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DIRECTOR OF CENTRAL INTELLIGENCE

Science and Technology Advisory Panel

02 DEC 1981

MEMORANDUM FOR:

FROM: [redacted] STAT

Executive Secretary, Science and Technology Advisory Panel

SUBJECT: Atmospheric Remote Sensing

1. As a follow-up to our discussions with JPL personnel on atmospheric remote sensing, I would like you to prepare a list of questions on the subject which I will forward to JPL for answer. In the future, we may want to follow-up these questions with a visit to JPL to discuss them. In order to provide more background, and possibly assist you in formulating your questions, I am forwarding a list of JPL capabilities in remote sensing based upon (1) existing instrumentation, (2) instrumentation under development, and (3) analytical capabilities which have arisen from current remote sensing of planetary atmospheres.

2. I have also attached a copy of E. David Hinkley's recent article on advanced instrumentation for remote sensing. Mr. Hinkley is the manager of JPL's Planetary Atmospheres Section and Program Leader for Sensor Technology. I anticipate that he will be in the Washington, D.C. area on 15-16 December. It may be possible to meet with him again at that time.

3. I appreciate your participating in this effort and request that you forward your questions to the STIC Secretariat by Friday, 11 December for a consolidated request to JPL.

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FUTURE SPACE APPLICATIONS PAPER

Advanced Instrumentation for Remote Sensing[1]

E. D. Hinkley[2]

Abstract

The need to measure meteorological and chemical properties of the Earth's atmosphere on a global basis is becoming increasingly important, in view of concerns about air quality, depletion of the ozone layer, and changes in the Earth's radiation balance and weather patterns. Advanced techniques are now being developed at several research centers which will enable key measurements to be made which are now either impossible to make or in need of improvement. Remote sensing from Spacelab/Shuttle and free-flying satellites will provide the platforms for instrumentation based upon advanced technology. Several laser systems are being developed for the measurement of tropospheric winds and pressure, and trace species in the troposphere and stratosphere. With regard to other types of instruments, a high-spectral-resolution, passive infrared sensor shows promise for measuring temperature from sea level up through the stratosphere, and an advanced microwave sounding unit is under consideration for the measurement of temperature and moisture profiles as well as precipitation intensity for operational weather forecasting. For wind measurements in the stratosphere and mesosphere, advanced optical and microwave instruments are being developed. Microwave techniques are also useful for measuring meteorological parameters at the air-sea interface. The evolution and current status of such advanced instrumentation for future measurements from space are described in this paper.

Introduction

Several technologically-advanced instruments are being developed for global measurements of the Earth's atmosphere from Shuttle and free-flying satellites. The techniques involve transmission and/or detection of electromagnetic radiation, using

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[1] The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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principles of absorption, emission, fluorescence, or scattering. The wavelength range encompasses the microwave through the ultraviolet, and passive as well as active instruments are being developed.

Several recent publications have gone into detail about the feasibility of using advanced instruments for global measurements from space. Some of the more general ones are the NASA Shuttle Atmospheric Lidar Research Program Report [1], the NASA Upper Atmospheric Research Satellite Program Report [2], and the report of the NASA Working Group on Tropospheric Pollution Planning [3]. Other publications of a more specific and detailed nature will be cited below, especially with regard to basic equations and signal-to-noise analyses which would require too much space to be shown here.

This paper provides a survey of advanced instruments and techniques being explored for global measurements of the Earth's atmosphere. Where possible, comparisons are made with existing techniques, and estimates of the expected measurement accuracy, spatial resolution, temporal resolution, and altitude of optimum application will be given.

Principles of Remote Sensing

The basic physical principals on which most of the current remote sensing instruments for species and meteorological measurements are based are (1) absorption, (2) emission, (3) fluorescence, and (4) scattering [4]. Several of the techniques to be described involve two of these mechanisms simultaneously. A brief review of the basic principles is given in this section.

Absorption

Absorption of electromagnetic radiation by atoms or molecules serves as the basis for remote measurements of several key species. Since nearly all molecules have rich spectra in the infrared, between approximately 2 and 20 μm, and pressure-broadening does not produce as severe a change in spectral signature as it does at longer wavelengths, this region is generally recognized as being the most useful one for species measurements based upon absorption. The Earth's atmosphere itself also absorbs radiation (although the absorption is higher in the ultraviolet than in the infrared), and this, together with some other considerations to be mentioned below, make other wavelengths (e.g., microwave or ultraviolet) more attractive for certain species.

Mathematically, for radiation of wavelength λ, the presence of a molecular species with a density N (cm^{-3}) and optical cross-section σ (cm^2) at wavelength λ, the transmittance, T, of the radiation over a pathlength L (cm) is given by the Beer-Lambert equation:

$$T = \exp(-N\sigma L). \qquad (1)$$

Equation (1) holds for narrow-band instruments, such as most lasers, which have emitting bandwidths much narrower than the width of the spectral line being interrogated. For other instruments, such as some spectrometers, Eq. (1) must be modified, resulting in a smaller effective cross section, with concomitant loss in sensitivity and specificity.

