Community Input to the NRC Decadal Survey from the NCAR Workshop on Air Quality Remote Sensing From Space: Defining an Optimum Observing Strategy

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Executive Summary

The Community Workshop on Air Quality Remote Sensing from Space was held in Boulder, Colorado, February 21-23, 2006, to examine what observational characteristics are required for the successful use of satellite remote sensing to measure environmentally significant pollutant trace gases and aerosols. Air quality (AQ) measurements are urgently needed to understand the complex consequences of increasing anthropogenic emissions, the biogenic response to changing temperature and humidity, and the escalating incidence of fire. The acknowledged urgency of this endeavor was reflected in the fact that the Workshop engaged more than 150 scientists and other AQ stakeholders with the primary goal of developing a strategy for future space-based capabilities. Four principal areas in which satellite observations are crucial for future AQ basic research and operational needs were identified: (1) AQ characterization for retrospective assessments and forecasting to support air program management and public health advisories; (2) Quantification of emissions of ozone and aerosol precursors; (3) Long-range transport of pollutants extending from regional to global scales; and (4) Large puff releases from environmental disasters. The recent advances in tropospheric remote sensing from low-Earth orbit (LEO) instruments such as MOPITT, GOME, MODIS, MISR, SCIAMACHY, OMI and TES have demonstrated the value of using satellites for both scientific studies and environmental applications. The Workshop agreed that the measurement capabilities for tropospheric O_3, CO, NO_2, HCHO, SO_2 and aerosols need to be continued and, at the same time, instrument capabilities and measurement algorithms for these species improved. Ideally, the AQ community envisions a scientific and observing framework for atmospheric composition that is analogous to that achieved for weather forecasting. In particular, our national weather prediction system relies on the combination of observations from geostationary Earth orbit (GEO), LEO, suborbital and surface platforms to derive a 4-dimensional view (3 spatial plus temporal) of the physical state of the atmosphere. Similar capability for AQ constituents will be required for AQ characterization and "chemical weather" forecasting. Workshop participants reached a consensus that multi-spectral sentinel missions (GEO or Lagrangian (L-1) orbit) that have high spatial and temporal resolution, and which are able to provide some species concentrations within the boundary layer, would be most beneficial to the AQ community. At the present time, GEO meets this measurement capability with the least amount of risk, and the greatest societal benefit from a U.S. perspective would be derived from placing such a satellite in an orbit capable of observing North America. The NOAA GOES-R operational suite of measurements from GEO will have some AQ relevant capability for ozone, carbon monoxide and aerosol. However, since NOAA's primary objective is improving weather forecasting, observations are not currently optimized for AQ applications and critical multi-spectral measurements in the UV and near-IR are not planned. Thus the Workshop stated the need for a new generation of dedicated AQ satellite missions that will also be part of an integrated observing

system including air monitoring networks, in situ research campaigns, and 3-D chemical transport models. The continued collaboration with NOAA to determine the most efficient and synergistic use of resources to meet AQ observational objectives from both GEO and LEO was emphasized by the Workshop. This is particularly important since GEO AQ observations will need to be complemented by operational global measurements of tropospheric gases and aerosols from NPOESS and other NOAA and European satellite systems. Over the longer term, global measurements for AQ with a sentinel capability could be obtained from L-1 orbit, but this approach requires more technical development to ensure the essential multi-spectral measurements and mitigate risk. Other approaches for AQ measurements discussed at the Workshop included multiple satellites flying in LEO formation and satellites perched in mid-Earth orbit (MEO), which can provide time-resolved observations (about 5 per day at mid-latitudes for all longitudes) but with UV/visible switching monthly between north and south. Each of these approaches has value and may provide synergy with objectives put forth by other Earth system science disciplines. The LEO-formation and multiple MEO instruments with limb viewing capability provide better vertical resolution in the middle and upper troposphere needed for understanding the impact of tropospheric and stratospheric chemistry on climate, and the resolution in the stratosphere needed to monitor the stability of the atmospheric ozone layer. The Workshop also concurred that a LEO would be the best platform for gaining an understanding of the composition and size characteristics of atmospheric aerosols by means of multi-angle, spectropolarimetric and stereoscopic-imaging techniques in conjunction with active (high spectral resolution lidar) measurements, which could provide aerosol information throughout the troposphere.

