

*Decadal Survey Concept
NRC RFI response May 16th, 2005*

*Observations of Tropospheric Air Chemistry Processes from a
Geostationary Perspective*

*Time-resolved measurements of tropospheric constituents, theme areas
1,3,4,6, medium to large size mission (~\$400-500M).*

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Abstract

The scientific rationale and benefits of a geostationary tropospheric air chemistry mission concept are presented in the context of a notional mission: Geostationary Observatory for Tropospheric Air Chemistry (GeoTRACE). GeoTRACE investigates the effects of gas and particle emissions, weather, and chemistry on the global pollutants carbon monoxide, ozone, and aerosols. These pollutants affect regional and global air quality, climate change, and the atmosphere's ability to cleanse itself. GeoTRACE information will strengthen efforts to predict these pollutants' behavior in the face of uncertain climate change and increasing population and industrialization. GeoTRACE maps global regions at 5 km × 5 km resolution from geostationary orbit. Each hour it measures the chemically linked tropospheric constituents nitrogen dioxide, formaldehyde, carbon monoxide, ozone, and aerosols. GeoTRACE incorporates the proven remote sensing capability of UV/Visible spectroscopy for nitrogen dioxide, formaldehyde, ozone and aerosols and of gas filter correlation radiometry for carbon monoxide. Alternative carbon monoxide and dioxide measurement methods such as high spectral resolution Fabry-Perot imaging or Fourier transform spectroscopic techniques currently in development could also be incorporated into a future platform instrument suite.

GEOSTATIONARY CHEMISTRY MISSION SCIENTIFIC OBJECTIVES

1.1 RESEARCH/APPLICATIONS GOALS, OBJECTIVES, AND JUSTIFICATION

Understanding the roles of tropospheric ozone (O₃) and aerosols in perturbing the Earth system is a research priority for NASA and the U.S. Global Change Research Program (USGCRP) [NAS 1995]. A major challenge for the USGCRP is determining the controlling chemical and transport processes for tropospheric O₃ and aerosols [NSTC 1999]. The Geostationary Observatory for Tropospheric Air Chemistry (GeoTRACE) answers this USGCRP challenge by addressing the question:

What are the effects of local and regional pollution on the global atmosphere, and what are the effects of global pollution on regional air quality?

This overarching Earth Science Enterprise (ESE) topic [NASA 2000] is composed of four focused science questions:

- **Q1: What are the spatial and temporal emission patterns of the precursor chemicals for ozone and aerosols?**
- **Q2: What are the influences of weather in transforming and dispersing emissions, ozone, and aerosols into the global pollution?**
- **Q3: What is the evolution of the pollutants ozone and aerosols, from chemical formation and transport to losses by chemistry and deposition?**
- **Q4: What are the regional budgets for carbon monoxide, ozone, and aerosols over North America and regions bordering the Indian Ocean?**

By answering these four questions through intelligent coupling of GeoTRACE and weather observations with models, we can contribute to three ESE research foci:

- Continental-scale air quality. *Changing global pollutant emission patterns and more stringent air quality standards bring to question the role of intercontinental transport on air quality [Jacob, et al. 1999; Jaffe, et al. 1999; NRC 2001].*
- Climate change. *Tropospheric O₃, a greenhouse gas, and aerosols, by direct and indirect radiative effects, have important but highly uncertain roles in climate change [Hansen, et al. 2000; IPCC 2001].*
- The atmosphere's ability to cleanse itself. *The atmosphere's ability to cleanse itself of chemicals (e.g., CO, CH₄, HCFCs) depends on the patterns and types of chemical emissions [WMO 1999; IPCC 2001].*

GeoTRACE enables answers to these science questions by measuring, from geostationary orbit, the tropospheric column densities of chemically linked nitrogen dioxide (NO₂), formaldehyde (CH₂O), carbon monoxide (CO), ozone (O₃), and scattering and absorbing aerosols (i.e., aerosol optical depth and single scattering albedo). Measured cloud heights help distinguish constituents in the planetary boundary layer (PBL) (< 3 km) from those in the free troposphere (FT). These constituents are measured every half hour during daylight with nominal 5 km horizontal resolution. The field-of-view is 5000 km × 5000 km.

One possible mission concept would start with sequential half-hour views of western and eastern North America and adjacent regions, giving hourly observations for the continental United States. Tropical biomass burning or pollution in South or Central America could be observed as targets of opportunity. After 14 months, the satellite could

be repositioned over the Indian Ocean. Here, GeoTRACE would observe the rapidly developing South Asia and adjoining regions for two years (i.e., two monsoon cycles). For a complete global view, we envision a future global network of geostationary satellites for pollutant observations based on GeoTRACE path finding concepts. Alternative orbits, which slowly drift over time, could also be considered to improve coverage.

The base instrument package for GeoTRACE would consist of a UV/Vis spectrograph to measure NO₂, CH₂O, O₃, and aerosols, and a CO measurement instrument such as a gas filter correlation radiometer or future Fabry-Perot imager.

