A Panchromatic Imaging Fourier Transform Spectrometer for the NASA Geostationary Coastal and Air Pollution Events Mission

Yen-Hung Wu*[a], Richard Key[a], Stanley Sander[a], Jean-Francois Blavier[a], David Rider[a]
[a] Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

ABSTRACT

This paper summarizes the design and development of the Panchromatic Imaging Fourier Transform Spectrometer (PanFTS) for the NASA Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission. The PanFTS instrument will advance the understanding of the global climate and atmospheric chemistry by measuring spectrally resolved outgoing thermal and reflected solar radiation. With continuous spectral coverage from the near-ultraviolet through the thermal infrared, this instrument is designed to measure pollutants, greenhouse gases, and aerosols as called for by the U.S. National Research Council Decadal Survey; Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond1. The PanFTS instrument is a hybrid instrument based on spectrometers like the Tropospheric Emissions Spectrometer (TES) that measures thermal emission, and those like the Orbiting Carbon Observatory (OCO), and the Ozone Monitoring Instrument (OMI) that measure scattered solar radiation. Simultaneous measurements over the broad spectral range from IR to UV is accomplished by a two sided interferometer with separate optical trains and detectors for the UV-visible and IR spectral domains. This allows each side of the instrument to be independently optimized for its respective spectral domain. The overall interferometer design is compact because the two sides share a single high precision cryogenic optical path difference mechanism (OPDM) and metrology laser as well as a number of other instrument systems including the line-of-sight pointing mirror, the data management system, thermal control system, electrical system, and the mechanical structure. The PanFTS breadboard instrument has been tested in the laboratory and demonstrated the basic functionality for simultaneous measurements in the visible and IR. It is set to begin operations in the field at the California Laboratory for Atmospheric Remote Sensing (CLARS) observatory on Mt. Wilson measuring the atmospheric chemistry across the Los Angeles basin. Development has begun on a flight size PanFTS engineering model (EM) that addresses all critical scaling issues and demonstrates operation over the full spectral range of the flight instrument which will show the PanFTS instrument design is mature.

Keywords: Imaging spectrometer, Fourier transform spectrometer, Michelson interferometer, air pollution monitoring, greenhouse gases, aerosols

1. INTRODUCTION

The Panchromatic Fourier Transform Spectrometer (PanFTS) is an imaging spectrometer based on a classical Michelson interferometer that incorporates several unique features. It can measure pollutants, greenhouse gases, and aerosols as called for in the Decadal Survey and the NASA Science Plan. With continuous spectral coverage from the near ultraviolet (0.26µm) through the thermal infrared (15µm), PanFTS is designed to meet and exceed all of the science requirements for the NASA Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission.

From geostationary orbit PanFTS can map all of North and South America every hour with high resolution measurements (temporal, spatial, and spectral) that capture diurnal variations in pollutants, aerosols, greenhouse gases, and transport tracers. These measurements will improve the understanding and prediction of rapidly evolving tropospheric chemistry which influences air quality and climate change.

Figure 1 shows the molecular species atmospheric absorption spectral bands relevant to the mission. The wide spectral coverage is important for retrieving the entire suite of GEO-CAPE target molecules, including several in widely different wavebands. Measurement of the same species in different spectral regions significantly enhances the information content of the vertical profile retrievals[2]. By measuring the spatial and temporal variation of these molecular concentrations in the atmosphere, the science data products will be extremely valuable to the research community and to operational agencies, such as NOAA and USEPA, which are responsible for developing effective air pollution mitigation strategies.

*Yen-Hung.Wu@jpl.nasa.gov; phone: (818) 393-5466

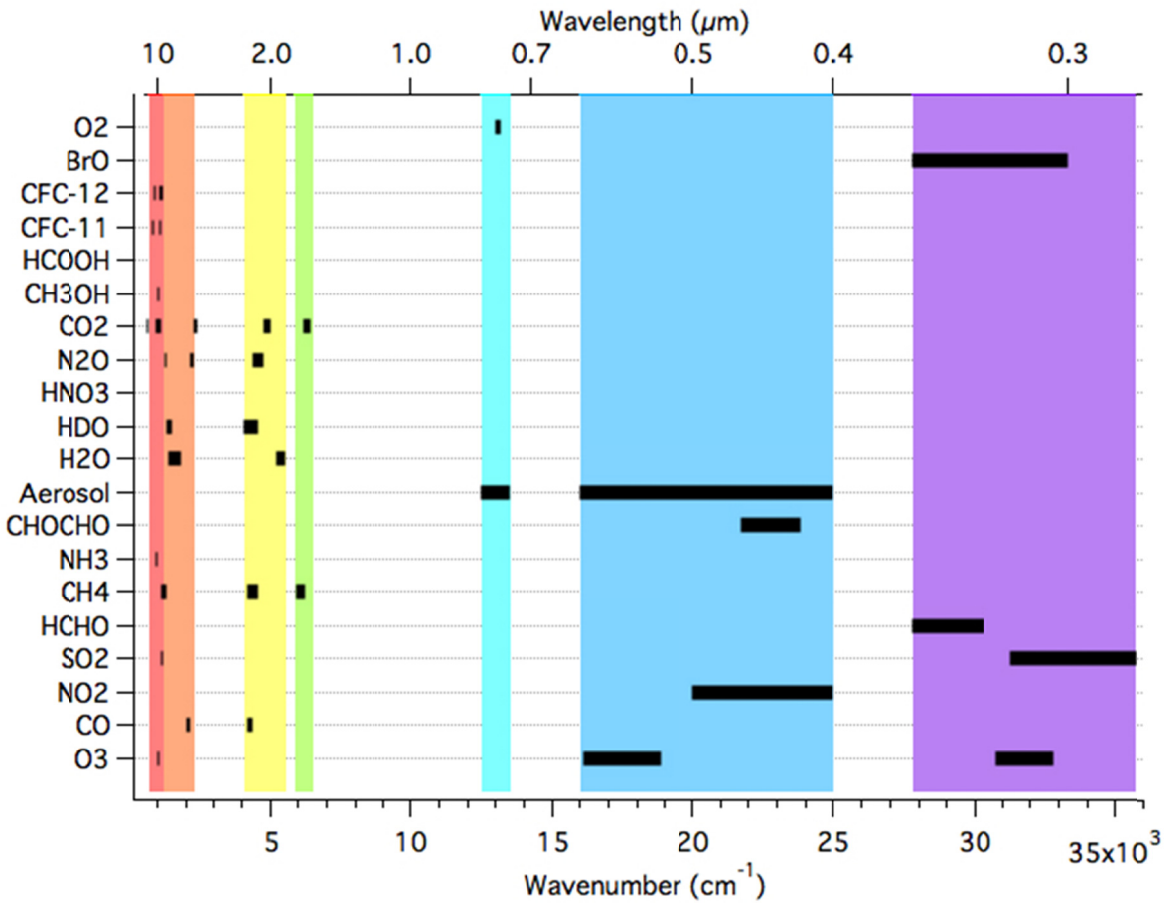

Figure 1. Measurement spectral bands of critical trace gases (O_3, CO, NO_2, SO_2) plus other highly desirable species.