1. Background

A Workshop was held at the National Center for Atmospheric Research in Boulder, Colorado, February 21-23 2006, titled Air Quality Remote Sensing From Space: Defining an Optimum Observing Strategy (AQRS). The primary goal of this community meeting was an examination of the key measurement characteristics that are required for the successful use of satellite remote sensing in measuring environmentally significant pollutant trace gases and aerosols, and was of particular importance for developing a future strategy for space-based observations. It engaged over 150 scientists and air quality (AQ) stakeholders from North America and Europe. This document represents a community statement from the Workshop on the future priorities for a space-based AQ mission. The Workshop proceedings and presentations are available at http://www.acd.ucar.edu/Meetings/Air_Quality_Remote_Sensing/index.shtml.

The current observation system for AQ is woefully inadequate to monitor population exposure and develop effective emission control strategies. Surface air measurement networks have insufficient coverage, and are generally lacking in the developing world. Ozone and aerosol formation depend in complex and nonlinear ways on the concentrations of precursors, for which little data are available. Management decisions for AQ require emission inventories for the precursors, and these are generally constructed by a "bottom-up" approach involving application of emission factors to activity rates. These inventories are often uncertain by a factor of 2 or more, particularly in the developing world. Better understanding is needed of the long-range transport of pollution, including on intercontinental scales.

Recent advances in tropospheric remote sensing from low-Earth orbit (LEO) have revealed the potential for applying satellite observations to AQ issues. Observations of NO_2 and formaldehyde from GOME, SCIAMACHY, and OMI have been used to place top-down constraints on sources of NO_x and VOCs including their inter-annual variability and trends. Observations of CO from MOPITT and AIRS have been used to constrain CO sources and to track the intercontinental transport of pollution plumes. Combined observations of ozone and CO from TES and MLS have mapped the continental outflow of ozone pollution. Aerosol optical depth (AOD) observations from MODIS and MISR have been used to infer surface air concentrations of aerosols. Assimilation of MODIS AOD observations and OMI ozone is being implemented in AQ analyses and forecasts.

Ideally, the AQ community envisions a scientific and observing framework for atmospheric composition that is analogous to that achieved for weather forecasting. In particular, our national weather prediction system relies on the combination of observations from geostationary orbit (GEO), LEO, suborbital and surface platforms to derive a 4-dimensional view (3 spatial plus temporal) of the physical state of our atmosphere. Similar capability for AQ constituents will be required for AQ characterization and "chemical weather" forecasting.

The Workshop addressed the capability of the NOAA operational satellite system to meet the requirements of the AQ scientific community. NOAA's operational weather

observations are essential for providing the atmospheric state parameters (T(p), H_2O) that are vital for accurate trace gas retrievals. In addition, the NPOESS program intends to provide stratospheric composition, which is required to separate the stratosphere from the troposphere in nadir column measurements for AQ. However, the U.S. operational satellites will not provide time resolved observations of the minimum suite of AQ constituents defined by the Workshop and described in the next section. Specifically, the next generation GOES series, extending from 2012 through 2029, is well along its formal requirements process
(https://osd.goes.noaa.gov/documents/MRD2B_Atmos_Base_04_Mar_05.pdf) and will not provide ozone precursors NO_2 and HCHO or multi-spectral observations to isolate boundary layer carbon monoxide as discussed at the Workshop.

AQ managers and researchers from U.S. EPA participated in the Workshop and identified their requirements for future AQ missions. EPA manages AQ for the nation, and is a premier partner as a data user in AQ observations from space. However, EPA does not have a charter to develop space-based remote sensing observational networks. Consequently, the AQ community envisions NASA providing scientifically sound, crucial AQ observations to advance and communicate the necessary scientific knowledge and understanding (http://www.earthchangestv.com/space/misstate.htm).

