Air Quality Investigation Constellation

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Foreword

As discussed in the NRC report, *Global Air Quality*, global population and urban population are increasing rapidly, and it is estimated that over a billion people are currently exposed to harmful air pollution (Schwele, 1995; Molina, 2004). Global measurements from the space shuttle have shown that air pollution is an international issue, with industrial and biomass burning emissions impacting both less developed nations as well as industrialized and rapidly growing developing countries (Akimoto, 2003).

With such large impacts to humans, it is imperative that we enable accurate prediction and control of global air pollution. This can be accomplished by a concerted program of emissions measurement, global air pollution measurement, and model development. This mission will contribute to our fundamental understanding of tropospheric chemistry, but more importantly, it uses remote sensing of the Earth to contribute to an important societal problem that is inherently global in scale.

Global chemical transport model development is hindered by the lack of observational data, especially vertically resolved chemical measurements. The new vantage point of this air pollution constellation mission will allow for multiple vertically resolved global measurements of air pollution each day. This information is essential for understanding the global context of air pollution – emissions, transformations, and concentrations of a suite of chemical species.

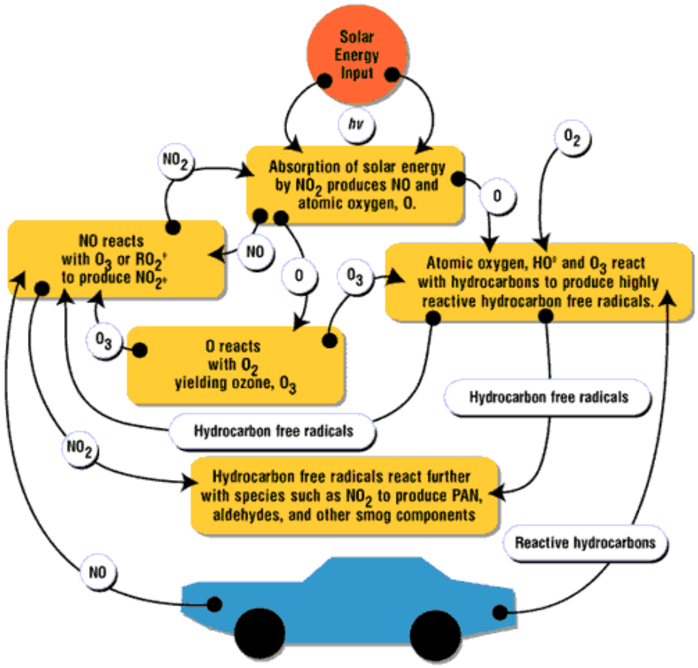
This mission concept is responsive to four of the seven panel themes identified in the NRC panel report (see Section 4.2); it provides opportunities for international collaboration (Section 4.10), fills data gaps (Section 4.6) as identified in the IGOS Theme Report on Integrated Global Atmospheric Chemistry Observations (IGACO), and offers the prospect of new instrument performance capabilities (Section 4.5) that can be transferred to operational missions. In addition, NASA's global measurement could benefit the US EPA and other nation's environmental agencies, as there will be feedback of improvements in understanding of transformation mechanisms and measurement information from urban to rural locations.

1.0 Mission Concept

1.1 Overview

This constellation mission concept is focused on measurements to quantify the sub-regional emissions of precursors of smog and particulate matter over the globe and to quantify the effects of transformation processes (transport, reaction, deposition) over long ranges on regional air quality. The complex relationship of emissions and photochemically produced constituents is illustrated in Figure 1.

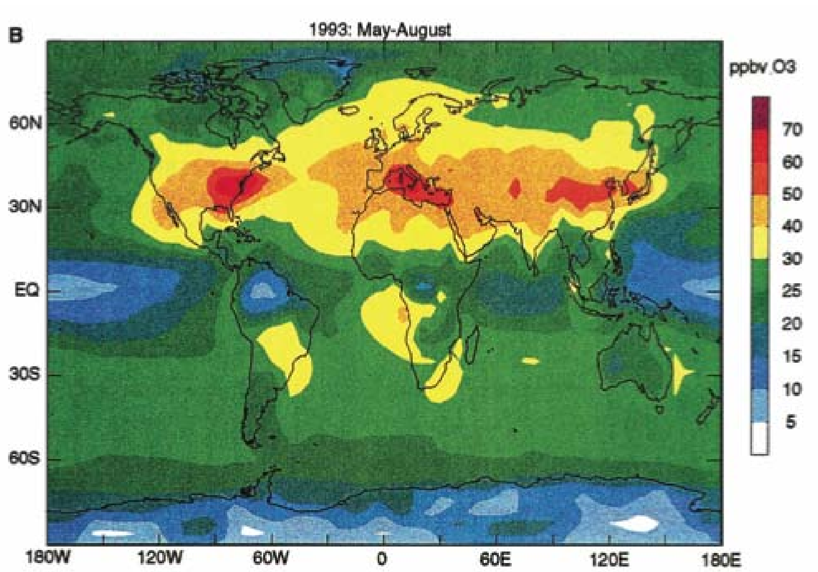
Figure 1. Photochemical Smog Scheme: ***Many chemical species are involved in highly non-linear chemistry that transforms the emissions into photochemical smog.***



