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(Manuscript submitted 29 March 2005, in final form 8 September 2005)

ABSTRACT

This paper presents an instrument model and observation simulations for the measurement of stratospheric winds and ozone concentration using a satellite instrument employing imaging and the Doppler Michelson interferometry technique. The measurement technique and instrument concept are described. The instrument model and simulations are based on initial design characteristics of the Canadian Stratospheric Wind Interferometer for Transport Studies (SWIFT) satellite instrument. SWIFT employs an imaging array and a field-widened Michelson interferometer. It will measure stratospheric winds and ozone densities using the wind-induced phase shifts of interferograms from atmospheric limb radiance spectra in the vicinity of the vibration–rotation ozone line at $1133.4335 \text{ cm}^{-1}$. The measurement simulation and analysis tools have been developed to assess the SWIFT instrument performance and to evaluate the impact of instrument and measurement characteristics on expected wind and ozone errors. Sample results of the measurement simulation and the related line-of-sight wind error noise levels are presented.

1. Introduction

The history of space-based wind measurements is very brief (McDade et al. 2002; Shepherd 2002). The High Resolution Doppler Imager (HRDI) instrument (Ortland et al. 1996) on the National Aeronautics and Space Administration’s (NASA’s) Upper Atmosphere Research Satellite (UARS) measured winds in the range of 15–105-km altitude, with the stratospheric measurements only taken in the daytime. On the same satellite, the Wind Imaging Interferometer (WINDII) (Shepherd et al. 1993) made wind measurements between 80 and 300 km. The Thermosphere Ionosphere Meso-sphere Energetics and Dynamics satellite’s (TIMED’s) Doppler Interferometer (TIDI) instrument (Killeen et al. 1999) measures the horizontal neutral winds in the altitude range of 60–300 km.

An extension to the space-based upper-atmospheric wind measurement techniques, previously developed for WINDII, down into the stratosphere is planned in order to investigate the dynamics of this region. The WINDII instrument measured winds in the upper mesosphere and lower thermosphere using Doppler shifts in visible airglow emission lines. The optical techniques it employed included phase-stepping interferometry, field widening of the Michelson interferometer, and imaging. The Stratospheric Wind Interferometer For Transport Studies (SWIFT) instrument employs the same techniques, but instead of operating in the visible
region, it operates in the IR region using an ozone thermal emission line.

The main observational objectives of the SWIFT experiment (Shepherd et al. 2001; McDade et al. 2002) are the simultaneous measurement of horizontal wind velocity vectors and ozone concentration in the stratosphere during day and night, which together are essential for understanding the global stratospheric dynamics and studying the transport of ozone. Profiles in altitude of wind and ozone densities are to be extracted from the same measurement with the target accuracies of 3 m s\(^{-1}\) and 5%, respectively, between 20 and 45 km. Considering these accuracies, a requirement of about 1 m s\(^{-1}\) has been imposed as an upper bound on the line-of-sight wind random error level, before inversion, resulting from measurement noise.

The SWIFT instrument recently completed a successful phase B study and is about to enter the phase C study of the Canadian Space Agency (CSA) for deployment as the primary instrument on their Chinook Mission, scheduled for launch in late 2010.

This paper presents a description of a SWIFT instrument model and the related measurement simulation. Section 2 explains the measurement concept. The instrument concept is described in section 3. The measurement simulation produces a set of raw measurement images as would be provided by the SWIFT instrument. The measurement simulation requires an instrument model and an atmospheric spectral radiance model. Aspects of the instrument model used to simulate the expected SWIFT observations and a summary of the instrumental measurement procedure are described in section 4. A brief description of the atmospheric radiance model applied over the spectral region and altitude range of interest is provided in section 5. Section 6 explains the method of four-point sampling of the interferogram for each pixel. Sample results of measurement simulations are presented and discussed in section 7. Section 8 describes the processing of the raw measurement images to a reduced set of calibrated images of atmospheric radiances and the recovery of the line-of-sight winds and their noise levels. A summary and some remarks are provided in section 9. A list of the symbols used in this paper is provided in the appendix.

2. Measurement concept

To measure a small Doppler shift caused by the winds, a narrow emission line is isolated from the complex limb spectrum of the stratosphere in the IR region using a narrowband optical filter system. The filtered emission line is projected through the field-widened Michelson interferometer to obtain the interferogram. The Doppler shift \(\delta \nu\) in the emission line resulting from wind velocity \(v_w\) is measured as a phase shift \(\delta \varphi\) of the interferogram as specified below:

\[
\delta \nu = \nu_o \frac{v_w}{c}, \quad (1)
\]

\[
\delta \varphi = 2\pi \Delta \delta \nu, \quad (2)
\]

where \(\nu_o\) is the rest wavenumber at the center of the line, \(c\) is the speed of light in a vacuum, and \(\Delta\) is the optical path difference between the paths of the two arms of the Michelson interferometer. Figure 1 shows the impact of a Doppler shift of the spectrum on the interferogram.

For a wind measurement of accuracy 1 m s\(^{-1}\), the
equivalent Doppler shift in the line wavelength is one part in $3 \times 10^8$. Such a measurement seems at first to be impractical. However, the situation is improved by measuring the phase shift of the interferogram at some large value of optical path difference, that is, by measuring the Doppler phase shift of fringes of high order of interference because, as shown in Eq. (2), the phase shift is proportional to the optical path difference. The SWIFT Michelson interferometer design considered in this paper has a large, fixed optical path difference of 18 cm (interference of the order of $-2 \times 10^4$) to which small increments are added during phase stepping. The optical path difference is chosen in consideration of obtaining acceptable phase resolution and line visibility, the limitation in size and mass of the instrument, the elimination of the contribution of other atmospheric lines, acceptable instrument background modulation for monitoring the phase and the position of the filters, and obtaining the desired signal-to-noise ratio (SNR).

One fringe is sampled at four phase steps ($-\pi/2, \pi/2, \pi, 3\pi/2$) by moving one of the Michelson mirrors piezoelectrically to four positions separated by quarter wavelength in path difference. Phase-stepping interferometry is discussed by Hariharan (1987, 1989), and in a simple approach by Shepherd et al. (1985). The algorithm used to deduce the fringe properties from these four measurements is described in section 8b. By combining Eqs. (1) and (2) and inserting the above values for optical path difference, wind accuracy, and wave-number of the center of the ozone line, we obtain

$$\frac{\delta \varphi}{2\pi} = \Delta \tau_0 \frac{v_w}{c} = \frac{1}{15 \, 000}. \quad (3)$$

Thus, the required wind accuracy of 1 m s$^{-1}$ corresponds to a phase measurement accuracy of 1/15000 of a fringe.

