Tropospheric Infrared Mapping Spectrometers (TIMS) for CO Measurements With Much Improved Vertical, Temporal and Spatial Resolution in the Lower Troposphere by Utilizing Both the 2.3 and 4.7 µm Regions

J.B. Kumer, A.E. Roche, R.L. Rairden, J.L. Mergenthaler,
Lockheed Martin Advanced Technology Center; Palo Alto, CA 94304
R.B. Chatfield,
NASA Ames Research Center, Mountain View, CA, 94035
R. D. Blatherwick and T. Hawat,
Denver University, Denver, CO, 80208

Abstract: **The Decadal Survey Report of the U.S. National Research Council "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" describes requirements for improved atmospheric measurements to gain crucial understanding for air quality, climate change, and weather.[1] Improved vertical and horizontal resolution, temporal resolution and coverage are required. Our NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP) project is focused on demonstrating a Tropospheric Infrared Mapping Spectrometers (TIMS) technology that would provide considerably improved measurements of Carbon Monoxide (CO), commensurate with the NRC report requirements. Nadir radiance acquired at a spectral resolution of the order of a few tenths cm^{-1} in the CO bands near 2.3 µm (solar reflective-SR) and 4.7 µm (thermal emissive-TIR), together with a signal photon-limited low noise design, would enable CO retrieval with improved vertical information in three independent layers including the lowest several km layer. The primary measurement goal is CO, but the spectra contain information that facilitates retrieval of column CH_4, and H_2O partial columns (vertical information), including considerable improvement in the boundary layer. The TIMS sensor system comprises separate module operating near 2.3 µm and 4.7 µm. The completed modules have been deployed in two ground-based atmospheric measurement campaigns at Denver University (DU). During these measurements The TIMS modules were co-located with the DU high resolution Bruker Fourier Transform Infrared Interferometer (FTIR) providing both high fidelity spectral validation and first order CO retrieval comparisons. We present a brief description of the two TIMS hardware modules and their operational characteristics. This is followed by examples of preliminary TIMS spectral radiances obtained by looking at both atmospheric emission and atmospheric solar absorption. Based on the observed spectral and radiometric performance, we then discuss concepts for application of the TIMS technology to both LEO and GEO air quality monitoring, emphasizing information retrieval in the first few km of the troposphere.**

1. Description of IIP-TIMS Hardware

1.1 Introduction

The TIMS sensor system comprises two separate high spectral resolution grating spectrometer modules, operating respectively in the CO thermal Mid Wave Infrared (MWIR) band near 4.68 µm (~ 2137 cm^{-1}), and the CO solar reflective Very Short Wave Infrared (VSWIR) band near 2.33 µm (~4292 cm^{-1}). Table 1-1 lists the module spectral regions and target parameters. Table 1-2 lists the module optical parameters.

TABLE 1-1 TIMS MODULE SPECTRAL PARAMETERS

	Spectral Range	Spectral Resolution	Targeted Parameters **Primary** **Secondary**
MWIR	2112–2160 cm^{-1} 4.735–4.63 µm	0.5 cm^{-1}	**CO** H_2O, O3,Clouds
VSWIR	4281–4301 cm^{-1} 2.336–2.325 µm	0.2 cm^{-1}	**CO** H_2O, CH4, Clouds,

Both modules use the "solid state" spectrometer technique[2-4] where each module has a fixed grating coupled with a HAWAII HgCdTe 1024x1024 detector array with 18.5 µm pixels.

Spectral information is read out along pixels in one dimension, and spatial along the other. The absence of spectral scanning mechanisms and spectral element time sharing maximizes integration time and radiometric sensitivity. The approach enables a more robust optomechanical system important to the launch environment, and ensures long-term on-orbit reliability and stability.

TABLE 1-2 IIP TIMS MODULE OPTICAL PARAMETERS

	Aperture	FOV Along Slit	FOV (pix)
MWIR	3.9 cm	10.4 deg	0.18 mrad
VSWIR	3.5 cm	4.9 deg	0.17 mrad

1.2. The TIMS IIP 4.68 μm MWIR Spectrometer Module

Apart from an external objective, the entire module, including a narrowband order sorting grating filter, mounts in a LN2-cooled dewar with hold time of ~ 36 hours. Fig. 1-1 shows the optical schematic and 1-2 the assembled dewar with camera control unit, and power supply. Total mass is ~ 55 kg.