2. INSTRUMENT DESIGN

Figure 2 shows the functional block diagram of the PanFTS. Simultaneous measurements over the broad spectral range from IR to UV is accomplished by a two sided interferometer with separate optical trains and detectors for the UV-visible and IR spectral domains. This allows each side of the instrument to be independently optimized for its respective spectral domain. The overall instrument is made up of several sub-systems including the pointing system, calibration system, fore optics, Michelson interferometer, metrology, dichroic beam splitter module, camera optics, focal plane array (FPA) camera package and signal-chain electronics, thermal control system and mechanical structure. The interferometer design is compact because the two sides share a single high precision cryogenic optical path difference mechanism (OPDM) and metrology laser as well as a number of other instrument systems[3].

Figure 3 is the opto-mechanical design for the PanFTS flight instrument. The instrument layout is highly symmetric and modular with many identical assemblies. This cost effective approach utilizes duplicated assemblies in the instrument which also allows the freedom to scale the PanFTS science measurement capabilities and to adapt to evolving mission requirements. One side of the instrument operates in the UV/Vis spectral region and the other side in the IR spectral region. The instrument is cooled to different temperature zones by high efficiency cryocoolers, described later, to

minimize instrument self-emission and detector readout electronic noise. Low thermal self-emission is essential to achieve the sensitivity needed to measure thermal emission radiation from the earth's atmosphere.

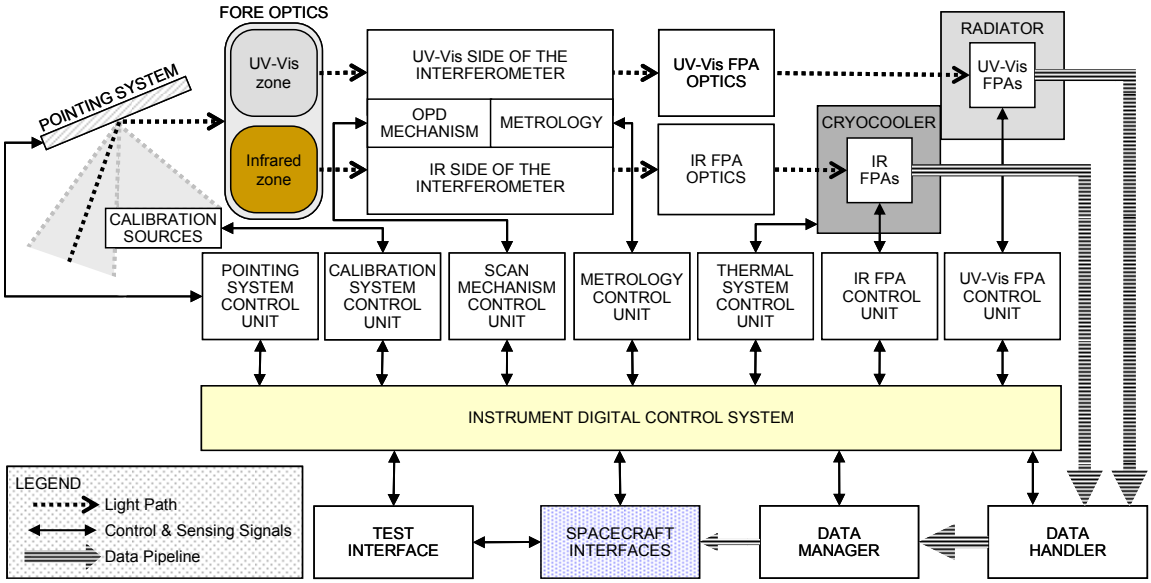

Figure 2. The PanFTS flight instrument functional block diagram

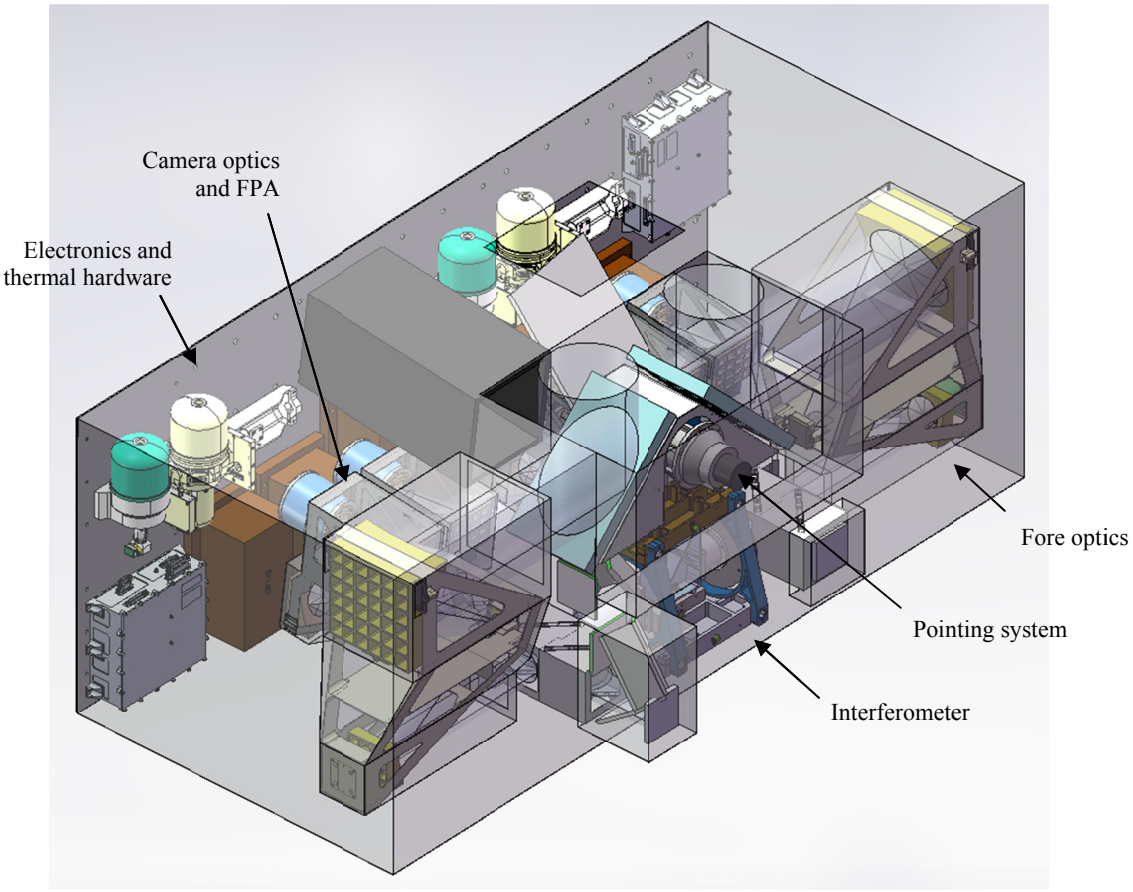

Figure 3. The opto-mechanical design of the PanFTS flight instrument

The PanFTS design is tailored for the GEO-CAPE mission that will operate in geostationary orbit. From geostationary orbit PanFTS can map all of North and South America with high resolution measurements (temporal, spatial, and spectral) that capture rapidly evolving diurnal variations in pollution, transport tracers, and greenhouse gases as illustrated in Figure 4.

