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Remote Measurement of Pollution—A 40-Year Langley Retrospective: Part I—Temperature and Gaseous Species

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April 2011

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Contents

Abstract

The National Aeronautics and Space Administration (NASA) phased down its Apollo Moon Program after 1970 in favor of a partly reusable Space Shuttle vehicle that could be used to construct and supply a manned, Earth-orbiting Space Station. Applications programs were emphasized in response to the growing public concern about Earth's finite natural resources and the degradation of its environment. Shortly thereafter, a workshop was convened in Norfolk, Virginia, on Remote Measurement of Pollution (or RMOP), and its findings are in a NASA Special Publication (NASA SP-285). The three primary workshop panels and their chairmen were focused on trace gas species (Will Kellogg), atmospheric particulates or aerosols (Verner Suomi), and water pollution (Gifford Ewing). Many of the workshop participants were specialists in the techniques that might be employed for the regional to global-scale, remote measurements from an Earth-orbiting satellite. The findings and recommendations of the RMOP Report represent the genesis of and a blueprint for the satellite, atmospheric sensing programs within NASA for nearly two decades. This paper is a brief, 40-year retrospective of those instrument developments that were an outgrowth of the RMOP activity. Its focus is on satellite measurement capabilities for temperature and gaseous species that were demonstrated by atmospheric technologists at the Langley Research Center. Limb absorption by solar occultation, limb infrared radiometry, and gas filter correlation radiometry techniques provided significant science data, so they are emphasized in this review.

1 Background and purposes

The Apollo Moon Program of NASA, though highly successful, would be ending in the early 1970s. Further production of the Saturn V, heavy-lift launch vehicle was cancelled in favor of developing a partially reusable, Space Shuttle vehicle that could be used to construct and then resupply a manned, Earth-orbiting observatory [Hansen, 1995]. NASA began to emphasize its Space Applications programs. There was growing public concern that natural resources were finite and that the Earth environment was being degraded. The Clean Air Act (CAA) was signed into law in 1970, and it meant a major shift in the role of the federal government in controlling air pollution. That legislation authorized the development of comprehensive federal and state regulations to limit emissions from both stationary (industrial) sources and mobile sources. Then, on May 2, 1971, the U.S. Environmental Protection Agency (EPA) was created to implement the various requirements of the CAA. The following year Congress passed the Clean Water Act (CWA) designed to limit pollutant discharges from point sources, such as industrial and municipal facilities.

Significant concerns were also raised in 1970 about the prospect of deleterious effects on life of the excess ultraviolet (uv) radiation from a chemical loss of ozone (O_3), as a result of the spread of water vapor (H_2O) from the exhaust plumes of a commercial fleet of supersonic transport (SST) aircraft flying in the lower stratosphere. Funding for the continued development of a Boeing SST prototype was halted by the U.S. Congress in March 1971, but primarily to await an interim decision on landing rights in the U.S. for the Anglo-French Concorde aircraft [Wayne, 1991]. Shortly thereafter, studies were reported on the likely catalytic loss of O_3 due to the nitric oxide (or NO) emitted by their engines. Several federal agencies, including NASA, were eventually assigned a Congressionally-mandated responsibility for researching and monitoring the stratospheric ozone layer under the CAA amendments of 1977. Laboratory reaction rate measurements and more accurate and extensive atmospheric observations that they funded would be key to understanding of the relative roles of transport and of the hydrogen and nitrogen oxide chemical families (HO_x and NO_x) on the ozone layer.

In the international arena two separate study groups met to assess the potential human impact on the global environment [SCEP, 1970; SMIC, 1971]. Their findings included recommendations for global observations and for further research to distinguish between the effects of man-made versus natural pollutants. In particular, they expressed a need for the identification and/or monitoring of specific environmental contaminants, including trace gas species, particles, and water pollutants. Environmental issues of the time included the regional-scale transport of pollution, acid rain, and the degradation of ecosystems and coastal estuaries. Thus, at a time when NASA was in transition it was natural to ask whether a segment of its technology workforce could demonstrate the use of atmospheric remote sensing techniques for making measurements of the global environment. NASA embarked on the development of satellite techniques for an improved understanding of the distributions, sources, and sinks of pollutants. The Agency had already demonstrated the promise of global weather observations and of communications from Earth-orbiting satellites. NASA had also been conducting systematic, scientific studies of the atmospheres of the other planets [Conway, 2008].

Morris Tepper, Director of Meteorology Programs, and Jules Lehmann, Manager of Advanced Instrumentation and Sensor Engineering Programs, both of NASA Headquarters, directed that Langley Research Center (LaRC) convene a Working Group on the topic of the Remote Measurement of Pollution (RMOP). They, along with Henry Reichle, Jr., and Wendell Ayers of Langley, quickly assembled a panel of experts and were the hosts for a Workshop on the RMOP in Norfolk, Virginia, August 16-20, 1971. The three primary RMOP panels and their chairmen were focused on gaseous air pollution (Will Kellogg), particle air pollution (Verner Suomi), and water pollution (Gifford Ewing). Two additional panels reviewed and reported on the principles of remote sensing and the associated instrument techniques. Findings of the RMOP panels can be found in NASA SP-285 [1971], and NASA went on to redefine the final satellite in its Nimbus series (Nimbus 7) as a "pollution patrol" satellite [Conway, 2008]. Later, several of its successful sensor prototypes were refined and became operational on NOAA satellites, as envisioned. Of course, the international community contributed to the development and deployment of their own satellite-borne sensors. The historical evidence indicates that the findings of the SCEP Report and the RMOP Workshop Report represent the genesis of and blueprint for the satellite Earth-sensing programs within NASA for the following two decades.

This report (or Part I) is a 40-year retrospective of the instrument developments and demonstrated remote measurement capabilities for temperature and gaseous species from Earth orbit that were an outgrowth of RMOP. A second report (or Part II) is planned, and it will be devoted to the remote measurement of clouds and particulate air pollution. Although the focus of Part I is on the research activities within LaRC, they are described within the context of the ongoing work at Jet Propulsion Laboratory (JPL), NASA Goddard and Ames, the National Oceanic and Atmospheric Administration (NOAA), and the academic and international communities. Section 2 reviews the early work on atmospheric measurements at Langley and notes several of the key players for the RMOP Workshop. Section 3 summarizes the objectives and recommendations of the Gas Species Panel in the context of what was known in 1971. The Panel focused on the inference of gas species profiles derived from the spectral signatures of their atmospheric transmission or infrared radiance. Because a good knowledge of the associated atmospheric density or temperature is also needed, Section 4 is a short summary of the progress since 1971 for achieving those accurate and co-located profiles. Section 5 is a more extensive account of the primary measurement techniques that were selected for obtaining gas species profiles from Earth orbiting satellites and Shuttle-launches from 1971-1985. Section 6 comments on the changing science priorities and the relevant technologies at Langley prior to the Earth Observing System (EOS) era. Section 7 discusses the complement of sensors for EOS and their capabilities. Section 8 looks briefly to the Joint Polar Satellite System (JPSS) and then to several proposed sensor applications from Langley for the coming decade. Finally, Section 9 reiterates the findings and concludes that many of the objectives of the original Gas Species Panel were met. Key papers are cited throughout to support the conclusions in this retrospective.

2 Historical context and key players

Langley Research Center has traditionally been focused on developing and applying measurement technologies for studies of flight models in wind tunnels or of test aircraft in the atmosphere. One might wonder why Langley Research Center was chosen to organize the RMOP activity. As the primary field center for NASA's predecessor, the National Advisory Committee for Aeronautics (NACA), Langley researchers contracted with the Weather Bureau and the Navy Department for the development of reference atmosphere models that represented the range of conditions to be expected for aircraft flight below about 20 km [Gregg, 1923; Diehl, 1926]. Later, the NACA extended its models to 120 km based on rocket soundings or from indirect measurements, such as meteor trails and ionospheric fade-out phenomena [Warfield, 1947; Craig, 1965]. Langley was also well-known for its expertise in the development of both *in situ* and remote optical measurement probes [Crumbly, 1970]. In the 1950s and 1960s Langley successfully conducted and/or managed the Echo satellite Project for passive space communications, the solid-propellant Scout launch-rocket program, the Apollo capsule re-entry Project FIRE, and the Lunar Orbital Program for selecting appropriate sites for Apollo landings on the Moon [Hansen, 1995]. Langley researchers developed and launched inflatable air density satellites to characterize the state of the thermosphere for estimating orbital lifetimes [e.g., Keating and Prior, 1967]. Many others were involved with the design and testing of structures and materials for spacecraft and with the evaluation of horizon sensing methods for navigation, guidance, control, and re-entry in support of the Mercury, Gemini, and Apollo programs.

Figure 1 is a time line that begins (at left) with the aeronautics-related activities at Langley prior to 1971. The next decade might be considered a time of "exploring new techniques for making measurements of Earth's atmosphere" within NASA. It wasn't long though before the concerns about the possible loss of stratospheric ozone prompted demonstrations of measurement methods for actually obtaining accurate temperature and gas species data at those altitudes. Langley in that intervening 40-yr period (at right) became focused on three principal satellite remote sensing methods—limb absorption via solar occultation, limb infrared emission, and gas filter correlation radiometry. The primary Langley instrument scientists responsible for applying those methods were M. Patrick McCormick, James M. Russell, III, and Henry G. Reichle, Jr., respectively. Presently, McCormick and Russell are the Co-directors of the Center for Atmospheric Sciences at Hampton University. Further satellite remote sensing initiatives from LaRC for the decade following 2010 are then noted at the bottom of Figure 1, and they will be discussed briefly in Section 8.

Several persons, besides Tepper and Lehmann, were important to the success of the RMOP Workshop. Edgar Cortright, a pragmatic environmentalist, was Langley Director from 1968-1975, and he led the program that sent the Viking 1 and 2 combined orbiter/lander spacecraft to Mars in 1975-76. While at NACA and then NASA Headquarters in the late 50s and early 60s, Cortright was involved with the formulation of technology for the Agency's meteorological satellites—Television Infrared Observation Satellite (TIROS) and Advanced Technology Satellite (ATS). In 1959 he suggested the name for the follow-on research satellite series, Nimbus. The Nimbus Project was managed initially by William Stroud of NASA Goddard and had a rocky beginning, but following the launch of Nimbus 1 in 1964 it eventually became the demonstration program for the satellite Earth-imaging and sounding instruments and for meteorological science within NASA [Conway, 2008]. At Langley Cortright supported the RMOP Workshop and formed the Flight Instruments Division (FID) and the Environmental and Space Sciences Division (ESSD), wherein some of the RMOP-recommended, sensor development and demonstration would occur. In 1972 NASA Headquarters formed an Office of Applications (OA), led by Chuck Mathews, a Langley veteran [Conway, 2008]. Specific NASA Earth-observing satellites and research instruments would be funded by OA and demonstrated via flight tests under contracts managed by Goddard Space Flight Center, Jet Propulsion Laboratory, and the Ames and Langley Research Centers. Initial support for instrument development was obtained through peer-reviewed proposals to the new Advanced Applications Flight Experiments (AAFE) Program, managed by Jules Lehmann of NASA Headquarters.

The NASA Environmental Quality Program Office (EQPO) was formed at Langley in 1972 and put under the direction of J. D. Lawrence, Jr., who had been Chief Scientist of ESSD. In 1976 Donald Hearth succeeded Cortright as Langley Director and formed the Atmospheric Environmental Sciences Division (AESD). Geographically, Langley is relatively close to Research Triangle Park in North Carolina, the location of the primary field center of the newly-formed EPA. This proximity to each other led to their joint conduct of several NASA/EPA field measurement campaigns in the early 1980s on studies of regional ozone and aerosol pollution events using a combination of ground-based, airborne, and satellite observing techniques [Fishman et al., 1985].

AESD was renamed the Atmospheric Science Division (ASD) in 1982, when emphasis on environmental issues was reduced within the Reagan administration and for NASA. Lawrence remained as the Head of AESD and then ASD for 18 years. The leadership of ASD continued thereafter under Robert Seals, Jerry Newsom, William Smith, Sr., and Leonard McMaster. ASD expanded its capabilities and is known presently as the Science Directorate (SD); it is currently led by Lelia Vann. Stephen Sandford leads Langley's Systems Engineering Directorate and contributes to NASA's Earth Science Programs by managing the development of advanced concepts and technologies and the demonstration of the measurement techniques both in the laboratory and from flight platforms. Somewhat necessarily, this retrospective is focused on the development and heritage of the satellite remote sensing activities at NASA Langley, where the author was a researcher for FID/ESSD/AESD/ASD/SD during his contract and civil service career from 1971-2010.

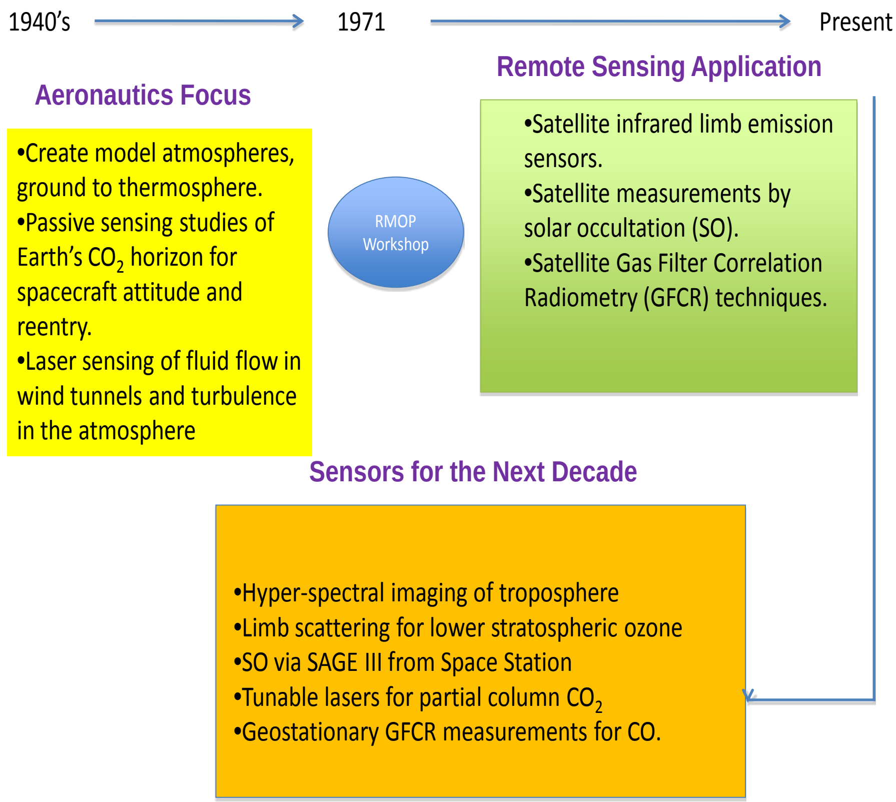

Figure 1. Time line of the application of techniques by NASA Langley for making measurements of the atmosphere.

