Using Fabry–Perot Interferometer Imagery from Space for the Measurement of Clouds and Trace Gases

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***Abstract*-Long-term measurements of the global distributions of clouds, trace gases, and surface reflectance are needed for the study and monitoring of global change and air quality. The Geostationary Imaging Fabry–Perot Spectrometer (GIFS) instrument is an example of a next-generation satellite remote sensing concept. GIFS is designed to be deployed on a geostationary satellite, where it can make continuous hemispheric imaging observations of cloud properties (including cloud top pressure, optical depth, and fraction), trace gas concentrations, such as tropospheric and boundary layer CO, and surface reflectance and pressure. These measurements can be made with spatial resolution, accuracy, and revisit time suitable for monitoring applications. It uses an innovative tunable imaging triple-etalon Fabry–Perot interferometer to obtain very high-resolution line-resolved spectral images of backscattered solar radiation, which contains cloud and trace gas information. An airborne GIFS prototype and the measurement technique have been successfully demonstrated in a recent field campaign onboard the NASA P3B based at Wallops Island, Virginia. In this paper, we present the preliminary GIFS instrument design and use GIFS prototype measurements to demonstrate the instrument functionality and measurement capabilities.**

I. Introduction

Earth observations from geostationary orbit (GEO) are ideal for providing long-term, diurnal, regional coverage of natural phenomena. Long-term measurements of a variety of trace gases, such as CO and H_2O, and clouds, including their global distribution, cloud top pressure, optical depth, and cloud fraction, are needed for global change and air quality studies. A compact, low-cost instrument capable of making these measurements is required to meet scientific research objectives for studies of climate and air quality in the 21st century.

The Geostationary Imaging Fabry-Perot Spectrometer (GIFS) instrument concept is an ideal approach to make trace gas and cloud property measurements with the desired spatial resolution, accuracy, and revisit time. It uses an innovative tunable imaging triple-etalon Fabry–Perot interferometer (FPI) to obtain hemispheric images of high-resolution spectral line shapes of O_2 Atmospheric band absorption lines and those of other trace gases of interest in backscattered solar radiation. The GIFS remote sensing technique takes advantage of the spectral line width and pressure broadening information embedded in the absorption line shapes to better determine optical depths of the absorbers and cloud properties, especially for clouds below 5 km. The GIFS team, based at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) and the University of Michigan (UM), has demonstrated the feasibility of this technique using data from the High Resolution Doppler Imager (HRDI) onboard the Upper Atmosphere Research Satellite (UARS) [1]. Lessons learned from this feasibility investigation have been leveraged to provide the design of GIFS, an optimal cloud-sensing instrument. The versatile GIFS concept can easily be modified to provide many other measurements that are applicable to current scientific objectives. In this paper, we present the sensing technique, a conceptual spaceborne instrument specifically designed for a GEO satellite, and the preliminary assessment of its measurement capability using a GIFS airborne prototype.

II. Measurement Technique

The GIFS measurement technique is based on very high spectral resolution measurements of O_2 Atmospheric band absorption of solar backscatter. The O_2 Atmospheric A, B, and γ ($X^3\Sigma_g$-$b^1\Sigma_g$, 0-0, 1-0, 2-0) band transitions located at around 762, 685, and 637 nm, respectively, have absorption cross sections ideal for probing the atmospheric O_2 density (and thus total density) in the Earth's lower and middle atmosphere. Recent calculations indicate that estimates of cloud top altitudes as well as optical depths can be retrieved from observations of the O_2 Atmospheric bands using a moderate-resolution (0.5–6.0 nm) spectrometer. The accuracy of the estimates can be improved by measurements with higher spectral resolution and/or higher signal-to-noise ratio, where it is possible to characterize the spectral shape of an individual absorption line.

Fig. 1 shows the calculated line shapes for a single O_2 B-band absorption line for a series of clouds of different cloud

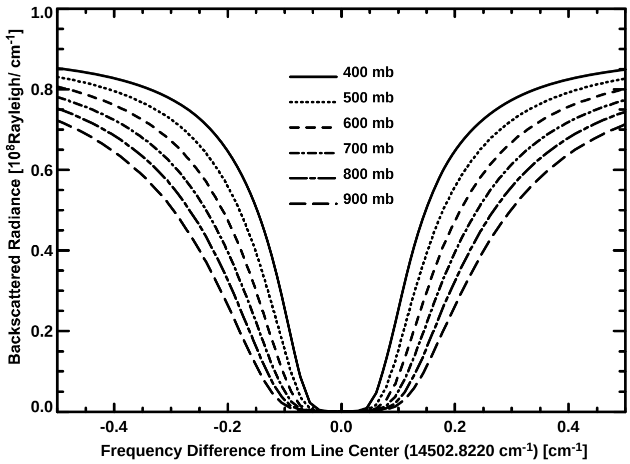

Fig. 1. Cloud backscattered solar radiance for clouds with tops at various pressure levels produced using line parameters from the HITRAN database and using the DISORT radiative transfer algorithm. For each trace, a cloud layer thickness of 100 mb and an optical thickness of 5 were assumed.

top pressures. The asymptotic radiance (~$1.0\text{x}10^8$ R/cm^{-1}) contains information about the effective optical depth and surface reflectance. The shape, especially the width, of the absorption line contains information about the pressure levels where the scattering/surface reflection occurs. The equivalent width of the absorption line contains the information about the amount of O_2 in the total scattering path. The spectral resolution needed for individual line measurements (~0.05 cm^{-1}) is technologically achievable through the use of an FPI.

