Remote Measurement of Pollution—A 40-Year Langley Retrospective: Part II—Aerosols and Clouds

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Abstract

A workshop was convened in 1971 by the National Aeronautics and Space Administration (NASA) on the Remote Measurement of Pollution (RMOP), and the findings and recommendations of its participants 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 regional to global-scale, remote measurements of the atmospheric parameters from Earth-orbiting satellites. In 2011 the author published a 40-year retrospective (or Part I) of the instrumental developments that were an outgrowth of the RMOP panel headed by Will Kellogg, i.e., on atmospheric temperature and gaseous species. The current report (or Part II) is an analogous retrospective of the vision of the panel led by Verner Suomi for the measurement of particulates (or aerosols) and clouds and for their effects on Earth's radiation budget. The class of measurement techniques includes laser radar or lidar, solar occultation, limb emission and scattering, nadir-viewing photometry or radiometry, and aerosol polarimetry. In addition, the retrospective refers to the scientific imperatives that led to those instrument developments of 1971-2010. Contributions of the atmospheric technologists at the Langley Research Center are emphasized, and their progress is placed in the context of the parallel and complementary work from within the larger atmospheric science community.

1 Introduction

By the 1960s climate scientists wondered whether Earth's environment could be altered due to anthropogenic activities, perhaps even globally [Landsberg, 1970]. This topic was also the focus of an MIT report entitled "Study of Man's Impact on Climate" [SMIC, 1971]. The National Aeronautics and Space Administration (NASA) responded by emphasizing its Earth applications program. Making measurements of Earth's environment was viewed as a natural extension of their ongoing efforts toward global weather observations from Space. Morris Tepper, Director of Meteorology Programs, and Jules Lehmann, Manager of Advanced Instrumentation and Sensor Engineering Programs, both at NASA Headquarters, directed that the Langley Research Center (LaRC) convene a Working Group on the topic of the Remote Measurement of Pollution (RMOP). A panel of experts met in August 1971 in Norfolk, Virginia. Their findings and recommendations can be found in NASA SP-285 [1971]. In particular, the panel reviewed and reported on the principles of remote sensing and the associated instrument techniques that ought to be considered for development and eventual deployment on a satellite platform. In Part I of his 40-year retrospective on the satellite measurement of atmospheric temperature and gaseous species, Remsberg [2011] concluded that "the historical evidence indicates that the findings of the RMOP Workshop Report represent the genesis of and blueprint for the satellite Earth-sensing programs within NASA for the following two decades". The RMOP Report is an early precursor to NASA's Decadal Survey for Earth Science and Applications from Space [NRC, 2007].

The present report (or Part II) extends the work of Remsberg [2011] and considers satellite techniques for the measurement of particle air pollution and the sensing of clouds. Members of the Particle Air Pollution Panel of RMOP are in Table 1, and Verner Suomi was their Chairman. Member names in bold print are tied directly to measurement concepts that were successful from Space following RMOP. Since the term "particles" (or particulates) often brings to mind plumes from industrial smokestacks, the more general designation "atmospheric aerosols" will be used instead throughout much of this report. Section 2 provides the motivations for obtaining more and better measurements of aerosols and clouds. It also mentions the expertise of the members of the Panel and reviews their recommendations in the RMOP Report. Section 3 recounts the sensor development for the detection and measurement of aerosols and clouds that occurred at LaRC prior to RMOP and that continued through the decade of the 1970s. Measurement techniques that are reviewed include laser radar (or lidar), solar occultation, limb emission and scattering, nadir-viewing photometry or radiometry, and polarimetry. Several instrument scientists and program managers at LaRC are recognized for their key roles in those developments. Section 4 is a brief account of the primary satellite instruments and the findings from them about aerosols and clouds from 1970 to 1983, just before the era of the Space Shuttle. Section 5 is focused on several satellite instruments from LaRC that were deployed on or from the Space Shuttle from 1984 to the mid 1990s. Section 6 describes briefly the prototype, but near-operational aerosol and cloud sensors of the follow-on Earth Observing System (EOS) era, and it places them in the context of similar observational programs of laboratories both in the U.S. and abroad. Section 7 reports on several new measurement approaches, based on recommendations of the NRC [2007]. Section 8 reflects on the progress that has been made and the way ahead. An Appendix provides the prospective of the author for this review.

Table 1. RMOP members of the Particle Air Pollution Panel and their affiliations in 1971.

Verner Suomi, Univ. of Wisconsin, Panel Chair

Henry Blau, Jr., Arthur D. Little, Inc.

Charles Byvik, NASA Langley

Robert Fraser, NASA Goddard

Gerald Grams, NCAR

Thomas Haig, Univ. of Wisconsin

Franklin Harris, Jr., Old Dominion Univ.

Benjamin Herman, Univ. of Arizona

Alfred Holland, NASA Wallops Station

J. Don Lawrence, NASA Langley

William Matthews, MIT

S. Harvey Melfi, NASA Langley

G. D. Robinson, Univ. of Connecticut

Zdenek Sekera, UCLA

2 Studies of aerosols and clouds prior to the RMOP Report

(a) Background

The SMIC and the RMOP Working Groups posed a number of questions related to aerosols and clouds. In fact, their concerns would presage those of the current series of reports from the Intergovernmental Panel on Climate Change [e.g., IPCC, 2007]. For instance, does wind-borne dust or products of combustion alter the nature of cloudiness or precipitation by their role as condensation nuclei for the droplets [Bryson, 1974; CCSP, 2009]? Are contrails from aircraft increasing the frequency of occurrence of cirrus clouds in air flight corridors and altering the atmospheric energy budget of those regions [Angell and Korshover, 1975]? How can climate scientists better represent and verify effects of aerosols and clouds and the variations in surface reflectivity in model simulations [Vonder Haar and Suomi, 1971; Rasool and Schneider, 1971]?

Aerosols and clouds have implications for both air quality and climate. For example, stratospheric aerosols from large volcanic eruptions attenuate the incoming solar radiation and alter the transmissivity and reflectivity (or albedo) of the atmosphere. Will Kellogg of the National Center for Atmospheric Research (NCAR) and Chair of the companion Gas Species Panel of the RMOP study was well recognized for his work on the dispersion of smoke plumes and of debris from high-altitude atomic bomb tests and later for his studies of the stratospheric aerosol layer [e.g., Kellogg, 1956; Kellogg et al., 1957; Kellogg et al., 1972]. Aerosol research in the 1950s and early 1960s in the U. S. was focused on the attachment of radioactive bomb debris onto aerosols in the stratosphere and its transport to and then within the troposphere [Junge, 1963; Reiter, 1971]. James Lodge, Richard Cadle, and Ed Martell at NCAR conducted field studies of radioactive debris, tropospheric freezing nuclei, and stratospheric aerosols and their precursor gases during the 1960s.

William Castleman of Brookhaven National Laboratory (BNL) and James Friend of Isotopes, Inc., conducted studies of the composition, size distributions, and microphysical properties of the stratospheric aerosols. Their work was an extension of earlier findings that were based on the cascade impactor and condensation nuclei counter measurements of Christian Junge and his colleagues at both the Air Force Cambridge Research Laboratory (AFCRL) and eventually at the Max-Planck Institute for Chemistry in Mainz, Germany [Junge and Manson, 1961; Chagnon and Junge, 1965]. Junge is perhaps best known for his characterization of the background stratospheric layer near 20 km [Junge, Chagnon, and Manson, 1961]. The so-called "Junge layer particles" were composed mostly of sulfate material. James Rosen of the University of Minnesota and later of Wyoming found that the tiny droplets above about 27 km were volatile in nature, according to their vaporization temperature within the heated inlet of his balloon-borne particle counter [Rosen, 1969]. He concluded that the Junge aerosols were most likely composed of concentrated aqueous solutions of sulfuric acid.

Remsberg [1973] conducted laboratory measurements of bulk solutions of sulfuric acid in the mid-infrared and analyzed those data for their optical constants, both real and imaginary. Palmer and Williams [1975] verified the measurements of Remsberg and then extended the optical constants to the visible and near infrared wavelengths. Crutzen [1976] proposed that the bulk of the background stratospheric, Junge or sulfate layer has its primary source from the photodissociation of carbonyl sulfide (CSO). In March 1963 the volcanic eruption of Mt. Agung provided a large perturbation to the Junge layer and led to visible scattering and twilight refraction phenomena for a year of so thereafter [Volz, 1969]. Major eruptions from Fuego (1974), St. Helens (1980), El Chichon (1982), and Pinatubo (1991) would enhance the background layer in coming decades.

Other than ice particles and water droplets, aerosols in the troposphere range from desert dust composed of silicate compounds to organic, black carbon from the incomplete combustion of fires and in smoke plumes. Peterson and Weinman [1969] reported on the optical and scattering properties of silicates for interpreting of the radiative effects of wind-blown dust layers observed above and downwind from the Rajasthan Desert of northwest India by Reid Bryson of the University of Wisconsin. Twitty and Weinman [1971] calculated the optical and scattering properties of organic, black carbon smoke particles. Such information along with estimates of size distributions and particle shapes is required for interpreting remotely-sensed data about the spectral extinction, angular scattering, and polarization properties of the aerosol layers. It is also presumed that the properties of the aerosols are changing with time, as they grow, coalesce, sediment, and otherwise mix with and evolve chemically in the atmosphere.

Smoke and aerosols from biomass burning or fossil-fuel combustion are sources of pollution in the lower troposphere, at least in urban regions and often extending across continental boundaries. The monitoring of atmospheric turbidity had been underway from ground stations in continental regions [Flowers et al., 1969]. In fact, increases in turbidity were believed to be responsible for the slight decrease of worldwide air temperatures since about 1940, despite the increasing amounts of atmospheric CO_2 [McCormick and Ludwig, 1967; Peterson and Bryson, 1968].

Photopolarimeters and imagers were being used to characterize the size distributions of the atmospheric dust and smoke plumes and to determine their scattering properties and effects on the transfer of radiation through them. Ground-based lidar instruments had been put in operation at a dozen or so stations worldwide. In particular, they were providing information about the seasonal and global-scale nature of volcanic aerosol layers in the lower stratosphere. Thus, the members of the atmospheric Particle Panel of RMOP felt that it was appropriate to ask whether such passive or active sensors could be operated from satellite platforms for a global survey of the properties and distributions of atmospheric aerosols and for a determination of their transport from one region to another.

A primary interest at that time for Verner Suomi, Chair of the Particle Air Pollution Panel, was on a more accurate determination of the effects of clouds on Earth's albedo and ultimately on the radiation budget of the Earth and its atmosphere. Suomi had already successfully demonstrated his visible, spin-scan camera approach for viewing the Earth and its cloud cover from Advanced Technology Satellites (ATS) in geostationary orbits and was beginning to obtain tropical wind vectors using the displacements of the high clouds from sequences of their pictures (e.g., see review by Lewis et al. [2010]). Up until then, the presence of clouds was mostly a nuisance for the satellite remote measurement of tropospheric temperature and water vapor. Broadband infrared sounding techniques from Space required clear skies for obtaining the profiles of both, which were needed as input to global weather forecast models. Later, of course, the advent of satellite-borne microwave sounders provided for the necessary tropospheric temperature profiles in the presence of clouds [e.g., Staelin et al. 1977; Smith, 2010]. Two reviews of the developing, satellite radiation budget measurement programs at LaRC have been published by House et al. [1986] and Smith et al. [2011], and the reader is referred to their more complete, historical accounts of the subject. Studies of the diurnal nature of clouds, the distributions of cirrus clouds and polar stratospheric clouds (PSC), and the verification of the microphysical properties of and radiative transfer within clouds are discussed briefly in the present report.

(b) Expertise and recommendations from the members of the RMOP Panel

Most of the members of the Particle Air Pollution Panel of Table 1 were selected for their specific theoretical or measurement expertise and understanding. An exception was Prof. William Matthews, a civil engineer and an organizer of the SMIC Report. He was a member of both the Gas Species and Particle Panels of RMOP because of his overall knowledge of the critical environmental problems of that time. Atmospheric aerosols have important biological and economic effects on local to regional scales and possibly on larger-scale, climatic effects. Biologically, high concentrations of particulates can lead to respiratory illnesses. Aerosols can damage plants and may also cause an increase in the acidity of precipitation, reducing the productivity of soils, forests, and fish stocks.

The other members of the Panel were conducting research on the composition, sizes, and distributions of atmosphere aerosols, as well as their sources and effects. To understand some of the likely measurement issues, Henry Blau and Alfred Holland had conducted laboratory studies of the aerosol scattering matrix for spheres and irregular particles, respectively. Franklin Harris, Jr., and Zdenek Sekera were involved with studies of the polarization of light by aerosols. Wind-blown dust and volcanic plumes are examples of natural occurrences of aerosols that affect visibility and the incoming solar radiation, sometimes for great distances from their source regions and for extended periods of time. Robert Fraser, Benjamin Herman, and G. D. Robinson analyzed how haze layers of the lower atmosphere scatter and otherwise reduce the incoming solar radiation to the ground. The Panel recognized that it is not easy to distinguish between natural and man-made particulate matter based on remote measurements of their visible extinction effects alone. Long-time records of atmospheric turbidity were available from a few stations that were far removed from local sources of pollution (e.g., Peterson and Bryson, 1968;

Ellis and Pueschel, 1971). That turbidity data showed both short and long-term variations, much of which may have been related to variations in the transport within the lower atmosphere. The Panel believed that sorting out the causes of such variations might be achieved best with a near global-scale, satellite monitoring program.

G. D. Robinson and Verner Suomi felt that a more immediate task was the improvement of the understanding of Earth's radiation budget. Robinson also reported that the interaction of aerosols with clouds could give rise to an increase in the absorption of shortwave radiation [SMIC, 1971]. Suomi, Colonel Thomas Haig, and their colleagues at the Space Science and Engineering Center (SSEC) of the University of Wisconsin were advocates of observing the cloud cover and of determining the reflected and emitted components of the Earth/atmosphere radiation using instruments onboard Earth-orbiting and geostationary satellites [Smith et al., 2011; House et al., 1986]. The RMOP report included recommendations for determining Earth's radiation budget that undoubtedly spurred further satellite sensor development within both NASA and NOAA. A series of Synchronous Meteorological Satellites (SMS) was envisioned for this purpose—later renamed Geostationary Operational Environmental Satellite (or GOES).

Suomi and co-workers showed that one could relate the changes in the albedo over Los Angeles, as measured from the ATS-3 spacecraft, to the visibility and local particle count in the lower atmosphere over the city. They noted that their finding was "perhaps the first quantitative detection of pollution from a satellite" [NASA SP-285, 1971]. Photographs taken in 1968 by astronauts also showed clearly the effects of pollution hazes. NASA was developing an Earth Resources Technology Satellite (ERTS) for obtaining images of the Earth's surface and cloud cover and its short-term and seasonal changes. ERTS-1 was launched in 1972 and later renamed Landsat-1. Its multi-spectral scanners (MSS) observed details about the reflectivity of clouds, vegetation, land and ice forms, as well as the presence and extent of haze layers on a global scale.

Professor Suomi also developed and flew balloon-borne, radiometersondes for obtaining atmospheric profiles of the net infrared fluxes (irradiances) due to clouds, water vapor, and aerosol layers [Kuhn and Johnson, 1966; Suomi and Kuhn, 1958]. Interpretations of the flux profiles were limited to a large extent by a lack of information on the spectral (absorbing) characteristics and/or scattering properties of each of those sources of irradiance. Therefore, the Panel recommended the initiation of a coordinated, physio-optical research program, whose purpose would be to advance the understanding of the optical properties and radiative characteristics of the real atmosphere. Later, Peter Kuhn modified the flux radiometer for the detection of clear air turbulence (CAT), based on the signal fluctuations in the 26-35 µm band of water vapor [Kuhn et al., 1978].

The Particle Panel recommended the establishment of a world-wide network of atmospheric turbidity monitors to determine what changes, if any, were occurring due to man-made aerosols.

They also recommended a number of supporting studies about the elements of the scattering matrix of atmospheric aerosols and on improvements in their mathematical and computational modeling. Members of the Panel realized that each of those aspects would be important for the development of models to assess the effects of both natural and man-made atmospheric aerosols on climate. Still, the Panel did not assemble a list of specific measurement requirements other than to note that it would be important to achieve good vertical resolution (~1 km) for the stratospheric aerosol layers and good horizontal resolution for tracking regional changes in tropospheric turbidity. With those issues in mind, Panel members J. Don Lawrence, Charles Byvik, Gerald Grams, and S. Harvey Melfi focused their attention on developing systems for the measurement of tropospheric and stratospheric aerosols using ground-based, backscatter lidar techniques.

Panel members made several recommendations for research satellite instruments, too. For example, they felt that the geographical coverage of a stratospheric aerosol experiment should be extended to the higher latitudes, like the one proposed for the Orbiting Solar Observatory (or OSO-J) by Gas Species Panel member, Ted Pepin, of the University of Wyoming. They thought that his approach could provide, quickly and economically, the basic data for understanding the global distribution of stratospheric aerosols. As an aside, it is noted that the originally-planned, OSO experiment was actually conducted on the Apollo-Soyuz Test Project as a Stratospheric Aerosol Measurements (ASTP/SAM) experiment in July 1975 [Pepin et al., 1977]. Further, they urged that a cooled infrared spectrometer be evaluated from a near-earth orbit for the sensing of distributions of small particles that could not be measured with photometers and, perhaps, for furnishing information on the chemical nature of the particles, too. The Panel believed that it was possible to characterize and monitor atmospheric turbidity on a global scale by measuring the degree of polarization of upwelling radiation with fast-response photopolarimeters [Sekera, 1967]. They recognized though that the target observation area would need to be kept in the field of view during a satellite traverse, in order to obtain information for a range of scattering angles. The Panel recommended that studies be made on the use of photopolarimeters from geostationary satellites, too. The Panel also urged that satellite-based lasers be developed for monitoring the spatial distributions of tropospheric and stratospheric aerosols on a global basis.

