Scientific Assessment of the SWIFT Instrument Design

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(Manuscript received 31 October 2012, in final form 6 April 2013)

ABSTRACT

The Stratospheric Wind Interferometer for Transport Studies (SWIFT) is a proposed satellite instrument. SWIFT is an imaging field-widened Doppler Michelson interferometer. It observes a thermal IR atmospheric emission line in a limb-viewing geometry in order to measure stratospheric winds and stratospheric ozone concentration profiles with global coverage during both day and night. SWIFT has the capability of improving the knowledge of the dynamics of the stratosphere and global distribution of and global transport of ozone. The target wind and ozone accuracies are \(3 \text{ m s}^{-1}\) and 5%–10%, respectively. The instrument is a follow up to the highly successful Canada–France Wind-Imaging Interferometer (WINDII) instrument on NASA’s Upper Atmosphere Research Satellite (UARS). To assess the suitability of the method of Doppler imaging Michelson interferometry for the measurement of stratospheric wind and ozone using the SWIFT instrument, a scientific assessment of the instrument performance was undertaken using forward and inverse modeling and error analyses. This paper is aimed at determining the technical and scientific feasibility of the SWIFT instrument and its ability to meet the science requirements. This paper also briefly describes the SWIFT experiment, the data retrieval algorithms, and technical challenges in stratospheric wind measurements. Meeting the wind accuracy requirement imposes tight requirements on instrument thermal stability, filter monitoring, and determination of reference phase calibration. The SWIFT instrument design shows a strong level of dependence on the knowledge of atmospheric N\(_2\)O concentration. The presence of N\(_2\)O as an interfering species degrades the SWIFT performance at all altitudes with the largest impact especially for altitudes below 30 km.

1. Introduction

The Stratospheric Wind Interferometer for Transport Studies (SWIFT) is a proposed limb-viewing satellite instrument designed for collocated simultaneous measurements of stratospheric winds and ozone concentration. SWIFT has the capability of improving our knowledge of the dynamics of the stratosphere, global distribution and global transport of ozone, midrange weather forecasting, and global change issues. The wind velocities and ozone densities are to be extracted from the SWIFT measurements with target accuracies of \(3 \text{ m s}^{-1}\) and 5%–10%, respectively, over most of the stratospheric altitude range. The main science objectives of the SWIFT instrument can be summarized in three main categories:

- stratospheric transport studies, including the Brewer–Dobson circulation and horizontal ozone fluxes, from collocated wind and ozone measurements;
- stratospheric tropical dynamical studies including the quasi-biennial oscillation (QBO), the semiannual oscillation (SAO), and equatorial waves; and
- improved medium-range weather forecasting through SWIFT data assimilation and its contribution to numerical weather prediction models.

The SWIFT instrument is an imaging field-widened Michelson interferometer, and the measurement technique is known as Doppler imaging Michelson interferometry. The SWIFT instrument is based on the Canada–France Wind-Imaging Interferometer (WINDII; Shepherd et al. 1993, 2012b) instrument that operated on board the National Aeronautics and Space Administration (NASA)’s Upper Atmosphere Research Satellite (UARS) from 1991 to 2003.

To assess the performance of the SWIFT instrument, a mission simulation model for the SWIFT experiment was developed to simulate the expected observations
of the instrument including the noise levels for different instrument characteristics, atmospheric conditions, and measurement scenarios. Retrieval of level 0 to level 2 data products from the simulated raw data was performed. The mission simulations combined with the data processing made it possible to simulate the science and onboard calibration measurements along the orbit and to perform the data processing accordingly. Using the mission simulation and data processing models, error analyses were performed in order to quantify random errors and systematic errors in wind and ozone. The results of the error analyses were used to assess the performance of the SWIFT instrument against the SWIFT science requirements. The analyses have determined the capabilities of the SWIFT instruments and defined its performance limit.