3 Objectives and recommendations of the RMOP gas species panel

(a) Objectives and focus

The primary role of the Space Applications programs of NASA is the development of satellite techniques for monitoring the effect of human activities on the environment. The RMOP participants made evaluations of the role of remote sensing in identifying specific pollutants and in measuring them with certain accuracies. Members of the Gas Species Air Pollution Panel are listed in Table 1. William Kellogg of NCAR was Chair of the Panel, and he was assisted by James Russell III and Gary Grew of Langley. Panel member, William Matthews of MIT, was an editor of the SCEP and SMIC Reports and had worked with Kellogg on those earlier study initiatives. The RMOP Panel reviewed the information about pollutants, e.g., their physics, chemistry, biological effects, distributions, etc. Member names in boldface print can be directly associated with satellite sensor concepts following RMOP. Further, the Panel decided at the outset that they would consider only those pollutants and trace gases that are important on a global or regional scale, i.e., scales most amenable to satellite sensing or areas of one million square kilometers or more.

There had already been efforts to study the stratosphere in the 1950s and early 60s related mostly to an understanding of the transport and distribution of radioactive debris from high-altitude atomic tests and the deposition or fate of the debris once it entered the troposphere. It was known that ozone is an effective tracer of stratospheric air entering the upper troposphere [Reiter, 1971]. There was also interest in determining the formation, transport, and decay of volcanic stratospheric aerosol layers, as they are useful analogs for the transport of radioactive bomb debris. The role of sulfur gases for the formation of both the stratospheric background and volcanic aerosol layers was a topic of research at that time. Will Kellogg was active in all these research areas throughout his career [e.g., Kellogg et al., 1957; Kellogg et al., 1972].

The release of a large quantity of H_2O from a fleet of supersonic transport (SST) aircraft had been reported as likely to cause a small, but measureable loss of column ozone [Harrison, 1970]. In 1971 a new issue arose about the chemical loss of ozone due to the molecules of NO originating with the high-altitude atomic tests of the early 1960s [Foley and Ruderman, 1973], and which would also be released by a fleet of SSTs [Johnston, 1971; Crutzen, 1970]. Concerns about the effects of both H_2O and NO on O_3 led to the rather comprehensive, scientific Climatic Impact Assessment Program (CIAP) conducted by the U.S. Department of Transportation (DOT) from 1971-74. It is important for the reader to recall that the scientific understanding of the chemical effects of H_2O and NO_x on ozone were quite uncertain at that time [e.g., Ellsaesser, 1982]. Further, although it was known that the concentrations of the manmade, but relatively inert, chlorofluorocarbon compounds (CFCs) were increasing in the troposphere, their eventual photolysis in the upper stratosphere and the involvement of their dissociation products in the destruction of ozone was not fully realized at the time of the RMOP Report.

Satellite measurement capabilities for obtaining vertical profiles of O_3 had been demonstrated for the upper stratosphere by 1971 from Orbital Astronomical Observatory (OAO) using stellar absorption and from Nimbus 4 by solar backscatter ultraviolet (BUV) absorption. Water vapor, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and nitric acid (HNO_3) had also been measured using ground-based, balloon-borne, or rocket-borne remote sensors by that time, but not yet with the accuracies that were needed to resolve questions about their interactions with ozone. The Panel wanted to achieve total O_3 and stratospheric O_3 profiles to 1% and 10% accuracies, respectively. Further, they desired measurement accuracies for H_2O (20%), CH_4 (0.2 ppm), N_2O (50 ppb), NO, NO_2, and CO (10 ppb), HNO_3 (1 ppb), and SO_2 (0.5 ppb) in the stratosphere, and they wanted to achieve them with vertical profile resolutions of a few kilometers. In fact, an underlying theme for all the sensors was how to obtain accurate species profiles with adequate spatial resolutions.

In the early 1960s concerns had also arisen about the effects of urban-scale pollution on regional air quality, due to earlier decisions to construct taller power plant stacks for the release of their point-source pollutants to somewhat higher altitudes within the atmospheric boundary layer. The members of the Gas Species Panel recognized that instead of the surface concentrations it may only be possible to measure the total burden of a gas above the surface because of the inherent limitations of the remote sensing concepts of that time. Total burden measurements of certain gases were being made already via ground-based, solar absorption techniques. Still, the Panel felt that knowing the horizontal spatial distributions of those gas burdens would be extremely helpful in following the transport of species from source regions and perhaps of their conversion to secondary pollutants. Such information was considered complementary with that being obtained from the ground-based instruments. The Panel wanted to achieve tropospheric measurement accuracies for CO_2 and CH_4 of 0.5 ppm and for O_3, CO, SO_2, and NH_3 of 10 ppb.

The Panel members judged that the following species could also have an impact on the quality of the global environment. For instance, the concentration of CO_2 had been increasing since the industrial revolution because of the burning of fossil fuels. CO_2 traps part of the outgoing infrared radiation emitted by the Earth's surface and contributes to an increase in the average surface temperature. NOAA's new program of Geophysical Monitoring for Climatic Change (GMCC) was headed by Panel member, Donald Pack, and was focused on global trends in CO_2 and possibly other source gases. Nadir-viewing, satellite remote sensors ought to prove useful in tracking the movements of CO_2 from its sources to its sinks. Carbon monoxide (CO), SO_2, NO_x, and halogen gases are other pollutants from the combustion of fossil fuels or products of certain agricultural and industrial activities. Atmospheric methane (CH_4), nitrous oxide (N_2O), hydrogen sulfide (H_2S), SO_2, and certain hydrocarbons have large, natural source components. Panel member, Allen Lefohn of EPA, was an expert on the effects of ozone and peroxyacetyl nitrates (PAN), secondary pollutants in the troposphere arising from photochemical reactions involving nitrogen oxides and hydrocarbons. Ozone itself is harmful to forest and agricultural plants. Panel member, John Ludwig of EPA, was a proponent of applying sensor technology to the study of emissions from pollution sources and the transport of pollution regionally and perhaps globally [e.g., Ludwig, 1971]. Such regional to global scale concerns had also been outlined in a related National Academy of Sciences Panel Report [NAS, 1969].

(b) Findings and recommendations

The Panel reported that tropospheric temperature profiling was successful in 1969 from Nimbus 3 with its satellite, multichannel infrared spectrometer (SIRS) instrument that included a reference blackbody for in-flight calibration [Wark and Hilleary, 1969]. Rudy Hanel and colleagues at NASA Goddard employed Michelson interferometry for their infrared interferometer spectrometer (IRIS) to identify species in the atmospheres of both Earth and Mars. IRIS operated successfully from Nimbus 3 and 4, revealing spectral features from tropospheric H_2O and lower stratospheric O_3, in addition to CO_2 [Hanel and Conrath, 1969].

Stratospheric temperature profiles were being retrieved reliably by John Houghton and colleagues of the University of Oxford from nadir radiances measured with a CO_2 gas-cell, correlation approach, i.e., their selective chopper radiometer (SCR) instrument on Nimbus 4 [Houghton et al., 1984]. Donald Heath of NASA Goddard was also obtaining stratospheric partial column ozone measurements using the BUV approach from Nimbus 4. Solar, limb absorption was shown to be useful for the measurement of atmospheric extinction and of O_3 by Panel Member, Ted Pepin, of the University of Wyoming. Balloon-borne, infrared limb emission techniques were being evaluated for the measurement of stratospheric trace gas species by David Murcray of the University of Denver, and an extension of those techniques had been proposed by Panel members, John Gille and James Russell, for the measurement of temperature, O_3, and H_2O on Nimbus F (designated Nimbus 6 after launch).

The Panel members developed a consensus of satellite remote sensing possibilities for the various measurements. Factors that they considered were the spectral signatures of the pollutants, difficulties with data interpretation in the ultraviolet, visible, infrared or microwave regions, and the availability and sensitivity of instruments and detectors in the different spectral ranges. A comprehensive feasibility study had been underway already, led by Panel member, Claus Ludwig [Ludwig et al., 1974]. Because many in the Panel also had experience with developing and applying one or more of the specific minor or trace gas measurement techniques, they were able to evaluate the sensor capabilities of that time. They classified them according to atmospheric limb or vertical profiling techniques, by uv backscatter, thermal emission, or absorption. Both solar and stellar uv measurements of O_3 had been demonstrated from balloon, rocket, and early satellite platforms. Balloon-borne, limb-infrared measurements showed promise for inferring profile measurements of minor and trace gases in the stratosphere, once the effects of temperature are included for the calculation of their forward radiances. They reported that solar absorption measurements offered good specificity and accuracy for many gases, although often only as column burdens for the tropospheric pollutants. Correlation spectrometry could be applied to the measurement of SO_2 in the ultraviolet (uv) and of NO_2 at visible wavelengths. Both grating and correlation spectrometers were being employed for the detection and tracking of atmospheric species by Panel members, Barney Farmer of JPL and

Tony Barringer of Environment Measurements Inc., respectively. Panel member, Philip Hanst of EPA, was using tunable gas lasers for the detection of pollutants from ground-based sources. On the other hand, the RMOP Panel judged that the prospects were still unclear for making useful atmospheric pollution measurements via a passive microwave sounder from a satellite.

The Gaseous Species Panel made the following, rather broad recommendations in their report. Distributions of the stratospheric gases that play a part in determining the photochemistry of ozone and of the atmospheric radiative equilibrium state should be measured concurrently on a global basis from satellites. Primary constituents of interest were H_2O, NO, NO_2, HNO_3, CH_4, and O_3 itself. Panel members did not establish that all these gases could be measured with current techniques; therefore they recommended that a development program be undertaken to determine the feasibility of measuring the species distributions to their required accuracies. Trade-offs are involved for making accurate measurements of radiance or transmission profiles and for retrievals of the information content and vertical resolution of their temperature and gas species profiles, as reviewed subsequently in Houghton et al. [1984]. Remote measurement techniques from satellites should be exploited to measure regional and global distributions of gaseous pollutants in the troposphere, as well—the objective being to establish sources and sinks and to assess the roles of these gases in the environment. Trace gases that might be measureable in this manner and to the required accuracy were CO, SO_2, NO_2, NO, and possibly CO_2. Studies would need to be initiated to relate the vertical burdens and surface concentrations of the trace gases, and the findings should be used in the planning of complementary programs to measure pollutants from both the ground and Space.

The Panel recommended that remote measurement techniques be developed and applied to determine vertical concentration profiles of pollutants, and that their measurements should be used to improve transport models and to study the space and time variations of species. They noted that laboratory studies were needed to obtain more accurate values of the basic absorption properties of the pollutant molecules, i.e., line strengths, half-widths, and positions in the infrared and microwave regions of the electromagnetic spectrum. Research programs would need to be focused on advancing the state-of-the-art beyond the current instrumentation capabilities**,** with particular emphasis on those systems that appear to be potentially feasible from satellite altitudes. The Panel relied somewhat on performance assessments that were being conducted for the different types of instruments: radiometers, grating spectrometers, interferometers, optical correlation spectrometers, and laser probes (e.g., see Ludwig et al. [1974] and references therein). They recommended that both microwave techniques and active systems employing lasers be explored more fully. Panel members, Jacob Becher of Old Dominion University and Gary Grew of Langley, provided insight on the possible effects of space radiation on likely optical measurement systems and detectors. In addition to satellites, the Panel members emphasized the need to use aircraft and balloon platforms, for studying regional pollution problems and for evaluating the new techniques for their eventual use from Space. It is also noteworthy that NAS [1969] recommended that the National Center for Atmospheric Research (NCAR) and NASA coordinate their programs and make better use of the NASA

Wallops Island facility in Virginia, a unique sounding rocket and radar tracking station for the testing of proposed, remote atmospheric probing methods.

Table 1. RMOP members of the Gas Species Panel and their affiliations in 1971

William Kellogg, NCAR, Panel Chair
Tony Barringer, Environmental Measurements, Inc.
Jacob Becher, Old Dominion Univ.
C. Barney Farmer, JPL
John Gille, Florida State Univ.
Gary Grew, NASA Langley
Philip Hanst, Div. of Chemistry and Physics, EPA
Allen Lefohn, Div. of Chemistry and Physics, EPA
Claus Ludwig, General Dynamics Corp.
John Ludwig, Office of Air Programs, EPA
William Matthews, MIT
Donald Pack, Air Resources Lab, NOAA
Ted Pepin, Univ. of Wyoming
James Russell, III, NASA Langley
Harold Yates, NESS, NOAA

4 Developments in temperature sounding techniques

The major objective of atmospheric measurements from satellites in the 1960s was to obtain global data on temperature and water vapor and on the presence of clouds for the purpose of improving weather forecasts. NASA Goddard led the technology development for the TIROS and Nimbus meteorology satellite programs, but in coordination with the needs of NOAA and Department of Defense (DOD). Houghton and Smith [1970] provide an excellent tutorial on the difficulties of developing a remote sensor having both high spectral resolution and significant energy-gathering power. The Selective Chopper Radiometer (SCR) on Nimbus 4 is their initial solution for achieving temperature profiles in the stratosphere from radiance measurements in the nadir direction. Their retrieved temperatures are of relatively low vertical resolution or no better than an atmospheric scale height. Panel member, Harold Yates, of the National Environmental Satellite Service (NESS) of NOAA reported on methods for the retrieval of temperature from CO_2 radiances, as well as retrievals of H_2O and O_3 profiles after applying those temperatures in their analyses of the infrared emissions from those two gases. That approach had been demonstrated several years earlier with the nadir-viewing experiments, Infrared Interferometer Spectrometer (IRIS) and Satellite Infrared Spectrometer (SIRS) on Nimbus 3, and from the Temperature Humidity Infrared Radiometer (THIR), IRIS, and SCR on Nimbus 4. In addition, atmospheric O_3 profiles of moderate vertical resolution were also obtained for the middle and upper stratosphere using the nadir-viewing BUV instrument on Nimbus 4.