Clouds reflect incoming solar shortwave radiation with an efficiency that depends on their thickness, or more specifically their optical depth. They also absorb infrared radiation from the Earth's surface and from the surrounding atmosphere and re-emit it according to the atmospheric temperature at the altitude of the cloud top. In fact, the presence of clouds and their top height may be determined based on temperatures inferred from radiances in the so-called "infrared window" channels from satellite sounder measurements [e.g., Houghton, 1986]. But, operational sounder data from polar orbiting satellites are obtained at only two local times per day. Because cloud frequency and altitude vary diurnally, the sounder data carry time-of-day sampling uncertainties that make it difficult to obtain a good measure of the radiative budget of the Earth/atmosphere from a satellite platform. Distributions and occurrences of thin or subvisible cirrus clouds were not known well, and even thin cirrus can have a significant effect on the outgoing long-wave radiation [Liou, 1974]. Finally, the finite field-of-view (FOV) of the pixels

making up satellite images means that the effects of subgrid-scale clouds were also not known well and had to be parameterized in climate models or estimated by other means for a proper interpretation of infrared imagery [Slingo, 1980]. Members of the SMIC Working Group asked for a satellite system for "monitoring the temporal and geographical distribution of the Earth-atmosphere albedo and the outgoing flux (IR) over the entire globe with an accuracy of at least 1%."

The report of the RMOP Panel led by Suomi includes a discussion of the seemingly intractable problem of how to obtain information about the properties and effects of clouds and aerosols from measurements of their scattering, absorption, and transfer of atmospheric radiation. In one respect, the determination of the radiative budget of the atmosphere and of aerosol extinction profiles is fairly straightforward. One only needs to obtain accurate measurements of the radiances or transmissions. In other words, one does not have to advance to the next step of conducting retrievals of the remotely-sensed, radiance or transmission, as is most often the case for obtaining the state parameters of the atmosphere—its temperature versus pressure profiles and its gas species profiles. For that next step one must also have accurate forward models of the radiance or transmission, and those models are generally limited by uncertainties in the spectroscopic line parameters of the given minor or trace atmospheric gases. Yet, the determination of Earth's radiation budget from satellite altitude is based only on measurements of the incoming solar radiance and the outgoing reflected and emitted radiances at top-of-atmosphere (TOA), and one must know how those measurements vary throughout the day and night and across all seasons, at various spatial scales, and over a range of scattering angles. In order to know the effects of clouds and aerosols within the atmosphere itself, one must know their distributions with altitude and their macroscopic scattering and absorbing properties. It is also helpful to have an independent measure of the radiation budget at the surface of the Earth, in order to verify what is being inferred from the reflected shortwave measurements at TOA.

Clouds are also present at high latitudes of the lower stratosphere and in the upper mesosphere. Stanford and Davis [1974] considered why the so-called mother-of-pearl clouds (MPC) occurred in the polar lower stratosphere in winter. Pioneer researcher, Otto Jesse, was concerned with the formation and occurrence of noctilucent clouds (NLC) in the opposing summer season of the polar upper mesosphere and whether they might be connected to particles from large volcanic eruptions [Schroeder, 2001]. Knowledge was being obtained on both types of clouds from ground-based measurements of their scattering characteristics and from *in situ* measurements with high-altitude balloons or rocket probes. Poultney [1972] reported that cheap, low-power lasers having a high-pulse rate could provide ground-based measurements of the upper altitudes that would rival those from rocket probes. The Panel members believed that satellite observations obtained with photometers, radiometers, and lidar could provide improved space/time coverage and perhaps add some information about the cloud particles themselves.

3 Evolution of measurement techniques and some key players at Langley

(a) A redirection toward satellite observations of the Earth/atmosphere

In the 1960s Langley personnel were actively studying options for a Manned Orbital Research Laboratory (MORL) in preparation for Skylab and much later for a proposed International Space Station (ISS). However, toward the end of the decade much of that work was reassigned to the Marshall and Johnson Space Centers [Hansen, 1995]. Thus, part of the workforce at Langley was still in transition from the phase down of its Apollo and MORL activities and toward the planned development and demonstration of the Space Shuttle at the time of the RMOP Workshop in 1971. As reported in Remsberg [2011] and in the Introduction, the early part of the 1970s was also when NASA was directed to focus more toward Earth applications and on what atmospheric measurements could be usefully conducted from a satellite or Earth-orbiting platform. Edgar Cortright, Center Director at Langley from 1968-1975, was largely responsible for implementing that vision, in addition to overseeing the Viking Project and the major ongoing research in aeronautics and in hypersonic flight at that time. Prior to coming to Langley, Cortright had served as Chief of the Advanced Technology Program, Assistant Director for the Lunar and Planetary Program, and most recently as Deputy Associate Administrator for Manned Space Flight at NASA Headquarters. In October 1970 Cortright announced a major reorganization and formed four research Directorates—Aeronautics, Space, Electronics, and Structures at Langley [Hansen, 1995]. Leading up to and immediately after that reorganization, the conduct of Earth applications activities was ably directed by Eugene S. Love and William H. Michael, Jr., of the Space Directorate and by G. Barry Graves, James E. Stitt, Howard B. Edwards, William Croswell, John Dodgen, and William Mace within the Electronics Directorate.

Figure 1 is an outline of the atmospheric measurement programs at Langley from when they were primarily focused on aeronautics, to Earth applications since the time of the RMOP report of 1971, and then on to the planned activities for the upcoming decade. Much of the remote sensor development at Langley was initiated within the Instrument Research Division (IRD) from which the Flight Instrumentation Division (FID) was formed in 1965. FID personnel became engaged with testing and qualifying prototype instruments from balloon, rocket, or aircraft platforms. Measurement techniques for the effects of aerosols and clouds that they evaluated included: lidar, solar occultation, limb emission and scattering, photometry or radiometry, and polarimetry, as well as a number of ground-based and *in situ* aerosol and cloud droplet counting, sizing, and polarization techniques that would ultimately be used to validate or otherwise characterize the remotely-sensed observations. A brief review is provided in the following subsections of the early work at Langley for each of those remote sensing techniques (see upper right of Figure 1). Langley had already formed in 1964 the Office of Flight Projects to include Flight Reentry Programs, the Scout (rocket) Program with launches from Wallops Island, and the Applied Materials and Physics Division (AMPD). The latter organization was a reformulation of the Pilotless Aircraft Research Division (PARD). William O'Sullivan and colleagues of PARD and later AMPD developed and demonstrated several early communications satellites (ECHO and PAGEOS). His successors went on to develop sensors based on those of Verner Suomi for the measurement of Earth's radiation budget from satellite orbit.

1940's → **1971** → **Present**

Aeronautics Focus

- Model atmospheres, ground to thermosphere for development of the X-15.
- Passive sensing studies of Earth's CO_2 horizon for spacecraft attitude/reentry.
- Laser sensing of fluid flow in wind tunnels and turbulence in the atmosphere

RMOP Workshop

Remote Sensing Application

- Laser radar or lidar from Space.
- Satellite measurements by solar occultation (SO).
- Limb emission and scattering
- Nadir viewing photometry and radiometry for cirrus and aerosols.
- Aerosol polarimetry

Sensors for the Next Decade

- Limb scattering from stratospheric aerosols for OMPS on NPOESS Preparatory Project (NPP).
- SO via SAGE III from International Space Station.
- High-spectral resolution lidar for the troposphere.
- Continuation of radiation budget record w/CERES.
- Further measurements of aerosols and clouds w/CALIPSO lidar.
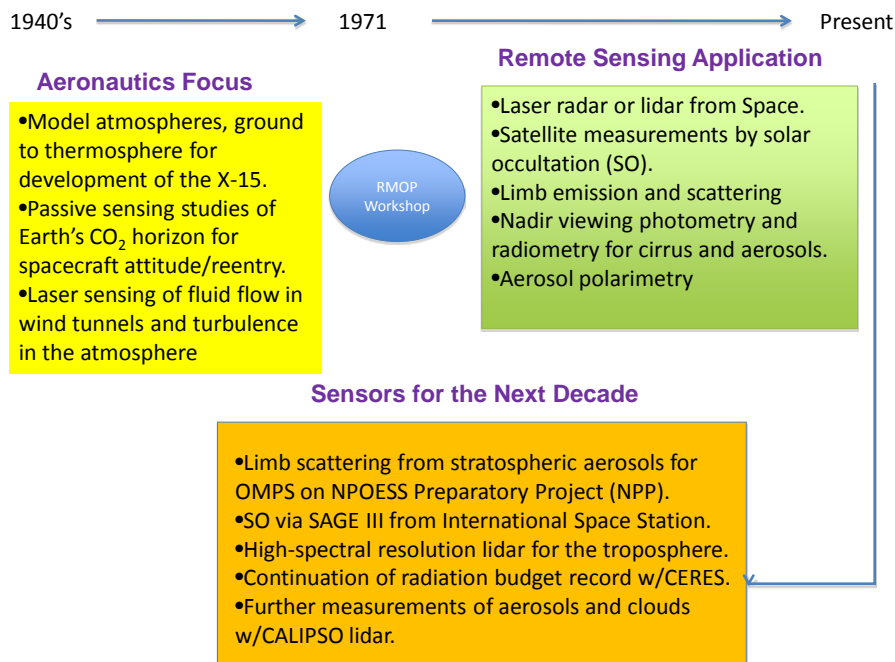
Figure 1. Time line of the development of techniques by NASA Langley for making measurements of atmospheric aerosols, clouds, and Earth's radiation budget.

The report entitled "*Research in Aeronautics and Space: Langley Research Center*" is a useful summary of the research programs at Langley during the 1960s [Cortright, 1971]. One can easily discern some of the origins of atmospheric science research at Langley from that report. Of particular interest at that time was the ongoing need to characterize the effects of atmospheric drag and the accompanying heat load for spacecraft re-entering the atmosphere from low Earth orbit. In addition, it is noted therein that Langley was instrumental in the design of launch vehicles and their propulsion options for a combined U.S./Canadian meteorological sounding rocket program.

Sensor concepts for aerosols and clouds that have been demonstrated successfully from Earth-orbit by Langley researchers are described in the following subsections, along with their primary advocates. The succession of satellite experiments is recounted in the subsequent chapters from the time of RMOP and on through to the Space Shuttle and EOS periods. Their achievements are also placed within the context of concurrent measurement programs of other national and international research organizations.

(b) Laser radar or lidar

Soon after the development of the laser, optical engineers Don Robinson and Joe Goad of IRD adapted that new technology for purposes of flow visualization in wind tunnels and for small particle holography at Langley [NASA, 1970]. Others were already training their optical radar or lidar systems toward the sky for detecting atmospheric turbulence and for characterizing smoke plumes and pollutant haze layers in the lower atmosphere [Collis et al., 1964; Clemesha et al., 1966]. Giorgio Fiocco and RMOP Panel member Gerald Grams made observations of the Junge aerosol layer in the stratosphere [Fiocco and Grams, 1964] and its volcanic enhancements following the eruption of Mt. Agung [Grams and Fiocco, 1967]. Further, Grams and Burt Schuster of NCAR and Robert Fox and James Weinman of the University of Wisconsin went on to install an organic dye laser in a lightweight lidar system and to obtain measurements of the Junge layer from the NASA CV-990 aircraft over both the Pacific and the western Atlantic Ocean regions in the summer of 1971 [Fox et al., 1973]. They found backscattering ratios of order 1.1 or an aerosol scattering component of only 10%, indicating that the lower stratospheric layer was nearly devoid of any significant volcanic influence at that time. Paul Davis of Stanford Research Institute (SRI) also conducted lidar measurements from the CV-990 aircraft, looking for signatures of cirrus and of boundary haze layers, as part of the Barbados Oceanographic and Meteorological Experiment (BOMEX) during the summer of 1969 [Davis, 1971]. His measurements were coupled with those from an airborne infrared radiometer, in an attempt to characterize the radiative forcing from the cirrus particles and the aerosol haze.

During the late 1960s RMOP Panel members, S. Harvey Melfi and J. Don Lawrence, Jr., along with M. Patrick McCormick and Douglas Woodman mounted their pulsed, ruby lidar system onto a T-33 jet aircraft and obtained enhancements in backscatter, which they associated with

regions of light turbulence [Lawrence et al., 1968]. Shortly after, Lawrence took a position as Chief Scientist of IRD, moving from the Physics Department of nearby College of William and Mary. Melfi and McCormick were also researchers in IRD. Lawrence and Melfi then moved to the newly formed Environmental and Space Sciences Division (ESSD) during the reorganization at Langley of 1970, while McCormick remained in IRD as Head of the Photo-Electronic Instrument Section. Along with William Hunt of Wyle Labs and William Fuller, Jr., they assembled a 48-inch mobile lidar system and then participated in a number of field measurement campaigns over the next decade. Lawrence and colleagues also contributed to BOMEX by conducting lidar observations from the cruise vessel *S. S. Advance* from Wilmington, NC, to the Barbados region and then to the mouth of Amazon River and back. They characterized the presence of dust layers in the lower stratosphere and also the dust at the top of the planetary boundary layer that had been transported westward from the African continent [Bach and Smith, 1970]. Their efforts were sponsored by the Research Triangle Institute (RTI) of North Carolina just prior to the time that the Environmental Protection Agency (EPA) was formed. A cooperative relationship was maintained between Langley and the EPA for studies of regional air quality for at least the next decade, and Edgar Cortright was very supportive of those joint activities.

McCormick and Fuller of IRD and Lawrence and Melfi of ESSD, among others, made upgrades to the transmitter, receiver, and electronics for what was to become their signature, ground-based 48-inch lidar system and much later a facility instrument at NASA Langley. Their first field campaign with the system was to Azusa, California, as part of a study activity of the air quality in the Los Angeles Basin in 1972. They also carried out routine measurements of the stratospheric layer over Langley during those years and were careful to maintain good calibrations for the system because of the very low aerosol backscattering ratios of that time [e.g., Hunt and Poultney, 1975]. Langley remote sensors were an important part of the Department of Transportation's Climatic Impact Assessment Program (DOT-CIAP) of the early 1970s. Of course, Langley was also interested in the findings from CIAP because of the implications for its further research toward a supersonic transport (SST) aircraft.

Lawrence and Ron Greenwood were selected in 1973 to direct a NASA Environmental Quality Program Office (EQPO) at Langley at the request of Morris Tepper. Shortly thereafter, Melfi left Langley for a supervisory position at the newly-formed, EPA remote sensing laboratory in Las Vegas, NV. McCormick had assembled an array of remote and *in situ* aerosol measurement capabilities and personnel within a new Aerosol Research Branch (ARB) by 1975. Key persons included William Chu and David Woods along with RMOP Panel member, Franklin Harris, Jr., a NASA contractor at the nearby Old Dominion University Research Foundation (ODURF). Burton Northam, Head of a new Lidar Applications Section (LAS) in ESSD, recruited new employees, Edward Browell and Ellis Remsberg, plus Sherman Poultney and Carolyn Butler at ODURF in 1973-74. Together IRD and ESSD continued on with the calibration of the 48-inch lidar system and with the monitoring of the stratospheric aerosol layer. They also evaluated lidar techniques for their application to atmospheric measurements from the ground and from Space.

The various techniques included resonance fluorescence, Raman scattering, and differential absorption lidar (DIAL), in addition to the more traditional method of laser backscattering.

McCormick and Northam conducted lidar measurements and compared them with University of Wyoming dustsonde profile measurements near San Angelo, Texas, in May of 1974, as part of requirements to characterize the Stratospheric Aerosol Monitor (SAM II) and Limb Infrared Monitor of the Stratosphere (LIMS) prototype instruments that would fly eventually on Nimbus 7 in 1978 [Northam et al., 1974; Remsberg et al., 1979]. However, they were all soon distracted by the much larger, lidar return signals that they observed at Langley, following a major eruption in Guatemala of the Fuego volcano in October 1974 [McCormick and Fuller, 1975; Remsberg et al., 1982]. McCormick and Fuller went on to assemble a smaller, 14-inch ruby lidar system and began to conduct airborne surveys of the dispersal of volcanic aerosol layers and to validate satellite measurements of stratospheric aerosols and cirrus clouds.

An Advanced Applications Flight Experiments (AAFE) Program Office was set up at Langley in the early 1970s and managed by Robert Parker, as directed by Cortright and by Leonard Jaffe and Jules Lehmann of NASA Headquarters [Croswell, www.ieeeghn.org]. The purpose of the AAFE Program was to develop instrument concepts for eventual flight on a satellite platform. In addition, personnel in IRD and ESSD were assigned as technical monitors of study contracts to assess the potential of lidar measurements from an Earth-orbiting, Space Shuttle platform. An important outcome of those studies was that Langley and SRI submitted two separate proposals to an Announcement of Opportunity in 1976 from the NASA Office of Space Sciences (OSS) for the conduct of lidar measurements of Earth's atmosphere on the Shuttle-based Spacelab I. Simulation studies indicated that it should be easy to obtain near global-scale characteristics of aerosols and clouds from a lidar system [Remsberg and Gordley, 1978; Russell et al., 1982]. The Langley proposal was entitled "Tropospheric Aerosol and Cloud Experiment (or TRACE)", and it was designed to be a demonstration of what might be achievable with a lidar system from an Earth-orbiting platform. It received an excellent technical rating and had the strong support of Lawrence, Donald Hearth (Langley Director), and Paul Holloway (Director for Space). No selection was made though because of the cost involved and of the competing and overlapping interests within the OSS and Office of Applications (OA) Programs at NASA Headquarters. However, the managers at OSS and OA recognized the lidar expertise within Langley. They later combined their Shuttle Atmospheric Lidar Programs in cooperation with the Centre National d'Etudes Spatiales (CNES) of France, and that decision led to a Shuttle Lidar Program Office being set up at Langley [NASA, 1979].

