Performance evaluation of a thermal Doppler Michelson interferometer system

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The thermal Doppler Michelson interferometer is the primary element of a proposed limb-viewing satellite instrument called SWIFT (Stratospheric Wind Interferometer for Transport studies). SWIFT is intended to measure stratospheric wind velocities in the altitude range of 15–45 km. SWIFT also uses narrowband tandem etalon filters made of germanium to select a line out of the thermal spectrum. The instrument uses the same technique of phase-stepping interferometry employed by the Wind Imaging Interferometer onboard the Upper Atmosphere Research Satellite. A thermal emission line of ozone near 9 μm is used to detect the Doppler shift due to winds. A test bed was set up for this instrument that included the Michelson interferometer and the etalon filters. For the test bed work, we investigate the behavior of individual components and their combination and report the results. © 2005 Optical Society of America

1. Introduction

Wind measurements of the atmosphere have been achieved by only a few satellite instruments in the past. Since superiority1 (product of the solid angle of acceptance and the resolving power) is a constant for normal optical spectroscopic systems, the responsivity is significantly reduced at the high spectral resolutions required to measure the small Doppler shifts. In the lower atmosphere, wind measurements of accuracies of ~3 m s⁻¹ are needed to advance existing dynamics knowledge, thus requiring a wavelength measurement to an accuracy of 1 part in 10⁵. The Fabry–Perot interferometer (FPI) on the Dynamics Explorer² satellite measured one component of the thermospheric wind while a triple-etalon version of the same instrument called the High Resolution Doppler Imager³ measured wind profiles in the mesosphere from daytime airglow emission and winds in the stratosphere from the absorption in molecular oxygen of scattered sunlight on NASA’s Upper Atmosphere Research Satellite (UARS), launched in 1991. This demonstrated the capability of the FPI instrument for these measurements.

The UARS also carried the Wind Imaging Interferometer (WINDII) instrument⁴ that measured wind profiles in the lower and middle thermosphere during both day and night for 12 years. WINDII used a field-widened Michelson interferometer¹,⁵ for which the superiority increases with resolving power, giving it a very high responsivity. It does not measure spectral shifts directly but rather determines wavelength changes from phase shifts in the observed interferogram.⁶ The field widening was exploited through imaging atmospheric vertical limb profiles in a single exposure. Using a bare CCD, WINDII exceeded its original objectives, which led to the consideration of whether a similar approach could be used for emission from the stratosphere.

The WINDII instrument uses airglow spectral emission lines as targets for the Doppler measurements, but this photochemical emission does not exist in the stratosphere. For stratospheric wind measurements, the only possible Doppler target is thermal emission. A feasibility study was conducted to determine whether the WINDII concept could be applied to thermal emission, and the result was positive; the concept instrument was given the name Stratospheric Wind Interferometer for Transport studies.

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However, the study determined that ultimate success would depend on four factors: (1) the identification of a suitable target emission line, (2) the ability to fabricate infrared filters of sufficiently narrow passbands to isolate the selected line, (3) the availability of infrared material with sufficient homogeneity to fabricate the interferometer, and (4) the implementation of a calibration source of sufficient stability to represent zero wind velocity with the required accuracy. This paper reports on the design, fabrication, and testing of these critical elements through the implementation of the SWIFT test bed.

2. SWIFT Instrument Concept

The Doppler Michelson interferometer concept has been described elsewhere and is summarized only briefly here. The Michelson interferometer is field widened by inserting a plate of refractive material of appropriate thickness in one arm of the interferometer; the thickness is chosen to make the coefficient of \( \sin^2 \theta \) equal to zero in the dispersion equation written as a function of off-axis angle \( \theta \). The path difference then varies as \( \sin^4 \theta \), a very slow variation with \( \theta \) near zero angle. The interferogram of the target single selected emission line (here the thermal emission line of an atmospheric minor constituent) is an oscillation corresponding to the center frequency of the line modulated by the Fourier transform of the line shape. The refractive plate is selected for a specific optical path difference (OPD) and the phase of the interferogram is measured by sampling the phase about that OPD.

