Panchromatic Fourier Transform Spectrometer for the GEO-CAPE Mission

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***Abstract*- The Panchromatic Fourier Transform Spectrometer (PanFTS) instrument is an imaging sensor for measurement of atmospheric composition (pollutants, greenhouse gases, transport tracers, aerosols) and ocean color. Key elements of PanFTS (optical design, scan mechanism, focal plane arrays) and testing are described. PanFTS is a candidate for flight on NASA's Geo-CAPE Decadal Survey mission.**

I. INTRODUCTION

The Panchromatic Fourier Transform Spectrometer (PanFTS) is a new instrument design being developed under NASA IIP funding. It is designed to measure trace gases and ocean color in support of the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission proposed as part of the NRC decadal survey for earth science. The goal of the PanFTS is to provide high spectral (0.06 cm^{-1}) and spatial resolution (0.25 and 7 km) measurements of the Earth's atmosphere and coastal oceans from about 0.26 to 15 microns.

The NRC decadal survey; *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* states that *"air quality measurements are urgently needed to understand the complex consequences of increasing anthropogenic pollutant emissions both regionally and globally. The current observation system for air quality is inadequate."* and recommends the GEO-CAPE mission to provide the measurements [1]. According to the Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS), air quality is defined by the concentrations of surface ozone (O_3), particulate matter (aerosols), and O_3 precursors, namely carbon monoxide (CO) and nitrogen dioxide (NO_2). The concentrations of these trace gases and aerosols are controlled primarily by chemical and dynamical processes within the planetary boundary layer (PBL). This point was emphasized by the Community Workshop on Air Quality Remote Sensing From Space, which concluded "*The ability to observe the boundary layer from space is a major priority for air quality applications*". In addition, the 2007 NASA Science Plan for the Science Mission Directorate calls for a multispectral mapping mission in geostationary or Lagrangian (L-1) orbit with the capability to resolve boundary layer processes. PanFTS will measure boundary layer O_3, aerosols and O_3 precursors (such as NO_2 and CO) at high spatial and temporal resolution that satisfy the science and measurement requirements defined for the GEO-CAPE mission and the NASA Science Plan.

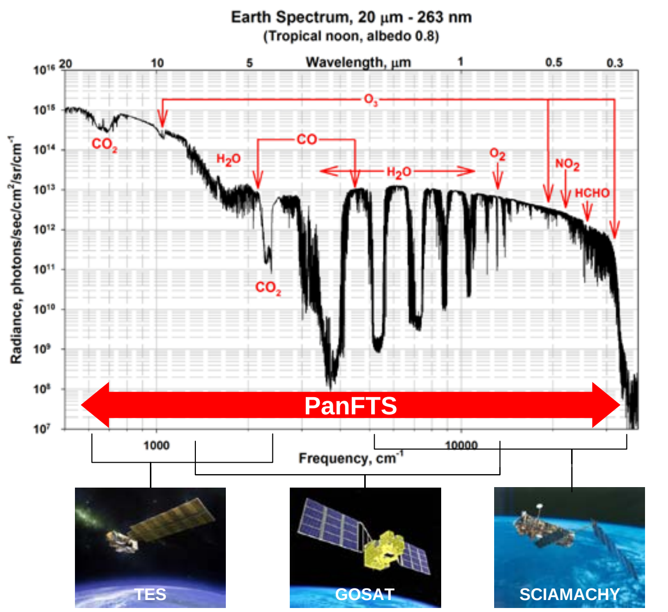

Fig. 1. The spectrum is a model calculation of the upwelling radiance (photons/(s-cm^2-sr^{-1})) and the most prominent molecular absorption bands that will be measured by PanFTS. Not shown are bands of other observable species such as HDO, CH_4, N_2O, CH_3OH, NH_3 and many others The spectral coverage encompasses the range of three current satellite instruments: TES, GOSAT and SCIAMACHY

PanFTS measures radiances in the mid-IR through the near-UV at high spectral, spatial, and temporal resolution. Combining UV, visible and IR spectra in a joint retrieval results in profiles that resolve the boundary layer ozone and its precursors along with improved profiling at all levels in the troposphere. The plan for the PanFTS IIP is to raise the instrument TRL from 3 to 6 by addressing key technology challenges including imaging focal plane arrays and wide-band optical design.

