GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL

[ ] REVISION NO. ____

Project No. A-3001 DATE: 7/17/81

Project Director: R. N. Trebits ~~School~~/Lab RAIL-RAD

Sponsor: Rockwell International Corp., Anaheim, CA

Type Agreement: Contract AlEM-3000044

Award Period: From 6/26/81 To ~~9/26/81~~ 10/31/81 (Performance) _____ (Reports)

Sponsor Amount: $10,000 Contracted through:

Cost Sharing: _____ GTRI/~~GIT~~

Title: Millimeter Wave Trade Study

ADMINISTRATIVE DATA OCA CONTACT William F. Brown x4820

1) Sponsor Technical Contact: J. J. Justice, D/280; Mail Code DF39; Rockwell International Corp.; Defense Electronics Operations; P. O. Box 1305; Anaheim, CA 92803

2) Sponsor Admin./Contractual Contact: J. F. Era; D/153, 031-DE46; Rockwell International Corp.; Defense Electronics Operations; P. O. Box 3105; Anaheim, CA 92803

Reports: See Deliverable Schedule Security Classification: Unclassified

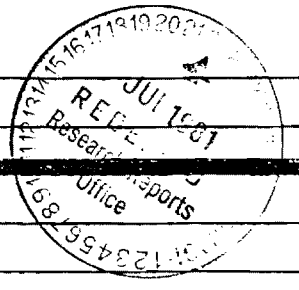
Defense Priority Rating: None

RESTRICTIONS

See Attached _____ Supplemental Information Sheet for Additional Requiremen

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed



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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 12/8/81

Project Title: Millimeter Wave Trade Study

Project No: A-3001

Project Director: R. N. Trebits

Sponsor: Rockwell International Corp., Anaheim, CA

Effective Termination Date: 10/31/81

Clearance of Accounting Charges: 10/31/81

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other _____

Assigned to: RAIL-RAD (School/Laboratory)

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FORM OCA 10:781

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

November 24, 1981

Rockwell International Corporation
Defense Electronics Operation
3370 Miraloma Avenue
Post Office Box 3105
Anaheim, California 92803

Attention: J. J. Justus, D/280, Mail Code DF39

Subject: Final Technical Report on Rockwell International Contract A1EM-3000044, Georgia Tech Project No. A-3001, "Millimeter Wave Trade Study," covering the period June 26, 1981 through October 26, 1981

Dear Sir:

This letter report summarizes technical activities performed by Georgia Tech under Contract A1EM-3000044, designated Georgia Tech Project No. A-3001. Dr. Robert Trebits served as Project Director, and Mr. Benjamin Perry served as Associate Project Director. This report was written by Dr. Trebits and Mr. Perry, with additional contributions from Dr. Robert Hayes.

An objective of this overall program is to perform a trade study to determine the optimal transmission frequency for a missile-borne radar operating against mobile land targets. However, the actual contracted task to Georgia Tech as part of this program concentrated on an investigation of the land clutter backscatter data base relevant to the selection of an optimal radar frequency. These data include foliated, non-foliated, and snow-covered terrain backscatter in the frequency range of 17.5 - 140 GHz. Polarization effects and designated depression angles were also pertinent factors in the assessment of these data.

A listing of reports, papers, and other sources of millimeter wave backscatter data is contained in this report, including an assessment of applicability and utility to Rockwell's air-to-ground seeker development. While numerous data sources were identified, the number of sources available to Rockwell essentially is restricted to Government funded data collection programs, since other companies' data bases are proprietary when funding was provided internally. We believe that there are sufficient data, however, to develop an empirical clutter backscatter model in the specified frequency range that can be used in a radar frequency/detection trade study.

The Rockwell program associated with this Georgia Tech task is the development of a radar seeker concept for an air-to-ground missile operating against mobile land targets under various weather conditions, clutter backgrounds, and sensor configurations. The environmental parameters specified by Rockwell for the seeker engagement are summarized in Table 1.

Table 1. Environmental Parameters

Clutter	Trees and farmland; foliated, unfoliated, and snow covered
Weather	Clear air; rain at 4 mm/hour; fog with 100 m visibility
Targets	Tanks, APCs, trucks; stationary Nominal radar cross section of 5 m^2
Ranges	1, 2, 4, and 8 kilometers
Altitudes	0 to 1000 feet
Depression angles	Grazing to 20 degrees
Missile velocity	500 to 5000 ft/sec

The computation of radar detection performance requires geometric, target, and transmission medium data summarized in Table 1, plus data descriptive of the radar system. A set of radar system parameters provided by Rockwell is presented in Table 2. Three different size missiles are implied by the different antenna diameters listed. Several optional radar configurations are also implied through choices of range resolution, polarization, and transmission frequency.

