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SURVEY OF METEOROLOGICAL REMOTE SENSORS

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16. Abstract

The preliminary results of a survey are presented which identify techniques for determining meteorological data by remote sensing, applicable to automatic data buoy platforms. Both passive and active techniques are reviewed with emphasis on the former, in view of their more advanced development status. The principal references listed in the bibliography section of the memorandum indicate that experimental data to date have been obtained using only stable instrument platforms in a clean environment. Operation on unstable instrument platforms in the severe ocean environment requires further study.

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SURVEY OF METEOROLOGICAL REMOTE SENSORS

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1.0 INTRODUCTION

This memorandum contains the findings of a preliminary survey performed to identify techniques for the remote measurement from automatic data buoy platforms of the following meteorological parameters: air temperature, air pressure, dew point, wind direction and speed, cloud cover, cloud-base height, and atmospheric electricity (altitude range from sea level to 9,000 meters).

The survey indicated various passive and active techniques potentially capable of measuring one or more of these parameters. Some of the techniques are in an early exploratory phase and require intensive development in order to warrant serious consideration; others are already in actual field use and appear applicable without major modifications. In this memorandum, a brief descriptive section is devoted to each individual pertinent technique, including an assessment of capabilities, limitations, and development status. The bibliography lists the principal publications to which reference should be made if more detailed information is desired.

Among the techniques identified, three passive methods have attained the necessary level of development for automatic unattended operation. For this reason, they take precedence in the order of presentation. The first two, microwave and infrared passive radiometers, are presently performing successfully in aircraft and in orbiting satellites. Microwave radiometers operate near the resonance of molecular oxygen (60 GHz) and of water vapor (22.5 GHz) and measure the profiles of atmospheric temperature, humidity, and total liquid water content (cloud, fog, rain). Infrared radiometers operate in and near the carbon dioxide bands (4.3 or 15 microns) and the water vapor band (6.3 microns) and measure the profiles of atmospheric temperature, humidity, and cloud ceiling. The third technique, which utilizes a passive network of ground stations to detect electromagnetic radiation in the 3 to 30 kHz band from distant lightning discharges (sferics), has been used for some time. The remaining passive and active techniques described in the memorandum require further study and development before their feasibility for data buoy service can be assessed. One method is the cross correlation of optical signals in the spectral range 0.3 to 1.2 microns. It appears potentially promising for measuring wind velocity. The other method is radar, utilizing lasers, microwaves, or acoustics. Observations of an exploratory nature have been reported of cloud ceiling measurements with laser radar, probably the most promising potential use of this technique. Exploratory results are also available on the application of acoustic radar for the measurement of the vertical profile of wind speed and direction, the vertical profile of atmospheric humidity, and the location and intensity of temperature inversions.

2.0 TECHNICAL DISCUSSION

2.1 Sources of Information

The necessary background regarding the objectives of the National Data Buoy Development Project was obtained by highly informative discussions with personnel of the U.S. Coast Guard and with the staff of their principal contractors, Texas Instruments, Inc., General Dynamics Convair Division, and the Travelers Research Corporation. Concurrently, information was collected from original papers and reviews in the technical literature. The most pertinent of these publications are listed in the bibliography section of this memorandum. Of particular value has been the Final Report, "Atmospheric Exploration by Remote Probes," by the Panel on Remote Atmospheric Probing to the National Academy of Sciences (see General References).

2.2 Passive Remote Sensing Techniques

As stated previously, these techniques are potentially the most promising for a data buoy system because of their successful performance on airborne and spaceborne instrument platforms.

2.2.1 Microwave Radiometers.- Microwave passive radiometers (ref. 1, 2) are capable of measuring the profiles of atmospheric temperature and humidity, and also the total atmospheric liquid water content, except under conditions of heavy rain. Observational data obtained with an airborne instrument (ref. 3) have been published and a satellite (Nimbus-E) equipped with a microwave radiometer was launched in April, 1970. The atmospheric temperature profile (ref. 4) is obtained by observing radiation emitted by molecular oxygen near 60 GHz (5 mm) where there is a group of some 40 frequencies characteristic of oxygen. At low pressures, these frequencies are discrete; at high pressures, owing to pressure-broadening, they merge into a continuous frequency band. Appropriate frequency channels can be selected where the radiation received corresponds to a particular altitude level of the atmosphere. The intensity of this radiation depends on the temperature of the atmosphere at that altitude. Consequently, a vertical temperature profile can be constructed based on the data recorded by the multi-channel receiver. For altitudes up to 5 km, the results are accurate within 1°K to 2°K. The altitude resolution of the profile is highest near ground level (0.1 km) and decreases to about 5 km, at an altitude of 10 km. The presence of thick clouds decreases the accuracy of measurements above the cloud. The required observation time ranges from a few seconds to ten minutes, depending upon the desired accuracy.

