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FINE-SCALE MEASUREMENTS OF MICROWAVE REFRACTIVITY PROFILES WITH HELICOPTER AND LOW-COST ROCKET PROBES

The recent development of computer models that can accurately predict radar performance under ducting or other anomalous propagation conditions has produced a need for high-resolution profiles of microwave refractivity in the lower troposphere. This article contains a brief description of two systems that can make the required meteorological measurements for use in those models. The first system is helicopter-based and has been used for research purposes to verify model performance. The second uses a low-cost rocket to carry a lightweight telemetry package to the desired altitudes. The rocket system shows promise for shipboard use where accurate, high-resolution refractivity profiles near the ocean surface are required.

INTRODUCTION

The development of the Electromagnetic Parabolic Equation (EMPE) computer code at APL has provided a tool for producing detailed maps of radar coverage for Navy radars. The validation of this computer code for making accurate predictions of radar coverage at low altitudes is described in an article by Dockery and Konstanzer elsewhere in this issue. To provide maximum prediction accuracy with the model, fine-scale vertical profiles of temperature, pressure, and relative humidity must be made within the region for which radar coverage is to be calculated. These parameters are used subsequently in determining microwave refractivity.

In the past, radiosondes have been used to make the types of measurements required for radar models. Conventional radiosondes, carried by balloons, can telemeter temperature, pressure, and relative humidity at sampling intervals of roughly 100 m in altitude. However, in order to calculate accurately the effects of meteorological parameters on the radar at low altitudes where significant variations can occur, measurements with a vertical resolution of a few meters extending to the water surface are usually required. Conventional balloon-borne radiosondes launched at sea from ships provide contaminated measurements in the vicinity of the ship because of the microclimate created by it. In addition, we cannot obtain essential measurements at altitudes below the normal deck level at which the radiosonde is released.

During the validation phase of EMPE, a system was constructed that is carried aboard a commercial helicopter. Although the helicopter instrumentation was originally conceived as a research tool to validate the EMPE code, it has been used and upgraded over a three-year period and has culminated in a useful and reliable operational tool for making routine meteorological measurements in support of numerous Navy tests.

To use the EMPE code or any other accurate propagation model for Navy ship operations when an instrumented helicopter is not available, a low-cost disposable system has been developed that may be launched to the desired altitude from a ship by means of a rocket. An instrument package is ejected from the rocket and is parachuted to the surface while telemetering to the ship the required fine-scale measurements of temperature, pressure, and relative humidity.

REFRACTIVITY MEASUREMENTS WITH THE HELICOPTER SYSTEM

A commercial helicopter, a Bell Jet Ranger, was chosen as the platform from which to make the experimental meteorological measurements because of its ability to make rapid soundings from the surface to an altitude of over 1500 m and because of its widespread availability in most localities where Navy tests are performed. Lightweight portable equipment was constructed that is easily mounted to the helicopter. Figure 1 shows an overall view of a Bell Jet Ranger as it was outfitted for a recent test at the NASA facility at Wallops Island, Va.

Figure 1—The Bell Jet Ranger helicopter used for making refractivity measurements.

Modified refractivity, M, is the input quantity for the EMPE code. A graphical display of modified refractivity versus altitude in real time has proven to be essential to gather data effectively with the helicopter. This is a convenient descriptor since negative slopes that appear in real-time plots are indicative of ducting regions.[1] Once the regions are identified, additional measurements are taken there. Modified refractivity may be expressed as[2]

$$M = \frac{77.6}{T}\left(p + \frac{48.1\, Re_s}{T}\right) + \frac{z}{r \times 10^{-6}} \, , \quad (1)$$

where T is the temperature in degrees Kelvin, p is the total pressure in millibars, R is the relative humidity in percent, e_s is the saturation water vapor pressure in millibars measured at temperature T, z is the altitude above sea level in meters, and r is the earth's radius in meters. The saturation water vapor pressure is dependent only on temperature.

Temperature, pressure, relative humidity, and altitude are measured independently on board the helicopter and are used to calculate modified refractivity. Temperature is measured with a thermistor having a 0.5-s response time. Relative humidity is measured with a VIZ premium carbon-film humidity element—a sensor that is similar to, but more precise than, the one used in National Weather Service radiosondes. The response time of the humidity sensor is 0.5 s at 25°C. Absolute pressure is measured by a conventional capacitive sensor. Altitude is measured with a radar altimeter to a resolution of 0.3 m between 0 and 1000 m.

