# *Robust IR Remote Sensing for Formaldehyde, Carbon Monoxide, Methane, and Ozone Profiles*

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## *Abstract*

NASA's technical excellence can be brought to fruition through a consistent, daily, global mapping of major IR-active and pollutant gases through the whole troposphere. This a mapping serves national needs to inform air-quality forecasting as well as to understand the accumulation of radiatively active trace gases, as well as the cleansing capacity of the global troposphere. All these goals can be served by a select choice of measurements, working synergistically. Infrared technology currently in incubator phase can be used to make broad maps HCHO, CO, $CH_4$, $O_3$, and $CO_2$, with useful vertical information, especially about near-surface air. The capabilities are known from the current generation of exploratory instruments. In this document we make the case that first demonstrations of this remote sensing technology from low Earth orbit would be most advantageous. We outline important synergies with validation of existing and planned flight instruments, and discuss co-manifestation with operational earth observing instruments to utilize the new technology at significantly reduced mission costs. Our updated report focuses more on tropospheric $O_3$ and two controlling precursors, lower-tropospheric HCHO and CO, since current expectations are that instruments launched by the United States will lack these vital measurements, and that infrared techniques we advocate can add significantly to the international effort. Measurements key to the assessment of global photochemistry and carbon cycling are simple, selectable, and economical additions in our revised presentation.

We propose instruments and missions like the multi-sensor Tropospheric Infrared Mapping Spectrometer (TIMS) to make daily measurements of the vertical structure of major trace gases and take full advantage of launch capabilities currently offered by the ESSP or NPOESS programs. Instrument costs would range from under $200 M to under $500 M, depending on launch vehicle availability. A demonstration instrument package with practical use appears to require even lower pre-launch costs. We expect that this would strongly and cost-effectively add to several proposed activities, such as those employing geostationary orbits and detailed laser sampling. As several scientists have pointed out, multiple satellite platforms with identical instrumentation would allow ~4 samples per day of the sunlit Earth (up to 8, day and night), with foreseeable cost savings on successive platforms. instrument packagee. Such technological efficiency will demonstrate NASA's direct relevance to national goals by improving air pollution forecasting, emergency preparedness, weather forecasting advancement, and climatic-process science.

Collaboration between NASA, NOAA, and other operational agencies to leverage off of broader national resources for instrument launch and operation should

be seen as a major drive towards cost-effectiveness in meeting critical national goals for monitoring climate change and regional air quality.

## *Background; the Opportunity*

The Earth Observing System satellites are now fully deployed, providing scientists and the nation with a rich legacy of information regarding the Earth's surface and the composition of the atmosphere, as well as a wealth of experience in satellite remote sensing technique. However, it has not yet fulfilled national expectations or needs. Specifically, the vertical distributions of carbon monoxide (CO), methane ($CH_4$), and ozone ($O_3$) in the troposphere are not yet documented, and we have almost no information about the vital lowest kilometer wherein we live. All of these are practically observable except perhaps boundary-layer ozone. A lack of such measurements is due in part to mechanical equipment failures or instrument-life preservation strategies in the complex remote sensing equipment, and also because remote sensing problems turned out to be slightly more complex than expected (for example, cloud and surface-radiative properties must be better sampled). Still, the EOS maps we have do set a standard: they have shown the nation that we

- must continue to track global pollution processes daily to make local pollution forecasts (the ICARTT-2004 experience),
- must follow events, e.g. seasons of major region-wide forest fires or flooding, and
- must track global radiatively active gases as they are affected by continual variation in climate as well as changing human activities. We must sense globally to forecast locally
- are pushing technology towards a goal of appropriate mapping for ozone and its varying precursors in the lower troposphere, and finding constraints of the first generation but also the real promise of the next.

To accomplish these ends, the sources of carbon monoxide, methane, and ozone must be fully revealed by remote sensing mapping techniques, otherwise current priorities for NASA and other agencies make it highly doubtful that the nation can mobilize the technologies and personnel to make these maps. We expect that, barring considerable transfer of funds and experienced personnel, NOAA will be fully occupied with the development of new generations of geostationary instruments (EOS 7 and 8 sensors) mid-infrared sounders (e.g., CrIS), and other instruments that are to be deployed on the National Polar-orbiting Operational Environmental Satellites (NPOESS). These instruments are all closely tied to pressing goals of improving temperature and water vapor profiling. In fact, new polar-orbiter instruments will aid these major efforts.