Liquid water content and the humidity profile of the atmosphere can be measured by observing radiation near 22.5 GHz

(1.35 cm) emitted by water vapor, in conjunction with a determination of the dew point at the surface. The accuracy of the method is claimed to be better than 5 percent. With the vertical distribution of the temperature and moisture established, the atmospheric pressure profile as a function of altitude can be derived from the hypsometric formula together with the surface pressure as a reference point. Microwave radiometers are costly. For example, the instrument on Nimbus-E (weight 70 lbs., power consumption 35 w) costs $250,000. The cost of a similar instrument produced in quantity for use on data buoys is estimated to be about $25,000. Further cost-reduction can be achieved by reducing the number of channels which, in turn, reduces the available altitude resolution.

2.2.2 Infrared Radiometers.- In regards to infrared radiometric techniques for remote meteorological measurements, the findings are as follows: Infrared radiometry, thus far, is the most successful technique for determining profiles of atmospheric temperature and humidity and for measuring the temperature and ceiling of clouds. Results obtained by several investigators with ground-based equipment have been published (ref. 5); signicantly, an infrared satellite radiometer which views the atmosphere from above presently provides the Weather Information Service with temperature and humidity profiles (ref. 6). Radiometric measurements and reduction of data are performed in the following manner. The atmospheric temperature profile is obtained by first measuring radiation emitted in and near the carbon dioxide bands (4.3 or 15 microns). Reduction of the data is then accomplished mathematically by "inversion" (ref. 7). Profiles obtained at 4.3 microns are better resolved in altitude than those obtained at 15 microns (and those at 5 mm, in the microwave region); however, the intensity of radiation at 15 microns is greater, measurements are made easier and in a shorter time. For best results, simultaneous measurements at both wavelengths are, therefore, desirable.

Once the atmospheric temperature profile has been established from measurements of radiation from carbon dioxide (whose relative concentration in the atmosphere does not vary with altitude), it is possible to determine the atmospheric humidity profile (the relative concentration of atmospheric water vapor is not constant with altitude). Measurements of the humidity profile are made at several wavelengths in the water-vapor band at 6.3 microns. Since there is some overlap of the water-vapor and carbon-dioxide bands, a small correction must be made in the temperature profile obtained from measurements of carbon dioxide radiation for effects of humidity. A much more pronounced dependence, however, exists on temperature as regards the humidity profile obtained from measurements of water-vapor radiation. Consequently, the temperature profile must first be corrected by an iterative mathematical manipulation before the humidity profile can be deduced accurately.

At infrared wavelengths, fog and haze degrade the accuracy of observations and clouds are opaque. Consequently, atmospheric profiles obtained from infrared observations under overcast conditions terminate at the cloud base. Under partial overcast, profiles can extend through openings in the clouds, provided that the angular resolution of the radiometer is sufficiently high. Since atmospheric transmission is considerably less degraded in the microwave region, all-weather capability requires a combination of microwave and infrared radiometry.

The first measurements of temperature profiles with a ground-based radiometer were performed in 1962 at the National Environmental Satellite Center in Suitland, MD, to establish the feasibility of the technique for ultimate use on satellites. Eight wavelength intervals in the carbon dioxide band at 15 microns were observed. Smoothed profiles were obtained to an altitude of about 1.3 km. The profiles were shown to be accurate to about 2°K by comparison with radiosonde measurements. It was also shown that results nearly as accurate could be obtained using only four wavelength intervals in the 15-micron band. Currently, a ground-based infrared radiometer is being operated by the Convair Division of General Dynamics, San Diego. Eight channels are employed, six in the 15-micron carbon dioxide band, one in the 18-micron water-vapor band, and one in the 11-micron atmospheric window. Temperatures are determined to an accuracy of 2°K at six altitude levels, typically 0.1, 0.3, 0.5, 1, 3, and 7 km. The altitude resolution of the profile is best near ground level (0.1 km) and decreases to about 4 km at the highest altitude (7 km).