The GIFS team has investigated the feasibility of retrieving cloud top pressure using nadir-viewing spectral line shape measurements of the O_2 B-band taken by HRDI, a triple-etalon FPI onboard the UARS spacecraft [1]. From our HRDI experience, we conclude that there are several advantages of a specially designed FPI measurement technique over its spectrograph counterparts:

- high-resolution absorption line spectra can capture pressure broadening and equivalent width information, yielding more accurate cloud top pressure and optical depth retrievals, especially for low-level cloud conditions;
- high-fidelity calculations of single-line spectra are less computationally expensive, allowing more efficient retrievals;
- individual lines can be selected that are free of contamination from water vapor, solar Fraunhofer lines, effects of temperature variation, and other complications in the data analysis;
- near-global high-spatial/spectral resolution line shape measurements over a 2-D spatial scene can be obtained with a short revisit time by the use of an FPI system operating in an imaging mode.

In order to implement the FPI measurement technique in a daytime imaging mode, we need the following instrument characteristics:

- an optical system that provides an adequate SNR and white light rejection to meet accuracy requirements, while acquiring images fast enough such that cloud features do not change appreciably during the acquisition of spectra;
- adequate spectral resolution to resolve pressure broadening signatures in O_2 line shapes;
- a single O_2 absorption feature suitable for providing cloud property information for various cloud types and heights;
- spatial scan capability to obtain global coverage with physically meaningful spatial resolution.

A concept for a spaceborne imaging FPI instrument, GIFS, has been developed to provide 2-D cloud properties from high–spectral resolution measurements of the O_2 absorption line in solar backscattered radiation. The baseline O_2 lines selected for the GIFS investigation are the B-band ^{P}P7 and ^{P}Q7 lines at 14,502.8219 cm^{-1} and 14,504.7954 cm^{-1} (the closest water vapor line is ~5 cm^{-1} away and there is no Fraunhofer feature nearby). These two lines are selected because their absorption cross sections are relatively insensitive to temperature. Therefore, the pressure levels of the cloud deck are the most important factors determining the absorption line shapes, making these two lines ideal for probing the troposphere, where large temperature variations (~100 K, summer-to-winter, surface-to-tropopause) are expected. Observations from a geostationary platform eliminate the spatial smearing during a spectral scan and the large Doppler shift correction that arises from the relative motion between Earth and the spacecraft, as would be encountered on a low Earth orbit (LEO). Doppler shifts due to wind-driven cloud motion (~0.002 cm^{-1} at the jet stream) are significantly smaller than the width of the absorption line, typically a few tenths of cm^{-1}. Furthermore, a geostationary orbit will assure cloud-free observations for surface reflectance measurements for each geophysical footprint within a reasonable time span (~1 week, based on statistics). The following section describes the GIFS design and operational concept.

III. GIFS Instrument Design

Only three FPIs have flown in space: FPI [2], HRDI [3–5] and TIDI [6,7], onboard the DE, UARS, and TIMED spacecraft, respectively. All three are high resolution FPIs that were primarily designed to measure Doppler shifts of upper atmospheric airglow emission lines. The GIFS design builds on these earlier instruments and is optimized for cloud and trace gas sensing (rather than high-altitude winds). While the HRDI instrument uses three etalons in tandem with two of the three tunable by the use of piezoelectric posts (DE/FPI and TIDI are single, fixed-plate etalon systems), GIFS is the first spaceborne FPI designed to piezo-scan all three etalons. The TIDI instrument uses a CCD detector but intentionally scrambles the incoming light to remove spatial information (similar to HRDI). GIFS will form spatially coherent images on the CCD detector and will therefore be the first instrument to combine a tunable tripe-etalon FPI (and its high–spectral resolution) with a simultaneous spatial imaging capability. The GIFS instrument consists of a two-axis scanning telescope, a tunable triple-etalon FPI with a CCD detector, and associated electronics. A block diagram of the GIFS instrument is presented in Fig. 2. Fig. 3

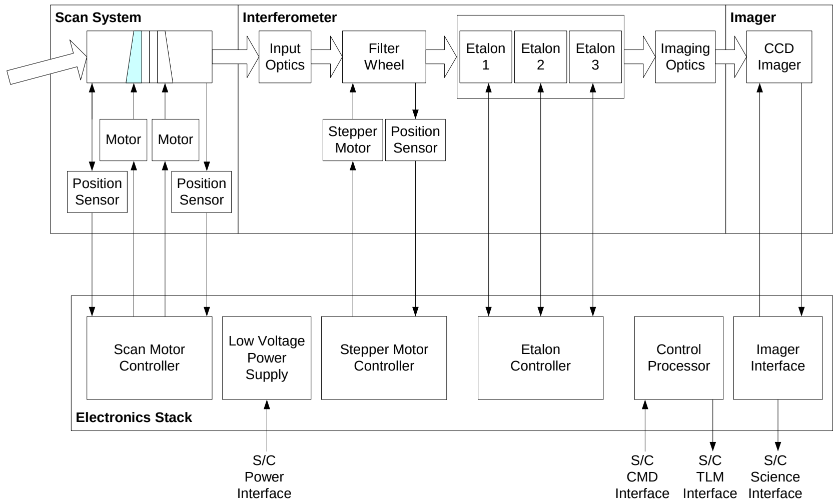

Fig. 2. GIFS instrument block diagram.

