July 1981 NASA Workshop on Passive Remote Sensing of the Troposphere

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Potential roles of passive remote sensors in the study of the chemistry and related dynamics of the lower atmosphere were defined by a tropospheric passive remote sensing workshop, and technology advances required to implement these roles were identified. A promising role is in making global-scale, multilayer measurements of the more abundant trace tropospheric gaseous species (e.g., O_3, CO, CH_4, HNO_3) and of aerosol thickness and size distribution. It includes both nadir- and limb-viewing measurements. Technology advances focus on both scanning- and fixed-spectra, nadir-viewing techniques with resolutions of 0.1 cm^{-1} or better. Balloon- and Shuttle-borne experiments should be performed to study the effects of instrument noise and background fluctuations on data inversion and to determine the utility of simultaneously obtained nadir- and limb-viewing data.

Background

A WORKSHOP on tropospheric passive remote sensing was held at Virginia Beach, Virginia, on July 20-23, 1981. One of the sponsors was the Office of Space Science and Applications (OSSA) which is responsible for NASA's tropospheric air quality program. The ultimate objective of this program is to apply NASA's space technology to assess and predict human impact on the troposphere, particularly on the regional and global scale where both the synoptic view afforded by satellites and the increasing importance of pollution on these scales suggests that space observations can play a unique and critical role. Both passive and acting sensing flight experiments are included in the program. Plans are uncertain, however, for passive sensing experiments following the initial series of measurements by the measurement of air pollution from satellites (MAPS) sensor starting with Shuttle 2 in Nov. 1981 and continuing through 1984. Therefore, OSSA's question for the workshop was "With the inherent advantages that passive sensors have regarding cost, simplicity, weight, power, and reliability, what is their long-range role in tropospheric research?" The other sponsor was the Office of Aeronautics and Space Technology (OAST) which is responsible for developing critical technologies to enable or enhance the performance of a wide variety of potential NASA missions. OAST's questions for this workshop were "What new technologies are needed to fully implement the role prescribed for passive remote sensors?" Also, "Based on technology trends, what are the most practical and affordable approaches for filling the projected technology gaps in critical areas, i.e., what technology developmental thrusts are recommended?"

The NASA Langley Research Center organized and conducted this workshop. Although the workshop responded directly to NASA program needs, the selected participants (Table 1) included nonNASA atmospheric scientists, measurement specialists, and instrument technologists and the workshop results also should serve their needs and those of their government, industry, and university colleagues.

Presented as Paper 81-0207 at the AIAA 20th Aerospace Sciences Meeting, Orlando, Fla., Jan. 11-14, 1982; submitted Jan. 22, 1982; revision received June 7, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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Role of Passive Remote Sensors

A viable role for passive remote sensors has been defined in global-scale, multilayer measurements of chemical and transport parameters. Under certain conditions limb-viewing sensors can measure upper tropospheric species with good vertical resolution, while nadir-viewing sensors with good horizontal resolution can measure total burden and possibly distinguish between boundary-layer and free tropospheric concentrations.

Chemistry Measurements

A "snapshot" of the global distribution of key species is important to the understanding of tropospheric photochemistry. These are generally the more abundant trace species whose lifetimes are longer than a few days. In Table 2 Logan[1] lists several key species in order of their abundance in the troposphere.

Extremely long-lived species, e.g., CO_2, tend to be fairly evenly distributed and only a few standard Earth-based measurement stations are required, while short-lived species are so locally variable that spatially extensive measurements are difficult to make and interrelate. Intermediate lifetime species can be remotely observed globally from spacecraft or aircraft and can provide useful information regarding sources and sinks of these species. For example, carbon monoxide (CO) is of considerable importance in tropospheric chemistry and has a lifetime in the order of months. Measurements have been made since 1968, but its seasonal behavior is not established and there are very few measurements over the Pacific Ocean. Global snapshots are needed for source, interhemispheric transport, and sink studies. (The MAPS experiment on the second Shuttle flight provides such data.)