Figure 1 shows a schematic drawing of the SWIFT flight instrument preliminary design at the time the test-bed study was in progress, for which a descrip-

(Fig. 1. Layout of the SWIFT instrument. NBIF, narrowband infrared.)
cluttered with tens of thousands of emission lines emitted by various molecular species (e.g., CH₄, N₂O, O₃, CO₂, etc.). Because of the interest in the shift of a single emission line, the spectral resolution requirements are high indeed. A typical half-width of an intermediate strength N₂O line at 20 km is ~0.002 cm⁻¹, so line-by-line calculations are required with an ~0.0002 cm⁻¹ resolution to satisfactorily resolve the line shape. The search for candidate lines would require us to assess all lines in the 9 µm spectral region and account for all interfering neighboring lines at these resolutions. This was deemed computationally prohibitive. Therefore it was decided to establish a two-stage line selection. For the first stage, selection criteria were established that afforded rapid identification of potentially suitable lines by approximate methods. In the second stage, thorough high-resolution line-by-line simulations were then undertaken to rigorously evaluate the line characteristics. The final selection of lines was based on whether candidate lines could achieve the desired wind accuracies.

The first-stage assessment of lines consisted of our evaluating all the lines near 9 µm using the following selection criteria: (a) isolation, (b) radiance, (c) line visibility, (d) degree of self-absorption, and (e) signal-to-noise ratio. This assessment was primarily based on the HITRAN⁹ (1992 and 1996) data set of emission lines complemented with some sample high-resolution line-by-line calculations using CN189.¹⁰ Candidate lines with strong emission strengths were favored in all the criteria except self-absorption. Here the two main criteria, isolation and self-absorption, are discussed. An approximate assessment of self-absorption consisted of assessing the optical depth at the line center assuming a Lorentzian line shape. This was supplemented with line-by-line calculations of limbs in which the self-absorption (SA) was evaluated using

\[
SA = \frac{(\text{peak strength/linewidth})_a}{(\text{peak strength/linewidth})_h},
\]

where \(h\) represents a hypothetical limb for which the line-by-line calculation was performed in which self-absorption was not allowed and \(a\) is an actual limb in which self-absorption was allowed. Self-absorption provides a measure of the degree of alteration of shape of the line. This parameter varies between 0 (very self-absorbed) and 1 (no self-absorption).

To evaluate line isolation, all emission lines were systematically scanned in the HITRAN⁹6 database near 9 µm. Each line was set as a candidate line, and the strength of all neighboring lines within 5 cm⁻¹ on either side of the line was assessed. The strength of each neighboring line was evaluated at the line center of the candidate line assuming a Lorentzian wing for simplicity and an idealized instrument filter function. For lines of different molecular species, the peak column density-weighted strengths were used assuming the U.S. Standard Atmosphere (1976). All candidate lines with interference below 10% were retained for stage 2. It was noted that the number of candidate lines satisfying the 10% criterion was sensitive to the characteristics of the filter function.

In the second stage, high-resolution calculations were performed to simulate the limb as observed by the SWIFT instrument and to perform the inversion for this model simulation. Various molecular species and line strengths were chosen, and it was possible to constrain the required values for the criteria of the line selection. It was determined that the line strength needed to be roughly between \(10^{-23}\) and \(5 \times 10^{-22}\) cm⁻¹/(molecules cm⁻²) for ozone, that the line amplitude must be ~2–4 \(\times 10^4\) kR (kilo Rayleighs) over the tangent height 20–40 km, the self-absorption had to yield a transmittance of ~0.15–0.2 over the line profile for the tangent height of interest, and the interference from adjacent lines had to be below 0.1%. The last requirement on line isolation was stringent indeed. Interfering lines at the candidate line center were restricted to be less than 0.1% of the candidate line strength at line center, both observed through the instrument filter. This 0.1% requirement leads to a systematic wind error of roughly 1–2 m s⁻¹. The stringent isolation requirements initiated the need for very narrowband Fabry–Perot etalons that are discussed in Subsection 2.B. Because of the importance of neighboring emission lines for the retrieval, comparisons of modeled line spectra with high-resolution satellite observations are currently under way. The line amplitude requirement leads to a signal-to-noise ratio of better than 400–800 and a wind random error of less than ~4–8 m s⁻¹ (for the instrument characteristics described in Subsections 2.B and 2.C). A final pass through all lines was performed using the finalized instrument filters and showed that some lines satisfied the inversion requirements as long as the interfering lines were of the same species or the relative

![Fig. 2](image-url)
column densities were known to a reasonable degree. The species giving selected emission lines were N₂O and O₃. Ozone was chosen since it allows for the additional study of ozone transport.