This paper presents a summary of the performance assessment and discusses the suitability of the method of Doppler Michelson interferometry using the SWIFT instrument for the measurement of stratospheric wind and ozone. Section 2 explains the measurement methodology. Section 3 provides the current state of satellite measurements of atmospheric winds. The SWIFT experiment and the science requirements are given in section 4. Section 5 explains the main technical challenges in stratospheric wind measurements. Section 6 briefly explains the data retrieval algorithms for the SWIFT measurements. The instrument conceptual design is described in section 7. Two main design options that are assessed in this paper are described in section 7. A description of the performance model is given in section 8. Section 9 presents and discusses the results of the performance analyses and scientific assessment of the instrument performance. Concluding remarks are provided in section 10.

2. Measurement methodology

A Doppler shift in the emission line wavelength from an emitting constituent carried by the wind is measured as a phase shift in the interferogram using a field-widened Michelson interferometer. The radiance spectrum about the target ozone emission line at 1133.4335 cm$^{-1}$ is isolated from the complex limb spectrum of the stratosphere in the thermal infrared (TIR) region using a narrowband optical filter system and is projected to the field-widened Michelson interferometer, which allows a four-point sampling of the interferogram of the Doppler wind-shifted spectrum (Shepherd 2002; Rahnama et al. 2006). The stratospheric wind and ozone density profiles are recovered from the produced four-point measurement images (Rahnama et al. 2006). SWIFT has two fields of view observing the limb at 48° and 132° with respect to the spacecraft velocity vector allowing the two near-orthogonal horizontal components of the wind to be measured.

For accurate wind measurements, a high phase resolution is required. This is achieved by measuring the Doppler phase shift of fringes of high order of interference produced by a field-widened Michelson interferometer. Employing a field-widened Michelson interferometer, only a fraction of a fringe is included in a wide field. This enlargement in field of view (FOV) combined with the use of sensitive detectors results in a high signal-to-noise ratio (SNR) of the interferogram. The large FOV can be exploited by using a camera instead of a single detector with the Michelson interferometer. For the SWIFT instrument, the use of a field-widened Michelson interferometer combined with an array detector allows the observation of a complete limb profile in one image. The field-widened Michelson interferometer employed for measurements of atmospheric radiance, wind, and temperature is often called the Doppler Michelson interferometer and the associated technique is called Doppler Michelson interferometry.

The measurement methodology and instrument concept are discussed in detail in Shepherd (2002), Rahnama (2003), Rahnama et al. (2006), Rahnama (2010), and Rahnama et al. (2012, 2013).

3. Satellite measurement of stratospheric winds

The history of space-based wind measurements is very brief (Shepherd 2002). The first application of the Fabry–Perot interferometry technique was employed on NASA’s *Dynamics Explorer 2* (Hays et al. 1981) for the measurement of thermospheric wind. The High-Resolution Doppler Imager (HRDI) instrument (Ortland et al. 1996) on NASA’s *UARS* measured winds using the Fabry–Perot interferometry technique. HRDI measured wind in the range of 15–105-km altitude, with the stratospheric measurements only in daytime. The HRDI measurement method for measuring stratospheric winds relied on scattering from aerosols. Stratospheric winds were then measured from the shifts of the absorption lines of atmospheric O$_2$ as the scattered light traveled toward the spacecraft. This has the problem that the aerosol distributions were not measured but modeled, so the uncertainty of the altitudes from which the winds were retrieved was high. This limited the accuracy of the wind profiles derived from the HRDI measurements.

The WINDII (Shepherd et al. 1993, 2012b) instrument on NASA’s *UARS* made wind measurements between 80 and 300 km (mesosphere and thermosphere) using Doppler shifts in visible airglow emission lines. The Thermosphere Ionosphere Mesosphere Energetics and
Dynamics (TIMED) Doppler Interferometer (TIDI) instrument on board the TIMED satellite (Killeen et al. 1999) was designed to measure the horizontal neutral winds in the altitude range of 60–300 km (mesosphere and thermosphere). Technical limitations following launch have until recently restricted the altitude range from about 70 to 115 km (e.g., Wu et al. 2011). The WINDII instrument is the only one that employed the method of Doppler Michelson interferometry.

The European Space Agency (ESA)’s Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus), expected to be launched in 2014, will provide global observations of line of sight wind profiles from the surface to about 20 km (Durand et al. 2004) using lidar techniques.