Instruments based upon the absorption of radiation through the atmosphere can be either active (e.g., laser or microwave sources) or passive (e.g., spectrometers, interferometers), and the detection process may involve either direct or heterodyne techniques.

Emission

All atoms and molecules emit electromagnetic radiation when their temperature is above absolute zero. Thus, the detection of this emitted radiation has been incorporated into several passive spaceborne instruments and is being proposed for several more. Measurements of meteorological parameters as well as species can be made by detecting radiation emitted by the Earth's atmosphere.

Since passive heterodyne detection becomes more sensitive at longer wavelengths, the submillimeter and microwave regions are especially useful for detecting upper atmosphere species where pressure broadening is low and background transmission high. Detection of emissions lines in the infrared from certain minor species can also serve as the basis for measurements of such meteorological parameters as temperature and winds, based in the first case on a comparison of emission from bands in different wavelength regions, and in the second case by subtle shifts in emitted wavelength caused by the Doppler effect.

Fluorescence

If radiation of an appropriately short wavelength (high energy) impinges upon certain atoms and molecules, they can be made to fluoresce. Fluorescence measurements are specific in two ways: (1) the wavelength of the incident electromagnetic radiation must coincide with an absorbing wavelength of the species; and (2) the fluorescent emission wavelength is characteristic of the species as well. Laser radiation in the visible and ultraviolet regions of the spectrum has been most useful in enabling the remote sensing of atoms and molecules using fluorescence. Because fluorescence is quenched as background pressure increases, and to avoid absorption by oxygen and other major components, the use of fluorescence techniques to detect trace atoms and molecules is generally limited to the upper atmosphere.

Scattering

Scattering of electromagnetic radiation by atmospheric constituents can be used to provide information about the nature of the scatterers as well as the intervening atmosphere. Multiple-wavelength measurements of backscattering of laser radiation from atmospheric aerosols in the ultraviolet through infrared regions of the spectrum can provide information as to the concentration and size distribution of the scattering centers, which are aerosol particles or molecules (depending on the wavelength region used) in the atmosphere. Research is also proceeding toward the development of techniques to remotely measure the chemical constituency of aerosol particles as well.

Scattering from aerosol particles serves as the basis for Differential Absorption Lidar (DIAL). These particles serve as scattering centers to reflect the laser radiation back toward the receiver. For DIAL, the measurement technique is based on the principle of absorption, discussed above, with time-gating of the return pulses used to determine distance.

Global Meteorological Measurements

This section contains descriptions of advanced instrumentation for remote measurements of winds, temperature, and pressure from an orbiting spacecraft. The discussion is arranged according to application, because in this context it is easier to compare the measurement requirements with capabilities of existing instruments and projected improvements expected from advanced instruments.

Winds

Global windspeed information is urgently needed in order to understand transport and dynamics of the atmosphere, which bear strongly on the formation and intensity of pollution episodes as well as on weather and climate, and of the stratosphere and mesosphere in order to understand upper atmospheric dynamics.

Infrared Laser Instrumentation to Measure Tropospheric Winds. Although cloud-tracking from orbiting satellites has been used in the past to indicate wind fields, there are two factors which limit the usefulness of cloud-derived windspeed information: (1) the altitudes of the clouds are unknown and do not cover all regions of interest; (2) the relationship between cloud drifting rate and windspeed is not well defined [5]. Even in the equatorial region, which is the main driver of atmospheric dynamics, surface measurements are not made on a routine basis. There is, therefore, a definite need for a new technique to measure tropospheric winds from an orbiting spacecraft. The needed accuracy is 1-2 m/sec, with anywhere from 10 km to 400 km horizontal resolution, depending on whether the application is operational forecasting or wide-scale modeling [6].

Huffaker has proposed [7] that a CO_2-based infrared laser heterodyne system could provide the necessary measurements of tropospheric winds from an orbiting spacecraft—either Shuttle at an altitude of 250-300 km, or an operational satellite at 800 km altitude. An airborne CO_2 laser system using the same principle of detecting the Doppler shift of back-scattered laser radiation has been operating at the Marshall Space Flight Center for several years [8]; thus, the technique has been demonstrated on a small scale. For particles with an average velocity component v along the direction of the laser beam, the Doppler shift of the backscattered radiation (scattered by aerosol particles moving with the wind field) is:

$$\Delta\nu = 2\nu_0(v/c), \tag{2}$$

where ν_0 is the original laser frequency and c the speed of light.

A spaceborne system to measure tropospheric winds would need a 10-joule CO_2 laser operating at 20 Hz pulse repetition rate, with a frequency stability during each pulse of 50 kHz or better [7, 9, 10]. The main difficulty seen for an operational satellite is the large power requirement of the laser itself, of several kilowatts. Although this power may be available on a 1-2 week Shuttle flight, it will require advances in energy storage or production onboard the spacecraft, and improvements in laser system efficiency, for flights of longer duration.