Ground-based atmospheric measurements of the 1960s indicated that one could also expect to obtain temperature and water vapor profiles from a satellite instrument operating at the microwave emission frequencies of O_2 and H_2O, respectively. A distinct advantage of the microwave measurement is that its signals are unaffected by clouds. One such instrument, the Nimbus E Microwave Spectrometer (NEMS), had already been developed for flight and was launched on Nimbus 5 in December 1972. An Infrared Temperature Profile Radiometer (ITPR), the Surface Composition Mapping Radiometer (SCMR), an Electronic Scanning Microwave Radiometer (ESMR) instrument, and an improved version of the Nimbus 4 SCR instrument also operated successfully from Nimbus 5. The SCMR and ESMR instruments were precursors to the more sophisticated imagers that would be deployed by Goddard and JPL from Earth observation satellites in the following decades. Imagery from SCMR also provided information about the transport of atmospheric dust and industrial pollution. Staelin et al. [1977] of MIT and personnel at JPL were successful in demonstrating retrievals of tropospheric and lower stratospheric temperature profiles with their Scanning Microwave Spectrometer (SCAMS) instrument on Nimbus 6 in 1975. Its successor, the Microwave Sounding Unit (MSU) instrument, was selected by NOAA for its series of TIROS operational vertical sounders (TOVS) beginning in 1979.

A Pressure Modulator Radiometer (PMR) instrument also obtained measurements of atmosphere radiance from Nimbus 6 [Curtis et al., 1974; Houghton et al., 1984; Lawrence and Randel, 1996]. The PMR instrument includes in its optical system gas cells containing CO_2 gas whose pressures are modulated at selected frequencies. This PMR approach is analogous to that of the SCR but has the distinct advantage that the transmission through the gas cell and the radiation incident at its detector is modulated only at the frequencies within the absorption lines of the CO_2 gas itself. In effect, the CO_2 in the cell acts as a spectrally selective filter for emissions from the CO_2 in the atmosphere. By this method one can essentially eliminate the effects of interfering emissions in the same wavelength band due to other atmospheric gases, and this approach was used later to infer the profiles of several trace gas species in the stratosphere, as well (see Section 5). The PMR instrument on Nimbus 6 carried two cells of CO_2, but with differing CO_2 amounts and pressure modulation ranges in order to be sensitive to radiance levels from the stratosphere and mesosphere. In this case because the atmospheric mixing ratio of CO_2 is uniform and known, one can infer the atmospheric temperature value that accounts for the radiance at the detector of each cell. Still, the final temperature profile obtained from the combined measurements from the two cells for a given sounding has an effective vertical resolution that is not much better than that from the SCR. However, on Nimbus 7 they used the PMR method to observe the atmosphere in the limb mode with the follow-on Stratospheric and Mesospheric Sounder (SAMS) experiment. The longer path of the limb-viewing geometry for the SAMS measurements and their narrower atmospheric weighting functions provided temperature profiles throughout the middle atmosphere from late 1978 to 1983 and with an effective vertical resolution of about 8 km [Barnett and Corney, 1984].

The PMR measurement of CO_2 radiance and the retrieval of atmospheric temperature from Nimbus 6 was the demonstrated precursor to the Stratospheric Sounding Unit (SSU) instrument for TOVS. The TOVS series of NOAA operational satellites also included a high resolution infrared radiation sounder (HIRS), whose capabilities were demonstrated initially on Nimbus 6 [Feddes and Liou, 1977]. HIRS was a 17-channel radiometer and its measurements together with those from the MSU provided the first opportunity for obtaining satellite temperature retrievals in cloudy atmospheres. Accurate retrievals of the temperature profile are critical for obtaining even low vertical resolution water vapor profiles from infrared channel radiances. Thus, NOAA combined the three instruments (HIRS, MSU, and SSU) for obtaining temperature profiles throughout the stratosphere and troposphere, even in the presence of clouds.

Unfortunately, the successful, joint NOAA/NASA operational satellite improvement programs were ended in 1982, when the U.S. government became less interested in sensor technology development for routine Earth observations [Conway, 2008]. It would be two decades later in 2002 when the Advanced TOVS (or ATOVS) sensor concept was launched by NASA on its EOS Aqua satellite. ATOVS consists of an Advanced Microwave Sounding Unit (AMSU) plus the Atmospheric Infrared Sounder (AIRS) of the JPL for temperature soundings [Chahine et al., 2006]. AIRS has nearly 2400 infrared channels and thereby provides improved S/N for the retrieval of both the tropospheric temperature and moisture profiles. AMSU is an improvement over the MSU, although with many fewer channels in the vertical than AIRS. Still, the microwave measurements are insensitive to the clouds.

In the early 1970s William Smith, Sr., of NOAA (and then of NASA Langley from 1997-2004) knew that the tropospheric infrared sounders must provide even greater vertical resolution, in order for their temperature and moisture profiles to gain further improvements in the weather forecasts. He proposed a High-resolution Interferometer Sounder (HIS) concept [Smith et al., 1979] based on the original IRIS instrument of Rudy Hanel. The development of HIS was aided by the experience gained by Harold Goldstein of General Electric with his Correlation Interferometer for the Measurement of Atmospheric Trace Species (CIMATS) instrument, a measurement concept supported at Langley through the AAFE Program. Smith built a prototype version of the HIS instrument and successfully tested it in a number of airborne campaigns. However, the full satellite realization of the original HIS concept was not achieved until some 25 years later upon the launch in 2006 of the European polar orbiting satellite MetOp-A and the Infrared Atmospheric Sounding Interferometer (IASI) with its more than 8400 infrared channels. Combinations of AMSU and AIRS on EOS Aqua and of AMSU, IASI, and the Microwave Humidity Sounder (MHS) on MetOp are leading to significant improvements in the skill of medium range weather forecasts at the present time [Smith, 2010]. Most recently, the combined goals of improved accuracy and much higher vertical resolution have been demonstrated for temperature and tropospheric water vapor from a set of six microsatellites using the Global Positioning System (GPS) radio occultation (RO) receivers and limb sounding techniques of the JPL [Anthes et al., 2008]. Those RO soundings are resolving the vertical temperature variations of the tropopause region and of the planetary boundary layer for the first time from satellites.

Nevertheless, even in 1971 the RMOP Panel members were aware that in order to obtain meaningful ozone data from its satellite-measured, infrared radiance profiles, it is critically important to also have co-located temperature profiles and with a vertical resolution that is very similar to that desired for the ozone. This capability is necessary in order to characterize the Planck function properly in the forward radiance model of the measured ozone radiances. Compatibility between the temperature and ozone is also important for a proper interpretation of the effects of both chemistry and transport on ozone in the stratosphere. Accurate pointing knowledge for the associated, co-located temperature and/or atmospheric density profiles is also required for the registration of the satellite, limb radiance or limb absorption measurements, as a function of pressure or altitude. This capability of obtaining high-quality, temperature, density, and radiance profiles was a significant factor for the design of the satellite instruments for the "pollution patrol" satellite, Nimbus 7, and thereafter, as noted in the next section.

5 Gas species profile or column measurements (1971-1985)

The Nimbus satellites operated in polar orbit, and they were focused mostly on the demonstration of sensor concepts. Observations from Nimbus 4 in 1970 provided measurements of good precision and near-global scale temperature and ozone distributions that were relatively accurate. However, it was clear to the RMOP Panel members that in order to resolve questions about the sources and fate of chemical pollutants in the stratosphere or the troposphere, one must obtain more accurate, global-scale data on the relevant trace gas species and with sufficient vertical resolution. Each sensor technique must be able to provide its retrieved species with acceptably small uncertainties. Tepper and J. D. Lawrence recognized in 1971 that improving the standing of the Space and Earth Sciences in the larger scientific community required renewed attention to the fundamentals of scientific practice, and operationally this meant engineering the instruments for credibility [Conway, 2008]. The capability for frequent, in-flight calibrations had to be developed for the instruments, and comparisons with known, co-located measurements would need to be carried out, especially during the test flights of a given instrument. Ultimately, the selection of an instrument for a spaceflight opportunity would be based on its scientific goals and on the performance of its test remote sensor.

Langley atmospheric science and engineering researchers began to play to their strengths in the 1970s and 1980s—solar occultation, infrared limb emission, radiation budget measurements, and lidar. It must be noted though that in the early to mid 1970s Langley technologists were also applying cameras, imagers, and laser fluorescence techniques to quantify the presence and effects of pollutants in rivers, lakes, and estuaries, as noted in the RMOP chapter by the Panel on Water Pollution. Panel Chair, Gifford Ewing, also pointed out that microwave radiometers would be very useful in providing continuous, all-weather monitoring from satellites of both the sea state and temperature. Personnel at Langley were developing state-of-the-art sensors for that very purpose and had been demonstrating them from aircraft platforms. However, strategic decisions were also being made within NASA in the mid to late 1970s, regarding what research activities to pursue further and whether to focus the work at specific NASA “Lead Centers”. As an example, shortly after its success with the Mars Viking Project, Langley was not tapped for a new planetary exploration mission. The subsequent phase-out of planetary science studies for Langley was perhaps a favorable outcome, since there would not be any new planetary missions launched by NASA after Voyager in 1977 and until Galileo and Magellan in 1989 [Conway, 2008]. In the late 1970s, Director Donald Hearth also decided to de-emphasize Langley’s water quality and microwave sensing activities, in part because it was felt that those capabilities were also being demonstrated effectively at JPL and Goddard. In general, further work on Earth imagers and microwave sounders came to a halt at Langley for the next two decades.

(a) Solar occultation

An opportunity arose for obtaining quantitative trace species profiles from low Earth orbit (LEO) by the technique of making solar absorption measurements through the Earth limb. Advantages of solar absorption measurements are high signal-to-noise (S/N), good vertical resolution, and excellent spectral discrimination [Russell, 1980]. Those capabilities were demonstrated by Panel member, C. Barney Farmer of JPL, with his balloon-borne Michelson interferometer operating from 1.3 to 5.5 micrometers and with funding from NASA's Applications Program [Farmer, 1974; Farmer et al., 1980]. Still, his co-worker, Robert Toth, found that he also had to obtain improved laboratory spectra for HCl and for both of its major interfering species, H_2O and CH_4, in order to obtain useful HCl profiles from the interferometer data. Thus, Toth and Farmer provided important updates for the line parameters of the minor and trace gas species that had been compiled earlier in the Air Force Cambridge Research Laboratory (AFCRL) trace gas catalog [McClatchey et al., 1973; Young, 1976]. NASA provided support for later versions of that spectral catalog, re-labeled the High Resolution Transmission molecular absorption (or HITRAN) database [e.g., Rothman et al., 1992]. Solar absorption survey studies were also conducted in 1983 using a Grille spectrometer on Spacelab 1 [Girard et al., 1988]. Balloon and aircraft measurements would become proof-of-concept for Farmer and his follow-on, Atmospheric Trace Molecule Spectroscopy (ATMOS) survey experiment that would fly successfully on four separate Space Shuttle missions—in 1985, 1992, 1993, and 1994 [Abrams et al., 1996]. ATMOS provided profile data for all the stratospheric species of interest in Section 3a. However, ATMOS had only relatively short observing opportunities via each Shuttle flight, and its profiles were limited to the latitudes of their sunrise or sunset measurements.

In the early 1970s NOAA contracted with Roland Drayson of University of Michigan for making feasibility studies of satellite, infrared absorption measurements of stratospheric minor constituents by solar occultation [Drayson et al., 1973]. They focused on those species that had been observed with the scanning infrared spectrometer of the University of Denver [Murcray et al., 1967] and for which AFCRL had already compiled molecular line parameters. However, the AFCRL listing of 1973 was limited to line parameters of only O_3, H_2O, CH_4, CO, and N_2O. NOAA personnel constructed a grating spectrometer and carried it aloft on a balloon to 39 km in June 1982, and they obtained useful profiles of O_3, H_2O, and HNO_3 via solar occultation [Weinreb et al., 1984].

Somewhat earlier, Panel member, Ted Pepin, demonstrated a simple, solar occultation limb-absorption radiometer concept, Stratospheric Aerosol Monitor (SAM), as part of the Apollo-Soyuz Test Project (ASTP) mission in 1975 [Pepin et al., 1977]. Based on that initial success, Pepin and Langley Principal Investigator, Pat McCormick, proposed for an extended measurement opportunity for a follow-on SAM II experiment on Nimbus 7. As originally proposed, they hoped to make measurements of O_3 and NO_2 in the visible with high vertical resolution (~1 km), based on Pepin's experience with making similar measurements from high-altitude balloons when he was a graduate student of Professor Ed Ney at the University of Minnesota. However, the SAM II instrument was descoped to measuring only aerosol extinction profiles at 1-µm wavelength and at just the high latitudes because of the polar orbit of Nimbus 7.

A follow-on proposal of McCormick and Pepin was accepted for a Stratospheric Aerosol and Gas Experiment (SAGE) on Applications Explorer Mission B (AEM-B), having an orbital inclination of 55˚ and allowing for observations equatorward of about 65˚ latitude in each hemisphere. Their instrument was launched in February 1979, and it obtained profiles of aerosol extinction at 0.45 and 1.0-μm and of O_3 and NO_2 across those latitudes each month [McCormick et al., 1979]. SAGE operations continued until November 1981. McCormick and William Chu of Langley designed another experiment, SAGE II, for measuring O_3 and NO_2 and having more channels for characterizing both the aerosol extinction profiles and their size distributions. They also added a channel for inferring water vapor profiles from solar transmission measurements at 0.94-μm. The SAGE II instrument operated from the Earth Radiation Budget Satellite (ERBS) that was deployed from Space Shuttle flight, STS-41G, in October 1984 with an orbital inclination of 57˚ or similar to that of SAGE I [McCormick et al., 1989]. Issues that they considered and addressed in successive versions of their algorithms were the absolute absorption cross-sections for the primary and interfering species along the limb path and a better model of the effects of refraction on the shape of the rising and setting Sun at the lower altitudes. SAGE II went on to become a huge success, providing very high quality, long-term measurements of aerosols and O_3 for nearly 21 years [Yang et al., 2006] and of H_2O for the many years when its absorption did not suffer from the large effects of the extinction by the volcanic aerosols.