Existing Scientific Knowledge

NO₂, CH₂O, CO, O₃, and aerosols form a critical constituent subset for understanding atmospheric chemistry. Interactions of sunlight, nitrogen oxides (NO_x=NO+NO₂), volatile organic compounds (VOCs), and CO create tropospheric O₃ and aerosols in a few hours (Figure 1). These interactions are non-linear with respect to emissions of NO_x, VOCs, and CO. For instance, O₃ production often increases with NO_x until NO_x reaches ~1 ppbv and then decreases at higher NO_x. At NO_x less than ~1 ppb, O₃ production is limited by the availability of NO_x (NO_x-limited); above the peak, it is VOC-limited. Formaldehyde (CH₂O) is a reactive product of the oxidation of both natural VOCs (mainly from forests) and anthropogenic VOCs. CO is a tracer of combustion. Surface values of NO₂, CH₂O, CO, O₃, and aerosols can change rapidly, as shown by NO₂ and O₃ data from Nashville in Figure 1 [E. Williams, R. Cohen, private communication]

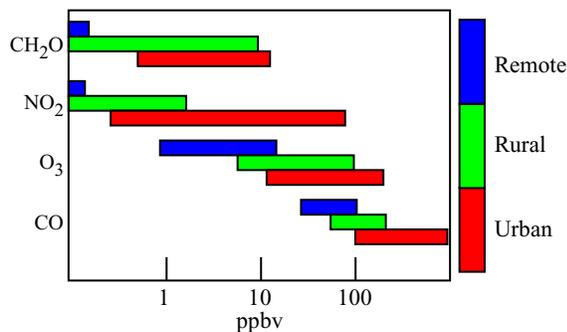
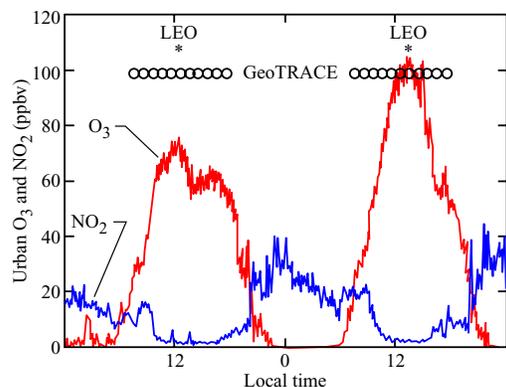


Figure 2 Hourly daytime GeoTRACE measurements (o) track rapid changes. LEO satellites measure once daily at best.

Figure 1 GeoTRACE is engineered to measure trace gases over their atmospheric ranges.

Remote areas (e.g. distant oceans) have less pollution than rural areas (e.g. farmland and forests) and urban areas, which emit most industrial pollution (Figure 2). Typical constituent ranges in these areas are shown in the figure. For instance, CH₂O is 1 to 10 ppbv in both rural and urban areas because natural and urban sources are comparable,

as shown by the colored bars in Figure 2. Emissions, ozone and aerosol production, and the dispersion of these pollutants from source regions to the global atmosphere depend on weather systems, from cloud scale (~1 km) to global scale (~10,000 km). Weather fronts and storms loft pollutants into the free troposphere (FT) above ~3 km, permitting long-range transport [Bethan, et al. 1998; Levy, et al. 1999; Cooper, et al. 2001]. O₃ and aerosols, with lifetimes of weeks, and other pollutants in the FT can travel across oceans. CO, with a lifetime of a few months, disperses throughout a hemisphere. Pollutant plumes from biomass burning, fires, and industrialization have been found even in remote regions of the Pacific.

By contrast, regional summertime stagnation episodes cause accumulation of pollutants in the PBL [Kasibhatla and Chameides 2000]. The associated high temperatures and sunshine lead to high natural VOC emissions and to rapid O₃ and aerosol production. Pollutants become well mixed throughout the PBL, but because NO₂, CH₂O, O₃, and aerosols in the PBL react or deposit on surfaces in hours to a few days, they travel only short distances.

Addressing the Science Questions with GeoTRACE Measurements

The current working knowledge of the processes controlling tropospheric O₃ and aerosols is not yet sufficient for predictive capability adequate for societal needs, even for North America. For the Indian Ocean region even less is known. The INDOEX field study in 1999 [Lelieveld, et al. 2001] found extreme pollution over the Indian Ocean from Indian outflow but could not reconcile it with estimates of Indian emissions. Answering the four GeoTRACE science questions will greatly enhance the knowledge of air pollution in North America and the Indian Ocean region. The discussions below show GeoTRACE's contributions to answering these questions. GeoTRACE takes hourly snapshots over an entire continent. Using GeoTRACE data with CTMs addresses the science questions in ways that would require data from a fleet of LEO satellites. Imagine looking at a high-resolution regional map of the tropospheric column densities for NO₂, CH₂O, CO, O₃, and aerosols. Hot spots of large column densities over and downwind of emission sources show large PBL constituent mixing ratios. Plumes in the FT appear as larger scale, more rapidly moving, less intense elevated column densities. Hour by hour map patterns change as a result of simultaneous chemistry and transport. Understanding the patterns' evolution comes from the use of CTMs, weather data, and methods for finding the plume altitude (as described in Section 1.2). GeoTRACE provides millions of individual time-varying signals of these constituents, an approach for process studies that is uniquely different from but complementary to intensive campaigns.

Experience with using satellite data (referenced below) and field data [e.g., Cowling, et al. 1998] shows that the precision and accuracy in Table 1 exceed the needs for addressing the following four science questions.