Measurements of Stratospheric Winds. The two techniques which show greatest potential for measuring winds in the stratosphere are visible lidar and correlation spectroscopy.

The visible lidar system is based upon backscattering from stratospheric molecules and aerosol particles. The Doppler-induced frequency shift is detected using a dispersive device, such as a Fabry-Perot etalon. It requires a very stable, pulsed laser operating in the visible region of the specturm; this will be difficult to achieve. A comprehensive article on the visible lidar approach to global wind measurements was recently prepared by Abreu [11].

A correlation-spectroscopy technique has been proposed [6], based upon wind-induced Doppler shifts in thermal emission lines of gases present in the atmosphere. Such measurements are made by viewing the limb of the atmosphere in an infrared spectral interval which contains an emission band of a minor constituent, such as N_2O, and optically correlating the emission lines with absorption lines of the same gas contained in a cell within the instrument. It is this correlation between the sets of spectral lines which constitutes a measurable parameter related to the wind speed; for if there is relative motion between the atmosphere and the gas in the cell, the atmospheric emission lines and the cell gas absorption lines are no longer exactly superimposed due to the Doppler shift. This approach to measuring stratospheric winds is now in the laboratory feasibility demonstration phase.

Microwave Limb Sounder To Measure Mesospheric Winds. The Microwave Limb Sounder (MLS) has been accepted for a Shuttle mission, with one of its goals to measure upper atmospheric winds. The MLS measures *both* horizontal wind components by means of an antenna system having two orthogonal fields of view. A digital autocorrelator provides the spectral resolution required for observing winds by the Doppler shift in emission lines. In principle, the observed Doppler shift of any microwave spectral line can be used, but the 118-GHz line of molecular oxygen appears to provide the best signal-to-noise ratio to the highest altitudes [6]. Using a 10-sec integration time, the MLS is projected to provide windspeed information of better than 10 m/sec in the altitude range of 70-110 km.

Wind Instrumentation Summary. It is obvious from the above discussions that no single instrument can cover the entire altitude region of interest for global wind measurements. Figure 1 illustrates this graphically, showing the main instruments which have been described and their optimum regions of application.

Advanced Meteorological Temperature Sounder

During the past decade, numerical weather prediction models have evolved far more rapidly than the capability of satellite-borne temperature sounders to supply appropriate input data. The current generation of passive infrared sounders is

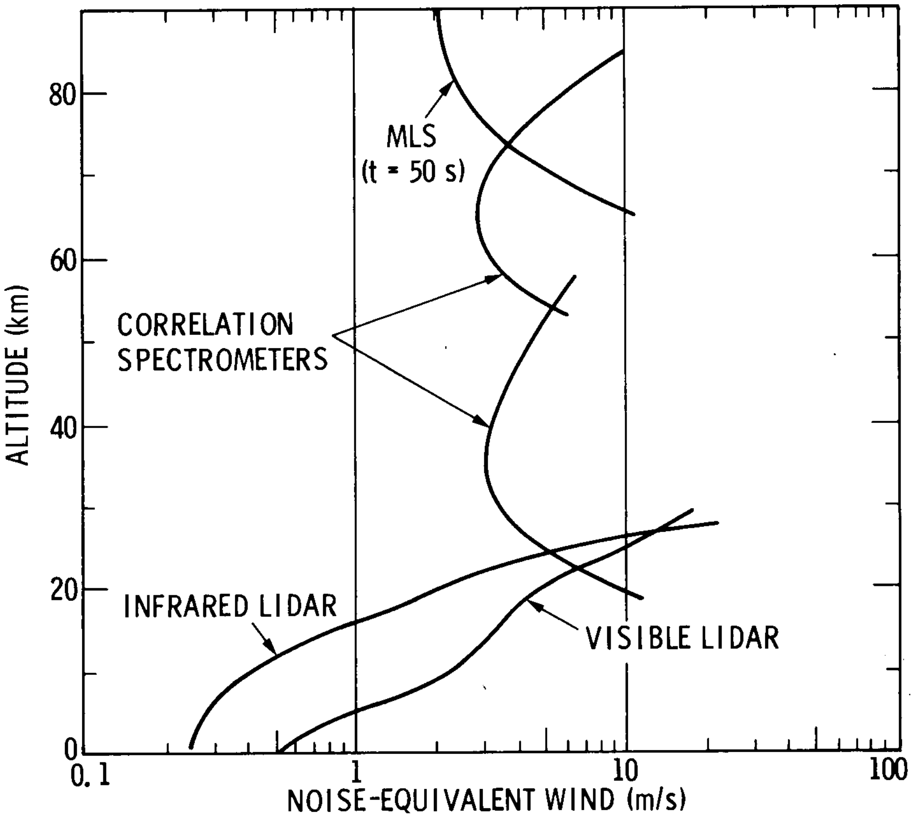

FIG. 1. Noise-Equivalent Wind Curves for Several Sensors. Integration Time is 1 Sec for All Instruments Except MLS, for Which it is 50 Sec

capable of measuring tropospheric temperature with a vertical resolution of only 5-6 km, whereas 2 km or better is needed. This limitation in vertical resolution is caused by the broadness of the weighting functions of current instruments. (When the weighting functions are broad, the emitted energy reaching the satellite will have components originating from a wide region of the atmosphere, thereby making reconstruction of fine-scale vertical details practically impossible.) Because of this, as well as cloud contamination and surface emissivity effects, the rms errors in the retrieved temperature profiles of around 2.5 K are also above what is required by the circulation models. The current generation of microwave sounding units for temperature have a vertical resolution of 8 km in the troposphere, which is even worse than the infrared. The microwave technique is better in the upper atmosphere, however.