shows the optical train of the GIFS instrument. Light from the telescope or from calibration sources is selected by positioning a scene selector mirror. Light is collimated, and passed through a narrow-band filter wheel to select any of several O_2 B-band transitions, spectral calibration lines, or incandescent light. The beam is expanded and passed through a set of three piezoelectrically tuned low-, medium-, and high-resolution etalons (LRE, MRE, HRE). Three etalons in series reduce the sidebands that would occur with a single etalon when trying to resolve a narrow spectral region within an atmospheric continuum. The beam is finally focused onto a CCD detector providing a two-dimensional, spectrally filtered image of the scene. Stepping the etalon gaps in resonance and acquiring a CCD image at each step produces a high-resolution spectrum at each spatial pixel. Coupling the FPI system with a two-axis scan system allows for acquisition of a mosaic of spectral images from a three-axis stabilized spacecraft. An embedded computer controls image collection, tuning/stepping of the etalons, and the pointing system. FPI science and instrument engineering data are sent to the spacecraft via a serial link for storage and

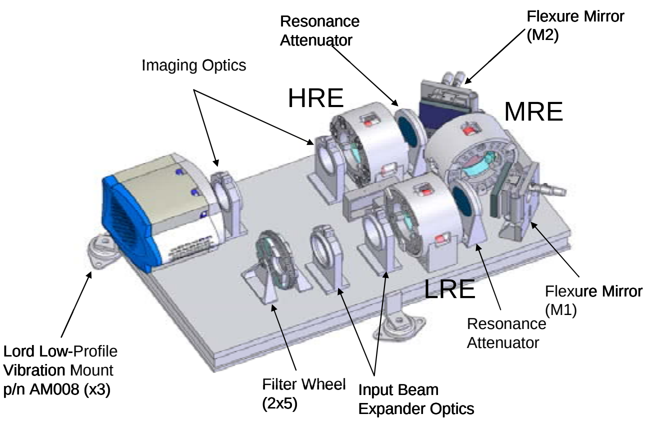

Fig. 3. Optical train of the GIFS instrument. HRE=High-Resolution etalon, MRE = Medium-Resolution etalon, LRE = Low-Resolution etalon.

downlink. Table I shows the GIFS design specifications and driving requirements determined by tradeoff studies between measurement accuracy, spatial resolution, integration time, and spectral coverage.

Telescope Scan System Two-axis scanning is accomplished with a baseline wedge scanner approach developed for MOLA (Mars Observer Laser Altimeter), GLAS (Geoscience Laser Altimeter System) and the lidar system on JIMO (Jupiter Icy Moons). The wedge scanner uses counter-rotating refractive wedges to deflect the line of sight through any desired range of angles about two axes.

Imaging FPI The imaging Fabry–Perot optical system consists of a triple-cavity filter (~4 cm^{-1} FWHM), a set of three 150 mm Spectrosil-B etalons, and a CCD detector. The gaps between each etalon are optimized to minimize the amount of white light leaked from the higher-order transmission. All three etalons have a 0.90 reflectivity ZnS–ThF_4 coating at 680 nm, giving rise to a reflectivity finesse of ~30. A system finesse of 20, a conservative estimate to include optical defects, results in an instrument resolution of ~0.05 cm^{-1}. The gaps of these three etalons are piezoelectrically controlled (with Michigan Aerospace Corporation's (MAC) new patented capacitive feedback scheme described in U.S. Patent #60/268789), and they are individually tuned so that all three etalons have maximum transmission at the same frequency. The three well-tuned and optically aligned/parallel etalons along with a filter effectively attenuate the background continuum outside the narrow transmission peak, as shown in Fig. 4.

GIFS forms a 2-D image on the detector, with each pixel mapping to a different geographical footprint. Each pixel has a peak transmission at a different resonance wavenumber following a concentric Fabry–Perot fringe pattern. The difference in the resonant wavenumber from the center pixel to another spatial pixel is determined by its incident angle to the etalon plates. For GIFS, the maximum plate incident angle is 1.345º (0.95º×0.95º etalon angular divergence), corresponding to 3.99 cm^{-1} difference in resonance frequency between the center pixel and the edge of GIFS field of view (FOV). In other words, operating under this imaging mode, a single GIFS acquisition produces a spectrally filtered image of a 2-D 3.6º×3.6º scene, and a high-resolution spectrum at each spatial pixel is accomplished by stepping the etalon gaps in resonance. The details of the spectral scanning technique will be described below.

The Fabry–Perot etalon system is placed in a vacuum housing and thermally controlled to minimize the thermal drift.