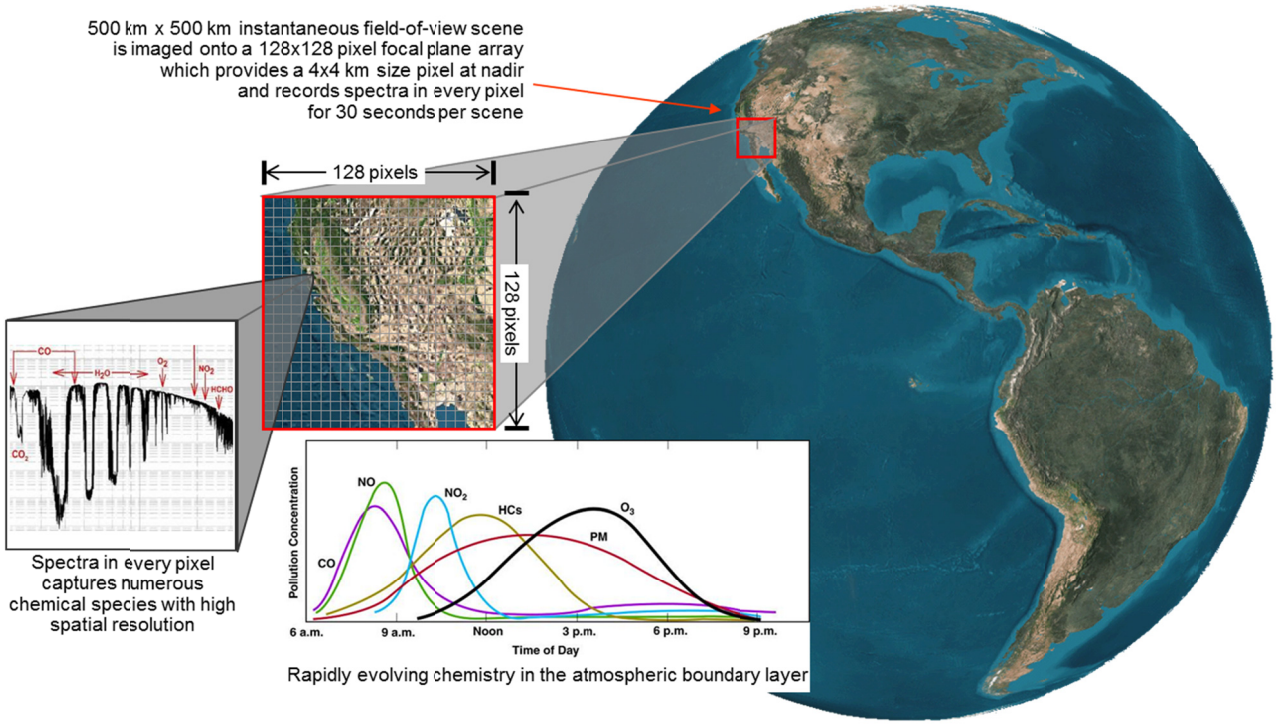

Figure 4. PanFTS imaging observation scenario for the GEO-CAPE mission

From geostationary orbit the PanFTS has a 500 km x 500 km instantaneous field-of-view. This scene is imaged onto a 128x128 pixel focal plane array which provides a 4x4 km size pixel foot print at nadir. The instrument captures an interferogram in every pixel for 30 seconds per scene. The interferograms are Fourier transformed into spectra by the FPA signal chain electronics to reveal absorption features at different wavelengths of the various species of interest (see color bins in Figure 1). Hourly mapping will identify the temporal variations of the gas molecular concentrations. From the geostationary orbit, the angular extent of Earth is about ±8.6º from nadir. The PanFTS pointing system has a two axis gimbaled mirror that can steer the instrument line-of sight to any location over the full earth disk.

2.1 Pointing System and Fore Optics

The pointing system has a flat steering mirror mounted on a two axis gimbal mechanism. The gimbal mechanism has two sets of stepper motors and harmonic drives. This combination yields a 0.001° per step rotation or 0.6 km projection on the ground from geostationary orbit. The pointing system's function is to direct and hold the instrument line-of-sight steady on a particular scene while interferograms are recoded, and to point to internal and external calibration sources.

The fore optics shown in Figure 5 is a 3-mirror afocal optical beam compressor. The entrance pupil is 166mm x 166mm and located at the steering mirror, and the aperture stop is 63mm x 63mm located at the exit of the compressor, which is the optical entrance to the interferometer. The compressor includes a field stop that eliminates light outside of the scene from scattering and reaching the FPA's. The tertiary mirror is mounted on a piezo tip-tilt stage, and its function is to correct thermal drift with respect to line-of-sight. The line-of-sight corrections are accomplished by observing well known landscape periodically, and co-align the FPA pixels on both UV/Vis and IR sides of the instrument.

