI in May, 2002.

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APPENDICES

Appendix A

Precipitation Observations Near 54 and 183 GHz Using the NOAA-15 Satellite

David H. Staelin and Frederick W. Chen

Abstract

Promising agreement over land and sea has been obtained between NEXRAD 3-GHz radar observations of precipitation rate and retrievals based on simultaneous passive observations at 50-191 GHz from the Advanced Microwave Sounding Unit (AMSU) on the NOAA-15 meteorological satellite. A neural network with three hidden nodes and one linear output node operated on 15-km resolution data at 183±1 and 183±7 GHz, plus the cosine of scan angle, to produce estimates that match well the morphology of NEXRAD hurricane and frontal precipitation data smoothed to 15-km resolution. A second neural network operated on the same three parameters used in the first network, but smoothed to 50-km resolution, plus spatially-filtered cold perturbations detected in three AMSU tropospheric temperature-sounding channels (channels 4-6), which also have 50-km resolution. Comparison with the same NEXRAD data smoothed to 50-km resolution yielded root-mean-square (rms) discrepancies for two frontal systems and two passes over Hurricane Georges of ~1.1 mm/h, and ±1.4 dB for those precipitation events over 4 mm/h. Only 8.9% of the total AMSU-derived rainfall was in areas where AMSU saw more than 1-mm/h and NEXRAD saw less than 1-mm/h, and only 6.2% of the total NEXRAD-derived rainfall was in areas where NEXRAD saw more than 1-mm/h and AMSU saw less than 1-mm/h.

IEEE Transactions on Geoscience and Remote Sensing, **28**(5):2322-2332, September 2000

Appendix B

AIRS/AMSU/HSB Precipitation Estimates

Frederick W. Chen and David H. Staelin

Abstract

Precipitation rates (mm/h) with 15- and 50-km horizontal resolution are among the initial products of AIRS/AMSU/HSB. They will help identify the meteorological state of the atmosphere and any AIRS soundings potentially contaminated by precipitation. These retrieval methods can also be applied to the AMSU 23-191 GHz data from operational weather satellites such as NOAA-15, -16, and –17. The global extension and calibration of these methods are subjects for future research.

The precipitation-rate estimation method presented is based on the opaque-channel approach described by Staelin and Chen [1], but it utilizes more channels (17) and training data, and infers 54-GHz band radiance perturbations at 15-km resolution. The dynamic range now reaches 100 mm/h. The method utilizes neural networks trained using NEXRAD precipitation estimates for 38 coincident rainy orbits of NOAA-15 AMSU data obtained over the eastern United States and coastal waters during a full year. The rms discrepancies between AMSU and NEXRAD were evaluated for the following NEXRAD rain-rate categories: <0.5, 0.5-1, 1-2, 2-4, 4-8, 8-16, 16-32, >32 mm/h. The corresponding rms discrepancies for the 3790 15-km pixels not used to train the estimator were 1.0, 2.0, 2.3, 2.7, 3.5, 6.9, 19.0, and 42.9 mm/h, respectively. The 50-km retrievals were computed by spatially filtering the 15-km retrievals. The rms discrepancies over the same categories for all 4709 50-km pixels flagged as potentially precipitating were 0.5, 0.9, 1.1, 1.8, 3.2, 6.6, 12.9, and 22.1 mm/h, respectively. Representative images of precipitation for tropical, mid-latitude, and snow conditions suggest the method's potential global applicability.

Appendix C

NPOESS Aircraft Sounder Testbed-Microwave (NAST-M): Instrument Description and Initial Flight Results

William J. Blackwell, John W. Barrett, Frederick W. Chen, R. Vincent Leslie, Philip W. Rosenkranz, Michael J. Schwartz, and David H. Staelin

Abstract

The National Polar-Orbiting Operational Environmental Satellite System (NPOESS) aircraft sounder testbed (NAST) has recently been developed and deployed on the NASA ER-2 high-altitude aircraft. The testbed consists of two co-located cross-track scanning instruments: a Fourier transform interferometer spectrometer (NAST-I) [1] with spectral coverage of 3.7-15.5 μm, and a passive microwave spectrometer (NAST-M) with 17 channels near the oxygen absorption lines at 50-57 GHz and 118.75 GHz. The testbed provides the first coregistered imagery from high-resolution microwave and infrared sounders and will provide new data that will help 1) validate meteorological satellite environmental data record (EDR) feasibility, 2) define future satellite instrument specifications, and 3) demonstrate operational issues in ground validation, data calibration, and retrievals of meteorological parameters. To help validate the performance and potential of NAST-M, imagery was collected from more than 20 overpasses of hurricanes Bonnie and Earl during the Convection and Moisture Experiment (CAMEX-3), Florida, Summer 1998. The warm core and convection morphology of Hurricane Bonnie (August, 1998) is clearly revealed both by aircraft-based microwave brightness temperature imagery and temperature retrievals within the eye. Radiance comparisons with the Advanced Microwave Sounding Unit (AMSU) on the NOAA-15 satellite and radiosonde observations yield root mean-squared (RMS) agreements of approximately 1 K or less.