Measurements of the first five species listed in Table 2 are needed to understand the photochemistry that controls the concentration of the OH radical and ozone (O_3). (OH is involved in numerous important chemical processes but is difficult to measure in situ and practically impossible to measure remotely.) Production of OH depends critically on the amount of NO. Global distribution of NO_x is poorly defined and there are no measurements from tropical continental regions. Furthermore, lightning may be a major source of NO_x! Lifetimes of NO_x are short and measurements of HNO_3 can enhance the understanding of sources of NO_x. Global distributions of ammonia (NH_3) and SO_2 are poorly defined. Methyl chloroform (CH_3Cl_3) plays a unique role. Its only known sink is by reaction with OH and its sources are

Table 1 Workshop organization

Workshop co-chairmen	
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Measurements and mission needs	
Jennifer A. Logan Harvard Univ.	Edwin F. Danielsen NASA Ames
Sensor systems panel David G. Murcray, Chairman Univ. of Denver	Sensing technology panel Robert H. Kingston, Chairman Lincoln Lab.
Michael Griggs Science Applications, Inc.	Frank Allario NASA Langley
Wilfred D. Hesketh NASA Langley	John A. Dodgen NASA-Langley
E. David Hinkley Jet Propulsion Lab.	Edward J. Hurley NASA Goddard
James M. Hoell, Jr. NASA Langley	John A. Jamieson Jamieson Sc. & Eng., Inc.
John A. Reagan Univ. of Arizona	A. Freeman Milton Naval Res. Lab.
Larry Rothman A.F. Geophy. Lab.	David D. Norris Jet Propulsion Lab.
Harold Zwick Canadian Center for Remote Sensing	

Table 2 Key tropospheric trace species

Species	Mixing ratio	Lifetime
H_2	$10^{-3}-10^{-2}$	---
CH_4	$\sim 1.7\times 10^{-6}$	4-8 yr
CO	$0.5-2.5\times 10^{-7}$	Months
O_3	$10^{-8}-10^{-7}$	Weeks
NO, NO_2	$10^{-11}-10^{-9}$	~1 day
HNO_3	$\sim 10^{-10}$	~Week(s)
SO_2	$\sim 10^{-10}-10^{-9}$	~Week(s)
NH_3	$(?)<10^{-10}-10^{-8}$	~Week(s)
CH_3CCl_3	10^{-10}	~8 yr

well known; therefore, it possibly can be used to test analytical models for the global distribution of OH.

Species listed in Table 2 are potential measurands for passive remote sensors with capability for horizontal resolution as fine as 20 km, vertical resolution of at least two layers in the troposphere, and total burden accuracies in the range of 5-20%. Understanding the chemistry involved in the formation of aerosols and in depletion processes such as acid rain impose similar requirements on passive remote sensors for the measurement of aerosol optical thickness and aerosol size distribution.

Transport Measurements

Large-scale inhomogeneities in meteorology such as cloud formations, weather fronts, and severe storms strongly affect tropospheric chemistry. There are important chemical processes that occur only under conditions that are coincident with such meteorological phenomena and the precursors and products of these processes are dramatically transported both horizontally and vertically.

A unique approach to analyzing species transport in such situations is to convert standard meteorological variables into quasiconservative scalers such as potential temperature and potential vorticity which correlate strongly with various tracer species. Danielsen[2] finds that positive correlation of ozone with such scalers (both vorticity and ozone are increasing or both are decreasing) indicates the source of the ozone is the stratosphere and negative correlation (vorticity is increasing while ozone is decreasing or vice versa) indicates the source is the troposphere. Shapiro[3] reports that the position and intensity of jet streams are revealed by measurements from the Nimbus 7 total ozone mapping spectrometer (TOMS). The long-term role for passive sensors in this regard is the measurement of selected tracer species and standard meteorological variables in three dimensions with temporal repeats every 3-9 h. Such measurements would be made in the vicinities of large-scale meteorological events on a worldwide basis.