Figures 2(a) and 2(b) show the retrieved wind and ozone density error levels as a function of height for the tangent region using the ozone emission line centered at 1133.4 cm⁻¹ (for an OPD of 10 cm). These early studies on error levels were produced from a reduced set of error sources. The two primary error sources are shown in Fig. 2. For the ozone concentrations, the major contributors to the error were temperature and pressure. Figures 2(a) and 2(b) indicate total wind and ozone density error levels of less than 3–4 m s⁻¹ and between 5% and 7%, respectively, over the tangent height range of 20–40 km. The best ozone lines selected are 1176.1 and 1133.4 cm⁻¹, and an example of a model spectrum is shown in Shepherd et al.⁷

B. Filter Requirements

In the implementation of the line selection results in the SWIFT concept study, it was proposed that two narrowband Fabry–Perot etalons each with a full width at half-maximum (FWHM) of 0.5 nm should be used for each field of view. The center wavelengths of these filters would be offset to compensate for the Doppler shifts induced by the spacecraft in the fore- and aft-looking fields of view. The primary function of these filters was to transmit the selected emission line and to block the nearby emission lines. They would be located in the collimated space before the fields of view are combined and presented to the Michelson interferometer. They would be cooled to −150 K to reduce their thermal emission and would be maintained at their setpoint temperature to an accuracy of ±0.05 K because of their relatively high sensitivity to temperature.

Parametric error analysis studies were performed to optimize the filter width. Wider values increase the nonozone phase contamination, but also decrease the sensitivity to thermal shifts. Most nearby contaminant lines are at a shorter wavelength; thus a somewhat wider etalon centered at longer wavelengths effectively increases the field of view of the etalons. The current value was selected by balancing between signal detection and line isolation.

A second etalon and interference filter pair was also planned to be used with the primary function of blocking unwanted thermal background on the detector. This pair would be located at the Michelson output and would be part of the cold section of the optics unit cooled to −100 K. The first element would be a narrowband Fabry–Perot etalon having a FWHM of 2.0 nm, and the second would be an interference filter with a FWHM of 18.0 nm. The latter’s function was to block the unwanted orders of the etalon. For the test bed, only the 2.0 nm etalon was used; and since the interference filter was a commercial item, it was not procured.

The wavelength λ of peak transmittance for an etalon that has a peak transmittance at λ₀ for normal incidence is given approximately by

$$\lambda_0 - \lambda = \lambda_0 n^2/2\pi^2,$$

where n is the refractive index. For a fixed passband width (λ₀ − λ), the off-axis angle is proportional to n, and use of germanium etalons with a large refractive index value of 3.947 (Ref. 11) accommodates the large field of view of the Michelson interferometer.

The FWHM requirement and the predicted finesse of the Ge etalons then sets the thickness of the etalons. These thicknesses were ~0.67 and ~0.16 mm for the 0.5 and 2.0 nm FWHM filters, respectively. The thickness-to-diameter ratio was thus between 100 and 300. The goal of the SWIFT test-bed filter design, fabrication, and characterization was to ensure that such filters could indeed be fabricated, would have the desired optical performance, and could be controlled thermally for tuning to the desired wavelengths.

Under the SWIFT test-bed project it was decided to fabricate and characterize one 2.0 nm FWHM etalon and one 0.5 nm FWHM etalon, both operating near 9 μm. While the exact combination and architecture of the filters depends on the emission line selected, the choice of an etalon filter with a FWHM near 2.0 nm is reasonable to reduce the thermal background to acceptable levels. Although the exact FWHM of the narrower-bandwidth etalon depends on the selected emission line, for the test bed a 0.5 nm wide filter was chosen. Another goal of the etalon test bed was to demonstrate tandem operation of the etalons, proving that the etalon passbands could be aligned by thermal control.

1. Experimental Setup for Etalon Testing

To maintain the filters at ~150 K during the tests, a custom-designed cryostat was procured and custom filter holders were fabricated. The cryostat consisted of a single liquid-nitrogen container with two filter holders attached to the work surface. For the spectral characterization of the etalons, the cryostat was contained in an interface structure that attached to the Fourier-transform infrared (FTIR) spectrometer (Bomem Model DA-8). The cryostat could be rotated within the interface structure to adjust the tilt of the filters with respect to the FTIR optical path. The cryostat was coupled to the FTIR as shown in Fig. 3.