II. PanFTS IIP INSTRUMENT DESIGN

The instrument design drivers that address the requirements of the GEO-CAPE mission are summarized in Table I. PanFTS will operate in a staring mode with a nominal 900 km x 900 km footprint ground patch. Each patch will be imaged by a 128 x 128 pixel array which provides a footprint with 7 km ground sampling distance per pixel at nadir. From geostationary orbit, PanFTS observations will sample about 50

TABLE I
PanFTS Instrument Design Drivers for GEO-CAPE Mission

Capability	Value
Field of Regard	50° N. to 45° S. latitude -35° to -125° longitude
Spatial Sampling	7 km ground sampling distance at nadir
Spectral range	0.26 to 15 microns
Spectral resolution	0.05 cm^{-1}
Spectral SNR	1000
Interferogram dynamic range	2^{16}
Sampling interval	approximately hourly
Lifetime	5 years

patches per hour to meet the temporal sampling requirement of the mission (hemispheric mapping every 1-2 hours). The sampling strategy is illustrated in Figure 2.

The PanFTS IIP instrument is being built to test develop and test key technologies on the evolutionary path to address the design drivers for the flight instrument. Therefore, the IIP instrument does not meet all the specifications of the flight instrument including spectral range (5 microns vs. 15 microns) and array size (4x4 array vs. 128 x 128 array). Layout of the IIP instrument is shown schematically in Fig. 3. The input light beams are directed into the interferometer from an illumination source (quartz halogen lamp for the laboratory setup or scattered atmospheric radiation for the field measurement setup). To overcome limitations associated with the bandwidths of available optical coatings for the interferometer beamsplitter and reflective optics, the sampled radiation is split into two stacked beams, one for the UV-visible region (0.26 to 0.7 micron) and on for the infrared region (0.7 to 5 microns). The subsystem components (interferometer, focal plane arrays, data processing) will be described below.

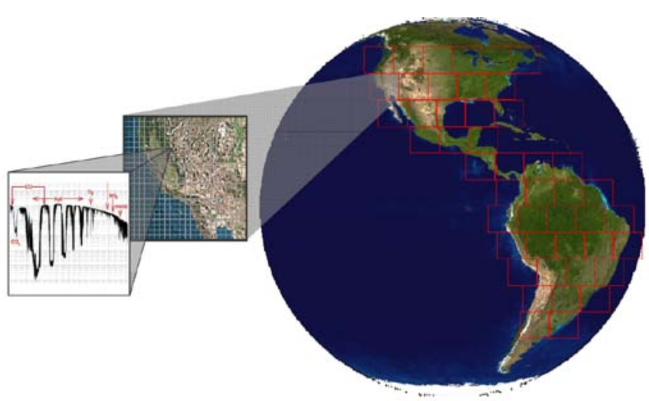

Fig. 2. Illustration of the wide-field (air quality) viewing mode for PanFTS in geostationary orbit. Each pixel in the focal plane array will map to a ground footprint that matches the GEO-CAPE sampling requirement. All the focal plane arrays will be co-boresighted to within a small fraction of a pixel over the duration of the measurement.

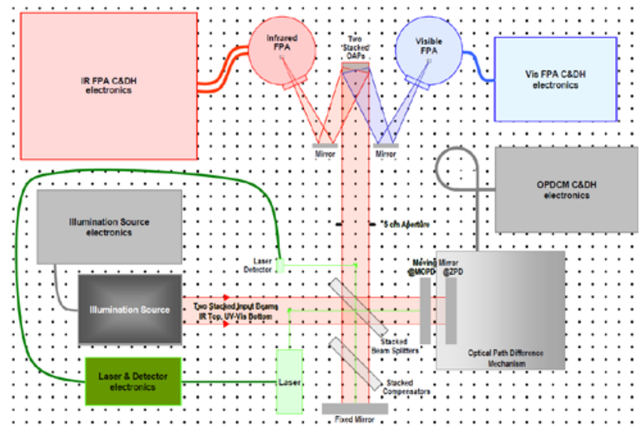

Fig. 3. Schematic layout of PanFTS IIP instrument. The major components include a collimated illumination source (quartz-halogen lamp), interferometer with stacked UV-visible and IR beams, optical path difference mechanism, focal plane arrays, and FPA command and data handling electronics. Fringes from a single-mode frequency stabilized laser are used for interferogram metrology and as an error signal for the dynamic alignment system.

A. Interferometer

The interferometer is a plane-mirror Michelson design that is modeled after JPL's Fourier Transform Ultraviolet Spectrometer (FTUVS) [2]. This design uses plane mirrors as reflecting elements rather than cube corners or cat's eye retroreflectors to maximize the optical throughput and fringe contrast. Beamsplitters and compensators are stacked to accommodate the spatially separate IR and UV-visible input beams. The optical path difference mechanism (OPDM) of the interferometer is a key development component of the IIP instrument. This mechanism controls the optical path difference between the two arms of the Michelson interferometer. Favorable experience with the FTUVS instrument resulted in the choice of a parallelogram four-bar linkage for the OPDM. This mechanism uses flexure pivots at the end of each link. The mechanism is driven by a non-contacting linear voice coil actuator consisting of a magnet fixed to the base and a moving coil. The position of the link is measured by an optical Moire encoder.