The module is fully operational and has been used to acquire zenith sky spectral radiances during ground campaigns in October-November, 2007 at DU, while co-located with the DU high resolution FTIR (Section 2). This module is scheduled for a ground campaign at DU in the spring of 2008.

The MWIR spectrometer is an example of the reflective Littrow configuration as discussed in grating design texts [5]

1.3 The TIMS 2.33 μm VSWIR Module

For the 2.33 μm module, due to the much shorter wavelength, only the detector arrays and limited optics need to be cooled to LN2 temperature. Thus the majority of the sensor optics is external to the dewar, and a much smaller dewar is used. It has a hold time of about 30 hours.

Fig. 1-3 shows a block diagram of the instrument and 1-4 shows the completed instrument with spectrometer case interfaced with the dewar. This module uses identical camera electronics to those for the MWIR. Total mass is ~40 kg.

This module is also fully operational and has been used to acquire solar absorption spectra in November, 2007 at DU along with the MWIR module. The VSWIR module is also scheduled for a ground campaign at DU in 2008.

2. DATA FROM TIMS MEASUREMENT CAMPAIGN AT DU

2.1 Introduction

The measurement configuration for the TIMS modules at DU is shown in Fig. 2-1. The TIMS hardware in position observing the zenith sky and solar diffuser is shown in Fig. 2-2.

The MWIR module views radiance emission from the zenith sky via a fold mirror, and the VSWIR module views absorption spectra in direct sunlight scattered from a diffuser plate. Both modules are closely contiguous with the FTIR heliostat. The FTIR can be operated at any desired spectral resolution from <0.01 cm^{-1} to ~ 1 cm^{-1}.