Design studies and numerical simulations have shown that an advanced instrument can be developed which is capable of retrieving clear column temperature profiles with a vertical resolution of 2 km in the troposphere and an accuracy of 1.5 K even in the presence of multiple layers of broken clouds. This new instrument is called the Advanced Meterological Temperature Sounder (AMTS), and has been proposed by Chahine, Kaplan, and Susskind [12].

AMTS is an infrared sounder for which the desired temperature accuracy and vertical resolution are achieved by careful choice of narrow-band channels in the 4.3-μm and 15-μm bands of CO_2. For temperatures in the troposphere, this can be met by a spectral resolution of 2 cm^{-1} in the high-J lines of the R-branch; and in the upper troposphere and stratosphere by a complementary set of 15-μm channels with a spectral resolution of 0.5 cm^{-1}. Elimination of the effects of clouds is accomplished by making simultaneous measurements in both bands.

A recent study [13] has shown that AMTS, with twenty-eight appropriately selected infrared channels, will be able to make the following measurements from a free-flyer spacecraft at an altitude of 800 km:

- Retrieve clear-column temperature profiles in the presence of up to three layers of broken clouds with an average rms error of 1.5 K throughout most of the troposphere;
- Simultaneously obtain humidity profiles with an accuracy of 20%;
- Recover day and night surface temperature of oceans and solid earth with an average absolute accuracy of 1.5 K;
- Map the fractional cover and height of multiple cloud layers globally (as seen from above) with a peak-to-peak accuracy of ±0.05 and 0.25 km, respectively;
- Determine the location of the tropopause to within 0.5 km.

The Advanced Meteorological Temperature Sounder is being proposed for a NASA free-flyer, Shuttle-launched mission in the mid-1980's. A CO_2 laser technique has also been proposed to measure tropospheric temperature [14-16], but it is not as far along as the AMTS in terms of readiness for an operational satellite.

Advanced Microwave Sounding Unit (AMSU) for Temperature and Humidity

The AMSU is a 20-channel microwave radiometer system under consideration by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) to provide soundings of atmospheric temperature and humidity profiles and precipitation distributions for operational weather forecasting. It utilizes rotational water vapor lines at 22.2 and 183.3 GHz for sounding the moisture profiles, and several channels in the 50-60 GHz oxygen band to sound the temperature profiles. The instrument is expected to provide atmospheric temperature measurements with an average rms accuracy of around 1.5 K between ground and 30 km altitude, and slightly less accurate profiles to 50 km altitude. The humidity measurements will have an rms accuracy which is better than or equal to the geometric sum of 0.2 g/cm^2 and 10% of the measured humidity.

The AMSU is the next generation microwave sounder for NOAA operational applications and represents the fourth level of sophistication in NASA systems of this type. Predecessor systems include the Nimbus 5 Microwave Spectrometer (NEMS), Nimbus 6 Scanning Microwave Spectrometer (SCAMS) and the Microwave Sounding Unit (MSU) currently being flown on TIROS-N and the subsequent NOAA series spacecraft. The AMSU will be used aboard the Advanced TIROS-N (ATN) spacecraft beginning with the NOAA-I mission.

Remote-Measurement Techniques for Atmospheric Pressure

Global measurements of atmospheric pressure are important in synoptic meteorology, numerical weather forecasting, atmospheric dynamics, and climate studies. At the present time, pressure data are gathered principally from land-based weather-monitoring stations, and are supplemented over the oceans by reports from ships and aircraft. The lack of data over large areas of the globe (in particular, over oceans in the southern hemisphere), poses a serious limitation for these studies.

The World Meteorological Organization has specified a set of observational requirements for the First Global Experiment of the Global Atmospheric Research Programme [17]. Measurements of pressure in data sparse regions are required with a horizontal resolution of 500 km and an accuracy of ±0.3%, equivalent to ±3 mb at the surface. A recent survey of user needs [18] indicates that a slightly higher accuracy of 1-2 mb may be desirable.