Table 2. Radar System Parameters

Probability of Detection	0.9
Probability of False Alarm	10^{-5}
Transmission Frequency	17.5 to 140 GHz
Antenna Diameter	6, 12, and 18 inches
Transmitter Bandwidth	300 MHz

Table 2. Radar System Parameters (continued)

Range Resolution	0.5, 3, and 6 m
Receiver Noise Figure	$F_n = \frac{f(GHz)}{50} + 7 - \frac{220}{f^2}$ dB
System Losses	6 dB
Search Mode Scan Rate	100 degrees/sec, nominal
Search Scan Width	± 10 degrees
Full Scan Time	0.25 to 2 seconds
Antenna Beamshape	Circular pencil beam
Beam Sidelobe Level	-22 dB peak
Transmission Polarization	Linear (H and V) or Circular
Pulse Compression Ratio	250:1 and 1000:1
Tracking Mode	Monopulse processing
Receiver Response	Matched

The objective of the work contracted to Georgia Tech was to determine the availability of clutter backscatter data sufficient for generation of an accurate reflectivity model. Such a reflectivity model would be used in the computation of radar detection performance as a function of transmission frequency and other selectable radar parameters. The frequency range of interest to Rockwell for this air-to-ground missile application is essentially the millimeter wave band covering frequencies between K_u-band (17.5 GHz specified lower limit) and the mid-millimeter wave band region (140 GHz). Primary emphasis was placed at the 95 GHz atmospheric window region, with additional effort directed at the other windows at 35 and 140 GHz.

Sources of clutter backscatter data are listed in this report, with no order of importance implied. Persons associated with or responsible for each data set are also included where known, along with their associated organization. For technical reports and papers, the authors and their affiliations are listed. We have also indicated an assessment of these data sets' applicability to this Rockwell development program.

1. "Radar Foliage Penetration Measurements at Millimeter Wavelengths," N. C. Currie, E. E. Martin, and F. B. Dyer, Technical Report on Contract DAAA25-73-C-0256, Georgia Institute of Technology, 31 December 1975.

Tree backscatter at X-, K_u-, K_a-bands, and 95 GHz, 0 and 29 degree depression angles, horizontal and vertical polarizations.

2. "Land Clutter Characteristics for Computer Modeling of Fire Control Systems," R. D. Hayes and F. B. Dyer, Technical Report I on Contract DAAA25-73-C-0256, Georgia Institute of Technology, 15 May 1973.

   Land Clutter backscatter at 0 to 90 degree depression angles, horizontal and vertical polarizations. Trees, crops, gravel, and snow at X-band. Desert, gravel, and snow at K_u-band. Trees and crops at K-band. Trees, crops, gravel and snow at K_a-band. Crops and asphalt at 70 GHz. Crops and asphalt at 95 GHz.

3. "Radar Land Clutter Measurements at Frequencies 9.5, 16, 35, and 95 GHz," N. C. Currie, F. B. Dyer, and R. D. Hayes, Technical Report #3 on Contract DAAA25-73-C-0256, Georgia Institute of Technology, 2 April 1975.

   Tree backscatter at 2 to 20 degree depression angles, horizontal and vertical polarizations.

4. "Radar Propagation Through Dust Clouds Lofted by High Explosive Test - MISER'S BLUFF, PHASE II," E. E. Martin, Technical Report on P.O. #14313, prime Contract DNA 001-77-C-0269, for SRI International, Georgia Institute of Technology, October 1980.

   Dust and debris backscatter at 35 GHz, 0 degree depression angle, horizontal and vertical polarizations.

5. "Measurements of MMW Radar Transmission and Backscatter - DIRT II," F. C. Petito and E. W. Wentworth, Night Vision Laboratory, 1978.

   Dust and debris backscatter at 95 GHz, horizontal polarization.

6. "Radar Millimeter Backscatter Measurements, Volume I, Snow and Vegetation," N. C. Currie et al., Technical Report No. AFATL-TR-77-92, Georgia Institute of Technology, July 1977.

Snow backscatter at 10 degree depression angle, vegetation backscatter at 35 and 45 degree depression angles, 35 and 95 GHz.