We will outline an opportunity for NASA's unique opportunity to close this gap, using as our prime example a Tropospheric Infrared Mapping Spectrometer (TIMS). This instrument, which is under development, details these gases with an elegant simplicity— a simplicity that promises a robust product for consequent operational sampling. Arguments for a coordinated infrared strategy are compelling since TIMS

development also provides risk-reduction for the CrIS, progress towards true $O_3$ mapping, and valuable experience for Mars sampling.

This report addresses issues relevant to several survey study panels, including: weather and chemical weather; climate variability and change; Earth system applications and societal needs; land-use change; and the global hydrologic cycle. Consideration by the first three panels is requested.

The technology we advocate here specifically serves as required highly technological support for the national undertaking to forecast adverse air quality, in particular, ozone pollution. NASA technology development has been requested to support these forecasts undertaken by NOAA and EPA.

More broadly, interest in learning about global near-surface trace gases has been thoroughly supported by major reviewing efforts. The International Working Group on Earth Observations [2005] has listed measurement of atmospheric constituents including ozone and greenhouse gases as having a high level of importance with respect to many "societal benefit areas": disasters, climate, agriculture, water, and energy. Additional connections are listed under "fire extent and severity," which is quantitatively measured by CO and $O_3$ emission, and under "atmospheric profiles" in that TIMS provides additional information, risk reduction and accuracy for temperature and water vapor profiles. The administration's Strategic Plan for the U.S. Climate Change Science Program [2003] states these foci

> Reduce uncertainty about the sources and sinks of greenhouse gases,
>
> Increase knowledge of the interactions among pollutant emissions, long-range atmospheric transport, climate change, and air quality management
>
> Develop information on the carbon cycle, land cover and use, and biological/ecological processes by helping to quantify net emissions of carbon dioxide, methane, and other greenhouse gases, thereby improving the evaluation of carbon sequestration strategies and alternative response options

Documents by the WMO [2002], IPCC [Houghton et al. 2001], and NRC[2001] which preceded these more focused plans stressed the information available from satellite data and the need for continued and improved sampling, especially as related to sources and climatically linked variability.

## *What we have learned from the EOS era*

A synthesis of theory and experience from the EOS instruments MOPITT, AIRS, and TES (and European Space Agency's SCIAMACHY) suggests the following lessons which allow NASA to complete its original, announced EOS goal of global compositional sampling:

- The portion of the infrared with solar-reflective and the adjacent shortwave thermal frequencies are informative and deserve specialized attention.
- Complex mechanical components are prone to failure or short expected lifetimes

- Pushing resolution to a fraction of a wavenumber in separate bands is an economical way to employ fully the fundamental physics of remote sensing.
- There are great, incompletely realized synergies in the compositing ofobservations in the UV, visible, short-wave, and middle/long wave IR.
- Technology can advance rapidly, and as new bus platforms are launched over time periods of much less than 20 years it is vital to take full advantage of technological improvements.

Our exposition will proceed from a brief description of unexploited technology to a description of the needs for sampling of CO, $CH_4$, and $O_3$, and then to the practicalities of demonstrating the new instruments and attaining orbit in an extremely efficient manner.

## *Species-focused Grating Mapping Spectrometry*

The Tropospheric Infrared Mapping Spectrometer brings to completion basic technological points of experience from the EOS-development era. Vertical distributions of trace gases can be mapped using the variety of information available in the infrared spectrum.