Some additional passive sensing measurements, perhaps acquired from separate observing platforms, that help in the understanding of sources, transport, and sinks of key tropospheric species are 1) weather conditions such as cloud cover, precipitation patterns, and lightning; 2) pollution episodes as indicated by satellite imagery of "hazy blobs"; and 3) land use parameters, such as the extent of biomass burning, deforestation estimates, and crop coverage areas. Measurement accuracy requirements for these quantities cannot be precisely defined—in some cases even qualitative measurements are useful—but the spatial and temporal resolution scales should be consistent with that specified for the other measurands.

Remote Sensing Approach

The workshop recommended a measurement scenario consisting of a combination of nadir viewing and limb viewing, especially for the measurement of such gases as O_3 and HNO_3. Measurement of these gases in the troposphere presents a unique challenge in that well over 90% of their total burden resides in the stratosphere. The measurement of other gaseous species and of aerosol parameters may be enhanced also by the combination of the two views.

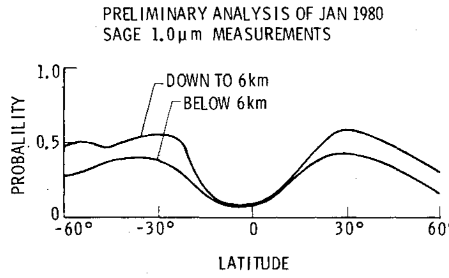

Fig. 1 Probability of limb viewing in the troposphere.

Limb Viewing

The dual-viewing approach represents a departure from established wisdom which avoided limb-viewing measurements in the troposphere because the measurements are not guaranteed due to frequent cloud interferences. Chu,[4] however, has preliminary space-flight statistics from the stratospheric aerosol and gas experiment (SAGE) which indicate that limb sensing of at least part of the upper troposphere is possible. Figure 1 shows that the probability of making infrared observations at 1.0-μm wavelength below the tropopause down to a height of 6 km is approximately 50% for the important midlatitudes! For these same regions there is approximately a 25% probability of making measurements below 6 km.

Sensing a useful fraction in the upper troposphere at equatorial latitudes is actually better than indicated in Fig. 1, since in those latitude regions the tropopause is 15 km or higher. So it can be assumed that, generally, there are large tropical areas where the upper troposphere is cloud free and limb sensing is a viable approach. Figure 1 does not show any longitudinal effects and many of the observations may be over clear semiarid lands and not over areas of high pollution potential. Interference from water vapor in the upper troposphere may be another complication. Nevertheless, the workshop felt that applying the considerable experience with limb-viewing sensors that has been gained in stratospheric measurement programs to the upper troposphere is a realistic and cost-effective step.

Figure 2 illustrates both the limb and nadir views. The relatively long path in the limb view provides an optical gain which is useful in sensing species that are either weakly absorbing or of low concentration or both. The radiance vs altitude weighting functions, illustrated by the limb infrared monitor of the stratosphere (LIMS) experiment normalized ozone signals from Gordley and Russell,[5] are typically quite sharp with most of the radiance coming from the first few kilometers above the tangent altitude. Thus, extremely good vertical resolution results. The horizontal weighting function, however, is spread out over several hundred kilometers. For the solar occultation mode its centroid is over the subtangent point, but for the emission mode it is displaced toward the remote-sensing instrument platform an amount which is related to the strength of the absorbing gas being sensed. The workshop noted several other aspects of limb sensing: 1) azimuthal scanning (emission only; not possible in solar occultation) will provide greater geographic coverage and information on diurnal effects; 2) limb sensing from balloon and aircraft altitudes, where the instrument is not completely out of the atmosphere, is also a viable mode offering some advantages for special investigations; and 3) the relationship of measurements made by limb sensing to those made by nadir sensing is not simple and short-term nadir-viewing Shuttle missions should be coordinated with existing solar occultation missions to study the feasibility of utilizing simultaneous measurements.