CCD Detector The GIFS CCD detector is a passively cooled, back-thinned, 1024x1024 frame transfer device, the E2V 4720. The quantum efficiency is ~0.88 at 680 nm. The reimaging optics will focus the instantaneous scene onto this CCD, which will be binned on-chip to produce a 512x512

TABLE I
GIFS ENGINEERING PARAMETERS

Engineering Parameters	Driving Requirement	Value
Telescope		
Aperture	throughput	79 mm
Field of view	spatial coverage	3.6°
Filter		
Type	line transmission	3 cavity
Peak transmission	signal to noise	>0.6
Spectral width	off-band rejection	0.4 cm^{-1} FWHM
Effective index	spectral shift	2
Interferometer		
# of etalons	off-band rejection	3
Clear aperture	sensitivity	150 mm
Gap thicknesses	spectral resolution, off-band rejection	0.5 cm (H) 0.205 cm (M) 0.0445 cm (L)
Free Spectral Range (FSR)	spectral resolution, off-band rejection	1.0 cm^{-1} (H) 2.44 cm^{-1} (M) 11.24 cm^{-1} (L)
Reflectivities	same as FSR	0.90
System finesse	same as FSR	20
Spectral resolution.	retrieval precision	0.05 cm^{-1}
Detector		
Array size	spatial resolution	1024 x 1024
Pixel pitch	angular resolution	13 μm
Read noise	signal to noise	<10 el /read
QE	signal to noise	0.88
Integration time	signal to noise	1 sec
System		
Pixel sensitivity	signal to noise	1.6×10^{-4} el/R/cm^{-1}/sec
Pixel resolution	footprint size	0.007°
Acquisition time	signal to noise	1 second
Pointing		
Control	minimize overlap	0.01°
Knowledge	spatial registration	0.001°

pixel image. The Fabry–Perot image will be read out at 1 Hz using a 12-bit A/D converter with a read noise of ~10 electrons.

Spectral Scanning Technique For cloud parameter retrievals, one needs to obtain, at every image pixel, a spectral profile of an O_2 absorption line spanning a spectral range of at least 2 cm^{-1} with a spectral sampling interval of <0.05 cm^{-1}. Fig. 5 illustrates the technique used to obtain the required spectral scans.

The filter is chosen such that, for a given pixel, the shift in the filter bandpass due to the FOV angle will match the change in the etalon transmission peak frequency. The bottom two panels of Fig. 5 show the filter bandpass for incidence angles corresponding to the center and corner pixels of the CCD, the two limiting cases.

Stepping the interferometer over its tuning range scans the wavenumber seen by different pixels over nearly identical ranges. However, at a given scan position the peak wavenumber varies with radius from CCD center, so there is a 4 cm^{-1} shift of the scan from CCD center to corner. For a given pixel,

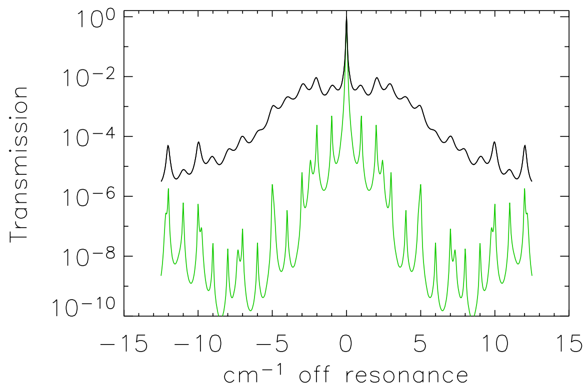

Fig. 4. Calculated GIFS interferometer transmission for ideal etalons (green) and realistic simulation (black), including defects and inter-etalon reflections. Also included in both is the 4-cm^{-1} FWHM filter.

a 2 cm^{-1} tuning range centered on the O_2 line visible through the shifted filter bandpass is required. A pair of O_2 lines separated by 1.97 cm^{-1} is targeted so that every pixel scans the required interval over at least one of the lines with an etalon scan range of 3.2 cm^{-1}. Sampling at a 0.025 cm^{-1} interval, each spectral scan requires 128 steps.

Fig. 5 shows the distribution of resonance wavenumbers across the detector at the first, middle, and last steps of the scan. The bottom two panels show the filter transmission spectrum as seen by the center and corner pixels, along with the corresponding interferometer transmission at the three scan steps. The spectral positions of the first and last scan steps are mapped up to the O_2 spectrum in the top panel, showing that the center pixel covers the 14,502.82 cm^{-1} line near the end of the scan, while the corner pixel covers the 14,504.80 cm^{-1} line near the beginning. The pixel-to-pixel variation of the line coverage phasing drives the necessity to scan a greater overall tuning range than is required for any single pixel.

At each spectral scan step, a single CCD unit image is exposed for 1 second. The 128-step spectrum to produce a spectral image requires 128 seconds to complete.

GIFS Operations Concept GIFS is designed to map cloud properties with 4.4-km resolution over a 120° disk of the Earth (60° in zenith from the geostationary position of the instrument). Coverage can be achieved using a mosaic of these two-dimensional, 512x512 pixel images. Each pixel would project to a 4.4 km square at the Earth, and the Earth disk will be covered by 25 images in a 5x5 mosaic. Given the scanning scheme described above, one entire mosaic takes ~1 hour to acquire.

Concentrating on limited areas for regional studies allows for a much faster mosaic acquisition. For example, North America can be covered by a 2x2 mosaic in ~10 minutes.