The Ge etalons were ~75 mm in diameter, with 50 mm clear apertures. After coating, the thin Ge etalons were coupled to two ~5 mm thick Ge rings using adhesive, one on each face. This provided a robust structure with which the etalons could be held in their mounts. The filter holder included resistance temperature detectors (RTDs) and thermofoil heaters. The configuration was found to maintain each etalon at uniform temperature to within 0.1 K. Independent temperature control was provided by a two-channel Lake Shore Model 340 temperature controller capable of maintaining a setpoint to within ±0.01 K for 30 min.
One of the side ports of the Fourier-transform spectrometer (FTS) was chosen as the output aperture through which it was possible to have access to a collimated beam. A plano–concave lens was used to spread the beam on the FTS detector. The Dewar container was filled with liquid nitrogen and a dual-channel temperature controller controlled the heaters around the etalon holder. The operating temperature of the filters was chosen to be 150 K, equal to that of the designated filter temperature for the real instrument. Five scans were made for each measurement and a period of 1 h was used to let the system stabilize before the measurement was taken.

Several tests were performed for these filters. First, the individual transmittances of the etalons were measured. Second, each etalon was tilted to a few degrees to measure the shift of wavelength as a function of incident angle with an accuracy of ±0.02 deg. Third, thermal tests on the etalons were performed. The temperature was set to 150, 152, 154, and 156 K and stabilized by the temperature controller. The transmittance was then measured. The fourth test was the change in transmittance for different locations on the etalon. This was done by sliding the detector to four different positions on the surface of the etalon. This test permitted an assessment of the nonuniformity across the 5 cm diameter etalon. Finally, the two etalons were placed in tandem and the overall transmittance was measured. The relative temperatures of the two etalons were changed and the variation of transmittance was observed. The tandem etalon was then tilted at 5° and its transmittance was measured and compared with that at normal incidence.

Aside from the spectral characterization of the etalons, their emissivity was also measured. This was done to determine their radiance as a function of temperature, allowing an operating temperature to be chosen such that etalon radiation would not significantly add to the errors of the atmospheric measurements. The setup for emissivity measurement of the filters is shown in Fig. 4. The etalons were placed in a Dewar, and, using a MCT single-element detector and a lock-in amplifier, we measured their thermal emission. First a black anodized plate served as a blackbody to calibrate the lock-in amplifier. Afterwards one etalon was placed in the Dewar and the voltages of the lock-in amplifier at different temperatures were measured. The etalon temperature was monitored to avoid very high or low temperatures and to keep it near 150 K with a few data points up to 160 K to plot the emissivity as a function of temperature. A chopper was placed between the etalon and the detector so that only thermal emission from the etalons would be detected and not that from external objects. An interference filter centered at 9.114 μm, and a 0.798 μm bandwidth was used to limit the detected passband.

2. Etalon Filter Test Results and Discussion

Transmittance of the filters. Using the settings described above, the transmittances of two individual filters were measured. A 50 cm⁻¹ (400 nm) range from 1100 cm⁻¹ (9.09 μm) to 1150 cm⁻¹ (8.69 μm) was used. The high resolution of 0.004 cm⁻¹ (0.03 nm) would create a large number of data points for a wider range, and hence the above-mentioned range was chosen to reduce the number of data points. Since only five scans were used for each measurement, an averaging program had to be used that
divided the transmittance spectrum into equal sections, each having two peaks, and then averaged the resultant intensity values. For filter 1, the averaging was done 25 times, improving the signal-to-noise ratio by a factor of 5. Figure 5 shows the average transmittance for filter 1. The measured spectrum showed a free spectral range of 15.4 nm, which was close to the nominal value of 15.0 nm, confirming the correctness of the procedure that controlled the thickness of the etalon. On the other hand, the FWHM was wider than the nominal value by a factor of 1.6 causing a decrease in finesse to a value of 18.7. This was probably due to a deviation of the two surfaces from parallelism and also nonuniformities of the etalons. The etalon surfaces were brought into parallelism through use of reference surfaces as there was no means available to measure the infrared fringes during manufacture. The surface parallelism was estimated by the manufacturer to be \( \sim \lambda/45 \) over the 25 mm aperture examined with the FTIR spectrometer. This, combined with reflectance and field-of-view factors, would result in a finesse of \( \sim 22 \), which was closely consistent with the observed finesse of the etalon. The transmittance of the peak was nearly 40%.