The field of view (FOV) for an instrument using a conventional Michelson interferometer would have to be restricted to a fraction of a degree. However, designing the Michelson interferometer with a refractive plate in one arm and placing the virtual images of the mirrors at the same distance from the beam splitter results in a pseudosymmetry about the beam splitter that produces enlarged fringes, allowing a field of view of $6^\circ \times 6^\circ$ inside the interferometer, translating to $2^\circ \times 2^\circ$ in the atmosphere. The field-widened Michelson interferometer employed for measurements of wind is often called the Doppler Michelson interferometer, and the associated technique is called Doppler Michelson interferometry. The field-widened Michelson was first proposed for measurement of Doppler temperature (Hilliard and Shepherd 1966) and was later extended to both wind and temperature measurements (Shepherd et al. 1985; Gault et al. 1985; Thuillier and Hersé 1988, 1991). It was successfully employed in the WINDII instrument (Shepherd et al. 1993). The details of the principle of Doppler Michelson interferometry have been described by Shepherd (2002) and by Rahnama (2003).

The advantage for SWIFT of the large field of view is that, like WINDII, it can be used with an array detector as an imager, allowing the observation of a complete limb profile in a single measurement. Because the instrumental characteristics vary slightly from pixel to pixel, data from each pixel are treated individually in the initial part of the analysis.

3. Instrument concept

SWIFT is a limb-viewing satellite instrument with two nearly orthogonal fields of view (FOV1, FOV2) observing the limb at 48° and 132° with respect to the spacecraft velocity vector for an altitude coverage of 15–65 km. Figures 2 and 3 show the viewing geometry for the SWIFT instrument. A certain volume of the stratosphere is imaged by the forward-looking FOV. Approximately the same volume is imaged by the aft-looking FOV about 9 min later for a nominal satellite altitude of 650 km. The 48° and 132° angles were chosen so that the two time-separated images of the same field are viewed from orthogonal directions. This stems from considering the SWIFT orbital geometry and the relative pitch of $-36^\circ$, in earth-fixed coordinates, between the two images implying required offsets from 45° and 135°. The instrument is mounted on the antisunward side of the spacecraft in order to protect it and its cooling radiators from the sun.

A schematic drawing of the instrument design applied for this paper is shown in Fig. 4. Each field of view is defined by a reflecting telescope (M1, M2, and M3) and a field stop (S) in the left and right optical channels. The incoming light is directed by the telescopes to the pointing mirror and then passed to the narrowband Fabry–Perot etalon (E1) where the main spectral isolation occurs. The two fields of view are combined at
the field combiner (M4) and passed to the field-widened Michelson interferometer, whose path difference is 18 cm. The wide- and medium-band filters (E2) eliminate the sidelobes of the narrowband filters. The view of the atmospheric emission modulated by the Michelson interferometer is projected onto the array detector through the transfer optics and camera. The two fields of view are imaged simultaneously and adjacent to one another, with one directly above the other at the detector array. The instrument responsivity is calibrated using three blackbody sources (BB1 and BB2) at known temperatures. ELS1 and ELS2 are emission line sources for phase calibration. The details of this instrument design are found in Rowlands et al. (1996), Scott et al. (1998, 2000), and Gault et al. (2001, 2002). Calibration issues are presented and discussed in Gault et al. (2002).

4. The instrument model

The instrument model calculates the simulated images of the atmospheric radiance, including instrument thermal background and instrumental signals during background calibrations at the detector and the corresponding error levels on a pixel-by-pixel basis. It maps the atmospheric and instrumental signals across the field of view considering pixel-by-pixel variation of filter transmission, optical path difference, Michelson phase, and phase step size. The model uses adjustable instrument parameters such as aperture size, telescope magnification, instrument visibility, filter parameters (width, finesse, location of filter axis, tilt, etc.), detector characteristics (quantum efficiency, dark current, readout noise, etc.), and Michelson interferometer parameters (optical path difference, phase step size, tilt, etc.). The Michelson interferometer’s modulation of the filtered instrument thermal background is also included in the model. The model accounts for measurement parameters such as field of view, detector format, integration time, and number of four-point measurements (corresponding to the four-phase steps) per profile measurement. The model also includes consideration of instrument-pointing-related aspects such as the Doppler shift contribution from satellite velocity and smearing in tangent heights over the measurement time interval. The products of the measurement simulation prior to the data processing are the four-point sampling of pixel-by-pixel measurement of atmospheric images and instrument background images. The simulation of the above images allows for adding random shot noise, readout noise, and digitization noise.

The instrument model has the capability of producing the instrumental and atmospheric images for different measurement scenarios and for different combinations of yaw and field of view. In this paper, each individual fringe-sampling measurement consists of four single exposures of 0.1 s taken successively at phase steps of \( \sim 0, \pi/2, \pi, \text{ and } 3\pi/2 \) corresponding to the four Michelson mirror positions. Two sets of 24 fringe sam-
nings of the atmosphere, each set preceded and followed by 12 fringe samplings for background calibrations, constitute the final measurement sequence. These numbers are based on a compromise between horizontal smearing and wind accuracies with the individual exposure time driven by the well depth of the candidate detector. The individual fringe-sampling measurements are coadded to improve the SNR. The images are presented at the pixel level without any binning and for one combination of yaw and field of view.

A simulation of the instrumental measurement is performed based on the instrument concept described in section 3 to calculate the interferogram for each pixel. The main components of the instrument model—the pixel-level simulations of filter functions, optical path difference, Michelson interferometer phase, and Michelson phase step size—are described in the following subsections (4a–4c). The values of the relevant system and measurement parameters are provided in Table 1. The applied values of the instrument parameters are found in Tables 2, 3, and 4. The calculation of the measurement using the instrumental model and resulting images are described in sections 6 and 7. More details on the instrument model and its different components can be found in Rahnama (2003).

a. Simulated filter pass bands

The stratospheric thermal emission spectrum contains many closely spaced lines. To isolate the ozone line from this complex spectrum, the effective bandwidth of the filter system has to be about 0.1 cm\(^{-1}\) (\(\sim 0.8\) nm) (Shepherd et al. 2001). A suitable line has to be identified to allow retrieval of winds to an accuracy of 3 m s\(^{-1}\) over an altitude range of 20–45 km. The line selection procedures for the SWIFT experiment consist of identifying a line that is both sufficiently isolated from neighboring lines and has acceptable strength.

| Table 1. Some of the measurement and system parameters. |
|-----------------|-----------------|
| **Parameter**    | **Value and unit** |
| Nominal satellite altitude | 650 km |
| Line-of-sight distance to limb at 40-km altitude | 2864 km |
| Satellite velocity | 7533 m s\(^{-1}\) |
| Fields of view | 1° vertical \(\times\) 2° horizontal per FOV |
| Detector array per FOV measurement | 81 \(\times\) 162 |
| Pixel size on limb | 0.635 km |
| Integration time of a single exposure | 0.1 s |
| Elapsed time between exposures | 0.01 s |

The isolation is dictated by the relative positions and strengths of neighboring lines, especially of other species, in consideration of an appropriate filter system. The range of acceptable line strengths is dominated by the signal-to-noise ratio and self-absorption (Mani et al. 2005).