Source: http://mtsu32.mtsu.edu:11233/Smog-Atm1.htm

When this highly non-linear chemistry takes place in the dynamic atmosphere of Earth, the pollutants often form far from emission sources, and are advected and mixed for days. Figure 2 is a snapshot of the global pollution that results from these processes.

Figure 2. Model Calculated Surface Ozone for May-Aug 1993: ***Photochemically produces ozone impact regions far from emission regions.***



Source: Akimoto, Science, 2003

Investigating the global air quality problem has two distinct aspects, understanding the emissions of the precursors of photochemical smog, and unraveling the chemical and dynamical processes that move the pollution around the globe. We identify two groups of chemical species with differing requirements for spatial and temporal sampling in response to these two aspects and then describe the satellite and sub-orbital instruments that could meet the measurement requirements. Table 1 provides an overview of the science questions, resulting measurement requirements, and the mission design to meet those requirements.

Table 1. Science Traceability Matrix: ***Mission science objectives are responsive to NASA science themes/questions, and national and international planning documents.***

Science Objectives	Scientific Measurement Requirements	Instrument Requirements	Mission Requirements
EMISSIONS: Quantify the subregional emissions of precursors of smog and particulate matter over the globe	**FREQUENCY**: Daily to weekly observations for 1 to 2 years minimum **HORIZONTAL & VERTICAL RESOLUTION**: 1. Horizontal scale of 5 to 20 km 2. Vertical resolution sufficient for columns for long lived species and to resolve the boundary layer for shorter lived species. **CONSTITUENTS TO BE MEASURED:** Nitrogen Oxides: NO and/or NO_2 Hydrocarbons: *Anthropogenic:* CO, CH_4 *Biogenic:* C_5H_8 (isoprene), CH_4 *Particulates:* silicate dust, SO_2 (gas) and/or sulfate aerosol, black carbon, sea salt	**INSTRUMENTS:** Four instruments are required: 1. UV/VIS/NIR Spectrometer • Measures columns of NO_2, CO, CH_4, SO_2, and aerosol optical depth 2. Nadir Thermal Emission Infrared Spectrometer • Measures vertically resolved O_3, H_2O, CO, CH_4	**FLIGHT SYSTEM**: Two spacecraft are required. **ORBIT DESIGN:** Two different vantage points are required to meet the measurement requirements. Flight System 1: 1. MEO to GEO orbit for multiple measurements per day (instruments 1&2)
LONG RANGE TRANSPORT: Quantify the effects of transformation processes (transport, reaction, deposition) over long ranges on regional air quality	**FREQUENCY:** Daily to weekly observations (A) and multiple measurements per day (B) for 1 to 2 years minimum **HORIZONTAL & VERTICAL RESOLUTION:** 1. (A) Horizontal scale of 20 to 50 km with columns weighted towards the boundary layer 2. (B) Horizontal scales of 5 to 20 km with 2 to 3 layers in the troposphere **CONSTITUENTS TO BE MEASURED:** Hydrogen Oxides: H_2O, OH and/or HO_2, H_2O_2, O_3 Nitrogen Oxides: NO and/or NO_2, HNO_3, PNA Hydrocarbons: *Anthropogenic:* CO, CH_4, PAN, ROOH, RNO_3, $RONO_2$, H_2CO, CH_3CHO, C_2H_2, C_2H_4, CH_3OH, acetone, C_3H_6, *Biogenic:* C_5H_8, CH_4, terpenoids *Particulates:* Surface area	3. Multiangle Spectroradiometer • Measures aerosols, with polarization (aerosol type) 4. Infrared Solar Occultation Spectrometer • Measures vertically resolved O_3, H_2O, H_2O_3, PNA, NO/NO_2, HNO_3, CO, CH_4, C_2H_2, PAN	Flight System 2: 2. Orbit of <1400 km for daily to weekly measurements (instruments 3&4)

Note: Top priority measurements are depicted in red while desired measurements are in blue. Not all the Emissions nor the Long Range Transport Scientific Measurement Requirements are met by a single platform.