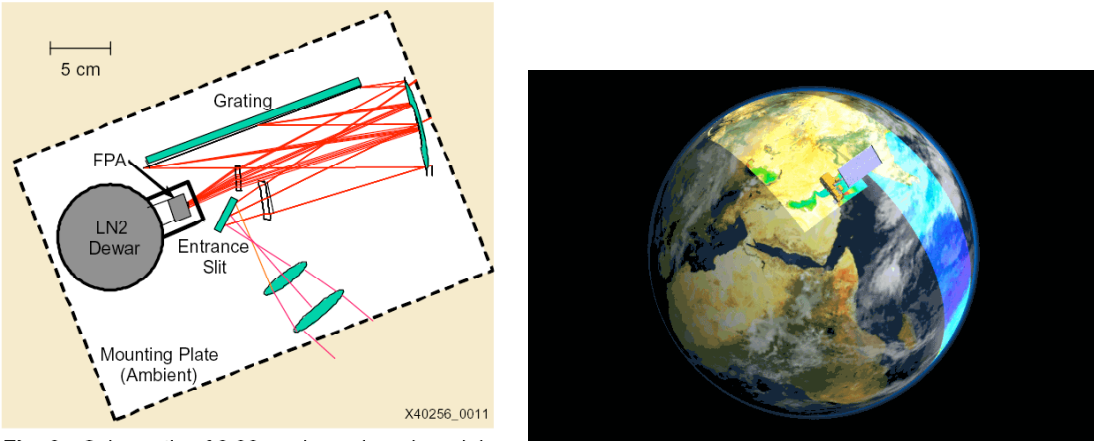


Figure 1: Grating mapping spectrometer concept as funded for IIP laboratory and limited field studies. The VSWIR brass board spectrometer for 2.33 μm is shown on the left. Daily (and nightly) global sampling of the whole Earth is illustrated on the right (note: the illustration was originally used to describe the MODIS instrument Y. Kaufman, AAAS Meeting, 2005). Also, TIMS swaths are wider and overlap fully.

This instrument concept has recently been selected for development by an Instrument Incubator Program grant to Lockheed-Martin's Advanced Technology Center (P.I., Jack Kumer). The concept is to use diffraction grating technologies with high-angle "echelle" geometries to obtain sub-wavenumber spectral resolutions within

especially informative spectral regions. As recent technology and instrument designs have shown (OMI, …), large two-dimensional detector arrays can be used for all but the extreme polar regions, with one dimension for the spectrum, and the other dimension for high spatial-resolution cross-track sampling (i.e. 2000-km wide swaths that allow for daily and nightly global sampling). Simultaneous mapping proceeds along the satellite track in a "pushbroom" motion. Configurations like these have proven increasingly popular for AIRS, and especially OMI, OCO, and CrIS. Figure 1 shows the basic concept of the spectrometers. In the basic conception there are few moving parts: simple and infrequent motions are needed only for calibration and possibly fine sighting adjustments. A representative set of measurements is listed in Table 1. It includes four grating mapping spectrometers (GMS) operating in the

- very Short Wave Infrared (VSWIR),
- short wave Infrared (SWIR),
- medium wave Infrared (MWIR) and
- long wave Infrared (LWIR)

Note the by the use of multiple slits, appropriate spectral filters and grating orders, the VSWIR and SWIR GMS can target several subregions. Cooling the detectors for all but the LWIR can be achieved passively radiatively, e.g. , as with design of the NPOESS CrIS. The LWIR detector requires active cooling. Cooling the MWIR passively is the most challenging, for some applications it may be of advantage to consider the use the active cooling for both the LWIR and the MWIR.

Each GMS is simple, compact, low-power, and optimally designed for its wavelength range. An advantage of these multiple small instruments is that failure of one tends to degrade only specific capabilities. Capabilities can be incrementally added by building on experience. For example, the funded Lockheed IIP technology development instrument employs three GMS gratings to obtain complete CO profile and column information, but more limited information on column $CH_4$ and tropospheric $O_3$. Since abundant basic spectral information is available, as with TES, unforeseen difficulties with surface reflectivity/emissivity or cloud effects can be studied and corrected. There are great advantages to the TES approach, a single narrow spot looking to the nadir, between clouds, and with sufficient spectral information to model clouds. With TIMS these are improved on by the finer spatial resolution available in the basic "elemental footprint" (ELF) sampling (~1.6 – 6.4 km) and with twice daily global coverage, thereby providing many opportunities to see between the clouds. . Data retrieval in the presence of clouds can be implemented with the additional spatial and spectral information afforded by TIMS. Multiple screened ELFs (e.g., for cloud interference, and other interference) can also be averaged together to improve the signal-to-noise ratio on larger aggregated footprints.

## *Summary: Sensitivities for High Resolution IR*

Just how much can be expected from this simple, robust technique? A summary for a subset of the measurements is given in table 2 below. The retrieval performance analysis given in table 2 is taken from Kumer et al [2005a, 2005b and 2006] The analysis is consistent with the evidence from existing satellite deployed infrared instrumentation exploiting direct spectroscopy, and from the consensus of the community that have built these instruments that the fundamental determinants of capability are spectral resolution and region and sensitivity (viz, lack of noise).Methods to achieve dispersion and photon detection have engineering ramifications, but do not affect achievable results.