Another clear difference between the two transmittance spectra was that filter 1 showed an asymmetry in its profile whereas filter 2 was symmetric. The asymmetry in filter 1 was another indication of deviation from parallelism. Since filter 1 had a narrower passband, the asymmetry was more visible than for filter 2. These measurements showed that there was a practical limit to achieving the design goal. The desired value of finesse could be approached with more control over the parallelism of the two surfaces by using an infrared interferometer to monitor the fringes.

**Variation of transmittance with temperature.** The temperature sensitivity tests were performed using the temperature controller, RTD sensors, and thermfoil heaters, described above. The temperature of the filter holder was increased at intervals of 2 K for each of the filters. The transmittance was measured at four different temperatures for each filter. Figure 7 shows the results of temperature sensitivity measurements for filter 1. As temperature increases, the refractive index of Ge increases and hence the transmittance peak shifts toward larger wavelengths or smaller wavenumbers as observed in Fig. 7. The theoretical shifts can be calculated by the following equation that takes into account the thermal expansion and change of index with temperature:

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta n}{n} + \frac{\Delta t}{t},
\]

where \( n \) is the index of refraction and \( t \) is the thickness of the etalon. The thermal expansion coefficient and the \( dn/dt \) value for Ge were used to calculate the theoretical shifts.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Parameter</th>
<th>Nominal Value</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Free spectral range</td>
<td>15.0 nm</td>
<td>15.4 nm</td>
</tr>
<tr>
<td>1</td>
<td>Thickness</td>
<td>0.684 mm</td>
<td>0.678 mm*</td>
</tr>
<tr>
<td>1</td>
<td>Passband</td>
<td>0.5 nm</td>
<td>0.8 nm</td>
</tr>
<tr>
<td>1</td>
<td>Finesse</td>
<td>30</td>
<td>18.7</td>
</tr>
<tr>
<td>2</td>
<td>Free spectral range</td>
<td>60.0 nm</td>
<td>59.3 nm</td>
</tr>
<tr>
<td>2</td>
<td>Thickness</td>
<td>0.171 mm</td>
<td>0.173 mm*</td>
</tr>
<tr>
<td>2</td>
<td>Passband</td>
<td>2.0 nm</td>
<td>2.5 nm</td>
</tr>
<tr>
<td>2</td>
<td>Finesse</td>
<td>30.0</td>
<td>23.4</td>
</tr>
</tbody>
</table>

*Using the measured value of free spectral range and a refractive index of 3.948 for Ge.
right-hand side of Eq. (3); knowing the wavelength of operation, the theoretical shifts can be calculated from Eq. (3). The following values were used for these calculations: \( n = 3.94, \frac{dn}{dt} = 3.111 \times 10^{-4} \text{K}^{-1} \) (Ref. 12), \( \alpha = 5.7 \times 10^{-6} \text{K}^{-1} \) (Ref. 13), where \( \alpha \) is the thermal expansion coefficient. The comparison between theory and experiment is shown in Fig. 8. The slope of the experimental line is calculated to be 0.725 nm/deg as compared with the theoretical line of slope of 0.775 nm/deg.

The same test was performed for the second etalon, and compatible results with theory were found.\(^8,14\) The measured values of shift with temperature were used later for the temperature tuning of the tandem etalon.

**Variation of transmittance with incident angle.** Measurements of tilt sensitivity of the filters were made by rotating the upper part of the Dewar that is attached to the filters and by measuring the angle with an accuracy of \( \pm 0.02^\circ \). Figures 9 and 10 show the result of the tilt sensitivity measurement for filter 1. The shift of the wavelength with angle is given by Eq. (2). Although this Equation is an approximation, it is valid to within 0.3\% of the true wavelength shift for \( t \leq 5^\circ \). Both the theoretical and the experimental shifts were plotted as a function of the square of the angle to compare their slopes in Fig. 10. The results show values that are comparable. Another visible effect was the decrease in the peak transmittance with angle that is due to a decrease in reflectivity of the etalon. The same tests were repeated for the second etalon, and the theoretical and experimental shifts were compared.\(^8,14\) The slope of the experimental line

![Fig. 8. Comparison between theory and experiment for temperature sensitivity of filter 1.](image1)

![Fig. 9. Tilt sensitivity for filter 1.](image2)

![Fig. 10. Comparison between theory and experiment for tilt sensitivity of filter 1.](image3)
is calculated to be 0.1 nm/deg² as compared with the theoretical line slope of 0.15 nm/deg.