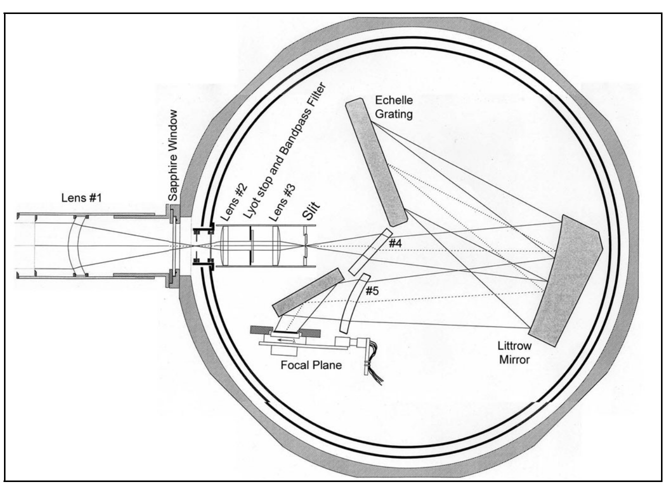

Fig. 1-1 TIMS 4.6 μm module schematic

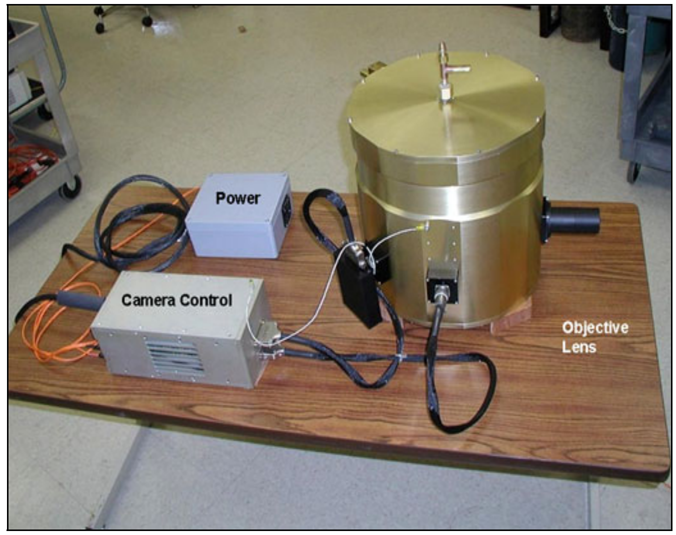

Fig. 1-2 TIMS 4.6 μm module hardware

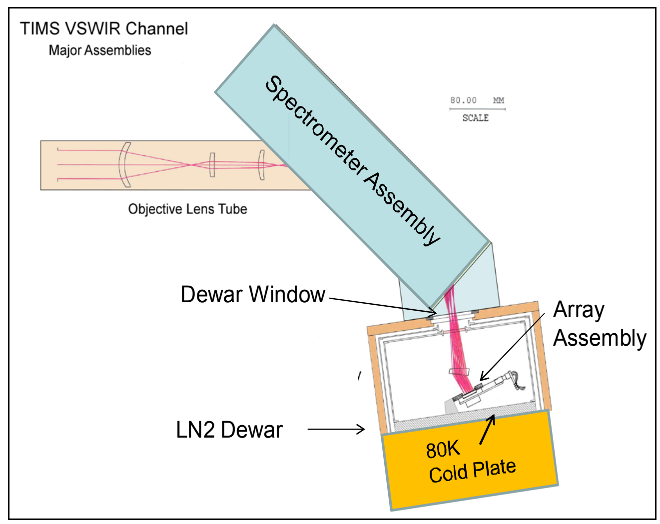

Fig. 1-3 2.3 μm module elements

Fig. 1-4 2.3 μm module assembled hardware

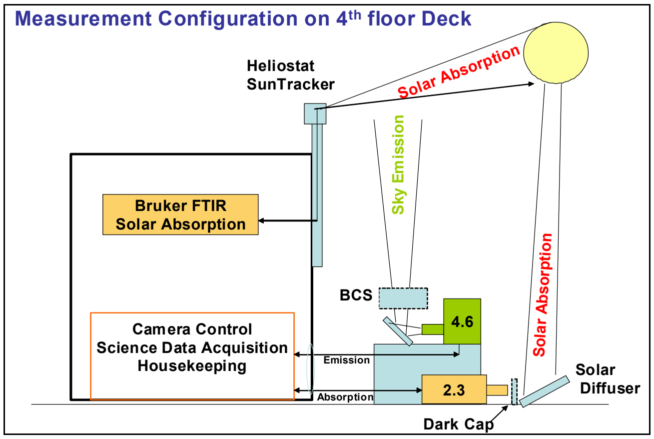

Fig. 2-1 TIMS modules at DU

The intent of running in conjunction with the FTIR is to provide a precise spectral registration validation of the TIMS spectral scale, and compare with CO retrievals derived from FTIR spectra.

Both modules are radiometrically calibrated prior to and following each series of measurements using multi-temperature full-aperture extended source blackbodies. For the MWIR, to monitor and remove instrument thermal backgrounds arising from temperature variations in the objective lens, sky emission views are alternated with views of a blackbody comparison source (BCS) of known temperature and emissivity. For the VSWIR solar scattering views are alternated with views of a front aperture shutter. As previously noted spectral calibration is achieved through a combination of gas-cell absorption spectra and direct comparisons with high resolution FTIR spectra.

2.2 Examples of Spectral Measurements and Preliminary CO Retrievals

MWIR Spectra at 4.7 μm—Fig. 2.3 shows an example of a zenith sky emission spectrum obtained by the MWIR module at DU October 20 under clear skies, overlaid with a 0.4 cm^{-1} Bruker FTIR solar absorption spectrum.

This region is rich in CO (and H_2O) emission spectra, as seen in Fig. 2-3. The inverted Bruker FTIR absorption spectrum overlay is for spectral comparison purposes only.