Weight and power consumption of infrared radiometers are modest. Present satellite instruments, for example, range from 10 to 100 lbs in weight and consume from 2 to 20 w. As to cost, the above mentioned Convair instrument is an engineering prototype developed for about $100,000. Produced in quantity for use in a data buoy system, it would, of course, be less costly, probably by at least a factor of five. The computer time needed for data analysis is inexpensive, typically ten profiles are computed for less than $5.

2.2.3 Detection of Lightning Discharges.- Electromagnetic disturbances produced by distant lightning are called sferics (ref. 8). Lightning consists of a multiplicity of electrical discharges which may persist for periods up to one second. The individual discharges produce electrical signals which may be of large amplitude in the very low frequency range (VLF, 3 to 30 kHz), of moderate amplitude in the transitional frequency range (3 to 30 MHz), and of small amplitude in the high-frequency range (0,3 to 3 GHz).

Electromagnetic disturbances also occur during a period from 10 to 30 minutes before the first lightning discharge (ref. 9). They are caused by minor discharges between electrically charged atmospheric cells. Such precursor discharges can be detected at frequencies near 10 MHz and serve as early warning of thunderstorm activity.

The simplest and least costly scheme which provides information on lightning activity in a given locality consists of a low-frequency narrow-band receiver with a threshold signal level which can be preset. This type of lightning detector has only limited range. The location and intensity of more distant storms is established by triangulation using the directional characteristics of a network of receiving stations with crossed-loop antennas. Since VLF signals propagate over distances of thousands of kilometers, a relatively small number of receiving stations suffice for this purpose. The intensity of a storm can be estimated by the rate at which the signals are received.

2.2.4 Cross Correlation of Passive Optical Signals.- Winds and atmospheric turbulence can be measured remotely by a combination of passive radiometry with advanced data processing and statistical analysis (refs. 10, 11). Several natural sources of radiation are available for this purpose; namely, sunlight (daytime only) and thermal emission from carbon dioxide and water vapor (day and night). Small local variations in density, temperture, and aerosol concentration can cause fluctuations in scattered or thermal radiation. Cross-correlation of such fluctuations detected by two or more radiometers can provide information on atmospheric turbulence and motion. To date, this technique has been used up to an altitude of only 100 meters above the surface to measure wind velocity. Observations are reported in the spectral range 0.3 to 1.2 micron, utilizing the fluctuations of sunlight scattered by aerosol particles. The aerosol particles, carried along by the wind, serve as a tracer for the wind velocity. Two narrow-view telescopes, spaced a fixed distance apart are set to point skyward such that their optical axes are located in two parallel vertical planes which are approximately perpendicular to the wind direction. To establish the validity of the method, most of the measurements to date have been made at an altitude corresponding to the top of a meteorological tower where the wind velocity could be measured directly with an anemometer. The altitude at which the wind is measured depends on the wind direction. If the wind direction is exactly perpendicular to the parallel vertical planes containing the optical axes of the telescopes, then the altitude of measurement is the height at which the telescope beams would intersect if the two vertical planes were coincident. For all other wind directions, an eddy can only traverse both beams at the altitude determined by the angle between the beams and the wind direction. Since in a practical case both the wind speed and the wind direction vary, the result obtained with the cross-beam system represents a complex type of averaging over both altitude and time. If the wind direction is fairly constant within ±20° of the plane of the beams, then the altitude region over which the averaging takes place will be small, and the measurement can be considered to yield an average wind velocity at the crossing altitude.

In order to obtain measurements of mean wind speed that are accurate to within 5 percent of the anemometer readings on top of the tower, an observation time of about 45 minutes is required. Efforts currently in progress to improve observational techniques and data processing methods may be expected to increase the altitude range and accuracy of the technique.