Nadir Viewing

Since the inception of NASA's space program, passive nadir-viewing sensors have been components of many payloads. The early sensors, for the most part, were visible and infrared imagers devoted to the measurement of cloud cover and the thermal and reflected solar radiation from the Earth's atmosphere. More sophisticated remote sensing systems quickly followed, culminating in operational satellites providing temperature and water vapor profiles on a global basis at a rate of up to six times per day. Each succeeding generation of passive sensors resulted in wider spectral coverage, higher spectral resolution, and narrower fields of view, which, in general, led to more accurate measurements with improved vertical and horizontal spatial resolution. As seen in Fig. 2, the atmospheric pathlength for nadir-viewing sensors is short compared to that for limb-viewing sensors, but for the more abundant trace species that are strong absorbers, the emitted (or the reflected solar) signals are adequate for passive remote sensing. Relatively narrow fields of view provide good horizontal resolution and the potential for sensing through broken clouds.

The key issues that remain regarding nadir sensing of the troposphere relate to sensitivity for weakly absorbing trace species, to sensing near the Earth's surface, and to vertically resolving the measurements. Near-surface sensing depends on a radiance contrast between the lowest atmospheric layers and the Earth's surface. For sensors using primarily emitted radiation, i.e., wavelengths greater than 3.5 μm, this translates into a need for a temperature contrast, which sometimes does not exist or is quite small. Vertical resolution is achieved by "inverting" spectrally resolved radiance data. It is intimately tied to the temperature and pressure dependence of the spectral band of the radiating gaseous species and the instrument passband. For example, CO_2 is a strong absorber which is mixed uniformly with altitude and measurements of its radiance in several spectral bands are inverted to obtain vertical temperature profiles. Conversely, the vertical profile of a variable gas can be measured, in principle, by inverting its spectral radiance measurements given in the vertical temperature profile. The vertical resolution is typically characterized by a signal function (normalized radiance vs altitude). Figure 2 shows signal functions for the MAPS instrument used for the measurement of CO. Obviously, with such broad signal functions, vertical resolution of a few kilometers is not possible, but at least two tropospheric layers can be measured and, perhaps, used to indicate significant differences between the boundary layer and the free troposphere.

Sensing off nadir is possible, also even up to fairly large surface incidence angles. It is particularly useful when full Earth coverage requirements demand a large swath width or when diurnal coverage requirements impose the need for wide angle scans. For the off-nadir mode, however, more frequent cloud interferences, aerosol scattering effects, and enlarged and distorted resolution elements (footprints) must be taken into consideration.

The workshop concluded that passive remote sensors viewing near the nadir exhibit promise and should be developed for two-layer measurements of some of the more abundant species such as O_3, CO, CH_4, HNO_3, H_2O and NO; and that for multilayer (i.e., >2) measurements of a wide range of species, a nadir-viewing instrument capable of obtaining continuous spectra in the 3.5-15-μm region with spectral resolution of at least 0.1 cm^{-1} is desired.

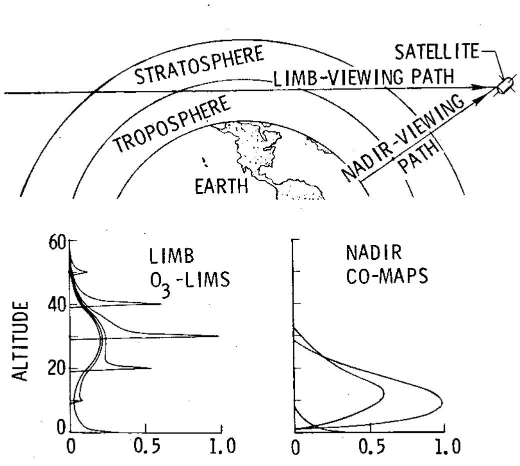

Fig. 2 Comparison of limb and nadir viewing.