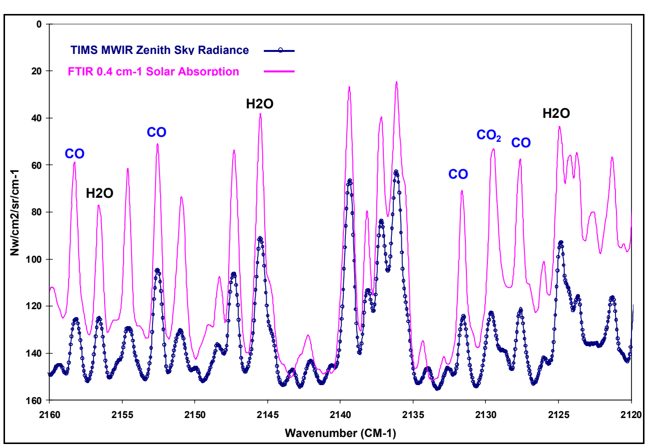

Fig. 2-3 TIMS 4.6 μm sky emission radiance compared with FTIR solar absorption spectra

Fig. 2-2 2.2 μm module assembled hardware

Fig. 2-4 shows a first-order fit between TIMS and a forward model in terms of radiance temperature, from which a retrieval for total CO column yielded a factor of 0.92 ±0.1 relative to climatology, compared with 0.86 from the EOS-Atmospheric Infrared Spectrometer (AIRS) and 0.76 from DU, a satisfactory result for this preliminary retrieval algorithm and initial data set.

VSWIR Spectra at 2.33 μm—Fig. 2-5 is an example of TIMS 2.33 μm solar absorption spectra overlaid with a Bruker FTIR spectrum at 0.2 cm^{-1}. The region has a number of well isolated CH_4 and H_2O lines, as indicated. CO lines are clearly evident with good S/N. Preliminary retrievals from such data are under way. Fig. 2-6 shows a fit between the TIMS data and a model as a first step towards this process.

We expect to show enhanced results from our second ground measurement scheduled for spring 2008.

3. APPLICATION TO SPACE BORNE AIR QUALITY MONITORING

In the TIMS 2.3 μm design, an intermediate image is formed at a field stop and a re-imaging optics train focuses the light on to the 2D array. This arrangement easily facilitates a

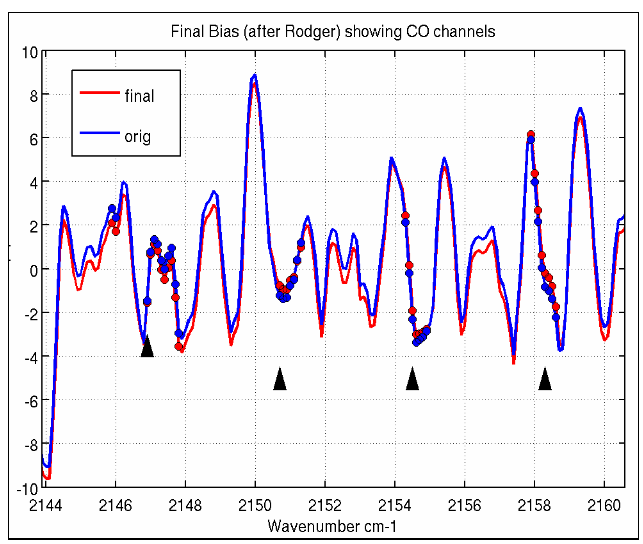

Fig. 2-4 TIMS 4.6 μm retrieval fit

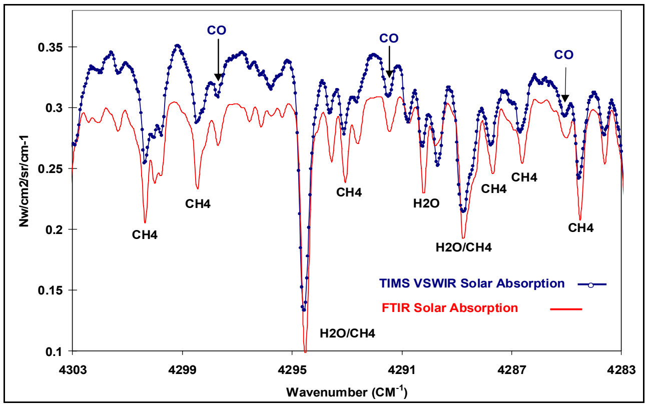

Fig. 2-5 2.3 μm solar absorption spectra compared with Bruker FTIR Spectra

modification to obtain simultaneous measurements in multiple spectral channels corresponding to various orders of the grating. Dichroic beam splitters would be used to direct the multiple orders to arrays that are specific to each order.