(b) Limb infrared emission

Although solar occultation is a powerful technique for obtaining good quality profiles of a number of minor and trace gas species during a single sunrise or sunset event, the RMOP Panel realized that one could use infrared, limb emission measurements to obtain daily, near-global species distributions and for both day and night from a polar orbiting, Nimbus-type spacecraft. Such measurements offered the promise of analyzing for the global-scale effects of both chemistry and transport on stratospheric ozone and its related species. To demonstrate this possibility, the Air Force Geophysics Laboratory (AFGL) conducted a SPectral Infrared Rocket Experiment (SPIRE) in 1977 for the purpose of identifying species emissions from the atmospheric limb [Stair et al., 1985]. However, it became clear that one must also be able to retrieve the atmospheric temperature accurately, in order to account for its effects in the retrieval of a given trace species from its spectral radiance profile. Simulations showed that the temperature profiles from, say, the nadir-viewing SSU did not provide the vertical resolution and the co-located information on temperature versus pressure that is needed for the accurate retrieval of ozone from an individual limb radiance profile.

An early version of the satellite limb infrared emission approach was demonstrated by Panel Member, John Gille, using the Limb Radiance Inversion Radiometer (LRIR), which obtained both temperature and ozone profiles for the stratosphere and lower mesosphere from Nimbus 6. In order to obtain good accuracies for single temperature and ozone profiles, Honeywell Radiation Center (HRC) provided cooling for the detectors and internal optics of the instrument to improve the S/N of the measured radiances [Kollodge et al., 1972]. Gille and House [1971] developed an algorithm for the retrieval of stratospheric temperature-versus-pressure or T(p) profiles using a spectrally-narrow channel, plus another much broader, radiometer channel centered on the 15-µm bands of CO_2. Their T(p) profiles were then used for the retrieval of the co-located ozone mixing ratio profiles from the LRIR radiance measurements near 9.6-µm [Gille, 1979]. Even so, the accuracies of the retrieved temperatures and, in particular, ozone were limited by an inexact knowledge of the spectral line parameters of O_3 at both 9.6 and 14.1-µm. In fact, one could say that the taking of solar occultation and/or infrared limb emission measurements was analogous to carrying out spectroscopic studies of a target molecule, where the atmospheric limb itself is substituted for the laboratory cell path and pressures.

A disadvantage of limb sounders that the Panel noted is that one must know where the instrument is pointing along the horizon with high accuracy. Detector noise can be a limitation for a radiance scan at the higher altitudes, where the radiances are becoming small. The LRIR instrument had internal reflections which compromised the ability to retrieve useful H_2O profiles from the LRIR radiances in the rotational band near 25 µm of its channel. Improvements in detector technology, the cooling of optical arrays, a decrease of the horizon scan rate, and more extensive pre-flight calibrations were all considered for limb-viewing instruments on Nimbus 7 and beyond, in order to achieve better S/N and to characterize the effects of spurious radiance from within the instrument itself.

At this point the reader is reminded that the findings and recommendations of the RMOP Panel did not really impact NASA's selection of rocket and satellite instruments prior to Nimbus 7, although the performance of those early instruments provided very useful information for the improved designs and alternate concepts for future Earth observing satellites. As an example, Langley researchers, John Dodgen, Howard Curfman, Antony Jalink, Jr., Richard Davis, and Thomas McKee conducted important measurements during the 1960s for sensing the Earth's horizon in support of spacecraft guidance and navigation studies and ultimately for preparations of the controlled re-entry of manned capsules into the Earth's atmosphere. In particular, they made initial measurements of the horizon with a four-channel radiometer (uv, visible, and near and middle infrared bands) on a Javelin rocket flight from Wallops Island in 1961 [McKee et al., 1964]. Hanel et al. [1963] of Goddard had made calculations of the infrared horizon for 5 separate spectral intervals in the infrared and concluded that the 15-µm region of CO_2 was the most suitable for a horizon sensor. Subsequently, Bandeen et al. [1963] verified those findings using measured horizon radiances from the medium resolution scanning radiometer on TIROS VII. Langley personnel initiated their Project Scanner in 1963 for the purpose of developing a more efficient horizon sensor based on radiances in the 15-µm bands. Two suborbital, ballistic rocket flights of a radiometer were made in 1966 to characterize the infrared signature of the horizon and eventually for obtaining accurate temperature profiles [McKee et al., 1969; House and Ohring, 1969]. Another aspect that they considered was how to account for the horizontal gradients in atmospheric temperature (and CO_2 radiance) along the tangent path of the measurements, especially for the winter hemisphere [Davis, 1969].

Those early horizon definition studies led to a high altitude balloon flight of the AAFE instrument, Lower Atmospheric Composition and Temperature Experiment (or balloon LACATE), on May 5, 1974, at the White Sands Missile Range, New Mexico, for the further measurement of the stratospheric minor gases, H_2O and O_3, and of the trace gases, HNO_3 and NO_2, that interact with ozone. Unfortunately, useful retrievals of their profiles from the LACATE radiances were hindered by an inadequate knowledge of the pointing attitude for sensors on the balloon platform. Nevertheless, balloon LACATE became the precursor to the Limb Infrared Monitor of the Stratosphere (LIMS) experiment launched on Nimbus 7 in October 1978. Analyses of the radiance profiles from LACATE revealed that they were contaminated slightly by reflected radiances, internal to the instrument itself. That experience led to further internal baffling and test calibration measurements for the LIMS radiometer, prior to its launch. LIMS operated for the planned 7+ month lifetime of the cryogen gases for its detectors. It provided measurements of temperature and O_3 and near-global profiles of stratospheric NO_2, HNO_3, and H_2O—primary objectives of the RMOP Panel as summarized in Section 3a. The quality of the retrieved LIMS temperature and species profiles was assessed by comparisons with rocket and balloon measurements during the mission life of LIMS [Gille and Russell, 1984, and references therein]. Such correlative measurement opportunities were designed by the NASA program and project managers to ensure the success of all the experiments on the Nimbus 7 "pollution patrol" satellite, as urged by the RMOP Panel.

Although the broad-band, limb radiometer approaches of LRIR and LIMS were limited by an inadequate, direct knowledge of the attitude and pointing of the Nimbus 6 and 7 spacecraft, the LIMS principal investigators, Gille and Jim Russell III (Panel member from Langley), successfully employed the so-called "two color method" of Gille and House [1971] for the retrieval of good quality T(p) profiles. One drawback for applying this method with LIMS was that one must have a good first-order, estimate of the atmospheric ozone because its 14-μm ν_2 band interferes significantly with the broad-band radiances of the LIMS CO_2 channels that were used to retrieve T(p). A first pass of the retrieval algorithms was used to obtain the horizontal temperature gradients and a reasonable estimate of the interfering ozone, followed by a second pass to obtain the final temperature and species profiles [Remsberg et al., 2004]. LIMS provided good quality profiles of H_2O and HNO_3, and also of O_3, at least after improved ozone line parameters became available in 1982 for its retrieval. On the other hand, this broadband radiometer approach is limited to the relative handful of trace species that do not suffer the large, spectral overlapping of their radiances by other gases. For instance, the goal of good quality NO_2 profiles for the lower stratosphere was limited by a spectral overlap with emissions from H_2O and from the O_2 continuum [Russell et al., 1984]. The LIMS-retrieved NO_2 was also biased high in the upper stratosphere due to a lack of knowledge in 1979 of the spin-splitting effects for its nearly-saturated, strong lines. After accounting for those effects, Remsberg et al. [2010] were able to achieve reasonably accurate profiles of NO_2, as well.

Goody [1968] demonstrated that one can use a gas correlation infrared spectrometer to identify the trace gas N_2O in the presence of an interfering ammonia gas, whose absorption lines are much stronger than those of the target N_2O gas in the PMR cell. By employing instrument cells of differing internal pressures one can make use of the pressure-broadened line shapes of the known amounts of the target gas in each of several instrument cells for a retrieval of the atmospheric trace gas profile from its measured radiances. With this approach the companion Nimbus 7 SAMS limb-viewing experiment [Drummond et al., 1980] provided for the first time the near-global scale distributions of CH_4 and N_2O with a vertical resolution of about 8 km. These source gases are converted chemically to H_2O and NO_x, as noted by the RMOP Panel (see Section 3a). The SAMS measurements of these two tracer-like gases gave an excellent indication of the large-scale seasonal and interannual transport within the mid-stratosphere [Jones and Pyle, 1984]. Further details about the daily variations of those species about their zonal means were limited, however, by the relatively low S/N of the individual radiance profile measurements from the PMR channels of SAMS. The low S/N was because it was decided to apply passive cooling methods to the SAMS channels, rather than be limited by the lifetime of the cryogen-gas coolers that were available at that time. Drummond hoped to obtain several years of data, at least. But because the passive radiation cooler did not achieve its design temperature, it was only possible for SAMS to provide zonally-averaged results for the gases CO at 4.7 µm, NO at 7.7 µm, and the CO_2 channel radiance at 4.3 µm [Taylor et al., 1981]. Cooled detectors would correct for that problem in an Improved SAMS (or ISAMS) experiment for a follow-on NASA research satellite, but not scheduled for launch until 10 years later (Section 6).

(c) Partial column ultraviolet scattering and absorption

Heath et al. [1975] developed a double uv-monochrometer instrument for Nimbus 7. Similar to the Nimbus 4 BUV, their solar backscatter ultraviolet (SBUV) experiment had 8 short wavelength channels for inferring the ozone profile above the main ozone density maximum and 4 longer wavelength channels for determining total atmospheric ozone [McPeters et al., 1984]. SBUV operated successfully from its launch in 1978 and until June 1990, and it appeared that the losses of ozone in the upper stratosphere were occurring at an alarming rate. Early on though, Robert Hudson of Goddard concluded that there was some degradation of the reflectivity of the diffuser plate of the SBUV instrument, which led to a more extensive set of independent verifications of the total ozone measurements from SBUV based on comparisons with ground-based Dobson station data and later on with Shuttle-borne or SSBUV instruments.

At the same time NASA and the ozone research community wanted to verify that the SBUV, LIMS, and SAGE ozone profile measurements were of high quality and accurate. To that end, Upper Atmosphere Research Program (UARP) managers, Shelby Tilford and Robert Watson, also sponsored several balloon-ozone, intercomparison campaigns (BOIC) from its launch facility in Palestine, Texas, for the several *in situ* ozone instruments that were part of their extensive, satellite ozone validation activities. More broadly, the various aircraft, balloon, and rocket ozone measurement programs of NASA and NOAA were designed to ensure that the atmospheric modeling community could be confident about the changes that they were predicting for the ozone. Their findings were also critical for an assessment of the related policy implications. NASA also provided support for laboratory studies of the key rates of the chemical reactions that affect the vertical distribution of ozone, a key factor in bringing about better agreement between observations and the chemical model results. Those updated rates formed the basis of the periodic JPL publications on the chemical kinetics and photochemical data for use in atmospheric studies [e.g., JPL Publication 09-31, 2010].

Adarsh Deepak and M. P. McCormick held a workshop in December 1976 on inversion methods for the atmospheric remote sounding data, supported by Morris Tepper and J. D. Lawrence [Deepak, 1977; Lenoble, 1977]. This gathering of the experts on retrieval methods was very timely for the selection, demonstration, and deployment of Earth-observing experiments like SBUV and the monitoring of ozone from operational satellites. Such ozone datasets would become critical to the periodic, World Meteorological Organization (WMO) ozone assessment reports and for the verification of climate/chemistry models of stratospheric ozone. Retrieval algorithms for the NASA SBUV and later the NOAA-based SBUV/2 ozone instrument profiles rely on the optimal estimation approach of Mateer [1977] and later of Rodgers [1990]. They showed that middle and upper stratospheric ozone could be determined with high accuracy and moderate vertical resolution, but that the quality of the retrieved partial column ozone of the lower stratosphere required information from the total ozone channels of SBUV and an estimate of the ozone profile shape below its density maximum—obtained later with the aid of the ozone profile data from SAGE.

Nimbus 7 also carried onboard the cross-track scanning, Total Ozone Mapping Spectrometer (TOMS), a space borne uv-monochrometer, which is the equivalent of the ground-based Dobson total ozone instrument [Heath et al., 1978; Bhartia et al., 1984]. TOMS ozone images were produced daily by NASA Goddard, and they are recognized widely as the primary visual measure of the variations of the Earth's ozone layer and later as a clear indicator of the extent of the Antarctic "ozone hole" in springtime [e.g., Schoeberl et al., 1986]. The development, testing, calibration, and deployment of the succession of TOMS instruments was a direct outgrowth of NASA's mandate under the Clean Air Act Amendments of 1977 and of the charge of the RMOP Panel, "that any changes in total ozone be monitored, and causes be identified." For example, the Panel wanted to be able to know yearly average total ozone to within 1%. However, the concerns about total ozone by the Panel were not limited by what might happen to its stratospheric layer, but also extended to the effects of tropospheric pollution on the regional and global scale ozone. As a result, a most important issue would soon become how to know about any changes in the long-term calibration of the TOMS instrument, as well as to understand how to splice together the long-term data records from a series of operational TOMS-like instruments.

A related part of the early horizon definition programs was to verify theoretical studies of the Earth's horizon in the ultraviolet and visible by analyzing the data taken with photometers aboard test rockets and the X-15 research aircraft by Langley [e.g., Hrasky and McKee, 1964]. Later, Malchow and Whitney [1977] of the MIT Draper Laboratory with support from NASA's AAFE Program explored the information content of visible, limb scattering and absorption measurements and the conduct of retrievals of stratospheric ozone and NO_2. In fact, photometric measurements of this kind were also obtained from Skylab in 1973, although their calibrations were deemed inadequate for a proper testing of the associated retrieval algorithms. In October 1981 NASA/JPL launched into orbit the Solar Mesosphere Explorer (SME) satellite experiment of Charles Barth of the University of Colorado (and formerly of JPL) for obtaining profiles of ozone, NO_2 and H_2O using the uv-visible and 1.27-μm limb scattering techniques [Barth et al., 1983]. SME obtained 4 years of quality ozone profiles from about 50 to 80 km and with a vertical resolution of order 4 km, and those data were used to verify chemical models of the ozone in the mesosphere. Aruga and Heath [1982] considered an extension of the limb scattering approach of MIT for the measurement of ozone from the altitude range of 70 to near 20 km, or down to where the SBUV partial columns contain less detail and attain a vertical resolution of only 10 to 15 km. However, the proof-of-concept of their technique in the presence of stratospheric aerosol layers would not be demonstrated clearly until much later (see Section 7).