The components of the filter system consist of one narrowband Fabry–Perot etalon filter in each optical chain, a wide-band interference filter, a medium-band etalon, and a long-pass filter. The values of the filter parameters are summarized in Table 2.

A narrowband, thermally tunable, solid Ge Fabry–Perot etalon filter E1 (in Fig. 4) is placed before the

| Table 2. Filter parameters. FWHM: filter bandwidth (cm\(^{-1}\)), FSR: Free Spectral Range (cm\(^{-1}\)), \(F\): finesse, \(\tau_{\text{max}}\): maximum transmittance, \(T_{\text{O}}\): operating temperature (K). The row and column numbers are provided relative to the top left corner of FOV1. FOV2 is underneath FOV1 on the detector array. |
|-----------------|-----------------|-----------------|
| **Filter**      | **FWHM** | **FSR** | **\(F\)** | **\(\tau_{\text{max}}\)** | **\(T_{\text{O}}\)** | **Row** | **Column** |
| Narrow          | 0.10     | 2.05    | 20     | 0.75   | 190    | 81.5 | 41 |
| Wide            | 2.31     | —       | —      | 0.9    | 100    | 81.5 | 122 |
| Medium          | 0.38     | 7.71    | 20     | 0.75   | 150    | 95  | 81.5 |

| Table 3. Michelson interferometer parameters. |
|-----------------|-----------------|
| **Parameter**    | **Value and unit** |
| Operating temperature (\(T_{\text{O}}\)) | 180 K |
| Optical path difference for normal incident at rest wavenumber of the ozone line (\(\Delta_{\text{O}}\)) | 18 cm |
| Length of the fixed-length arm (\(t_{\text{i}}\)) | 4.503 cm |
| Length of the open arm (\(t_{\text{o}}\)) | 1.866 cm |
| Index of refraction of ZnSe (\(n_{\text{ZnSe}}\)) | 2.413 |
| Linear expansion coefficient of ZnSe (\(\alpha_{\text{ZnSe}}\)) | 5.79 \(\times\) 10\(^{-6}\) K\(^{-1}\) |
| Rate of change of optical path difference with temperature (\(d\Delta/dT\)) | 6.9 \(\times\) 10\(^{-4}\) cm K\(^{-1}\) |
| Rate of change of refractive index of ZnSe with temperature (\(dn_{\text{ZnSe}}/dT\)) | 5.7 \(\times\) 10\(^{-5}\) K\(^{-1}\) |
| Rate of change of optical path difference with wavelength (\(d\Delta/d\lambda\)) | \(-474\) |
| Mirror incremental step | 0.2 nm |
| (Row, column) location of near (\(k - (1/2)\) phase step, \(k = 1, \ldots, 4\)) | (81, 81) |
| Horizontal tilt | 6° |
| Vertical tilt | — |

\(a\) Accetta and Shumaker (1993)
\(b\) Browder and Ballard (1969)
\(c\) Gault et al. (2002)
\(d\) Feldman et al. (1978)
field combiner in each optical channel. Each channel needs a narrowband tunable filter to allow for the Doppler shift induced by the spacecraft’s velocity. The narrow filters are to be thermally tuned over a range from almost 0.3 nm to shorter wavelengths for the fore-limb FOV and to longer wavelengths for the aft-limb FOV. The role of the narrowband filters is to isolate as much emission as possible from the target ozone line and to block the IR radiation from the telescopes and the pointing mirrors. The wide- and medium-band filters (E2) in Fig. 4 are placed immediately in front of the detector to eliminate the sidelobes of the narrowband filters and to limit the signal from the instrumental thermal background. The wide-band filter is a nontunable interference filter with a coating of dielectric materials and is located behind the Michelson interferometer. The medium-band filter is another solid Ge Fabry–Perot etalon.

The peak transmission wavenumber for each pixel is simulated using the relation (Shepherd 2002)

$$\nu_{\text{peak}}(i) = \nu_{\text{peak}}(0) \left( 1 - \frac{r^2}{2n^2} \right)^{-1},$$

where \(i\) is the off-axis angle for each pixel and \(n\) is the effective index of refraction of the filter materials. To achieve a high transmission of the target ozone line across the field of view, the wavelength of the peak transmission at zero off-axis angle is shifted by almost 0.25 nm to longer wavelengths with respect to the target line. The wide and medium filters are tilted by almost 1° with respect to each other to avoid the creation of a rogue Fabry–Perot resonance cavity. Figure 5 illustrates the peak transmission wavelength for the narrow filters for the pixels of the fields of view.

The filter passband functions of the Fabry–Perot etalon filters are simulated using the Airy function and the filter parameters given in Table 2. The total filter function is found from the product of the filter functions of the individual filter components. Figure 6 shows the total filter function for two different sample pixels. The filter transmittance at the position of the target ozone line is shown in Fig. 7 for the pixels of one of the two fields of view. The design and the test bed of the filters are explained by Mani et al. (1999), Mani (2001), and Gault et al. (2002).