GIFS is a next-generation passive imaging instrument that can provide 2-D measurements of cloud top pressure and optical depth. Existing LEO spaceborne passive cloud instrumentation measure horizontal swaths along the satellite track and must collect data over a day to provide global coverage. GIFS

TABLE II
UNCERTAINTIES FOR A CLOUD WITH A TOP OF 800 MB AND A CLOUD BOTTOM AT 900 MB

Cloud optical depth	Optical depth uncertainty	Cloud top pressure uncertainty (mb)	Cloud height uncertainty (m)
1	0.009	24	240
5	0.08	12	126
50	6	8	85

would provide extended monitoring of large sectors of the Earth disk and hemispheric coverage with a spatial resolution of 4.4 km (~4 km for GOES) and a revisit time of roughly an hour (~26 minutes for GOES). Because of its high-resolution O_2 absorption sensing technique, GIFS can provide similar cloud property measurements with greatly improved precision and accuracy and extend the measurement capability for low-lying clouds. GIFS would reduce the uncertainty in comparable cloud top pressure measurements using microwave and infrared radiometry, currently between 0.5 and 1.5 km [8,9] for medium and high clouds. Uncertainties associated with the cloud top pressure from the infrared CO_2 channels of GOES are ~100 mb for low-cloud conditions [10] GIFS would provide significantly improved retrievals, with uncertainties ~20 mb (see Table II).

Similar O_2 absorption techniques for cloud sensing can potentially be achieved by using a spectrograph or Fourier transform spectrometer. However, providing measurements with GIFS spatial resolution, spatial coverage, revisit time, and precision/accuracy is very technologically challenging and prohibitively demanding of spacecraft resources.

IV. EXPECTED MEASUREMENT UNCERTAINTY

The GIFS instrument design has been optimized to provide the most precise and accurate cloud property retrievals by challenging all aspects of the instrument technology under cost constraints. This optimization not only has involved a survey of existing cloud measurement techniques and instrument technology but also a series of forward measurement simulations and backward cloud property retrievals. Although the retrieval technique employed here is still rudimentary (i.e., a simple multi-parameter fit), the results provide us a good estimate of the expected accuracy/precision of retrieved cloud properties for any particular instrument design.

Tables II and III summarize the expected GIFS measurement uncertainties for two different cloud decks over open ocean (0.01 surface albedo) at a solar zenith angle and an observer zenith angle of 40º. The error estimates presented above assume knowledge of the surface albedo and the cloud bottom pressure (can be iteratively estimated from cloud type, given cloud top pressure and optical depth). In general, the larger the cloud optical depth, the less sensitive the retrieval is to the uncertainties of these two parameters. A geostationary orbit, in general, will assure cloud-free observations for a good surface albedo measurement for any geophysical footprint within a reasonable time span (~1 week). One should be able to use albedo maps generated by GIFS to constrain the retrieval processes without introducing significant systematic error. The

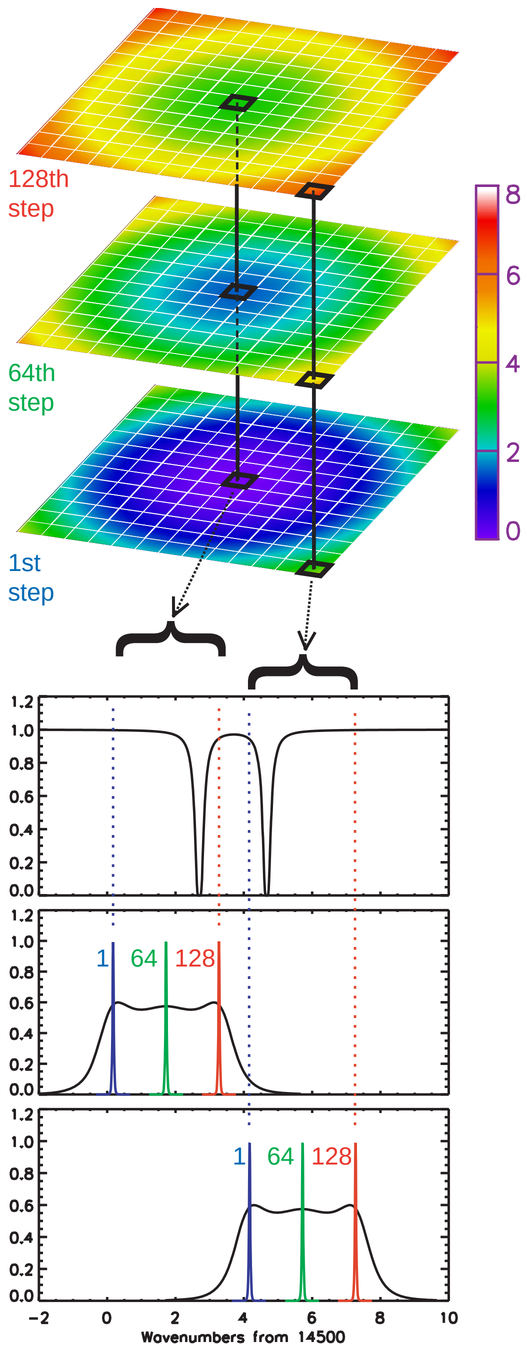

Fig. 5. FPI Scan. The upper three color panels represent the wavenumber resonant across the CCD for the first, middle, and last etalon steps of the 128-step scan. The lower two plots show the etalon resonance (narrow peaks) for the same three steps and their relation to the filter bandpass (black curves) for the center (center plot) and corner (lower plot) pixels. The upper plot shows the O_2 spectrum, with dotted lines indicating the scan ranges of the center and corner pixels. These two pixels correspond to the extreme etalon incidence angles and therefore the extreme limits of the scan ranges.

systematic errors introduced by not knowing the cloud bottom pressure can be as large as the reported measurement precisions for optically thin clouds (optical depth of ~1). For these two types of low clouds, the precisions of GIFS cloud top height measurements are generally ~100 m for various cloud optical depths, and slightly larger for thin clouds. It is clear

TABLE III
UNCERTAINTIES FOR A CLOUD WITH A TOP OF 500 MB AND A CLOUD BOTTOM AT 600 MB

Cloud optical depth	Optical depth uncertainty	Cloud top pressure uncertainty (mb)	Cloud height uncertainty (m)
1	0.006	15	220
5	0.06	8	116
50	4	5	79

that GIFS can provide critically needed low altitude cloud measurements that are difficult to obtain from current infrared brightness temperature measurements.