4. The SWIFT experiment

There are plans to extend the space-based upper-atmospheric wind measurement techniques, previously developed for WINDII, down into the stratosphere in order to investigate the dynamics of this region. The main observational objectives of the SWIFT experiment (Shepherd et al. 2001) are the simultaneous and collocated measurement of horizontal wind velocity vectors and ozone concentration in the stratosphere during day and night.

There are essentially no operational observations of wind vectors above the level reached by the radiosondes (i.e., the troposphere; Li et al. 1998; Lahoz et al. 2005). In the extratropics, stratospheric winds can be derived, to a reasonable approximation, from the temperature field using assimilation models. However, in the tropics, winds cannot be accurately derived from the temperature field (Li et al. 1998; Lahoz et al. 2005) because of the weaker Coriolis force (the relation between wind and temperature breaks down at the equator where the Coriolis force goes to zero). It is generally recognized that there is a lack of high-resolution accurate stratospheric wind measurements during both daytime and nighttime, and there is not currently a good estimate of the state of the tropical stratosphere (Lahoz et al. 2005). This is the main motivation for the SWIFT experiment. SWIFT has the capability of improving the quality of stratospheric analyses in the tropics, particularly the tropical winds (Lahoz et al. 2005).

SWIFT’s target line is an ozone emission line with the central wavenumber of 1133.4335 cm\(^{-1}\) (wavelength of \(\sim 8.8227\) \(\mu\)m). From SWIFT’s measurements, stratospheric ozone concentration will be derived at the same time as the stratospheric wind velocities. From simultaneous collocated measurements of wind and ozone, the global transport of ozone can be studied. The Brewer–Dobson circulation is expected to increase with global climate change (Garcia and Randel 2008; Shepherd and McLandress 2011). Global measurements of stratospheric wind and ozone will help better predict how fast ozone will move from the tropics to the poles. This will allow us to better understand the difference between natural variations of ozone and ozone depletion caused by human activities (ESA 2002; CSA 2006).

SWIFT measurements can potentially provide operational stratospheric wind measurements for medium-range weather forecasting. An observing system simulation experiment conducted by Lahoz et al. (2005) suggests that SWIFT wind and ozone measurements would improve data assimilation for weather forecasting applications. For the work by Lahoz et al. (2005), a wind error of 5 m s\(^{-1}\) and ozone concentration error of 10% over a 25–40-km altitude range were assumed. The assumed vertical resolution was 2 km. SWIFT’s measurements were designed to complement those of ADM-Aeolus since SWIFT is to provide winds above 15–55 km.

SWIFT’s horizontal resolution is expected to be better than 400 km within the tropics and better than 600 km for outside the tropics. This horizontal resolution is sufficient to observe equatorial waves for the studies of tropical dynamics (Shepherd 2002). Measurements of the zonal-mean zonal wind will provide better understanding of the quasi-biennial oscillation and semiannual oscillation, which is expected to lead to improvements in climate models. The SWIFT main science requirements, based on SWIFT’s Mission Requirements Document (MRD), are given in Table 1. SWIFT’s main observational parameters are given in Table 2.

5. Technical challenges in stratospheric wind measurements

The SWIFT instrument is largely based on the WINDII instrument. 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 SWIFT instrument employs the same techniques, but instead of operating in the visible region, it operates in the infrared (IR) region using an ozone thermal emission line.

The target lines for the WINDII instrument were relatively isolated airglow emission lines, while SWIFT functions in the TIR region, a very spectrally crowded region and technically a more difficult region of the spectrum. Moreover, the molecular emissions from many species make the stratospheric spectra more complex compared to mesospheric and thermospheric (mostly atomic) spectra (the atmospheric region for the WINDII instrument). Therefore, a narrowband filter system is required to isolate the target ozone line from the forest of stratospheric spectral lines. The narrowness of the filter system results in the sensitivity of the wind measurements to changes in the position of filter passbands (Rahnama et al. 2013). Additionally, in the lower stratosphere, the ozone emission line width is comparable to the filter width. Therefore, the filter system modifies the spectrum, which makes accurate wind measurements even more difficult for the lower stratosphere.