All sensors are digitized at a 2-Hz rate to a 12-bit precision by an analog-to-digital converter interfaced with an IBM-compatible microcomputer. The computer converts all raw digitized measurements to engineering units, calculates modified refractivity, and displays a continuously updated plot of modified refractivity versus altitude on a computer monitor. A hard-copy printout of the modified refractivity plot is available on a dot matrix printer. In addition, pressure, temperature, relative humidity, altitude, modified refractivity, and time are recorded on a floppy disk for future analysis or for input to EMPE. Figure 2 is a view of the computer data acquisition system fastened to the rear passenger seat of the helicopter. Figure 3 is a closeup view of the temperature-humidity and static-pressure probe mounted beneath the aircraft and the plate on which the radar altimeter antennas are mounted. The housing attached to the front of the rectangular box on the end of the slender pole contains the temperature and humidity sensors. The curved tip creates a partial vacuum that pulls in air around the slots visible just in front of the box. The probe protects the humidity element from heating errors caused by direct sunlight and from damage by high-speed airflow. It also helps prevent cloud particles and light rain from impacting the sensor and permanently degrading its performance. The low-cost precalibrated humidity element is replaced daily or whenever it becomes wet.

All measurements are made while the helicopter is flying at an airspeed greater than 30 m/s to ensure proper flow through the sensor probe. Soundings are made with the helicopter ascending or descending at a rate of 1.5 to 3 m/s. With a sampling rate of 2 Hz, a vertical resolution of roughly 0.75 to 1.5 m is obtained. Under those conditions, the relatively high forward airspeed coupled with a low vertical speed ensure that the main rotor wake is well below and behind the helicopter and that uncontaminated air is being sampled.

On a number of occasions, helicopter measurements have been compared with those from conventional radio-


Figure 2—The data acquisition computer and sensor electronics strapped to the rear seat of the helicopter.

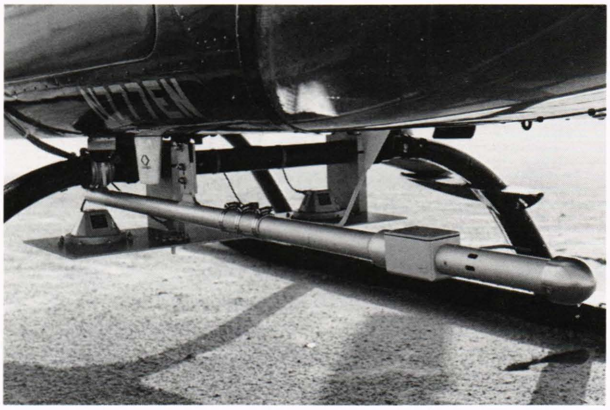

Figure 3—Closeup view of the meteorological probe. The housing at the end of the pole contains temperature and humidity sensors; the small probe to the right is the static port for measuring atmospheric pressure. The radar altimeter antennas are located on the horizontal plate bolted to the helicopter skid support.

sondes. Although the helicopter measurements have a much better spatial resolution than do those of the radiosonde, the comparisons are otherwise considered excellent. The result of one such comparison made at Wallops Island is shown in Fig. 4. The helicopter circled the radiosonde from the time of release and ascended at nearly the same rate. The figure shows the fine refractivity detail that is available with the helicopter data (dotted line) and the rather coarse data obtained from the conventional radiosonde (solid line), which samples temperature, pressure, and relative humidity at intervals of approximately 100 m. Refractivities measured with the radiosonde at the surface are not generally considered to be accurate since they are obtained before the balloon is released and therefore without airflow through the instrument. Poor agreement at the surface is not considered significant.

In the future, a loran-C receiver will be used to determine the helicopter's position independently of radar tracking in areas where loran reception exists. The data will be recorded on the computer disk. In addition, a downward-pointing infrared radiometer will be used to record surface water temperature in an effort to explain the horizontal variability of refractivity profiles occasionally observed in coastal areas.