### Table 4. Instrument responsivity parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel étendue ( A \Omega )</td>
<td>( 2 \times 10^{-14} ) m^2 sr</td>
</tr>
<tr>
<td>Exposure time (integration time) ( t )</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Filter attenuation ( \tau_{\text{filter}} )</td>
<td>0.4455</td>
</tr>
<tr>
<td>Nonfilter attenuation in the instrument ( \tau_{\text{nf}} )</td>
<td>0.2782</td>
</tr>
<tr>
<td>Quantum efficiency ( q )</td>
<td>0.75 electron photon(^{-1})</td>
</tr>
<tr>
<td>Analog-to-digital unit ( C_{\text{ADU}} )</td>
<td>85 electron count(^{-1})</td>
</tr>
<tr>
<td>Reference wavenumber (wavenumber of the center of the ozone line) ( \nu_0 )</td>
<td>1133.4335 cm(^{-1})</td>
</tr>
</tbody>
</table>

![Fig. 5. Peak transmission wavelength for the narrowband etalons.](image)

The peak transmission wavelength at the axis of the narrow filter corresponding to the FOV1 is about 8.8228 μm and that for the FOV2 is about 8.8231 μm. The narrow filters are thermally tuned over a range of almost 0.3 nm; to shorter wavelengths for the forelimb FOV and to longer wavelengths for the aft-limb FOV to account for Doppler shift resulting from spacecraft motion.

### b. Simulated Michelson interferometer phase and phase step size

The SWIFT field-widened Michelson interferometer is made of ZnSe components mounted on a ZnSe base.
plate. The beam-splitter substrate and compensator are two plane-parallel plates of ZnSe with an average angle of incidence of 30°. One arm is open (in vacuum) and the other is made of ZnSe. The reference length of the open arm is set so that the desired field-widening condition is achieved (Shepherd et al. 1985). There is a mirror at the end of each arm. The mirror of the open arm is mounted on piezoelectric actuators and is moved to produce the quarter-wavelength steps. The Michelson characteristics are given in Table 3. The axis of the Michelson interferometer is tilted by 6° along the horizontal direction to avoid returning passes of reflections from the beam splitter.

The nominal (k − 1)π/2 phase steps (k = 1–4) are intentionally positioned at the geometric centers of each field of view. The mirror phase for each pixel for the kth phase step is determined by

$$\varphi_k(i) = (k - 1) \times 4\pi \times \left[ \frac{\pi/2}{4\pi d_i t_o} \right] d \times t_o \cos \frac{i}{\cos i},$$

(5)

where i is the pixel off-axis angle (relative to the axis of the Michelson), i_c is the off-axis angle at the central pixel, d is the incremental step of the Michelson phase stepper, and t_o is the rest wavenumber of the center of the ozone line. In Eq. (5), the square bracket pair represents the greatest integer function that gives the greatest integer less than or equal to what is contained within the brackets. The Michelson phase is shown in Fig. 8 for the second phase step for the pixels of the combined fields of view. The corresponding design of the Michelson interferometer is explained by Gault et al. (2002).

c. Simulated optical path difference

The optical path difference as a function of off-axis angle is found from

$$\Delta(i) = \Delta_0 - \left( t_2 + \frac{t_1}{n} \right) \sin^2 i - \left( t_2 + \frac{t_1}{n^2} \right) \frac{\sin^4 i}{4}$$

$$- \left( t_2 + \frac{t_1}{n^3} \right) \frac{\sin^6 i}{8},$$

(6)

where n, the refractive index of ZnSe at the operating temperature of the Michelson interferometer (180 K), is 2.413 (Accetta and Shumaker 1993), and i is the pixel off-axis angle for the tilted Michelson interferometer. The values of the fixed-length arm (t_1) and the open arm (t_2) are given in Table 3 (by convention t_1 > 0 and t_2 < 0). Here, \Delta_0 is the optical path difference for normal incident given by

$$\Delta_0 = 2(n t_1 + t_2).$$

(7)

The details and derivation of the above equations are found in Gault et al. (1985). Applying these equations for each pixel, the optical path difference of each pixel is obtained. This is shown in Fig. 9.

5. The atmospheric radiance model

The atmospheric radiance model calculates spectral radiances resulting from the thermal emission of various chemical species for refracted ray tangent heights between ∼14 and ∼65 km at increments of ∼0.64 km with the wind profile as an input. This resolution cor-
responds to the vertical extent of each pixel in the field of view. The target line for the SWIFT experiment is an ozone line at 1133.4335 cm$^{-1}$ in the $\nu_2$ vibration–rotation band. The spectrum about this line as would be observed in the limb is calculated by numerical integration along the instrument line of sight as given by Eqs. (8) and (9):

$$L_\nu = \int_0^s B_\nu[T(s)] \times \left( \sum_p \sigma_{\nu p} n_p \right) \times \tau_p(s) \times ds,$$

with

$$\tau_p(s) = \exp \left( - \sum_p \int_0^s \sigma_{\nu p} n_p \times ds \right),$$

where $L_\nu$ is spectral radiance [W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$]; $\sigma_{\nu p}$ and $n_p$ are the absorption cross section (cm$^2$ molec$^{-1}$) and number density of species $p$ (molec cm$^{-3}$), respectively; $B_\nu[T(s)]$ is the value of the Planck function at wavenumber $\nu$ (cm$^{-1}$) and temperature $T$ (K) [W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$], and $\tau_p(s)$ is the transmittance between the instrument and a point at a distance $s$ (cm) along the line of sight.

The atmospheric radiance model, set up by Y. J. Rochon, relies on an adapted version of the line-of-sight integration software of Gallery et al. (1983). It served to calculate spectral radiances at a sampling interval of 0.000 17 cm$^{-1}$ and over the spectral range of ±0.6 cm about the 1133.4335 cm$^{-1}$ ozone line. The vertical profiles of temperature, pressure, and 16 radiatively active atmospheric constituents are from the U.S. Standard Atmosphere, 1976 (United States Committee on Extension to the Standard Atmosphere 1976), Anderson et al. (1986), and mixing ratio profiles based on midlatitude balloon measurements (Peterson and Margitan 1995). Emission contributions from altitudes up to 80 km are included in the calculations.

The absorption cross-sectional spectra were determined using line-by-line calculations. The line characteristics were from the High Resolution Transmission (HITRAN) 2000 database with updates (Rothman et al. 2003). The water vapor continuum contribution taken from Moderate Resolution Transmission (MODTRAN) (Kneizys et al. 1996) was added to that of the water vapor lines. A value of $-0.003$ cm$^{-1}$ atm$^{-1}$ was assumed for the pressure-shifting coefficients of the ozone lines. The representation of the Voigt line shape from Kuntz (1997; which follows from Schreier 1992 and Humlicek 1982) was taken as reference.

Figure 10 shows a sample limb radiance spectrum for a tangent height of 34 km near the ozone 1133.4335 cm$^{-1}$. Figure 11 presents the same spectrum as that in Fig. 10, but with total filter transmission included showing how the neighboring lines are suppressed with respect to the target ozone line.