Additionally, TIR instruments have high instrument thermal backgrounds arising from the lenses, mirrors, and other optical elements in the optical train, including the Michelson interferometer itself. To reduce the thermal emission including the detector dark current, TIR instruments require cryogenic cooling of the detector, as well as cooling of the instrument components. This put further demands on the filter system, which has to be capable of blocking most of the instrument thermal background.

The IR materials, such as germanium, are very sensitive to temperature changes because of the high thermal sensitivity of the index of refraction (Rahnama 2003; Rahnama et al. 2012). This makes the stratospheric wind measurements very sensitive to instrument thermal drift. This imposes technical difficulties in designing the instrument and also makes the wind retrieval algorithms more complex.

Calibration and monitoring procedures for the SWIFT instrument are also more complex than those for the WINDII instrument. In particular, the reference phase calibration and filter monitoring for the SWIFT instrument are two of the main critical issues, both from the technical and algorithm point of view (Rahnama et al. 2012).

The demands on the manufacturing and the lack of experience with some of the critical components of the instruments, including the wideband filter and the field-widened Michelson interferometer, to operate in the TIR region impose another constraint in designing the instrument. Fortunately, there is experience and existing expertise for the WINDII Michelson interferometer, but WINDII used combinations of glasses for thermal compensation and the very limited number of materials available in the TIR region made this impossible for SWIFT.

Therefore, several major technical enhancements are required to overcome the difficulties intrinsic to stratospheric wind measurements in the TIR region.

### 6. The data retrieval algorithms

This section briefly explains the data retrieval algorithms for the SWIFT measurements, including the retrieval of line-of-sight (LOS) wind, inverted wind, and ozone concentration. The algorithms are described in detail in Rahnama (2003, 2010) and Rochon et al. (2006).

The signal at the detector has a contribution from the instrument thermal background in addition to the atmospheric emission. The instrument thermal background is measured during background calibration (by viewing the deep space) and is removed from the signal at the detector to recover the atmospheric signal. The background-subtracted atmospheric signals of each phase step are coadded to improve the SNR. The signal levels are converted to $W m^{-2} sr^{-1}$ for data processing. The images obtained are referred to as radiance images $I_1$ to $I_4$, where indices 1 to 4 refer to the four phase steps.

The LOS data retrieval algorithm includes the removal of the instrumental contribution to recover the atmospheric signal; coadding the recovered atmospheric exposures; calculation of SNR of a single exposure as well as that of coadded images; simulation of the reference phase; calculation of phases induced by spacecraft motion and Earth rotation; calculation of the total phase of the interferogram; calculation of line visibility; calculation of the mean value of the interferogram; and the recovery of LOS wind and calculation of random
error standard deviation of LOS wind. Because the instrumental characteristics vary from pixel to pixel, data from each pixel are treated individually in the initial part of the analysis. The main products of the LOS data retrieval are the total phase of the interferogram and coadded images of recovered atmospheric signal for each phase step (I₁ to I₄ radiance images). Coadding is necessary in order to make rapid phase stepping possible and still obtain an adequate SNR.

To obtain the LOS wind, the total phase of the interferogram is calculated from the signal at the detector on a pixel by pixel basis. By removing the known instrumental zero wind phase, the phase due to Earth rotation and the phase induced by spacecraft motion from the total phase, the LOS wind phase is obtained from which the LOS wind and its random error standard deviation are calculated. Sample products of the LOS data retrieval are presented in Rahnama (2003, 2010) and Rahnama et al. (2006).

The ozone density and inverted wind are found by inverting the radiance images (I₁ to I₄) produced by the mission simulation model using iteration techniques and a simplified version of the mission simulation model (as a forward model) with prior knowledge of the atmospheric state expressed as a priori. The radiance images are inverted using a Newton–Gauss iterative scheme using a maximum a posteriori (MAP) solution approach (i.e., optimal estimation) with added differential regularization (Rodgers 2000). The retrieval of wind and ozone profiles performed through inversion relies on comparing the measured atmospheric radiances in W m⁻² sr⁻¹ to values determined from an estimate of the atmospheric state.