The key requirements that drive the OPDM design are the following:

Maximum optical path difference:	10 cm
Maximum physical travel:	5 cm
Maximum mirror tip/tilt error:	1 microradian
Full translation duration:	1 minute
Velocity stability over full range of travel:	better than 1%
Operating temperature range:	180-320 K
Operational lifetime:	5 years (more than 2.6 million cycles)
Moving mirror diameter:	12 cm

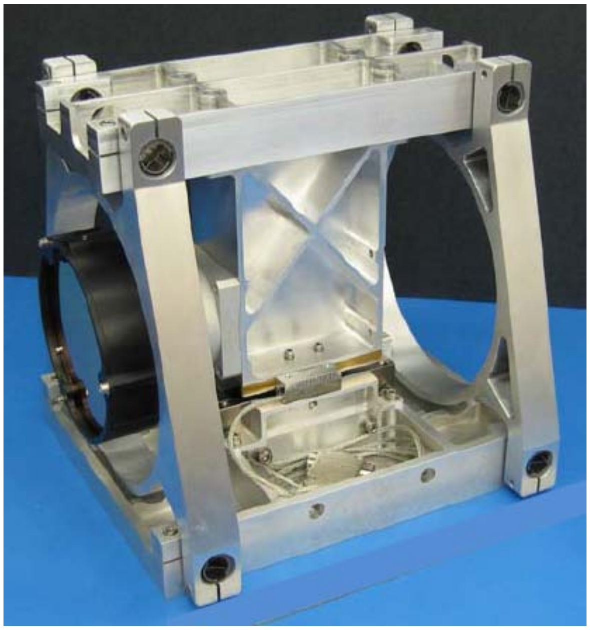

Fig. 4. Photograph of the PanFTS optical path difference mechanism. Flex pivots are used at the corners of the linkage bars. The voice coil actuator and position transducer are mounted on the fixed section of the linkage at the bottom.

The maximum tip/tilt error specification of 1 microradian is driven by the requirement to maintain high fringe contrast at the highest optical frequency (40,000 cm^{-1}) and resolving power. To meet the specification, careful design and fabrication of the OPDM are utilized to keep the tip/tilt error to less than 100 microradians over the full physical travel, with a dynamic alignment system used to reduce the residual error to the required value. To implement dynamic alignment, we measure the phase difference of the fringes across the waist of the metrology laser. This is used as an error signal with which to make small corrections to the tip and tilt of the moving mirror mounted on a flexure stage driven by piezoelectric transducers. Tests using an autocollimator and fringe contrast measurements with the OPDM installed in the interferometer show that the mechanism exceeds the tip/tilt specification by a large margin. The dynamic alignment system is currently being implemented and will be tested during the second year of the IIP task. To test the OPDM in a flight-like environment, a year-long accelerated life test of the mechanism in vacuum at the optical bench temperature of 180 K will also be performed.

B. Focal Plane Arrays

Unlike dispersive spectrometers, which require rapid mechanical scanning of the entrance slit image across the scene, Fourier transform spectrometers are sensitive in two spatial dimensions. To take advantage of this feature, an imaging FTS focal plane must have a large dynamic range (> 14 bits) and high speed (10 kHz frame rate or more). Arrays with formats on the order of 128 x 128 are required to take advantage of the full FTS field. These characteristics lead to very high data rates, on the order of 1 Gb/s or more. With these rates, it is advantageous to digitize the detector array signals on the FPA read-out integrated circuit (ROIC), or better yet, in each pixel.

The PanFTS IIP instrument uses two imaging FPAs, an indium antimonide array for the 1-5 micron region, and a silicon array for the 0.3-1 micron region. The IR array is a commercial 256x256 hybrid with analog outputs operating in a windowing mode. Two external (off-chip) 16-bit ADCs digitize the two detector outputs under control of a Xilinx FPGA. This array demonstrates the technology required for an imaging Fourier transform spectrometer at rates approximating the requirements of the Geo-CAPE mission. The second FPA is a custom hybrid using a silicon photosensitive layer for the UV-visible spectral region. The ROIC is a 4x4 array of second-order delta-sigma ADCs with sufficient resolution (14 bits) and speed (16 kHz frame rate) to meet the requirements of the PanFTS IIP instrument. The ROIC has been designed to test three circuits: a conventional second-order single-loop switched capacitor delta-sigma modulator, and two variants. The ROIC is being fabricated by a commercial foundry, and will be bump-bonded to silicon photosensitive arrays. A companion Advanced Component Technology task (D. Rider, PI) is currently focused on development of a 128x128 ROIC for applications to UV-visible interferometry and high speed imaging. This circuit will also meet the requirements of 14 bit resolution and 16 kHz frame rate using a design that incorporates an ADC in each pixel footprint. This ROIC will be hybridized and integrated into the PanFTS IIP instrument in the near future.

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