7. "Reflectivity and Emissivity Characteristics of Snow, Ice, and Wet Ground at Millimeter Wave Frequencies," R. D. Hayes, J. A. Scheer, and T. L. Lane, Proceedings of the Eigth DARPA Tri-Service Millimeter Wave Conference, Georgia Institute of Technology and AFATL, April 1979.

35 GHz backscatter at 10 to 60 degree depression angles, horizontal and vertical polarizations.

8. "Terrain and Sea Scatter Workshop," F. Ulaby and J. A. Stiles, 1980, prepared by the University of Kansas Remote Sensing Laboratory.

Land and sea backscatter data and models at 10.7, 37, and 94 GHz and depression angles of 27 and 57 degrees.

9. "Microwave Remote Sensing of Snowpacks," W. H. Stiles and F. J. Ulaby, University of Kansas Remote Sensing Laboratory, Contract NAS9-15003 for NASA, June 1980.

Backscatter data of snowpacks at K_u- and K_a-bands, depression angles of 10 to 90 degrees, horizontal, vertical and circular polarizations.

10. "Millimeter Wave Radar Transmission Through High Explosive Artillery Barrages," F. C. Petito, Night Vision Laboratory, and R. L. Harris, Systems Planning Corporation, Proceedings of the Eighth DARPA Tri-Service Millimeter Wave Conference, April 1979.

Transmission data at 95 GHz and 0 degree depression angle.

11. "Effects of Smoke Obscurants on Millimeter Waves," J. E. Knox, Ballistics Research Laboratory, Proceedings of the Eighth DARPA Tri-Service Millimeter Wave Conference, April 1979

Attenuation data at 35, 95, and 140 GHz

12. "Millimeter Foliage Penetration Measurements," N. C. Currie et al., AP-S International Symposium, Georgia Institute of Technology, 1976

Data at 10, 16, 35, and 95 GHz, 0 and 29 degree depression angles, horizontal and vertical polarizations. Note: This is the same data base quoted in 1.

13. "Comparisons of Microwave Winter/Summer Foliage Penetration, Part II," N. C. Currie and T. P. Morton, Georgia Institute of Technology, on Contract CX 1069 for MIT/Lincoln Laboratory, January 1977

Penetration data at 10 and 16 GHz, 29 degree depression angle, horizontal and vertical polarizations

14. "Radar Backscattering Data for Agricultural Surfaces," T. L. Oliver and W. H. Peake, Technical Report TR 1903-9 on Contract NSR-36-008-027, Ohio State University, February 1969.

Agricultural crops backscatter data at 1.8, 10, 15, and 35 GHz, at 20 to 70 degree depression angles, horizontal and vertical polarizations.

15. "Near-Millimeter Wave Technology Base Stude, Volume I: Propagation and Target/Background Characteristics," S. M. Kulpa and E. A. Brown (co-chairman), U.S. Army ERADCOM, Harry Diamond Laboratory, November 1979.

Propagation and backscatter data from 10 to 213 GHz and far infrared, 0 to 90 degree depression angles, horizontal and vertical polarizations.

16. "Reflectivity and Emissivity of Snow and Ground at Millimeter Waves," R. D. Hayes, N. C. Currie, and J. A. Scheer, Georgia Institute of Technology, on Contract F08635-76-C-0221 for Eglin AFB, April 1976.
Note: above also found in IEEE 1980 International Radar Conference Proceedings.

Active and passive data from 10 to 60 degree depression angles, 35 and 95 GHz, horizontal and vertical polarizations.

17. "Some Properties of Radar Returns from Rain at 9.375, 35, 70, and 95 GHz," N. C. Currie, F. B. Dyer, and R. D. Hayes, IEEE Radar 75 Conference, Georgia Institute of Technology, 1975.

Horizontal, vertical, and circular polarizations

18. "Backscatter from Ground Vegetation at Frequencies Between 10 and 100 GHz," R. D. Hayes, F. B. Dyer, and N. C. Currie, APS-International Symposium, Georgia Institute of Technology, October 1976.

Data at 2 to 23 degree depression angles, horizontal and vertical polarizations.

Sources number 19 through 24 are from the IEEE Eastern 79 Conference Record, October 1979.