It should be noted that the optical depth derived here is only an effective value, i.e., corrected for forward scattering. Our simulations show that there is essentially no information in the backscattered radiance signatures about the scattering phase functions within the clouds. The effective optical depths, however, are most useful for estimating radiative losses in clouds for modeling purposes.

V. INSTRUMENT INCUBATOR PROTOTYPE

The NASA Instrument Incubator Program (IIP) has provided support to develop, deploy, and test a GIFS prototype on a suitable aircraft platform in order to increase the technical readiness level of the GIFS concept. For this IIP effort, the prototype will provide high-spectral resolution measurements of individual O_2 absorption lines to obtain 2-D maps of cloud top pressure and optical depth. Such an instrument has never been developed, flown, and tested. Successful testing and operation of the prototype will provide an opportunity to demonstrate the GIFS instrument concept and measurement capability.

A photograph of the prototype optical system is shown in Fig. 6. The prototype is designed to produce imagery spectrally similar to the conceptual flight instrument described above, so that the data analysis and cloud parameter retrievals can be tested with flight-like data. Like the flight GIFS, the prototype is an imaging triple-etalon system with approximately 0.05-cm^{-1} spectral resolution.

A few significant differences from the flight system are incorporated for cost savings and to adapt to the different environment of the aircraft. First, the etalon diameters are reduced to 50 mm from 75 mm to save cost. The narrowband prefilter diameter is reduced accordingly. Second, the exposure time is reduced to 0.2 s from 1.0 s to avoid excessive image smearing from aircraft motion. These two changes reduce signal level by a factor that is made up for by increasing the solid angle viewed by a pixel, so that the overall signal expected from the prototype is comparable to the flight system. The spatial resolution of the scene still remains better than the planned flight instrument since the aircraft will be much closer than a geostationary satellite to the cloud deck. Divergence angles at the etalon are kept similar to the flight version so that the prototype sees comparable aperture finesse effects. Third, the detector is an off-the-shelf CCD camera, which saves the packaging

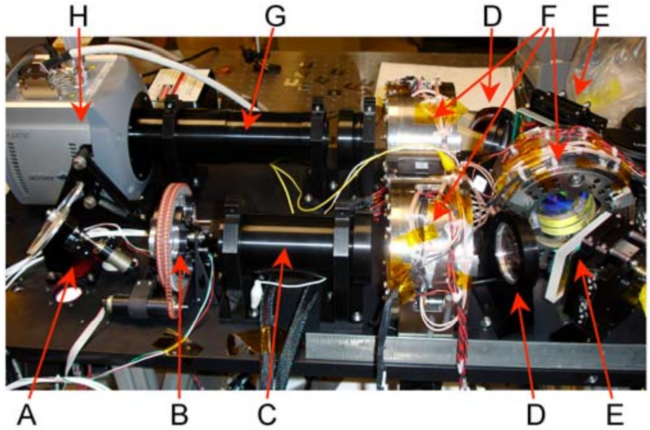

Fig. 6. Prototype optical bench. Light enters through the scene selector and housing (A) and passes through the narrow-band filter (B) and beam expander (C). Resonance attenuators (Dx2) suppress inter-etalon reflections, and fold mirrors (Ex2) turn the path through the etalons (Fx3). Reimaging optics (G) image the scene and the fringe pattern on the camera (H).

and fabrication cost of an in-house detector system that has already been flight proven. Fourth, the scan system and telescope planned for the flight GIFS are omitted from the prototype. The scene is viewed directly through the narrowband filter, with imaging ultimately performed by the fringe imaging optics. This is possible because the desired divergence angles at the etalon fortuitously map to reasonable fields of view for the aircraft geometry, while at geostationary they must be magnified to match the Earth disk. Finally, the prototype interferometer is housed in a temperature-controlled pressure vessel (Fig. 7) in order to precisely stabilize the intra-etalon index of refraction—in flight the etalons would be vacuum spaced.

In addition to the aircraft field campaign described in the following section, ground-based observations of clouds, clear-sky atmospheric radiance, and direct sunlight will be conducted to characterize O_2 absorption line spectroscopy, check data analysis and retrieval software, and test instrument readiness for fieldwork.

Fig. 7. Prototype instrument environmental chamber for aircraft deployment, mounted on wire rope vibration isolators and stiffened to prevent volume changes as the aircraft cabin pressure falls. The instrument views the scene through a 45° fold mirror in the rectangular baffle on the right end of the chamber.