| Table 1 Mission sensitivity analysis. Measurement needs for science translate into required column density measurement capability. | | | |
|--|--|-----------------|---|
| Level 3 data Products | Needed mixing ratio precision (Δ) | Needed Accuracy | Column density capability* mol.cm ⁻² |
| NO ₂ | 0.2 ppbv | ±20% | 5.0 × 10 ¹⁴ |
| CH ₂ O | 1.0 ppbv | ±20% | 2.5 × 10 ¹⁵ |
| O ₃ | 5 ppbv | ±10% | 1.3 × 10 ¹⁶ |
| CO | 10 ppbv | ±20% | 1.0 × 10 ¹⁷ |
| aerosol opt. depth | 0.02 | ±0.05 or ±20% | N.A. |
| aerosol single scat. albedo | 0.01 | ±0.03 | N.A. |
| Cloud cover | N.A. | ±20% | N.A. |
| Cloud height | N.A. | 40hPa@800 hPa | N.A. |
| Resulting requirements for measurements of constituent temporal changes | | | |
| dNO ₂ /dt | 0.4 ppb/hr | ±30% | 1.0 × 10 ¹⁵ /hr |
| dCH ₂ O/dt | 2.0 ppb/hr | ±30% | 5.0 × 10 ¹⁵ /hr |
| dO ₃ /dt | 10 ppb/hr | ±15% | 2.5 × 10 ¹⁶ /hr |
| dCO/dt | 20 ppb/hr | ±30% | 2.0 × 10 ¹⁷ /hr |
| * Assumes PBL height of 1 km. | | | |

Q1: What are the spatial and temporal emission patterns of the precursor chemicals for ozone and aerosols?

Regional emission inventories for the precursor gases NO_x, VOCs, and CO are generally not known to better than a factor of 2 to 5 [Hanna, et al. 2001; Guenther, et al. 2000]. Direct emissions of soot and organic aerosols are also poorly quantified [Houyoux, et al. 2000]. Even less well known is the day-to-day variability of these emissions.

GeoTRACE will greatly improve emission inventories for NO_x, VOCs, CO, and aerosols. The spatial and temporal patterns in observed tropospheric columns of NO₂, CH₂O, CO, and aerosols can be related to corresponding emission patterns. Further quantification of emissions comes from inverting CTMs. This approach improved emission estimates of NO_x and VOCs from the GOME NO₂ and CH₂O data [Thomas, et al. 1998; Chance, et al. 2000; Leue, et al.

2001], of CO from MOPITT CO data [Lamarque, et al. 2000], and of dust and biomass burning emissions from TOMS aerosol index data. GeoTRACE provides spatial and temporal resolution more closely matched to actual emissions than these existing sensors. GeoTRACE sub-urban scale resolution and continental span will greatly improve emission inventories [Bergamaschi, et al. 2000].

GeoTRACE information will:

- decrease emission uncertainties by at least a factor of two for its viewing regions.
- constrain emissions in CTMs much better than any previous data set.

Q2: What are the influences of weather in transforming and dispersing emissions, O₃, and aerosols into the global pollution?

The interactions of weather processes with evolving pollutants have large uncertainties [NRC 1991]. Each day emissions and pollutants are well mixed throughout the PBL by turbulence. The PBL height itself increases rapidly in the morning, thus changing the mixing volume. Synoptic systems and storms sweep pollutants from the PBL into the FT. In addition, pollution traveling great distances in the FT can mix down, influencing surface air quality, as occurred in 1999 when pollution from Canadian wildfires affected Nashville air quality [Wotawa and Trainer 2000].

Studying the influence of weather requires the superpositioning of GeoTRACE tropospheric column densities, their spatial and temporal differences, and weather data on similar spatial scales in CTMs. For example, observed tropospheric column densities will

evolve as a front passes through a region, lifting constituents into the FT. Or, tracking the edges of elevated CO column densities moving with the speed of winds in the FT will indicate intercontinental transport. These observations will test the transport in CTMs.

GeoTRACE information will:

- improve the understanding of the interactions of chemistry and transport on urban-to-continental scales. This improved understanding will lead to better regional and global CTMs.
- be used with regional and global CTMs, by comparison and inverse modeling, to address ESE topics.

Q3: What is the evolution of the pollutants ozone and aerosols, from chemical formation and transport to losses by chemistry and deposition?

While CTMs generally reproduce averaged observed O₃ away from source regions [Wang, et al. 1998], they have difficulty for specific events, short-term variations, and close proximity to sources [Kasibhatla and Chameides 2000]. The situation for aerosols is worse [Chin, et al. 2001; Penner, et al. 2001]. Uncertainties in wind, cloud cover, NO₂ photolysis, and natural VOC inventories create 20-80% uncertainties in calculated O₃ [Hanna, et al. 2001]. Calculated organic aerosols have larger uncertainties [Kanakidou, et al. 2000].

GeoTRACE's simultaneous measurements of a critical constituent subset for atmospheric chemistry permits study of processes such as rush hour, vegetation respiration, and fires. Studying these non-linear, rapid processes is possible because the emissions and pollutants are co-located in the well-mixed PBL or in large plumes. Whereas ground-based networks are confounded by simultaneous changes in emissions, chemistry, and PBL heights, GeoTRACE measures changing tropospheric column densities, thus giving a more accurate picture of the emissions and the total O₃ and aerosol production. Downwind of the sources, only longer-lived constituents remain. GeoTRACE can track the evolution of O₃ and aerosols by comparing their changes with those of the longer lived tracer of transport, CO, in combination with GeoTRACE cloud height measurements, CTMs, and weather data.

GeoTRACE information will:

- map the evolution by non-linear chemistry and transport of chemically linked constituents and pollutants on urban-to-continental scales for the first time.
- enable Lagrangian studies of pollution evolution in the PBL and large FT plumes.

Q4: What are the regional budgets for CO, O₃, and aerosols over North America and regions bordering the Indian Ocean?

The standard approach for deriving chemical budgets on continental scales is to use CTMs constrained and evaluated with observations. The observations applicable for this purpose are presently limited to ground-based networks—and then only for North America [U.S. EPA 1997] and aircraft campaigns. The resulting data are sparse and generally inadequate to constrain the different budget terms including emission inventories, PBL transport and chemistry, and inflow/outflow.