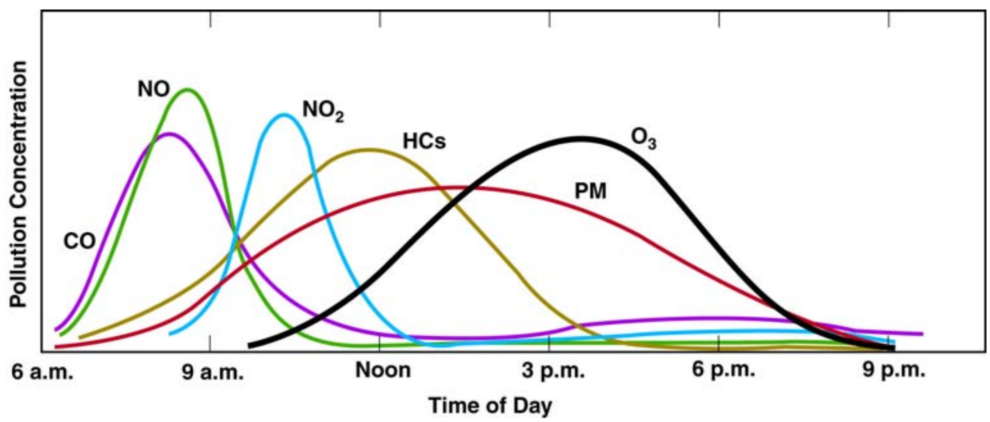
1.2

Observational Variables and Characteristics of Measurement

1.2.1 Photochemistry Question

Photochemically produced pollutants (O_3, H_2O, OH and/or HO_2, PNA, NO and/or NO_2, HNO_3, CO, CH_4, PAN, C_5H_8, aerosol surface area) require two approaches, one focused on the global picture, and another focused on the temporal evolution. A global understanding can be provided by daily to weekly observations on 20-50 km scale with a column weighted towards the boundary layer. These measurements should be complemented with multiple measurements per day with 2 to 3 layers in the troposphere to study the transformation processes that occur over the daylight hours (see Figure 3). A suborbital component will provide additional vertical information and measure species that can not be remotely sensed. This is described more fully in Section 1.3.

Figure 3. Time Variability of Photochemical Smog: ***Multiple measurements are needed each day to understand the relationship between emissions (NO, CO, HCs) and photochemically produced ozone.***



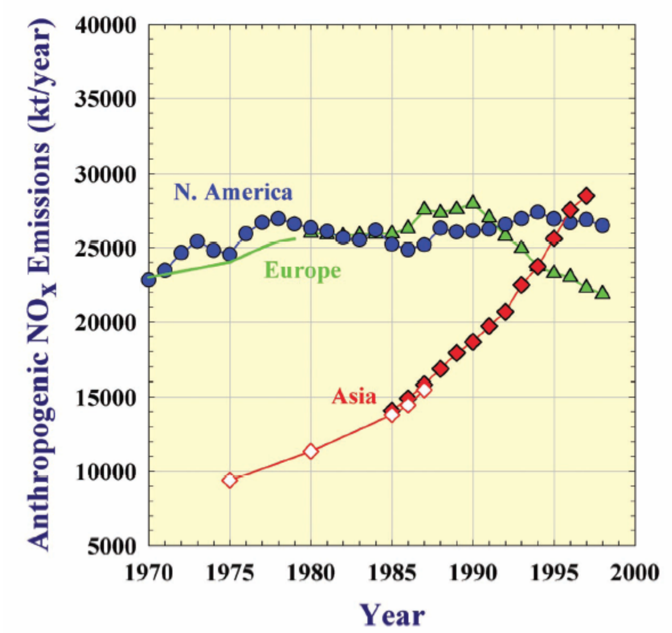
Adapted from "Earth Under Siege", R. Turco

1.2.2 Emission Question

The emissions important to air quality include NO, NO_2, CO, CH_4, C_5H_8, aerosols, SO_2. These are the key species that drive the chemical cycle of smog production (see Figure 1, Section 1.0).