Technology Needs

In the effort to establish the role of passive remote sensors and to identify the technology necessary to implement that role, the workshop reviewed existing passive sensing techniques. The sensing tree of Fig. 3 is included to help

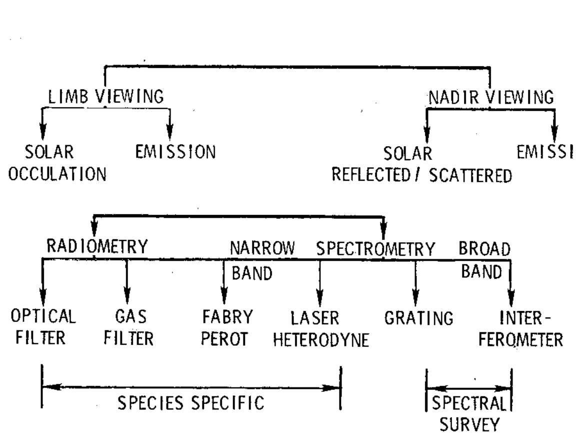

Fig. 3 Passive remote sensing tree.

illustrate the fact that flight sensors, which generally consist of a limited number of basic types, are usually of design tailored for a particular view (e.g., limb or nadir), with a particular initial radiant energy source (e.g., thermal emission or solar reflected), and sense particular species of spectral bands important to the atmospheric discipline. The task for the workshop was to determine which techniques have the most potential for the tropospheric air quality discipline and what technology advances are needed to realize that potential.

Limb-Sensing Technology

All of the existing limb-viewing sensors were developed for the stratospheric discipline. Some were designed for emission measurements, such as the Nimbus 7 limb infrared monitor of the stratosphere (LIMS)[6] optical-filter radiometer and the stratospheric and mesospheric sounder (SAMS) gas-filter radiometer. Others were designed for solar occultation measurements, such as the applications explorer mission-stratospheric aerosol and gas experiment (AEM-SAGE)[7] optical filter radiometer, the Earth radiation budget experiment (ERBE), halogen occultation experiment (HALOE)[8] gas-filter radiometer and the upper atmospheric research satellite-atmospheric trace molecule spectroscopy (UARS-ATMOS)[9] interferometer spectrometer.

The workshop felt that adaption of stratospheric sensors to the tropospheric discipline needs was an atmospheric spectroscopy task representing significant engineering challenges and requiring some moderate technology advances in things like cryogenic systems and data inversion, but no technology gaps were foreseen. Furthermore, much of the new technology needed for nadir sensing would likely be applicable to limb sensing. Therefore, the workshop spent little time considering limb-viewing technology and focused primarily on nadir-viewing sensing technology.

Nadir-Sensing Technology

Of the six basic types of sensors shown in Fig. 3, only the optical- and gas-filter radiometers have had space flight experience in nadir viewing. The Landsat multispectral scanner data have been used to tropospheric aerosol loadings[10] and the MAPS[11] sensor on Shuttle 2 measured vertically weighted average mixing ratio of CO. The task is to extend the number of species that can be measured by species-specific sensors such as the gas-filter radiometer and to complement them by sensors that survey a complete spectral region. This presents a real technical challenge because the optical path is short, signals from some species are weak, and the background radiation and noise effects may be overwhelming. Table 3 compares the generic types of nadir-viewing sensors and summarizes their advantages and disadvantages.

Generally, the workshop felt that in the long term the preferred strategy would be broadband spectrometry in thermal emission, because all the species in a spectral region with sufficient signal would be measured day or night. It allows more monitoring flexibility regarding species, e.g., new species of interest and interferants would be measured, and it has the potential for good vertical resolution. There is no doubt, however, that it is complex and must handle much data. So the question remains, "Is there a realistic sensing system which, upon accounting for fundamental physics and practical engineering limits, has the potential for doing the prescribed nadir-sensing job?" To answer this question the workshop considered a number of sensing system scenarios.