The Workshop identified satellite observations as crucial for the future of AQ management, involving four major axes of application:

1. Air quality characterization for retrospective assessments and forecasting to support air program management and public health advisories;

2. Quantification of emissions of ozone and aerosol precursors;

3. Long-range transport of pollutants extending from regional to global scales;

4. Large puff releases from environmental disasters.

While the importance of exploiting the value of assets already in space was recognized, the limitations of these assets (which were generally not designed for AQ applications) were also emphasized. The Workshop strongly stated the need for a new generation of satellite missions for AQ as part of an integrated observing system that also includes surface air monitoring networks, in situ research campaigns, and 3-D chemical transport models.

2. Measurement requirements

Remote sensing instrumentation on satellites greatly augments existing AQ observing systems by providing continuous and global information on regional build-up of pollutants, long-range transport, emissions (in a form suitable for inverse modeling), and environmental disasters. Beyond this monitoring role, satellites can provide a wealth of data for testing our understanding of the factors controlling AQ and for improving AQ forecasts. The measurement requirements for future satellite missions directed at AQ can be classified in terms of (1) species measured, (2) horizontal resolution and coverage, (3) temporal resolution and coverage, and (4) vertical resolution including boundary layer observation capability. These are discussed successively here. Support from in situ observations and models is also essential, and is discussed in section 4.

Species measured. Top-priority AQ measurements from space for which capabilities have already been demonstrated (but still need improvement) include tropospheric ozone, CO, NO_2, HCHO, SO_2, and aerosols. These can be observed in regions of the spectrum extending from the UV-A to the microwave. The AQ community expressed a great interest in developing the measurement capability of NH_3 which plays a vital role in the formation of aerosols and improving the ability to observe aerosol composition and size distribution from space, for example through multi-angle and polarization measurements. Additional gas-phase species of interest, for which tropospheric retrievals from space are exploratory and in need of future study, include H_2O_2, PAN, HNO_3, HNO_4, acetylene, HCN, glyoxal, and formic acid. Beyond this chemical information, there is also a strong need for observations of physical climate and land surface variables to improve emission inventory estimates and better forecast the development of pollution episodes. Important physical variables in this regard include boundary layer height (accessible by lidar aerosol observations), surface roughness, soil moisture, land cover, and winds.

Horizontal resolution and coverage. Fine horizontal resolution in satellite measurements is of obvious value for AQ objectives. It is also required for the quality of nadir satellite retrievals to have horizontal homogeneity of the viewing scene (surface reflectivity and emissivity, and clouds). These considerations drive the need for sensors with horizontal resolution of better than 10 km (preferably 2-5 km). At the same time, horizontal coverage must be at least on a continental scale for observation of regional pollution episodes, and must further extend to a global scale for observation of intercontinental transport and large puff releases. Data collection and retrieval rates can represent a major limitation to such a combined requirement for horizontal resolution and coverage. Some leeway can be obtained by relaxing the constraint on horizontal resolution to 10 km outside of source regions, and in particular over oceans where the surface is relatively uniform, and where the interest from an AQ standpoint is mainly focused on long-range transport. Improved coverage at the expense of horizontal resolution is desirable to track plumes or to guarantee at least some measurements over a specific region for a particular event.

Temporal resolution and coverage. The high short-term variability of AQ requires that observations have high temporal resolution and coverage in source regions for AQ applications; this is a severe shortcoming in the currently available satellite data (all are from LEO with at most one or two observations per day at a given location). High temporal resolution enables characterization of (1) the synoptic spatial scale development of pollution episodes, (2) the diurnal variation of emissions, (3) the state of atmospheric composition for purposes of inverse modeling and data assimilation (forecasting), and (4) large puff releases. Hourly resolution or better is also desirable to be consistent with the typical temporal resolutions of surface monitoring data and regional models, as well as the metrics used in AQ standards. Missions that continually monitor a specific region can be used as "sentinels" to alert the modeling and observational communities that normal conditions no longer exist and that emissions inputs for AQ forecast models must be altered significantly and quickly. Temporal resolution does not have to be as high for observations of long-range transport, and in the case of intercontinental transport a frequency of observation of a few times per day would be sufficient.