Emission measurements are required to understand the concentration of the necessary ingredients for photochemical smog, and because describing potential future developments involves inherent ambiguities there is great uncertainty in future emission estimates (Figure 4). Therefore, emissions should be measured daily to weekly for 1 to 2 years with horizontal scale of 5 to 20 km to understand the current emissions, to provide inputs to emission trends models, and as the essential input to photochemical models. Long-lived species can be measured as integrated atmospheric columns, and shorter lived species require vertical resolution that resolve the boundary layer.

Figure 4. Future Emission Estimates: ***Emissions are expected to increase dramatically in the coming decade, and growth patterns in Asia are highly uncertain.***



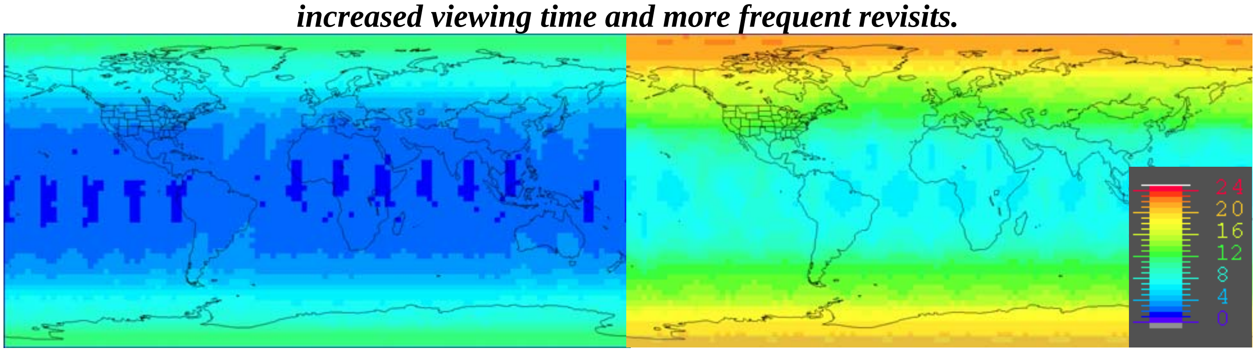
Source: Akimoto, Science, 2003

1.3 <u>Instrumentation to Meet Measurement Requirements</u>

As Table 1 illustrates, a two-satellite constellation will be used to meet the measurement requirements. The uv/vis/nir spectrometer and nadir thermal emission spectrometer will be in a MEO to GEO orbit for multiple measurements per day and the multiangle aerosol measurement and infrared solar occultation instrument will be in an orbit of less than 1400 km for daily and weekly measurements.

The advantage of a MEO orbit (in the range of 2000 to 6000 km) is the increased temporal sampling (see Figure 5), but this comes at the expense of the spatial resolution for the same optics. A GEO orbit would allow continuous viewing of some portion of the earth, thus the evolving chemistry could be measured at a small time step. The disadvantage of GEO is that only a fraction of the earth is seen, unless international cooperation allows for multiple GEO satellites with similar instrumentation. This type of international collaboration is described in Section 4.10.

Figure 5. Percent Viewing Time LEO vs. MEO Orbits: ***The new MEO vantage point offers increased viewing time and more frequent revisits.***



Note: The per repeat cycle percentage of available viewing time for the LEO orbit (left) is far less than the MEO orbit depicted on the right.

The solar occultation and multiangle polarizing radiometer will be placed in a more traditional low earth orbit. There are limitations on the orbit height of a multiangle measurement, since the scattering angles are reduced as the orbit height is increased. The solar occultation durations decrease as the orbit height increases. An orbit range from 1000 to 1400 km has been selected as optimizing the trades of coverage, revisit time, and measurement technique restrictions. Figure 6 illustrates the global coverage that could be achieved in one day for a multiangle measurement in a high inclination orbit. Ninety percent of the globe would be sampled in 3 days with this arrangement. Figure 7 maps out the solar occulations that would be achieved in a 40 degree inclination orbit over a one month period. Solar occultations can be made twice in an orbit period.

Figure 6. MISR Image: ***A multiangle polarizing spectroradiometer would cover these types of swaths daily; achieves 90% global coverage in 3 days.***