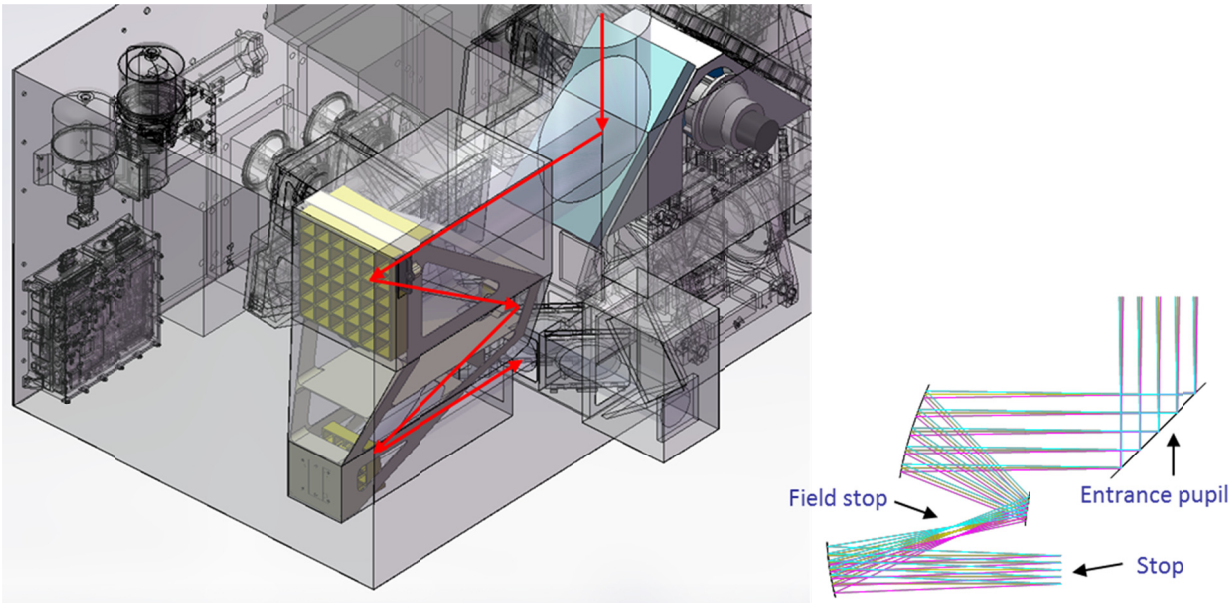

Figure 5. The PanFTS pointing system and fore optics configuration

2.2 Michelson Interferometer, Metrology, and Dichroic Beam Splitter

The Michelson interferometer and its optical path difference mechanism (OPDM) shown in Figure 6 are the heart of the PanFTS instrument. The two sides of the PanFTS instrument share a common OPDM, which enables the simultaneous co-located IR and UV/Vis measurements of a scene. The IR side utilizes a corner cube configuration to double the maximum optical path length. It has the zero path difference at the end of the scan which yields a single sided interferogram. The UV/Vis side has a flat mirror, and has the zero path difference at the middle of the scan. This yields a double sided interferogram. This arrangement provides higher spectral resolution and improved SNR for the IR and UV/Vis sides, respectively.

The OPDM design uses eight rotational flex pivots to connect the linkages together, much like a four-bar-linkage parallelogram. The stage is driven by a non-contacting linear voice coil actuator with a magnet fixed to the base and an electrically actuated coil that drives the upper part of the mechanism. The flex pivots are rated for infinite life because the flexing angle is only a fraction of yield strain of the material, with the mechanical motion range of ±25 mm from its neutral position. The design has no moving contact surfaces so there are no lubricant or mechanical wear out risks. An optical encoder with 5 nm resolution provides accurate and repeatable position data.

However, by design, a flex pivot center of rotation shifts away from its mechanical axis as a function of the rotation angle. In addition, due to the manufacturing tolerances, the eight flex pivots in an OPDM will have slightly different spring constants. As a result of these two effects, the OPDM does not maintain perfect alignment during a scan. This misalignment can be minimized by carefully choosing eight "matched" flex pivots, and orient them in a way to minimize the magnitude of the misalignment.

The residual misalignment, however, can mask out the interferogram fringe contrast. Therefore, an internal metrology system is used to detect misalignment, and close a feedback control loop with a piezo tip/tilt actuator mounted behind the flat mirror for the UV/Vis side (IR side with the corner cube configuration is insensitive to this misalignment). The metrology system also measures the scan distance, so the time domain interferogram can be phase corrected into the path difference domain interferogram. Both are key for obtaining high resolution spectra.

An equally important component to PanFTS is the optical coating design. Because of the separation of the IR and UV/Vis channels, coating design can be optimized. Gold and UV enhanced aluminum coatings are applied to the reflective optics for the IR and UV/Vis sides, respectively. The separation also makes the design and manufacturability of the 50/50 beam splitter and the broadband anti-reflection coating for the compensator manageable. A series of dichroic beam splitters are placed at the Michelson interferometer output, and further branched into finer spectral bins.

Figure 6: The PanFTS Michelson Interferometer and OPDM

2.3 Camera Optics and Focal Plane Array Package

The camera optics has four mirrors. This allows the focal Plane Array (FPA) package to be located closer to its signal chain electronics and to the cryocooler which is advantageous during integration. The entrance of the FPA package is aligned with the exit pupil which is also the cold aperture stop. Both the cold field stop and the cold aperture stop are essential for minimizing the thermal background illumination and thermal load on the FPA. The FPA is hard mounted to the cold finger of the FPA package, and cooled via a thermal strap by the cryocooler. Three concentric cylinders mechanically connected in series, made from thin G10 materials, create a large thermal resistance between the cold finger and the rest of the FPA package.

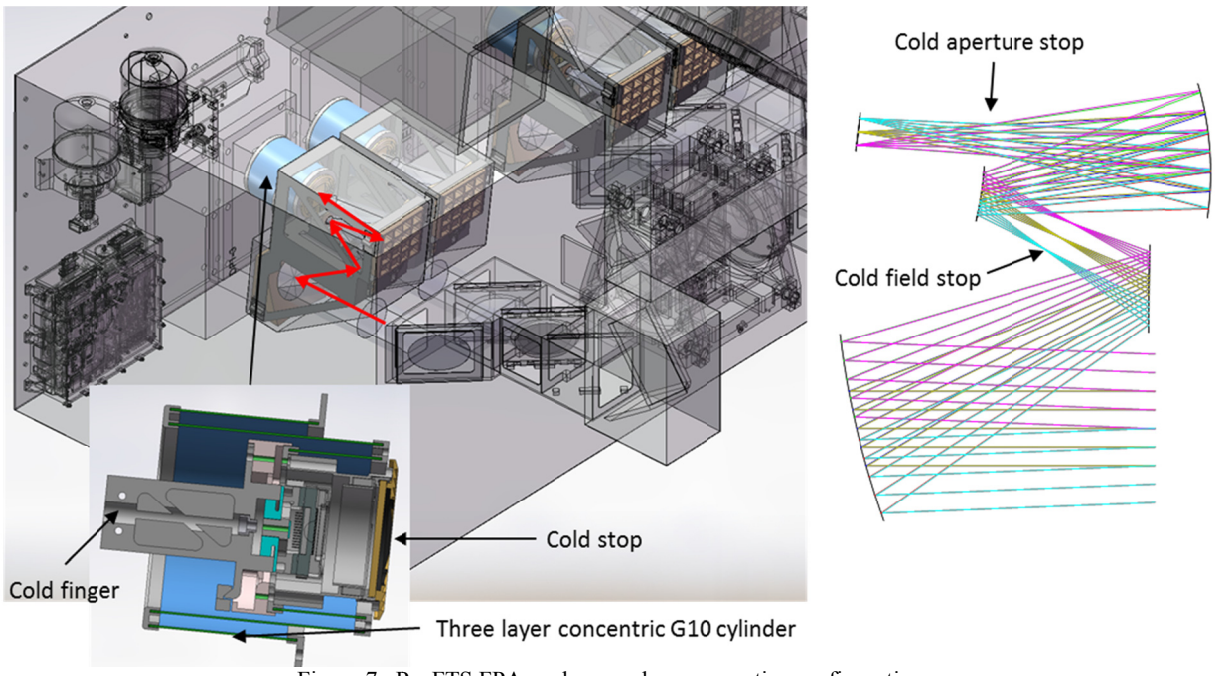

Figure 7. PanFTS FPA package and camera optics configuration

2.4 All Digital Focal Plane Arrays

Another advanced technology in the PanFTS is a 128 x 128 pixel all digital FPA developed by JPL[4]. This innovative high throughput digital FPA provides a digital output for each pixel, which eliminates the need for off-chip signal chain electronics needed by conventional FPAs. This substantially reduces FPA signal chain complexity, volume, mass, power, implementation risk and cost.