Vertical resolution including boundary layer observation capability. The ability to observe the boundary layer from space is a major priority for AQ applications. This is a difficult problem because of interferences from clouds, aerosols, and air scattering, as well as uncertainty in surface reflectivity. In the thermal-IR, lack of temperature contrast with the surface limits boundary layer information. For trace gases, multispectral methods involving nadir-sounding in the UV/visible, near and thermal-IR, and limb microwave can be used to infer boundary layer information on ozone, CO and others, as well as providing some vertically-resolved measurements for the middle and upper troposphere. The combination of nadir sounding with limb sounding in the UV/visible, IR and microwave provides vertical resolution in upper troposphere, stratosphere (and above) to separate the lower troposphere. It is unlikely that vertical resolution within the boundary layer for key species such as ozone and CO can be achieved. Active (lidar) observations can provide high vertical resolution for aerosols and ozone but with sparse horizontal coverage compared to passive techniques. Advanced lidar techniques, such as high spectral resolution methods, provide the ability to discriminate aerosol types with vertical resolution, but power requirements limit these instruments to LEO.

Vertical resolution in the free troposphere is important for observing long-range transport, as this transport often involves layers of about 1 km thickness that may retain their integrity over intercontinental scales. The laminar structure results from delivery of emissions to the free troposphere through frontal lifting, convection, and pyroconvection in the case of large buoyant fires. Limb and stereo (multi-angle) observations may offer the needed vertical resolution to characterize such layers in cloud-free regions, although limb observations are typically limited to altitudes above 6-8 km and much of the intercontinental transport of pollution takes place at lower altitudes.

3. Orbital requirements

Different orbits have different advantages and disadvantages for AQ observations. There are important trade-offs among quantitative (and achievable) requirements on the degree of (1) horizontal resolution and coverage, (2) temporal resolution, and (3) vertical resolution.

Low-Earth orbit (LEO). All current satellite observations of atmospheric composition are from low-altitude (< 1000 km) polar orbiters. These are relatively inexpensive, allow limb and multi-angle viewing (the latter is important for aerosol properties, as demonstrated by MISR), and are so far the only option for active remote sensing (i.e. lidar systems). However, they provide only sparse temporal resolution (at best 1-2 revisits per day). A sun-synchronous orbit provides no information on diurnal cycles of AQ; a precessed orbit can supply this information but the return time for a particular time of day is then exceedingly long and unrepresentative. Temporal resolution can be improved by using broad cross-track swaths, but this is eventually limited by viewing angle; by using an inclined orbit, but higher latitudes are then sacrificed; or by using a constellation of satellites. However, constellations are challenging with respect to calibration. Passive sensors with broad spectral coverage (from UV-A to thermal-IR) for global-scale observation of pollution transport, and multi-angle, stereoscopic-imaging with spectropolarimetric synergy with a lidar system, support observations that provide information on aerosol composition and optical properties. Research instrumentation successfully demonstrated in LEO has been successfully transferred to the operational meteorological satellites operating from sun-synchronous LEO, for example SBUV and GOME.

Mid-Earth orbit (MEO). A mid-Earth orbit at 1200-1500 km altitude, employing broad-swath instruments, can give a needed combination of temporal, vertical, and horizontal resolution, along with global coverage. It can accommodate a full spectrum of observations from the UV to the microwave. This orbit is also sufficiently low to allow limb sounding. Two-hour temporal resolution can be achieved by the overlap of measurement swaths from successive orbits. The same class of launch vehicle used for LEO payloads can be used for MEO launches. Although the radiation environment at the 1200-1500 km low MEO altitudes being considered is not nearly as severe as for higher MEO orbits, it should be confirmed that a UV/visible instrument can operate as needed in the chosen orbit.