The following scenario uses innovative ideas with regard to orbit, viewing geometry, and sensor configuration and is included to illustrate the scope of workshop's considerations. It assumes a need to sense in the visible and near-infrared regions for aerosols and in the thermal infrared region as far as 15 μm for gaseous species, and it assumes the spectral radiances from these species is in the order of 10^{-6} W/cm^2 sr cm^{-1}. Global-scale, multilayer measurements with approximately 20-km horizontal spatial resolution and temporal repeats of approximately 6 h are envisioned. In addition to the spectral radiances, auxiliary measurements necessary to interpret the radiance data are made from a sensor platform whose views allow quasicontiguous coverage and whose revisits and lifetime allow diurnal, seasonal, and long-term sampling. The time frame is the 1990's and, with affordability a prime criterion, a single Shuttle-launched space platform is

Table 3 Comparison of nadir-sensing techniques

	Advantages	Disadvantages
	Gas filter radiometry[12]	
	Low data rate	No detailed spectra
	Minimal data reduction	Limited temperature profiles
	High throughput (spectral and angular)	Test cells limited
		Species fixed after launch
	Broadband spectrometry[13]	
All types	Detailed spectral data	High data rate and processing
	Survey data	Have complex calibration
	Vertical discrimination	Complex optical train
		Requires long-term alignment stabiity
Grating (with linear array)	Simple mechanism	Needs line array for sensitivity
		Large area gratings
Interferometer	High throughput	Background fluctuations
		Lifetime of high scan rate reflector
	Narrow-band spectrometry[14,15]	
Laser heterodyne spectroscopy	High spectral resolution for vertical discrimination	Limited tuning range
Fabry-Perot	Simplicity	Limited tuning range
		Temperature stability

chosen. Orbit choices range from geosynchronous (GEO) altitudes to traditional low-Earth orbits (LEO) of the order of 1000 km, including some attractive intermediate altitude orbits which allow good spatial coverage, especially with the use of off-nadir sensors. Spatial resolution requirements dictate optics sizes ranging from 1 m or more in GEO to 20 cm or less in LEO. This scenario chooses an intermediate orbit of 5000 km, which means the optics must be approximately 0.5 m. The selected sensing strategy is emission spectroscopy requiring the 3.5-15-μm range to be surveyed completely with a resolution of better than 0.1 cm^{-1}.

It appears to be technologically feasible to make the desired measurements using one large instrument with a single set of fore-optics. An example is a spectrometer which covers the wavelength region using several gratings and associated multielement line array detectors. The key elements of such a sensor would include large aperture fore-optics, a spectrometer with a large multiblaze grating, linear arrays with 1000 elements per spectra, supporting structure and electronics, mechanical chopper, cross-track scanning mirror, grating adjustment mechanism, and a cooling system to control the fore-optics, the spectrometer, and the detector arrays. Another feasible sensor is a modulated (Fourier transform) interferometer which uses one detector for each spectral sub-band to be sensed (perhaps of the order of ten detectors). This class of instrument is intrinsically sensitive because it does not require an entrance slit and because each spectral frequency is measured for the total spectral observation time. The instantaneous field of view of the instrument is limited by the path difference required so that the sensor must be spatially scanned to achieve spatial coverage. Path difference (delay) scanning of the instrument requires an accurate linear translation device which requires excellent engineering for linearity, regularity, maintenance of alignment, and long life. The type of Fourier transform spectrometer most currently used is a Michelson beam splitting interferometer. The cylindrical symmetry of this device is not easily adapted to use with multiple fields of view. It has been suggested that an alternative multiaperture interferometer supported by a grating for preselection of bands be used for this application. Such a sensor with cryogenically cooled detectors and filters with D^*'s in the range from 10^{11} to 10^{13} appears to have potential for making good signal-to-noise ratio measurements within the dwell time allowed by the orbit geometry and the scan or stare modes of operation. With assurances derived from considering such sensing system scenarios, the workshop proceeded to a more detailed look at nadir-sensing technology.