Microwave Pressure Sounder to Measure Surface Pressure. The Microwave Pressure Sounder is an active instrument which emits bursts of energy in the

60-GHz frequency region and detects the fraction backscattered from the sea surface. The technique can provide surface pressure measurements over the ocean by measuring beam absorption due to molecular oxygen, which is uniformly mixed with other components of the atmosphere; the amount of oxygen being directly proportional to atmospheric surface pressure. Other factors, such as the atmospheric temperature profile, the presence of water vapor and liquid water, and the properties of the ocean surface, also affect the measured absorption; however, the microwave frequencies are selected to be in a region where these other absorptions vary slowly with frequency, and their effects can be removed by making additional measurements outside the oxygen band.

Spectroscopic calculations [19] show that the absorption coefficient for a vertical path through the atmosphere varies as surface pressure raised to a power of between 1.5 and 2 over the frequency range of interest. The nearer the frequency is to the band center, the stronger will be the change in absorption coefficient for a given change in surface pressure. A 6-channel instrument with an emitted power of 2 watts is expected to be able to measure surface pressure with a standard deviation error of between 1 mb (no clouds) and 2 mb. In addition to surface pressure, the instrument will provide estimates of water vapor and liquid water content of the atmosphere, and of the surface roughness of the sea. The Microwave Pressure Sounder is being proposed as an instrument for a free-flying NASA satellite of the mid-1980's.

Laser Measurements of Atmospheric Pressure. Because spectral lines broaden with increasing background pressure, this phenomenon can be used as an indicator of atmospheric pressure. Korb has proposed [15] to determine atmospheric pressure on a global basis using a spaceborne laser system in which the transmittance is measured of a laser beam whose wavelength is midway between two absorption lines of molecular oxygen. By using the LIDAR (Laser Radar) technique, whereby only a small region at a known distance from the spacecraft is probed, it should be possible to derive the vertical profile of atmospheric pressure [20]. Laboratory feasibility tests are currently underway to determine whether or not this laser technique can measure pressure with the necessary precision.

Global Measurements of Atmospheric Species

Tropospheric Trace Species

Global measurements of several key tropospheric species can be made using active laser techniques. Airborne measurements based on the principles of resonance fluorescence [21] and differential absorption [22, 23] have shown potential for future spaceborne applications.

The simplest laser approach to measuring tropospheric species is one based upon differential absorption of continuous-wave (cw) laser radiation backscattered from the Earth's surface. Measurements of tropospheric ozone have been made over the past few years from an airborne system using an instrument called the Laser Absorption Spectrometer (LAS) [24]. Using two CO_2 lasers, the LAS measures the airplane-to-ground absorption due to ozone for a laser line which is absorbed by ozone, and compares it with absorption of the second laser line which is beyond the ozone-absorbing region. By ratioing the two return signals, effects of turbulence and changing reflectivity of the Earth's surface are largely eliminated.

The present LAS system utilizes two 1-watt cw CO_2 lasers, and has provided ozone measurements on the west coast [25], east coast [26], and midwest [27]. Since range-gating is not possible with a cw system, no altitude-dependent studies of species concentration can be made unless the airplane itself flies at different altitudes. Some altitude information (with a vertical resolution of around 5 km) can be obtained, however, using the pressure dependence of the spectral line shapes. Extrapolations to Shuttle indicate that two 10-watt lasers will be able to perform species measurements on a global basis. Species which may be measured with this technique include O_3, NH_3, C_2H_4, $CC\ell_4$, $C_2H_3C\ell$, and HNO_3.

A pulsed, tunable infrared laser can provide range information lacking with a cw system, with the potential of providing 1 km vertical resolution. A laser with the required wavelength coverage, energy (25 J/pulse), pulse repetition frequency (15 Hz), stability, and overall efficiency is not yet available, but laboratory development is continuing.

Stratospheric Trace Species

The key question with regard to the stratosphere at the present time is, "Is the ozone layer being depleted and thereby producing an increase in the amount of solar ultraviolet radiation impinging on the Earth's surface?" A comprehensive experimental and theoretical study sponsored by the U.S. Department of Transportation looked at the ozone question in terms of emissions which would be produced by a fleet of SST's (supersonic transports) [28]. Using instruments that were quite advanced at the time, and relying mainly on high-flying aircraft and balloon flights, their conclusion was that there would be no discernible depletion of stratospheric ozone arising from a fleet of SST's [29]. However, research is still progressing in order to verify this finding and to study as well the potential impact of sub-sonic commercial aircraft operating just below the stratosphere.

Whereas many of the species resulting from aircraft engine emissions and thought to participate in ozone destruction are measurable with conventional techniques, other reactions which may tend to deplete the ozone layer involve such difficult-to-measure free radicals as $C\ell O$ and HO_2. Although some *in situ* techniques do exist for these species, there are no remote-sensing techniques which would permit their measurement from an orbiting spacecraft.

