Airborne Imaging Fabry-Perot Interferometer System for Tropospheric Trace Species Detection

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***Abstract*—Monitoring tropospheric chemistry from space is the next frontier for advancing present-day remote sensing capabilities to meet future high-priority atmospheric science measurement needs. Paramount to these measurement requirements is that for tropospheric ozone, one of the most important gas-phase trace constituents in the lower atmosphere. Such space-based observations of tropospheric trace species are challenged by the need for sufficient horizontal resolution to identify constituent spatial distribution inhomogeneities (that result from non-uniform sources/sinks and atmospheric transport) and the need for adequate temporal resolution to resolve daytime and diurnal variations. Both of these requirements can be fulfilled from a geostationary Earth orbit (GEO) measurement configuration.**

The Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI) was recently selected for funding within NASA's Instrument Incubator Program (IIP). Within this project we will develop and demonstrate an airborne sensor to mitigate the risk associated with an advanced atmospheric remote sensor intended for geostationary-based measurement of tropospheric ozone and other trace species. The concept is centered about an imaging Fabry-Perot interferometer (FPI) observing a narrow spectral interval within the strong 9.6 micron ozone infrared band with a spectral resolution ~0.07 cm^{-1}. This concept is also applicable to and could simplify designs associated with atmospheric chemistry sensors targeting other trace species (which typically require spectral resolutions in the range of 0.01 - 0.1 cm^{-1}), since such an FPI approach could be implemented for those spectral bands requiring the highest spectral resolution and thus simplify overall design complexity. The measurement and instrument concepts, enabling technologies, approach for development and demonstration within IIP, and a summary of progress-to-date will all be presented.

I. Introduction

Measurement of tropospheric chemistry is identified as one of the key areas to be included in Earth science missions of the 21st century in the NASA Office of Earth Science (OES) Strategic Enterprise and Science Research Plans. While many species are fundamental to enabling atmospheric chemical processes, ozone is clearly recognized as one of the most important gas phase trace constituents in the troposphere. Its importance stems from three main roles: 1) ozone is a key oxidant in tropospheric photochemistry; ozone photolysis is one of the principal sources of the hydroxyl radical (OH), which is the most important radical species associated with the photochemical degradation of anthropogenic and biogenic hydrocarbons; 2) exposure to enhanced levels of tropospheric ozone [1]-[2] negatively impacts health, crops, and vegetation; ozone is responsible for acute and chronic health problems in humans and contributes toward destruction of plant and animal populations; and 3) as a greenhouse gas it contributes toward radiative forcing and climate change. The objective of the Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI) within NASA's Instrument Incubator Program (IIP) is to develop and demonstrate an airborne sensor to further the development of an advanced atmospheric remote sensor intended for geostationary-based measurement of tropospheric ozone and other trace species, which fits directly within the OES Atmospheric Ozone and chemistry measurement themes.

II. Technical Approach

Observations of tropospheric trace species face two fundamental challenges: 1) the need for sufficient spatial resolution to identify the spatial distribution inhomogeneities of constituents that result from non-uniform sources/sinks and atmospheric transport, and 2) the need for adequate temporal resolution to resolve daytime and diurnal variations. Both of these requirements are ideally fulfilled by observation from geostationary orbit. While differential absorption lidar and other active sounding systems operating from low Earth orbit could permit high vertical resolution, they would only provide relatively sparse horizontal spatial sampling. The Tropospheric Emission Spectrometer (TES) instrument on the EOS-CHEM satellite is expected to provide the first global data set on distribution of tropospheric ozone. However, the EOS Request for Information panel has recommended technology development to achieve higher horizontal resolution than will be possible with the EOS-CHEM payload [3]-[4]. This would address the key tropospheric ozone process-related questions that are expected to remain in the post-CHEM time period.

Earlier NASA-sponsored research [5] has shown that a tropospheric ozone measurement capability can be achieved using a satellite-based nadir-viewing device making high spectral resolution measurements with high signal-to-noise ratios, and that a Fabry-Perot interferometer (FPI) is quite suitable for this task. Implementation in the infrared portion of the spectrum utilizes the strong 9.6 micron ozone band and yields continuous day/night coverage independent of solar zenith angle. Using an FPI affords high optical throughput while operating at high spectral resolution, and has a proven success record in previous applications. The same technology being advanced for TTSS-FPI is applicable to measurements of other trace species, and could greatly simplify other atmospheric chemistry sensor designs (which typically require spectral resolutions in the range of 0.01 - 0.1 cm^{-1}) by implementing for spectral bands requiring the highest spectral resolution in those applications and thus simplify overall design complexity.