**Variation of transmittance with the position of the detector.** To observe a possible variation of transmittance from different regions of the 5 cm diameter filter, the detector was moved to five different positions (up, down, left, right, and center), looking through a 2.5 cm diameter lens. The sliding plate shown in Fig. 3 made such movements possible. These tests showed that the transmittance peak is shifted sideways by \(-0.05\) cm (0.4 nm) for the up and down positions with respect to the center. However, the shifts are too large to be due to temperature difference (of the order of 1 K) since thermal tests on the filter holder under the same conditions showed gradients nearly ten times smaller. These shifts were probably due to nonuniformities in the etalon thickness. Figure 11 shows the observed shifts with position for the first etalon.

The estimated width of the passband can be determined from Fig. 11. The total passband width is determined by superposition of the three peaks shown in the figure and is approximately twice the measured value for the individual peak. Its value is \(-1.6\) nm for the first filter. For the flight model, a 3.39 μm Fizeau interferometer has been fabricated to provide metrology on the optical thickness uniformity of the etalons.

**Tandem Etalons and Temperature Tunability.** Since the real instrument is designed to use tandem etalons, the two etalons were placed in tandem and tested to find their combined transmittance. Analyzing the data on Fig. 12 shows that the tandem etalon has a free spectral range close to that of the second etalon (60.4 nm) and a bandwidth close to that of the first etalon (0.8 nm). This was expected from the tandem operation of the etalons.

To tune the two etalons, both filter transmittance curves at the same temperature were plotted and the experimental temperature sensitivity curves were used to calculate the corresponding temperature that would bring them into alignment. It turned out that having the first etalon 1.5 K warmer than the second etalon was sufficient to have the maximum intensity at a particular peak. Considering the peak at around 1116 cm⁻¹ (8.96 μm), it was observed that the maximum intensity was achieved when the temperature difference between the two etalons is 1.5 K. As the temperature of the first etalon was kept constant, the temperature of the second etalon was changed to \(+2\) K from the first setting, and Fig. 12 shows that its intensity decreased equally for both settings with the adjacent peak increasing for the two settings. This was a demonstration of temperature tuning of a tandem etalon.

Since the ratio of the thicknesses of the two etalons was specified as 4 by the manufacturer, one expected the peak intensity values to be identical for the optimum temperature setting, with every fourth transmittance peak of filter 1 aligned with the transmittance peak of filter 2. In fact they were different and this was due to the thickness ratio not being exactly equal to 4. The individual filter measurements showed a free spectral range ratio of 3.92, which could account for the observed unequal peak intensities.

**Emissivity measurement.** Using the measurement of etalon irradiance versus lock-in voltage and the calibration curve of the detector, the irradiance of the etalon was plotted against the irradiance of the blackbody, and a least-squares linear fit to the data gave a slope equal to the emissivity of the etalon. This plot is shown in Fig. 13.

The emissivity was calculated to be 3%, which was much smaller than the initial estimates for the radiometric calculations of the instrument. This new value opened up the possibility of keeping the etalons...
at a warmer temperature than 150 K and hence could
save power for the real instrument.8

C. Michelson Interferometer

1. Experimental Setup

The experimental setup to test the Michelson interferometer is shown in Fig. 14. A prototype Michelson interferometer was used for these tests. The Michelson interferometer used in the test bed employed a fixed-mirror configuration containing a BK7 glass hexagon hollowed out along the beam path with a 50% transmittance beam splitter in the center. The beam splitter consisted of two parallel plates of zinc selenide (ZnSe) separated by a 1 mm air gap with optically contacted ZnSe pads: BK7 and ZnSe were chosen as building materials because they have nearly identical coefficients of thermal expansion. The short arm was a 2.6 cm air gap and the other arm was a long solid ZnSe block (6.3 cm thick) transparent to the thermal radiation to be observed. This configuration resulted in an OPD between the two arms of approximately 25 cm at normal atmospheric pressure.