19. "Atmospheric Attenuation at Millimeter and Submillimeter Waves," Vincent J. Falcone of the Air Force Geophysical Laboratory, Hanscomb AFB, and L. W. Alreau.
20. "Atmospheric Turbulence Effects on Millimeter Wave Propagation," R. W. McMillan and J. C. Wiltse, Georgia Institute of Technology

Data at 94 and 140 GHz.

21. "140 GHz Multipath Measurements Over Varied Ground Covers," H. B. Wallace, BRL

Multipath measurements over asphalt at a 0 degree depression angle.

22. "Multifrequency Millimeter Radar Sea Clutter Measurements," R. N. Trebits, N. C. Currie, and F. B. Dyer, Georgia Institute of Technology.

Data at 9.5, 16.5, 35, and 95 GHz, horizontal and vertical polarizations, 0.5 to 7.8 degree depression angles.

23. "95 GHz Pulsed Radar Return from Trees," R. D. Hayes, Georgia Institute of Technology.

Foliated tree backscatter data from 2 to 30 degree depression angles, horizontal and vertical polarizations lumped.

24. "Millimeter Wave Propagation in Smoke," J. E. Knox, BRL

Data at 35, 94, and 140 GHz, 0 degree depression angle.

25. "Millimeter Wave Propagation Measurements Over Snow," D. T. Hayes of Hanscomb AFB, U. H. W. Lammers, R. A. Marr, and J. T. McMally, EASCON 1978

Terrain and sea backscatter data at 35, 98, and 140 GHz, 15 to 90 degree depression angles, horizontal and vertical polarizations.

26-30. DARPA/Tri-Service Millimeter Wave Work Shops and Conferences, Applied Physics Laboratory, December 1974; San Diego, November 1976; Harry Diamond Laboratory, November 1977; Eglin AFB, April 1979, Huntsville, October 1981.

31. "Millimeter Wave Reflectivity of Land and Sea," R. N. Trebits, R. D. Hayes, and L. C. Bomar, Microwave Journal, Georgia Institute of Technology, August 1978.

Backscatter data from 9.5 to 95 GHz, horizontal and vertical polarizations, 2 to 90 degree depression angles.

32. "A Model for Predicting the Rain Backscatter from a 70 GHz Radar," Alan Downs, BRL Report MR 2467, March 1975.

    Uses Richard and Kammerer data

33. "Radar Clutter Models at 95 GHz," R. D. Hayes, U.S. Army ARRADCOM Memorandum Report ARSCD-MR-80001, Georgia Institute of Technology, September 1980.

    Foliated tree and agricultural crop backscatter models at 95 GHz.
    Uses data at 9.375, 35, and 95 GHz and depression angles under 25 degrees.

34. Target and Background Information Library System (TABILS), Millimeter Wave Data Base at Eglin AFB; Jim McLaughlin responsible.

    Backscatter data at 35 and 95 GHz, depression angles of 12, 30, and 75 degrees, horizontal and vertical polarizations; high resolution clutter cells.

35. STARTLE Measurements with Martin-Marietta Radar System, Night Vision and Electro-optics Laboratory, Ft. Belvoir, Virginia; Bill Ealy responsible.

    Coherent, ground-to-ground, 95 GHz backscatter data of ground clutter, trees, vegetation, military targets.

36. Snow and Ice Backscatter, Cold Region Laboratory, SNOW I Conference Record (to be printed in 1982).

Backscatter, emissivity, and propagation data have been identified on this effort at the atmospheric windows above K_u-band, at 35, 95, and 140 GHz. For frequencies

above 17.5 GHz the data base thins out rapidly. However, several isolated frequency applications are worthy of note. An FAA radar, the ASDE II (Airport Surface Detection Equipment), operates near the water absorption line near 22.4 GHz, so presumably the FAA possesses K-band backscatter data at a variety of depression angles. A Sperry FM/CW radar implementation for a missile uses millimeter wave frequencies, but corresponding data collected of background/target backscatter appears to be company proprietary.

There are several government-owned data bases at 35, 95, and 140 GHz available to contractors on Government funded development programs and also may be available for IR&D projects. The quantity of data at 35 and 95 GHz is essentially comparable, but only a single source was identified at 140 GHz. Data are scheduled to be collected within the next several years on two radar systems at 220 GHz, one of which was designed and constructed by Georgia Tech for the Night Vision and Electro-optics Laboratory (reference Dr. Ward Trussel, responsible person).