A geostationary-based implementation is ultimately desired for this concept for the many operational benefits it enables, including:

- higher spatial and temporal resolution than low Earth orbit (LEO)
- species source/sink identification and atmospheric transport characterization
- quick repeat views to study regional pollution episodes on mesoscale meteorological time and space scales
- viewing of same surface region throughout day/night which will allow separating surface, troposphere and stratosphere variability (i.e. from temporal characteristics in addition to spectral)
- viewing the same scene as a function of surface/lower atmosphere thermal contrast variations (ensuring scene views during maximum thermal contrast, and thus minimum retrieval error, conditions)
- maximizing the likelihood of cloud-free views of any given location, and optimizing the ability for cloud removal for any given time (i.e. having high spatial resolution views of nearest neighbors, which may be cloud-free).

. *A. Measurement Concept*

Molecular collisions during the absorption/emission process give rise to collisional or pressure broadening, and the corresponding profile function can be represented by the Lorentz line shape. The Lorentz half-width is proportional to pressure and is approximately inversely proportional to the square root of temperature. The other significant mechanism for broadening in the terrestrial atmosphere is Doppler broadening, which originates from a Doppler shift in the frequency of radiation associated with the absorption/emission feature due to thermal motion of the radiating molecules. Unlike the Lorentzian half-width, the Doppler half-width does not have a pressure dependence and therefore its change with altitude is due to temperature alone. The Voigt profile is formed from the convolution of two independent broadening formulas (i.e., Lorentzian and Doppler) and in the high or low pressure limits approaches the Lorentz or Doppler profiles, respectively. Figure 1 illustrates the approximate Lorentz, Doppler, and Voigt half-widths as a function of altitude for ozone lines within the 9.6 micron band (using reasonable surface values for the Lorentz and Doppler half-widths [6] and Lorentz half-width temperature dependence coefficient [7]) and shows the basis for this measurement concept: tropospheric information content in the measured signals can be maximized by spectrally isolating wings of strong ozone lines, since wings of strong lines are due primarily to pressure broadening in the troposphere.

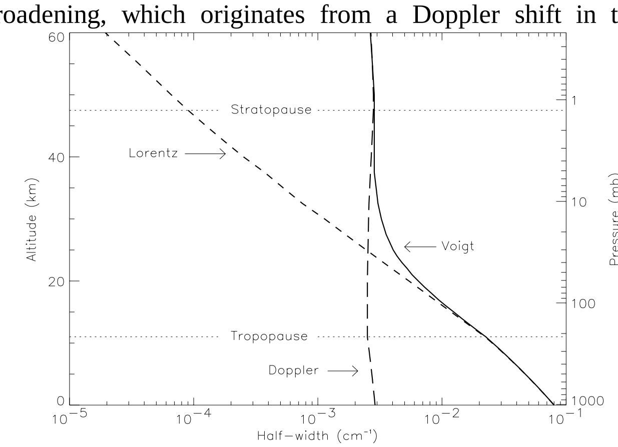

Figure 1. Approximate altitude dependence from 0 to 60 km of Lorentz, Doppler, and Voigt half-widths.

B. Instrument Concept

The TTSS-FPI instrument concept employs a double-etalon FPI to achieve the necessary high-resolution (0.068 cm^{-1}), narrow-band infrared emission measurements within the strong 9.6-micron ozone band. This implementation requires a single-order transmission function, rather than the periodic nature of the standard Fabry-Perot instrument bandpass (which can be advantageous when observation of periodic spectra is desired). This is achieved using additional optical elements (specifically, a low resolution etalon, LRE, a high resolution etalon, HRE, and an ultra-narrow bandpass filter all arranged in a series configuration) to reduce the effect of unwanted passbands, improve sideband rejection, and extend the effective free spectral range. Figure 2 summarizes the formation of a single-order, double-etalon instrumental transfer function

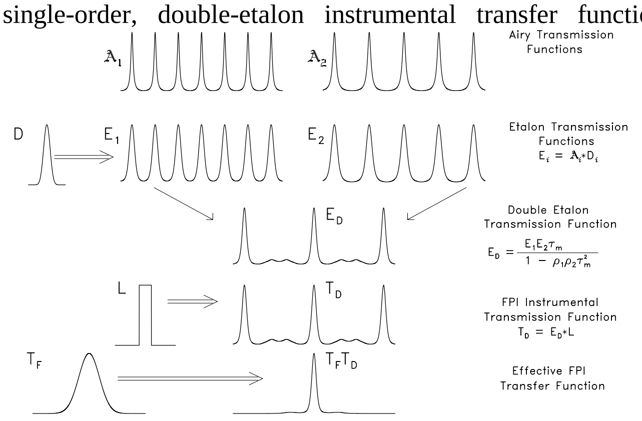

Figure 2. Schematic diagram summarizing the formation of a single-order, double-etalon instrumental transfer function.