During this time Edward Browell, James Hoell, Syed Ismail, and Scott Shipley of Langley and Robert Allen and Frank Mills of ODURF continued to develop and demonstrate the use of DIAL technologies within the Atmospheric and Environmental Sciences Division (AESD), headed by J. D. Lawrence. A focus for their work in the late 1970s and early 1980s was on the application of laser measurement techniques in field studies of the regional air quality. The EPA was keenly interested in understanding how urban haze plumes extended to the regional and continental

scales. They relied on satellite imagery and the airborne, UV-DIAL lidar measurements of the haze layers for a verification of their model predictions of the transport of aerosols and ozone. In particular, Langley personnel participated in the EPA Persistent Elevated Pollution Episode/Northeast Regional Oxidant Study (PEPE/NEROS) program of 1980, as well as a subsequent study of pollution episodes in the Tidewater Virginia region [Browell et al., 1985; Shipley et al., 1984]. Joint studies led by researchers at the University of Wisconsin were also carried out using their airborne prototype, high-spectral resolution lidar (HSRL) instrument [Shipley et al., 1983] that was based on the initial optical radar measurements of aerosol-to-molecular backscatter ratios along with a frequency analysis of their Doppler-broadened spectra in the manner of Fiocco et al. [1971]. It was anticipated that advances in the HSRL technology could still be made for providing better measurement stability and aerosol-to-molecular discrimination.

(c) Solar occultation

Prof. Alfred Nier of the University of Minnesota and his student, Ed Ney, did pioneering work in mass spectrometry for the separation and analysis of the isotopes of uranium in the early 1940s. Much later, Nier was responsible for the mass spectrometer that was on the Viking Lander spacecraft.   Ney went on to conduct measurements from high altitude balloons of atmospheric cosmic rays. Both Ney and later J. D. Lawrence, Jr., worked under the guidance of Prof. Jesse Beams and were awarded doctoral degrees from the University of Virginia. Ney returned to Minnesota to accept a faculty appointment in Physics and Astronomy some years later. Lawrence and his student, M. Patrick McCormick, of The College of William and Mary stayed abreast of Ney and his research activities, as they undertook their early lidar studies of the stratosphere. Two graduate students of Ney, James Rosen and Theodore Pepin, had been conducting measurements with photoelectric particle counters from balloons from 1965 to 1968 that showed the variability and characteristics of stratospheric aerosols and their apparent systematic changes with time. Before that, Rosen [1964] had been searching for evidence of meteoritic debris in the stratosphere. Pepin also evaluated solar occultation methods from the balloon platforms for sensing the aerosol layers. Later, Pepin and McCormick teamed up to conduct solar extinction measurements using a simple photometer with a diode detector, as part of the Apollo-Soyuz Test Project (or ASTP) [Pepin et al., 1977]. Comparison measurements for the ASTP mission were obtained near Kansas City by Rosen with his balloon-borne particle counter and by McCormick and Fuller with the 48-inch lidar system.

Pepin participated in the RMOP Workshop as a member of its Gas Species Panel and was initially interested in making occultation measurements of ozone. Based on the quality of the aerosol extinction from the photometer on ASTP, he and McCormick proposed the Stratospheric Aerosol Monitor II (SAM II) experiment for flight on the Nimbus 7 satellite in October 1978 and also the Stratospheric Aerosol and Gas Experiment (SAGE) that flew a few months later on an Applications Explorer Mission or AEM-2 satellite [McCormick et al., 1979; Russell, 1980]. Ed Mauldin, III, was the Instrument Manager for SAM II and SAGE. Philip Russell of SRI and RMOP Panel members, Grams and Benjamin Herman, were also members of the Science Teams

for both experiments. Nimbus 7 was a polar orbiting satellite, which meant that SAM II obtained solar occultation measurements only at the high latitudes. But, the AEM satellite operated from a highly-precessing orbit at an inclination of 55 degrees, which enabled SAGE to make occultation measurements across most latitudes of the southern and northern hemisphere at least within the time frame of a month or so. Together, these two satellite experiments provided global-scale information on the stratospheric aerosol layer for the first time. Their measurements were necessarily limited by the fact that tropospheric cloud tops along the occultation tangent path often obscured the setting or rising Sun. Otherwise, their visible to near-infrared (to 1-µm) measurements provided many advantages for obtaining the aerosol profiles with good vertical resolution and accuracy.

McCormick and Leonard McMaster brought additional researchers to Langley, including Thomas Swissler of Systems and Applied Sciences Corporation (SASC) and Adarsh Deepak. Soon after, Deepak formed an Institute for Atmospheric Optics and Remote Sensing (IFAORS) in Hampton, VA. William Chu, Swissler, and Pi Wang (IFAORS) developed the aerosol and gas species (ozone and NO_2) algorithms for SAM II and SAGE. Patrick Hamill (SASC), Geoff Kent (IFAORS), and Glenn Yue (IFAORS) provided detailed assessments of the quality of the aerosol profile data. SAM II operated from October 1978 until 1991 and then periodically until near the end of 1993. SAGE operated from late February 1979 through November 1981. Validation of the aerosol profiles is described in Russell et al. [1981; 1984]. Kent and McCormick [1984] is a good summary of stratospheric aerosol optical depth data from SAM II and SAGE. Distributions and occurrences of cirrus clouds indicated the low-altitude limit for the extinction profiles from SAGE [Woodbury and McCormick, 1983]. SAGE also observed the volcanic plume from the Mt. St. Helens eruption of May 1980 and its subsequent effects for the lower stratosphere of the northern hemisphere. In addition, SAM II provided good estimates for the first time of the wintertime occurrences of the so-named, polar stratospheric clouds (PSC). All during this time, Rosen and colleague David Hofmann of the University of Wyoming continued to make balloon-borne, *in situ* measurements of the aerosols, and a number of other research groups conducted routine measurements of the aerosol layers with their ground-based lidar instruments.

(d) Limb emission and scattering

In the late 1950s and early 1960s Langley navigation and guidance specialists conducted measurements of the horizon as part of their development of sensor concepts for controlling the attitude of spacecraft in Earth orbit. They measured horizon radiances from the ultraviolet (uv) to the middle infrared region of the spectrum from a Javelin rocket flight out of the Wallops Flight Facility in 1961 [McKee et al., 1964]. They supported the launch of the Ariel 2 radio astronomy satellite from a Scout X-3 rocket in March 1964. Ariel 2 carried a photometric instrument from the UK Meteorological Office, and Miller [1967] reported on the attenuation of ultraviolet light by ozone from its measurements of the Earth's limb and on their attenuation at 380 nm by the stratospheric aerosol layer. At about the same time Langley researchers made complementary measurements in the near to middle infrared region with sensors mounted in the tail of an X-15 research aircraft [Jalink et al., 1968]. Their exploratory measurements of the

infrared horizon eventually led to the radiance measurements and retrievals of atmospheric temperature and constituent profiles by the Limb Radiance Inversion Radiometer (LRIR) on Nimbus 6 in 1975 and by the LIMS experiment on Nimbus 7 in 1978. John Gille and James M. Russell III, Co-Team Leaders of LIMS and members of the RMOP Gas Species Panel, and Frederick House of Drexel University provided good estimates of the uncertainties that were present in the registration of the satellite-measured, limb radiances [Gille and Russell, 1984; Wilson et al., 1979].

With the sponsorship of Morris Tepper of NASA Headquarters and of J. D. Lawrence, Jr., the first International Interactive Workshop on Inversion Methods in Atmospheric Remote Sounding was hosted by M. P. McCormick and A. Deepak (IFAORS) in Williamsburg, VA, in December 1976. Experts from that research community presented papers and shared their views on the information content that could be obtained from limb scattering, emission, and absorption measurements. Papers related to the retrieval and interpretation of stratospheric aerosol sizes and their optical parameters were presented by Malchow and Whitney [1977] and Chu [1977], and by the RMOP Panel members, Herman [1977] and Pepin [1977]. They achieved quantitative results and placed estimates of uncertainty on the measurements and the retrieved parameters. They also showed that it should be possible to validate the various retrieved parameters against auxiliary measurements obtained from airborne sensors or with suitable, ground-based and balloon-borne techniques obtained along the tangent track viewed by the satellite instrument.

Cox [1981] reported on the significant absorption/emission signatures in the visible from clouds composed of water or ice. [Liou, 1981] considered the effects of clouds in the infrared, particularly in those spectral regions where the absorbing effects of gaseous H_2O, CO_2 and ozone are absent or weak. He also made recommendations for better measurements of the clouds, especially for cirrus (see also next two subsections). Since cirrus cloud particles are significant scatterers/absorbers/emitters in the visible through the infrared, they inhibit limb observations of the troposphere much of the time. As an example, the Nimbus 7 LIMS measurements were sensitive to radiances from the tops of cirrus clouds, from PSCs, and to a lesser extent from the aerosols of the Junge layer. The Solar Mesosphere Explorer (SME) was a similar, limb-sounding experiment launched in October 1981 from a Delta rocket vehicle and managed by the Jet Propulsion Laboratory (JPL). SME made measurements of scattered and absorbed light in its ultraviolet and visible channels and of thermal emissions with its two infrared channels [Barth et al., 1983]. The presence of stratospheric aerosols from the eruption of the El Chichon volcano in April 1982 caused the top of that aerosol layer to became the effective low altitude limit for accurate retrievals of the SME profiles of ozone and NO_2 in the uv and visible, at least for some months thereafter. Its infrared radiances from H_2O were also severely affected by the aerosols. In Section 2 it was noted that Rosen [1971] had inferred that the aerosols were likely composed of aqueous H_2SO_4, which is a very effective absorber/emitter in the middle infrared.

(e) Nadir-viewing photometry or radiometry

In the summer of 1969 Langley and Old Dominion University (ODU) sponsored a preliminary design study for an operational Earth resources survey system. University faculty and a number of Langley researchers participated in that joint effort. The information contained in their final report led to the initial Earth applications activities at Langley [Carver et al., 1969]. It also was a basis for Langley's involvement with the RMOP Panel on Water Pollution and the remote sensing measurements that they advocated. A natural local collaboration developed between Langley and the nearby Virginia Institute of Marine Sciences of The College of William and Mary and the Department of Oceanography at ODU and because of the mutual proximity to the Chesapeake Bay of all three organizations. Langley Director, Cortright, also formed a Space Technology Division as part of his new Space Directorate in 1970, but it soon took on the name Space Applications and Technology Division (SATD). Personnel in the Electromagnetics Research Branch of IRD were also using microwave radiometers to obtain state parameters of the sea surface [e.g., Swift, 1974]. With support from the AAFE Program, they went on to conduct airborne and satellite measurements using more-advanced radar scatterometer instruments over the next decade.

The first Earth Resources Technology Satellite (ERTS-1) contained sensors fashioned after those on Nimbus 4, an early meteorology satellite managed by NASA Goddard. ERTS-1 was launched into polar orbit on July 23, 1972 and was renamed Landsat-1. It carried a red-green-blue (RGB) vidicon camera and a 4-channel, multi-spectral scanner (MSS) radiometer operating in the infrared. Panel member, Robert Fraser, and colleagues from Goddard combined radiances from the MSS with calculated values from a radiative transfer model to estimate the mass of particulates in a vertical column of dust transported westward from northern African and across the Atlantic Ocean [Fraser, 1976]. Bruce Wielicki of Langley began to use Landsat MSS data by 1980 to develop a higher-resolution source of "cloud truth" for calibrating the cloud properties determined from the lower spatial resolution, meteorological satellites [Wielicki and Welch, 1986]. Although the Landsat MSS measurements suffered from an inadequate calibration standard for their radiances, they laid the ground work for the improved MODerate-resolution Imaging Spectro-radiometer (MODIS) instruments on the EOS satellites that are operating today [Shenk and Salomonson, 1972; Salomonson et al., 1989].

In the late 1950s Langley was focused on developing unmanned, large inflatable balloons to serve as passive communications satellites and to provide estimates of atmospheric drag in low-Earth orbits. Such orbital decay information was important for defining the controlled descents of the manned spacecraft that would soon follow. Knowledge about orbital drag was also important for the Mars Viking spacecraft, and the Viking Project was at the top of Cortright's agenda during the late 1960s and for its Mars landings in 1976. Remote observations of Mars had already revealed occurrences of persistent dust storms at the surface of Mars, and those events became a focus of meteorological studies by Seymour Hess of Florida State University and Robert Henry of Langley soon after the spacecraft landed on Mars [Tillman et al., 1979].

Suomi and RMOP Panel member, G. D. Robinson, were more interested in making satellite measurements of Earth's radiation budget, however [SMIC, 1971]. Joel Levine, who joined Langley Research Center in the late 1960s, was focused on studies of the atmospheres of other planets, including Mars. But prior to that time, he and Al Arking of the Goddard Institute for Space Studies (GISS) had reported on the relatively low, reflectivity or albedo that they obtained for the Earth and its atmosphere based on quasi-global data from TIROS VII [Arking and Levine, 1967]. Even so, they were mindful that the visible-channel reflectivities from TIROS needed to be corrected upward due to a probable degradation of its sensors during launch. Several years later, Vonder Haar and Suomi [1971] reported on their analyses of 39 months of radiation budget measurements. They obtained an estimate of the mean global albedo of 30% and found a net radiation balance, at least within the measurement accuracies of the radiometers.

In the mid-1970s Langley researchers, Linwood Callis, Robert Boughner, and V. Ramanathan (NASA/NRC Postdoctoral Fellow) turned their attention to the development of radiative-convective models and calculated the effects of scattered radiation from the Earth's surface and the atmosphere in the uv, visible, and infrared. Bruce Barkstrom, a radiation scattering and transfer specialist, was a faculty member of George Washington University from 1974-79 in its Joint Institute for the Advancement of Flight Sciences (JIAFS) that was located at Langley. Others were considering how to improve on the measurement of Earth's radiation budget, in part due to the directives from the RMOP Panel headed by Suomi and in response to his keen interest in the topic. G. L. Smith, Gary Gibson, Edwin Harrison, and colleagues of SATD conducted orbital analyses and offered Earth-viewing strategies for obtaining more complete measurements of Earth's radiation budget from low Earth orbit [Smith et al., 2010]. They credit George Sweet of Langley for an initial satellite concept of three spherical integrating detectors, having different color coatings of black, white, and aluminum and thus different skin temperatures. His concept was titled Long-time Zonal Earth Energy Budget Experiment (LZEEBE), and its prospects were judged along with two other proposed measurement concepts from Suomi of Wisconsin and from Vonder Haar of Colorado State [Yates, 1977]. The LZEEBE and the Wisconsin concepts required dedicated satellite platforms and orbits that were different from those of the operational TIROS satellite system. Although the LZEEBE concept was not selected for further funding, it eventually led to the design of Langley's Earth Radiation Budget Experiment (ERBE) that would be launched from Space Shuttle in 1984. Barkstrom was hired by Langley in 1979 to be Experiment Scientist and Science Team Leader of ERBE (see Sections 4 and 5).

Prior to that time, G. L. Smith of Langley served as a member of the Experiment Teams for the Earth Radiation Budget (ERB) instruments on both Nimbus 6 and 7. The Nimbus satellites were polar orbiters and had the same sampling issues as TIROS in both space and time for the radiation budget parameters that they obtained, in addition to the adequacy of the calibrations of their radiances. Smith was concerned with how to relate wide FOV radiometer measurements to radiances emitted at a finer spatial resolution from the top-of-atmosphere [Smith and Green, 1981]. There were also concerns about the low-resolution radiances measured at just two local times from polar orbiters. To that end, Patrick Minnis and Harrison analyzed GOES satellite imagery to estimate the effects of the diurnal variability of cloud radiances [Minnis and Harrison,

1984]. McKee and Cox [1974] developed models of the scattering of visible radiation by clouds of finite horizontal extent, and Feddes and Liou [1977] considered the effects of multi-layered clouds on the upwelling radiances. All of these early results were used as an aid in the design of the ERBE experiment that was launched in 1984. Excellent reviews of the radiation budget studies up to the time of ERBE can be found in House et al. [1986] and Smith et al. [2010].

Studies had been conducted on the transfer of radiation within the atmosphere before there were satellite sensors for making top-of-atmosphere measurements. For instance, Panel member, Robinson, co-authored one of the earliest theoretical studies of the loss of radiant energy to space, due to infrared emissions from the surface, from cloud layers, and from the diffuse water vapor, carbon dioxide, and ozone molecules [Goody and Robinson, 1951]. In addition, Suomi and colleagues obtained some initial measurements of profiles of net radiation in the atmosphere [Suomi et al., 1954]. John Gergen in collaboration with Ed Ney and colleagues at U. of Minnesota also conducted balloon-borne measurements of total atmospheric infrared radiation with their "Black Ball" integrating radiometers [Gergen, 1957]. However, the Black Ball measurements presented a number of uncertainties. Suomi's flat plate radiometersonde measurements were more consistent and easier to relate to the underlying surface or cloud scene. He also found that radiometersonde measurements near the tropopause were quite sensitive to the presence of thin cirrus and ozone and to variations in upper tropospheric water vapor. Pilipowskyj et al. [1968] determined that the downward-directed, infrared irradiance (or flux) that they measured in spring of 1965 from the subtropical lower stratosphere could not be explained by the presence of gaseous emitters. They postulated that the excess was due to large numbers of stratospheric aerosols of small radius, presumably composed of concentrated, aqueous sulfuric acid according to the independent, vapor pressure measurements of Rosen [1971]. The quantitative effects of each of these radiative sources are still be evaluated today, but are being based now on combinations of better radiometric and lidar measurements, as will be noted in Section 6.

The role of clouds on the radiative balance, energetics, and circulation of the atmosphere was being considered well before the RMOP Workshop, based in part on the early balloon-borne and satellite-based radiometric measurements. Early on, Greenfield and Kellogg [1960] reported on their calculations of the spectral nature of the atmospheric infrared radiation fields that one could expect to observe looking down on the troposphere, perhaps eventually from a meteorological satellite. They showed that only about one-third of the surface radiation escapes in the tropics in the so-called "window region" from 8 to 13 micrometers. In other words, that "window" is not at all transparent. On the other hand, at the middle latitudes about two-thirds of the upward emission originates from the ground; the water vapor content of the atmosphere is much lower at middle latitudes. Similar variations with latitude were observed using the broadband radiation sensors of the early TIROS satellites [Nordberg et al., 1962]. Gergen [1965] also observed large variations with both time and space from balloon measurements of the outgoing infrared radiation at nighttime, and he thought that the changes were due primarily to cirrus clouds. Liou [1986] and Schiffer and Rossow [1983] concluded that the effects of cirrus clouds were one of the major unsolved components in weather and climate research. How to estimate the effects of

aerosols and clouds on the transfer of radiation was addressed analytically by David Adamson of Langley [Adamson, 1975] and on the inference of the sea surface temperatures (SSTs) from satellite imagery by Xu and Smith [1986] and Xu and Sun [1991]. Section 6 points to progress that has been made on that issue by Langley researchers in the current decade, based on passive and active remote sensing techniques and combinations of satellite datasets obtained with them.