(d) Correlation radiometry and active sensing for tropospheric species

Because of the concerns about ozone that were paramount in the 1970s, the development of satellite-borne remote sensors by NASA was focused mostly on the several key parameters and species that might affect it. However, there was also interest and concern about what changes might be occurring for the chemistry of the troposphere. The NASA Office of Space and Terrestrial Applications (OSTA) and Langley's EQPO sponsored a series of lectures on the topic in 1977 to revisit the scientific imperatives for an understanding of the chemistry of the troposphere [Levine and Schryer, 1978]. The RMOP Panel knew that making such measurements from a satellite would not be easy. Nevertheless, the feasibility of observing air pollutants in the troposphere with satellite-borne sensors was considered in the early 1970s by Panel member, Claus Ludwig, and colleagues [Ludwig et al., 1974], and the prospects for one species mentioned in Section 3a looked quite promising—carbon monoxide (CO). In the mid 1970s Harold Goldstein of General Electric and Peter Lebel of Langley conducted measurements of CO and CH_4 with the Carbon Monoxide Pollution Experiment (COPE) correlation interferometer near 2.3 μm from an aircraft with support from the AAFE Program. COPE gave atmospheric column density measurements of CO and their values were verified with profiles obtained with *in situ* samplers. In fact, such validation activities were the impetus for NASA and, in particular, Langley's airborne tropospheric field campaigns of the next several decades.

RMOP Panel Co-Chair, Henry Reichle of Langley, went on to lead the development of a gas filter correlation radiometer operating at 4.7 μm for making measurements of column CO from both an aircraft platform and eventually on the second engineering test flight of the Space Shuttle (STS-2) in 1981 [Reichle et al., 1986]. His concept became known as the Measurement of Air Pollution from Satellites (MAPS), and he would fly it again on Shuttle in 1984 and twice in 1994 [Newell et al., 1999]. MAPS provided low vertical resolution profiles of tropospheric CO across the low and middle latitudes. Newell et al. [1999] found that high levels of CO were associated with regions of biomass burning. They also reported finding low values of upper tropospheric CO associated with relatively high values of potential vorticity, suggesting that those air samples originated from the stratosphere. The MAPS measurements were really the first demonstration that one could anticipate conducting studies of extended layers of atmospheric pollution from a satellite platform, and they would lead to more concerted attempts during the EOS era. The measurement of tropospheric column ozone or ozone profiles from a satellite platform was also considered in the 1970s and 1980s, with an emphasis on active sensing techniques.

J. D. Lawrence, Jr., M. P. McCormick, and S. H. Melfi of Langley's Instrument Research Division (IRD) had conducted laser backscatter measurements in the late 1960s for the purpose of sensing turbulent regions of the atmosphere. They also reported evidence of Raman scattering by H_2O in the lower atmosphere and by SO_2 in a smoke plume from a power generating plant [Melfi et al., 1969; Melfi et al., 1973]. Quantitative Raman measurements of SO_2 were demonstrated subsequently by Poultney et al. [1977]. However, it was clear that the Raman scattered signals were much too weak to be considered for remote sensing of tropospheric gases using a laser system operating from a space platform. Instead, Langley and JPL supported study contracts in the 1970s to determine the technology investments that would be needed for conducting profile measurements in the troposphere using the concept of a differential absorption lidar (DIAL) from a Space Shuttle platform. It soon became clear that accurate profile measurements of tropospheric H_2O ought to be possible from Space. Remsberg and Gordley [1978] noted that DIAL would not be as feasible for measuring tropospheric ozone because of the attenuation of its tropospheric return signals by the much larger column ozone amounts of the stratosphere. It would be necessary to tune the DIAL system to several pairs of absorbing and non-absorbing uv-wavelengths. Several years later, Ed Browell of Langley led an international working group of experts in assessing in more detail what gas species might be sensed with laser systems operating from Space [NASA, 1979]. Over the next several decades those prospects became more fully realized with the development and demonstration of the use of stable, tunable laser systems in a number of airborne field campaigns focused on regional studies of ozone in the troposphere and even into the lower stratosphere. The performance of the Langley airborne uv-DIAL system also demonstrated that it is certainly possible to obtain useful measurements of the regional-scale variations of tropospheric ozone from low Earth orbit and with an altitude resolution of order 2 km [Browell et al., 1998].

6 Changing priorities and technology advancements (1986-1996)

(a) *Science and politics*

In the 1980s the nation was coping with the ravages of inflation following the Vietnam War. There was also a decrease in public awareness and support within the U.S. regarding environmental issues. The Reagan administration put limits on the research and enforcement activities of the EPA and reduced funding within the NASA Earth applications programs. Government support waned within NOAA and NASA for enhancing the satellite technology, especially following the recession of 1982. There was a contraction of NASA's engineering and technician workforce, and there were greater incentives for their activities to be undertaken by contractors or entirely by the private sector in some instances. Thus, it was a time of adjustment and retrenchment for NASA. Opportunities were few for actually demonstrating instrument concepts from satellite orbit. Investments in new technologies also dwindled, and the proof-of-concept of measurements from low Earth orbit had to be carried out from the Space Shuttle. As a consequence, instrument performance was often demonstrated from aircraft and balloon platforms, as part of field campaigns focused on gaining an understanding of the budgets of trace chemicals in the troposphere. Further, in the late 1980s and early 1990s the Reagan and Bush administrations opted to move away from the Space Shuttle as a primary delivery vehicle for satellites to low Earth orbit. Instead, they envisioned using it to construct the International Space Station (ISS) and to have it as an intermediate staging platform for sending probes to Mars and beyond.

Effects of man-made compounds from SST exhaust plumes and due to the release of CFC compounds into the atmosphere continued to be a paramount concern of atmospheric scientists during this period because of their potential effects on stratospheric ozone. It was clear that the measurement technologies to be adopted would be based on their ability to both characterize the natural stratosphere and to understand the effects of pollutant perturbations to its chemical makeup. The culture for Earth Science research also changed within NASA. Prospective, in-house science and technology studies were selected as a result of positive reviews from the external peer community, in large part. Langley continued to focus on the development of sensing technologies for the study of stratospheric ozone because that knowledge was important for clarifying what role questions about ozone might play in the further development of high speed civil transport (HSCT) aircraft at Langley and the potential role of such aircraft for the international trade balance of the U. S. Sorting out the role of man-made versus natural forcings for Earth's climate was also becoming an area of interest within NASA. For instance, stratospheric aerosol layers from the eruptions of Mt. St. Helens in 1980 and from the much larger eruption of El Chichon in 1982 were easily detected and monitored with the SAM II and SAGE satellite instruments by Langley researchers. It was also known that such volcanic aerosol layers led to a temporary cooling of surface temperatures, at least for those latitude zones where the volcanic aerosol optical depth was greatest.

The major NASA Earth Science satellite initiative during the 1980s was the Upper Atmosphere Research Satellite (UARS) with a large payload of twelve separate experiments. UARS carried four experiments focused on improving our understanding of the effects of chemistry and transport on stratospheric ozone [Reber et al., 1993]. They included the Halogen Occultation Experiment (HALOE) [Russell et al., 1993], the Cryogenic Limb Array Etalon Spectrometer or CLAES [Roche et al., 1993], the Microwave Limb Sounder (MLS) [Waters et al., 1996, and references therein], and the ISAMS instrument [Taylor et al., 1993]. RMOP Panel member, James Russell III, proposed HALOE for obtaining near-global measurements of HCl and HF profiles plus a number of other species, including ozone itself. HCl and HF are the end products of the chemistry of halogen compounds in the stratosphere. His concept for HALOE was developed under the AAFE Program, and it was demonstrated through flight tests of a brassboard instrument on the CV-990 research aircraft. HALOE employed both broadband infrared radiometry and gas filter correlation radiometry for obtaining single profiles of a number of trace gas species via solar occultation. The CLAES and ISAMS experiments together measured the primary chlorofluorocarbon source molecules plus a number of molecules that were used to isolate the roles of the several chemical families on the ozone profile. CLAES relied on cooled detector arrays and very narrow spectral intervals for its measurements. ISAMS obtained nine months of good data before its chopper mechanism failed. More importantly, UARS carried MLS for measurements of chlorine monoxide (ClO), ozone, and other related species using millimeter-wavelength, thermal emission heterodyne techniques. The development and demonstration of the ground-based and airborne versions of MLS were also supported under the AAFE Program, as urged by the members of the RMOP Panel.

The goal of achieving accurate species profile measurements with adequate vertical resolutions was pursued by the satellite remote sensing community as early as 1975, prior to the launch of Nimbus 7 and before demonstrations of the success or deficiencies of its sensors. In fact, the MAPS experiment concept had also been proposed for Nimbus 7, but it was concluded that the MAPS gas filter technology and algorithms were not yet sufficiently mature. At about that time Russell et al. [1977] recognized that it would be feasible to use gas filter spectroscopy for the measurement of stratospheric halogen compounds via solar occultation. In addition, Park et al. [1980] developed methods for obtaining co-located T(p) profiles for the vertical registration of the transmission profiles from the HALOE channels. They proposed using a narrow band radiometer operating in the 4.3-μm region of CO_2 for that purpose.

All four stratospheric experiments on UARS took advantage of the improved vertical resolution of the long atmospheric path offered by a limb-viewing geometry. S/N was increased by the use of cooled detectors having longer cryogen lifetimes or a Stirling-cycle refrigerator for CLAES and ISAMS, respectively. CLAES measurements were made at focused, narrow spectral intervals to reduce the effects of radiances from unwanted, interfering species. During late 1991 and early 1992 the measurements from SAGE II and from the HALOE, ISAMS, and CLAES experiments were affected by the stratospheric aerosols from the eruption of Mt. Pinatubo, which occurred in June 1991 or three months prior to the launch of UARS. Most fortunately, the MLS measurements were unaffected by the interfering volcanic aerosols.

The disastrous Shuttle Challenger accident occurred on January 28, 1986, bringing about a two-year hiatus before there would be any further launches of the Space Shuttle. UARS had been scheduled for a launch from Shuttle in 1989, but it was not placed into Earth orbit until September 1991. Earlier it was noted that the hiring of atmospheric remote sensing specialists was very limited within NASA during the 1970s and 1980s. Most of the instrument development work was conducted by civil servants upon being re-directed from other activities that had been de-emphasized following the Apollo era. HALOE was Langley's contribution to UARS. By having a workforce that was focused on specific technologies, it was possible for Langley to bring HALOE in-house eventually and complete its fabrication. The two-year launch delay also meant that there was more time for conducting additional tests and calibrations of HALOE. Those additional studies of the performance of HALOE were very helpful for a proper characterization of the 14-year time series of its atmospheric species and temperature profiles.

To stay abreast of the advancing measurement technologies, Langley, Goddard, Ames, and JPL hired contractors during this period to help with the development and demonstration of new or improved sensors for Earth applications. At Langley they contributed to the SAGE II, HALOE, MAPS, and ISAMS Projects, both prior to and following their launch. Several of those contractors were hired later as NASA researchers or technologists. They include Mike Pitts, Larry Thomason, Chip Trepte, and Joe Zawodny with SAGE II, Marty Mlynczak, Jae Park, Curtis Rinsland, and Mary Ann Smith with HALOE, and Estelle Condon, Pamela Rinsland, and Vickie Connors with MAPS. Brian Connor contributed to ISAMS and led its ozone validation paper [Connor et al., 1996]. Still, much of the Project work was performed by dedicated contractors at Systems and Applied Sciences Corp. (SASC), Hughes STX, Corp., Science and Technology Corp. (STC), Science Applications International Corp. (SAIC), Gordley and Associates Technical Software (GATS, Inc.), and PRC Kentron, Inc., as well as The College of William and Mary and Old Dominion University.

(b) *The "Antarctic ozone hole" and trends in global ozone*

Prior to 1985 and before the measurements from UARS, the likely effects of reactive chlorine on upper stratospheric ozone had become understood reasonably well based on ground-based microwave measurements of both ClO and O_3 by Joe Waters and on the multiple balloon-borne soundings of the CFC source molecules by NOAA and NASA. The U. S. subsequently banned its use of CFCs as propellants, and the political conflict over stratospheric ozone cooled down considerably [Conway, 2008]. As is normally the case however, scientific priorities often change before it is possible to develop a measurement concept and demonstrate its promise from an Earth orbiting research satellite. The announced discovery of an "Antarctic ozone hole" in 1985 plus NASA's mandate to monitor the health of the ozone layer as part of the CAA amendments of 1977 meant that there was an even greater urgency for understanding this unanticipated loss of polar ozone and for developing a strategy to reverse it, if possible. Fortunately, much of the measurement technology that had been developed and tested under the

AAFE Program was available for making more focused sets of polar ozone measurements from NASA research aircraft. Those airborne campaigns were conducted in conjunction with the ongoing observations at ground-based sites in Antarctica and in the Arctic that were supported by NOAA and the National Science Foundation (NSF). Data obtained with the TOMS, SBUV, SAGE II, and ATMOS experiments were also available for studying the "Antarctic ozone hole". Initial findings from those satellite data sets are reviewed in Russell and McCormick [1987]. Thus, the focus on ozone with UARS moved from the upper stratosphere to the lowermost stratosphere and to what was happening at polar latitudes, in particular. It also meant that heterogeneous chemical processes must be incorporated into chemical models of the ozone and verified with measurements. A comprehensive summary of the "Antarctic ozone hole" issue can be found in Solomon [1999].