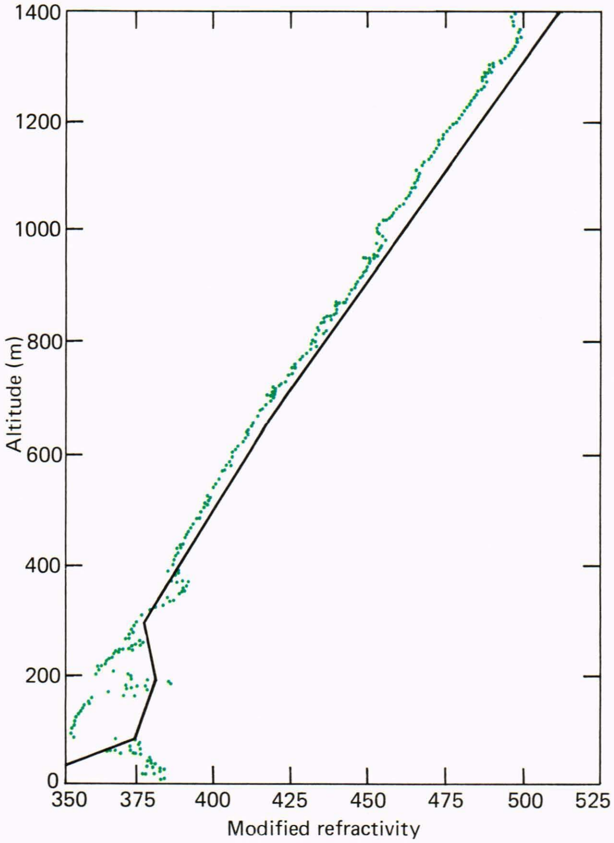

Figure 4—Comparison of helicopter-measured modified refractivity (dotted line) with radiosonde-measured modified refractivity (solid line). The data were taken on Aug 15, 1985, at Wallops Island, Va., at 1343 to 1351 EDT.

REFRACTIVITY MEASUREMENTS WITH THE ROCKET SYSTEM

The helicopter system has been shown to describe accurately the modified refractivity profiles and it has been used successfully for many Navy ship radar tests. At times, however, there have been requirements to measure refractivity profiles when it was impossible or inconvenient to use the helicopter system. Therefore, a simple, low-cost, disposable rocketsonde system was developed using off-the-shelf hobby rocket components. Figure 5 shows the prototype rocket in its launcher. The rocket is now being manufactured for APL by Flight Systems, Inc., Raytown, Mo.

The nonmetallic rocket is electrically fired from the launcher and carries the instrument package to an altitude of 150 to 800 m, depending on the size of the engine. At peak altitude, a time delay that is integral to the engine fires a small charge that ejects the package. The package, which is attached to a parachute 1 m in diameter, then descends at a nominal rate of 2 m/s, while the lightweight rocket body and nose cone tumble safely to the surface.