GeoTRACE will dramatically change that situation by providing hourly measurements throughout a year to map concentrations and inflow/outflow fluxes over major pollution source regions. These measurements will considerably improve the ability of CTMs to compute budgets, in particular through the use of chemical data assimilation methods.

GeoTRACE information will:

- provide the data necessary to constrain budgets of CO, O₃, and aerosols on regional to continental scales.

Relationship to Existing or Approved Missions

Existing Earth Observing System (EOS) instruments that measure tropospheric pollutants include MOPITT for CO, TOMS for O₃, MODIS/MISR for aerosols and the AURA instruments TES and OMI, which combined measure tropospheric CO and O₃, upper tropospheric nitric oxide, and tropospheric aerosols. These missions are all in low Earth orbit (LEO). GeoTRACE and these LEO instruments measure many of the same atmospheric constituents using similar physics. LEO instruments measure each location once a day at best with horizontal resolution >20 km; GeoTRACE measures every half hour with nominal 5 km resolution (Figure 1). Nadir viewing LEO instruments (other than lidar) have vertical resolution of ~6 km; GeoTRACE will be able to distinguish between enhanced tropospheric columns in the FT and PBL. GeoTRACE will use the global maps from LEO measurements to identify specific events, like biomass burning or forest fires, for GeoTRACE targeted observations.

1.2 MEASUREMENT OBJECTIVES

UV/Vis Spectrometer Measurements

The primary measurement objective of the UV/Vis instrument is the hourly mapping of tropospheric columns for NO₂, CH₂O, O₃, aerosol optical thickness, and single scattering albedo across regions such as the U.S. NO₂ and O₃ have significant background levels in the stratosphere as well as high variability in the troposphere. Separating the tropospheric column from the total column is a critical measurement requirement. Measuring from geostationary orbit provides three approaches for extracting the tropospheric column: 1) cloud slicing, 2) Rayleigh slicing, and 3) morphological/dynamical analysis. The first step in deriving tropospheric column density is making precise total column measurements. The GeoTRACE concept draws on TOMS, SBUV/2, and GOME experience to define the UV/Vis instrument and retrieval techniques. Total column O₃ is determined using TOMS techniques. Backscatter albedos at different wavelengths are compared with pre-computed expected albedo values in a computationally efficient, table lookup retrieval algorithm. Due to Rayleigh scattering, the traditional ultraviolet TOMS wavelengths are less sensitive to ozone in the lower part of the atmosphere [Klenk et al 1982, Hudson, et al 1995]. GeoTRACE will extend the ozone retrieval to include wavelengths in the visible Chappuis ozone bands ensuring that the measured backscattered light has completely penetrated the atmosphere to the surface.

Total column NO₂ and CH₂O are determined using techniques developed for GOME [Thomas, et al. 1998; Leue, et al. 2001; Chance, et al. 2000]. Spectra are fitted using least-squares analysis, simultaneously including contributions from interfering species, the Ring effect, and the oxygen collision complex. The small NO₂ absorption (0.4% peak-to-peak) sets the instrument's SNR requirements. Measuring 10% changes in the NO₂ column requires a SNR of ~2000.

UV measurements are uniquely sensitive to absorbing or non-sulfate aerosols. Absorbing aerosol properties are derived by algorithms developed for GOME data [Gleason, et al. 1998; Torres, et al. 1998; Hsu, et al. 1999]. By using spectral radiance

measurements in the visible spectrum and in the infrared from the gas filter correlation radiometer, we can derive aerosol properties (size and optical thickness) for both absorbing and scattering aerosols [Kaufman, et al. 1997].

Some vertical tropospheric resolution is possible using cloud slicing methods [Joiner and Bhartia 1995] because the absorption occurs only above a reflecting surface, whether ground or a cloud. GeoTRACE's 5 km resolution and hourly sampling enable analysis with a variety of cloud conditions over several individual adjacent locations during the course of a day, and thus enable profile extraction. At a minimum, the troposphere can be separated from the stratosphere, as has been demonstrated with tropical deep convective clouds that reach the tropopause [Ziemke, et al. 1998]. Further, the average tropospheric O₃ derived from the slope of O₃ column abundance with cloud height agreed with balloon profiles [Ziemke, et al. 2001].

Cloud height can be measured with sufficient accuracy by quantifying the Ring Effect (observing the filling-in of Fraunhofer lines) [Joiner and Bhartia 1995]. From GeoTRACE data, effective cloud heights can be determined by several independent methods: the Ring Effect, O₂-O₂ complex measurements, and the CH₄ and N₂O column measurements from the IR instrument.

Both NO₂ and O₃ tropospheric columns can be found by Rayleigh slicing techniques. Rayleigh slicing requires diurnal measurements over the same Earth location, which is possible only from GEO. The altitude at which a particular wavelength is Rayleigh scattered is a function of solar zenith angle [Solomon, et al. 1987; Perliski and Solomon 1993]. Thus, profile information can be extracted from measurements made at different solar zenith angles during sunrise and sunset.

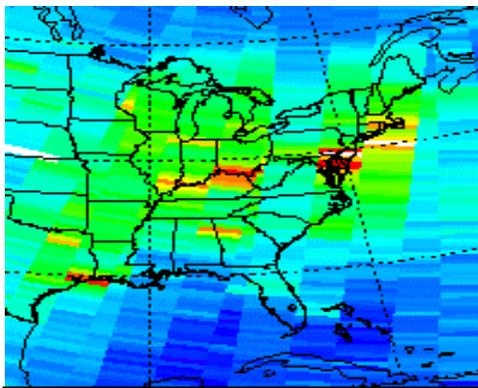


Figure 3 GOME NO₂ April 1-3, 1998.