This straightforward modification would provide for an expanded space borne application of TIMS that would add simultaneous measurements in bands near 3.28, 3.58 and 9.51 μm. These would provide optimized vertical information for O_3 in the troposphere including the boundary layer (BL), and for HCHO. The combined set including CO, provides three of the four most important tropospheric species for air quality, the fourth being NO_2. NO_2 could be included by further expansion of the TIMS, but that will not be discussed in this paper.

This TIMS space borne concept would then utilize two multi-channel spectrometers:

- A 2-channel expanded TIMS that would acquire data in two bands centered near 2.33 and 3.28 μm
- A 3-channel expanded TIMS that would acquire data in three bands centered near 3.58, 4.65 and 9.51 μm

Measurement in these five spectral regions would provide for retrieval of:

- Partial columns of O_3 in the BL, in the middle troposphere, in the upper troposphere and lower stratosphere (UTLS), and in layers above that

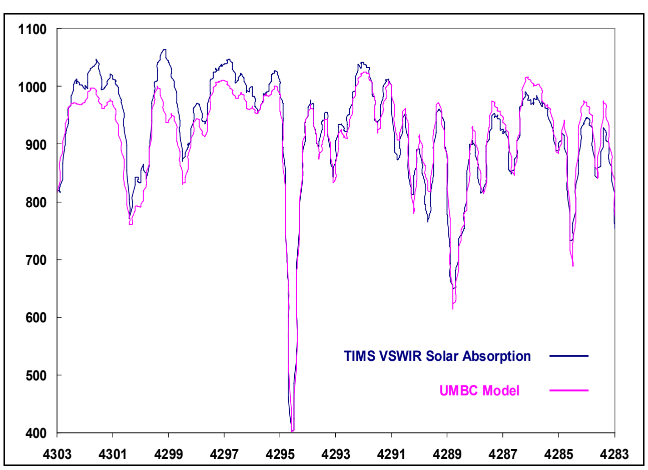

Fig 2-6 2.3 μm spectra compared with model

- Total column HCHO with precision intrinsically about four times better than can be obtained with UV measurements
- CO in the BL, in the middle troposphere, and in the UTLS
- Partial columns of H2O in the lower troposphere including the possibility for 2 partial columns in the BL
- Total columns of CH4 and N2O

For a LEO deployment concept the data are acquired on contiguous footprints of about 2 km (SR) and 4 km (TIR) at nadir, and swath widths of about 2800 km providing daily global coverage in the SR and twice daily in the TIR. This concept supports the science measurement goals of the Decadal Survey (DS) Global Atmospheric Composition Mission (GACM).

For a GEO deployment concept aimed at deployment on the NRC Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission, 3 scans would be provided as shown on Fig. 3-1. These satisfy the GEO-CAPE requirement for coverage from 45°S to 50°N of South and North America in hourly intervals. In this concept a scanning mirror system feeds a reflective telescope to produce a collimated output beam. This beam is relayed to a beamsplitter that feeds a pupil to the objective lens of a 2-channel expanded TIMS (S1) and a 3-channel expanded TIMS (S2). It is shown schematically on Fig. 3-2.