from the Airy (A), defect (D), aperture (L), and bandpass filter (T_F) functions. Larar et al. [8] describe such a system for a cross-track spatially scanning non-imaging instrument configuration. The system being advanced herein incorporates an advanced focal plane array (FPA) detector to perform spatial imaging, and spectral tuning is accomplished through precise mechanical scanning of etalon plate gaps; Larar et al. [9] describe such a system for geostationary implementation.

C. Space-Based Measurement Feasibility

The feasibility of tropospheric and total ozone

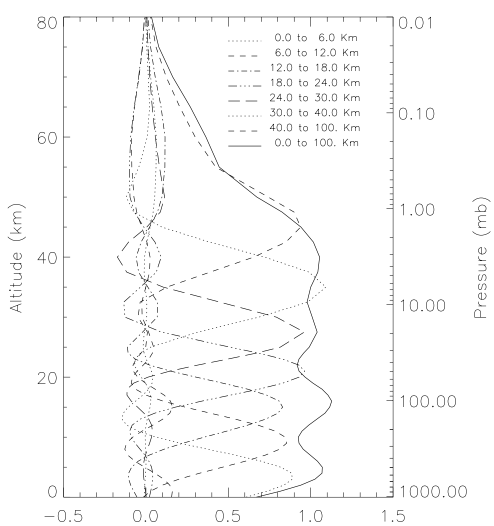

Figure 3. Averaging kernels for merged layers (1976 Standard Atmosphere)

observations from a LEO-based platform using a double-etalon FPI has been demonstrated in an earlier study [10]. Similar or better performance at much higher spatial and temporal resolutions is obtainable from a geostationary-based implementation since such a configuration allows for longer scene dwell times to achieve desired signal-to-noise ratios (SNR). The Larar and Drayson study [10] indicates vertical discrimination capability between tropospheric and stratospheric ozone fields using the proposed instrumentation, supporting the threshold minimum measurement performance of obtaining integrated column amounts for both the troposphere and stratosphere. Additionally, the measurement goal of some profiling capability also appears achievable since an averaging kernel analysis has shown that approximately seven independent pieces of vertical information should be obtainable for this ozone retrieval, with roughly three located in the troposphere. Averaging kernels roughly representing such vertical boundaries are shown in Figure 3 for a set of 7 narrow layers along with one covering the 0 to 100 km range corresponding to 'total ozone'. This analysis also estimated the achievable vertical resolution to decrease with altitude and range from ~6 km near the surface to ~8 km in the upper troposphere and from ~8 km to ~11 km in the stratosphere. This reduction in vertical resolution with altitude is a direct consequence of the decrease in ozone line half-width with height (ranging from roughly 0.08 cm^{-1} near the surface to ~0.003 cm^{-1} in the upper stratosphere) observed with a fixed instrument spectral resolution (which is ~0.07 cm^{-1} for this measurement concept). An error analysis, which considered the impact on retrieved integrated ozone amounts from the most significant uncertainties associated with this particular measurement, showed the proposed instrumentation to enable a good measurement of absolute ozone amounts and an even better determination of relative changes. Expectations are that this technique can enable integrated tropospheric ozone determination to within ~10% precision and ~20% accuracy, and knowledge of total column ozone abundance to within ~4% precision and ~5% accuracy. While further studies are still to be performed for a GEO implementation, current results support preliminary feasibility of this space-based measurement and these estimates compare quite favorably with the capabilities of the limited number of instruments/techniques that are currently planned to make similar observations in the future [9].

Accurate ozone retrievals require concurrent knowledge of atmospheric temperature and water vapor along with surface characteristics (i.e. temperature and emissivity). Such geophysical information can be easily obtained from infrared spectral radiance measurements acquired with, for example, a lower-resolution FTS system using currently available technology. While our IIP demonstration objectives for this sensor can be accomplished acquiring these ancillary data products from other readily available sources (i.e. GOES products, radiosonde profiles, surface calibration site data, etc.), we will obtain such desired data by flying jointly with the NPOESS Airborne Sounder Testbed-Interferometer (NAST-I) instrument [11]. Besides being a cost-effective approach by piggy-backing on a NAST-I flight of opportunity, a greatly-enhanced combined data set will result.