The detector used for the test bed was a Sentinel microbolometer array camera. To produce a reasonable signal-to-noise ratio for the Michelson characterization, a CO2 laser was used as the source. This laser was a feedback-stabilized grating tunable 3 W source set at 9.26 μm. The laser beam propagated through a dispersing lens onto an aluminum diffuser plate to generate a large uncollimated monochromatic source. The diffuse source was then reimaged as shown in Fig. 14 using a set of ZnSe lenses through the Michelson interferometer itself and focused onto the thermal detector. The high-intensity laser source was necessary for this experiment due to intensity losses of ~10⁻³–10⁻⁴ at the diffuser plate along with the relatively low sensitivity of the uncooled detector. A frame grabber was used to display an image on the

monitor, and several images were recorded that could then be analyzed.

For the characterization of the Michelson interferometer, a pressure scanning system was used instead of the piezoelectrically scanned mirror proposed for the flight unit. The interferometer was placed in an enclosure as shown in Fig. 14, and a supply of dry nitrogen was connected to the chamber via a manual pressure controller. The custom-designed enclosure contained ZnSe windows for the optical input and output. Changing the pressure of the gas inside the chamber changed the refractive index of the gas and hence the optical path of the beam, causing the scanning of the fringes.

To regulate the Michelson interferometer temperature, a recirculating cooler was used to circulate coolant throughout the walls of its enclosure. The Michelson interferometer was never cooled to temperatures below 0 °C since it was not known whether the bonding between ZnSe and BK7 could tolerate these low temperatures, although a cooling test is necessary for the future flight unit.

2. Test Results and Discussion

The parameters that were measured during the Michelson interferometer characterization were visibility, pressure scanning cycle, field widening, and temperature sensitivity. The Haidinger fringes that are defined as the fringes at infinity were observed when the field stop (a circular aperture) was imaged onto the detector. To perform the visibility measurement, the Michelson interferometer was scanned across the field of view, and the signal for each pixel was then plotted against pressure and a function as shown below was fitted to the experimental data:

\[ I = A \cos \left( \Phi_0 + \frac{\delta \Phi}{\delta \rho} \right) + O. \] (4)
The variables to be fitted for each case were $A$, the amplitude of the interferogram; $O$, the offset of the interferogram; $\Phi_0$, the initial phase; and $\delta\Phi/\delta P$, the change in phase due to pressure changes. Once $I$ was calculated for each of the pixels in the image, the relative phase and visibility of each pixel could be determined. Figure 15 shows the plot of normalized intensity versus pressure for different pixels and several representative fits. The observation that the cosine curves were slightly offset from each other was due to a phase shift from pixel to pixel, and this indicated that there was a small change in the OPD as a function of field angle. This is because each pixel imaged a point corresponding to a different off-axis angle, resulting in a distribution of field angles being observed across the detector array. Because the instrument was field widened at this wavelength, this path difference was less than one wavelength across the entire field of view. The Haidinger fringe seen here was sharply defined by the field stop and was observed by focusing the camera to infinity. An average visibility of 0.94 was calculated for the Michelson interferometer.

Figure 16 shows a map of pixel phase over the array detector for all the pixels of the detector from experimental determination. Each phase data point plotted here was calculated numerically using a least-squares fitting routine of a 15-point data set to the interferogram equation; just like those shown in Fig. 15. The phase was plotted versus off-axis angle and compared with the expected values for different lengths of the air arm for on-axis and off-axis cases as shown in Fig. 17. It is to be noted that the design length of the air arm was 25.7 mm, in close agreement with measurement. The wiggles in the experimental data near the zero field angle are secondary fringes resulting from recirculated light interfering with the primary pattern.

The phase uncertainty observed in this study is consistent, within experimental error, with that expected from characterized test-bed error contributions. The main contributions to these uncertainty fluctuations are scattered laser intensity during the pressure scan and the relatively poor sensitivity of the microbolometer detector combined with the commercial video frame grabber. Pressure uncertainty adds only a small noise contribution, and thermal drifts mainly affect the determination of $\delta\Phi/\delta P$ due to large thermal inertia of the system.

Other measurements, such as measurements of nonuniformities of ZnSe, were made by looking at the Fizeau fringes (localized fringes due to inhomogeneity of the path difference), but are not reported here.