(f) Aerosol polarimetry

Diran Deirmendjian of the RAND Corporation and Alex Green of the University of Florida developed theoretical models for the detection of aerosol scattering from measurements of the intensity patterns of the solar aureole [Deirmendjian, 1959; Green et al., 1971]. However, they stressed that more work was needed to sort out the effects of the underlying surface reflectance on the scattering patterns. Hariharan [1969] assembled a breadboard photometer and obtained transmission measurements at three separate viewing angles from the beam direction and, thus, characterized the aerosols from their polarizing effects. Since the precision of his results were quite good, the polarimeter concept appeared promising for eventual operation from an airborne or a Space platform, as envisioned earlier by RMOP Panel Member Zdenek Sekera of UCLA.

The characterizations of aerosol and cloud particle distributions were a focus of the 1976 Workshop on Inversion Methods in Atmospheric Remote Sensing sponsored by Tepper and Lawrence and hosted by M. P. McCormick and A. Deepak in Williamsburg, VA. In 1971 Prof. Sekera showed that the effects of aerosols and clouds on the transfer of atmospheric radiation depend on the optical properties of the scattering/absorbing particles. He and Jacob Kuriyan went on to model aerosol effects on the flux transfer of radiation through the atmosphere, and they checked their solutions against multi-spectral extinction measurements and angular scattering measurements via a polarimeter [Kuriyan, 1977]. They also envisioned making such measurements from a satellite. Deepak [1977] and Green and Klenk [1977] considered how to invert scattering patterns within the solar aureole and how to relate those patterns to the properties of the intervening aerosols. Twitty et al. [1976] conducted airborne measurements of the solar angular scatter using a scanning photometer and then inverted them to obtain aerosol size distributions. Their findings agreed reasonably with *in situ* measurements of the aerosols. Previously, Panel Member Al Holland demonstrated that non-spherical aerosols would also reduce the fraction of energy in the backscatter direction, as compared with that from spherical particles [Holland and Gagne, 1970]. Thus, it seemed likely that remote measurement techniques could be employed for the characterization of ice versus water clouds and for identifying the sources of aerosols in tropospheric haze layers, perhaps even from a satellite.

Panel Member, Ben Herman, described methods for inverting lidar angular scatter and solar extinction data for the determination of aerosol size distributions [Herman, 1977; Herman et al., 1971]. Platt [1973] used lidar and radiometric measurements of cirrus clouds to obtain better estimates of their effects on the radiative budget, as recommended in the SMIC and RMOP reports. At about the same time, Gibson et al. [1977] reported that the backscatter and extinction

coefficients for cirrus that they observed could not explained, if the cloud particles were spheres or randomly-oriented. Their findings indicated that one ought to be able to learn more about the nature of the ice crystals in the clouds from measurements of their depolarization ratios. Once again, it was clear that improved measurement methods would be needed to sort out the role of both aerosols and clouds on the transfer of radiation in the atmosphere and for specifying their effects properly in forecast studies with climate models.

Pioneering studies of the reflectivity of surfaces and suspended aerosols were also conducted in the laboratory by Jack Margolis and Dan McCleese of JPL and later by RMOP Panel Member, Robert Fraser, of NASA Goddard [Margolis et al., 1972; Mekler et al., 1984]. Their experiments provided important data for the verification of theoretical calculations of the diffuse reflectivity and the scattering of radiances by a layer of aerosols. Kaufman and Joseph [1982] devised methods for extracting quantitative information on surface albedo and aerosol extinction from satellite imagery. They employed a two-stream approximation for radiative transfer that William Meador and Willard Weaver of Langley used for planetary atmospheres [Meador and Weaver, 1980]. Kaufman and Joseph showed that those methods were also successful when applied to a Landsat image of Saharan dust transported westward off the coast of North Africa.

4 Research on aerosols and clouds from the time of RMOP to the early 1980s

This section summarizes findings about aerosols and clouds from the early period of satellite observations, and it places them in the context of similar research programs elsewhere. To begin with, the U. S. Atomic Energy Commission (AEC) had been assigned the responsibility of developing regulations, of monitoring for the effects of atmospheric bomb debris, and for the dispersion of radioactive pollutants from commercial nuclear power plants in accordance with the Atomic Energy Act Amendments of 1954. Elmer Reiter of Colorado State University prepared a excellent compendium for AEC on the relationships between the distributions of radioactive bomb debris, stratospheric aerosols, and ozone [Reiter, 1971]. Elterman et al. [1969] and Rosen [1969] also contain extensive descriptions of what was known in 1971 about the distribution and character of the stratospheric aerosols. Early field measurement programs showed that there were correlations between the radioactive debris, aerosols, and ozone [Kroening and Ney, 1962; Rosen, 1968; and Danielsen and Mohnen, 1977]. Further, Rosen et al. [1975] reported on positive correlations between stratospheric aerosols and ozone from series of balloon-borne profile measurements at selected station locations. They also showed that the altitude of the peak of the aerosol layer was closely related to the height of the tropopause and its variation with latitude and season. Reiter explained those correlations as being due to the effects of atmospheric transport on their respective distributions.

Radiative effects of the volcanic aerosols from the 1963 eruption of Mount Agung in Indonesia were modeled successfully by Hansen et al. [1978]. They showed how the aerosols cooled the Earth's surface and warmed the lower stratosphere, based on detailed information that was reported on the composition, size, and distributions of the aerosols [e.g., Cadle and Grams, 1975] and on the concurrent temperature observations. Cadle et al. [1976] and Itabe et al. [1977] simulated the global dispersion of the observed aerosol cloud from the 1974 eruption of Mount Fuego in Guatemala using state-of-the-art, two-dimensional transport models. Later, Karin Labitzke observed an increase of several degrees from her meteorological analyses at the Free University of Berlin of northern subtropical temperatures in the lower stratosphere following the 1982 eruption of the El Chichon volcano in the Philippines. McCormick and colleagues associated that warming with the enhanced aerosol extinction that they measured along latitudinal transects with their airborne 14-in ruby lidar [Labitzke et al., 1983]. Shortly thereafter, William Bandeen assembled a group of experts at NASA Goddard to assess the effects of aerosols and gases from El Chichon for the retrieval of Earth/atmosphere temperature and ozone from the satellite sensors of that time [Bandeen and Fraser, 1982]. Bandeen's report includes findings of Michael King and Fraser of Goddard on the combined radiative effects of the volcanic aerosol layers for measurements of the atmosphere by remote sensors. They found that sensor signals in the visible and ultraviolet were definitely affected; temperatures obtained from the infrared sounders were also affected slightly.

The National Air Pollution Control Administration (NAPCA) was established within the U. S. Department of Health, Education, and Welfare in 1965. NAPCA was primarily concerned with controlling vehicular emissions, but it also supported programs for the measurement of particle

concentrations and the dispersal of smoke plumes from stationary power plants [e.g., Pilat and Ensor, 1970]. Both monitoring and regulatory functions were taken over by the EPA when it was established in 1971. The effects of tropospheric haze layers on the climate had also been estimated from a rather, straightforward calculation by Charlson and Pilat [1969], but they were careful to note the importance of having better information about the relative magnitude of the backscattering and absorption coefficients of the haze aerosols in addition to their total attenuation. Herman and Browning [1975] carried out more detailed radiative transfer calculations of the reflected solar flux, along with the sensitivity of those results to the primary variables of solar elevation angle, ground albedo, and aerosol refractive index. They showed that haze aerosols can either increase or decrease the reflected flux, depending on the underlying ground albedo. They expected a similar outcome for haze layers overlying a low cloud deck. Rasool and Schneider [1971] conducted initial calculations of what to expect about the combined effects of increases in atmospheric carbon dioxide and in aerosols on Earth's climate. James Hansen of NASA GISS and James Pollack of Cornell University also calculated reflectivity in the near infrared from both liquid water and ice clouds and then compared the values with observations. Their goal was to develop better models of the effects of clouds for the transfer of atmospheric radiation [Hansen and Pollack, 1970].

As indicated earlier in Section 3e, observational studies of tropospheric haze layers were initiated using multi-spectral scanner data from Landsat-1 [Fraser, 1976] and with the Advanced Very High Resolution Radiometer (AVHRR) sensors on the NOAA satellites [Griggs, 1983]. Similar imagery was also available from the SMS or GOES sensors of NOAA and from the Defense Meteorological Satellite Program (DMSP) sensors of the Department of Defense (DOD). Weinman et al. [1981] evaluated the sensitivity of such sensors versus wavelength by calculating the effects of smoke clouds from brush fires that one should expect to see with a nadir-viewing, infrared channel centered at 11.5 micrometers, as opposed to radiances obtained at shorter wavelengths. The launch of TIROS-N in 1979 also marked the start of the routine monitoring of sea surface temperatures (SST) using AVHRR measurements [e.g., Ohring et al., 1989]. Thus, there was a critical need for the development of additional remote sensing techniques, as recommended by the RMOP Panel. The obvious goal was to obtain quantitative information about aerosols and clouds and their effects on the radiative budget of the Earth's atmosphere.

The World Meteorological Organization (WMO) conducted an international Global Atmospheric Research Program (GARP) in the 1970s to obtain more comprehensive measurements of the troposphere and stratosphere for the overall purpose of improving general circulation and weather forecast models. Primary participants in addition to the U.S. were France, Great Britain, Japan, and the USSR, although scientists from about 20 nations were involved. The extensive BOMEX field experiment of the summer of 1969 was a precursor of the GARP Atlantic Tropical Experiment or GATE of 1974. Fleming and Cox [1974] of Colorado State University modeled the divergence of the net radiation in the presence of cirrus clouds in anticipation of the activities of GATE. They showed that the radiative budget at the surface of the Earth was most dependent on shortwave optical thicknesses of the clouds, while broadband emissivity was more important for their effects on the atmospheric heat budget. They verified the calculations with the aid of

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satellite photometry and cloud imagery obtained during BOMEX, plus some limited in situ and lidar measurements. William Shenk and Robert Curran of NASA Goddard had also begun to classify tropical cloud imagery, according to their broadband spectral signatures as seen with Medium Resolution Infrared Radiometer (MRIR) on Nimbus 3 during BOMEX [Shenk and Curran, 1973; Shenk et al., 1976]. They were able to discriminate between clear skies and cirrus cloud cover, using the MRIR radiances in the water vapor region of 6.5 to 7.0 µm. Their studies led to the inclusion of a Temperature-Humidity Infrared Radiometer (THIR) sensor on Nimbus 6 and 7 as an aid to interpreting the measurements from the Earth radiation budget (ERB) instruments that were also onboard [Stowe, 1984].

The Nimbus 7 spacecraft of 1978 carried the SAM II sensor from Langley. SAM II obtained measurements of stratospheric clouds as well as aerosols, but only for the high latitudes because of the limitation for viewing an occultation event of the rising or setting Sun from a high-inclination (98˚) polar orbit. The AEM-2 satellite of 1979 had an orbital inclination of only 56˚. Thus, its SAGE instrument obtained measurements of stratospheric particles across low and middle latitudes that were complementary to those of SAM II [Kent and McCormick, 1984]. In fact, the SAGE aerosol extinction measurements were also very useful for characterizing the dispersion of the volcanic layers from the eruption of Mt. St. Helens of 1980 [Deepak, 1982].

Prof. John Stanford of Iowa State University had been studying polar stratospheric clouds (PSCs), particularly their relationship with stratospheric water vapor and temperature [Stanford, 1973; Stanford, 1977; Douglass and Stanford, 1982]. The SAM II experiment gave new information on the distribution and occurrence of the PSCs, and the airborne 14-in lidar of Langley provided information on the phase of the cloud particles from measurements of their depolarization ratios [Kent et al., 1986]. The Nimbus 7 LIMS experiment also observed regions of enhanced infrared limb emission in Arctic winter, most likely from PSCs. Austin et al. [1986a] were able to partially corroborate that inference based on their calculations of ice saturation using co-located temperatures from the Stratospheric Sounding Unit (SSU) and water vapor profiles from LIMS. At that time the existence of PSCs was largely a curiosity. Information about PSCs was limited to model studies for their formation and of the microphysical growth and decay of their particles [Steele et al., 1983]. Until the mid 1980s it was still unclear whether or not PSCs contributed to a heterogeneous loss of ozone in polar springtime [e.g., McCormick and Trepte, 1986].

Nevertheless, the wealth of new data on PSCs, aerosols, and water vapor from SAM II, SAGE, and LIMS prompted Robert Watson and Robert Schiffer of NASA Headquarters to sponsor a Workshop on PSCs that was held in Virginia Beach, VA, in June 1983. Patrick Hamill of San Jose State University, Adarsh Deepak of IFAORS, and Leonard McMaster of Langley hosted the Workshop. They brought together a group of 20 experts, including James Pollack, Brian Toon, and Ed Danielsen of NASA Ames, James Hansen of NASA GISS, Andrew Heymsfield of NCAR, John DeLuisi and Dieter Kley of the NOAA Aeronomy Laboratory, and David Hofmann of University of Wyoming, among others. Attendees were grouped into two panels: Radiation

Balance, Climate and Dynamics (led by Hansen) and Stratospheric Chemistry, Water Vapor, and Cloud Microphysics (led by M. P. McCormick). Much of the discussion within each panel was focused on trying to understand the nature of the satellite, airborne, balloon-borne, and ground-based observations of the PSCs and their precursor species. Each group formulated a number of outstanding questions, as summarized in the PSC Workshop Report [Hamill and McMaster, 1984].   Their recommendations for further studies became the basis of research focused on PSCs, stratospheric aerosols, and heterogeneous chemical processes over the following decade, supported with funds from NASA's Upper Atmospheric Research Program.

5 Earth observations in the Space Shuttle era

(a) Changing priorities for satellite measurement technologies at Langley

Proposals were solicited by NASA as early as the mid 1970s for the design, assembly, and eventual demonstration of Shuttle-borne instruments for making improved observations of the Earth and its atmosphere. Many of the measurement concepts were an outgrowth of or reinforced by the RMOP Report and supported by funds from the AAFE Program. It was hoped that other Federal agencies or commercial interests might decide to underwrite the operational use of a prototype instrument upon its successful demonstration by NASA. For example, for the advancement of weather forecasting NASA had already formed a partnership with NOAA to improve the technology of the remote sensors for its weather satellites. Column ozone measurements were also demonstrated by NASA on Nimbus 4 and 7, and those prototype sensors became the basis of operational ozone measurements using a series of second-generation, Solar Backscatter Ultraviolet (SBUV 2) instruments beginning with the NOAA-9 spacecraft in 1985 and continuing through NOAA-N' of 2009. NASA also received a Congressional mandate to monitor atmospheric ozone as part of the Clean Air Act amendments of 1977. That monitoring activity began with the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7 in 1978 and continued on with similar satellite instruments on the Meteor 3 spacecraft of Russia in 1991 and on Earth Probe from a Pegasus launch in 1996. Total ozone is being measured today with the Ozone Monitoring Instrument (OMI) on EOS Aura that was put into orbit in 2004. The OMI instrument was constructed by the Netherlands for NASA and is a cooperative effort with Finland.

Space Transportation System (STS) is the formal name for NASA's Space Shuttle program, which was designed to ferry astronauts and instrument payloads to low Earth orbit (LEO). From the point of view of Earth observations STS was touted as an economical way to gather data with an engineering model of an instrument, return it to Earth, and then to improve the instrument and re-evaluate it on another flight. The period for that operational approach extended from the early 1980s to the mid 1990s, when the emphasis for the use of the Shuttle was changed toward the construction of the International Space Station (ISS). Since the Shuttle was launched from Cape Canaveral, it was not possible for an instrument to be tested from or inserted into the high-inclination (polar), Sun-synchronous orbits that were the norm for NOAA's TOVS and NASA's Nimbus satellites. On the other hand, the 57° inclination orbit of Space Shuttle was ideal for the launch of the ERBE and SAGE II instruments on the Earth Radiation Budget Satellite (ERBS) in 1984, for the launch of the Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite (UARS) in 1991, and for the demonstration of the Lidar In-space Technology Experiment (LITE) from the cargo bay of STS-64 in 1994. The focus of this section is on those four Earth observation experiments from Langley. Although this review of the experiments is necessarily very brief, the reader can easily access descriptions of their design and operations and of an extensive set of published scientific findings based on their measurements. Findings about the composition of the volcanic aerosols will also be noted later in this section, as deduced from flight observations on STS-45 in March 1992 of the Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument of C. Barney Farmer and Michael Gunson of JPL.

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In the early 1980s NASA and Langley changed their focus from studies of the urban to regional-scale pollution that was of interest to the EPA toward studies of long-range transport of aerosols and source gases and their consequences for climate and air quality on the global-scale. NASA concluded that its airborne campaigns should be more broadly supportive of the validation of satellite experiments and/or focused on obtaining a better understanding of specific atmospheric chemical, microphysical, and/or radiative processes [e.g., CCSP, 2009]. Thus, NASA shifted the emphasis of its Earth observation and applications programs toward the development of sensors that could operate from satellites or aircraft and provide data on the critical environmental issues of the current and coming decades. However, NASA also experienced cutbacks in the money that was available for the development and demonstration of new sensing concepts and improved technologies. Much of the success that was achieved from the mid 1980s and through the 1990s was a result of the funding that had been available through the AAFE Program in the 1970s and because of the urging of Morris Tepper and his three RMOP Panels.