Specific spatial and temporal resolutions will be defined during the initial airborne sensor definition study, incorporating the geostationary science implementation goal of ~ 4 km for spatial footprint [9] and the NAST-I airborne nadir pixel size of ~ 2.5 km [11].

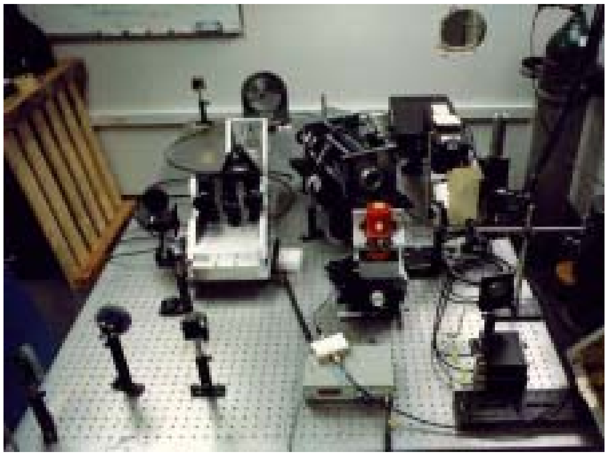

Figure 4. FPI laboratory breadboard system at UM/SPRL used for ground-based solar absorption ozone measurements.

D. Maturity of Concept

During the past few years we have developed a ground-based double etalon FPI at the University of Michigan's Space Physics Research Laboratory (UM/SPRL) as part of a program sponsored by NASA LaRC and funded through the OES Sensor and Detector Technology Program. The program has successfully developed critical component technologies and demonstrated the predicted ground-based operation of a double etalon FPI laboratory breadboard in the 10-micron spectral region. The laboratory breadboard (Figure 4) has been used to collect solar absorption spectra that compare very well with spectra simulated using the optical properties of the instrument and atmospheric conditions. The choice of a solar-absorption application (rather than the intended emission mode of implementation) was a cost-effective (i.e., requiring smaller optics) approach for

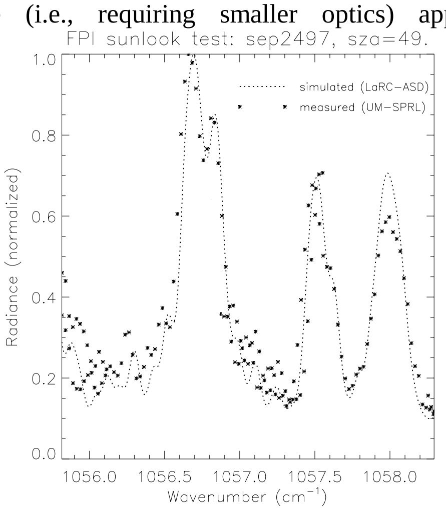

Figure 5. Partial spectrum from a typical scan with the laboratory breadboard.

accomplishing the desired proof-of-concept objectives. Figure 5 shows a portion of a typical scan where the overlapping sections of the spectrum are clearly identifiable. Note that deviations from a perfect match-up between simulated and measured spectra are explainable by uncertainties in knowledge of exact instrument characteristics and atmospheric conditions during the scan [12].

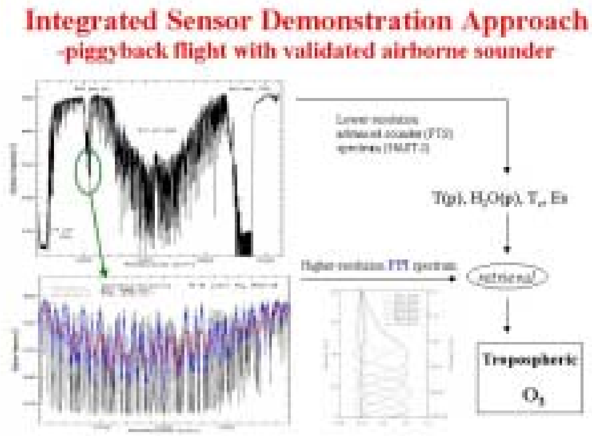

Figure 6. Integrated sensor demonstration approach for TTSS-FPI within IIP.