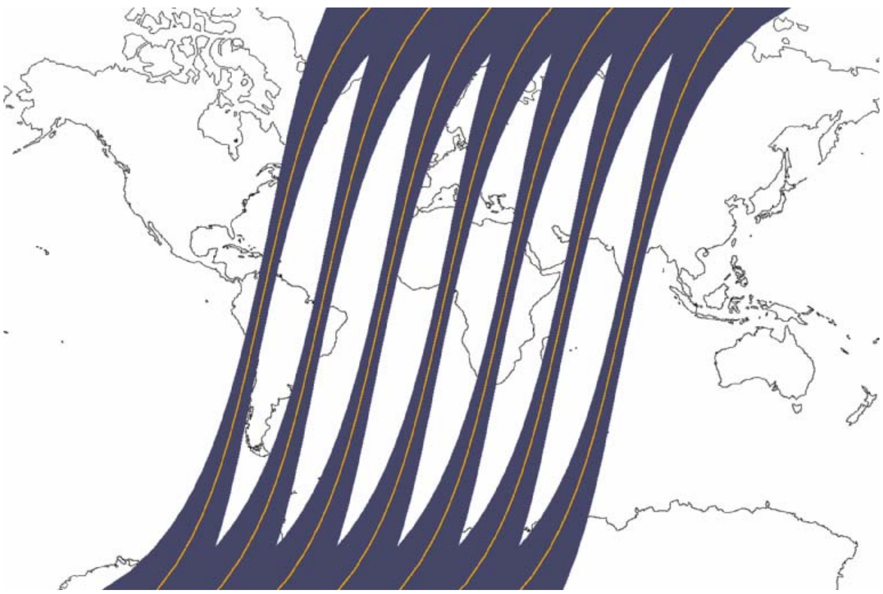
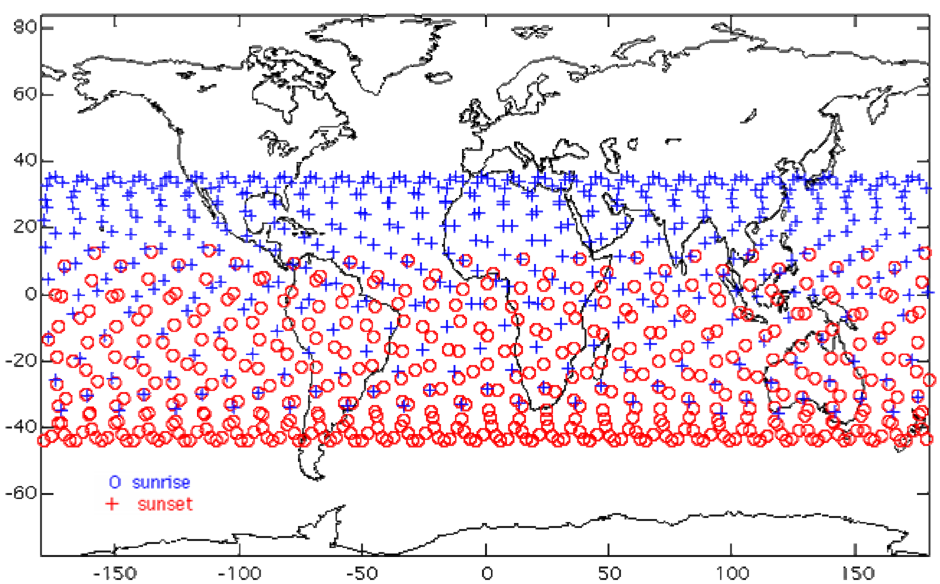


Figure 7. Occultation Map: ***Over a one month periods, the globe is well sampled. Exact details depend on the inclination of the orbit.***



There are some key air quality species that can not currently be measured by remote sensing techniques, namely C_5H_8 and HO_2. In addition, many larger organic molecules can not be measured remotely but would be very useful in verification of photochemical reaction schemes. Finally, validation of remotely sensed techniques is essential. For these reasons, the air quality constellation should include a suborbital program, with UAVs or aircraft measurements. Such measurements would at minimum provide grab samples of C_5H_8 and in situ sampling of HO_2. A more extensive program could be developed of longer term monitoring with UAVs to perform vertically resolved measurements over periods of days in one region. This project would leverage existing and planned national and international observation programs (see Table 2; Section 4.6 and Table 3; Section 4.10).

This mission must be part of a larger program of development of chemical transport models, chemical-climate models, data assimilation techniques, and computational tools and resources that will facilitate the use of massive data sets. NASA is leading efforts such as these through a number of programs including REASON, AIST, ACMAP, and others. In this response we will not describe this aspect further, but it is clearly recognized as an essential aspect in addressing global air quality.

2.0 Advances to Earth Science/Operational Capabilities

This mission would make great contributions to Earth science, as our current understanding of global air pollution and long range transport and production of tropospheric air pollutants is extremely limited. By choosing an MEO orbit, we can provide multiple measurements per day of photochemical species with vertical profile information. In addition, by measuring emissions and chemically produced species at the same time, we can fully understand the chemical cycle, rather than relying on extrapolation in time and space between the chemical species.