During the Cortright era, Robert Hess and Frank Allario of Langley made the transition from plasma physics research and into the newly-formed ESSD headed by William Michaels. They and their colleagues, James Hoell and Glenn Sachse, began to develop gas lasers and solid state laser technologies for the remote sensing of the atmosphere. They also applied the laser heterodyne spectroscopy (LHS) technique for measurements of minor and trace gases from onboard aircraft. By 1982 much of their laser technology work was relocated to the Electronics Directorate, where Hess and his team became focused on the measurement of Doppler winds and gas species. Hess retired in 1995 after logging a distinguished, 50-year career [Hansen, 1995]. Allario had been Head of the Laser Physics and Applications Section, while he was in ESSD and AESD. In December 1982 he was selected as Chief of the Flight Electronics Division (FED), the new name for FID after 1976. Allario went on to lead the Electronics Directorate until his retirement in 1996. In all of those positions he advocated for opportunities to demonstrate active remote sensors from Space. Today, the members of the Laser Remote Sensing Branch of Langley's Engineering Directorate are continuing to refine and apply those technologies for the sensing of the atmosphere with an eye toward making measurements of atmospheric winds from a Space platform [e.g., Koch et al., 2007].

The current retrospective does not include an account of the early work on remote measurements of water quality. Those activities were de-emphasized at Langley in the early 1980s, in part due to the demonstrated success of the Coastal Zone Color Scanner (CZCS) experiment of NOAA/NASA Goddard (e.g., see Section 5 of Remsberg [2011]). The CZCS measurement concept was defined in the early 1970s and operated successfully on Nimbus 7 from 1978 to 1986, providing multi-spectral imagery similar to that from the MSS on Landsat but with improved S/N and with corrections for the intervening atmospheric aerosols above water surfaces [Hovis et al., 1980]. The Langley organizations of SATD and ESSD and their personnel were reformed initially in 1976 into two divisions focused on remote sensing studies of the atmospheric and marine environment, respectively—AESD headed by Lawrence and the Marine

Applications and Technology Division (MATD) headed by Brian Pritchard. However, by 1982 many of the researchers in MATD had been integrated into the atmospheric and radiation budget research activities within AESD. At about the same time McCormick's Branch (ARB) was moved to AESD from IRD. A Radiation Sciences Branch (RSB) was also formed under the leadership of Edwin Harrison. However, the satellite Earth observation programs were still managed from within Langley's Projects Office. AESD was becoming well-known as the Earth Science organization within Langley; it was renamed simply as the Atmospheric Sciences Division (ASD) in 1982.

All during the 1970s researchers in IRD and in FID/FED had been demonstrating their considerable expertise toward the application of microwave remote sensing techniques [Croswell, www.ieeeghn.org]. Linwood Jones and Calvin Swift conducted airborne measurements with a radar scatterometer funded by the AAFE Program in support of similar measurements of sea surface winds from Skylab [Jones et al., 1981]. Jones was a member of the Science Team for a Seasat-A Scatterometer System (SASS) that operated successfully for three months in 1978 on the Seasat-1 satellite managed by JPL [Born et al., 1979]. Another instrument on Seasat was a copy of the scanning multichannel microwave radiometer (SMMR) of NASA Goddard that was flown on Nimbus 7 later that same year. Nimbus 7 SMMR was very successful and obtained nearly 9 years of sea surface temperatures, sea ice coverage, sea-surface winds, column water vapor, and rainfall rates [Gloersen et al., 1984]. The Langley group also had competition from Charles Elachi of JPL, who was preparing his Shuttle Imaging Radar (SIR-A) for observations of the Earth's surface as part of an engineering flight of the Space Shuttle in November 1981 [Elachi et al., 1986]. Even so, the deletion of a proposed National Oceanic Satellite System (NOSS) [Ruttenberg, 1981] from the NASA/NOAA budget of FY 1982 was a key factor in the decision by Langley Director, Donald Hearth, to transition away from satellite microwave remote sensing activities. Funding was also reduced in the NASA/NOAA budget for any further development of the relevant microwave technologies. Langley funded a final study showing that it was feasible to transfer their current technologies to other Federal agencies and/or commercial users [Akey, 1981]. Croswell, Jones, and Swift left Langley shortly after and carried on with their successful careers in the private sector and/or academia.

(b) ERBE and SAGE II on the ERBS satellite of 1984

Dedicated measurements of Earth's radiation budget were begun with the ERB instruments on the polar orbiting satellites Nimbus 6 and 7, even though their measurements were taken at just two local times each day. Instead, Langley's ERBE instrument as launched on ERBS from the Space Shuttle Challenger (STS-41G) in 1984 was in a slowly precessing orbit. ERBE obtained measurements across most all local times in about 2 months and provided some information on the diurnally-varying effects of clouds. ERBE consisted of a scanner and a non-scanner radiometer package. The scanner package contained three scanning radiometers—a shortwave, a longwave, and a total radiometer. The nonscanner package consisted of two wide-field-of-view (WFOV) radiometers for measuring shortwave and total radiation and for viewing the entire Earth disc. ERBE also had two medium-field-of-view (MFOV) radiometers that observed over a

much smaller solid angle. The nonscanner also included a solar monitoring radiometer. Instrument packages identical to these were flown on the polar orbiters, NOAA-9 and NOAA-10, but with different Equator crossing times (0230 and 0730 LST, respectively). Barkstrom and Smith [1986] provides an excellent overview of the rationale for and initial results from ERBE.

Although Langley was assigned the responsibility for the Earth Radiation Budget Project (and ERBE) in 1978, the final experiment design was a melding of three separate proposals including one from Langley, another from Suomi of University of Wisconsin and a third proposal headed by Vonder Haar of Colorado State University [Yates, 1977]. Descriptions of the early developments that led to the ERBE concept can be found in Barkstrom and Hall [1982] and in more detail in Smith et al. [2010]. Several individuals at Langley were particularly important to the effort, including George Sweet, Bruce Barkstrom and the 17 members of his ERBE Science Team, Cal Broome and Charles Woerner (Project Managers), Jack Cooper (Experiment Manager), Glenn Taylor (Instrument Manager), Mike Luther and Leonard Kopia (Instrument Engineers), and James Kibler (Head, Data Management Team). Paul Holloway, Director for Space at the time, gave his full support to the effort. Harry Press, who earlier in his career was an aeronautical researcher at NACA Langley [e.g., Press and Houbolt, 1955], was Manager of the NASA Headquarters Meteorology Program Office in 1978 and located at NASA Goddard. In accordance with recommendations from an independent National Academy of Science Panel, Press made certain that the instrument package would meet the scientific requirements for obtaining improved measurements of Earth's radiation budget. The final selection was made by Morris Tepper, and shortly thereafter the core science effort at Langley was consolidated into Lawrence's AESD within the Radiation Sciences Branch, headed by Edwin Harrison.

The ERBE nonscanner operated for 15 years and the scanner for five. The ERBE datasets and the validation criteria for judging their acceptability can be found in Barkstrom et al. [1989]. Wielicki and Green [1989], Charlock and Ramanathan [1985], and Ramanathan et al. [1989] determined the effects of cloud radiative forcing on the radiation budget using the ERBE data. In fact, Harrison et al. [1990] found that clouds cool the Earth on the average and for all seasons. On the other hand, Prabhakara et al. [1993] used ERBE data to show that cirrus clouds are very effective in trapping the outgoing longwave radiation. ERBE also provided the first accurate diurnal variations of regional radiative parameters over the globe for climate studies, and its data represented a new "radiation standard" for validating and improving general circulation models and for the purpose of assessing model studies of climate sensitivity.

ERBS also carried aloft the Stratospheric Aerosol and Gas Experiment II (or SAGE II) [McCormick et al., 1989]. Note that SAGE I operations had ended in November 1981 due to the failure of its power systems. That meant that no occultation measurements had been obtained for the low and middle latitudes during the period directly following the eruption of El Chichon in April 1982. Principal Investigator, M. P. McCormick of Langley, knew that such a data gap in the aerosol record was a missed opportunity; he and his colleagues at Langley and at Ball Aerospace looked forward to continuing those measurements with SAGE II on ERBS. The

Science Team was expanded from that of SAGE I to include Derek Cunnold, Giorgio Fiocco, Motokazu Hirono, Ron Nagatani, Jacqueline Lenoble, David Murcray, and David Rind [McCormick, 1987]. As it turned out, SAGE II operated successfully from 1984 to 2005. SAGE II monitored the decay of the aerosol layer from several years after the El Chichon event and its approach to "background conditions" and then witnessed the immense eruption cloud from the Mt. Pinatubo volcano in June 1991 and its subsequent dispersal and implications for tracer transport [e.g., Pitari, 1993]. Joe Zawodny, Science Mission Manager at Langley for ERBS, noted recently that the 21-year record of aerosol data from SAGE II is almost as important as its record of ozone measurements. Early on, the SAGE I data of 1979-1981 and the SAGE II data 1984-1990 were used to generate a climatological distribution for the "background" stratospheric aerosols [Hitchman et al., 1994]. Further, the long time series of aerosol data from SAGE II, as described by Thomason and Peter [2006], is important for the assessments of climate models for the effects of volcanic aerosols on the global surface temperatures.

In the early 1980s the inability of stratospheric chemistry/transport models to properly simulate the wintertime abundance on nitric acid vapor (HNO_3), as measured by the Nimbus 7 LIMS experiment, led to the prospect that heterogeneous chemical reactions were converting NO_x to HNO_3 on surfaces of stratospheric aerosols [Austin et al. 1986b]. A co-author on that LIMS/model study, Susan Solomon of the NOAA Aeronomy Laboratory, became focused on the likelihood that heterogeneous chemical processes on surfaces of PSC particles were releasing chlorine radicals that were responsible for the catalytic loss of polar stratospheric ozone [Solomon et al., 1986]. The Airborne Antarctic Ozone Experiment (AAOE) campaign of 1987 obtained crucial measurements of ozone and chlorine monoxide (ClO) that essentially confirmed the hypothesis of Solomon et al. Upon this realization of the causes of the observed loss of polar ozone in springtime, it became clear that the measurements from SAM II and SAGE II could provide the critical time series data about aerosol surface area versus altitude and latitude for modeling the effects of those heterogeneous reactions [see Thomason and Peter, 2006, and references therein]. Although the aerosol extinction measurements of SAGE II were similar to those of SAGE I, the SAGE II instrument contained 4 aerosol channels (from 0.385 to 1 µm) for estimating aerosol concentrations and the size distribution parameters that were needed for the calculation of aerosol surface area. Extensive correlative measurements were conducted for those aerosol parameters [Russell and McCormick, 1989], in accord with the stated goal of Don Lawrence toward the attainment of more useful, quantitative information from the satellite-borne remote sensors.

The validity of the volcanic aerosol parameters from the SAGE II data was also evaluated by Glenn Yue, Lamont Poole, M. P. McCormick, Robert Veiga, and Pi Wang from Langley, at least for the 6-month period following the Pinatubo eruption [Yue et al., 1995]. They found good agreement between the SAGE II aerosol extinction profiles and the lidar profiles obtained by their colleagues in Italy. However, they also found that the observed ozone had become reduced somewhat from that at the altitude of the volcanic aerosol layer just prior to the eruption. Solomon et al. [1996] showed that such changes at the mid latitudes were also consistent with their model simulations that included a heterogeneous loss of ozone at middle latitudes. Thus,

while estimates of the stratospheric aerosol optical depth (AOD) were important for studies of the Earth's radiation budget, estimates of aerosol surface area were more important for understanding the effects of aerosols on ozone.

(c) HALOE on the UARS satellite of 1991

The HALOE instrument used a gas filter approach for the measurement of trace gas profiles in the stratosphere by solar occultation absorption [Russell et al., 1993]. The concept was proposed in 1975 and selected for development under the NASA Office of Applications AAFE Program in 1976. Its design phase was completed late in 1979. A brassboard model was constructed and tested in the laboratory and then from onboard flights of the high-altitude, Convair 990 aircraft in the early 1980s. Originally, it was hoped that HALOE might be ready in time to be considered for ERBS and its launch in 1984, but the readiness of the gas filter technology was not really clear until it was demonstrated in an initial flight of the Measurement of Air Pollution by Satellite (MAPS) instrument on an engineering flight of the Space Shuttle in November 1981. Nevertheless, HALOE had been selected for a flight opportunity on UARS that was scheduled for launch from the Space Shuttle in autumn 1989 [Reber et al., 1993]. Due to the tragic loss of the Shuttle Challenger in 1986, that opportunity was delayed until September 1991 or 16 years from the time of the initial HALOE proposal. Even so, HALOE went on to operate nearly flawlessly from 1991 to November 2005—a significant tribute to James Russell III, HALOE Principal Investigator of Langley. He was assisted by a dedicated team of engineers and technicians, initially at TRW Corporation and then within Langley and by a number of software specialists plus the members of his HALOE Science Team. Project management for HALOE was handled by James Raper, Dewey Smith, Thomas Jones, Lloyd Keafer, and Edward Sullivan. Engineering design and testing was led by Antony Jalink, Robert Spiers, Charley Stump, Alvin Moore, and Donald Hesketh, while Larry Gordley (GATS, Inc.), Jae Park, and Lance Deaver led the software development. Edward Sullivan, John Wells, and Warren Hypes were involved with the HALOE instrument operations and the sets of correlative measurements for the assessment of the quality of the HALOE data, particularly during its initial 3-yr period. Al Beswick, Gale Harvey, Curtis Rinsland, and Mary Ann Smith of Langley and Chris Benner and Malathy Devi of The College of William and Mary conducted and analyzed the important spectroscopic measurements of the HALOE instrument prior to flight, as well as during the development of the forward model of the HALOE retrieval algorithm.

The HALOE instrument included gas filter channels for four trace gases (HCl, HF, CH_4, and NO), plus four radiometer channels for O_3, H_2O, CO_2, and NO_2. Mark Hervig (GATS, Inc.) led the development of an algorithm for the retrieval of aerosol extinction profiles from the four additional radiometer channels that were in tandem with the gas filter channels. The extinction profiles that he obtained were evaluated against co-located aerosol measurements from SAGE II and from balloon-borne optical particle counters of Terry Deshler at the University of Wyoming [Hervig and Deshler, 2002]. Measurements of aerosol extinction at mid infrared wavelengths can be related most directly to their mass density profiles, although Hervig supplied estimates of their surface area density profiles, too.

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From 1991 through 1992 the aerosol extinction profiles from HALOE were enhanced because of the volcanic layers from the eruption of Mt. Pinatubo. Aerosol extinction effects were more noticeable for those UARS experiments that operated in the infrared limb emission mode, i.e., the Cryogenic Limb Array Etalon Spectrometer (CLAES) and the Improved Stratospheric and Mesospheric Sounder (ISAMS). In fact, Eluszkiewicz et al. [1997] diagnosed the effects of the volcanic aerosols from the CLAES data on the diabatic heating rates and the net circulation of the stratosphere. Aerosol extinction profiles from the visible wavelengths of SAGE II were affected, too, and for many more months. Grainger et al. [1993] reported good agreement from their analyses of infrared emission from the spectral channels of the UARS ISAMS instrument, using optical constants for concentrated aqueous sulfuric acid for the aerosols. Halperin and Murcray [1987] came to similar conclusions from earlier analyses of mid infrared spectra of the El Chichon aerosol layer that they obtained from their balloon-borne infrared limb spectrometer.

(d) ATMOS on the Space Shuttle

The Atmospheric Trace Molecule Spectroscopy (ATMOS) Fourier transform spectrometer of Barney Farmer of JPL was flown four different times on the Space Shuttle—in 1985, 1992, 1993, and 1994. James Russell was a scientific collaborator for ATMOS on its initial flight in 1985. He focused on an assessment of its retrieved profiles of the nitrogen oxide gases in the stratosphere [Russell et al., 1988]. The second flight of ATMOS occurred from March 24 to April 2, 1992, or 9 months following the eruption of Mt. Pinatubo. Curtis Rinsland of Langley analyzed the broad underlying variations in the ATMOS transmission spectra at mid infrared wavelengths for extinction due to aerosols composed of sulfate material [Rinsland et al., 1994]. Their forward model for the aerosol extinction was based on aerosol size distributions estimated from concurrent SAGE II measurements and also using refractive indices (real and imaginary components) appropriate for concentrated aqueous sulfuric acid. They reported reasonably good agreement between their model and the spectral variations of the observed transmission measurements from ATMOS. The findings from the ATMOS data and from the UARS ISAMS data are quite in line with the early conclusion of Rosen [1971] that the boiling point of stratospheric aerosols is consistent with that of a concentrated solution of aqueous sulfuric acid.

(e) The Lidar In-space Technology Experiment (LITE)

Cirrus clouds were identified as a major unsolved component in weather and climate studies by Bretherton and Suomi [1983] in their proposed plan for an International Satellite Cloud Climatology Project (or ISCCP). In response, Thomas et al. [1990] of the University College of Wales used their ground-based, doubled Nd/YAG lidar system for determining the polarizing character of cirrus cloud crystals. At about the same time Ed Eloranta and colleagues at the University of Wisconsin upgraded their HSRL instrument that had been initially supported with funds from the AAFE Program. As a result of their increased transmitter power with a CuCl laser and of their modifications to the configuration of the system receiver, the Wisconsin group

was able to obtain stronger backscatter returns and more details about cirrus particles from their measurements, too [Grund and Eloranta, 1991]. The field programs associated with the First ISCCP Regional Experiment (or FIRE), managed by Scott Wagner and David McDougal of Langley, provided information about the scattering and radiative properties of the cloud particles and was very helpful for the interpretation of the spectral imagery from the satellite sensors [e.g., McDougal, 1993; Cox et al., 1987; Winker and Vaughan, 1987].

As indicated in Section 3b, the development of lidar technologies was continuing to thrive under the leadership of M. Patrick McCormick and Ed Browell, among many others, and at the urging of Lawrence. McCormick used his 14-inch ruby lidar in field programs designed to corroborate the aerosol measurements from SAM II and SAGE II. He also led the deployment of several airborne in situ sensors for the purpose of characterizing the scattering properties of the aerosol particles. Ed Browell led Langley's participation in a number of dedicated airborne field measurement campaigns for ozone and water vapor with his DIAL instruments, which also provided important information about the aerosol backscatter profiles in the troposphere and lowermost stratosphere [Browell et al., 1998]. Browell was ably assisted during this period by Scott Shipley, Syed Ismail, William Grant, Carolyn Butler, Susan Kooi, Marta Fenn, Robert Allen, and Arlen Carter.