Geostationary orbit (GEO). A geostationary orbit at 36,000 km altitude allows continuous observation of the required suite of AQ constituents in the nadir. Measurements in the spectral range from UV to thermal-IR present no major technological difficulty. Horizontal resolution of 2-5 km is achievable. Continuous staring allows for effective cloud clearing and improvement in signal. Spatial coverage is limited by the stationary view of Earth: polar regions cannot be observed; and a minimum of three satellites is required for global observation of lower latitudes. Data rates for a satisfactory combination of horizontal resolution and coverage will be higher than existing space instruments, but they are still relatively small compared to those used in telecommunications. Launch cost is higher than for a LEO/MEO satellite, but may be leveraged by piggy-backing on a GEO satellite launched for other purposes (e.g., weather operations, communications).

Lagrange-1 orbit (L-1). An Lagrange-1 orbit at 1.5 million km altitude allows global continuous daytime coverage, thus combining the advantage of LEO/MEO for global coverage with the advantage of GEO for temporal resolution in daylight. A mission in L-1 orbit would link AQ observation needs with those of the upper atmosphere, space weather, and solar physics communities. Measurements for the spectral range from UV to near-IR are feasible but pose a higher technological challenge than from GEO (requiring, in particular, a larger telescope). Horizontal resolution of 5 km is achievable. Launch cost is comparable to that for GEO.

4. Integration with in situ observations and models

Satellite observations for AQ must be part of an integrated observing system including surface air routine monitoring networks, research campaigns involving surface sites and aircraft, and chemical transport models that can assimilate this ensemble of observations and make useful predictions to assist AQ management. This integrated observation system has been described in the IGOS-IGACO and is required as a component of the GEOSS ("system of systems") initiative.

Surface air monitoring networks provide the necessary infrastructure for documenting population exposure to air pollutants. They are dense in populated centers of North America and Europe, but much sparser elsewhere. Even in the United States, with over 1000 monitoring sites, the density of the networks is considered insufficient to adequately monitor population exposure. Satellite data would be of considerable value to provide continuous coverage, using data assimilation models to combine the space-based and in situ observations into a continuous mapping of surface air concentrations.

Intensive short duration research campaigns can provide a wealth of targeted chemical information that is not accessible from space but is of considerable importance in improving our understanding of processes underlying ozone and PM formation and fate. Such campaigns directly benefit improvements in models, through diagnosis and module refinements, which in turn enable development of more effective emission control strategies and accountability assessments of program implementation. Specific examples include measurements of radicals, speciated volatile organic compounds, air toxics, and detailed aerosol characterization.

Chemical transport models are the essential tools by which the relationship between emissions, meteorology, and pollutant concentrations can be understood. In the context of an integrated observing system for AQ, they play additional crucial roles in (1) synthesizing observations from different measurement platforms, (2) enabling the retrieval of non-measurable variables (e.g., emissions) through inverse analyses of observations, and (3) examining new observations through Observation System Simulation Experiments (OSSEs) for added value. Such applications represent a major challenge for existing models and will require considerable development in their capabilities.

5. Priority air quality mission

Future observation of AQ from space has an ensemble of requirements for horizontal resolution and coverage, temporal resolution, and vertical resolution. Meeting all of these requirements cannot be achieved from a single platform. Hourly temporal resolution with 2-5 km horizontal resolution over source regions is a particular imperative as it addresses strongly stated needs by the AQ management community for monitoring population exposure, for AQ nowcasting and forecasting, and for detection and tracking of plumes. Within the framework of existing or readily developable technology, the priority AQ mission calls for a satellite in GEO making observations on the continental scale, with

North America being of prime domestic interest. This GEO satellite should have spectral observation capabilities ranging from the UV-A to the thermal-IR in order to address the measurement requirements laid out in section 2. The continuous sampling supports atmospheric model studies, and additional constituents may be observed to benefit other science communities.

The AQ mission from GEO is complemented by the planned operational meteorological missions from LEO. The ESA/EUMETSAT Metop series of platforms flying in a descending node having an equator crossing time of 9:30 a.m. have the GOME-2 and IASI instruments on board. There are three planned satellites as part of Metop that will operate from 2006 until 2019. These satellites will provide global measurements of relevance for long-range transport of pollution. The NPOESS missions will provide at least two platforms later in the day having instrumentation complementary to GOME-2 and IASI.