E. Airborne System Implementation Approach

The next logical step in advancing and validating this measurement technique is performing atmospheric measurements from a more realistic configuration (i.e. making nadir-viewing emission observations). This would address several critical operational challenges associated with this measurement; most importantly, signal impact from background (surface) variability of temperature, emissivity, and topography. Within IIP we will demonstrate an integrated instrument system from an airborne platform to provide technique validation, demonstration of enabling components within an integrated system, the utility of the imaging technique and evaluate FPA small/large format tradeoffs, and autonomous operation, all from a more relevant environment than possible from the ground. Subsequent atmospheric test flights will be a crucial risk-mitigating activity for the eventual spaceflight instrument by validating enabling technologies and providing additional measurement concept verification.

Within IIP we will demonstrate this FPI device with a lower-resolution advanced sounder Fourier Transform Spectrometer (FTS) sensor measuring spectra concurrently from the same airborne platform. Specifically, we intend to have piggyback flights with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed Interferometer (NAST-I) sensor aboard the high-altitude Proteus aircraft [13]-[14]. NAST is a suite of airborne infrared and microwave spectrometers developed for the Integrated Program Office (IPO) that has been flown on the high altitude NASA ER-2 and Northrup Grumman Proteus aircraft as part of the risk reduction effort for NPOESS (i.e., the NPOESS Cross-track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS)). The NAST-I is a Michelson interferometer that derives its heritage from the non-scanning High resolution Interferometer Sounder (HIS) developed by researchers at the University of Wisconsin [15]. It scans the Earth beneath the aircraft with a nominal spatial resolution of approximately 2.5 km within a cross-track swath width of about 45 km; its unapodized spectral resolution is 0.25 cm^{-1} within the 3.6 - 16.1 micron spectral range. NAST-I is a scientifically-sound sensor that has flown ~85 missions for ~450 flight hours, the majority on Proteus. Flights concurrent with NAST-I will enable temperature and water vapor profiles along with surface characteristics (i.e., temperature and emissivity) to be implemented into the TTSS-FPI ozone retrieval; additionally, a lower-resolution observation of the entire ozone band will be available for cross-calibration verification. Figure 6 illustrates the concept behind this piggyback demonstration flight.

F. Enabling Technologies

The instrument system is an imaging Fabry-Perot interferometer (FPI) based on a tunable double etalon designed to collect high resolution (R~15000) spectra of the Earth/atmosphere in the 9.6 micron ozone band over an infrared FPA. Spectral information is acquired by taking a series of images at different FPI plate separation distances. As the FPI is scanned, each pixel measures a signal that represents the convolution of the instrument transfer function with the spectrum incident at that pixel location. For each plate separation setting, slight differences in effective center wavelength occur as a function of exact pixel location, because the surfaces of equal phase difference are curved, not flat like the focal plane array. Thus the FPI needs to be scanned beyond the spectral range required for field center to ensure all spatial elements in the three-dimensional spatial-spectral data set have complete spectral coverage. To enable the spectrally tunable imaging FPI measurement technique proposed for TTSS-FPI, for achieving high-resolution over narrow spectral ranges, three enabling technologies will be demonstrated within IIP:

1. precision control of etalon plates to demonstrate accurate spectral tuning and parallelism control of the LRE and HRE;
2. high-sensitivity two-dimensional infrared detector arrays to demonstrate the required SNR and imaging configuration; and
3. spectral and radiometric calibration, to demonstrate spectral registration and absolute intensity fidelity in radiance measurements.

1). *Precision Etalon Control*. A key feature of the proposed measurement concept is the optical performance and spectral tuning of the FPI, which is achieved by controlling the spacing and parallelism between the etalon plates. Alignment/tuning of the etalon plates during the aircraft prototype demonstration will employ a laser-based technique, analogous to what was used in the laboratory breadboard, combining low voltage piezoelectric actuators, stable frequency lasers and angle interferometry to produce a small, low power system that is scalable to the optimum performance and versatility desired for a space-based Fabry-Perot interferometer.

2). *High Sensitivity 2-D Infrared Detector Arrays*. A top priority of the airborne prototype design phase has been to perform a trade-off study to simultaneously specify the pre- and post-optics configurations, the instrument FOV, integration times, and spectral bandwidth to be required: all of these parameters are pending determination of the detector array(s) required and devices available to us. Large-format detector arrays with 1024 or more rows would likely be desired for a geostationary application of this concept. However, besides being constrained by both time and budget in the procurement of such a large array, a much smaller format (~ 64 x 64) will likely be more than sufficient for demonstration purposes within IIP. The key to a low cost subsystem is avoidance of design and small-lot manufacturing costs by relying on of-the-shelf products, commercial products, and spares from other programs whenever possible. This subsystem has two major components, the focal plane-dewar and the data capture electronics. We have already identified candidate detector arrays and ROICs, hardware items already in production for other programs, potentially suitable for this application. The dewar would likely be cooled by liquid N_2 to around 77 K. Performance characteristics of these devices and delivered focal plane assemblies would depend upon status of available vendor inventory upon procurement. It is worth noting, however, that at the time of this writing candidate detector arrays with suitable characteristics for this aircraft prototype (i.e., format of 64 x 64 and expected D* better than 5×10^{10} cm $Hz^{1/2}$ W^{-1} at 77 K) have been identified.