In 1985 Langley researchers carried out design studies for a spaceborne lidar demonstration experiment, using hardware similar to that of the airborne 14-inch lidar of McCormick and Fuller. A science steering group submitted a proposal for an instrument called LITE in May 1990 [McCormick et al., 1993], and LITE became a payload on the flight of STS-64 on September 9, 1994. The LITE experiment team acquired 53 hours of backscatter data, and the detail from the sequences of the orbital backscatter profiles that they were able to see was quite astounding. Thus, the relatively simple, LITE experiment provided new information about tropospheric aerosols in the boundary layer and above, plus information about the vertical structure and continuity of thin cirrus clouds near the tropopause [Winker et al., 1996]. Such detail would allow for improved estimates of the effects of aerosols and clouds on the transfer of radiation throughout the troposphere. Data of this kind were what Suomi and Bretherton were hoping to obtain, when they put forth in their vision of 1983 that such quantitative information would be important to have. It was also the culmination of what Lawrence hoped to see from a spaceborne lidar mission. All through his time at Langley from 1967 until his retirement from NASA in 1994, Lawrence had promoted the lidar research activities with an eye toward the achievement of the successful operations of LITE from the Space Shuttle.

6 The era of NASA's Earth Observing System (EOS)

(a) Toward studies of global climate science

This section contains a brief review of NASA's EOS program and places it in the context of the Earth observation activities of the international community. Because of their proven capabilities of making satellite measurements of Earth's radiation budget with ERBE and of atmospheric aerosols with SAGE II and LITE, Langley's engineering and atmospheric science teams were well positioned to apply their knowledge to the growing research field of global climate change. Three satellite instruments from Langley will be emphasized and discussed in turn in the next subsections: Clouds and the Earth's Radiant Energy System (CERES), SAGE III, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). Then a following subsection will describe how their measurements are complementary with those of the other EOS instruments and from the satellite observing systems of the international community.

Conway [2007] devotes two entire chapters to the fitful beginnings of EOS in his historical account of NASA's atmospheric science programs. He notes that the initial planning for a U. S. climate observing system got underway in 1977, following closely on the earlier SMIC and RMOP reports. Verner Suomi urged once again that NASA and NOAA coordinate their planning for global climate observations. However, the necessary funding for NOAA to move ahead with its plan was cut back sharply in the early 1980s, along with their participation in the development of the necessary measurements and the transfer of new technologies from NASA. Still, NASA continued with developing improved satellite Earth observation techniques but at a much slower pace. It was nearly ten years later in 1988 that NASA issued an Announcement of Opportunity (AO) for instrument proposals, science teams, and interdisciplinary investigation teams for EOS.

An EOS Handbook provides the historical perspective and time line of activities within the EOS Program [Parkinson et al., 2006]. NASA's initial vision for EOS was to conduct 15 years of Earth observations from sets of three successive satellites, each one having a complement of identical instruments. Payload instruments were selected in 1989, based in large part on the technologies that were an outgrowth of AAFE. The WMO also hosted a meeting in 1988 on global climate change, which led to the creation of the first IPCC Panel. Thus, it soon became clear that the international community would be embarking on its own satellite programs for monitoring Earth and its atmosphere. As the cost of the U. S. EOS initiative grew larger in the 1990s, the NASA vision was scaled back to just three distinct satellite Earth observation platforms. Each of the eventual platforms, Terra, Aqua, and Aura, had a different overall scientific objective, and the requirement was scrapped for each of them to have two follow-on satellite platforms with identical instruments and spaced over intervals of five years. Instead, it was decided that it would be more appropriate to collaborate with our international colleagues and to promote a mutual exchange of datasets.

It was also realized that it may not have been a good idea to keep fixed the measurement technologies and data processing systems for an entire 15-yr monitoring period. As part of NASA's Mission to Planet Earth (MTPE) initiative of 1993, lead NASA Center roles were assigned to Goddard (Earth System Science), Langley (Atmospheric Science), JPL (Instrument Technology), and Stennis (Commercial Remote Sensing). Programs were also re-established in the mid-1990s for the development of advanced technologies for making observations from Space—reminiscent of the foregoing AAFE program. Those technology programs included the New Millenium Program (NMP), the Instrument Incubator Program (IIP), and the Earth System Science Pathfinder (ESSP) Program of the NASA Headquarters Science Mission Directorate (SMD); today their Program Offices are located at JPL, Goddard, and Langley, respectively. The NASA EOS Program also brought about a change in philosophy in the management of the experiments that would be selected. Two classes of instruments were considered: Facility instruments, such as Moderate-resolution imaging spectroradiometer (MODIS) [King et al., 2003] on Terra and the Atmospheric Infrared Sounder (AIRS) on Aqua, and PI-led instruments, such as the Multi-angle Imaging Spectro-Radiometer (MISR) [Diner et al., 1999]. Initial data retrieval algorithms would have to be made available prior to flight and documented in Algorithm Theoretical Basis Documents (ATBD), and the data products would be provided to the science community via an EOS Data and Information System (or EOSDIS). Effectively, this requirement meant that in order for a given experiment to be selected, its measurement concept must have a certain established heritage. Langley had that capability with ERBE and SAGE II.

Significant personnel changes occurred in ASD at Langley in the mid 1990s, following the retirement of Lawrence. McCormick was moving ahead at that time with his new satellite instruments, SAGE III, and another lidar, CALIPSO. Russell was developing Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), an experiment supported by the NASA's Office of Space Sciences (OSS). However, they did not have an experiment on one of the three primary EOS platforms. They decided to take their retirement from NASA in 1996 and enlarge their opportunities at nearby Hampton University (HU), where they founded its Center for the Atmospheric Sciences (CAS). They also continued with their respective Principal Investigator roles for SAGE II and HALOE. Robert Seals, who had worked earlier in the Upper Atmosphere Program Office of Shelby Tilford at NASA Headquarters, served as an interim Chief directly after Lawrence. Seals had been involved with the UARS Upper Atmosphere Data Pilot in support of Tilford and later with the Atmospheric Effects of Aviation Program (AEAP) of Howard Wesoky in the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. But Seals would soon move to assist Roy Dunkum in managing the EOS Distributed Active Archive Center (DAAC) at Langley. Darrell Branscome then appointed Jerry Newsom to be the Acting Chief of ASD until William Smith, Sr., of the University of Wisconsin and its Cooperative Institute for Meteorological Satellite Studies (CIMSS) took the helm in 1997. Smith was already integrally involved with developing improved satellite sounders for both the EOS and the next-generation, polar and geostationary satellites for NOAA. Of course, he had been an important player in the design of the radiation budget sensors and the interpretation of their measurements from Nimbus 6 and 7 and from ERBS. He was also very supportive of the impending launch of CERES on the Tropical Rainfall Measurement Mission (TRMM) satellite.

Up and coming researchers began to assume leadership roles for the several experiments proposed by Langley for EOS. For example, although the CERES experiment was led initially by Bruce Barkstrom, that role was handed off to Bruce Wielicki in 1996 and then to Norman Loeb in 2007. Barkstrom became involved at that time with helping to streamline the operations and to reduce the costs of NASA's immense EOSDIS. Another atmospheric scientist, Patrick Minnis, had been working with Edwin Harrison in the early 1980s to estimate the role of diurnally-varying clouds in the interpretation of the radiation budget measurements from ERBE [Minnis and Harrison, 1984]. Later, he and David Young verified those estimates using the data from ERBE plus spectral radiance measurements from the AVHRR sensors on the NOAA GOES satellites. As an aside, Minnis received early training in the atmospheric sciences at Colorado State University from Professor Steven Cox, who had been a graduate student of Verner Suomi at the same time as Thomas Vonder Haar. In the late 1980s Minnis commenced working for his Doctoral Degree under the guidance of Prof. K.N. Liou at the University of Utah, where they became focused on the inference of cirrus cloud properties from satellite-observed visible and infrared radiances. That work led later to his studies of the effects of contrails from aircraft and their transformation to cirrus particles [Minnis et al., 1998]. Charles Whitlock, Thomas Charlock, and later Paul Stackhouse (from Colorado State) led a team of researchers focused on the surface and atmospheric radiation budget (SARB), an important component of the Earth radiation budget and an expected by-product of the upcoming measurements from CERES. Stackhouse also began to assemble the short-wave datasets and to analyze them for their seasonal and regional differences and for their solar energy potential.

Lamont Poole of McCormick's ARB returned to graduate school at the University of Arizona, where Sean Twomey and RMOP Panelist Benjamin Herman were faculty members. Poole conducted theoretical and analytical studies to determine the probable composition and sizes of the PSC-type particles from measurements of their depolarization ratios of the return signals from his airborne lidar system [Poole et al. 1988]. David Winker, a lidar specialist, worked with Poole and Mary Osborn (Hughes STX) to conduct similar airborne lidar studies of the Pinatubo aerosols in 1991. Winker then served as Deputy Project Scientist for the LITE experiment, and went on to be the Principal Investigator for CALIPSO. Mike Pitts and Charles (Chip) Trepte were graduate students in the early 1980s at Georgia Tech under the guidance of Derek Cunnold (SAGE II Science Team Member). They came to Langley to provide validation support for the SAGE datasets on ozone and aerosols at that time. Trepte attended the University of Wisconsin and was awarded his doctoral degree in the early 1990s under the guidance of Professor Matthew Hitchman. Together, they analyzed time series of the stratosphere aerosol distributions from SAGE II and found that the tracer-like characteristics of the aerosol layer revealed the effects of the tropical quasi-biennial oscillation. Trepte and Pitts would later assume leading roles in the processing and scientific use of the cloud and aerosol data from CALIPSO.

Marty Mlynczak, who received his M. S. degree under the guidance of Verner Suomi in 1984, began his career at Langley as a member of the HALOE Project. He obtained his doctoral degree from the University of Michigan in 1989 on the topic of non-local thermodynamic effects

(NLTE) and retrieval algorithms for mesospheric ozone. Upon James Russell's move to HU in 1996, Marty retained his role as Associate Principal Investigator for SABER and continued in that role through its launch in late 2001 and beyond. In 1996 John Wells and Ellis Remsberg carried on with the responsibilities for the ongoing HALOE Project in coordination with Russell. Joseph Zawodny, who came to Langley in 1988 from the NOAA Aeronomy Lab, served as Project Scientist for SAGE II from 1996-2005. Larry Thomason came to Langley in 1989 from the Air Force Geophysics Laboratories and from the University of Arizona before that, where he worked with Professors John Reagan and Benjamin Herman. Thomason subsequently led a study of the long-term changes in the stratospheric aerosol layer, based primarily on the measurements from SAGE II [Thomason et al., 2008]. William Chu, an original member of the SAGE II experiment team, became Project Scientist for the EOS experiment SAGE III that was launched onboard the Russian Meteor 3M spacecraft late in 2001. David Flittner, Didier Rault, Pitts, Poole, Thomason, and Trepte were important contributors to the SAGE III Project, as well. Leonard McMaster, who had been the Assistant Head of McCormick's ARB for many years, advanced to serve as the Chief of the Atmospheric Sciences Division from 2001 to 2006. Lelia Vann returned to the University of Arizona and was awarded her doctoral degree in atmospheric science in 2003. She was nominated to succeed McMaster in 2006 and is Chief of the current Science Directorate (SD) at Langley.

New ground-based and airborne lidar systems were being developed during this period for the purpose of making more detailed measurements of aerosols and clouds. Rich Ferrare came to Langley from Goddard, where he had been working with former RMOP Panel member, Harvey Melfi. Rich has conducted lidar measurements at the Department of Energy's Atmospheric Radiation Measurement (ARM) site in Oklahoma, as well as in numerous other field programs. Chris Hostetler, of the University of Illinois (faculty advisor, Chester Gardner) and Jonathan Hair, of Colorado State University (faculty advisor, Joe She) were hired at Langley in the middle to late 1990s, whereupon they undertook the development of a new-generation HSRL system. Ferrare, Hostetler, and Hair are demonstrating the technologies that will be critical to the measurement strategies for aerosols and clouds and their effects on the radiation budget and climate in the coming decades (see Section 7).

(b) CERES

The optimal orbits for making the necessary spatial and time-resolved measurements of Earth's radiation budget were determined from simulation studies carried out primarily by Edwin Harrison and Gary Gibson [Harrison et al., 1990]. In fact, Harrison's group conducted orbital analyses for the trade studies of many of the instruments proposed for EOS. In particular, CERES was an investigation to examine the role of cloud/radiation feedbacks for the Earth's climate system [Wielicki et al., 1996]. The CERES investigators planned to incorporate the simultaneous cloud property data derived using the EOS narrowband imagers and profilers, MODIS and AIRS, to provide a consistent set of cloud/radiation datasets, including SW and LW radiative fluxes at the surface and at several selected levels within the atmosphere.

Excellent summaries of the Earth radiation budget studies at Langley prior to CERES, plus a description of the series of CERES instruments that have been flown so far can be found in Smith et al. [2010] and Smith et al. [2011]. The proto-flight model of the CERES instrument was flown in 1997 on the TRMM spacecraft, which was in a precessing orbit with an inclination of 35˚, at an altitude of 350 km, and having a footprint size at the ground of 10 km. That first instrument operated successfully for 9 months, after which it was turned off because of problems with the TRMM power supply. Two more CERES instruments began their operations from the Terra spacecraft in early 2000, and another pair of instruments would obtain measurements from onboard the Aqua spacecraft to be launched in 2002. All along, a major goal of CERES has been to measure the Earth's radiation budget more accurately and over a period of at least at decade for the purpose of verifying the variations of Earth's radiation budget, as predicted by climate models on both the regional and global scales. That effort includes the critical interannual variations in the global net radiation and their relation to El Nino/Southern Oscillation (ENSO) events. Loeb et al. [2006] made use of data from both MODIS and MISR for improving the angular distribution models (ADM) that they employed for analyzing the TOA radiative flux measurements from CERES. Sun et al. [2004] developed additional ADMs based on the Polarization and Directionality of the Earth's Reflectance (POLDER) measurements [Deschamps et al., 1994] on the Japanese ADEOS satellite, in order to characterize the phase function of ice particles and the effects of cirrus on the measured reflectivity at TOA. Over the years the various CERES sub-teams have worked to bring about a fusion of data from across 11 instruments on 7 spacecraft, in order to obtain the first long-term, integrated observations of the broadband, surface-to-TOA values of Earth's radiation budget.

(c) SAGE III

SAGE III was a NASA EOS instrument launched into a Sun-synchronous orbit aboard the Russian Meteor 3M spacecraft in December 2001. Its measurement heritage follows that of the earlier SAM II and SAGE experiments. The SAGE III instrument had a total of nine aerosol channels with center wavelengths from 384 nm to 1545 nm and using charge-coupled device (CCD) detector arrays to improve their measurement S/N [Chu et al., 2002]. Aerosol profile measurements were obtained from February 2002 through March 2006. They were made mainly at the higher latitudes, where chemical processes on surfaces of aerosols and PSCs led to an enhanced loss of polar ozone during winter/spring. SAGE III was also an early example of the international cooperation that has been part of the overall success of NASA's EOS Program.

The quality of the SAGE III aerosol data was verified initially by comparisons with those from SAGE II [Thomason and Taha, 2003; Yue et al., 2005] and from the Polar Ozone and Aerosol Measurement (POAM) satellite instrument [Thomason et al., 2007]. Comparisons were also conducted as part of a dedicated NASA airborne campaign, entitled SAGE III Ozone Loss and Validation Experiment (or SOLVE II). In particular, Russell et al. [2005] found reasonably good agreement between the aerosol optical depth measurements from SAGE III and from their airborne sun photometer during SOLVE II. Later, Thomason et al. [2010] reported better

accuracies for the SAGE III aerosol extinction profiles based on an improved, Version 4 algorithm.

(d) CALIPSO

Immediately following the LITE mission of 1994, design studies were begun at Langley for a free-flying, spaceborne lidar. The basic instrument system was kept fairly simple and closely related to that of LITE. A proposal was submitted to the NASA ESSP program in May 1998, and it was selected for funding in December. This lidar experiment is a combined effort between the U. S. and France, entitled Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (or CALIPSO) [Winker et al., 2003]. CALIPSO was launched in late April 2006 and began its continuous backscatter measurements by mid June. CALIPSO is in flight formation as part of EOS Aqua and its A-Train constellation of satellites and is still operational in 2012—a major achievement. CALIPSO, along with its companion cloud radar on CloudSat [Stephens et al., 2002], is providing a multi-year global view of the vertical structure of aerosols and clouds that is crucial to determining their role in the climate system [Winker et al., 2010]. The CALIPSO payload consists of a two-wavelength polarization lidar system from Ball Aerospace and Technologies Corporation (BATC) for the determination of optical and microphysical properties of aerosols and cloud layers in the troposphere. The excellent performance for the two flight lasers can be traced to the 3-year life test that was carried out from 1998 to 2001 with a space-qualified, prototype laser—the so-called risk reduction laser or RRL [Winker et al., 2003]. The CALIPSO experiment also includes a visible, wide field camera (WFC) and the imaging infrared radiometer (IIR), both supplied by the French Space Agency (CNES). Together, the data from the three instruments are being used to identify aerosols and cloud layers and their reflective and absorbing properties [Winker et al., 2009].

An important design study by Langley was focused on how to maintain and properly characterize the polarized signals at the CALIPSO system receiver [Alvarez et al., 2006]. Then, Hu [2007] developed an algorithm for delineating the phase of the water in cloud particles, based on the linear polarization measurements obtained with the lidar system. In another application the tropospheric returns from CALIPSO have been used to characterize dust aerosols in remote regions of the globe, where they have not been sampled well by any other means [Huang et al., 2007]. Numerous other research groups are making use of the CALIPSO datasets. In fact, there are already more than 500 publications and/or presentations related to the CALIPSO experiment or that rely on its datasets (see http://www-calipso.larc.nasa.gov).