TABLE IV
SUMMARY OF GIFS P3B FLIGHTS

Flight date (YYYYMMDD)	Flight duration (HH:MM)	Coincident measurements
20080130	01:53	[engineering flight]
20080201	03:38	HSRL, CALIPSO
20080205	01:46	CALIPSO
20080207	04:43	CALIPSO
20080212	02:49	CALIPSO
20080214	03:09	Aura

VI. NASA/P3B FIELD CAMPAIGN DEMONSTRATION

Fabrication of the GIFS prototype was completed in the fall of 2007. Laboratory testing and calibration was conducted at APL both before and after an aircraft field campaign on the NASA P3B. The GIFS prototype instrument was integrated onto the P3B and flown on a series of test flights from Wallops Island, VA, in early February 2008. After an engineering test flight, five science flights were flown, as summarized in Table IV. The P3B flew at an altitude of 6–7 km along and just off the Atlantic coast, imaging scenes ranging from cloud-free to completely cloudy over both land and ocean surfaces. A NASA Langley video camera was co-manifested and used to image the scene below the aircraft and aid in the analysis of the GIFS data.

Example GIFS images are shown in Fig. 8. These images were taken from the 20080207 flight, when the aircraft was flying at an altitude of 6.5 km over broken clouds. The images represent two different steps in the GIFS spectral scan sequence. The circular fringes are caused by individual lines in the O_2 B band absorption spectrum (cf. Fig. 5). The spatial resolution on the ground of the 512x512 image is roughly 1 m. When the scene is sufficiently homogeneous, it is possible to do a retrieval using a single image, since it contains the lines of interest with an instantaneous spectral coverage of ~4 cm^{-1}.

The 20080201 science flight was coordinated with the airborne NASA/Langley High Spectral Resolution Lidar (HSRL), flown on the Langley King Air B200, for GIFS measurement assessment and validation. HSRL provides highly accurate measurements of cloud height (top and bottom), thickness, and optical depth crucial for validation of the GIFS prototype cloud retrievals. The B200 overflew the P3B by about 4,000 ft and shared essentially the same nadir view, allowing for direct comparison.

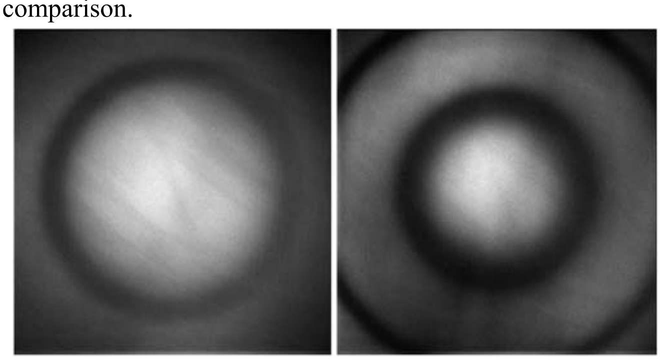

Fig. 8. Sample GIFS images, collected over broken clouds from an altitude of 6.5 km onboard the NASA P3B on 20080207. The images are at two different steps in the spectral scan sequence. Circular fringes are caused by individual lines in the O_2 B band absorption spectrum. The spatial resolution of these 512x512 images is approximately 1 m.

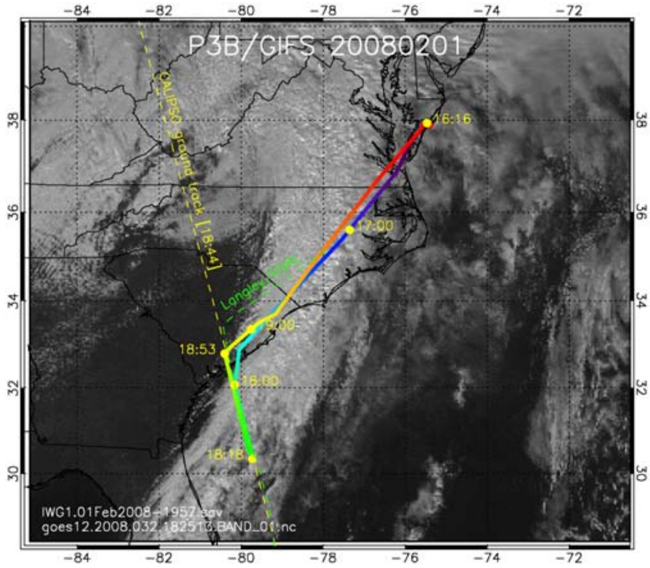

Fig. 9. P3B/GIFS 20080201 flight track. Times along the track are indicated in color from red to blue with specific times noted (HH:MM UT). The ground tracks of the Langley B200/HSRL airborne lidar and CALIPSO are also shown. Aircraft coincidence occurred between 18:18 and 18:53, with CALIPSO passing overhead at 18:44. The overlaid GOES cloud image was from the CONUS scan beginning at 18:25.

Significant portions of the science flights were flown along the CALIPSO and Aura satellite ground tracks for further opportunities for comparison, as indicated in Table IV. The CALIPSO lidar provides active measurements of cloud properties and morphology that are important for the validation of the GIFS retrieval. The P3B/GIFS and Langley B200/HSRL flew in formation along the CALIPSO track on the 20080201 flight for a three-way coincidence, as shown in Fig. 9. The cloud top heights from this period, as retrieved by HSRL and CALIPSO, are shown in Fig. 10.