Ground based observations show that this technique separates tropospheric and stratospheric components of NO₂ [McKenzie, et al. 1991; Preston, et al. 1997; 1998]. We have extended the methods developed by McKenzie, et al. and Preston, et al. using the retrieval formalism developed by Twomey [1977]. Our analysis shows the retrieval errors for tropospheric NO₂ are less than 10%. GeoTRACE can use the same Rayleigh slicing techniques to determine the tropospheric O₃ column. The O₃ retrievals are based on the Rayleigh scattering cross section difference

between the UV Huggins Band and the visible Chappuis band. This difference enables the clean separation of tropospheric and stratospheric O₃ column components.

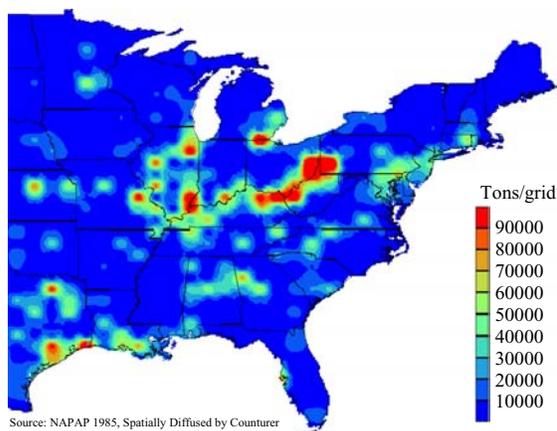


Figure 4 NO_x point source emissions.

Morphological/Dynamical separation depends on the difference in spatial and temporal scales between the stratosphere and the troposphere. Column densities vary more slowly over larger scales in the stratosphere than in the troposphere. Retrievals from GOME show that anthropogenic NO₂ signatures can be detected even with GOME's coarse spatial (40 km × 320 km) and temporal (3-day) resolution (Figure 3). The NO₂ variations

in Figure 3 are spatially correlated with tropospheric NO_x emission sources (Figure 4), although exact correspondence should not be expected between a 3-day GOME map and annual NO_x emissions. GeoTRACE's high spatial and temporal resolution will permit even sharper features and better separation between troposphere and stratosphere.

(Note: The following section highlights CO measurement requirements based on work done at the NASA - Langley Research Center(LaRC), however the precise instrumentation, correlation radiometer, Fabry-Perot, FTIR etc. needs further study. The current LaRC Geostationary concept is presented in more detail in a companion submittal entitled " Earth's First Time-Resolved Mapping of Air Pollution, Emissions, and Transport from Space [Fishman, et al.]

IR Gas Filter Correlation Radiometer Measurements

The primary objective of the GeoTRACE infrared (IR) gas filter correlation radiometer is hourly mapping of CO across regions such as the U.S. CO is principally a tropospheric constituent, and GeoTRACE measures the tropospheric CO directly. Using both surface reflected sunlight at 2.3 μm and thermal transmission at 4.6 μm, GeoTRACE measures both total and free tropospheric CO columns. The PBL column is the difference of the total and free tropospheric CO columns.

CO measurements require spectral resolution of the order of the rotational line width (0.2 cm⁻¹) to separate the CO signature from spectral interference by other gases. Gas filter correlation radiometry (GFCR) uses a sample of the gas of interest as a highly selective filter to match narrow spectral features and the line spacing in the atmosphere. The integrated spectral information comes from the difference of signals that are obtained through gas cell filters with different gas conditions. Gas filter correlation radiometry achieves effective high-resolution measurements that are equivalent to measurements from a spectrometer with a spectral response function identical to the gas cell absorption spectrum. GFCR provides the advantages of substantially larger throughput and SNR, stability of instrument line shape, and tractable data volume. Measurements of global tropospheric CO from space were first obtained by LaRC's MAPS experiment using

GFCR [Reichle, et al. 1986; 1990; 1999] and subsequently by MOPITT [MOPITT website].

Building on the experience from MAPS and MOPITT, GeoTRACE uses GFCR in two infrared regions: solar reflectance at 2.3 μm in one spectral bandpass, and thermal upwelling radiation at 4.1 – 4.6 μm in four spectral bandpasses. In combination with these five spectral bandpasses, four gas cells, separately filled with CH_4 , N_2O , and two different amounts of CO , generate 20 data channels. Combining these channels permits column retrievals of the CO , CH_4 , and N_2O , and provides retrieval by-products of surface temperature, atmospheric temperature, surface emissivity, and total column water vapor with the same spatial and temporal resolution.

CH_4 and N_2O , which have nearly uniform mixing ratios in the troposphere, are retrieved to 2% for reference to verify the column depth and identify clouds in the field of view. In cloudy pixels, the amount of CH_4 and N_2O above the clouds provides two separate estimates of cloud height for use in GeoTRACE's UV/Vis retrievals.

Sensitivity and definition studies for the GeoTRACE IR instrument used standard techniques [Gordley, et al. 1994 and Marshall, et al. 1994 derived from Rodgers 1990], and the 1996 version of the HITRAN line parameter database [Rothman, et al. 1998]. An analytical model of the instrument was used in a trade study of fixed gas cell pressures and lengths against SNR and sensitivity to errors. The eigenvector analysis of the sensitivity matrix indicates that, like MOPITT, GeoTRACE will resolve three layers in the troposphere and retrieve total column CO to better than 10%. Retrieval noise, errors in atmospheric temperature profile, and errors in column water vapor result in root mean square sensitivity to these errors of less than 10% of the CO total column. These analyses indicate that GeoTRACE will provide CO measurements with precision and vertical resolution comparable to MOPITT, but with improved spatial resolution ($5 \times 5 \text{ km}^2$ compared to $22 \times 22 \text{ km}^2$ for MOPITT) over the selected Earth surface region, and enhanced temporal resolution (revisit time of one hour over the U.S. compared with three days for MOPITT).