2.1.1 Earth Science Applications and Societal Needs

The proposed air quality constellation mission has great societal relevance, as global air quality is an international problem, and millions of people are impacted through direct health impacts and indirect impacts such as crop damage. This mission builds on the current state of knowledge of air pollution chemistry and meteorology, and our experience with past and existing measurement systems has brought us to a design that will allow for simultaneous measurements of the essential chemical species, facilitating use of these measurements in modeling and analysis. These data and their subsequent modeling and analysis will provide information that supports decision-making by policy makers, resource managers, industry and the citizenry on issues related to health, and environmental sustainability.

2.1.2 Chemical Weather

The observations proposed will improve prediction and understanding of air quality by providing frequent and long-term spatial measurements of key constituents of photochemical smog and its precursors. The available data will be supportive of new and improved forecast products for the EPA and local environmental agencies. In addition, the data collected will be available for analyses toward a better understanding of the role of assimilation of satellite products in addressing the problems of prediction.

2.1.3 Climate Variability and Change

Current analyses regarding the potential increase in global average temperatures and sea levels are based upon "scenarios" about the future that include assumptions about global development patterns, population growth, energy sources, economic development, and technological change. The state and changes in state of key climate forcings (i.e., carbon dioxide, aerosols, ozone, other greenhouse gases, solar, volcanic) are vital to our understanding and predicting climate variability and change. As per the IPCC Report, *Climate Change 2001: The Scientific Basis,* further research is required to improve the ability to detect, attribute and understand climate change, to reduce uncertainties and to project future climate changes. The proposed constellation would provide some of the needed additional systematic and sustained observations; and provide needed data for modeling and process studies identified in the IPCC Report.

2.1.4 Human Health and Security

The constellation proposed would directly contribute to our understanding of the patterns and dynamics of the dispersion of ozone, which has significant toxic impacts to humans and plants. The quality of the air is an important aspect of the environmental system, impacting human health and security.

3.0 Cost

This mission, as presented, is expected to fall within the Large mission cost category (>$500M). Preliminary estimates based on engineering judgment and analogy to operational instruments, suggest the constellation, including operations for five years, would cost on the order of approximately $1.2 B. Further study may elicit cost reduction through contractor agreements for bulk-buys (spacecraft bus and launch vehicle), reduced cost for development of heritage instruments, and the potential for shared and/or mission specific dual payload launches. In addition, future planning suggests significant cost savings through collaborations with complimentary missions and on-going UAV activities.

4.0 Responsiveness to Evaluation Criteria

4.1 A High Priority Mission

The measurements addressed by this mission concept directly address concerns identified in the NRC report, *Global Air Quality: An Imperative for Long-Term Observational Strategies* (2001). That report identified two key questions that are key to understanding global air quality, and this mission directly addresses the first question.

- *How is global air quality affected by the international and intercontinental transport of air pollutants?*
- *How can global air quality change affect, and in turn, be affected by global climate change?*

The implementation plan of the WMO's Global Climate Observing System (GCOS) includes an action (A25) to "Develop and implement a comprehensive plan to observe the vertical profiles of GHGs, ozone, and aerosols utilizing commercial and research aircraft, pilotless aircraft, balloon systems, kites, ground-based lidars and satellites". That report also points to the IGOS Theme Report on Integrated Global Atmospheric Chemistry Observations (IGACO).

4.2 Contribution to Panel Themes

The seven panel themes identified in the NRC panel report are:

1. **Earth Science Applications and Societal Needs**
2. Land-use Change, Ecosystem Dynamics, and Biodiversity
3. **Weather (including chemical weather and space weather)**
4. **Climate Variability and Change**
5. Water Resources and the Global Hydrologic Cycle

6. **Human Health and Security**
7. Solid-Earth Hazards, Resources, and Dynamics

The Air Quality Investigation Constellation will significantly contribute to themes 1), 3), 4) and 6). Examples of the types of contributions to these theme areas are given in Section 2.0.

4.3 Important Scientific Questions Addressed

The Air Quality Investigation Constellation mission objective is to quantify the long range transport of pollutants and their effects on air quality and ecosystems; and to determine the effects of changing climate on global and regional air quality. To meet this mission objective this concept addresses two key questions:

1. What are the subregional emissions of precursors of smog and particulate matter over the globe?
2. What are the effects of transformation processes (transport, reaction, deposition) over long ranges on regional air quality?