Technology Thrusts

Tropospheric measurements may be carried out by the various instrument techniques shown in Fig. 3 and Table 3. Limb measurements, necessary for low concentration species, would be carried out using solar occultation. This allows effective measurements down to the order of 10 km in the absence of heavy cloud cover. Satisfactory operation of this type of instrument has been demonstrated and no new unique technology seems to be needed for the tasks reviewed by the workshop. In contrast, the nadir-pointing systems, required for measurements of the free troposphere and boundary layer, all require significant new designs as well as presently unavailable components. Although the advantages and disadvantages, both from measurements and technology viewpoints, were reviewed in detail and a long-term measurement strategy using broadband spectrometry is preferred, the choice of the optimum system is far from clear. On the one hand, the optimum trade-off between complexity and data yield has not been determined. On the other, there has not been sufficient study and analysis to determine how well a specific system will operate even if all the technology becomes available. It is, therefore, obvious that detailed system studies are needed for the candidate approaches. The detailed requirements of the user, the evaluation of the instrument designer, and the relative costs should be the three determining factors for implementation of a system development and support of the appropriate new technologies. The workshop, however, made the following recommendations. 1) Although the spectral scanning strategy is preferred, gas-filter radiometer instruments (e.g., MAPS and HALOE) should be developed concurrently with a scanning instrument, since radiometers may provide near-term two-layer tropospheric measurements of gases such as CO and CH_4 with only modest improvements in system performance. 2) Feasibility studies for both gas-filter and spectrally scanning instruments should be initiated to study a) the extent to which nadir-viewing systems can obtain two or more layer profiles within the troposphere, b) the accuracy requirements on knowledge of molecular line parameters, meteorological parameters, radiance levels, background variability effects, and c) the extent to which solar scattering can be used to obtain lower level tropospheric data. 3) Existing spectrally scanning radiometers (e.g., interferometers) and/or gas-filter systems should be employed on balloon and Shuttle platforms to study the effects of instrument noise and background fluctuations on inversion techniques.

Table 4 Technology thrusts

	Gas filter
	Gas filter test cells
	Linear, high dynamic range detectors
	Highly uniform optical elements
Broadband spectrometry	
All types	Onboard smart processing[16]
	Cryogenics/cooling
Grating type	10^3 element arrays[17,18]
	Large gratings
Interferometer type	Mitigation of background fluctuations
	Multiaperture, multiband interferometer
	Inflight alignment verification
Narrow-band spectrometry	
Laser heterodyne type	Tunable lasers and heterodyne arrays
Fabry-Perot	Improved coatings at long wavelengths

Table 4 summarizes the critical technology needs for the various instruments. In one sense, this table indicates the needs once a system is chosen. In a larger sense, the technology requirements and their apparent difficulty and cost should be a critical part of the instrument evaluation studies. Certain technology thrusts, however, are needed regardless of the sensing system choice. Examples from Table 4 are 1) detector arrays, 2) cryogenic cooling (of sensors and optics), 3) sophisticated optical elements, and 4) data processing as an integral part of the sensor. Although not explicit in Table 4, to this list should be added an item, 5) calibration techniques and equipment. The workshop reiterated calibration needs delineated in the 1979 flight technology workshop.[19] In response to the continuing need for more sensitive and accurate measurements over the full globe for long periods of time producing great volumes of data, the workshop felt that the application of technology advances in these five areas would yield the greatest benefit in passive remote sensing of the troposphere.

Conclusions

A modest but meaningful and challenging role has been defined for passive remote sensors in the tropospheric air quality program. It deals with the chemistry and transport of the more abundant trace species with intermediate lifetimes. It prescribes global-scale, multilayer measurements using both limb- and nadir-viewing techniques with both species-specific and spectral-survey sensors. Since spectral-survey sensors have potential for detecting "new" species of interest and interferants, these sensors could play a valuable complementary role to that of active sensors.

Regarding technology developments, the application of limb-viewing sensors to the troposphere should be relatively easy because of the rich science and technology heritage being provided by the stratospheric program. Development activities, therefore, should concentrate on the nadir-viewing sensors. The recommended technology thrusts are in the areas of 1) applying maturing technologies such as detector arrays and sensor-integral data processing to both species-specific and spectral-scanning sensors, and 2) performing the detailed system studies and flight evaluation tests on the candidate approaches.

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