The two primary sources of bias error for satellite remote sensors are due to an inadequate knowledge of the satellite (and sensor) orbital attitude and to their co-located temperature profiles, particularly for thermal infrared measurements. Findings from the early infrared horizon sensors of Langley's Project Scanner, from radiance modeling studies, and from the TIROS and Nimbus research satellites indicated the need for even better capabilities for Earth-referenced, in-flight controls and for the instrument attitude and pointing of UARS [Phenneger et al., 1985]. Improved retrievals of the temperature versus pressure or T(p) profiles were also attained as a result of more accurate forward models for their CO_2 radiance and/or transmission profiles. Forward models for the minor and trace species of UARS benefitted from improvements in the line parameters of the target gases and their interfering species, particularly those of CH_4 for the retrieval of HCl from HALOE. In general, comparisons of the UARS measurements with those from independent techniques showed that the species profiles from UARS are reasonably accurate, as well as precise. Even for SAGE II, it was found that a better accounting for the secondary effects of the ozone cross section at 0.935 μm plus an adjustment for a "spectral drift" of the interference filter of that channel gave improved profiles and trends for lower stratospheric H_2O in its Version 6.2 dataset [Thomason et al., 2004]. Thus, even though SAGE II and the several experiments on UARS were designed to acquire important information about the effects of chlorine radicals on upper stratospheric ozone, their measurements became focused primarily on the issue of Antarctic ozone depletion.

From the mid-1980s onward, another scientific measurement requirement was presented to the remote sensing community because of the effects of reactive chlorine on the ozone profile that had been realized for both the upper stratosphere and for the polar regions of the lower stratosphere. Specifically, could the trends in ozone and the parameters that control it be measured with the accuracies that were needed? Because instruments on research satellites like Nimbus 7 were not designed with that goal in mind, it was necessary to re-consider how well each instrument was calibrated over time and whether any orbital changes for their parent spacecraft might affect their derived trends. Frederick and Serafino [1985] anticipated such requirements for the operational SBUV sensors, for example. Soon thereafter, Harold Johnston of University of California, Berkeley, chaired an Ozone Trends Panel for NASA. That Panel issued a report of findings that led to new activities within the satellite remote sensing community for the monitoring of both temperature and ozone [WMO, 1988]. In general, they concluded that satellite, solar occultation instruments ought to be able to provide reliable trends, primarily because they have an exoatmospheric calibration for each sunrise or sunset profile and because there is less of a chance for a long-term change in their instrument components. One exception is the possibility for degradation in the characteristics of the interference filters. Another related requirement for quantifying changes in the distributions of species from multiple satellites is to know that each of the separate datasets have been processed using the same version of the spectral line parameters for a given species. This latter requirement might mean that a reprocessing of an early dataset would need to be undertaken, in order to compare it with the data from a follow-on experiment. For the TOMS and SBUV sensors, significant efforts were devoted toward just how to account for discontinuities in the datasets from a succession of those instruments [e.g., Hilsenrath et al., 1995]. Miller et al. [1997] confirmed that the SBUV and Umkehr measurements are only able to quantify the long-term variations of ozone for the middle to upper stratosphere. The RMOP Panel did not really foresee or address such circumstances for the assessment of ozone trends in its report of 1971, although they did lay the groundwork for conducting further studies of any instrument related issues.

Since reliability was uncertain for the trends in remotely-sensed ozone and related species from the early satellite measurements, NASA became involved in 1991 in what is now known as the international Network for the Detection of Atmospheric Composition Change (NDACC), presently co-chaired by Geir Braathen of WMO and Mike Kurylo, a former NASA Program Manager. In some respects NDACC is a replacement for the Meteorological Rocket Network (MRN) and its routine soundings of the state of the middle atmosphere. The NDACC consists primarily of ground-based remote sensors, some of which were being developed and demonstrated at the time of the RMOP Report. They include Rayleigh backscatter (temperature and aerosols), sodium vapor fluorescence (temperature), DIAL (ozone and aerosols), and Raman (water vapor) lidar systems, microwave radiometers (ozone, water vapor, and ClO profiles), uv/visible and Fourier Transform Infrared (FTIR) spectrometers (for measuring column content of a number of trace species), and Dobson instruments (total column ozone). In fact, Remsberg [1986] made early use of Rayleigh lidar soundings from the French lidar group of Marie-Lise Chanin for his validation study of the quality of the LIMS temperature profiles of the upper stratosphere and lower mesosphere. Brian Connor of Langley, Rich Bevilacqua and Gerald Nedoluha of the Naval Research Laboratory), John Olivero of Penn State University (but originally at Langley), Alan Parrish of University of Massachusetts, and Phil Solomon of State University of New York (SUNY) at Stony Brook, conducted ground-based microwave measurements of species profiles from California, Hawaii, New Zealand, and at McMurdo Station, Antarctica, in support of UARS. Curtis Rinsland, Joel Levine, and Thomas Miles of Langley analyzed for long-term trends in the tropospheric species, CO and CH_4, from time series of solar spectra taken since 1951 from the Jungfraujoch Observatory in Switzerland [Rinsland and Levine, 1985; Rinsland et al., 1985]. Long-term variations of ozone, H_2O, and temperature from NDACC station data are still serving as an independent check of the findings from the satellite data records [Steinbrecht et al., 2009].

During the late 1980s and early 1990s there was renewed interest within the U. S. aircraft industry toward a HSCT plane that would fly more quickly to the countries on the "Pacific Rim", as well as to Europe or to the Middle East and India. Studies were instituted in the early 1990s by Howard Wesoky of NASA's Office of Aeronautics and Space Technology (OAST) about the likely effects of HSCT emissions on the atmosphere and on the prospects for cleaner engine combustion technologies in reducing those emissions. The early work of the RMOP Panel was still relevant to that activity because much of the original purpose of the Panel arose out of similar concerns in 1971 about the effects of emissions from SST aircraft. NASA formed a High Speed Research Project (HSRP) Office at Langley and assigned Alan Wilhite to manage its activities. Richard Stolarski of Goddard led an associated Panel in a study of the Atmospheric Effects of Stratospheric Aircraft (AESA). In fact, the combined HSRP/AESA provided most of the support for the atmospheric assessment models that would be used to predict environmental impacts of a fleet of the supersonic planes. European researchers conducted their own studies but with a focus on the effects of the current and future subsonic fleet. Of course, there were also concerns about the effects of their additional emissions on polar ozone, particularly from trans-oceanic flights across the high northern latitudes. With that in mind, NASA sponsored several comprehensive model/measurement (M&M) study activities, including comparisons with the remotely-sensed, distributions of ozone and its related chemical species from UARS. HSRP/AESA also supported laboratory studies of the heterogeneous processes that affect polar ozone.

The combined HSRP/AESA program assisted with further developments in remote sensing technologies and their demonstrations for the stratosphere and troposphere, as carried out during dedicated NASA airborne research campaigns and from studies of aircraft emissions and their related tropospheric species. For example, Langley researchers, Glenn Sachse and Glen Diskin, conducted airborne species measurements using gas filter correlation and tunable diode laser techniques. Ed Browell and co-workers made DIAL lidar measurements of ozone and aerosols from a DC-8 aircraft. Bruce Anderson conducted in-flight measurements of the gaseous and particulate aircraft emissions injected to the atmosphere. There was also a succession of airborne campaigns as part of NASA's larger Global Tropospheric Experiment (GTE) program, managed by Joe McNeal. GTE activities at Langley were managed by John Mugler, Robert Harriss, James Hoell, Richard Bendura, and James Crawford. Many of the initial airborne test flights were assisted by personnel at the NASA Wallops Flight Facility, as envisioned earlier by the RMOP panel members. Demonstrations of the sensor technologies within GTE provided the foundation for the subsequent satellite instrument validation activities that would be needed in the upcoming EOS era and for studies of any trends in tropospheric ozone.

Jack Fishman of Langley was the first to suggest that photochemical ozone production in the troposphere can be inferred for the tropics from an analysis of TOMS total ozone data [Fishman et al., 1986]. He found a positive correlation between the MAPS CO and TOMS total ozone values at low latitudes, related to regions of biomass burning. Fishman and Larsen [1987] went further and obtained estimates of the spatial variations in the tropospheric ozone column by integrating the stratospheric ozone profiles above the tropopause from SAGE profiles and then subtracting those column amounts from the co-located TOMS total ozone. They would later show that enhancements for their so-called "tropospheric ozone residual (or TOR)" also indicated that there was *in situ* production of ozone resulting from large-scale, biomass burning activities [Fishman, et al., 2003]. The amount of the TOMS total column ozone that resides in the troposphere is only of order 10-15%. Thus, the calculation of TOR is affected by even small errors in the stratosphere ozone column from SAGE and in the total ozone from TOMS. Earlier, Remsberg et al. [1984] used a similar bootstrap method for a validation of stratospheric ozone from LIMS. Their approach was to find co-located ozonesonde and LIMS profiles, integrate the LIMS ozone profile above the 70-hPa level in the stratosphere, and then to add that amount to the integrated ozonesonde values from the ground to 70 hPa. Their combined sums were then compared with the ground-based Dobson total ozone value at the location of the sonde measurement. On average, the LIMS plus ozonesonde sum agreed with the Dobson data to 0.8% with a root-mean-square (RMS) difference of 5.4%. However, positive biases in the LIMS ozone were apparent in the lowest parts of the stratosphere, such that the LIMS data could not be used reliably to generate daily maps of the zonal variations in the TOR.

Other nations were developing and deploying their own Earth observation satellites during this period. Their contributions are mentioned here only briefly; the reader should consult the associated experiment websites and/or published articles for more details. For example, the European Space Agency (ESA) launched two European Remote Sensing satellites, ERS-1 and ERS-2, respectively, in 1991 and 1995. In particular, the Global Ozone Monitoring Experiment (GOME) sensor on ERS-2 was a nadir-scanning uv, visible, and near infrared spectrometer for measuring total ozone and column amounts of NO_2 and for detecting other tropospheric trace gases [Burrows et al., 1999]. GOME represented a significant next step for making global measurements in the troposphere, and it was followed in 2006 by a second generation instrument on the MetOp satellite. Column ozone measurements were continued with the deployment of TOMS instruments on the Meteor-3 spacecraft in 1991 and on Earth Probes (EP-TOMS) in 1996, as well as with copies of the SBUV sensor on the series of NOAA operational satellites. The Polar Ozone and Aerosol Measurement (POAM II and III) experiments of NRL were launched on the French SPOT 3 and 4 spacecraft in 1993 and 1998, respectively. POAM II measured stratospheric profiles of ozone and NO_2, and POAM III added H_2O profiles [Lumpe et al., 2006]. The Improved Limb Atmospheric Spectrometer (ILAS) and another TOMS instrument were launched into orbit in 1996 by the Japanese Space Agency on its Advanced Earth Observing Satellite (ADEOS). A second ILAS instrument began operations from ADEOS II in 2002. Atmospheric scientists at University of Wuppertal, Germany, deployed their Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) instrument as a Shuttle Pallet Satellite (or SPAS) on flights in 1994 and 1997 [Offermann et al., 1999; Grossmann, 2000]. CRISTA employed three telescopes pointing at the Earth's limb and at different horizontal angles, in order to provide measurements of a higher spatial density. POAM, ILAS, and CRISTA were focused on making measurements of important minor and trace stratospheric species, especially at the higher latitudes.

Satellites launched from the Space Shuttle are in slowly precessing orbits and, in the case of UARS, required occasional yaw maneuvers to meet their thermal and viewing requirements and to maintain proper solar array exposure throughout the year [Reber et al., 1993]. Another example of a satellite in a precessing orbit is the Tropical Rainfall Measuring Mission (TRMM)—a cooperative venture of the U.S. and Japan and launched by the Japanese Space Agency in November 1997. The goal of TRMM was to quantify rainfall amounts and latent heat release at low latitudes as a function of the local times associated with convective development [Kummerow et al., 1998]. On the other hand, the major goal of NASA's EOS satellite observations was to monitor the global surface and atmospheric environment and to relate any changes in their characteristics to natural and/or anthropogenic activities. Indeed, this objective strains the capabilities and ingenuity of the satellite remote sensor community. The goal of resolving statistically significant variations or trends in a given surface or atmospheric parameter across all latitudes meant that the observations must be made from satellites in Sun-synchronous, polar orbits. As a result, the EOS spacecraft sequence of Terra, Aqua, and Aura, were launched by Atlas or Delta rockets from Vandenberg Air Force Base in California.

7 An Earth Observing System (EOS) plus international contributions (1997-2010)

Selections of the experiments for the three EOS spacecraft were really made in the early 1990s, and many of the instruments merely represented refinements of earlier atmospheric sounders and Earth imagers. Imaging experiments selected for Terra and Aqua had their heritage based on similar instruments on Nimbus and Landsat, and on NOAA's Advanced Very High Resolution Radiometer (AVHRR). NASA had also gained quite a bit of experience for the selections for Aura, as a result of the testing and deployment of the engineering or preflight instrument models and algorithms for UARS. Members of the several EOS advisory panels were briefed on the expected performance of the various instruments proposed for EOS, and they provided recommendations to NASA. Algorithms for the creation of the EOS datasets were reviewed and made available in Algorithm Theoretical Basis Documents (ATBD) prior to launch, and the science teams associated with the experiments were urged to provide their data and report on preliminary results shortly after launch. This approach was certainly different from the traditional role of a Science Team, as led by a Principal Investigator. One caveat for NASA's vision of multiple copies of each EOS instrument was the subsequent realization that significant technology improvements would become available and ought to be incorporated into any follow-on versions of the instruments.

The EOS "flagship" spacecraft Terra was launched in December 1999 into a late morning orbit, and it carried two instruments for sounding the troposphere—Goddard's Moderate-resolution Imaging Spectroradiometer (MODIS) [King et al., 2003] and the Measurement of Pollution in the Troposphere (MOPITT) of University of Toronto, Canada [Liu et al., 2005]. MODIS continues to provide, near global-scale information on temperature, precipitable water, clouds, and aerosols in the troposphere some ten years after launch. MOPITT is providing distributions of tropospheric CO using the pressure modulation or length modulation, gas filter correlation approach [Drummond et al., 2010]. Rodgers and Connor [2003] conducted an initial validation of CO from MOPITT using an optimal estimation approach to account for the information content of its measurements, and they found good agreement for the CO from MOPITT and from a ground-based FTIR measurement. EOS Aqua was launched in May, 2002, into an afternoon orbit, and it carried a second MODIS instrument plus JPL's cross-track scanning, grating spectrometer AIRS. The AIRS instrument measures tropospheric CO, CH_4, CO_2, O_3, H_2O, and volcanic levels of SO_2. As an example of its capabilities, McMillan et al. [2005] showed daily, global maps of CO from AIRS and their excellent correlations with biomass burning activity. Recent work of the AIRS experiment team has been focused on retrievals of O_3 and CO_2. The third EOS satellite, Aura, was launched in July, 2004, and it carried two stratospheric instruments—a second-generation MLS from JPL and the High Resolution Dynamics Limb Sounder (HIRDLS with PIs John Barnett and John Gille) of the University of Oxford and NCAR [Taylor, 2011]. An Ozone Monitoring Instrument (OMI with PI Pieternel Levelt) of the Netherlands and the Tropospheric Emission Spectrometer (TES with PI Reinhard Beer) of JPL round out the Aura payload. The Aura satellite is also in an afternoon orbit along with Aqua and several other satellites. They are flying in a formation that has been dubbed as the "afternoon or A-Train".