IEEE Transactions of Geoscience and Remote Sensing, **39**(11):2444-2453, November 2001.

Appendix D

Temperature Profile Retrievals with the NAST-M Passive Microwave Spectrometer

by

Robert Vincent Leslie

Submitted to the Department of Electrical Engineering and Computer Science
on May 5, 2000, in partial fulfillment of the
requirements for the degree of
Master of Science

Abstract

The National Polar-orbitting Observational Environmental Satellite System (NPOESS) Aircraft Satellite Testbed (NAST) employs a passive microwave spectrometer (NAST-M) with channels in the oxygen absorption bands near 54-GHz and 118.75 GHz. NAST-M has two coregistered total-power radiometers, which were flown on NASA's high-altitude ER-2 aircraft. The 54-GHz radiometer has a single-sideband receiver with a total of eight channels ranging from 50.2 GHz to 56.2 GHz, and the double-sideband 118-GHz radiometers has six functioning channels with center frequencies from 118.75 ± 0.8 GHz to 118.75 ± 3.5 GHz. The nadir spatial resolution is 2.6 km from an altitude of 20 km. NAST-M has an antenna reflector that scans ± 64.8° from nadir and makes 19 measurements with a spacing of 7.5°.

This thesis presents accurate temperature retrievals obtained during WINTEX (WINTer EXperiments, Madison, WI, March/April 1999) using flight data from the NAST-M Microwave Sounding Unit (AMSU-A) passive microwave spectrometer onboard the NOAA-15 satellite. Upper bounds to NAST-M's sensitivity and accuracy are < 0.3 K and <1.5 K, respectfully.

A non-linear statistical/physical temperature profile retrieval technique was implemented with a multi-layer feedforward neural network (MFNN). The NAST-M brightness temperature and the aircraft's altitude are preconditioned (decorrelated, normalized, and biased) and entered into the MFNN to estimate the coefficients of the orthogonal expansion of the temperature profiles. The temperature profile training ensemble of radiosonde data is TIGR, which is segregated into mid-latitude winter profiles. Liebe's Millimeter-wave Propagation Model (MPM) is used to transform the TIGR profiles into simulated NAST-M brightness temperatures. The rms retrieval errors based on the training and validation sets were < 2 K in the mid-troposphere and closer to 3 K at the surface and close to the aircraft.

WINTEX flight data are compared with radiosondes and AMSU-A temperature retrievals. Initial NAST-M/MFNN temperature perturbation images of the lower atmosphere are also presented; they suggest the possible detection of thermal waves on the order of 1 K peak-to-peak with a period of ~20-60 km.

Appendix E

Retrieval of Cloud-Cleared Atmospheric Temperature Profiles from Hyperspectral Infrared and Microwave Observations

by

William Joseph Blackwell
Submitted to the Department of Electrical Engineering and Computer Science
on May 14, 2002, in partial fulfillment of the
requirements for the degree of
Doctor of Science

Abstract

This thesis addresses the problem of retrieving the temperature profile of the Earth's atmosphere from overhead infrared and microwave observations of spectral radiance in cloudy conditions. The contributions of the thesis are twofold: improvements in 1) microwave instrumentation and 2) hyperspectral signal processing and estimation algorithms.

The NPOESS Aircraft Sounder Testbed-Microwave (NAST-M) passive spectrometer was designed, fabricated and deployed. NAST-M provides accurate brightness temperature measurements in 16 channels near the oxygen absorption lines at 50-57 GHz and 118.75 GHz, permitting the first reliably accurate retrieval images of temperature profiles and precipitation structure in cloudy areas.

The correlation structure of the NPOESS Aircraft Sounder Testbed-Infrared (NAST-I) instrument noise was analyzed in the spectral and spatial domains using the Iterated Order- Noise (ION) algorithm [1] for two representative flights. Results indicate that vibration-induced noise was the dominant component, but that it could be significantly reduced by filtering in the spatial domain.

Novel multi-pixel cloud clearing and temperature profile retrieval algorithms were developed for simulated Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU) radiances using neural networks. RMS temperature profile retrieval errors of ~0.5 K were obtained for all levels of the atmosphere from 0-15 km in clear air at a horizontal resolution of 2000 km^2 and a vertical resolution of 1 km. RMS radiance errors under cloudy conditions for altitudes from 0 to 10 kilometers ranged from 1.25 K to 0.1 K for radiance retrievals near 15 microns, and from 0.8 K to 0.05 K for radiance retrievals near 4 microns.

Validation of the simulation results with NAST observations was hampered by the lack of a statistically-diverse data set accompanied by cloud truth. An upper bound on cloud-clearing performance (NEΔT) was estimated to be approximately a factor of two worse than the simulation results accompanied by ground truth. An improvement of approximately 25 percent in RMS radiance cloud-clearing performance was realized by rejecting 20 percent of soundings based on a neural network-derived metric.