Hybrid FPAs typically consist of a photosensitive diode pixel array electrically connected to a read out integrated circuit (ROIC) as illustrated in Figure 8. The photosensitive array is bump-bonded (hybridized) to the ROIC with indium metal bumps. This approach provides great flexibility in that the detector array and readout electronics can be individually optimized for different spectral regions.

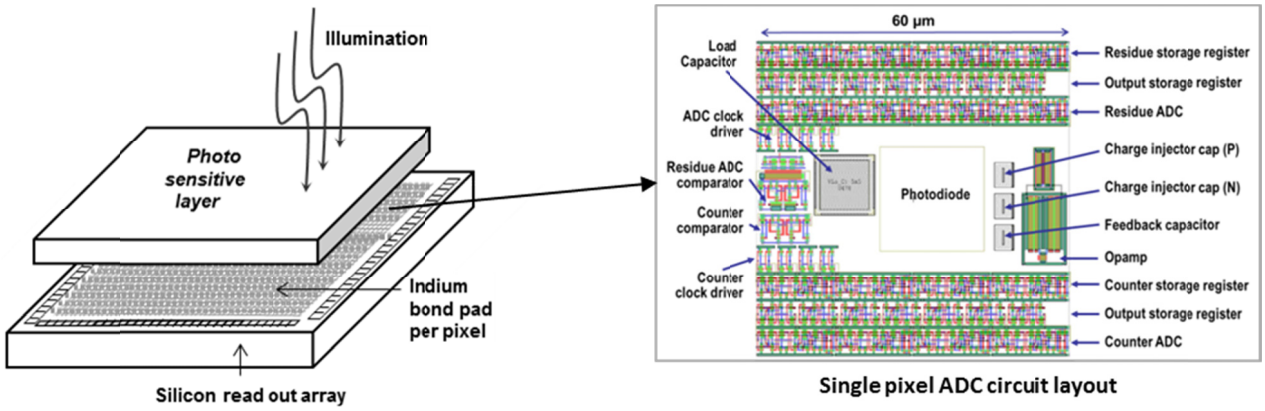

Figure 8. Hybrid FPA architecture where each pixel has its own separate ADC

The ROIC is the heart of the digital FPA. In the JPL 128x128 pixel ROIC, each pixel has its own 14-bit analog-to-digital converter. This in-pixel ADC approach provides fast frame rates up to 16 kHz without requiring extraordinary speed in the ADC as would be the case if each ADC had to handle the multiplexed output from several pixels. Additionally, analog-to-digital conversions are done in all pixels simultaneously, enabling snap shot operation rather than a "rolling shutter" readout. All pixels are read out at the same time which eliminates problems with conventional rolling shutter readouts where pixels are read out sequentially introducing artifacts from crosstalk between pixels when adjacent pixels reset. Figure 8 also shows the unit cell ADC circuitry in each of the ROICs 16384 pixels. A small photodiode was included in the unit cell layout to enable preliminary testing of the ROIC without the need for it to be hybridized to a photosensitive detector array. While the photodiode it is too insensitive for the PanFTS science measurements, it has been invaluable for demonstrating the essential features of the ROIC. In 2010, fifty ROIC chips were manufactured by a commercial foundry. To demonstrate the performance potential of the ROIC array it was incorporated in the Fourier Transform Ultraviolet Spectrometer (FTUVS) which is shown in Figure 9. FTUVS is an operational instrument at JPL's Table Mountain Facility which makes routine measurement of atmospheric composition.

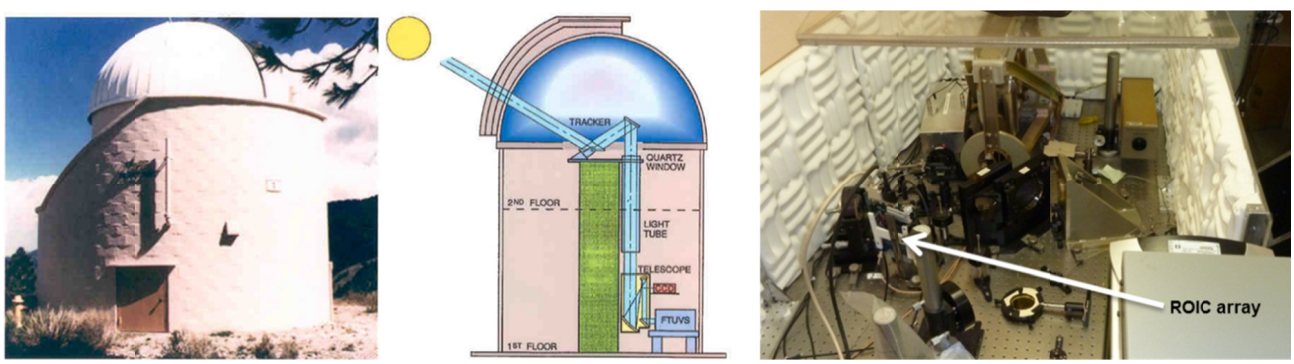

Figure 9. ROIC array incorporated in the FTUVS instrument at the Table Mountain Observatory

Over a period of several days the ROIC acquired a series of spectra covering a wide range of atmospheric and measurement conditions. Figure 10 shows the results from a single pixel which is representative of the results for the entire array.

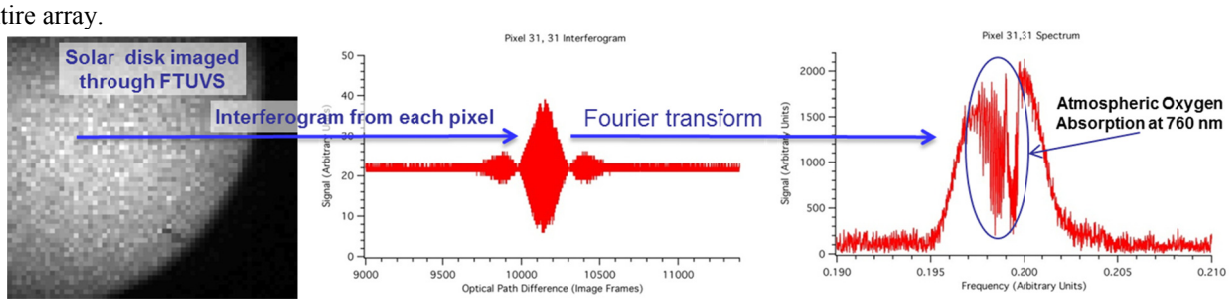

Figure 10. ROIC array acquisition of atmospheric oxygen absorption

Successful ROIC operation in the FTUVS demonstrated the capability to make scientific measurements of atmospheric composition like those needed for the GEO-CAPE mission. Operation in a relevant environment (an operational imaging FTS measuring atmospheric composition) advanced the ROIC technology maturity to TRL 5. Work is under way now to hybridize the ROICs with silicon p-type, intrinsic, n-type (SiPIN) photodiode detector arrays. The resulting high speed imaging FPAs will be operated in the PanFTS engineering model as well as the GEO-CAPE Read Out Integrated Circuit (ROIC) In-Flight Performance Experiment (GRIFEX). The GRIFEX CubeSat mission will provide spaceborne validation of the ROIC/FPA and its signal chain electronics for the PanFTS.