At this point it is noted that RMOP Panel member, H. G. Reichle, Jr., of Langley, also proposed his MAPS experiment for Terra, but that MOPITT was selected instead. Nevertheless, Reichle assisted the MOPITT team by providing them with his datasets on CO and details about the characteristics of the MAPS instrument. He later made modifications to the MAPS instrument and obtained improved results for retrievals of mid-tropospheric CO from two flights of MAPS on Shuttle in 1994 [Reichle et al., 1999]. He and his colleagues at Langley also participated in a joint U.S./Russian activity in 1997 to install the MAPS instrument on the orbiting space station, MIR. But because of a collision of a supply vehicle during its docking attempt with MIR, the planned operations of MAPS from MIR were never carried out. Several years later MIR was de-orbited with MAPS aboard, and no backup instrument remained for another flight opportunity. RMOP Panel member, James Russell, III, also proposed the experiment Spectroscopy of the Atmosphere using Far Infrared Emission (SAFIRE), but a second-generation of the JPL MLS experiment was chosen for EOS Aura. Langley's only successful contribution to the suite of EOS satellite payloads was SAGE III. It was launched aboard a Russian Meteor-3M satellite in December 2001 and represented a continuation of the earlier SAGE experiments by Pat McCormick. SAGE III obtained measurements by both solar and lunar occultation for nearly 4 years and was focused on species and processes associated with ozone at polar latitudes. Technological advances, such as Charge Coupled Device (CCD) linear array detectors, were also employed for obtaining the profile measurements from SAGE III [Wang et al., 2006].

Atmospheric instruments on the EOS payloads were designed to obtain temperature and/or species profile or column information with adequate S/N (and accuracies) and improved vertical resolutions, where possible. MLS continues its excellent performance for the monitoring of ozone and its related species from the upper troposphere and well into the mesosphere. In addition, Aura MLS provides profile information about stratospheric OH using a 2250 GHz receiver. The OMI instrument succeeds TOMS in continuing the monitoring of total ozone on the global scale [Levelt et al., 2006]. OMI is also providing estimates of column NO_2 and bromine oxide (BrO), although Salawitch et al. [2010] cautioned that sometimes part of the BrO column must be attributed to its partial column amounts of the lower stratosphere. TES, along with GOME-2, MOPITT, and AIRS is providing new information on regional-scale pollutant molecules and their relation to industrial and biomass burning sources. In particular, TES is obtaining good estimates of ozone in the upper versus the lower troposphere in regions of biomass burning [Jourdain et al., 2007]. Finally, despite the unfortunate, partial restriction of its view of the horizon, HIRDLS is delivering good quality, high vertical resolution profiles of a number of species in the stratosphere, at least down to the tops of clouds [Gille et al., 2008]. HIRDLS represents a significant advance over earlier infrared limb sounders. It contains four CO_2 and three O_3 radiometer channels, in order to provide a more linear response between changes in the radiances with altitude. HIRDLS is providing retrieved temperature and ozone profiles throughout the stratosphere and with vertical resolutions of better than 2 km. The relatively narrow spectral widths and vertical dimensions for its channels required the use of cooled, low noise detectors. Pressure-modulated gas cells were not used for the HIRDLS instrument. Thus, S/N for the radiance profiles of HIRDLS is improved over that of ISAMS.

In the 1990s NASA's Earth observing activities fully considered the associated contributions of other nations—Japan, Canada, Russia, and the European Union. They were beginning to deploy their own enhanced satellite measurement capabilities. The European Space Agency launched an environmental satellite (ENVISAT) into orbit in 2002, and it carried three experiments focused on measurements from the upper stratosphere to the lower mesosphere. They are the relatively, high spectral resolution, limb emission experiment Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), the Global Ozone Monitoring by Occultation of Stars (GOMOS), and the (SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY) or SCIAMACHY. MIPAS resolves molecular spectra and provides information about isotopic species as well as emissions from vibrationally-excited molecular transitions [Fischer and Oelhaf, 1996]. As such, its measurements are being used to determine the sources of the observed atmospheric radiances. Wargan et al. [2005] showed that the higher accuracy of the MIPAS ozone leads to a substantial improvement in model assimilated ozone below the ozone maximum, compared with that from SBUV. The Canadian Space Agency launched a SCIence SATellite (SCISAT) on a Pegasus XL vehicle from Vandenberg AFB in 2003 with funding from NASA. SCISAT carried a second-generation ATMOS instrument or the Atmospheric Chemistry Experiment (ACE) into near polar orbit for the observation of chemical species in the middle atmosphere via solar occultation [Bernath et al., 2005]. SCISAT carries a second occultation instrument, Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO), that has been used successfully to obtain profiles of water vapor in the upper troposphere/lower stratosphere (UT/LS) [Sioris et al., 2010]. Canadian researchers also teamed with those from Finland, France, and Sweden on the launch of the Swedish satellite ODIN in 2001. It consisted of a sub-millimetre radiometer (SMR) and the Optical Spectrograph and Infrared Imaging System (OSIRIS), the latter functioning essentially as a limb-scattering instrument. In general, POAM, GOMOS, ACE, OSIRIS, and SAGE III were focused on obtaining an improved understanding of the processes affecting the distributions of polar ozone. Further tests of limb scattering techniques are being conducted using data from OSIRIS and SCIAMACHY in the manner of the Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment (or SOLSE/LORE) of 1997, as analyzed by Flittner et al. [2000] and McPeters et al. [2000].

NASA's Office of Space Science launched the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite in December 2001. TIMED carried four experiments, including the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER). SABER provides near global-scale temperature and ozone, and nitric oxide (NO) radiance profiles, among other parameters. Together, the radiances from these three species are being used to characterize the energy balance of the mesosphere and lower thermosphere. It is noteworthy that the genesis of the SABER experiment dates back to the SPIRE measurements of 1977 by AFGL. The SABER concept was initially proposed by RMOP Panel member, James Russell III, in 1977 or during the time frame of the middle atmosphere experiments of Nimbus 6 and 7. However, the selection of SABER for TIMED did not occur until 1993. Thus, the SABER instrument team was able to incorporate a number of improvements for its onboard cooler and detectors during the intervening years [Russell et al., 1999]. The inclusion of the effects of line mixing for the strong-line, 15-μm region of CO_2 led to improved accuracies for the forward radiance model in the SABER local thermodynamic equilibrium (LTE) algorithm for T(p) in the stratosphere and lower mesosphere. That model also provides a more accurate registration of the radiance profiles with pressure for all the retrieved species profiles, as indicated with comparisons of the SABER T(z) with those from the Rayleigh and Na lidar measurements and from the MIPAS data [Remsberg et al., 2008]. Chris Mertens of GATS, Inc., and later of Langley, developed the non-LTE forward models for the T(p) retrievals and for the observed CO_2 radiances from the mesosphere and lower thermosphere [Mertens et al., 2001]. Marty Mlynczak supplied the non-LTE algorithm for retrievals of ozone profiles from the 9.6-µm radiances and also an algorithm for deriving ozone from the $O_2(^1D)$ radiances [Mlynczak et al., 2007].

Satellite measurements of OH fluorescence at 309 nm were conducted by NRL with its Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER) from March 2007 to October 2009 [Englert et al., 2010]. SHIMMER OH values are in agreement with those from Aura MLS and with a standard photochemical model from 60 to 80 km, resolving a long-standing discrepancy about the chemical effects of HO_x radicals on ozone. The SHIMMER instrument also demonstrates the many technological advancements for middle ultraviolet measurements since the time of the Javelin rocket test measurements of the horizon made from Wallops Island in 1961 [McKee et al., 1964]. Steady increases of atmospheric CO_2 have led to a cooling of the upper atmosphere and a contraction of thermospheric densities, as determined by Langley researchers from satellite drag measurements over many years [Keating et al., 2000]. The Solar Occultation for Ice Experiment (SOFIE) instrument was launched in April 2007 on the Aeronomy of Ice in the Mesosphere (AIM) spacecraft by a Pegasus vehicle from Vandenberg AFB. James Russell, III, of Hampton University is the Principal Investigator of this NASA Small Explorer (SMEX) satellite mission. The SOFIE instrument concept is a direct outgrowth of the design of HALOE on UARS [Gordley et al., 2009a]. SOFIE data are being used to look for evidence of trends in temperature and species near the summer mesopause. Such occultation experiments are especially suitable for studies of global atmospheric change, as envisioned by the members of the Gas Species Panel of the RMOP Workshop.

8 Joint Polar Satellite System (JPSS) and future sensing prospects

Since the early days of weather forecasting, it has always been clear that good measurements of the temperature and moisture profiles are needed as input to the models in order to maintain some skill in their predictions out to 5 or 7 days. On the other hand, the goal of monitoring the atmosphere for its climate-related changes requires accurate, long-term measurements of the radiatively-active constituents of CO_2 (or temperature), H_2O, and O_3. Satellite measurements of the air quality must be made on urban to regional scales, in order to link pollutants to their sources. Thus, in many respects the observational goals for weather, climate, and air quality are incompatible and difficult to achieve with single satellites, such as EOS, ENVISAT, or MetOp.

The next-generation sensors for the U. S. operational satellite system JPSS were selected in the early 1990s, based on an updated set of measurement goals and environmental data records (EDRs) for its temperature sounder and imager and for its ozone measuring instrument (the Ozone Mapping and Profiler Suite or OMPS). The temperature sounder combines a cross-track infrared sounder (CrIS) with an Advanced Technology Microwave Sounder (ATMS). The JPSS Visible/Infrared Imager Radiometer Suite (or VIIRS) has its heritage from EOS MODIS and the previously operational AVHRR sensor of NOAA. OMPS has its heritage from TOMS or OMI plus SBUV, although NOAA's technical advisory panel report of 1995 recognized that an SBUV-type sensor cannot provide ozone with vertical resolutions of any better than 6 to 8 km. Nevertheless, it is hoped that the ozone EDR of 3 to 5 km vertical resolution can be obtained for the lower stratosphere using a limb-scattering algorithm. NASA intends to demonstrate the capabilities of all these sensors on its National Polar-orbiting Operational Environmental Satellite System (or NPOESS) Preparatory Project (NPP) satellite in 2011. In this regard, NPP should also be considered as another in the long series of NASA research satellites.

A major goal of the NPP sensors is to be able to obtain climate quality measurements of stratospheric ozone, plus the tropospheric moisture and temperature profiles for weather forecast models. It is expected that the relevant sensors will benefit from the improved on-board calibrations and better spatial resolutions of their measurements. William Smith, Sr., of Langley and now of Hampton University also proposed his Geostationary Imaging Fourier Transform Spectrometer (GIFTS) instrument for a flight opportunity, but its demonstration was secondary to the NASA evaluation of the sensors on NPP. Nevertheless, Smith along with Xu Liu, Dan Zhou, and Allen Larar of Langley are applying their algorithms for the efficient use of hyperspectral measurements from the sounders and imagers on the MetOp satellite [Liu et al., 2006], and they are preparing to evaluate similar spectral measurements from CrIS on NPP. David Flittner and Didier Rault of Langley have developed limb-scatter algorithms that can be used for retrievals of ozone in the lower stratosphere with a vertical resolution of order 3 km.

The NASA Science Mission Directorate (SMD) now follows a blueprint for its Earth Science satellite observation program based on a Decadal Survey document prepared by the National Research Council [NRC, 2007]. The Orbiting Carbon Observatory (OCO) satellite is part of that strategy. OCO is designed to measure and map column CO_2 amounts in the lower troposphere and hopefully to link any elevated amounts to their source regions. A feasibility test of the OCO concept was performed using near infrared measurements of CO_2 at 1.6 µm from spectral measurements of the SCIAMACHY experiment on ENVISAT, and the results are promising [Boesch et al., 2006]. NASA launched OCO in 2009, but it failed to achieve orbit. An OCO-2 instrument is being readied for a launch opportunity in 2013. In a parallel effort the Japanese Space Agency launched its Greenhouse gases Observing Satellite (GOSAT) in January 2009, and they are obtaining useful measurements of CO_2 and CH_4 from Earth orbit [Butz et al., 2010].

NASA's Decadal Survey missions are segmented into Tier 1, Tier 2, and Tier 3 experiment payloads, and the Tier 1 experiments have been named. The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Project at Langley is one of those Tier 1 experiments. An important resource and motivator for the members of the RMOP Panel of 1971 was Richard Goody of Harvard University. Most recently, he and his colleagues advocated for the monitoring of Earth's climate from satellites, and their vision was included as part of CLARREO [Goody et al., 2002]. CLARREO is being designed to achieve the longer-term spectral radiance measurements that are necessary for an improved understanding of Earth's climate [Huang et al., 2010; Sandford et al., 2010]. In fact, atmospheric survey measurements with the proposed infrared spectrometer of CLARREO are very reminiscent of the SIRS and IRIS instruments that were flown by Wark and Hanel on Nimbus 3 and 4. Furthermore, the observations from the GPS/RO satellites of JPL/NSF are already showing that it is possible to achieve profiles of temperature and moisture in the troposphere with even better vertical resolutions and accuracies then envisioned from infrared sounders. A similar RO sounder is being considered for CLARREO, as well. Bruce Wielicki, CLARREO Mission Scientist at Langley, hopes to apply better preflight and in-flight calibration methods for its sensors. However, budgetary constraints may delay this Tier 1 experiment until after 2020.