(e) Complementary measurements within EOS and from the international community

Other EOS instruments are also focused on clouds and the radiation budget. For instance, information from MODIS on Terra and Aqua is being used to help with the interpretation of the CERES data, and the MISR instrument on Terra is providing information about cloud height [Davies and Molloy, 2012]. Geostationary Earth radiation budget (GERB) data from Europe's

Meteosat Second Generation (MSG) satellite are being combined with the radiances from its companion instrument, Spinning Enhanced Visible and Infrared Imager (SEVIRI), which provides information on cloud particle phase and size [Sandford et al., 2003; Bugliaro et al., 2011; Dammann et al., 2002]. In addition, the SABER instrument of Langley is providing information on the energetics and radiative budgets of the mesosphere and lower thermosphere and their variations in response to the changes of the solar cycle [Mlynczak, 1997; Mlynczak et al., 2010].

Another satellite in the EOS A-Train formation is PARASOL, carrying the French instrument POLDER for obtaining polarization measurements of aerosols and their Stokes parameters. In many respects the MISR and POLDER measurements of tropospheric aerosols are complementary to those from CALIPSO. Stratospheric aerosols and PSCs were observed by the series of Polar Ozone and Aerosol Measurement (POAM) instruments of the Naval Research Laboratories (NRL) [e.g., Fromm et al., 1999], by the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on ENVISAT [Valhellemont et al., 2005], from the Atmospheric Chemistry Experiment (ACE) on the Canadian SciSat [Bernath et al., 2005], and with the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) experiment on ENVISAT [Ovigneur et al., 2011]. Stratospheric aerosol measurements were also obtained from the Optical Spectrograph and InfraRed Imaging System (OSIRIS) on the Swedish satellite Odin and were used in an intercomparison study of similar products from SAGE III [Bourassa et al., 2012]. Finally, the Solar Occultation for Ice Experiment (SOFIE) must be mentioned, in part because it has its heritage from the HALOE Project at Langley [Gordley et al., 2009]. SOFIE was launched on the Aeronomy of Ice in the Mesosphere (AIM) satellite in 2007. The AIM Project is led by James Russell at nearby Hampton University, and SOFIE is still operating successfully today. Its measurements are being used to characterize and explain the occurrence and persistence of the polar mesospheric clouds that occur in summer at the high latitudes.

Although the measurement technologies for the EOS instruments were mature when they were selected in the early 1990s for a flight opportunity, it is important to recognize that their algorithms were still undergoing improvements post-launch. Once their initial data were evaluated, improved versions of those datasets were generated for the wider benefit of the atmospheric research community. One might say that the EOS experiments have really been providing research datasets because their information content is still being assessed by the atmospheric scientists as they study the data. The wisdom of the proponents of the EOS program is evident from the fact that the datasets from the multiple instruments have been truly complementary for a more complete assessment of the role of clouds and aerosols on Earth's radiation budget and for those processes that affect the climate. There has also been redundancy for the measurements from some of the instruments, such that one can directly compare their joint findings and obtain a better idea of their mutual uncertainties. That insight has been important especially for the design of the next-generation, operational remote sensors onboard the renamed, Suomi NPP (or National Polar-orbiting Partnership) satellite that was launched by NASA on behalf of NOAA in November 2011.

7 Present-day, satellite remote sensing of Earth's radiative budget and aerosols

(a) NASA's Decadal Survey Plan and responses from Langley

NASA is now following the recommendations found in the National Research Council's Decadal-Scale blueprint for the Earth Sciences [NRC, 2007]. In effect, the vision of the NRC Report builds on the accomplishments since RMOP and EOS but urges that the U. S. government reinvest in new Earth observing systems. The Report notes alarmingly that future plans for Earth observations and for the follow-on, operational Joint Polar Satellite System (JPSS) "are generally less capable than their Earth Observing System (EOS) counterparts". The NRC panel did not prioritize the recommended Earth Science measurements but simply placed the various instrument concepts into Tier 1, 2, or 3 categories, according to their demonstrated technical readiness levels (TRL).

Following the issuance of the NRC Report, NASA and NOAA restored the Ozone Mapping and Profiling Suite (OMPS) onto the Suomi NPP that was launched in November 2011. Didier Rault of LaRC and Robert Loughman of Hampton University are using their limb-scatter algorithm for obtaining the aerosol profiles for the retrieval of lower stratospheric ozone from OMPS [Rault and Loughman, 2007]. A copy of the CERES instrument is also aboard Suomi NPP. Initial results indicate that it is working well, according to CERES Instrument Scientist, Kory Priestley of Langley. In addition, William Smith of Hampton University and Daniel Zhou, Allen Larar, and Xu Liu at Langley have shown that one can obtain very high resolution, surface spectral emissivities (SSE) from the Infrared Atmospheric Sounding Interferometer (IASI) aboard the European Metop-A satellite, and they are able to clearly distinguish the variations in the land skin temperature from those of the surface emissivity [Zhou et al., 2011]. Such information is important for determining variations in the forcings on the surface boundary layer within operational forecast models. Zhou and colleagues are currently applying their algorithms to the radiances from the Cross-track Infrared Sounder (CrIS) instrument of Suomi NPP.

The reader should bear in mind that the members of the NRC panel anticipated that both the Orbiting Carbon Observatory (OCO) satellite of JPL and the Glory satellite of NASA GSFC/GISS would be launched and operated successfully, prior to the full implementation of their blueprint. Unfortunately, both missions failed to achieve orbit—OCO in 2009 and Glory in 2011; they are being rescheduled for second flight opportunities in the near future but at the cost of delaying some of the goals of the original NRC report. The payload for Glory includes an Aerosol Polarimetry Sensor (APS), a high-spatial resolution cloud camera, and a Total Irradiance Monitor (TIM). The combined measurements of Glory are intended to characterize the microphysical and optical properties of aerosols over a range of surface and atmospheric conditions [Mishchenko et al., 2004].

The NRC Report recommended providing at least two new satellite opportunities related to the observed climatic effects of gases, clouds, and aerosols: (1) a Tier 1, Climate Absolute Radiance

and Refractivity Observatory (CLARREO) mission of low cost for tracking regional changes in the outgoing radiance with an absolute, spectrally-resolved interferometer and (2) a Tier 2 Aerosol/Cloud/Ecosystems (ACE) mission of higher cost, consisting of a backscatter lidar, a multi-angle polarimeter, and a Doppler radar focused on studies of the radiative effects of aerosols and clouds. Candidate instruments were proposed by Langley for those mission opportunities, and they are introduced briefly in this subsection.

The importance of having accurate spectral radiance measurements from CLARREO was demonstrated by Harries et al. [2001], using measurements from 1996 of the Interferometric Monitor of Greenhouse gases (IMG) instrument on board the Japanese ADEOS satellite and their comparisons with measurements from the Infrared Interferometric Spectrometer (IRIS) on Nimbus 4 taken some 27 years earlier. Harries et al. [2001] detected variations in the outgoing longwave radiation at specific wavelengths, and related them to the changes in the greenhouse gases over that time span. The measurement and calibration requirements for conducting a more dedicated, joint NOAA/NASA climate monitoring mission are outlined in Ohring et al. [2005]. The concept of CLARREO that was highlighted in the NRC Report is an outgrowth of that study, and Bruce Wielicki and David Young of Langley have proposed a set of instruments for the mission based on their experience with CERES. Of particular importance is the fact that they would measure for the first time the spectral variations of the outgoing radiance from Space across the far infrared region of 15 to 50 µm. Outgoing radiance in that spectral region is sensitive to emissions from cirrus clouds and from atmospheric water vapor [Kratz et al., 2005]. A balloon-borne, far infrared instrument entitled Far-InfraRed Spectroscopy of the Troposphere (FIRST) was developed by Langley under the NASA IIP. Initial measurements were made by Marty Mlynczak and colleagues from high altitudes in a demonstration of FIRST [Mlynczak et al., 2005]. However, due to funding constraints the CLARREO mission has been dropped from the current NASA budget projection as a Tier 1 mission and is undergoing further study. Hopefully, a climate monitoring mission of this general design will be restored in the near future.

Ramanathan et al. [2001] argued that human activities are releasing tiny particles into the atmosphere and that these aerosols enhance scattering and absorption of solar radiation. Such particles may also produce brighter clouds that are less efficient at releasing precipitation and that increase the solar heating of the atmosphere. The IPCC Report [2007] emphasizes that these direct and indirect aerosol forcing effects are complex and represent a major uncertainty for the understanding and prediction of global climate change. Such is the goal of the Tier 2 ACE mission concept. A new-generation, airborne HSRL (lidar) instrument [Hair et al., 2008] has been proposed by Langley in support of ACE. HSRL has been used successfully to obtain datasets on aerosol extinction, aerosol optical thickness, aerosol backscatter, and depolarization ratios as part of 18 separate field missions over North America since 2006 (see also Burton et al. [2012]). For several of those field campaigns the HSRL instrument was flown along with the research scanning polarimeter (RSP) of Brian Cairns of NASA GISS—the RSP is a prototype for the measurements to be obtained with Glory. The HSRL and RSP prototype instruments represent a candidate payload for the Tier 2 ACE satellite mission called for in the NRC Report.

Recently, NASA has also been considering instruments for scientific operations from onboard the International Space Station (ISS). In fact, following the launch of SAGE III on the Russian Meteor-3M spacecraft in 2001, Langley and Ball Aerospace and Technologies Corporation built a second instrument with the hope that it could be attached to the ISS in 2005. However, that opportunity was put on hold due to a change in the design of ISS, so the copy of the SAGE III instrument was stored in a Clean Room at Langley. After the assembly of the ISS was complete and upon the retirement of the Space Shuttle vehicle, NASA renewed solicitations for instrument payloads that might be easily accommodated and operated from onboard the ISS. Joe Zawodny and Patrick McCormick proposed to upgrade and re-calibrate SAGE III for ISS, in order to restart the long time series of measurements of aerosols and ozone of the low and middle latitudes that they had obtained earlier with SAGE II. In support of that goal, Vernier et al. [2009] had already extended the SAGE II time series of aerosols with the aid of the measurements from CALIPSO, at least since mid 2006. Soon thereafter, Solomon et al. [2011] reported that the variations of the near-background, stratospheric aerosol layer can explain the observed reductions in the expected rate of increase in global surface temperatures due to the greenhouse gases. Thus, keeping track of the changes for the stratospheric aerosols is critical to an understanding of the global surface climate, too. In early 2012 the efforts of Langley to put a copy of SAGE III on ISS were approved to proceed on to Phase B instrument development and testing. The refurbished SAGE III instrument is tentatively scheduled to be ferried from the Kennedy Space Center into low Earth orbit by late 2014 and attached by astronauts to the ISS.

(b) Recent scientific imperatives

Many of the original atmospheric concerns of the SMIC and RMOP reports about the effects of clouds and aerosols have been answered by the research community, at least qualitatively, in the years that have followed. Yet as if often the case, new and more quantitative measurements are being asked for, and there is now a desire to know about the effects of the observed changes both regionally and on the global scale. This subsection relates several instances where researchers at Langley are making progress toward the understanding of those effects.

Hansen et al. [2005] stressed that the reliability of a climate model simulation ought to be tested against observations, but only if the relevant datasets have been properly characterized and/or combined. In their commentary Trenberth and Fusallo [2010] reported on a recent disparity for changes in the net radiation versus the heat content of the oceans, implying that there has been "missing energy" in the system since 2005. They concluded that the "observations are unable to fully account for the recent energy variability". Loeb et al. [2012] re-examined the multi-year measurements of Earth's net radiation budget using the reflected solar and emitted thermal radiation from CERES and the incoming solar radiation from the Total Irradiance Monitor (TIM) instrument on the Solar Radiation and Climate Experiment (SORCE) satellite, but normalized to the estimates of the upper ocean heat uptake from the Argo network of buoys that provide better sampling of the ocean temperatures. Their more detailed analysis indicates no energy imbalance

on annual timescales, especially after considering the uncertainties for the respective datasets. More importantly, the relative variations of the net radiation and the buoy data agree, too.

Langley researchers are also making scientific advances about the effects of clouds and aerosols by considering the multiple satellite and airborne datasets. As an example, Kato et al. [2011] employed cloud data from CALIPSO and CloudSat with radiances from MODIS to gain better estimates of both the top-of-atmosphere (TOA) flux and fluxes at the Earth's surface. Sun et al. [2011] combined CERES, MODIS, CALIPSO, and AIRS data to obtain a quantitative assessment of the influence of subvisual clouds on Earth's shortwave radiation. Atmospheric aerosols have an impact on the vertical development of clouds and on precipitation, in large part due to their radiative effects as pointed out by Li et al. [2011] and Bollasina et al. [2011]. In order to quantify those effects better, Langley researchers have conducted calculations based on observed datasets from field campaigns with regard to the transport and radiative effects of mineral dust layers and of carbonaceous aerosols from biomass burning activities [Fairlie et al., 2007; Natarajan et al., 2012]. Such studies are important for obtaining a good characterization of effects of the aerosols for simulations of air quality and the regional climate and for estimating the aerosol optical depth (AOD) and particulate loading from the MODIS and MISR datasets.

Trenberth et al. [2010] showed that in order for climate models to simulate changes in the TOA net fluxes properly, they must include effects of volcanic aerosols in addition to other factors such as the sea surface temperatures. Further, Solomon et al. [2011] concluded that even the rather minor variations of the background stratospheric aerosols are important for such simulations. Thomason et al. [2008] produced time series of aerosol extinction and surface area density (SAD) from the SAGE II data. SAD is an important parameter for determining the effects of heterogeneous chemistry for ozone in the lower stratosphere. Currently, Larry Thomason is finding somewhat larger, but more accurate values of total SAD by combining the infrared aerosol extinctions from HALOE with those from the shorter wavelengths of SAGE II.

Pitts et al. [2009] have been able to distinguish among the several types of particles that compose PSCs, based on their examination of the CALIPSO data. Vernier et al. [2009] also uncovered a somewhat unexpected finding about the aerosol backscatter profiles from CALIPSO in the tropical mid stratosphere. Often it is presumed that the lidar backscatter signal above about 30 to 32 km is wholly due to the molecular scatter component. However, when Vernier et al. used operational satellite temperature profiles for their calculations of the molecular scatter contribution, they found that the observed total-to-molecular backscattering ratios from CALIPSO remained larger than 1.0 up to 35 km or so. Thus, by re-normalizing the CALIPSO scattering ratio profiles to the higher altitude range of 36 to 39 km, they obtained larger AOD values for the lower stratosphere, too. This new insight has been applied to the generation of corrected time series of the stratospheric AOD from the combined series of SAGE II, CALIPSO, and GOMOS aerosol measurements [Vernier et al., 2011]. Thus, model studies can now be conducted on the radiative effects of variations of aerosols for the global climate with better accuracy, as for example in the recent analyses of Booth et al. [2012].

8 Summary

It is amazing to reflect on the very significant amount of progress that has been achieved in the 40-year period since the call of Landsberg [1970] for the activation of an adequate worldwide monitoring system for an assessment of possible anthropogenic changes on the climate. His urging came at a time when the "subject of climatology" was still somewhat qualitative and descriptive. As a measure of the average weather, climatology was often thought of in terms of its role for the economic geography and the living conditions characteristic of a region. Concerns about aerosols were focused more toward the air quality and visibility in a local region than to their effects on the global climate. The radiative and microphysical effects of persistent contrails within known air corridors had been estimated but were largely unverified at that time. It was clear that better knowledge was critically needed on the radiative, microphysical, and chemical forcings of the aerosols and clouds, in order to make assessments of changes in the air quality and for studies of variations of the regional and global climate.

Will Kellogg, G. D. Robinson, and Williams Mathews of the SMIC Study Group of 1971 were asked by Morris Tepper to take leading roles in the RMOP Workshop. Verner Suomi was recruited to lead the Particulate Panel of the RMOP. The participants of both studies were truly visionary, in that they saw the importance of making Earth/atmosphere measurements both globally and from Space. They were also correct in asking for the development and calibration of the diverse measurement techniques for obtaining quantitative estimates of the aerosols and clouds and of the surface emissivity. Langley researchers have played key roles since that time in the demonstration of the passive radiometric and photometric techniques and of active laser radar (lidar) sensors, both in the laboratory and from balloon and airborne platforms. The leaders of AESD/ASD, Don Lawrence and later William Smith and Leonard McMaster, served as important advocates for moving the various technologies toward their demonstration and ultimate use from satellite orbit. Lelia Vann, current leader of the Science Directorate (SD), continues to support those goals. The author provided some highlights of that progress in his report at the 10th History Symposium of the American Meteorological Society (AMS); his presentation can be viewed at the online site for the meeting [Remsberg et al., 2012].

Some of the scientific questions raised in the RMOP Report have already been sorted out with regard to the atmospheric processes related to aerosols and clouds. Yet, the various observational datasets must still be merged together carefully, and the uncertainties for their respective measurements need to be decreased further [IPCC, 2007]. Certainly, the overarching issues for climate change are contentious and not going away. The task ahead is to proceed with a dedicated monitoring for any changes in the Earth/atmosphere radiation budget and land/sea changes and to be able to predict with more certainty the effects of the long-lived, atmospheric greenhouse gases and of the natural and manmade aerosols. It is also clear that this important task will require close cooperation among researchers, innovative approaches for the observational satellite systems of the future, and commitments from governmental agencies, such as NASA, NOAA, and ESA [NRC, 2012].

Appendix A—Perspective of the author

This account by EER of the RMOP activity and its legacy is shaped necessarily by his own background and experience. EER was introduced to remote sensing studies of the atmosphere in 1962, upon his acceptance into a Cooperative Work/Study undergraduate program at what was then known as the Virginia Polytechnic Institute (or VPI) in Blacksburg, VA. His seven, alternating work quarters were spent at the National Radio Astronomy Observatory (NRAO) in Green Bank, WV, from 1962-65. He received his job assignment for each work quarter from John Findlay, Deputy Director of NRAO. Findlay had been a noted British ionospheric physicist at Cambridge University before coming to NRAO as a designer of radio telescope antennas. Along with Will Kellogg, Findlay was a founding member of the Committee on Space Research (COSPAR) in 1958. Findlay also served as Chair of the Lunar and Planetary Missions Board from 1967-71, when he advised NASA on the planning and conduct of missions to the planets and the Moon and its manned Apollo missions.