**Table 1. Spectral Regions and Measurements for TIMS**

| Spectral Region | Approx. $\lambda$ | Frequency resolution | Nadir ELF [1] | Primary Measurement (potential measurement) | Consequent Additional Benefits |
|---|---|---|---|---|---|
| VSWIR | 2.09 μm | < 0.16 $cm^{-1}$ | 1.6 km | column $CO_2$, clouds | ratio vs $CH_4$:$CO_{20}$ columns for [$CH_4$] |
| VSWIR | 2.25 μm | < 0.16 $cm^{-1}$ | 1.6 km | column $CH_4$, $N_2O$, clouds | ratio $CH_4$:$N_2O$ |
| **VSWIR** | **2.33 μm** | **< 0.13 $cm^{-1}$** | **1.6 km** | **column $CH_4$, CO, $H_2O$, clouds** | **BL CO, $CH_4$, and $H_2O$ columns, clouds & BL[2]** |
| SWIR | 3.33 μm | < 0.58 $cm^{-1}$ | 3.2 km | $CH_4$, $H_2O$ and $C_2H_6$ column | good vertical info for $CH_4$ &$H_2O$ |
| **SWIR** | **3.56 μm** | **< 0.35 $cm^{-1}$** | **3.2 km** | **HCHO, $CH_4$, $N_2O$, and maybe some $O_3$ info** | **VOC; high precision column info and some vertical info for HCHO, $CH_4$ & $N_2O$** |
| MWIR | 4.65 μm | < 0.20 $cm^{-1}$ | 3.2 km | CO, $O_3$ and $H_2O$ | CO profile[4], tropo-spheric $O_3$ and BL $H_2O$ |
| LWIR [3] | 9.5 μm | < 0.11$cm^{-1}$ | 6.4 km | $O_3$ partial columns (PCs) | PCs @ 0-6, 6-12, & 12-22 km |

1- ELF: Elemental (smallest sampled) footprint
2- BL: Planetary Boundary Layer, also [$CH_4$] is total atmospherically averaged $CH_4$ mixing ratio
3- Active cooling required; for others, shorter wavelength operation facilitates passive (radiative) cooling
4 - CO profile and $H_2O$ BL require retrieval that simultaneously utilizes the VSWIR and MWIR data

**Bold:** Highest Priority Black: Clear Priority Blue Type: Added value/risk-reduction priority

Table 2 indicates the sensitivity that may be expected with a relatively fully configured package of four small, light grating mapping spectrometers, ones which exploit the wavelengths that are described below. The table concentrates on total-column and lowest-kilometers quantities, since these are typically the most desired. However, payloads of various complexity, dependent on budget vs science return are easily accommodated. Simplest would be just the single VSWIR GMS that provides significant basic information such as column amount. Next the addition of the MWIR provides profile information for CO (and $H_2O$) including excellent boundary layer measurements. It also adds capability for tropospheric ozone, and another partial column from the tropopause to the lower stratosphere. The further addition of the SWIR GMS provides a capability primarily for high precision column HCHO, but also provides profile information including the boundary layer for $CH_4$, and further information on $O_3$ and $C_2H_6$ column and some vertical information for $N_2O$ and $H_2O$. The addition of the LWIR provides the ultimate in vertical resolution for $O_3$, but would require the added complexity of active cooling for its detector.

**Table 2. Summary of TIMS Retrieval Precision**

| Species | Vertical Region Sampled | Retrieval Precision |
|---|---|---|
| CO VSWIR | Total Column, daytime | < 1.5% |
| CO VSWIR and MWIR | 0–2 km, daytime | ~ 8.5% |
| HCHO SWIR | Total Column (PBL dominates) (~2 ppb PBL, 1 x $10^{16}$ molec $cm^{-2}$) | ~ 8% by day & ~ 40% at night |
| $O_3$ from SWIR spectral measurements. | Total Column | ~ 2% day ~5.7% night |
| $O_3$ partial columns (PC) from MWIR spectral measurements | 0 - 11 km* | ~ 7% |
| | 11 - 22 km | ~ 2% |
| $O_3$ partial columns from TES-like LWIR spectral measurements. | 0–6 km (mostly 2–6 km) | ~ 4% |
| | 6 - 12 km | < 2 % |
| | 12 - 22 km | < 2% |
| $CH_4$ VSWIR | Total Column, daytime | ~ 1% |
| $CH_4$ VSWIR and SWIR | 0–3 km, daytime | ~ 3.0 % day |
| note: * The MWIR and the LWIR analysis assumes constraint by UV measurements, e.g., as specified for the OMPS | | |