Fig. 11 shows GIFS O_2 B band spectra obtained during the GIFS/HSRL/CALIPSO coincidence on 20080201 at three different times with cloud top heights of approximately 3.5, 2.5, and 1.5 km. The spectral brightness at the asymptotic wings of the absorption lines gives direct measurements of the optical thickness of the clouds, while the cloud top and bottom heights

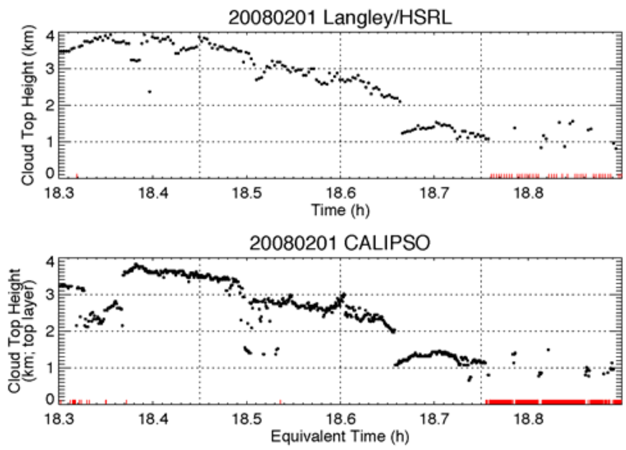

Fig. 10. Cloud top heights as measured by the Langley/HSRL airborne lidar and the CALIPSO satellite along the GIFS/HSRL/CALIPSO track on 20080201 from 18.3 to 18.9 h UT in GIFS/HSRL flight time.

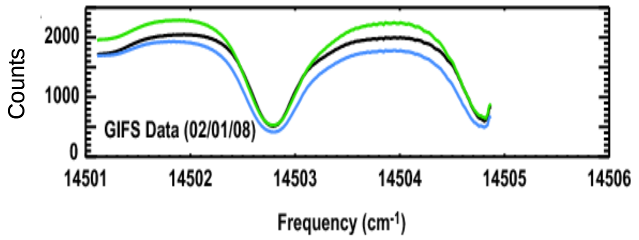

Fig. 11. GIFS O_2 B band spectra obtained during the GIFS/HSRL/CALIPSO coincidence on 20080201 at three different times, with cloud top heights of approximately 3.5 (black), 2.5 (green), and 1.5 km (blue).

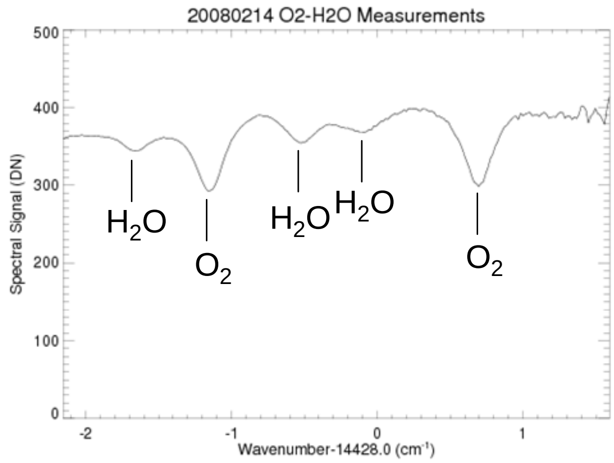

Fig. 12. GIFS spectra near 693 nm containing both O_2 and H_2O absorption features, from the 20080214 flight.

are embedded in the line shapes (i.e., width and depth). The effects of different cloud structures can clearly be seen in the GIFS measurements.

High-resolution spectroscopy is also ideal for minor, trace gas measurements. There exist many H_2O absorption features within the O_2 B band spectral region. With the unique tuning capability of the GIFS instrument, one can easily select spectral regions that provide simultaneous tropospheric O_2 and H_2O measurements. A specially designed H_2O measurement mode was implemented during the flight of 20080214. One typical nadir-looking spectrum obtained by GIFS is shown in Fig. 12. For this fight, a different narrow-band filter near 293 nm, allowing a different set of the lines in the B band and multiple H_2O lines to be observed by the instrument. Because these lines are at nearly identical wavelengths, the photons follow essentially identical optical paths through the atmosphere. With the O_2 absorption providing the total density, one can therefore retrieve the H_2O mixing ratio directly from a single GIFS spectral image.

VII. Concluding Remarks

GIFS is the first piezo-electric tuned triple-etalon Fabry–Perot imager, and it has been specifically optimized for atmospheric sensing from geostationary orbit. An airborne prototype has been constructed and successfully demonstrated in flight on the NASA P3B during a field campaign based at Wallops Island, VA. Preliminary analyses validate the GIFS measurement technique and sensing concept, providing 2-D images of cloud properties from high-spectral resolution measurements of O_2 absorption lines in solar backscattered radiation.

We have also demonstrated how GIFS can be used to measure water vapor mixing ratio, underscoring how the versatile GIFS design could be easily adapted for additional measurement capabilities. For example, this type of instrument and sensing concept can be applied to other tropospheric trace gas measurements in the infrared, e.g., CO, H_2O, CH_4, and N_2O.

Acknowledgment

We thank the P3B ground and flight crews during the flight campaign. We also gratefully acknowledge the support of JHU/APL for internal research funding of the initial development of the GIFS instrument concept and continuing support from the NASA Instrument Incubator Program.

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