Trace species in the stratosphere have narrow infrared absorption lines, very near the Doppler limit of 0.002-0.01 cm^{-1}. Conventional instruments, such as filter channel infrared radiometers and spectrometers or interferometers have instrument spectral widths which broaden the spectra, resulting in a potential loss in both specificity and sensitivity. An advanced interferometer called ATMOS is being constructed under a NASA contract to operate on Space Shuttle and provide a rapid scan of the infrared "fingerprint" region, using solar occultation, of stratospheric gases with a resolution of 0.01 cm^{-1}. The Microwave Limb Sounder (MLS) will provide species measurements in the upper stratosphere and mesosphere from the Upper Atmospheric Research Satellite (UARS) when it is launched in the mid 1980's.[3]

A laser heterodyne spectrometer (LHS) is a passive instrument which employs a laser beam as local oscillator and a distant object, such as the sun, as the source of radiation, with the measurement by solar occultation [30]. The JPL Laser Heterodyne Radiometer (LHR), which is a specific instrument of the LHS variety, has flown twice into the stratosphere to measure $C\ell O$. Good agreement was found with *in-situ* measurements made by Anderson [31, 32].

Another laser heterodyne spectrometer is being constructed by NASA Langley Research Center for operation onboard one of the Shuttle flights. It employs several diode lasers as local oscillators, and will be able to measure a variety of atmospheric trace species [33].

Table I is a summary of some of the atmospheric species for which laser remote-sensing instrumentation is being developed. This is only a partial list because of the wide variety of organizations throughout the world that are developing laser instruments for their own specific applications.

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[3] During the maiden flight of the balloon-borne MLS on 20 February 1981, the first simultaneous remote measurements were made of O_3 and $C\ell O$ in the stratosphere. Results are being analyzed and will subsequently be published [36].

TABLE I. Atmospheric Species Optimally Measured using Laser Instrumentation

Species	Region	Laser technique	Status
H_2O	Atmosphere	Absorption; near-IR DIAL	Aircraft flights ongoing
OH	Atmosphere	Induced fluorescence	Aircraft flights ongoing
CO	Atmosphere	IR absorption	Aircraft flights ongoing
$CH_3C\ell$	Atmosphere	Laser absorption spectroscopy	Spectroscopy in progress
O_3	Troposphere	IR absorption, DIAL	Aircraft flights ongoing
$C\ell O$	Stratosphere	Laser heterodyne spectroscopy	Balloon flights ongoing
HO_2	Stratosphere	Laser heterodyne spectroscopy	Spectroscopy in progress
$C\ell ONO_2$	Stratosphere	Laser heterodyne spectroscopy	Spectroscopy in progress
NO_x	Stratosphere	IR absorption	Balloon flight planned
O_3	Stratosphere	Induced fluorescence	Balloon flight planned

Stratospheric Aerosols

Global measurements of aerosols in the stratosphere are needed primarily to understand stratospheric heterogeneous reactions relating to the ozone depletion question. In addition, stratospheric aerosols may affect our climate and, indirectly, air quality. Clusters of sulfuric acid molecules (from sulfur compounds emitted at ground level) are thought to act as condensation nuclei leading to the growth of stratospheric aerosols which are the principal components of the Junge layer. The sink for sulfur occurs when the heavier aerosols settle out of the stratosphere into the troposphere, forming a dilute "acid rain." Consequently, in addition to measuring the concentration and size distributions of aerosols in the stratosphere, it is important to determine their chemical composition as well.

A High Spectral Resolution Lidar (HSRL) has been developed by researchers at the University of Wisconsin [34] to measure the spatial distribution of the atmospheric aerosol optical extinction coefficient on both regional and global scales. The HSRL uses a nitrogen UV laser to optically pump a high spectral resolution dye laser, the output of which is directed into the atmosphere. A 35-cm-diameter receiver telescope collects the light backscattered by aerosol and air molecules, and the return signal is analyzed using a high-spectral-resolution, two-channel Fabry-Perot spectrometer.

The HSRL measures the aerosol optical extinction coefficient by distinguishing light which is backscattered by the aerosol from that backscattered by air molecules. Quantities such as the aerosol optical extinction coefficient, backscattering phase function, aerosol-to-molecular scattering ratio, and visibility can be derived from this information.

Identification of the chemical composition of stratospheric aerosol particles may be possible using a multiwavelength (infrared) backscattering technique called DISC [35]. A preliminary study of this approach indicates that sufficient lidar sensitivity can be obtained at 220-km orbital altitude with 10-J CO_2 laser and a 1-m-diameter collector. The measurement principle is based on the fact that the aerosol particle backscatter coefficient shows a dependence on wavelength that is characteristic of its composition. This could also be a powerful tool for tropospheric aerosol analysis if the backscatter signatures of different tropospheric aerosols are distinctive enough for the technique to work.