# *Carbon Monoxide*

Experience from the ICARTT pollution study— obtained by NASA, NOAA, and European agencies during the summer of 2004— proved that both pollution forecasting and advancement of basic science will require everything we could learn from the EOS

instruments and more; indeed, all that is physically possible from remote sensing will be needed. AIRS samples a partial-column of carbon monoxide with very full geographic coverage. When fires in northern Canada, Alaska, and Siberia proved important to condition in the Eastern USA, AIRS was able to pick up the signal. Effects from highly industrialized East Asia were also seen but were more problematic: essentially the fires put CO directly up in the altitude range where AIRS could see them, but surface emissions from East Asia were only seen downwind, if and when they were lofted. MOPITT gave valuable partial information about the vertical location of CO. Heald et al [2004] found that assimilation of East Asian emissions and their effects on North America were limited by the need to time-average MOPITT's samples due to its limited swath and cloud effects; in addition, the CO could not be compared to the model at the surface emission source.

National requirements for CO to be available to 3 to 4 vertical levels in the atmosphere are for these reasons:

* urban pollution
* forest fire effects on pollution
* estimation of forest fire severity (immediate estimate of total fuel burned)
* estimation of national disaster severity (immediate estimate of total fuel burned)
* unsuspected sources of carbon monoxide (illegal, fugitive or unsuspected sources)

TIMS can use both absorption and emission to estimate detailed vertical distributions, as shown in Figure 2.

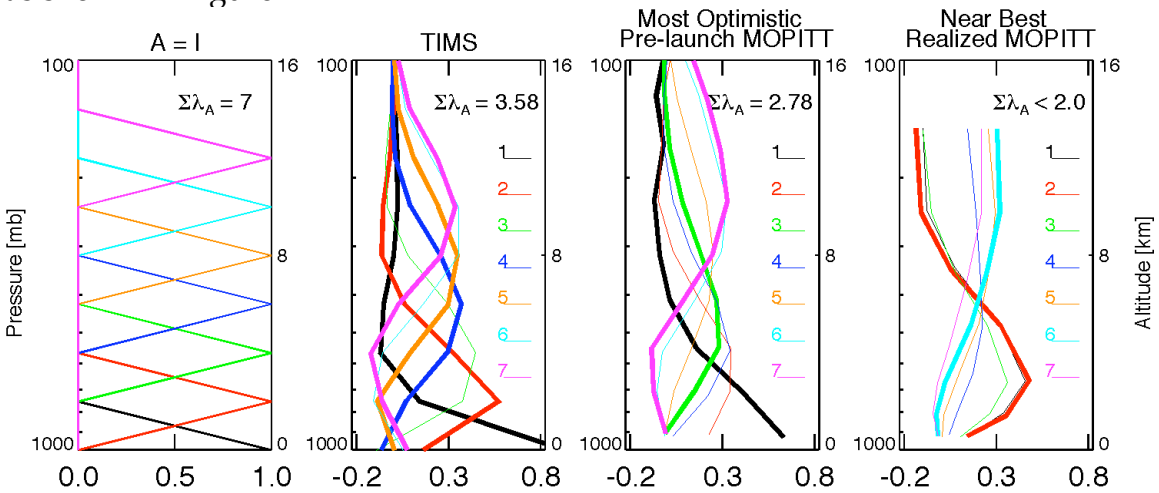


Figure 2: TIMS description of CO (averaging kernel plot showing vertical resolution and ability to use data). (Leftmost) Input "idealized averaging kernel; The width of the averaging kernel gives the vertical resolution of the retrieval, 2 km for all heights this "idealized" case. The peak of averaging kernel is the fraction "true" profile in a solution that is a linear combination of "true" and "a priori" profiles. In this idealized case the profile retrieved at 2km intervals has no contribution from the "a priori'. (Second) Preliminary linear error analysis after Rodgers [2001] showing expected TIMS capabilities to sense these layers. The sum of the averaging kernel eigenvalues indicate

that 3–4 pieces of profile information are expected: note resolution of the boundary layer. (Third) MOPITT envisioned capabilities. (Fourth) MOPITT best actual capabilities. AIRS estimates do not separate upper and lower troposphere as much as MOPITT, and TES may give slightly better than one broad mid-tropospheric estimate. When layer-averaged mixing ratios are estimated, the maxima of the resolving functions improve towards 1.