As mentioned in Section 4.1 above, the measurements addressed by this mission concept directly address concerns identified in the NRC report, *Global Air Quality: An Imperative for Long-Term Observational Strategies* (2001).

NASA's Earth Science Research Enterprise identifies air quality as an important area of understanding for the response of the earth system. Specifically:

1. What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?
2. What trends in atmospheric constituents and solar radiation are driving global climate?
3. How well can future atmospheric chemical impacts on ozone and climate be predicted?

4.4 Applications and/or Policy Making

The IGACO report provides detailed discussion of the species required to address global tropospheric air quality, and summarizes current and planned remote sensing capabilities. The advantages of GEO over LEO are discussed, but potential MEO solutions are not considered. The WMO/CEOS *REPORT on a STRATEGY for INTEGRATING SATELLITE and GROUND-BASED OBSERVATIONS of OZONE* extensively discusses the importance of measuring not only global ozone, but the source gases (emissions), reservoir species, and radicals. The tropospheric gases identified in that report as needing to be observed regularly over long periods of time over a broad range of meteorological conditions are O_3, temperature, water, winds, CH_4, CO, NO_2, and NO.

4.5 Long-Term Monitoring

The air pollution constellation concept could serve as the prototype for longer term monitoring missions. NPOESS has instruments that are similar in concept (CRISS), but the spectral resolution is not sufficient to retrieve vertical resolved profiles of chemical species. This mission could provide a record to connect the EOS era measurements and future operational missions. In addition, this mission offers the prospect of new instrument performance capabilities that can be transferred to operational missions.

4.6 Synergy with Other Observational Systems

Table 2 provides an overview of the domestic missions that will be occurring in the future. There are significant data gaps in measurements of chemical species that could be filled by the Air Quality Investigation Constellation, specifically the direct measurements of tropospheric ozone currently being performed by Aura TES. Water vapor and aerosol measurements from other sounders can be used to fill in temporal and spatial gaps. The aircraft measurements of the NOAA CMDL will be valuable in validation of the proposed measurement and reduce the number of species that must be measured for this project. Potential international collaborations are discussed in Section 4.10

Table 2. Planned Domestic Missions During the 2010-2015 Time Period: ***The Air Quality Investigation Constellation, if approved, would fill significant data gaps in needed chemical species measurements.***

Constituent	Spacecraft	Aircraft
Tropospheric O_3	**NO DIRECT MEASUREMENTS PLANNED FOREIGN OR DOMESTIC**	• NOAA CMDL
CO_2	**NO PLANNED DOMESTIC MISSIONS**	• NOAA CMDL (LT)
CH_4	**NO PLANNED DOMESTIC MISSIONS**	• NOAA CMDL (LT)
Tropospheric NO_2	**NO PLANNED DOMESTIC MISSIONS**	**NO PLANNED DOMESTIC MISSIONS**
H_2CO	**NO PLANNED DOMESTIC MISSIONS**	**NO PLANNED DOMESTIC MISSIONS**
CO	**NO PLANNED DOMESTIC MISSIONS**	• NOAA CMDL (UT/LS)
H_2O	• NPOESS CRISS (P) • NPOESS ATMS (P)	**NO PLANNED DOMESTIC MISSIONS**
SO_2	• NOAA SBUV-2 (C) • NPOESS OMPS 10	**NO PLANNED DOMESTIC MISSIONS**
Tropospheric Aerosols	• MSG, GOES, MTG (C) • NPOESS, AVHRR-3, VIIRS (C) • NPOESS VIIRS (C)	**NO PLANNED DOMESTIC MISSIONS**

Source: Adapted from IGOS Theme Report on Integrated Global Atmospheric Chemistry Observations
Notes: C = column, LT = lower troposphere, P = profile, UT/LS = upper troposphere/lower stratosphere,

4.7 Cost-Benefit

It is estimated that over a billion people are exposed to air pollution globally. Air quality monitoring and reporting need to be upgraded and made readily available to the public. Air pollution damage to people, crops and wildlife in the United States alone totals tens of billions of dollars each year[1] and most studies of the economic impact of air pollution on agriculture have found that a 25% reduction in ambient ozone would provide benefits of at least $1-2 B annually (Murphy, 1999). Reliable and complete inventories of emissions from different sources are crucial for identifying priority areas for intervention; and timely information about air quality, emissions, and health and other benefits of reducing emissions is needed to support regulatory decisions.