MOPITT algorithms provide the basis for GeoTRACE GFCR retrievals for CO using similar spectral bands and a closely related gas filter correlation technique [Pan, et al. 1998]. Instrument SNR requirements were derived from modeled sensitivity and retrieval analysis for 10% accuracy of total column CO (Figure 5). The absolute radiance is

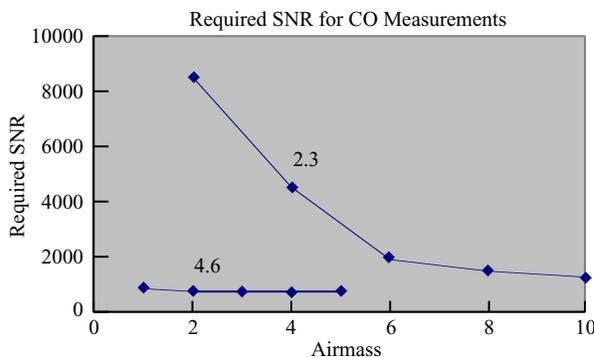


Figure 5 GeoTRACE CO SNR requirements determined from expected line-of-sight airmass.

similar in both spectral regions, but the spectroscopic signature of CO is less intense at 2.3 μm , where higher SNR is required. The airmass at 40° latitude from the sub-satellite point is approximately 2.6. This achievable design for 10% measurement accuracy provides margin for performance trades that meet the 20% CO accuracy requirement in Table 1.

With fixed-condition gas cells, GeoTRACE algorithms for retrieving

CO are based on the optimal estimation technique of Rodgers (1976, 1990), the MOPITT retrieval process [Pan, et al. 1998], and the GeoTRACE instrument model developed for the sensitivity studies [Neil, et al. 2000] described above.

In summary, a geostationary chemistry mission which could accomplish the measurement requirements outlined here, would make significant contributions to several science theme areas within the Earth Science research program, particularly in the study of chemical weather and the evolution of pollution events directly relevant to societal needs. While not addressed in this example, a geostationary platform would also be advantageous for additional instrumentation to map CO₂ sources and sinks to address climate variability. The links between science objectives and measurement requirements is presented in Appendix A, Science Traceability Matrix, along with a ROM lifetime mission cost estimate.

Appendix A – Science Traceability Matrix and Cost Estimate

| Science traceability matrix. | | | |
|---|---|---|---|
| Science Objectives | Scientific Measurement Requirements | Instrument Functional Requirements | Mission Functional Requirements |
| Q1: What are the spatial and temporal emission patterns of the precursor chemicals for ozone, and aerosols? | Measure O ₃ , NO ₂ , CH ₂ O, aerosols, cloud heights | Spectral Radiance @ 315-600 nm | UV/Vis Imaging Spectrometer, GeoSpec IIP or similar |
| | Measure ΔNO ₂ = 5 × 10 ¹⁴ cm ⁻² (sets ΔCH ₂ O) | SNR 2000 @ 430 nm | |
| | Optimize pixel size for cloud coverage | 5 km × 5 km ground pixel @ 40 deg latitude | |
| | Measure ΔO ₃ = 1.3 × 10 ¹⁶ cm ⁻² (note: Δ = precision) | SNR 1000 @ 315 nm | TBD: Trade study needed, IR Imaging Gas Filter Correlation Radiometer/Fabry-Perot or traditional spectrometer |
| | Measure CO in PBL and FT | High Resolution Radiance at 2.3 μm and 4.6 μm | |
| | Measure ΔCO = 1 × 10 ¹⁷ cm ⁻² | SNR 2500 (low radiance); 9500 (high radiance) @ 2.3 μm and SNR 700 @ 4.6 μm | |
| | Simultaneous Constituent Measurements | Near Coincident Spectral Measurements | |
| Q2: What are the influences of weather in transforming and dispersing emissions, ozone, and aerosols into the global pollution? | Map emission sources | 5 km × 5 km ground pixel @ 40 deg latitude | Array Detector, Narrow IFOV |
| | Measure diurnal changes | Measure once per hour | GEO, frequent science data down links |
| | Measure over land and ocean | 2-axis scan mirror, 1000:1 scene dynamic range | 19° Field of Regard, hybrid detectors |
| | Measure ΔNO ₂ = 5 × 10 ¹⁴ cm ⁻² (sets ΔCH ₂ O) | SNR 2000 @ 430 nm | N/A |
| Q3: What is the evolution of the pollutants O ₃ and aerosols, from chemical formation and transport to losses by chemistry and deposition? | Measure over land and ocean | 2-axis scan mirror, 1000:1 scene dynamic range | 19° Field of Regard, hybrid detectors |
| | Map emission sources | 5 km × 5 km ground pixel | Array Detector, narrow IFOV |
| | Measure Δ NO ₂ = 5 × 10 ¹⁴ cm ⁻² (sets ΔCH ₂ O) | SNR 2000 @ 430 nm | N/A |
| | Measure diurnal changes | Measure once per hour | GEO, frequent science data down links |
| Q4: What are the regional budgets for CO, O ₃ , and aerosols over North America and regions bordering the Indian Ocean ? | Measure seasonal variations of CO, O ₃ , and aerosols | 3 year mission lifetime On-board calibration | 3 year mission lifetime |
| | Map emission sources | 5 km × 5 km ground pixel | Narrow IFOV |
| | Map continent and regions up and down wind | 5° × 5° FOV 2-axis scan mirror | Array detector |