Two Tier 2 missions for the study of atmospheric composition are under study at Langley and Goddard and another one at JPL. The first effort at Langley is an outgrowth of a 2008 Workshop on the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), and it is a concept from Ed Browell. The experiment will make measurements of column CO_2 using tunable laser sensing technologies from a satellite, hopefully later in the decade. Langley, Goddard, and JPL personnel have already been conducting coordinated, airborne tests of laser systems operating at the 1.57 and 2.06 µm lines of CO_2 for the purpose of demonstrating the method, and the initial results are promising. The second Langley/Goddard mission concept is called Geostationary Coastal and Air Pollution Events (GeoCAPE). It consists of a gas filter correlation radiometer (GFCR) for making measurements at both 2.3 µm and 4.6 µm, in order to distinguish amounts of CO in the atmospheric boundary layer. Currently, its technology follows from the earlier MAPS concept, and Doreen Neil is the Langley instrument scientist. GeoCAPE is also being designed to carry a high spatial resolution, hyperspectral spectrometer that will operate in the uv and visible region, as well as an imaging spectrometer; Scott Janz of Goddard is the instrument scientist for the high spatial resolution experiment. All three instruments would make measurements from geostationary orbit, in order to monitor regional-scale pollutants and the ecology of coastal zones over relatively short time intervals. The Tier 2 experiment from JPL is labeled a hyperspectral infrared imager (HyspIRI) and is being designed to operate from low Earth orbit. All the Tier 2 mission concepts are in their Pre-phase A study period.

Tropospheric measurements of CO are being made with MOPITT on EOS Terra [Drummond et al., 2010], but its measurements of column CO and CH_4 are limited to some extent by the small amount of thermal contrast between the surface and the top of boundary layer. The solar backscatter measurements of column CO by MOPITT are affected by the natural variations of the surface albedo in the short time that it takes for the chopper to switch between the absorbed and non-absorbed channels for the gas filter correlation measurement. Gordley et al. [2009c] have devised a Digital Array Gas Radiometer (DAGR) concept that will minimize any degradation due to the natural variations of the surface albedo. The DAGR approach could be applied to both imager and sounder measurements of gases in the atmospheric boundary layer. On the other hand, Schneising et al. [2011] are showing that they are already obtaining reasonably accurate column-averaged results for CO_2 and CH_4 with the spectrally-selective and sensitive grating spectrometer, SCIAMACHY. Similar capabilities are being demonstrated with the data from the instruments on the Japanese GOSAT.

The international atmospheric science community has also been focused on developing chemistry/climate models (CCM) that can predict the changes that one can expect for stratospheric ozone due to a decrease in ozone-depleting substances (ODS) but modulated by the changes from increases in the greenhouse gases (GHG), in particular CO_2 and CH_4. Model simulations have been conducted for the period of 1979 to the present, and the results have been compared with the satellite temperature and ozone records for verification. In fact, an engineering model of SAGE III is being refurbished and tested at Langley in preparation for attaching it to the ISS in 2014 for the purpose of adding to the lower stratospheric ozone record. An implicit assumption for the ozone analyses is that the models are representing properly all of the physical processes that are important at climate time scales. Yet, it is clear that the combination of radiosonde data and satellite records are lacking the necessary calibrations for a proper verification of the predictions from the same CCMs.

Accurate, long-term observations with high vertical resolutions are also needed to isolate the radiative effects of the changing GHG on climate, especially for H_2O close to the tropopause [Solomon et al., 2010]. It is also critical to be able to differentiate between the long-term changes in ozone due to anthropogenic and natural forcings. Solar occultation (SO) provides accurate profiles and trends of O_3 and H_2O in the lower stratosphere and with the necessary vertical resolution of at least 2 km [e.g., Gordley et al., 2009b]. One concern about the SO technique has been that it does not provide a near-global set of profiles each day. However, Remsberg and Lingenfelser [2010] concluded that the SO sampling from SAGE II and HALOE was adequate for resolving the seasonal and longer-term variations in stratospheric ozone. They also found that the vertical resolution from SO is adequate for separating out the effects on ozone of the 11-yr, solar uv-flux forcing from those due to the longer-term changes of the GHG. A further important benefit of GPS/RO measurements of temperature in the lower stratosphere and of SO measurements of stratospheric ozone and H_2O is that it is much easier to obtain good calibrations for RO and SO measurements.

9 Summary

This report provides a brief review of the measurement methods employed at Langley to characterize the atmospheric environment. Early remote methods include passive sensing of the Earth's horizon and active sensing of atmospheric turbulence. In the early 1970s NASA began to emphasize its Earth applications programs and its capabilities for measuring regional to global-scale atmospheric pollution from Earth orbit. A workshop (RMOP) was held in 1971 to define the environmental problems and the remote sensing techniques that could be applied to their study. An RMOP Workshop Report was the outcome, and it represented a blueprint for the associated technology developments that would be pursued for the following two decades.

This report is a retrospective account of the developments that led to the successful use of satellite sensors for measuring temperature and gaseous species profiles of the atmosphere. Researchers at NASA Langley focused their attention on developing atmospheric remote sensors based on solar occultation, limb infrared emission, and gas filter correlation radiometry. Auxiliary *in situ*, passive, and active measurement techniques were also developed and operated from ground-based, balloon-borne and/or aircraft platforms for the purpose of verifying the measurements from the engineering or pre-flight models of the proposed satellite instruments. Final selections for a satellite flight opportunity were ultimately based on the scientific goals of the experiment and on the demonstrated performance for its instrument. A theme throughout the report is the need to obtain good accuracy and precision for the measurements and their retrieved quantities, while providing the desired spatial resolutions at the same time.

During the initial two decades following RMOP, candidate technologies were funded through NASA's AAFE Program. Since the mid-1990s sensor developments have been supported from NASA's New Millenium Program (NMP), Instrument Incubator Program (IIP), and the Earth System Science Pathfinder (ESSP). Selections for flight opportunities follow the guidelines provided by the NRC in 2007 as part of NASA's Decadal Plan for the Earth Sciences. It is emphasized that many of the candidate instrument concepts of today still rely on the proof-of-concept, sensor demonstration approaches that Morris Tepper, Don Lawrence, Jr., William Kellogg, and the members of his RMOP subpanel asked for in their report of 1971. Langley and NASA continue to develop new instruments based on this long heritage of making remote measurements of the atmosphere (also see Remsberg et al. [2011]).

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Appendix A

Acronyms:

AAFE	Advanced Applications Flight Experiments
ACE	Atmospheric Chemistry Experiment
ADEOS	ADvanced Earth Observing Satellite
AEM	Atmospheric Explorer Mission
AESA	Atmospheric Effects of Stratospheric Aircraft
AESD	Atmospheric Environmental Sciences Division
AFCRL	Air Force Cambridge Research Laboratories
AFGL	Air Force Geophysics Laboratories
AIM	Aeronomy of Ice in the Mesosphere
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASD	Atmospheric Science Division
ASTP	Apollo-Soyuz Test Project
ATBD	Algorithm Theoretical Basis Document
ATMOS	Atmospheric Trace Molecule Spectroscopy
ATMS	Advanced Technology Microwave Sounder
ATOVS	Advanced TOVS
ATS	Advanced Technology Satellite
AVHRR	Advanced Very High Resolution Radiometer
BOIC	Balloon Ozone Intercomparison Campaign
BUV	Backscatter Ultra-Violet
CAA	Clean Air Act

CCD	Charge Coupled Device
CCM	Chemistry Climate Model
CFC	Chlorofluorocarbon
CIAP	Climatic Impact Assessment Program
CIMATS	Correlation Interferometer for the Measurement of Atmospheric Trace Species
CLAES	Cryogenic Limb Array Etalon Spectrometer
CLARREO	CLimate Absolute Radiance and REfractivity Observatory
COPE	Carbon Monoxide Pollution Experiment
CrIS	Cross-track Infrared Sounder
CRISTA	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere
CWA	Clean Water Act
DAGR	Digital Array Gas Radiometer
DIAL	DIfferential Absorption Lidar
DOD	Department of Defense
DOT	Department of Transportation
EDR	Environmental Data Record
ENVISAT	ENVIronmental SATellite
EOS	Earth Observing System
EP	Earth Probes
EPA	Environmental Protection Agency
EQPO	Environmental Quality Program Office
ERBS	Earth Radiation Budget Satellite
ERS	European Remote Sensing
ESA	European Space Agency
ESMR	Electronic Scanning Microwave Radiometer

ESSD	Environmental and Space Sciences Division
ESSP	Earth System Science Pathfinder
FID	Flight Instruments Division
FTIR	Fourier Transform InfraRed
GATS	Gordley and Associates Technical Software
GeoCAPE	Geostationary Coastal and Air Pollution Events
GFCR	Gas Filter Correlation Radiometer
GHG	GreenHouse Gases
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GMCC	Geophysical Monitoring for Climate Change
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
GOSAT	Greenhouse gases Observing SATellite
GPS	Global Positioning System
GTE	Global Troposphere Experiment
HALOE	HALogen Occultation Experiment
HIRDLS	HIgh Resolution Dynamics Limb Sounder
HIRS	High-resolution Infrared Radiation Sounder
HIS	High-resolution Interferometer Sounder
HITRAN	HIgh-resolution TRANsmission
HRC	Honeywell Radiation Center
HSCT	High Speed Civil Transport
HSRP	High Speed Research Program
HyspIRI	Hyperspectral InfraRed Imager

IASI	Infrared Atmospheric Sounding Interferometer
IIP	Instrument Incubator Program
ILAS	Improved Limb Atmospheric Spectrometer
IRD	Instrument Research Division
IRIS	InfraRed Interferometer Spectrometer
ISAMS	Improved Stratospheric And Mesospheric Sounder
ISS	International Space Station
ITPR	Infrared Temperature Profile Radiometer
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
LACATE	Lower Atmospheric Composition And Temperature Experiment
LaRC	Langley Research Center
LIMS	Limb Infrared Monitor of the Stratosphere
LORE	Limb Ozone Retrieval Experiment
LRIR	Limb Radiance Inversion Radiometer
LTE	Local Thermodynamic Equilibrium
MAESTRO	Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
MAPS	Measurement of Air Pollution from Satellites
MHS	Microwave Humidity Sounder
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIT	Massachusetts Institute of Technology
MODIS	MODerate-resolution Imaging Spectro-radiometer

MOPITT	Measurement Of Pollution In The Troposphere
MRN	Meteorological Rocket Network
MSU	Microwave Sounding Unit
NACA	National Advisory Committee for Aeronautics
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDACC	Network for the Detection of Atmospheric Composition Change
NEMS	Nimbus E Microwave Spectrometer
NESS	National Environmental Satellite Service
NMP	New Millenium Program
NRL	Naval Research Laboratory
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
OA	Office of Applications
OAO	Orbiting Astronomical Observatory
OAST	Office of Aeronautics and Space Technology
OCO	Orbiting Carbon Observatory
ODS	Ozone Depleting Substances
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OSIRIS	Optical Spectrograph and InfraRed Imaging System
OSTA	Office of Space and Terrestrial Applications

PAN	Peroxy-Acetyl Nitrate
PMR	Pressure Modulator Radiometer
POAM	Polar Ozone and Aerosol Measurement
RMOP	Remote Measurement Of Pollution
RO	Radio Occultation
RMS	Root-Mean-Square
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
SAFIRE	Spectroscopy of the Atmosphere using Far InfraRed Emission
SAGE	Stratospheric Aerosol and Gas Experiment
SAIC	Science Applications International Corporation
SAM	Stratospheric Aerosol Monitor
SAMS	Stratospheric And Mesospheric Sounder
SASC	Systems and Applied Sciences Corporation
SBUV	Solar Backscatter Ultra-Violet
SCAMS	SCAnning Microwave Spectrometer
SCEP	Study of Critical Environmental Problems
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY
SCISAT	SCIentific SATellite
SCMR	Surface Composition Microwave Radiometer
SCR	Selective Chopper Radiometer
SD	Science Directorate
SHIMMER	Spatial Heterodyne Imager for Mesospheric Radicals on STPSat-1
SIRS	Satellite InfraRed Spectrometer
SMD	Science Mission Directorate

SME	Solar Mesosphere Explorer
SMEX	SMall Explorer
SMIC	Study of Man's Impact on Climate
SMR	Sub-Millimeter Radiometer
S/N	Signal-to-Noise
SO	Solar Occultation
SOFIE	Solar Occultation For Ice Experiment
SOLSE	Shuttle Ozone Limb Sounding Experiment
SPAS	Shuttle PAllet Satellite
SPIRE	SPectral Infrared Rocket Experiment
SSBUV	Shuttle SBUV
SST	SuperSonic Transport
SSU	Stratospheric Sounding Unit
STC	Science and Technology Corporation
SUNY	State University of New York
TES	Tropospheric Emission Spectrometer
THIR	Temperature Humidity Infrared Radiometer
TIMED	Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics
TIROS	Television InfraRed Observation Satellite
TOMS	Total Ozone Mapping Spectrometer
TOR	Tropospheric Ozone Residual
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
UARP	Upper Atmosphere Research Program
UARS	Upper Atmosphere Research Satellite

UT/LS	Upper Troposphere/Lower Stratosphere
VIIRS	Visible/Infrared Imager Radiometer Suite
WMO	World Meteorological Organization

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14. ABSTRACT

The National Aeronautics and Space Administration (NASA) phased down its Apollo Moon Program after 1970 in favor of a partly reusable Space Shuttle vehicle that could be used to construct and supply a manned, Earth-orbiting Space Station. Applications programs were emphasized in response to the growing public concern about Earth's finite natural resources and the degradation of its environment. Shortly thereafter, a workshop was convened in Norfolk, Virginia, on Remote Measurement of Pollution (or RMOP), and its findings are in a NASA Special Publication (NASA SP-285). The three primary workshop panels and their chairmen were focused on trace gas species (Will Kellogg), atmospheric particulates or aerosols (Verner Suomi), and water pollution (Gifford Ewing). Many of the workshop participants were specialists in the techniques that might be employed for the regional to global-scale, remote measurements from an Earth-orbiting satellite. The findings and recommendations of the RMOP Report represent the genesis of and a blueprint for the satellite, atmospheric sensing programs within NASA for nearly two decades. This paper is a brief, 40-year retrospective of those instrument developments that were an outgrowth of the RMOP activity. Its focus is on satellite measurement capabilities for temperature and gaseous species that were demonstrated by atmospheric technologists at the Langley Research Center. Limb absorption by solar occultation, limb infrared radiometry, and gas filter correlation radiometry techniques provided significant science data, so they are emphasized in this review.

15. SUBJECT TERMS

Remote sensing; Satellite; Pollution; Species; Temperature

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