In the early 1960s Torleiv Orhaug and V. R. Venugopal reported that variations in atmospheric water vapor and subvisible cirrus were the likely primary cause of fluctuating and interfering noise effects for the transmission of sub-millimeter to centimeter wavelength signals from astronomical sources to the ground-based telescopes at Green Bank [Venugopal, 1963].   In 1964 at the direction of Frank Low and Arnold Davidson, EER conducted and analyzed daily measurements of the transmission and absorption of the direct sunlight in a water vapor band centered at 0.9375 micrometers and as a function of the zenith angle of the Sun or the atmospheric mass path. Measurements were also taken at 0.880 micrometers, a nearby reference wavelength that was unaffected by the water vapor absorption.   Frank Low concluded from the data that the skies over Green Bank were not always ideal for millimeter-wave astronomy, although he went on to report on a number of scientific findings from exploratory measurements of the planets and the Moon with his 5-ft prototype instrument at Green Bank [Low, 1966]. Low and Davidson surveyed a number of dryer locations with their same hand-held, spectral hygrometers, as part of a study to determine a suitable location for a proposed, 36-ft infrared telescope. The Kitt Peak National Observatory, AZ, was the site that they decided upon. The telescope was built according to a design by Findlay, and they began routine operations in early 1968. It is noted that it was the early, innovative work of Frank Low and his low-noise, infrared detector technology that led the astronomy community to consider and develop the InfraRed Astronomical Satellite (IRAS) in 1983, the Infrared Space Observatory in 1995, the Herschel telescope in 2009, and to give a top priority to NASA's James Webb Space Telescope (JWST).

EER shifted away from Physics and began graduate studies in the Department of Meteorology at the University of Wisconsin in 1966. His research studies were on the effects of water vapor and aerosols on the transfer of radiation in the atmosphere—a focus area of Professor James Weinman, his thesis advisor for both the MS and PhD degrees. His MS degree work consisted of an analysis of photographic transparencies of scattered sunlight from near the Earth's horizon that were obtained by astronauts L. Gordon Cooper and Charles "Pete" Conrad from Gemini III, IV, and V. He related the vertical extent of the scattering layers and of the profiles of their blue-

to-red ratios to the presence and sizes of the stratospheric aerosols. EER also held semester-long, teaching assistantships at that time with Professor Verner Suomi, with climatologist Eberhard Wahl, and with synoptic meteorologist Frank Sechrist. He remembers witnessing at the U. of Wisconsin in 1967 the first, RGB-color, global-scale images from Suomi's Spin-Scan Camera that was on NASA's ATS-3 satellite.

EER enjoyed a chance meeting with Christian Junge, the namesake of the stratospheric aerosol layer, when Junge was visiting Reid Bryson at Wisconsin in 1969. Shortly thereafter, Junge became a Work Group Leader for the SMIC Study Report. That same year Professor James Weinman introduced EER to Ed Ney at University of Minnesota, but it was not until many years later that EER learned that Ney had shifted his attention to infrared astronomy in the mid 1960s based in part on the work of Frank Low. Further, EER did not meet James Rosen at that time because Rosen had already taken a position at the University of Wyoming. Thus, EER was unaware that Rosen had already obtained particle counter data indicating that sulfuric acid was a likely constituent of the stratospheric aerosol layer. Instead, based on information that he would glean from the International Critical Tables and solution eutectic diagrams, EER concluded that the most likely composition for the aerosols was aqueous solutions of concentrated sulfuric acid or its ternary mixture with nitric acid. But data on the optical constants of these materials did not exist for confirming their presence in infrared spectra of the atmospheric aerosol layers.

At the urging of Weinman and upon an invitation from Professor Bryce Crawford, Jr., EER relocated to the Molecular Spectroscopy Laboratory (MSL) group in the Chemistry Department at Minnesota in September 1969. Crawford and his postdoctoral student Donald Lavery instructed EER on how to take the measurements in the mid-infrared and over a range of incidence angles with their laboratory spectrometer. He applied their very sensitive technique of attenuated total reflectance (ATR) spectroscopy to the concentrated aqueous solutions of sulfuric acid, nitric acid, and also ammonium sulfate [Remsberg et al., 1974]. It was a bold (or in the case of EER, naive) undertaking because all the other members of the MSL group at that time were focused on making spectral measurements and obtaining line assignments of simple triatomic molecules in their gaseous state. But after making a number of attempts, EER obtained good quality laboratory spectra from his solution samples by June 1970.

Shortly after his return to Wisconsin, EER presented his new datasets and optical constants at an NCAR Workshop on atmospheric particulates [Remsberg, 1971]. He then used his newly acquired data to calculate aerosol extinction profiles and provide an explanation for the excess emission that Pilipowskyj et al. [1968] observed in the lower stratosphere using Suomi's radiometersondes and as verified with ground-based lidar soundings. EER also searched for signatures of those materials in balloon-borne, measurements of limb infrared spectra of the lower stratosphere that had been obtained by David Murcray of the University of Denver. However, the balloon flights of Murcray were made in early 1969, when the aerosol loading in the stratosphere was small. As a result, EER was unable to conclusively determine whether the aerosols of that time were due to any of the three materials that he had measured in the

laboratory. In addition, many in the research community were openly skeptical that sulfuric acid was really an important component of stratospheric aerosols, despite the indications from the vaporization temperatures of the particles that were sampled and heated in the balloon-borne counters of Rosen [1971]. In fact, only years later did Rinsland et al. [1994] confirm that sulfuric acid was the best candidate for explaining the rather broad absorption features in the spectra from the Pinatubo aerosols that they observed and analyzed from the 1992 flight of ATMOS—or some 9 months after the eruption of the volcano. The optical constant data of EER that Rinsland used have since been added to the refractive index database of HIgh-resolution TRANsmission (HITRAN), as discussed by Massie and Goldman [2003].

In the meantime, Frank Low had carried out infrared observations of Venus with a telescope at the Catalina Observing Station of the University of Arizona in 1967 and found broad absorption features in the 8 to 12 micrometer region [Gillett et al., 1968]. Hanel et al. [1968] observed mid infrared emission spectra for Venus from the Harvard Observatory in 1967 using their Michelson interferometer. They reported an absorption feature at about 11.2 micrometers that they could not identify. Later though, A. T. Young [1974] was able to fit the broad features in both their sets of spectra with his simulations based on the data of Remsberg [1973] for 75% by weight aqueous sulfuric acid.   Samuelson et al. [1975] also found a reasonable match of the spectra that they obtained at MacDonald Observatory in 1969, based on the optical constants of EER.

EER came to NASA Langley in 1971 and worked as a contract employee through The College of William and Mary and then with ODURF the following year. Based on his recent PhD work, he simulated limb infrared emission signals that one might expect to see from a balloon-borne prototype of the Nimbus 7 LIMS experiment.   He developed specifications for a dedicated aerosol channel in the window region of the spectrum, but the data from that channel in an instrument on a balloon test flight out of White Sands, NM, were unsuitable for making a confirming analysis. A similar aerosol channel was specified for the Nimbus 7 LIMS experiment, but it was deleted from the flight model of that instrument as a cost saving measure. It is worth noting though that because of the large effect of the aerosol emission from the El Chichon volcano on the limb infrared measurements of the SME satellite in 1982, the limb infrared emission instruments on UARS (i.e., CLAES and ISAMS) did include separate channels for the purpose of measuring the broadband emission from just the aerosols.

In the late 1960s and the 1970s Ney and Pepin adopted the spectral hygrometer or solar differential absorption approach of Low and Davidson [1965] for judging the changes in column water vapor during periods when they were making infrared observations from high altitude balloons. Landau [1982] improved on that initial hygrometer, so that it would be possible to observe either the Sun or the Moon (day and night sky conditions). In both cases they kept the same pair of wavelengths, 0.9375 and 0.880 micrometers, used by Low and Davidson. Later, McCormick and Pepin also made use of the 0.94 micrometer region for their solar occultation measurements of water vapor with the SAGE II instrument.

EER was hired as an employee in the Lidar Applications Section of ESSD at NASA Langley in 1973. J. D. Lawrence, Jr., was fully supportive of his activities during that time, especially those related to analyses of the stratospheric aerosols observed with the 48-inch lidar and to the feasibility studies that he made with regard to a future lidar system operating from the Space Shuttle. However, by 1980 EER became fully focused on the validation and characterization of the measurements of temperature and gaseous species from Nimbus 7 LIMS and on any possible contaminating effects for their profiles from the unmeasured aerosols and clouds. From there he went on to analyze solar occultation measurements from the UARS HALOE experiment for the distributions and trends of water vapor throughout the middle atmosphere. His involvement in the remote sensing of the middle atmosphere extends from 1980 until 2010, a span of time when he was a member of the LIMS, HALOE, and SABER Project and/or Science Teams.

Appendix B—Acronyms

AAFE	Advanced Applications Flight Experiments
AAOE	Airborne Antarctic Ozone Experiment
ACE	Atmospheric Chemistry Experiment
ACE	Aerosol/Cloud/Ecosystems
ADEOS	ADvanced Earth Observing Satellite
ADM	Angular Distribution Model
AEAP	Atmospheric Effects of Aviation Program
AEC	Atomic Energy Commission
AEM	Atmospheric Explorer Mission
AESD	Atmospheric Environmental Sciences Division
AFCRL	Air Force Cambridge Research Laboratories
AIM	Aeronomy of Ice in the Mesosphere
AIRS	Atmospheric Infrared Sounder
AMPD	Applied Materials and Physics Division
AMS	American Meteorological Society
AOD	Aerosol Optical Depth
APS	Aerosol Polarimetry Sensor
ARB	Aerosol Research Branch
ARM	Atmospheric Radiation Measurement
ASD	Atmospheric Science Division
ASTP	Apollo-Soyuz Test Project
ATBD	Algorithm Theoretical Basis Document
ATMOS	Atmospheric Trace Molecule Spectroscopy
ATR	Attenuated Total Reflectance
ATS	Advanced Technology Satellite

AVHRR	Advanced Very High Resolution Radiometer
BATC	Ball Aerospace and Technologies Corporation
BOMEX	Barbados Oceanographic and Meteorological Experiment
BNL	Brookhaven National Laboratories
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAS	Center for the Atmospheric Sciences
CAT	Clear Air Turbulence
CERES	Clouds and the Earth's Radiant Energy System
CIAP	Climatic Impact Assessment Program
CIMATS	Correlation Interferometer for the Measurement of Atmospheric Trace Species
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CLAES	Cryogenic Limb Array Etalon Spectrometer
CLARREO	CLimate Absolute Radiance and REfractivity Observatory
CNES	Centre National d'Etudes Spatiales
COSPAR	Committee on Space Research
CrIS	Cross-track Infrared Sounder
COS	Carbonyl Sulfide
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DIAL	DIfferential Absorption Lidar
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense

DOT   Department of Transportation

ENVISAT   ENVIronmental SATellite

ENSO   El Nino/Southern Oscillation

EOS   Earth Observing System

EOSDIS   EOS Data and Information System

EPA   Environmental Protection Agency

EQPO   Environmental Quality Program Office

ERB   Earth Radiation Budget

ERBE   Earth Radiation Budget Experiment

ERBS   Earth Radiation Budget Satellite

ERTS   Earth Resources Technology Satellite

ESA   European Space Agency

ESSD   Environmental and Space Sciences Division

ESSP   Earth System Science Pathfinder

FED   Flight Electronics Division

FID   Flight Instrumentation Division

FIRE   First ISCCP Regional Experiment

FIRST   Far-InfraRed Spectroscopy of the Troposphere

FOV   Field-Of-View

GARP   Global Atmospheric Research Program

GATE   GARP Atlantic Tropical Experiment

GATS   Gordley and Associates Technical Software

GeoCAPE   Geostationary Coastal and Air Pollution Events

GERB   Geostationary Earth Radiation Budget

GISS   Goddard Institute for Space Studies

GOES   Geostationary Operational Environmental Satellite

GOMOS   Global Ozone Monitoring by Occultation of Stars

GSFC   Goddard Space Flight Center

HALOE   HALogen Occultation Experiment

HITRAN   HIgh-resolution TRANsmission

HSRL   High Spectral Resolution Lidar

HU   Hampton University

IASI   Infrared Atmospheric Sounding Interferometer

IFAORS   Institute For Atmospheric Optics and Remote Sensing

IIP   Instrument Incubator Program

IIR   Imaging Infrared Radiometer

IMG   Interferometric Monitor of Greenhouse gases

IPCC   Intergovernmental Panel on Climate Change

IR   InfraRed

IRAS   InfraRed Astronomical Satellite

IRD   Instrument Research Division

IRIS   InfraRed Interferometer Spectrometer

ISAMS   Improved Stratospheric And Mesospheric Sounder

| ISCCP | International Satellite Cloud Climatology Project |
| ISS | International Space Station |

JIAFS	Joint Institute for the Advancement of Flight Sciences
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JWST	James Webb Space Telescope

LaRC	Langley Research Center
LAS	Lidar Applications Section
LEO	Low Earth Orbit
LHS	Laser Heterodyne Spectroscopy
LIMS	Limb Infrared Monitor of the Stratosphere
LITE	Lidar In-space Technology Experiment
LRIR	Limb Radiance Inversion Radiometer
LW	Long-Wave
LZEEBE	Long-time Zonal Earth Energy Budget Experiment

MAPS	Measurement of Air Pollution from Satellites
MATD	Marine Applications and Technology Division
MFOV	Medium Field-Of-View
MISR	Multi-angle Imaging Spectro-Radiometer
MIT	Massachusetts Institute of Technology
MSL	Molecular Spectroscopy Laboratory

MODIS	MODerate-resolution Imaging Spectro-radiometer
MORL	Manned Orbital Research Laboratory
MPC	Mother-of-Pearl Clouds
MRIR	Medium Resolution Infrared Radiometer
MSG	Meteosat Second Generation
MSS	Multi-Spectral Scanner
MTPE	Mission To Planet Earth

NACA	National Advisory Committee for Aeronautics
NAPCA	National Air Pollution Control Adminstration
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEROS	NorthEast Regional Oxidant Study
NLC	NoctiLucent Clouds
NMP	New Millenium Program
NOAA	National Oceanic and Atmospheric Administration
NOSS	National Oceanic Satellite System
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-orbiting Partnership
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRL	Naval Research Laboratory

OA	Office of Applications

OAST	Office of Aeronautics and Space Technology
OCO	Orbiting Carbon Observatory
ODURF	Old Dominion University Research Foundation
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OSIRIS	Optical Spectrograph and InfraRed Imaging System
OSO	Orbiting Solar Observatory
OSS	Office of Space Sciences
PAGEOS	Passive Geodetic Earth Orbiting Satellite
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PARD	Pilotless Aircraft Research Division
PEPE	Persistent Elevated Pollution Episode
POAM	Polar Ozone and Aerosol Measurement
POLDER	Polarization and Directionality of the Earth's Reflectance
PSC	Polar Stratospheric Clouds
RGB	Red-Green-Blue
RMOP	Remote Measurement Of Pollution
RRL	Risk Reduction Laser
RSB	Radiation Sciences Branch
RSP	Research Scanning Polarimeter
RTI	Research Triangle Institute

SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
SAD	Surface Aerosol Density
SARB	Surface and Atmospheric Radiation Budget
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stratospheric Aerosol Monitor
SASC	Systems and Applied Sciences Corporation
SASS	Seasat-A Scatterometer System
SATD	Space Applications and Technology Division
SBUV	Solar Backscatter Ultra-Violet
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY
SD	Science Directorate
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SIR	Shuttle Imaging Radar
SMD	Science Mission Directorate
SME	Solar Mesosphere Explorer
SMIC	Study of Man's Impact on Climate
SMMR	Scanning Multichannel Microwave Radiometer
SMS	Synchronous Meteorological Satellite
S/N	Signal-to-Noise
SO	Solar Occultation
SOFIE	Solar Occultation For Ice Experiment
SOLVE	SAGE III Ozone Loss and Validation Experiment
SORCE	Solar Radiation and Climate Experiment
SRI	Stanford Research Institute

SSE	Surface Spectral Emissivities
SSEC	Space Science and Engineering Center
SST	SuperSonic Transport
SSTs	Sea Surface Temperatures
SSU	Stratospheric Sounding Unit
STS	Space Transportation System
SW	Short-Wave
THIR	Temperature Humidity Infrared Radiometer
TIM	Total Irradiance Monitor
TIROS	Television InfraRed Observation Satellite
TOA	Top-Of-Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TRACE	TRopospheric Aerosol and Cloud Experiment
TRL	Technical Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TRW	Thompson Ramo Wooldridge
UARS	Upper Atmosphere Research Satellite
UK	United Kingdom
VPI	Virginia Polytechnic Institute

WFC   Wide Field Camera

WFOV   Wide Field-Of-View

WMO   World Meteorological Organization

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A workshop was convened in 1971 by the National Aeronautics and Space Administration (NASA) on the Remote Measurement of Pollution (RMOP), and the findings and recommendations of its participants 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 regional to global-scale, remote measurements of the atmospheric parameters from Earth-orbiting satellites. In 2011 the author published a 40-year retrospective (or Part I) of the instrumental developments that were an outgrowth of the RMOP panel headed by Will Kellogg, i.e., on atmospheric temperature and gaseous species. The current report (or Part II) is an analogous retrospective of the vision of the panel led by Verner Suomi for the measurement of particulates (or aerosols) and clouds and for their effects on Earth's radiation budget. The class of measurement techniques includes laser radar or lidar, solar occultation, limb emission and scattering, nadir-viewing photometry or radiometry, and aerosol polarimetry. In addition, the retrospective refers to the scientific imperatives that led to those instrument developments of 1971-2010. Contributions of the atmospheric technologists at the Langley Research Center are emphasized, and their progress is placed in the context of the parallel and complementary work from within the larger atmospheric science community.

15. SUBJECT TERMS

Earth radiation budget; aerosols; clouds; history; pollution; remote sensing; satellite

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