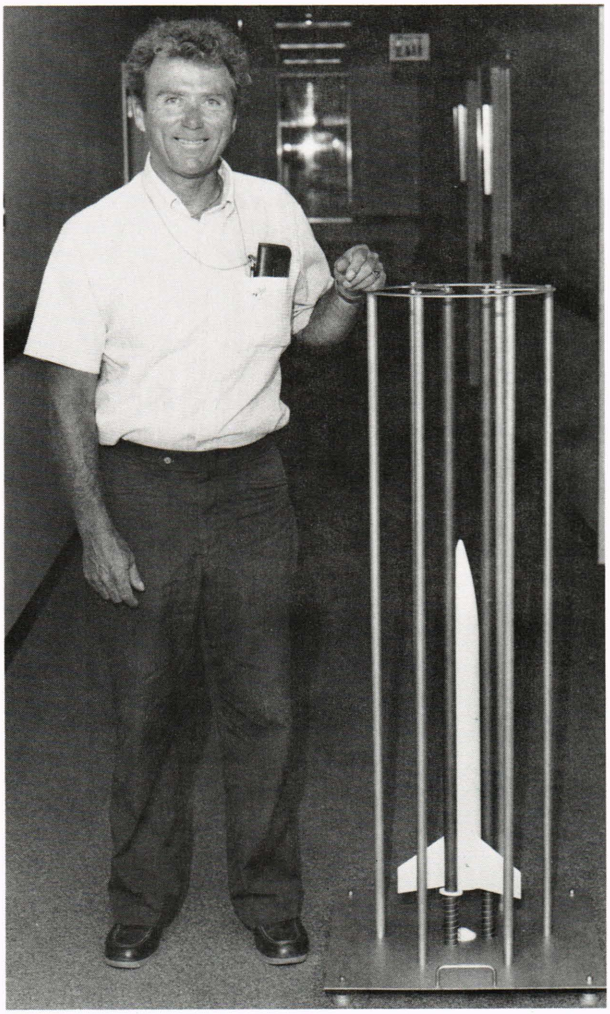

Figure 5—A complete rocketsonde installed in the launcher.

The instrument package is a commercially available unit that telemeters temperature, pressure, and relative humidity to a nearby receiver. The altitude is derived from the pressure measurement. The data are displayed in real time on a dot matrix printer and recorded on a computer disk interfaced with the receiver system. The entire data acquisition system and the disposable instrument packages are manufactured by AIR, Inc., Boulder, Colo. All data recorded thus far during actual tests have been telemetered at 5-s intervals. A new system now available at APL will allow a complete set of measurements to be made at 1-s intervals. At a descent rate of 2 m/s and a 5-s sampling rate, a vertical resolution of roughly 10 m is obtained; the 1-s sampling rate will yield a vertical resolution of 2 m. The pertinent characteristics of the rocket system are listed in Table 1; Fig. 6 shows the individual components.

The low-density nonmetallic rockets are extremely reliable and very safe. Experiments at APL in which the rocket nozzles were deliberately obstructed so that the motor cases ruptured after ignition resulted in immediate extinguishment of the propellent. Fragments of the motor case had such a low momentum that they were completely stopped by the thin wall of the rocket body.

Rocketsondes have been used to support several radar propagation tests. On a number of occasions they have been launched from ships at sea, although not yet from Navy ships. Test firings have been made from vessels as small as 7 m long. Several tests in Puerto Rico and at Kwajalein Atoll have demonstrated that Navy shipboard use of the rocketsondes should be reliable.

Figure 7 shows a comparison of low-elevation rocketsonde data with helicopter data taken in the vicinity of the rocketsonde at nearly the same time. The relatively coarse altitude resolution of about 10 m for the rocketsonde can be compared to the 0.75- to 1.5-m resolution of the helicopter. With the forthcoming introduction of high-resolution instrumentation, a 2-m resolution is expected. All comparisons of the rocketsonde with helicopter data have shown extremely good agreement.

CONCLUSIONS

Helicopter measurements of pressure, temperature, and humidity have proven highly effective in arriving at high-resolution profiles of modified refractivity in three-dimensional space. The measurements may easily be repeated to check for consistency, and variabilities as functions of space and time may be established. Real-time readouts of modified refractivity permit the immediate characterization of the ducting environment for Navy test predictions and for ensuring adequate data collection for later EMPE computations.

The low-cost rocketsonde that measures modified refractivity is a reliable and low-cost tool for making the

Table 1—Rocketsonde characteristics.

Rocket length	66 cm
Rocket diameter	63.5 mm
Total launch weight	453 g
Instrument package weight	113 g
Parachute size	91.4 cm
Rocket propellent	Ammonium percholate-polyurethane
Propellent weight	56 g for 757-m-altitude motor
Total cost per shot:	
All materials lost	$160
Rocket and package recovered	$10

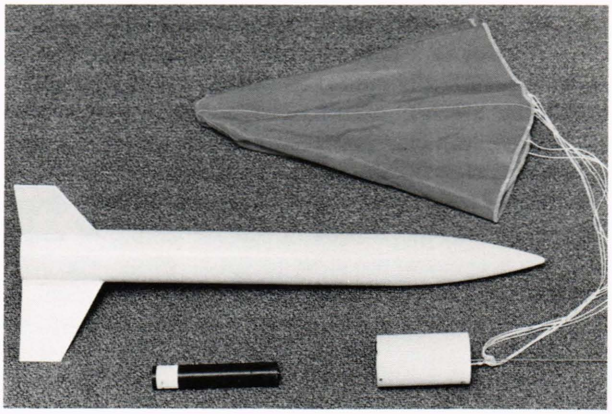

Figure 6—Component parts of the rocketsonde including the rocket body, engine, and instrument package attached to a parachute.