The main part of the inversion data retrieval model is the forward model. In addition to the forward model, the inversion model consists of a matrix equation and a diverging condition between the solution estimate and prior knowledge of the atmosphere to be satisfied using iterations (Rochon et al. 2006). The retrieval forward model (herein referred to as the forward model) is a compressed, short, and approximated version of the mission simulation model (herein referred to as the mission simulation model). A spectral radiance sampling interval of 0.0003 instead of 0.00017 cm⁻¹ and a maximum LOS integration path increment of 50 instead of 5 km are some of the simplifications of the forward model compared to the mission simulation model (Rochon et al. 2006).

The LOS wind standard deviations and differences are useful in conducting sensitivity analyses and instrument design optimizations (Rahnama et al. 2013; Rahnama 2010). Unlike inversion analyses, the LOS wind analyses accurately represent the impact of instrument characteristics on wind recovery. The main reason for that is because inversion involves many shortcuts and approximations and more importantly inversion introduces model errors, which may not be easily differentiated from instrumental error sources. LOS wind recovery was used in evaluating the sensitivity of wind recovery to different instrument characteristics and to optimize the instrument design. Error analysis results obtained through inversion are used for scientific assessment of the instrument performance.

7. The SWIFT instrument

Among a number of different design options, two main design options are assessed in this paper. Herein, the two design options are referred to as design option A and design option B. A schematic drawing of the instrument design for design option A is shown in Fig. 1. Each FOV is defined by a reflecting telescope (M₁, M₂, and M₃) and a field stop (S) in the left and right optical channels. The telescope is an all-aluminum reflective design in order to maintain thermal stability of the alignment. The incoming light is directed by the telescopes to the pointing mirror and then passed to the narrowband Fabry–Perot etalons (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. The field combiner is
a reflecting prism. The wideband and medium-band filters (E2) eliminate the sidelobes of the narrowband etalons. The view of the atmospheric emission modulated by the Michelson interferometer is projected to the array detector through the transfer optics and camera lens. 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 (Rahnama et al. 2012). Note that the pointing mirror system allows the fields of view to be raised or lowered by up to 1.5° in order to adjust changes in the altitude of the spacecraft and to measure the instrument’s thermal background by pointing to deep space.

A narrowband thermally tunable solid Ge Fabry–Perot etalon filter E1 (in Fig. 1) is placed before the field combiner in each optical channel. Each channel needs its own 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 of almost 0.3 nm (≈0.04 cm⁻¹), to shorter wavelengths for the fore limb FOV and to longer wavelengths for the aft limb FOV. The components of the filter system consist of one narrowband Fabry–Perot etalon filter in each optical chain, a wideband interference filter, a medium-band etalon, and a long-pass filter. The role of the narrowband filters is to isolate to the required extent emission from the target ozone line and block the TIR radiation from the telescopes and the pointing mirrors. The medium-band filter is another solid Ge Fabry–Perot etalon. To achieve a high transmission of the target ozone line across the FOV, the wavelength of the peak transmission at the zero off-axis angle is shifted by almost 0.25 nm (≈0.03 cm⁻¹) 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.

For design option A, the wideband and medium-band filters E2 (in Fig. 1) are placed in front of the detector to eliminate the nearby sidelobes that are not blocked by the narrowband filters. These two filters also partially block the instrumental thermal background signal. The wide band filter is a nontunable interference filter made of germanium with a coating of dielectric materials and is located behind the Michelson interferometer.

For design option A, a filter bandwidth of 18 nm (2.31 cm⁻¹) is assumed for the wideband filter. However, further studies showed that the fabrication of wideband filters with a width of 18 nm would likely not be feasible. Fabrication of wideband filters with a width less than 48 nm (6.16 cm⁻¹) was considered to be difficult, if possible at all. This means the wideband filter bandpass must be increased to at least 48 nm. This will result in an increased instrument thermal background. Moreover, preventing recirculated fringes by tilting the filters may not be feasible as was assumed for design option A. Therefore, in order to prevent ghosting as a result of recirculated fringes, tilting the filters is likely required. This would increase thermal background emission from the components near and surrounding the Michelson interferometer. Instrument thermal background is a major noise source for the SWIFT instrument (and generally for TIR instruments). To reduce the increased instrument thermal background, one potential solution is to move the narrow filter to the combined field. The design with the narrowband filter in the combined field is referred to as design option B. Note that for design option A, the narrow filters partially block the emission from the telescopes and pointing mirrors only.