6. Four-point sampling of pixel-by-pixel measurement

The interferogram for each pixel is sampled at the detector at four points corresponding to the four mirror steps to obtain phase and visibility for each pixel, from which the Doppler wind is obtained as explained in section 2. This method of imaging the interferogram onto an array detector at four phase steps is called four-
point sampling of pixel-by-pixel measurement. Each pixel represents a projected spatial element at the limb, which for the SWIFT experiment is 0.635 km \times 0.635 km as seen from orbit. The assumed detector is a HgCdTe array with 256 \times 256 pixels, each 40 \mu m \times 40 \mu m.

The equation representing the interferogram for a given pixel is
\[
N_{k,l}(\Delta) = R_{ij} \int \frac{\tau}{1 - \tau} f_\ell(\tau) L_{ij}(\tau) \times [1 + U_{ij} \cos(2\pi\Delta_{ij} + \varphi_{k,l})] \times d\tau,
\]
(10)

where \( R_{ij} \) is the instrument responsivity (counts per pixel of W m\(^{-1} \) m\(^2 \) sr), \( f_\ell(\tau) \) is the relative total filter function, \( L_{ij}(\tau) \) is the atmospheric or instrumental spectral radiance [W m\(^{-2} \) sr\(^{-1} \) (cm\(^{-1} \))\(^{-1} \)], \( U_{ij} \) is the instrument visibility, \( \Delta_{ij} \) is the optical path difference (cm), and \( \varphi_{k,l} \) is the Michelson interferometer kth phase step in radians, all as seen from the pixel at row \( \ell \) and column \( j \) of the detector and \( \tau \) is a wavenumber (cm\(^{-1} \)). The resulting signals at the detector \( N_{k,l}(\Delta) \) are in units of counts per pixel. The atmospheric model used for the simulation only accounts for variations of the atmospheric quantities in the vertical direction. Also, the tilt of the field of view relative to the horizon and curvature of the earth are not applied in these simulations. Therefore, for the simulations reported here the atmospheric spectral radiances vary only with rows but not with the columns of the detector. As was done for the WINDII instrument (Rochon 2000), given the pointing knowledge for each pixel on each measured image, it will be possible to interpolate radiances of each image column to a common tangent height profile before summing over image columns. For this simulation, the instrument responsivity as well as the instrument visibility is assumed to be the same for all pixels. The instrument visibility is expected to be as large as 0.94.

The instrument responsivity \( R \) is defined by
\[
R = \frac{A\Omega r_{filter} T_{ref} q}{C_{ADU} h c \tau_0},
\]
(11)

where \( h \) is Planck’s constant (J s) and \( c \) is the speed of light in a vacuum (cm s\(^{-1} \)). The parameters related to the instrument responsivity are given in Table 4. The value of the instrument responsivity, based on the values given in Table 4, is roughly \( 2.5 \times 10^6 \) counts per pixel of W m\(^{-1} \) m\(^2 \) sr.

The main elements needed to perform the measurement simulation are the interferogram for each pixel [Eq. (10)] consists of the simulated filter pass bands and the optical path difference for each pixel, Michelson interferometer phase images, the Michelson phase step size described in section 4, the instrument, measurement and system parameters given in Tables 1–4, the atmospheric radiance model described in section 5, and a radiometric model used to simulate the instrument thermal background emission. Sample results of the measurement simulation are presented as contour plots in the next section. Other results of the measurement simulation are found in Rahnama (2003).

7. The simulated signal at the detector

This section presents and discusses the SWIFT-simulated images as would be observed at the detector. The pixel-level values of the atmospheric image are determined from Eq. (10), where \( L_{ij}(\tau) \) is the output of the atmospheric model with Doppler shift effects resulting from satellite motion, with wind included. Here, each image is a single exposure of 0.1 s (Table 4). Four images are produced by consecutively applying the four phase steps following Eq. (5). Figure 12 shows the simulated signal from atmospheric emission only for phase step 1. The pattern on this image reflects the variation over the field of the filter transmittance function and the phase step, the dependence of optical path difference on pixel positions, and the tangent height variation of atmospheric spectral radiances within a column. The image also shows that the signals are much weaker
for higher tangent heights. The increases in signal toward the vertical edges near the lower corners of the image are because of incomplete suppression of other ozone and nitrous oxide lines.

The signals recorded at the detector include not only atmospheric emission, but also the radiation emitted by different components of the instrument, because there is not perfect blocking of the instrument thermal background. Therefore, during the atmospheric measurement, the signal at the detector has a contribution from both the atmospheric and instrumental emission. To simulate the instrumental signal, the spectral radiances of each component of the instrument are calculated from the blackbody function and the component emissivity and temperature. The system transmittance between the component and the detector is applied to determine the spectral radiance of the component as would be seen at the detector. The narrowness of the transmittance function results in producing modulated radiances interferograms from the spectrally flat spectral emission of most components. Only the constant term of the interferogram needs to be modeled for components located between the Michelson interferometer and the detector. The instrument thermal background images for the four phase steps are the sum of the respective contributions from the dark current of the detector and from the thermal background of the instrument components. The dark current of the detector in section 6 is 20 nA cm$^{-2}$ at 55 K. The modulation with phase step produced by the narrowness of the pass bands of the filter components for the instrument thermal background signals is at the level of $\sim$0.05%.

The sum of the instrument thermal background and atmospheric signals is referred to as the combined signal. Measurement noise is applied to the combined signal and the instrumental signal. It has contributions from shot noise, readout noise, and digitization noise. The detector readout noise variance $\sigma_d^2$ for the detector of section 6 is set to $4 \times 10^4$ e$^2$ per pixel. The measurement noise variance for each pixel is calculated using the following relation:

$$
\sigma_N^2 = \frac{N}{C_{ADU}} + \frac{\sigma_d^2}{C_{ADU}^2} + \frac{1}{12},
$$

where $N$ is the signal level in counts and $C_{ADU}$ is the analog-to-digital unit (electron per count). The first term represents the random shot noise; the second term is the detector readout noise variance; and the third term is the digitization noise variance, which is found from root-mean-square (rms) integral over a width of $\pm 0.5$ (maximum digitization error).$^1$ The noise is set using a random Gaussian deviate. Note that for the current count rate, the random Gaussian does not significantly deviate from the random Poisson, which would be required for lower count rates. Figures 13 and 14, respectively, show the images of instrument background signal and the combined signal with noise added for phase step 1. A comparison between the two images

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$^1$ If the quantization error is denoted by $e$ (half of the code width), the rms integral is $\langle e^2 \rangle = \int_{-0.5}^{0.5} u^2 \, du = (1/12)$. 
shows that the combined signal is dominated by the instrument background signal as would be expected for IR instruments.\textsuperscript{2}

### 8. Data processing

In this section, the recovered atmospheric signal and the corresponding SNR are presented and the algorithm for wind recovery is described. The line-of-sight wind, herein referred to as wind or Doppler wind, is the wind determined for each pixel without inversion that represents some weighted average wind along the line of sight of each pixel. The random noise standard deviations of these winds are derived through propagation of the measurement noise variances. Wind differences can serve in evaluating the sensitivity to different instrument characteristics. These standard deviations and differences are useful in conducting evaluations on instrument performance and conditions. The calculated wind random error standard deviations are presented with more results found in Rahnama (2003).