Cost Estimate

(in millions)

| | |
|--------------------|-------|
| UV/VIS instrument | \$25 |
| SWIR/IR instrument | \$25 |
| Spacecraft | \$100 |
| Ground system | \$10 |
| Data Processing | \$8 |
| Validation | \$5 |
| Project Management | \$5 |
| Subtotal | \$178 |
| Education/Outreach | \$4 |
| Launch | \$175 |
| Subtotal | \$357 |
| Reserve | \$107 |
| Total | \$464 |

Appendix B– References

- Bergamaschi, P., et al. 2000: Inverse modeling of the global CO cycle: 1. Inversion of CO mixing ratios, *J. Geophys. Res.*, 105, 1909.
- Bethan, S., et al. 1998: Chemical air mass differences near fronts, *J. Geophys. Res.*, 103, 13,413.
- Chance, K., et al. 2000: Satellite observations of formaldehyde over North America from GOME, *J. Geophys. Res.*, 27, 3461.
- Chin, M., et al. 2001: Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and sunphotometer measurements, *J. Atmos. Sci.*, in press.
- Cooper, O.R., et al. 2001: Trace gas signatures of the airstreams within North Atlantic cyclones: Case studies from the North Atlantic Regional Experiment (NARE '97) aircraft intensive, *J. Geophys. Res.*, 106, 5437.
- Cowling, et al. 1998: Introduction to special section: southern oxidants study Nashville/Middle Tennessee ozone study, *J. Geophys. Res.*, 103, 22,209.
- Fishman J., et al. 2005: Earth's First Time-Resolved Mapping of Air Pollution, Emissions, and Transport from Space, *NRC Decadal Survey Concept Submittal*, 2005.
- Gleason, J.F.; Hsu, N.C.; Torres, O. 1998: Biomass burning smoke measured using backscattered ultraviolet radiation: SCAR-B and Brazilian smoke interannual variability. *J. Geophys. Res.*, 103, 31969-31978.
- Gordley, L. L.; Marshall, B.T.; and A.D. Chu 1994: LINEPAK: Algorithms for modeling spectral transmittance and radiance. *J. Quant. Spectrosc. Radiat. Transf.*, 52, 563-580.
- Guenther, A., et al. 2000: Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. *Atmos. Environ.*, 34, 2205-2230.
- Hanna, S.R., et al. 2001: Uncertainties in predicted ozone concentrations due to input uncertainties for the UAM-V photochemical grid model applied to the July 1995 OTAG domain, *Atmos. Environ.*, 35, 891.
- Hansen, J., et al. 2000: Global warming in the twenty-first century: An alternative scenario, *Proc. Natl. Academy of Sciences*, 97, 9875-9880.
- Houyoux, M.R., et al. 2000: Emission inventory development and processing for the Seasonal Model for Regional Air Quality (SMRAQ) project, *J. Geophys. Res.*, 105, 9079.
- Hsu, N.C., et al. 1999: Comparisons of the TOMS aerosol index with Sun-photometer aerosol optical thickness: Results and applications, *J. Geophys. Res.*, 104, 269-6279.
- Hudson, R.D., et. al. 1995: On the derivation of tropospheric column ozone from radiances measured by the total ozone mapping spectrometer, *J. Geophys. Res.*, 100, 11137-11145.
- IPCC (Intergovernmental Panel on Climate Change) Albritton, D.L.; Meira Filho, L.H. 2001: Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, U.K.
- Jacob, D.J.; Logan, J.A.; and Murti, P.P. 1999: Effect of rising Asian emissions on surface ozone in the United States, *Geophys. Res. Lett.*, 26, 2175-2178.
- Jaffe D.A., et al. 1999: Transport of Asian air pollution to North America. *Geophys. Res. Lett.* 26, 711-714.
- Joiner, J.; and Bhartia, P.K. 1995: The determination of cloud pressures from rotational Raman scattering in satellite backscatter ultraviolet measurements. *J. Geophys. Res.*, 100, 23,019-23,026.
- Kasibhatla, P.; and Chameides, W.L. 2000: Seasonal modeling of regional ozone pollution in the eastern United States, *Geophys. Res. Lett.*, 27, 1415.
- Kanakidou, M., et al. 2000: Human-activity-enhanced formation of organic aerosols by biogenic hydrocarbon oxidation, *J. Geophys. Res.*, 105, 9243.
- Kaufman, Y.J., et al. 1997: Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *J. Geophys. Res.*, 103, 17051-17067.