2.5 Calibration Sources

Calibration and flat fielding of the FPA's are critical for retrieving the molecular concentrations from the spectra. For the IR FPA's, the steering mirror will look into an internal 300K blackbody plus the cold space for the hot and cold calibrations, respectively. The UV/Vis FPAs will view both the Sun via an internal scatter plate and view dark space to accomplish the bright and dark calibrations, respectively.

2.6 Temperature Zones and Thermal Control System

PanFTS instrument is partitioned into many different temperature zones, beginning at 290K at the steering mirror, and ending at 65K and 120K at the IR and UV/Vis FPA's, respectively as shown in Figure 11. All the electronics and the cryocoolers are mounted on the passive radiator, which has a constant view to cold space. There are two 2-stage cryocoolers that provide the cooling to the entire instrument (Figure 12). A 2-stage cryocooler is comprised of a Northrop Grumman High Efficiency Cooler (HEC) plus a split 2nd stage coaxial cold head. The HEC cooler provides the necessary cooling to the FPAs, while the 2nd stage provides cooling to the optics and structures at higher temperatures. This cryocooler is rated TRL-9.

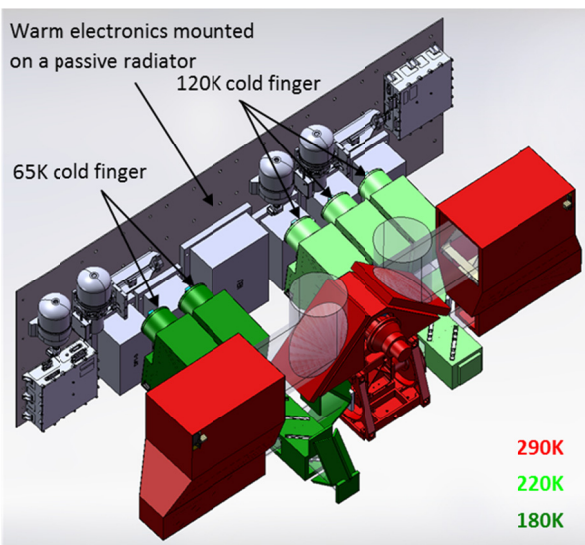

Figure 11. PanFTS temperature zones

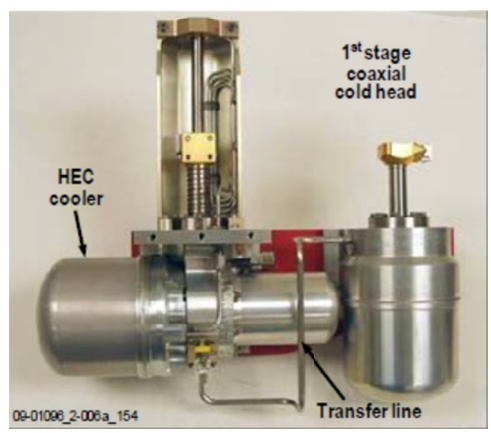

Figure 12. Northrop Grumman HEC cryocooler

3. BREADBOARD INSTRUMENT RESULTS

The optical beam compressor, dichroic beam splitter, camera optics, and FPA package operating at their respective temperatures are deemed low technical risk. They either have analog flight heritages or built-in adjustment capability to accommodate mechanical distortions due to thermal drifts. The OPDM is mounted on the 290K structure, while the corner cube on the IR side and the flat mirror on the UV/Vis side are cooled to 180K and 220K, respectively. The mechanical performance of the OPDM when it has a large thermal gradient across the structure, flex pivots, piezo tip/tilt stage, voice coil and encoder is a technical risk being addressed by thermal vacuum testing.

3.1 OPDM Thermal Vacuum Testing

Figure 13 shows a flight size high precision, cryogenic OPDM system prior to starting testing under simulated space conditions to demonstrate the stability and reliability of the design. One of the three flight size OPDMs has currently completed approximately 700,000 cycles in vacuum at -100 degrees C which is about 27% of the 2.5 million cycle life test, with no discernable changes in behavior. The OPDM is cycling full travel (0 mm to 50 mm), simulating operation under mission conditions. The test system allows control of the piezo mechanism throughout its full range. Data from the piezo tests, as well as the stage motion precision and smoothness, are collected by a quad cell system. In this quad cell system, a helium-neon laser is targeted onto a flat mirror on the OPDM, and the flat mirror is articulated by a piezo-actuated tip/tilt stage. The reflected beam is split off from the path onto the quad cell. This allows fine measurement of the tip/tilt of the OPDM optical system. The thermal chamber is controlled and monitored by a Labview program. Temperature, pressure and electronic parameters are monitored and recorded. The OPDM structure is monitored by several type-T thermocouples. Email alarms are generated for out of range values. Should there be a power failure or unexpected temperature excursion, the system automatically shuts down safely. The collected data archive will be analyzed to assess the effects of the space thermal and vacuum environment on the OPDM system.