Moving the narrowband filters to the combined field may degrade the degree of isolation of the atmospheric ozone target line from the forest of spectral lines in the stratosphere in the TIR spectral region. Note that for design option A, each channel has a narrowband tunable filter in order to correct for the Doppler shift induced by the spacecraft’s velocity. The narrow filters have to be tuned by almost 0.3 nm, to shorter wavelengths for the fore limb FOV and to longer wavelengths for the aft limb FOV. To have only one narrow filter in the combined field as opposed to one narrow filter in each FOV, the tilt and central wavelength of the narrow filter have to be optimized to obtain acceptable line isolation for both fore and aft fields of view. The disadvantage of this is that one of the fields of view may result in degraded performance, or the asymmetric throughput distribution across the field between fore and aft fields may result in noticeably different performance for the two fields of view, which may increase the complexity of the data retrieval algorithm.

The baseline detectors for design options A and B are Teledyne MCT (HgCdTe) TCM2620 and Teledyne MCT TCM2621, respectively. The values of the main parameters of the detector and electronics units (EU) for the two design options are summarized in Table 3. The values of the main common instrument parameters for the design options are given in Table 4. The instrument responsivity for design options A and B are respectively 2.5 × 10⁶ and 1.6 × 10⁶ counts per pixel of W⁻¹ m² sr. The instrument characteristics are discussed in detail in Rahnama (2010).

The two design options require different measurement scenarios given the differences in the detector and EU parameters for the two design options. The measurement scenario for design option A is 12B, 24A,
12B, 24A, and 12B, where B represents a set of four-point instrument background measurements and A represents a set of four-point atmospheric measurements. Each image has an exposure time of 0.1 s. Hence, for one profile measurement, there are 84 four-point images (i.e., total of 336 exposures). Considering a 10% dead time, the time for a complete measurement profile will become $84 \times 0.1 = 37$ s. For design option B, the measurement scenario is 4B, 4A, and 4B, where again B represents a set of four-point instrument background measurements and A represents a set of four-point atmospheric measurements. Each image has an exposure time of 0.75 s. Hence, for one profile measurement there are 12 four-point images (i.e., total of 48 exposures). Considering a 10% dead time, the time for a complete measurement profile will be $12 \times 0.75 = 40$ s.

It is also worth reminding the reader that for design option A, the narrowband filters are located in the fore optics while the medium-band and wideband filters are in the transfer optics between the Michelson interferometer and the detector. The filters for design option A may not drift at the same rate given that they are located in different thermal environments. The problem with the filter passbands drifting at different rates is that the resulting total filter function may change shape because of differential thermal drifts. Monitoring the shape of the total filter passband may be difficult. One of the main advantages of design option B to design option A is that the narrowband, medium-band, and wideband filters are all in the same thermal environment, thereby ensuring that the drift rates would be similar.

Assessing the two design options is possible only by performing detailed and in-depth error analyses. The next two sections discuss the performance model and the results of the error analyses.

### 8. The performance model

A mission simulation model was developed in order to simulate the expected observations of the SWIFT instrument. An atmospheric radiance model (Rochon et al. 2006; Rahnama et al. 2006), the SWIFT instrument models and observational simulation model are the main components of the mission simulation model (Rahnama 2010, 2003). The mission simulation is a numerical integration model and produces a set of raw measurement images as would be provided by the SWIFT instrument. This mission simulation model is capable of simulating both science and onboard calibration measurements along the orbit (Rahnama et al. 2012; Rahnama 2010). A description of the mission simulation model is given in Rahnama (2010). A performance model was developed based on the mission simulation model. The synthetic raw data produced using the mission simulation model were processed using the SWIFT data processing model. The performance model was used to perform error analyses. The results of the data retrieval and error analyses were compared to the science requirements to assess the instrument performance. The scientific assessment of the instrument performance includes calculations of the combined effect of all random and systematic error sources on inverted wind and ozone concentration for a number of different inversion and processing conditions for two main design options with calibration and monitoring.