## *Formaldehyde*

Over the past five years, fully mapped measurements of formaldehyde (HCHO) and nitrogen dioxide ($NO_2$) in the UV-Visible regions have revolutionized the understanding of tropospheric ozone production using remote sensing technology. Exact quantification from the UV-Visible measurements has been problematic, as the determination of "air-mass" factors relating radiances to concentration profiles is still an active field of research. Unless designs change quite dramatically, the neither HCHO or $NO_2$ can be reported by the OMPS instrument which will succeed OMI. We have recently reported that detector technology has improved sufficiently that the determination of HCHO in the 3.56 μm region of the infrared is now extremely appealing [Kumer et al., 2006]. True, this 3.56 μm region is one of minimum upwelling radiation and features are normally considered to be determined by emission. However, the low concentrations of formaldehyde indeed make it primarily a feature in absorption: actually, this is a benefit of low concentration, since inferences of near-surface formaldehyde are easier! Measurements and theory show total column of HCHO is often dominated by concentrations in the lowest kilometer or so, with a few important exceptions.

HCHO column of $10^{16}$ molecules/cm$^2$ should be measurable with 8% precision [Kumer et al, 2006], using the same linear estimation theory for high-spectral resolution measurements that has proved its value in predicting the performance of the TES instrument admittedly for other compounds. Somewhat lower concentrations can be estimated with proportionally higher error bars. These appear to be superior precision estimates to the UV techniques, and we have proposed to pursue a joint error analysis of the methods to check this. IR or IR+UV techniques promise to move our mapping of ozone-forming peroxy radical from the broad, often isoprene-dominated view currently available, towards views of individual cities and small regions, details now at the edge of instrumental precision. Spatial detail comparable to the currently available nitrogen oxide detail will illuminate and constrain the plume-scale ozone production process so important to many ozone forecasts.

Simultaneous formaldehyde, nitrogen dioxide, and UV-flux measurements can go a very long way statistically in determining smog-ozone production rates. Measurements of these from space provide strong constraints on smog models in any situation; moreover, the geographical comparison of the chemical composition of different regions afforded by these measurements provides an undeniable advantage in improving smog simulation,

Infrared measurements do not, of course, completely supplant UV remote sensing to determine smog formation rates. Reactive nitrogen oxides and UV flux must be estimated with other instruments. However, infrared measurements are nearly insensitive to aerosol scattering effects, and formaldehyde maximizes in certain regions of aerosol scattering — i.e., smog ozone and smog aerosols do frequently coincide. The path length and location of the UV signal can contribute to a complex retrieval problems. Infrared measurements can give simple column information with possibly a small amount of vertical information, while UV measurements may contribute *some* height information due to the competition of scattering and absorption, as is the situation with ozone. Each method may have other unexpected complexities: our major point is that the complexities will differ, and these differences maximize available information from a joint retrieval using UV and IR.

## *Methane*

Variations in methane are much more accurately observed using IR technology like TIMS: 1–2% precisions should be attainable. The long-lived gas has typical variations of similar magnitude over large regions. Intermittently, however, one must expect variations of greater magnitude: major natural gas leaks, very intermittent periods of strong emissions from wetlands (as methane-carrying regions are stirred up, stimulating emission), and similar events. Because these events are difficult to observe in worldwide detail of time and space, it seems likely that perceptions of relative roles of methane emissions will be reevaluated following sustained daily global observation. Broad patterns of variation in methane should follow broader, slower emission patterns. These will be captured by assimilation models of global weather and composition. Because assimilation models can "learn" from daily updates of information, as with weather forecasts, they can adapt surprisingly well to plentiful and adequately precise (but not necessarily accurate) data.

Figure 3 shows the surprisingly detailed vertical distributions available for methane. The usefulness of IR technology at this degree of accuracy has recently been demonstrated [Frankenberg et al., 2005]. The European satellite SCIAMACHY can sense only total column at ~3% precision for $CH_4$ column, [Dils et al., 2005], but provides useful new information about the tropical regions— regions that require continued observation because of their rainfall variability. TIMS improves greatly on the horizontal spatial resolution with its 1.5–3.2 km footprint, and provides vertical information. Specifically it helps diminish questions about variability of in the uppermost parts of its profile, and gives a near-surface estimate. The desirability of near-surface estimates for source detection were also noted [Frankenberg et al., 2005]. TIMS $N_2O$ measurement allows for variations in the stratosphere to be removed quite substantially, since stratospheric profiles are similar.