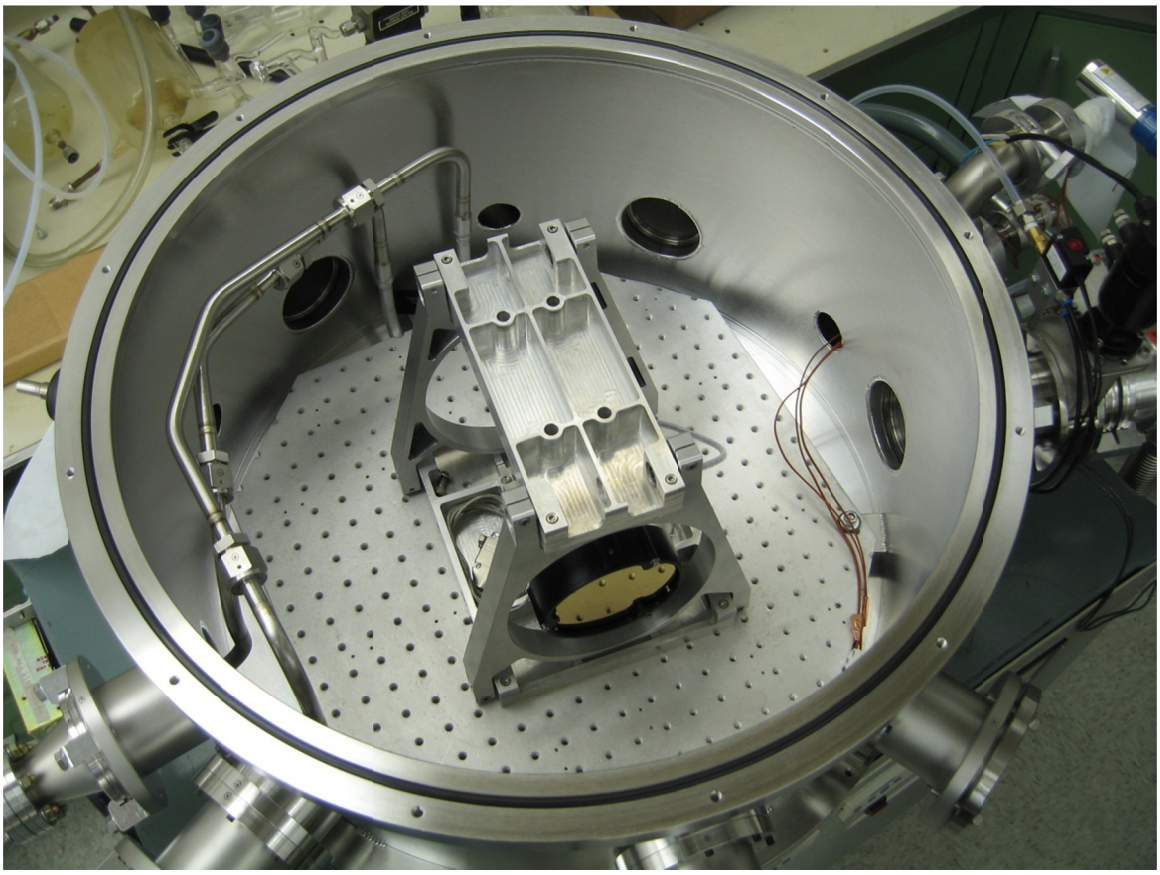

Figure 13. The OPDM inside the thermal vacuum chamber prior to testing

3.2 PanFTS Breadboard Testing

The PanFTS breadboard shown in Figure 14 is the core of the interferometer portion of the instrument.

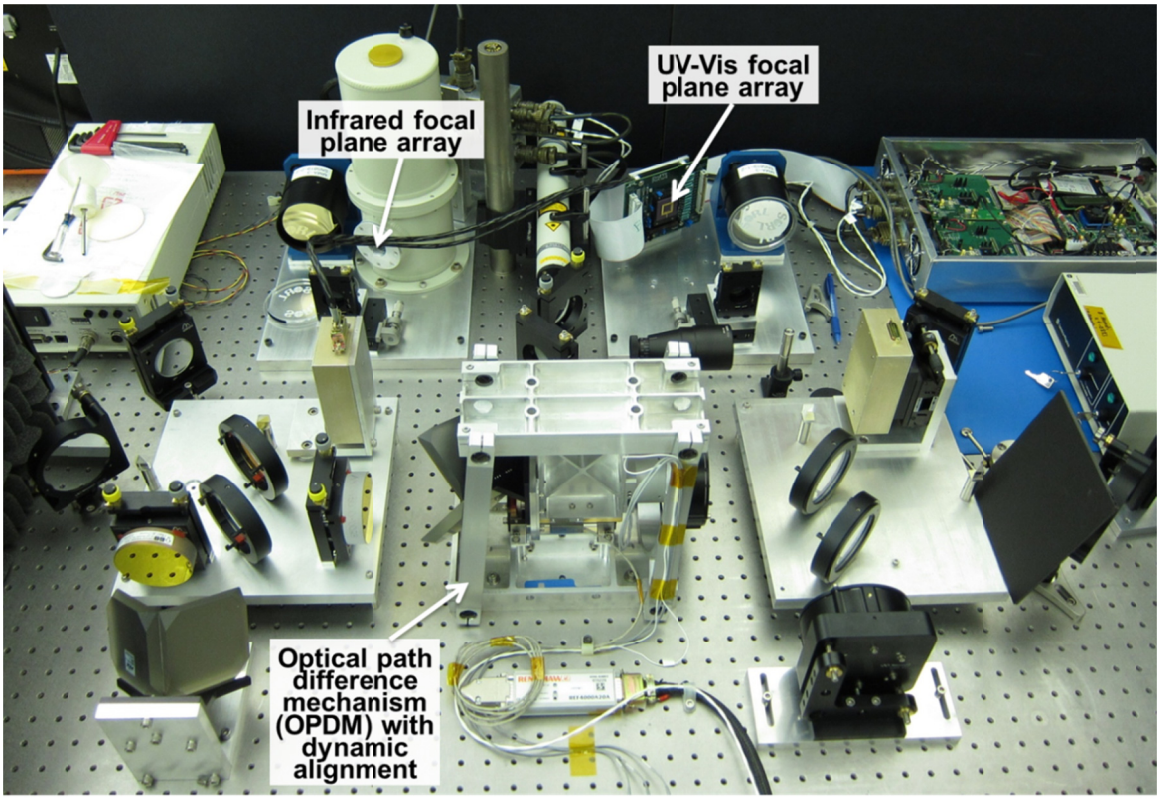

Figure 14. The PanFTS breadboard

The optical beam size, the ratio of FPA pixel size to nadir pixel spatial resolution, interferometer optical path difference and moving mirror velocity all match the observing scenario from geostationary orbit. Functionality for these operational parameters has been demonstrated in the lab. Figure 15 shows simultaneous IR and Vis measurements of Nitrogen dioxide (NO_2). NO_2 mapping is one of the key GEO-CAPE science requirements.

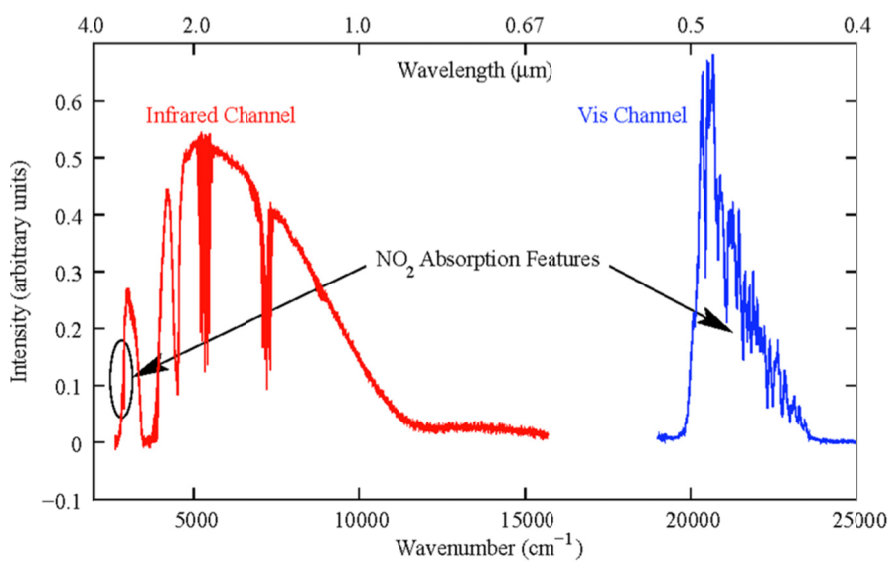

Figure 15. PanFTS breadboard simultaneous IR and Vis measurements of NO_2

Currently the breadboard is set to begin operations in the field at the California Laboratory for Atmospheric Remote Sensing (CLARS) observatory on Mt. Wilson measuring the atmospheric chemistry across the Los Angeles basin as illustrated in Figure 17.