#### a. The recovered atmospheric radiances

To recover the atmospheric radiances, the instrument thermal background signal for the four phase steps and all 24 measurements are removed from the corresponding combined signals. For the instrument background calibration, the pointing mirror will be rotated to point to deep space where the atmospheric emission is essentially zero. Figure 15 shows the recovered (background subtracted) atmospheric signal in counts per pixel for phase step 1 of the same measurement as shown in Figs. 13 and 14. The difference between the recovered atmospheric signal image and the pure atmospheric signal (Fig. 12) is because of measurement noise in both the background and combined signal images. The SNR estimate of a single 0.1-s exposure is found from the recovered atmospheric signal and the corresponding noise level. The variance of noise level of the recovered signal is typically between 9.4 and 9.9 squared counts per pixel for most of the pixels. Figure 16 shows maximum SNR for each tangent height for the same recovered atmospheric signal as in Fig. 15. The very small value of SNR at high tangent heights is because of the very weak signal at these tangent heights.

The 24 background-subtracted atmospheric signals of each phase step are coadded to improve the SNR. The signal levels are converted to watts per square meter per steradian for data processing. The obtained images are denoted by $I_1$–$I_4$, where indices 1–4 refer to the four

\textsuperscript{2}To detect IR radiation, the photosensitive material of the IR detector consists of a semiconductor material of low band gap. This results in a large number of thermally excited charge carriers, and therefore the IR detectors have high dark counts. The detector will be cooled to reduce this effect. In addition, blackbody radiation occurs dominantly in the IR region of the electromagnetic spectrum (except for very high temperatures where the radiation is both visible and IR). Therefore, IR instruments have high instrument thermal backgrounds arising from the lenses, mirrors, and other optical elements in the optical train, including the Michelson interferometer itself. The optical elements will be cooled to reduce the thermal emission.

Fig. 14. Combined signal (sum of atmospheric and instrument background signals) with noise added in counts per pixel for phase step 1, FOV1. The signal level varies between 7100 and 8700 counts per pixel.

Fig. 15. Recovered (background subtracted) atmospheric signal in counts per pixel for phase step 1, FOV1. The difference between the recovered atmospheric signal image and the pure atmospheric signal (Fig. 12) is because of measurement noise in both the background and combined signal images.
phase steps. The resulting \( I_1-I_4 \) radiance images are shown in Fig. 17. The differences in the patterns of the images are because of the modulation of the interferogram.

### b. The wind recovery algorithm

For the pixel at row \( \ell \) and column \( j \) of the detector, the pixel interferogram of the Doppler-shifted line can be written in terms of instrument visibility \( U_{\ell j} \), line visibility \( V_{\ell j}(\Delta) \), mean value of the interferogram \( I_{\ell j} \), and total phase of the interferogram \( \varphi_{\ell j} \) as (Rahnama 2003)

\[
I_{k\ell j}(\Delta) = I_{\ell j}[1 + U_{\ell j} \times V_{\ell j}(\Delta) \cos(\varphi_{\ell j} + \varphi_{k\ell j})],
\]

where \( I_{k\ell j}(\Delta) \) is the value of the interferogram at the \( k \)th phase step of \( \varphi_{k\ell j} \). For wind measurements made by satellite instruments, the relative velocity of the source and the instrument is determined by a combination of earth rotation, spacecraft motion, and motion of emitting species (wind). Each of these three causes a shift in line wavenumber and, consequently, induces phase shift in the interferogram in addition to the instrument intrinsic phase. The product \( U \times V(\Delta) \) known as combined visibility is defined as

\[
U \times V(\Delta) = \frac{I_{\text{max}}(\Delta) - I_{\text{min}}(\Delta)}{I_{\text{max}}(\Delta) + I_{\text{min}}(\Delta)}
= \frac{[I_o + A(\Delta)] - [I_o - A(\Delta)]}{[I_o + A(\Delta)] + [I_o - A(\Delta)]} = \frac{A(\Delta)}{I_o},
\]

where \( U \) is the instrument visibility that accounts for the imperfections of the Michelson interferometer, \( I_{\text{max}}(\Delta), I_{\text{min}}(\Delta), I_o, \) and \( A(\Delta) \) are the maximum value, minimum value, mean value, and the amplitude of the interferogram in the neighborhood of the fringe of interest as measured by an imperfect instrument, respectively; and \( V(\Delta) \) is the fringe visibility that depends on the location of the fringe in the interferogram, line shape, and line width. The narrower the line, the higher the modulation of the interferogram becomes, which leads to a higher visibility and vice versa.

For the four-point sampling, Eq. (13) becomes a set of four equations with three unknowns, where \( I_{1\ell j}, I_{2\ell j}, I_{3\ell j}, I_{4\ell j} \), are known from the measured radiances, \( \varphi_{1\ell j}, \varphi_{2\ell j}, \varphi_{3\ell j}, \varphi_{4\ell j} \) are known from the Michelson phase steps, and \( U_{\ell j} \) will be determined as part of the instrument characterization; \( V_{\ell j}(\Delta), \varphi_{1\ell j} \) and \( I_{\ell j} \) are the three unknowns per pixel.

The pixel interferogram can be expressed as a truncated Fourier series in terms of incremental change in optical path difference \( \Delta \). The three Fourier coefficients are known as apparent quantities \( (J_1, J_2, J_3) \) (W m\(^{-2}\) sr\(^{-1}\)). These are determined using the method of weighted least squares. Line visibility, the total phase of the interferogram, and the mean value of the interferogram for each pixel are then obtained from the apparent quantities (Shepherd et al. 1993; Rochon 2000; Rahnama 2003). The below relation gives the total phase of the interferogram in terms of the Fourier coefficients:

\[
\varphi = \tan^{-1} \left( \frac{J_1}{J_2} \right),
\]

The standard deviations of the \( I_1-I_4 \) radiance images as well as those of \( J_1, J_2, \) and \( J_3 \) radiance images are calculated. The SNR found from the \( I_o \) radiance image indicates an improvement in SNR almost by a factor of \((24 \times 4)^{1/2} \approx 9\) compared to the SNR of a 0.1-s exposure. The resulting \( J_1, J_2, \) and \( J_3 \) radiance images and the corresponding standard deviations are found in Rahnama (2003).