Conclusion

Several key measurements of the Earth's atmosphere which must be made in order for us to understand important processes relative to changes in the stratospheric ozone concentration, in weather and climate, and in environmental quality, cannot be made at the present time due to a lack of suitable instrumentation. As a result of laboratory research into new detection techniques,

TABLE II. Summary List of Advanced Sensors and Applications

Application	Technique	Instrument/sensor
Winds		
Troposphere	Doppler/IR backscattering	CO_2 lidar
Stratosphere	Doppler/VIS backscattering	VIS lidar
	Correlation spectroscopy	IR correlator
Mesosphere	Doppler/emission	Microwave limb sounder
Temperature	IR emission	Advanced meteorological temperature sounder
	Microwave emission	Advanced microwave sounding unit
Pressure		
Sea-surface	Microwave absorption	Microwave pressure sounder
Troposphere	IR absorption	Laser pressure sounder
Species		
Troposphere	IR absorption	Laser absorption spectrometer; IR DIAL
Stratosphere	Fluorescence	Laser fluorosensor
	IR absorption	Laser heterodyne, ATMOS
Mesosphere	Microwave emission	Microwave limb sounder
Aerosols		
$< 0.5\ \mu m$ dia	UV/VIS scattering	$< 0.7\ \mu m$ UV/VIS lidar
$> 0.5\ \mu m$ dia	IR scattering	$> 0.7\ \mu m$ IR lidar

advanced remote sensors are being developed with the expectation that several of them will eventually be used to measure meteorological variables (winds, temperature, pressure) and species (trace molecules, atoms, and aerosol particles) on a global basis. Some of the techniques described in this paper are listed in Table II along with their potential applications. Many of these are expected to be deployed on Shuttle or on free-flying operational spacecraft during the 1980's, and should provide important inputs to our knowledge of the Earth's atmosphere.

Acknowledgment

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ATMOSPHERIC REMOTE SENSING CAPABILITIES

A. Using Existing Equipment with Minor Modifications

1. Laser Absorption Spectrometer for Active Remote Sensing and Measurement of Gaseous Species in the Lower Atmosphere (Dr. M. S. Shumate): Airborne and eventually spaceborne detection and measurement of gaseous species. Has demonstrated usefulness by airborne measurement over past several years over various area of the country.

2. High Resolution Ground-Based Interferometer for the Measurements of Properties of the Atmosphere, Clouds, Dust, and Hazes (Dr. Reinhard Beer): NASA-developed instrument, developed primarily for ground-based astronomy, is available for atmospheric trace gas measurements to infer both the properties of the sources of trace gases and characteristics of the intervening atmosphere.

3. Detection and Communication using an Airborne Acousto-Optic Spectrometer (Dr. T. B. H. Kuiper): An acousto-optic spectrometer, intended to operate from an aircraft with a frequency resolution of 0.5 MHz over a bandwidth of 500 MHz, is being assembled. Continued progress in solid state lasers and integrated optics devices are expected to yield an instrument with unsurpassed frequency range, stability, and sensitivity.

4. Precise Position Determinations using Radio Interferometry (Dr. M. Janssen): The Table Mountain radio interferometer and the Owens Valley Radio Observatory millimeter interferometer represent available technologies for very precise determinations of position and direction in passive and active systems.

5. Surveillance System for the Radio Frequency Region using the SETI Multichannel Analyzer (Dr. S. Gulkis and Dr. E. Olsen): An operational multichannel spectrum analyzer has been developed for the RFISS and SETI programs. It will detect and measure 65,000 channels in the radio-frequency region with a bandpass of 20 MHz and a resolution of 0.3 kHz.

6. Fast Near-Infrared Spectrometer for Remote Aircraft Surveillance (Dr. J. Apt): The new JPL near-IR (0.6 - 5.4 microns) linear array will detect and take spectra of objects 120 times faster than is now possible. Its greatest military value would probably be in high-speed airborne surveillance of the Earth's surface.

7. Field Measurements from Table Mountain Observatory (Dr. J. Apt): The Table Mountain Observatory is well-situated both for communcations with satellites, and the performance of photometry and spectral measurements, as well as for operational tests of lasers and other systems in cooperation with Edwards Air Force Base.

8. Remote Sensing of Sea-Level Meteorology using SMMR (Dr. E. G. Njoku): JPL has developed and demonstrated the use of an advanced microwave instrument to remotely measure sea surface temperature, winds, atmospheric water vapor, and liquid water content. The instrument is the Scanning Multichannel Microwave Radiometer (SMMR) which was flown on Seasat. Potential DoD applications include ship routing, submarine detection, and surface and meteorological data for directing field operations.

9. Microwave Instrumentation for Upper Atmosphere Measurements (Dr. J. W. Waters): Microwave techniques for remote sensing of the upper atmosphere (10-150 km) have been developed and partially implemented. Experiments have been performed from ground, aircraft, and balloon platforms, and are being developed for use on spacecraft. By measurements of upper level winds, temperature, magnetic field, and gaseous species, potential DoD applications include trajectory determinations and improvement in theoretical models for predicting atmospheric conditgions following nuclear events such as 'forecasting communications capabilitiesd and fallout distribution.

B. Involving Development of New Instruments using Demonstrated Techniques

1. Infrared Spectroradiometer for Passive Remote Sensing and Measurement of Gaseous Species in the Lower Atmosphere (Dr. Reinhard Beer): Based upon instruments successfully implemented on the Pioneer-Venus Spacecraft in 1978 and 1979.