3). *Calibration*. Measured data need to be calibrated in radiance, phase and wavelength. The radiometric calibration for every element in the spatial-spectral datacube is derived by measuring apparent signal as a function of FPI plate separation from the onboard blackbody source(s). From these measurements, gain and offset for each datacube element can be calculated. To improve SNR of the calibration spectra, reference scans can be averaged together.

The phase correction accounts for variation in center wavelength as a function of pixel location for a given FPI setting. For any off-axis pixel located at (x,y) in the array, a given wavelength, λ_o, with maximum transmission on-axis for some gap setting, z_o, has maximum transmission at a different FPI gap setting, z_o+p(x,y). The array of values describing this difference in gap setting, p(x,y), is called the phase map. This array can be determined by illuminating the spectrometer with a monochromatic light source such as a laser and then collecting a series of spectral images across the full Nyquist-sampled FPI scan. The phase map obtained with this method is independent of wavelength and therefore can be applied to all spectral channels. After the phase map has been determined, wavelength calibration can be obtained; candidate techniques for achieving spectral calibration are still under consideration. The most straightforward method would be to scan across two different spectral features and then solve for etalon spacing at each position. This would require two very narrow spectral features in the atmospheric spectrum or view of an internal monochromatic calibration source. Another approach would be to use a laser metrology system to measure plate separation very accurately and require only one spectral reference to determine the wavelength calibration.

While our in-flight calibration approach is still TBD for the aircraft prototype, we expect to use a combination of a blackbody source, a laser, and the detected spectrum. A small blackbody source will be located outside of the optical bench housing where it may be viewed by the instrument via a mechanized mirror.

Optics & Electronics. The optical bench will support the pre-optics, the etalons, and the focusing optics and will be mated to the detector housing. The instrument optics will be cooled via thermal connection of the optical bench to a liquid nitrogen reservoir. Avoiding condensation will necessitate evacuation of a housing placed around the bench since the instrument would otherwise come into contact with water vapor during the flight. The bench will be maintained at a constant temperature at or below 170 K. This evacuation and cooling will closely simulate the space-based environment, although the liquid cryogen would be replaced with passive radiators and, if needed, active coolers. Suitable orbital temperature control technology already exists and is used frequently on spacecraft; hence our cryogen-based system is easily scaled to space while lessening the cost of this demonstration project. The optical components will be primarily coated ZnSe lenses and/or gold-coated mirrors as deemed appropriate during the design stage. A collector, field lens, and collimator will be the major components in the pre-optics. This arrangement maintains wavelength/viewing-angle information contained in the Fabry-Perot transfer function (as desired for a spatially-imaging device).

Flight electronics will consist of a signal power conditioning deck, an etalon control deck, a detector array power deck, a detector array data deck, a temperature control deck, a mechanical/blackbody source control deck, and a standard PC-based flight computer. Off-the-shelf control electronics for the alignment laser will be re-packaged for the aircraft prototype. Wherever possible existing designs for these cards will be used, thus providing some leveraging of our project by some of the ongoing work at LaRC, SBRS and UM/SPRL. Cooling of the electronics package, if required, will be provided through an interface with the aircraft cooling system.

III. Summary

Tropospheric ozone is a high-priority measurement identified in the NASA Office of Earth Science (OES) Strategic Enterprise and Science Research Plans. The airborne FPI system (TTSS-FPI) described herein would demonstrate a new measurement capability intended for "direct" geostationary Earth orbit (GEO)-based observation of tropospheric ozone. The concept exploits spatial and temporal benefits obtainable from a GEO-based imaging system, for example, monitoring of regional pollution episodes. The instrument concept and technologies are also applicable to measurement of other important atmospheric trace species. The science justification for pursuing this capability along with the concepts behind the measurement and instrumentation have been described. Also, the approach for development and demonstration of this airborne system within NASA's Instrument Incubator Program have been discussed.

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