The alternative MEO or L-1 orbits provide a critical bridge to other Earth Science interests, as described in the next section. They have considerable value for AQ applications, but from a strict AQ perspective it would be difficult to prioritize them over GEO. A MEO mission has the advantages of global perspective and better vertical resolution (for a single MEO satellite); its 2 hour revisit time has a pattern that precesses though all local times on a seasonal basis, and the UV/visible/near-IR measurements (made at all longitudes over broad mid-latitude bands) switch between northern and southern hemispheres on a monthly basis. An L-1 mission would combine the advantages of global and continuous observation but there is a 5-km limit on horizontal resolution. Further technological developments over the next decade could make an L-1 mission important in the longer term.

Some limitations of a GEO platform are lack of global coverage and limited vertical resolution. These shortcomings could be overcome with a companion LEO platform including (1) a high spectral resolution lidar for vertical resolution of the boundary layer and free tropospheric aerosol plumes, combined with improved aerosol characterization; and (2) multi-spectral passive sensors ranging from the UV-A to the microwave with multi-angle and polarimetric capability in selected bands, for global observation of pollutant transport and aerosol type.

An AQ mission from space to be launched over the next decade is of compelling importance for addressing urgent needs in managing AQ and protecting public health. Such a capability will also address research needs to improve our understanding of the global processes that affect AQ.

6. Potential cross-cutting missions

Satellite missions offer cross-cutting opportunities to serve the interests of multiple research communities. For example, the MODIS instrument is perhaps better known for its surface mapping than its aerosol observation capabilities. The OMI instrument is generating considerable interest for its AQ applications but its prime purpose is to monitor stratospheric ozone. It is important when defining AQ missions to also consider the needs of multiple science communities. From this standpoint, MEO and L-1 missions may have more potential than the above GEO mission and may be regarded as cross cutting missions.

A MEO mission including multiple daily global coverage and limb observations serves some needs of the AQ community and also provides global mapping of atmospheric composition including aerosols that serves the interests of the climate community. It provides good vertical resolution in the stratosphere and the upper troposphere that can provide key measurements for earliest-possible warning of changes in the stability of our ozone shield, well before changes are evident in ozone itself. Limb microwave observations of the middle and upper troposphere offer unique information on water vapor and clouds to improve meteorological assimilation and test climate models. These platforms are uniquely advantageous for better understanding the mechanisms that underlie the recovery of the stratospheric ozone hole and stratosphere-troposphere exchange, and thus how these processes influence atmospheric composition and AQ.

Similarly, an L-1 mission provides a continuous global perspective that is of great value for the AQ community in addition to meeting scientific objectives of other disciplines. High-resolution global data for CO_2 and methane in the near-IR are possible from L-1 and would revolutionize our ability to constrain surface fluxes for these gases. Continuous global measurement of aerosol reflectances would enable better understanding and monitoring of aerosol radiative forcing. The spectral range observed from L-1 can be extended into the extreme and far UV (EUV/FUV) to enable global viewing of the ionosphere. Solar irradiance and space environment instruments would further allow investigation of the effects of solar variability on Earth's climate and serve the needs of the space weather community.

Linking to the interests of the broader Earth Science community thus calls for consideration of two potential bridging missions, both of great value for AQ as well as for other applications:

- A MEO mission in low-inclination orbit to provide broad-swath nadir mapping together with limb observations in the spectral range from UV-A to microwave. This mission should bridge the interests of the AQ community with those of the global atmospheric composition, physical weather, and climate communities. A second MEO satellite could later be deployed for operational needs that require more continuous temporal coverage.

- An L-1 mission providing global observation with 5-km resolution in the spectral range from E-UV to the near-IR (and possibly thermal-IR), and including in situ space environment instruments as well as solar sensors. This mission should link the interests of the AQ community with those of the global atmospheric composition, climate, ecosystems, upper atmosphere, space weather, and solar physics communities.