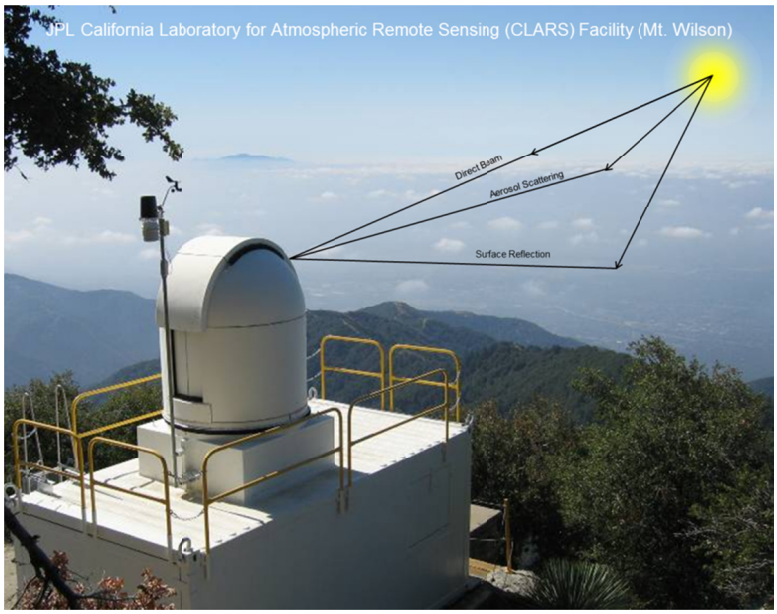

Figure 16. The PanFTS will make atmospheric composition measurements over the Los Angeles basin

4. PANFTS ENGINGEERING MODEL INSTRUMENT

Development has begun on a flight size PanFTS engineering model (EM) that addresses all critical scaling issues and demonstrates operation over the full spectral range of the flight instrument. The PanFTS EM will build on the many successful breadboard developments which have already demonstrated the capabilities required for the PanFTS including the instrument architecture for panspectral measurements, the high precision, long life, cryogenic OPDM, and the high-speed, high precision all digital FPAs. The EM will tie together several component technologies in a system level instrument capability demonstration for making simultaneous UV-Vis and IR measurements under space flight like environmental conditions (thermal-vacuum at 180 K) as illustrated in Figure 16. This will demonstrate that critical design requirements have been achieved such as optical alignment stability, interferometer modulation efficiency, and low instrument background emission in the IR. This is essential to reduce flight instrument development risk and show that the PanFTS design is mature and ready to be implemented in a flight instrument.

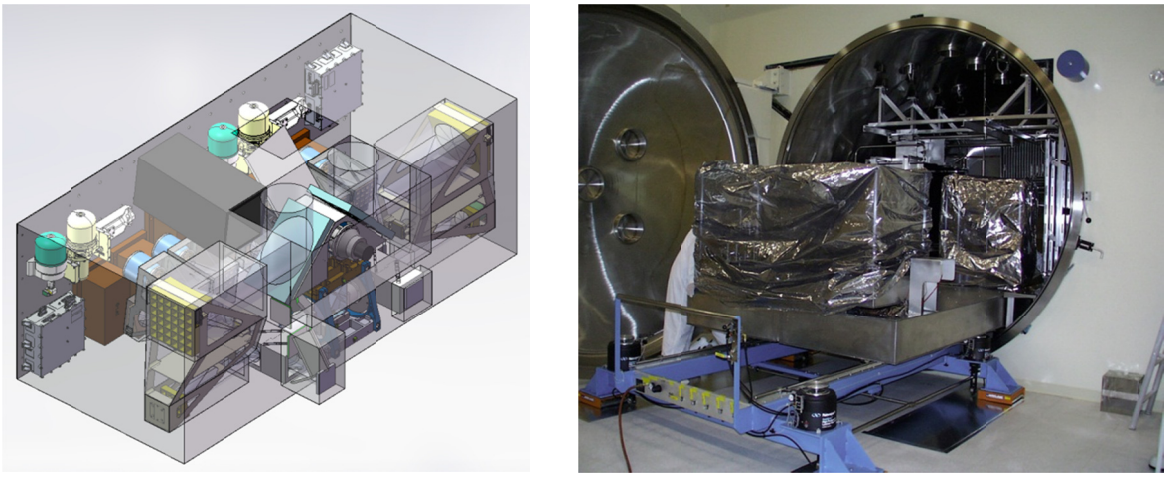

Figure 16. A flight size PanFTS EM instrument will demonstrate simultaneous IR and Vis measurement capability under space flight like environmental conditions

5. CONCLUSION

PanFTS is designed to meet and exceed all of the GEO-CAPE mission objectives. The instrument is an imaging spectrometer based on a classical Michelson interferometer that incorporates several unique features. The wide spectral coverage from near ultraviolet to thermal infrared are spatially separated between the two sides of the OPDM, which allows the channels to be independently optimized. Two advanced technologies, the OPDM and the 128x128 all digital FPA with in-pixel digitalization have demonstrated the capabilities needed for PanFTS. These technologies will be incorporated in a flight size PanFTS EM instrument that will demonstrate simultaneous IR and Vis measurement capability under space flight like environmental conditions. This will demonstrate that critical design requirements have been achieved and show that the PanFTS design is mature and ready to be implemented in a flight instrument.

6. ACKNOWLEDGEMENTS

Support from the NASA Instrument Incubator Program is gratefully acknowledged. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration. Copyright 2011, California Institute of Technology. Government sponsorship acknowledged.

REFERENCES

[1] NRC "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," National Research Council, 2007.

[2] A. Eldering et al,. PanFTS: Panchromatic measurements for unprecedented vertical sensitivity and temporal resolution of trace gases, Hyperspectral Imaging and Sounding of the Environment (HISE) Topical Meeting, Optical Society of America, Toronto, July, 2011

[3] S. Sander et al,. Panchromatic Fourier Transform Spectrometer (PanFTS) for Geostationary Measurements of Atmospheric Composition, NASA Earth Science Technology Forum, June 2011.

[4] D. Rider et al,. Fast Imaging Detector Readout Circuits with In-Pixel ADCs for Fourier Transform Imaging Spectrometers, NASA Earth Science Technology Forum, June 2011.