Thesis Supervisor: David H. Staelin
Title: Professor of Electrical Engineering

Appendix F

Passive Microwave and Hyperspectral Infrared Retrievals of Atmospheric Water Vapor Profiles

by

Jay Brian Hancock

Submitted to the Department of Electrical Engineering and Computer Science on May 21, 2001, in partial fulfillment of the requirements for the degree of Master of Science in Computer Science and Engineering

Abstract

Two clear-air relative humidity profile estimators were designed and implemented using neural networks. The microwave estimator is the first to utilize 54-, 118-, and 183-GHz channels for simultaneously retrieving a relative humidity profile. It utilized 2 separate instruments simultaneously. The first instrument is a medium-resolution dual-band radiometer with one set of 8 double-sideband 118-GHz channels and a second set of 8 single-sideband 54-GHz channels. The other instrument is a high-resolution double-sideband radiometer with a set of 3 183-GHz channels, and additional channels at 89, 220, and 150 GHz. The infrared estimator is among the first to utilize a hyperspectral infrared aircraft instrument for relative humidity profile retrievals. The infrared instrument is a 9000-channel interferometer operative over the wavelength range of 3.8 – 16.2 microns. Both estimators utilized neural networks of comparable topology and training methods. The training data was generated from the SATIGR set of 1761 RAOBs using a different implementation of the discrete radiative transfer equation for each estimator.

The test data were from two clear-air ER-2 aircraft flights during the tropical CAMEX-3 mission near Andros Island. The retrievals were robust in the face of unknown instrument bias and noise, which introduced a difference between the training data and the flight data. A noise-averaging technique achieved robustness in exchange for a degradation in sensitivity of the retrieval algorithms. Robustness was demonstrated by the retrieval agreement between the microwave and infrared instruments. The theoretical average rms error in relative humidity for the various techniques on the training set was 12% for the microwave estimator, 11% for the infrared, and 10% for a linear regression of the two. In application to two flights, the rms error was 9.4% for the microwave, 7.7% for the infrared, and 7.7% for the combination, based on comparisons with nearby radiosondes.

Thesis Supervisor: David H. Staelin
Title: Professor of Electrical Engineering

Appendix G

Precipitation measurements using 54 and 183 GHz AMSU satellite observations

by

Antonio Fuentes Loyola

Submitted to the Department of Electrical Engineering and Computer Science on May 21, 1999, in partial fulfillment of the requirements for the degrees of Bachelor of Science in Electrical Science and Engineering and Master of Science in Computer Science and Engineering

Abstract

Brightness temperatures from the Advance Microwave Sounding Unit (AMSU) respond in part to precipitation. In two separate experiments, the Tb's from AMSU were combined and input to a simple neural network to yield precipitation estimates. This neural network was trained with data from the Next Generation Radar (NEXRAD). In the first experiment, two AMSU-B humidity channels were used as inputs to the network, namely 183±3 and 183±7 GHz. In the second experiment, four AMSU-A temperature profile channels were used instead, all with center frequencies around 54 GHz. For both of these cases, the training and test data corresponded to a major frontal passage in the eastern United States and a hurricane.

The precipitation estimates from the first experiment, which had an RMS error of 0.015 inches/15min, were used to define nonoverlapping geographic regions centered at all significant precipitation cells. The total estimated precipitation was then integrated in each of these regions, and the rain integrals, along with the areas of each of the regions, were input to a second neural net trained with NEXRAD data based precipitation integrals over the same regions. NEXRAD missed regions were 2.3 percent of the AMSU-based estimated rainfall, and AMSU missed regions where 11.8 of NEXRAD-estimated rainfall. After processing using the second neural network, the regional RMS error between AMSU and NEXRAD based precipitation estimates was 0.24 [log10 (m^3s^{-1})].

The second experiment, in which AMSU-A data were used to estimate precipitation, involved pre-processing the Tb's to remove scan angle dependencies and surface emissivity effects. The scan angle dependency was removed by subtracting cross-scan averages and adding averages at nadir. The surface emissivity effects were removed using Linear Least Squares estimation, based on the AMSU-A window channel, which is most sensitive to the surface. Separately, AMSU-B data at 183±7 GHz was used in combination with an adaptive threshold technique to define regions of precipitation. These regions were then set to zero and later filled with two-dimensional

interpolation in every AMSU-A channel, which allowed for isolation of the effects of rain in AMSU-A. Once these perturbations were separated they were input to a neural net, which trained with NEXRAD data. The net yielded estimates with an error of 0.008 inches/15 min, significantly lower than that of the first experiment. At the regional level, a much better agreement of AMSU and NEXRAD-based rain was achieved, even without the use of a second neural net such as the one used in the first experiment.

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