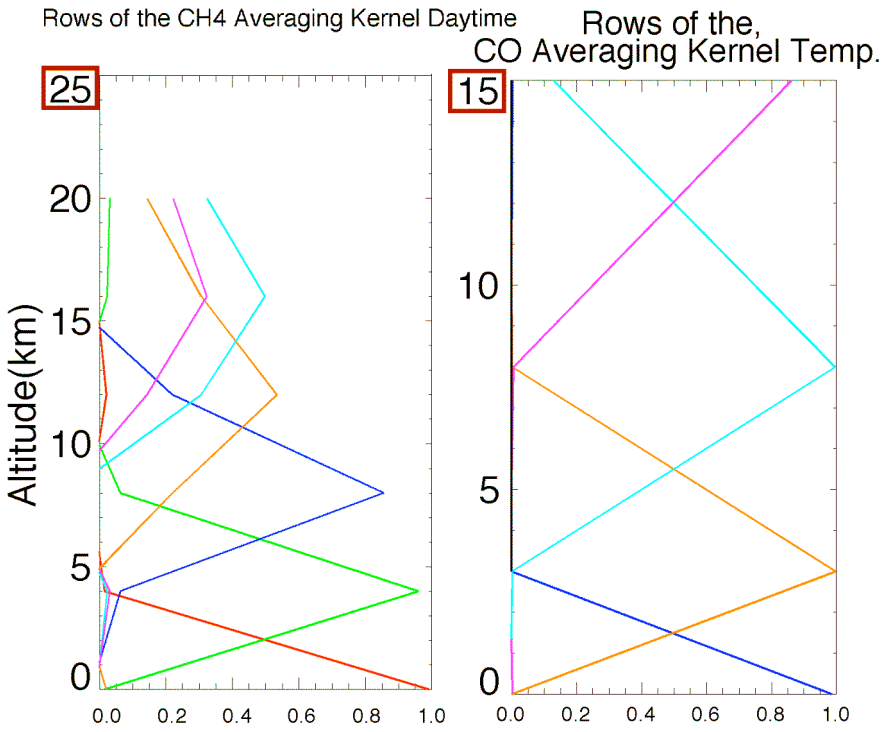


Figure 3: TIMS description of $CH_4$ and CO sampling. The theoretical vertical resolution is shown here. (Note higher values than Figure 2). The lowest five curves show a preliminary estimate of the ability of TIMS to resolve approximately 4.6 distinct pieces of information in the vertical dimension, mostly in troposphere. The red line shows very good sensing ability for perturbations in boundary layer methane.

## *Ozone*

Ozone is vital in investigating large-scale pollution, the effects of common fires and conflagration, and global temperature variation. Ozone's close links to large-scale winds and temperature — as well as economic damage— give it a prime role in NOAA's new daily forecasting responsibilities. Experience has proven that lower tropospheric ozone, where the pollutant is toxic, is difficult to estimate from space. The total ozone column measured by UV techniques (TOMS, OMI, etc) is excellent, but the region below 4 km altitude is poorly sensed.

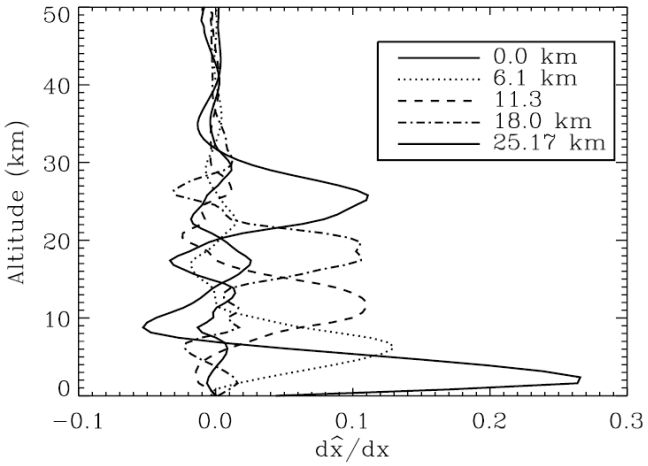


Figure 4. Prelaunch estimates of the ability to measure tropospheric ozone from TES; post-launch performance fulfills expectations. Note that although TES documentation claims only ~6 km resolution in the vertical, there is relatively great sensitivity between 1–4 km in the lower troposphere [Bowman et al., J. Geophy. Res., 2002]. Initial, unpublished assessment of the instrument suggests good sensitivity does reach from 2–4.5 km. In this region, various factors degrade the sensitivity of ultraviolet-based ozone instruments.