Finally, the last measurement reported in this subsection is the combining of the Michelson interferometer and the narrowband filter to do a pressure scan. It was not known prior to this test whether the presence of the etalon filter would alter the scanning properties of the Michelson. For this test the filter and Michelson interferometer were operated at room temperature since the Michelson could not be cooled; cooling the filters alone would not have served any purpose. The tandem filter was placed between the first two ZnSe lenses of the telescope shown in Fig. 14 and was temperature tuned to the wavelength of the CO$_2$ laser. Figure 18 shows the plot of normalized intensity versus pressure and a least-squares sine fit to the data. The visibility from the graph was calculated to be 0.9, consistent with the earlier measurement of visibility for the Michelson interferometer alone. The pressure scanning cycle also remained the same as the Michelson stand-alone case at 11 psi. Therefore it was concluded that the presence of the
filter did not alter the scanning properties of the Michelson interferometer.

D. Experimental Setup and Results for the Calibration Source

Because the phase of the Michelson interferometer will drift in orbit, a calibration source that provides a phase reference is required. The most appropriate would be a thermal emission line source and a gas cell containing a gas with an appropriate spectral line. Ammonia was found to contain lines close to those of the selected ozone line. Chemical stability and line-width issues have been assessed positively for use of ammonia as a calibration source. There remains some uncertainty in the pressure-shift coefficient of the target ammonia line. The setup for the calibration source test is shown in Fig. 19. The gas cell is 20 cm long and the ZnSe windows are 5 mm thick. Two outlets were placed at the side of the cell for gas filling and depletion and also for pressure gauge connections. The same lock-in amplifier, detector, and chopper used in the emissivity test were used here as well. For the actual test, a slightly different setup was used. A 45° mirror was facing the open window of the cell and right below it a container filled with liquid nitrogen was centered at the optical axis. The cell was filled with ammonia at atmospheric pressure and the lock-in voltage was noted. Afterwards the gas was depleted by equal amounts and each time the pressure and the lock-in voltage were noted until the whole cell was depleted. A black anodized plate used as a blackbody source was placed over the liquid-nitrogen container, facing the empty gas cell and was heated to calibrate the lock-in. Several measurements at different temperatures were taken to plot lock-in voltage versus temperature that was converted to irradiance. Therefore the calibration source voltages could be converted to irradiance at different pressures.

Figure 20 shows the result of this test. The shape of the curve is explained as follows. At small pressures, the irradiance increases with an increase in pressure due to the presence of more molecules but no pressure-broadening effect is taking place yet. At pressures of ~300 Torr, the increase in pressure causes pressure-broadening effects to take place and the slope increases. By further increasing the pressure, the gas saturates at ~500 Torr and acts like a blackbody, so the curve becomes flat at high pressures.

An irradiance of $10^{-4}$ W cm$^{-2}$ Sr$^{-1}$ was observed for 12 Torr pressure (typical pressure of the stratosphere) for this calibration source. This irradiance is 2 orders of magnitude stronger than the irradiance of the desired ozone thermal emission line and makes the calibration source suitable for operation.

3. Conclusions

The key technologies for the operation of the SWIFT instrument were demonstrated in this paper. The etalon filters were tested thoroughly, and although the measured finesse were smaller than the nominal values due to limitations in fabrication techniques, a reasonable passband and finesse were obtained. Temperature sensitivity and tilt sensitivity tests
showed results compatible with theory. The etalons were found to be nonuniform over the whole 50 mm aperture since a 2.5 cm examined area showed a passband shift with different areas of the filter examined. The problem can be avoided with better manufacturing techniques such as use of an infrared interferometer to monitor the fringes during the fabrication and to produce better uniformity. The emissivity of the etalons was found to be 3%, which allowed a higher operating temperature than 150 K for the filters and hence showed a potential of saving power for the future flight instrument.

The thermal field-widened Michelson interferometer, which was the first built in this region, showed a high visibility of 0.9 and a pressure scanning cycle of 11 psi. Its field-widening properties were examined by observing the phase images and were found suitable. The Michelson interferometer was also scanned with filters tuned to the laser wavelength, and it was found that it maintained its visibility and sinusoidal modulation characteristics.

Finally, a calibration source with ammonia was made and tested. It showed a reasonable irradiance, 2 orders of magnitude larger than the target ozone spectral line that made it suitable for operation.

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