We assume that the GEO deployed expanded TIMS focal plane arrays have 1024 x 1024 pixels (as do our IIP demonstration TIMS), with slits that are 1024 pixels long, oriented north-south (NS). The common scanner facilitates co-registration of the spectral channels. A pixel length along the slit projects to 3 km at nadir so the projected slit length is 3072 km NS. The scanner pushbrooms the slit in the east-west (EW) direction to execute the 3 scans as shown on Fig. 3-1 in about 50 minutes. This leaves about 10 minutes per hourly

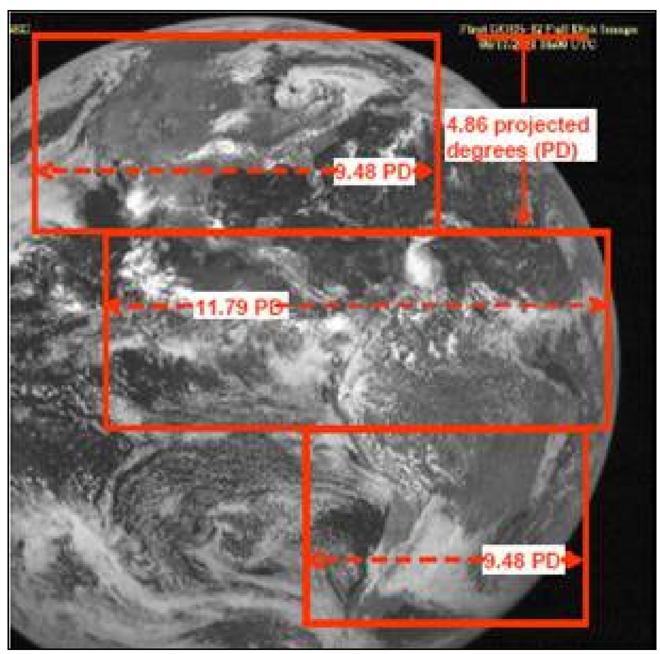

Fig. 3-1 Scan pattern per hour of GEO deployed expanded TIMS projected on to first light image from GOES 12.

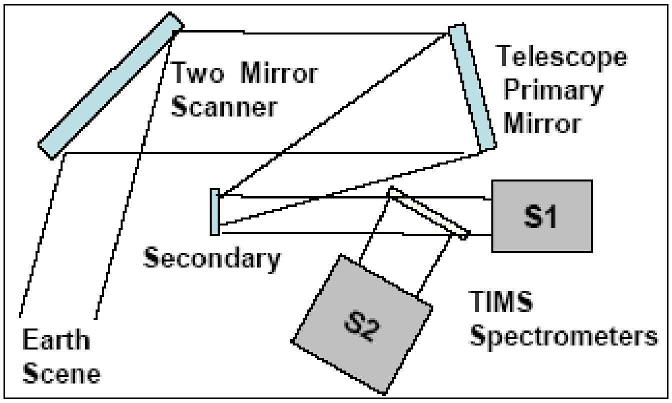

Fig. 3-2 Schematic of expanded TIMS application for GEO-CAPE

repeat interval for calibration exercises. Footprints are about 3 x 3 km for the 2.33 µm region, 6 x 6 km for the 3.28, 3.58 and 4.65 µm regions, and about 12 x 12 km for the 9.51 µm region. This enables high quality retrieval of O_3, HCHO, CO, H_2O, CH_4 and N_2O as described above.

ACKNOWLEDGEMENT

We wish to acknowledge the contributions of Tom Jamieson and Lynn Huff at LMATC, and Frank Murcray and Aaron Goldman at Denver University. This work is supported by the NASA ESTO Instrument Incubator Program.

REFERENCES

[1] Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, National Research Council; ISBN: 0-309-66900-6, 400 pages, 8 1/2 x 11, (2007).

[2] Kumer, J.B.; Mergenthaler, J. L.; Roche, Rairden, R. L., and Chatfield, R. B., Tropospheric infrared mapping spectrometers (TIMS) for Air Quality measurements, Proc. of SPIE Vol. 6299, 629908, (2006).

[3] Kumer et al, Tropospheric infrared mapping spectrometers (TIMS) for Air Quality measurements, presented at the Air Quality Workshop http://www.acd.ucar.edu/Meetings/Air_Quality_Remote_Sensing/Presentations/Posters/4.P.Kumer.pdf

[4] Roche, A.E.; Kumer, J.; Mergenthaler, L; Rairden, R.: A high spectral resolution solid state infrared spectrometer for air quality measurements; Proceeding SPIE, Vol 6744, October 2007.

[5] See for example http://grating.newport.cpm/information/handbook/handbook.asp