2.3 Active Remote Sensing Techniques (Radar)

Radar techniques have been employed so far only for exploratory and feasibility studies in measuring the meteorological parameters of concern in this review. At optical and properly chosen microwave frequencies, the most promising application of radar is the measurement of the cloud ceiling (ceilometer). The optical radar (Lidar) (ref. 12) consists of a laser transmitter which can produce a short pulse of radiation (typically 10 nanoseconds with an energy content of about one joule) and a receiver which measures the time interval between the instants of transmission of the pulse and of reception of the return signal reflected by the cloud. The accuracy of the method depends on the manner in which the cloud boundary can be defined, and in theory, is better than one meter. The technique is potentially capable of also measuring the thickness and turbidity of clouds (ref. 13) and is being extended to the detection of fog banks and the determination of visibility in fog.

Conceptually, there are several other applications of Lidar (ref. 14) as described below which appear potentially attractive, particularly because of the exceptionally well-collimated beam of the laser source and its high-power density. However, a serious difficulty arises from the scattering of laser radiation by atmospheric particulates. Radiation at high intensity in the visible portion of the spectrum also presents a hazard to the human eye which requires extreme caution when applied to vertical probing in locations with frequent overflights by aircraft. With further development, the following applications of various types of Lidar show promise to lead to useful operational remote sensing systems:

Measurement of Wind Speed.- Velocity of air flow has been determined in wind tunnels by measuring the change of frequency of laser radiation scattered by particulate matter in the air stream. Flow velocities in the range from 0.5 cm/sec to Mach 3 have been measured in this manner in the laboratory, with accuracies better than 0.05% at the high end of the range and 50% at the low end (refs. 15, 16, 17).

Measurement of Humidity Profile.- The feasibility of determining the concentration profile of water vapor has been demonstrated to an altitude of 2 kilometers with an accuracy better than ±5% (ref. 18). Due to the presence of water-vapor molecules, a portion of signal reflected by the atmosphere undergoes a characteristic change in frequency (Raman scattering). The intensity of the radiation at this characteristic frequency as a function of altitude is a measure of the humidity profile.

Measurement of Temperature Profile.- The feasibility of measuring atmospheric temperature in the absence of clouds to an altitude of 15 kilometers has been demonstrated by G. Fiocco (ref. 19) (European Space Research Organization). This complicated technique utilizes a laser transmitter which produces radiation at a single frequency and a receiver which is capable of measuring the return signal, broadened in frequency by the thermal motion of the molecules, as a function of altitude. The reported accuracy of the measurement was within 1 degree of a simultaneous radiosonde observation.

In regard to the health hazards of laser radiation, technology is under development by DOD to produce laser sources at wavelengths in the near infrared (1.5 micron and up) where physiological damage does not occur. For hazardous lasers, damage threshold criteria based on pulse power, pulse duration, and integrated power are being established in order to maintain operational levels within safe limits.

Also under development are various methods to measure the profiles of wind speed and direction and the humidity profile by acoustic radar (refs. 20, 21). Acoustic radar offers the potential of three methods of measuring the wind profile. These methods are independent because they make use of three different characteristics of the return signal: the frequency spectrum, the angle of arrival, and the temporal distribution of the signal pattern across the ground. The possibility of using multi-frequency acoustic radar to derive the vertical profile of humidity has been pointed out by Little (ref. 22). The method makes use of the known dependence of acoustic absorption on humidity and temperature.

Acoustic techniques have several limitations the magnitudes of which remain to be determined. The most fundamental of these is the absorption of acoustic waves by the atmosphere which limits the present range to between 1000 and 2000 meters. Adverse weather conditions, such as strong winds, hail, and rain increase the ambient noise level. Man-made interference, a serious problem on land, need be of little concern at sea. Another drawback of acoustic radar is the low velocity of acoustic waves which limits the pulse repetition rate of the transmitter for large distances. The generally low cost of acoustic equipment and its reliability are features in its favor.

3.0 CONCLUSIONS

The foregoing material, clearly far from exhaustive, constitutes an initial overview of meteorological remote sensing which indicates the dearth of techniques pertinent to data buoy requirements. Apart from the three passive techniques emphasized in the initial section, the prospects are not encouraging. But even in the case of the various highly-developed passive radiometers and directional radio-frequency detectors, these devices presently operate only in a clean and stable environment. Severe weather, ocean spray, and the instability of the buoy platform present novel and difficult engineering problems which require solution. The utility and cost-effectiveness of any remote sensing system will largely depend on its long-term ability to function in the unfavorable ocean environment.

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