Current assimilation and forecast models can only use information from above 4–5 km and attempt to calculate smog ozone production below that level. Nadir-sounding IR sensing techniques can significantly improve ozone sensing in this region. While UV excels at the total ozone column, IR techniques– with their complex interpretation of thermal emission– give valuable extra information about the lowermost atmosphere just above the surface. They also provide estimates at night.

## *Water, Temperature, and Carbon Dioxide*

In addition to the above chemical composition information the TIMS technology provides needed risk reduction, precision, and breadth to several other major Earth Science objectives. By sampling in detail the optical absorption of water vapor, the VSWIR capabilities of TIMS provide risk-reduction and extra capability to the CrIS instrument's tasks. (CRIS: a Cross-track Infrared Sounder, a vital component of NPOESS that carries on the capabilities of AIRS.) By sampling carbon dioxide lines at high detail, the instrument also provides risk-reduction regarding temperature. TIMS can resolve fine structure due to non-local-thermodynamic equilibrium effects in the mesosphere. These variable effects can then be removed directly from CrIS temperature retrieval, which depends on the carbon dioxide bands.

Direct sensing of the total column density via the $O_2$ absorption is not needed since the precision is not so high that traditional surface pressure analyses would add appreciable error. Nevertheless, large-scale features in the carbon dioxide distribution (such as those caused by rain forests and convection acting on large-scale distributions)

will be sensed, and TIMS can geographically broaden the information provided by instruments like OCO.

## *Conclusions and Recommendations*

Precisely tailored and efficient choices for tropospheric sampling using TIMS are clearly available, and they will aid immensely in forecasting both the largest-scale effects on pollutant ozone and also fine details. Most cost effective and usefully, NASA should put substantial effort to put TIMS into low Earth Orbit, preferably co-manifested with complimentary instruments. This allows both global-scale ozone and precursor sampling and also ~3-km scale sampling of significant CO and HCHO maxima, thus putting a magnifying glass on the urban scale.

NASA's roles might be to fund development of the instrumentation to a stage ready for launch. NASA has begun this with the funding of an Instrument Incubator Proposal. The traditional ESSP concept could be broadened to support this development. NASA would not, however, have launch costs or the major costs of downlink and initial processing for weather-related purposes. Costs would be kept below $200 M. NASA should fund initial validation measurements of radiances and concentrations, perhaps in coordination with NOAA's own pollution research needs. International partners like the IAGOS investigators on commercial aircraft will aid with ozone, carbon monoxide and water vapor measurements; instruments like the EOS Microwave Limb Sounder and its successors will fill in above the level of the aircraft flights. The advantages of geostationary sampling which can observe significant portions of North America with useful time and spatial resolution, have been stated by many others. The complexities, limits on view, and data rates added by geostationary sensing imply a need for synergistic help from the robust sensors we advocate. NASA should also commit to a small but steady role in disseminating high-level data to the scientific community, reassessed and improved as capabilities and needs change. NASA would also support those aspects of TIMS technology that are useful to planetary studies, and insure interchange of information.

The NPOESS process will continue to evolve. Should satellite Instrument-of-Opportunity slots not be available on future configurations of NPOESS, TIMS technology makes an smaller mission, preferably in an orbit close to one utilizing an ozone instrument (OMPS, OMI, an ESSP instrument), and possibly coordinated with land-use satellites that would inform emission studies. Multi-instrument NPOESS opportunities would make sense.

In conclusion, there is real opportunity to exploit infrared sensing technology to fill a current gap in capabilities, and it is unlikely that technological advancement in the United States will close the gap without NASA. Many national needs are served by the technology: better weather forecasting, better knowledge of extreme fires, studies of the effects of climate change on biogeochemical processes (wetlands and fire prevalence), as well as the basic work of pollution forecasting and useful knowledge true greenhouse gas sources.

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