- Klenk, K.F., et al. 1982: Total ozone determination from the Backscattered UltraViolet (BUV) experiment, *J. Applied Meteorology* 21, 1672-1684.
- Lamarque, J.F., et al. 2000: Assimilation of Measurement of Air Pollution from Space (MAPS) CO in a global three-dimensional model. *J. Geophys. Res.* 104, 26,209-26,218.
- Lelieveld, J., et al., 2001: The Indian Ocean experiment: Widespread air pollution from south and southeast Asia, *Science*, 1031-1036.
- Leue, et al. 2001: Quantitative analysis of NO₂ emissions from Global Ozone Monitoring Experiment satellite image sequences, *J. Geophys. Res.*, 106, 5493.
- Levy, H., et al. 1999: Simulated tropospheric NO_x: Its evaluation, global distribution, and individual source contributions, *J. Geophys. Res.*, 104, 26,279.
- Marshall, B.T.; Gordley, L.L.; and D.A. Chu 1994: BANDPAK: Algorithms for modeling broadband transmission and radiance. *J. Quant. Spectrosc. Radiat. Transfer*, 52, 581-599.
- McKenzie, R. L.; et al. 1991: Altitude distributions of stratospheric constituents from ground-based measurements at twilight. *J. Geophys. Res.*, 96, 15,499-15,551.
- MOPITT website: visibleearth.nasa.gov/Sensors/Terra/MOPITT.html
- NAS: National Academy of Sciences board on sustainable development 1995: *A review of the U.S. global change research program and NASA's mission to planet Earth/Earth Observing System*, National Academy Press, Washington, 96.
- NASA 2000: Exploring our home planet. Earth Science Enterprise Strategic Plan, Washington, D.C. www.earth.nasa.gov
- Neil, D.O., et al. 2000: Tropospheric carbon monoxide measurements from geostationary orbit, *Satellite remote sensing of clouds and the atmosphere*, *SPIE Proc.*, 4168, 265 – 273.
- NRC: National Research Council 2001: *Global air quality: An imperative for long-term observational changes*, National Academy Press, Washington, D.C.
- NRC: National Research Council 1998: *The atmospheric sciences: Entering the 21st century*, National Academy Press, Washington, D.C.
- NRC: National Research Council 1991: *Rethinking the ozone problem in urban and regional air pollution*, National Academy Press, Washington, D.C.
- NSTC: National Science and Technology Council 1999: *Our changing planet, the FY2000 U.S. global change research program*, Office of Science and Technology Policy, Washington, D.C., 100.
- Pan, L.; Gille, J.C.; Edwards, D.P.; and Bailey, P. L. 1998: Retrieval of tropospheric carbon monoxide for the MOPITT experiment. *J. Geophys. Res.*, 103, 32277.
- Penner, J., et al. 2001: A comparison of model- and satellite-derived depth and reflectivity, *J. Atm. Sci.*, in press.
- Perliski, L. M.; and Solomon, S. 1993: On the evaluation of air-mass factors for atmospheric near-ultraviolet and visible absorption-spectroscopy. *J. Geophys. Res.*, 98, 10,363-10,374.
- Preston, K.E.; Jones, R.L.; and Roscoe, H.K. 1997: Retrieval of NO₂ vertical profiles from ground-based UV-visible measurements-method and validation. *J. Geophys. Res.*, 103, 19089-19097.
- Preston, K.E., et al. 1998: Accurate derivation of total and stratospheric vertical columns of NO₂ from ground-based zenith-sky measurements. *J. Atmos. Chem.*, 30, 163-172.
- Reichle, H.G., Jr., et al. 1986: Middle and upper tropospheric carbon monoxide mixing ratios as measured by a satellite borne remote sensor during November 1981. *J. Geophys. Res.*, 91, 10865-10887.
- Reichle, H.G., Jr., et al. 1990: The distribution of middle tropospheric carbon monoxide during early October 1984. *J. Geophys. Res.*, 95, 9845-9856.
- Reichle, H.G., Jr.; et al. 1999: Space shuttle based global CO measurements during April and October 1994, MAPS instrument, data reduction, and data validation, *J. Geophys. Res.*, 104, 21443-21454.

- Rodgers, C.D. 1976: Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Rev. Geophys.*, 14, 609.
- Rodgers, C.D. 1990: Characterization and error analysis of profiles retrieved from remote sounding measurements. *J. Geophys. Res.*, 95, 5587-5595.
- Rothman, L.S., et al. 1998: The Hitran molecular spectroscopic database and HAWKS (Hitran Atmospheric Workstation) 1996 Edition. *J. Quant. Spectrosc. Radiat. Transl.*, 60, 665-710.
- Solomon, S.; Schmeltekopf, A.L.; and Sanders, R. W. 1987: On the interpretation of zenith sky absorption-measurements. *J. Geophys. Res.*, 92, 8311-8319.
- Thomas, W.E., et al. 1998: Detection of biomass burning combustion products in Southeast Asia from backscatter data taken by the GOME spectrometer, *Geophys. Res. Lett.*, 25, 1317-1320.
- Torres, O., et al. 1998: Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical basis, *J. Geophys. Res.*, 103, 17,099-17,110.
- Twomey, S. 1977: Introduction to the mathematics of inversion in remote sensing and indirect measurements. *Elsevier Scientific Publ.*
- U.S. EPA, *PAMS performance evaluation program final report*, 1997: Off. of Air Qual. Plann. and Stand., Research Triangle Park.
- Wang, Y.; Jacob, J.; and J.A. Logan 1998: Global simulation of tropospheric O₃-NO_x-hydrocarbon chemistry. Origin of tropospheric ozone and effects of nonmethane hydrocarbons, *J. Geophys. Res.*, 103, 10,757.
- WMO, *Scientific Assessment of Ozone Depletion: 1998*, Global ozone research and monitoring project, Report No. 44, Geneva, 1999.
- Wotawa, G.; and M. Trainer 2000: The influence of Canadian forest fires on pollutant concentrations in the United States, *Science*, 288, 324.
- Ziemke, J.R., et al. 1998: Two new methods for deriving tropospheric column ozone from TOMS measurements: The assimilated UARS MLS/HALOE and convective-cloud differential techniques. *J. Geophys. Res.* 103, 22,115-22,127.
- Ziemke, J.R.; Chandra, S.; and P.K. Bhartia 2001: "Cloud Slicing": A new technique to derive upper tropospheric ozone from satellite measurements, *J. Geophys. Res.*, 106, 9853-9867.