The total phase of the interferogram found from the four-point sampling method has contributions from the phase resulting from the earth’s rotation \( \varphi_r \), the phase induced by spacecraft motion \( \varphi_s \), the phase resulting from wind \( \varphi_w \), and the phase of the instrument. The satellite and earth rotation phases are calculated based

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\(^3\) The optical surfaces are not perfectly flat and smooth, the optical glass in the Michelson interferometer is not ideally homogeneous, the mirrors are not perfectly aligned, etc. Generally, the instrument visibility depends on the quality of the Michelson interferometer.
Fig. 17. The resulting $I_1$–$I_4$ radiance images (from top left, counter clockwise; W m$^{-2}$ sr$^{-1}$). The central panel illustrates how the radiance of a typical pixel varies. The differences in the pattern of the images are because of Michelson interferometer modulation. The radiance of the images is as low as $10^{-7}$ W m$^{-2}$ sr$^{-1}$ at higher tangent heights and up to $-6 \times 10^{-4}$ W m$^{-2}$ sr$^{-1}$ for lower tangent heights.
on a simplified viewing geometry. For the pixel at row \( \ell \) and column \( j \) of the detector the satellite and earth rotation phases are, respectively, found from

\[
\varphi_{\sigma\ell j} = 2\pi \tilde{\nu}_o \Delta_o \frac{v_{\sigma\ell j}}{c}, \quad \text{and} \quad \varphi_{c\ell j} = 2\pi \tilde{\nu}_o \Delta_o \frac{v_{c\ell j}}{c},
\]

where \( \tilde{\nu}_o \) is the wavenumber at the center of the line, \( c \) is the speed of light, and \( v_{\sigma\ell j} \) is the velocity of the spacecraft projected along the line of sight of the pixel, \( v_{c\ell j} \) is the projected earth rotation velocity at the geographical location corresponding to the pixel tangent point, and \( \Delta_o \) is the effective optical path difference that accounts for variations of optical path difference with shift in wavelength (Thuillier and Hersé 1988).

By removing the earth rotation phase, satellite phase, and instrument phase from the total phase of the interferogram, the phase resulting from wind \( \varphi_{w\ell j} \) is obtained. For this study, a simulated reference wind phase (Rahnama 2003) is used as an approximation to the instrument phase. The Doppler wind (line-of-sight wind) \( v_{w\ell j} \) is proportional to the Doppler phase and is given by

\[
v_{w\ell j} = \frac{\varphi_{w\ell j} c}{2\pi \tilde{\nu}_o \Delta_o}.
\]

The line-of-sight wind is obtained for each pixel and the corresponding standard deviation is calculated. The random variance of the Doppler wind \( \sigma^2_w \) is found from the relation

\[
\sigma^2_w = c^2 (2\pi \tilde{\nu}_o \Delta_o)^{-2} (J_2^2 \sigma^2_2 + J_3^2 \sigma^2_3) (J_2^2 + J_3^2)^{-2},
\]

where \( J_2 \) and \( J_3 \) are the Fourier coefficients \( (\text{W m}^{-2} \text{sr}^{-1}) \), \( c \) is the speed of light, \( \Delta_o \) is the effective optical path difference, \( \nu_o \) is the wavenumber at the center of the line, and \( \sigma^2_2 \) represents the random variance of the Fourier coefficients. Here, the derived line-of-sight wind actually includes some contribution from the instrument phase; this constant image contribution is removed when taking differences of wind images in sensitivity analyses. Statistically averaging of the columns of the pixel map of line-of-sight wind, assuming constant tangent height along each row, provides a resultant line-of-sight wind profile. A corresponding noise-level profile is also obtained. This is shown in Fig. 18. This indicates random error level for Doppler wind in the range of 1–2 m s\(^{-1}\) for the tangent height range of 15–45 km. The large values at higher tangent heights are because of the low SNR at those heights.

9. Summary and remarks

A software package has been developed for the purpose of simulating the expected observations of the SWIFT instrument. The simulated data have been processed to obtain a resultant profile of Doppler wind random error standard deviations. For the instrument characteristics specified in this paper, the SNR of a single 0.1-s exposure of recovered atmospheric radiance varies from \(~160\) to \(~60\) over the tangent height range of 15–45 km. Averaging over two sequences of 24 measurements increases the SNR by a factor of \(~7\). Averaging over a pixel row results in a further improvement in the SNR by a factor of \(~12\). The profile of Doppler wind noise level indicates a random error within 1–2 m s\(^{-1}\) for a tangent height range of 15–45 km.

The measurement simulation and Doppler wind recovery algorithm is being used with various choices of instrument parameter values and measurement scenarios to investigate the feasibility of satisfying the desired targets in wind accuracy in consideration of some critical instrument characteristics such as thermal drift in filters. This is work in progress and will be published in the future.

Inversion is required to obtain Doppler wind profiles as well as collocated ozone densities. Inversions applied to measurements simulated with this software and a related evaluation of wind and ozone errors are presented by Rochon et al. (2006). As shown in that paper, achieving the desired target accuracy in wind profiles...
implies satisfying the required ozone concentration target accuracy.

The results of this work and the work of Rochon et al. (2006) demonstrate the concept feasibility of simultaneous measurement of stratospheric wind and ozone densities.

Acknowledgments. The authors acknowledge the support of the Canadian Space Agency (CSA); the European Space Agency (ESA); Natural Sciences and Engineering Research Council of Canada (NSERC); and the Centre for Research in Earth and Space Technology (CRESTech), Ontario, Canada. COM DEV Ltd., and W. A. Gault, York University, developed the instrument configuration. S. Dobbie contributed to line selection while at York University. M. Kowalski and M. Cann, York University, and C. Boone from the University of Waterloo contributed to the line-by-line absorption cross-sectional calculation software.