4.8 Degree of Readiness

This type of mission has a high degree of readiness, and it integrates measurement approaches that have already been proven on existing satellite missions. The proposed instrument suite has significant heritage:

1. The proposed uv/vis/nir spectrometer would be an instrument with capabilities that combine those of OMI and SCHIAMACHY.
2. The multiangle spectroradiometer would be an instrument with capabilities similar to MISR.
3. The nadir thermal emission infrared spectrometer would be an instrument with the capabilities of TES.
4. The infrared solar occultation spectrometer would be an instrument with the capabilities of ATMOS or ACE.

[1] http://healthandenergy.com/air_pollution_fees.htm

No new technologies are required to implement the Air Quality Investigation Constellation mission.

4.9 Risk Mitigation and Strategic Redundancy

Mission risk is mitigated by the use of heritage instrument designs. Strategic redundancy (complementary measurement) is realized through the collaborations identified in Sections 4.6 and 4.10.

4.10 Synergy with National and International Plans

This mission contributes to the application and policy making use of remote sensing measurements, as air pollution problems are closely tied to emission control strategies, and developing effective air pollution regulations requires that the long term transport and photochemical transformation processes be well understood.

Collaboration with international partners is vital to this program, as the European METEOP mission is the only future planned measurement for a number of chemical species (see Table 3). The Air Quality Investigation Constellation uniquely provides vertical profiles of ozone. The international measurements of columns of chemical constituent could provide increased time resolution for these measurements or allow for the descope of the UV/Vis instrument from the MEO/GEO platform. Again, if a GEO orbit was selected, the international partners would provide complementary measurements, not redundant measurements.

Table 3. Potential Spacecraft and Aircraft Mission Collaborations: ***While the Air Quality Investigation Constellation is needed to fill significant data gaps, great potential for collaboration exists.***

Constituent	Spacecraft	Aircraft
Tropospheric O_3	• METOP 1,2,3 GOME-2 05[1] • NPOESS OMPS 10[1]	• MOZAIC (P, UT) • CARIBIC (P, UT) • NOAA CMDL
CO_2	• METOP IASI (C)	• JAL (UT/LS) • CARIBIC (UT/LS) • NOAA CMDL (LT)
CH_4	• METOP IASI 05 (C)	• JAL (UT/LS) • CARIBIC (UT/LS) • NOAA CMDL (LT)
Tropospheric NO_2	• METOP 1, 2, 3 GOME-2 05 (C)	• MOZAIC (P, UT) • CARIBIC (P,UT)
H_2CO	• METOP 1, 2, 3 GOME-2 05 (C)	• CARIBIC (UT/LS)
CO	• METOP IASI 05 (T, C)	• JAL (UT/LS) • MOZAIC (TP, UT/LS) • CARIBIC (TP, UT/LS) • NOAA CMDL (UT/LS)
H_2O	• METOP MHS 05 and AMSU (C) • METOP IASI (P) • NPOESS CRISS and ATMS (P)	• MOZAIC (TP, UT/LS) • CARIBIC (TP, UT/LS)
SO_2	• NOAA SBUV-2 (C) • METOP 1, 2, 3 GOME-2 05 (C) • NPOESS OMPS 10	• CARIBIC
Tropospheric Aerosols	• MSG, GOES, MTG (C) • METOP, NPOESS, AVHRR-3, VIIRS (C) • NPOESS VIIRS (C)	• MOZAIC (UT) • CARIBIC (UT)

Source: Adapted from IGOS Theme Report on Integrated Global Atmospheric Chemistry Observations
Notes: C = column, LT = lower troposphere, P = profile, UT = upper troposphere, UT/LS = upper troposphere/lower stratosphere, T= troposphere, TC = total column, TP = troposphere profile, VP = vertical profile; [1]These missions plan to obtain indirect 0_3 measurements (NO DIRECT MEASUREMENTS PLANNED)

REFERENCES:

Akimoto, 2003:

Molina, 2004:

Murphy, 1999: James Murphy, Mark Delucchi, Donald McCubbin, and H.J. Kim, "The Cost of Crop Damage Caused by Ozone Air Pollution From Motor Vehicles" (April 1, 1999). *Institute of Transportation Studies.* Paper UCD-ITS-REP-99-03.

Schwele, 1995:

CHEMICAL SPECIES:

NO - nitrogen monoxide
NO2 - nitrogen dioxide
CO - carbon monoxide
CH4 - methane
C5H8 - isoprene
SO2 - sulfur dioxide
HO2 - hydroperoxyl radical
OH - hydroxyl radical
PNA - pernitric acid
HNO3 - nitric acid
PAN - peroxy acetyl nitrate