2. Applications of Tunable Carbon Dioxide Lasers to Fieldable Systems for Remote Species Detection (Dr. R. T. Menzies): Small, portable carbon dioxide laser systems for the remote detection of trace gases in the atmosphere are now possible because of recent developments both at JPL and in industry. The spectral flexibility offered by these lasers allows them to detect a wide variety of gases in a battlefield environment.

3. Microwave Transmitter and Communication System (Dr. M. Janssen): As a result of the development of a millimeter-wavelength horn antenna with exceptionally high off-axis signal rejection, the capabilitity exists for the construction of a system as a feed for a secure microwave communication system or for a very high efficiency radar transmitter.

4. All-Sky Wideband Maps using COBE (Dr. S. Gulkis): The development of the COBE (Cosmic Background Explorer) instrument will permit the complete mapping of the sky background diffuse infrared and microwave radiation in the 1 micron to 13 millimeter wavelength region.

5. Large Space Telescope for Microwave Communication (Dr. T. Kuiper): Preliminary designs have been made for a large (10-30 m) far-infrared telescope based on active optics principles.

6. Spaceborne Optical Instrumentation (Dr. R. W. Carlson): JPL has demonstrated capabilities in the area of spaceborne instrumentation for remote sensing, such as optical instrumentation, laboratory spectroscopy, and the ability to perform spectroscopic analysis on remotely-sensed data.

7. Stratospheric Wind Measurements using Passive Infrared Sensing (Dr. D. J. McCleese): The ability to measure stratospheric winds with a passive infrared correlation sensor has been demonstrated in the laboratory. Its potential application to military programs would be in the area of highflying aircraft, missiles, and weather.

8. Remote Microwave Measurements of Meteorological Parameters (Dr. D. A. Flower, Dr. R. K. Kakar, and Dr. E. G. Njoku): The Microwave Sounder Unit (MSU) has been demonstrated on the TIROS-N satellites. The Advanced Microwave Sounder Unit (AMSU), which is an advanced version of the instruments already flown, will be able to provide improved vertical resolution and coverage for atmospheric temperature and moisture profiles and will provide measurements of sea surface roughness as well. A Microwave Pressure Sounder (MPS) is being developed for remotely atmospheric surface pressure from satellites.

9. Microwave Technology and Systems Development (Dr. J. W. Waters): As a result of a variety of field measurements using microwave instrumentation over the past 20 years, JPL has developed an in-house expertise to apply such instruments to a variety of applications. The ability to carry out such a project from design to construction and field demonstration, without the need for substantial external inputs, represents a unique implementation team.

C. Analytical Projects based on Space Research

1. Analytical Capability and Spectroscopic Information Bank Relevant to Transmission of Electromagnetic Radiation, Radiative Transfer, and Determination of Thermodynamic Parameters (Dr. Glenn S. Orton): The capability exists at JPL to analyze atmospheric propogation and radiative properties, based upon technology developed for other planetary atmospheres, which are of direct interest to military needs.

2. Non-LTE Radiative Transfer Theory (Dr. J. Appleby): Radiative transfer methods have been developed to treat the breakdown of local thermodynamic equilibrium (LTE), which occurs in the upper layers of all planetary atmospheres. Terrestrial applications include analyses of emissions from exhaust plumes, and laser beam transmission.

3. Analysis of Remote Sensing Data (Dr. R. W. Carlson): Studies of the atmospheres and surfaces of other planets have necessitated the development of a capability to accurately assess the significance of the data received. This capability can be applied directly to DoD Earth-observing missions in such areas as meteorology, gaseous transport and chemical conversion, and various indicators of surface changes in vegitation and vehicular transport.

4. Speckle Imaging to Reduce Amospheric Blurring (Dr. J. Apt): JPL has developed an ability to achieve spatial resolution approximately five times greater than is permitted by atmospheric blurring. This could be valuable for improving the resolving power of long-range photography.

5. Image Processing and Large Data Base Manipulation (Dr. L. S. Elson): The ability to perform advanced image and large data base processing would have military applications in terms of understanding thermal balance of the atmosphere, albedo, upper atmospheric waves, circulation and transport, and cloud structure and morphology.

6. Electromagnetic Wave Propagation Predictions (Dr. H. M. Pickett): Computer models for predicting electromagnetic wave propagation in the 0-3000 GHz region have been developed and extensively tested at JPL for altitudes to 150 km. A catalogue of atmospheric spectral lines and parameters for frequencies up to 3000 GHz has been assembled and is continuously being upgraded. Potential DoD applications include prediction of propagation characteristics under a variety of field operational scenarios, and developing secure communications sytems.

7. Communication in the Presence of Irregular Particles (Dr. M. S. Hanner): Scattering from irregularly-shaped particles can have a noticeable effect on communications. In depth studies of the reflection and scattering of electromagnetic radiation from such particles have been made in order to examine the properties of interstellar dust clouds and cometary tails. The influence of such dust particles on communication through the atmosphere can be ascertained by applying this analytical procedure in reverse.