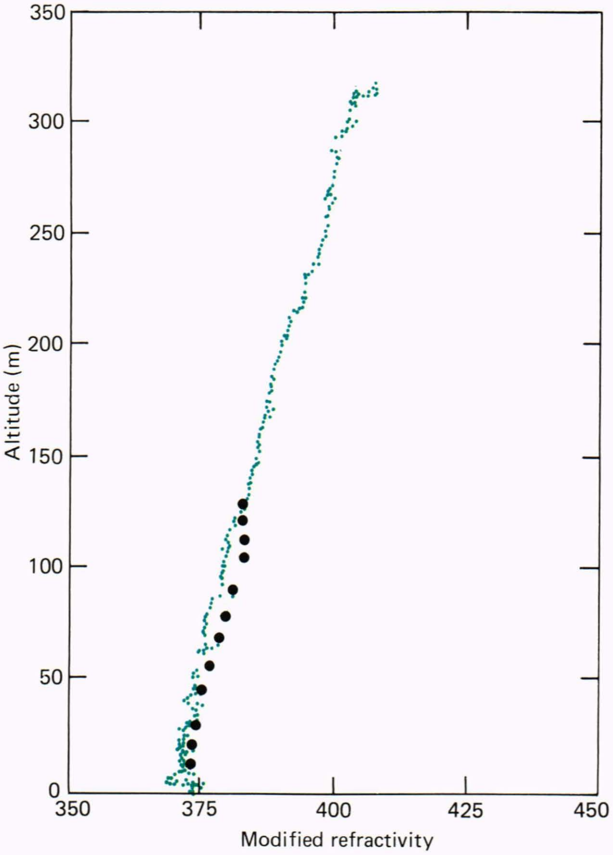

Figure 7—Comparison of vertical refractivity profiles measured with the helicopter (dotted line) and the rocketsonde (closed circles). The data were taken in Puerto Rico on Sep 16, 1986.

high-resolution measurements required for sophisticated radar propagation models. Rocketsondes may be launched from Navy ships and may be used under circumstances in which the use of a helicopter system is inconvenient or impossible.

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[1] H. W. Ko, J. W. Sari, and J. P. Skura, "Anomalous Microwave Propagation Through Atmospheric Ducts," *Johns Hopkins APL Tech. Dig.* **4**, 12–26 (1983).

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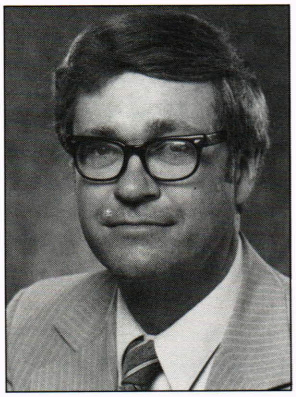
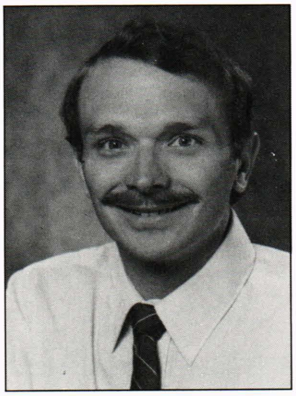
THE AUTHORS



JOHN R. ROWLAND received the B.S.E.E. degree in 1968 from Kansas State University. After joining APL in 1968, he studied clear-air turbulence and precipitation using radar and other remote and in-situ sensors. Since then, he has developed automated techniques for analyzing ocean-wave spectra and raindrop-size spectra and has conducted studies related to the remote detection and identification of insects with radar and lidar. His current responsibilities include the study of meteorological effects on radar ducting.



STEVEN M. BABIN was born in Oklahoma City in 1954 and received a B.S. with special distinction in engineering physics in 1976. He received an M.D. in 1980 from the University of Oklahoma and an M.S.E.E. from the University of Pennsylvania in 1983. He has been employed at APL in the Space Geophysics Group since 1983. His work has included Seasat SAR image analysis and X-band radar backscatter studies of internal ocean waves. During the past three years, he has been involved with research associated with measurements of the refractive index using in-situ and remote-sensing methods.