APPENDIX

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
<td>optical path difference (cm)</td>
</tr>
<tr>
<td>$\Delta_0$</td>
<td>optical path difference at wavenumber 1133.4335 cm$^{-1}$ for normal incident (cm)</td>
</tr>
<tr>
<td>$\Delta_{\ell j}$</td>
<td>optical path difference for pixel at row $\ell$ and column $j$ (cm)</td>
</tr>
<tr>
<td>$\Delta_{\ell}^{eff}$</td>
<td>the effective optical path difference for pixel at row $\ell$ and column $j$ (cm)</td>
</tr>
<tr>
<td>$\delta \Delta$</td>
<td>incremental change in optical path difference (cm)</td>
</tr>
<tr>
<td>$\delta \nu$</td>
<td>Doppler shift in the line (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\delta \phi$</td>
<td>phase shift in the interferogram (rad)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>wavelength ($\mu$m)</td>
</tr>
<tr>
<td>$\nu_r$</td>
<td>wavenumber (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\nu_{peak}(i)$</td>
<td>peak transmission wavenumber as a function of off-axis angle (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\sigma_{\nu, p}$</td>
<td>absorption cross section of species $p$ (cm$^2$ molecule$^{-1}$)</td>
</tr>
<tr>
<td>$\sigma_j^d$</td>
<td>detector readout noise variance ($e^2$ pixel$^{-1}$)</td>
</tr>
<tr>
<td>$\sigma_N^2$</td>
<td>measurement noise variance (squared count)</td>
</tr>
<tr>
<td>$\tau_\nu (s)$</td>
<td>transmittance between the instrument and a point at a distance $s$ along the line of sight filter attenuation</td>
</tr>
<tr>
<td>$\tau_{filter}$</td>
<td>maximum filter transmittance</td>
</tr>
<tr>
<td>$\tau_{max}$</td>
<td>nonfilter attenuation in the instrument</td>
</tr>
<tr>
<td>$\phi$</td>
<td>phase of the interferogram (rad)</td>
</tr>
<tr>
<td>$\phi_k$</td>
<td>Michelson interferometer $k$th phase step (rad)</td>
</tr>
<tr>
<td>$\phi_{\ell j}$</td>
<td>Michelson interferometer $k$th phase step for pixel at row $\ell$ and column $j$ (rad)</td>
</tr>
<tr>
<td>$\varphi_r$</td>
<td>the phase due to earth rotation (rad)</td>
</tr>
<tr>
<td>$\varphi_s$</td>
<td>the phase induced by spacecraft motion (rad)</td>
</tr>
<tr>
<td>$\varphi_{\ell j}$</td>
<td>total phase of the interferogram for pixel at row $\ell$ and column $j$ (rad)</td>
</tr>
<tr>
<td>$A(\Delta)$</td>
<td>the phase resulting from wind (rad)</td>
</tr>
<tr>
<td>$A_\Omega$</td>
<td>amplitude of the interferogram (counts per pixel or W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$B_\nu (T)$</td>
<td>pixel étendue (m$^2$ sr)</td>
</tr>
<tr>
<td>$C_{ADU}$</td>
<td>value of the Planck function at wavenumber $\nu$ and temperature $T$ [W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$]</td>
</tr>
<tr>
<td>$f_{\ell}(\nu)$</td>
<td>the analog-to-digital unit (electron per count)</td>
</tr>
<tr>
<td>$c$</td>
<td>speed of light in vacuum (m s$^{-1}$ or cm$^{-1}$)</td>
</tr>
<tr>
<td>$d$</td>
<td>incremental step of the Michelson interferometer phase stepper (nm)</td>
</tr>
<tr>
<td>$F$</td>
<td>finesse</td>
</tr>
<tr>
<td>$FSR$</td>
<td>filter bandwidth (full width at half maximum; cm$^{-1}$)</td>
</tr>
<tr>
<td>$FWHM$</td>
<td>relative total filter function for pixel at row $\ell$ and column $j$</td>
</tr>
<tr>
<td>$f_{\ell j}(\nu)$</td>
<td>mean value of the interferogram for pixel at row $\ell$ and column $j$ (counts per pixel or W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$I_1-I_4$</td>
<td>radiance corresponding to the four phase steps (W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$I_{\max}$</td>
<td>maximum value of the interferogram in (counts per pixel or W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$I_{\min}$</td>
<td>minimum value of the interferogram (counts per pixel or W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$i$</td>
<td>off-axis angle ($^\circ$ or rad)</td>
</tr>
<tr>
<td>$i_c$</td>
<td>off-axis angle at the central pixel ($^\circ$ or rad)</td>
</tr>
<tr>
<td>$J_1$, $J_2$, $J_3$</td>
<td>Fourier coefficients or apparent quantities (W m$^{-2}$ sr$^{-1}$)</td>
</tr>
<tr>
<td>$j$</td>
<td>pixel column index</td>
</tr>
<tr>
<td>$k$</td>
<td>phase step index</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>spectral radiance [W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$]</td>
</tr>
<tr>
<td>$L_\nu$</td>
<td>atmospheric or instrumental spectral radiance for pixel at row $\ell$ and column $j$ [W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$]</td>
</tr>
<tr>
<td>$\ell$</td>
<td>pixel row index</td>
</tr>
<tr>
<td>$n$</td>
<td>signal level (value of sampled interferogram) for pixel at row $\ell$ and column $j$ (counts per pixel)</td>
</tr>
<tr>
<td>$N_{\ell j}(\Delta)$</td>
<td>(effective) index of refraction</td>
</tr>
</tbody>
</table>
number density of species $p$ (mole cm$^{-3}$)

$p$ species index

$q$ quantum efficiency (electron per photon)

$R_{ij}$ instrument responsivity for pixel at row $i$ and column $j$ (counts per pixel of W$^{-1}$ m$^2$ sr)

$s$ distance along the line of sight (cm)

$T$ temperature (K)

$T_O$ operating temperature (K)

$t$ exposure time (integration time) (s)

$t_i$ length of the fixed-length arm of the Michelson interferometer (cm)

$t_2$ length of the open arm of the Michelson interferometer (cm)

$U_{ij}$ the instrument visibility for pixel at row $i$ and column $j$

$U \times V(\Delta)$ combined visibility

$V_{ij}(\Delta)$ line visibility for pixel at row $i$ and column $j$

$v_{ei}$ the projected earth rotation velocity at the geographical location corresponding to the pixel at row $i$ and column $j$ (m s$^{-1}$)

$v_{ei}$ the velocity of the spacecraft projected along the line of sight of the pixel at row $i$ and column $j$ (m s$^{-1}$)

$v_w$ wind velocity (m s$^{-1}$)

$v_{w,ij}$ Doppler wind (line-of-sight wind) for pixel at row $i$ and column $j$ (m s$^{-1}$)


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