At the lower end of the frequency band of interest, there are at least three data sets available for Government funded programs. K_u-band data were collected on the MICOM MARFS program and should be available through Lloyd Root, MICOM, in Huntsville. MIT Lincoln Laboratory also has K_u-band backscatter data in connection with the HOWLS program, and Don Temme is the appropriate contact there. Finally a considerable amount of clutter backscatter data have been collected by the Georgia Tech Engineering Experiment Station as part of several government funded efforts. These data are also available to users for both Government and commercial applications. Nick Currie is the responsible person at Georgia Tech for these data.

K_a-band backscatter data ($\sim$ 35 GHz) are available from several sources. Dick McGee at the Army's Ballistic Research Laboratory is a contact for SADARM and STAFF program data, including radiometric data. Georgia Tech Engineering Experiment Station data at 35 GHz collected for the Air Force Armament Laboratory are available through Nick Currie at Georgia Tech. These data included backscatter from snow-covered and wet terrain and were collected in coherent, swept frequency, and polarization diverse radar modes. Georgia Tech also contributed coherent 35 GHz backscatter data, collected from an airborne platform, to the Air Force's TABILS data base. TABILS is discussed in more detail later in this report.

Backscatter data at 95 GHz are available at the Ballistic Research Laboratory and through the HOWLS program at Lincoln Laboratory. The Georgia Tech Engineering

Experiment Station has additional terrain backscatter data available through Nick Currie. A large quantity of 95 GHz data resides at the Night Vision and Electro-optics Laboratory at Ft. Belvoir, Virginia. Bill Ealy is the responsible person there for the STARTLE development program. Data have been collected by NVEOL personnel at Camp A. P. Hill, Virginia, using the Martin-Marietta Corporation STARTLE system. The Camp Hill terrain is made up of gently rolling hills, with tree line boundaries. Near zero grazing angle measurements of terrain and vehicle backscatter have been made. Vehicle backscatter data include stationary targets, with and without engines running, plus moving targets in clear areas and against tree lines, at a variety of target aspect angles and radial velocities. Reduced data are estimated to be completed and available in approximately six months.

NVEOL personnel will repeat these measurements with the Rockwell STARTLE system starting in early 1982. A year's time has been estimated to collect and reduce the data associated with the Rockwell STARTLE system.

The Air Force TABILS data base also contains airborne-collected 95 GHz backscatter data. The Environmental Research Institute of Michigan (ERIM) collected these data for TABILS at the same time that Georgia Tech collected 35 GHz backscatter. A second Air Force 35-95 GHz airborne measurement program is under preparation for Europe in early 1982. Data collected on this program will also become part of the TABILS data base.

The Target and Background Information Library System (TABILS) is a comprehensive data base of target and terrain signature data collected by various measurement programs. Of interest to Rockwell's millimeter wave system development efforts are the 35 and 95 GHz data collected by ERIM and Georgia Tech during 1980. TABILS data include many types of terrain characteristic of eastern Europe: plowed fields, forests, urban areas, and various fields of agricultural crops. Military targets were characterized at both frequencies for a variety of radar modes, polarizations, and depression angles. TABILS is accessible through remote computer terminals to Department of Defense agencies, as well as to Government funded educational institutions and corporations. The actual imagery data are stored at Eglin AFB, Florida on a master tape.

Backscatter data at 140 GHz were identified only at the Army's Ballistic Research Laboratory (Dick McGee). The utility of these data to Rockwell was not determined.

The quantity and quality of accessible data at 35 and 95 GHz suggest that clutter backscatter models can be generated at least at these frequencies in the millimeter wave band. Extrapolation of clutter models upward in frequency from K_u-band, but perhaps not all the way to 140 GHz is feasible with the accessible data.

Much more millimeter wave backscatter data have been identified that are company proprietary to such companies as Martin-Marietta, Sperry, Hughes, and Westinghouse, among others. These data will not be accessible, of course, to potential competitors of millimeter wave system development programs, except on the basis of a particular teaming arrangment.

The next obvious step in this Rockwell program is the indicated clutter modeling and a study of adverse weather losses and backscatter characteristics of rain, snow, ice fog, clouds and ground fog, through at least 95 GHz, before the transmission frequency trade study needed for an air-to-ground missile application. A sufficient quantity of useful data is accessible to Georgia Tech to perform the first task of backscatter modeling. At that point, we will be able to properly address the trade study of radar frequency selection for this application.

Respectfully submitted,

Robert N. Trebits
Project Director

APPROVED:

J. D. Echard, Chief
Radar Applications Division