### Table 3. Main parameters of the detector and EU for the two design options.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design option A</th>
<th>Design option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum efficiency</td>
<td>0.75 electron photon$^{-1}$</td>
<td>0.65 electron photon$^{-1}$</td>
</tr>
<tr>
<td>Readout noise variance</td>
<td>$4 \times 10^4$ electron$^2$ pixel$^{-1}$</td>
<td>$3.7 \times 10^6$ electron$^2$ pixel$^{-1}$</td>
</tr>
<tr>
<td>Well capacity</td>
<td>$1.4 \times 10^6$ electron</td>
<td>$1.4 \times 10^7$ electron</td>
</tr>
<tr>
<td>Analog-to-digital unit (ADU)</td>
<td>85 electron count$^{-1}$</td>
<td>850 electron count$^{-1}$</td>
</tr>
<tr>
<td>Integration time of a single exposure (exposure time)</td>
<td>0.1 s</td>
<td>0.75 s</td>
</tr>
<tr>
<td>Elapsed time between exposures</td>
<td>0.01 s</td>
<td>0.075 s</td>
</tr>
<tr>
<td>Array format</td>
<td>$256 \times 256$ pixels$^2$</td>
<td>$256 \times 256$ pixels$^2$</td>
</tr>
<tr>
<td>Atmospheric window per FOV</td>
<td>$81 \times 162$ pixels$^2$</td>
<td>$81 \times 162$ pixels$^2$</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>$40 \mu m$</td>
<td>$40 \mu m$</td>
</tr>
<tr>
<td>Dark current</td>
<td>20 nA cm$^{-2}$ at 55 K</td>
<td>20 nA cm$^{-2}$ at 58 K</td>
</tr>
</tbody>
</table>

### Table 4. Main common instrument parameters for the design options.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical path difference for normal incident at rest wavenumber of the ozone line</td>
<td>18 cm</td>
</tr>
<tr>
<td>Instrument visibility</td>
<td>0.94</td>
</tr>
<tr>
<td>Diameter of the input aperture</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Magnification</td>
<td>3</td>
</tr>
<tr>
<td>Focal length of the camera</td>
<td>0.06 m</td>
</tr>
<tr>
<td>Camera F/#</td>
<td>1.5</td>
</tr>
<tr>
<td>Effective bandwidth of the filter system</td>
<td>0.1 cm$^{-1}$ (0.8 nm)</td>
</tr>
<tr>
<td>Filter attenuation</td>
<td>0.4455</td>
</tr>
<tr>
<td>Nonfilter attenuation in the instrument</td>
<td>0.2782</td>
</tr>
<tr>
<td>Pixel étendue</td>
<td>$5.18 \times 10^{-10}$ m$^2$ sr</td>
</tr>
</tbody>
</table>
incorporated into data processing. The results of the error analyses are presented and discussed in the subsequent section.

9. The performance assessment

To assess the instrument performance, the combined effects of all random error and all main systematic error sources on inverted wind and ozone concentration for both design options A and B were calculated. To compare the performance of design options A and B, ozone and wind are inverted under the same inversion and processing conditions for the two design options. The random error sources are shot noise, readout noise, and digitization noise. The systematic error sources are filter thermal drift, thermal drift in instrument components, Michelson Optical Path Difference (OPD) thermal drift, spacecraft velocity knowledge of 1 m s\(^{-1}\), instrument point spread function (PSF), and tangent height pointing knowledge of 450 m. Instrument PSF is a measure of the blurring of the image (Träger 2012). A thermal stability of 10\(^{-3}\) K s\(^{-1}\) is assumed. Thermal drift causes a shift in the filter passbands, shift in Michelson OPD, and drift in the instrument background signal (Rahnama et al. 2013; Rahnama 2010). Filter passband monitoring of 5.14 \times 10^{-5} \text{cm}^{-1} and OPD monitoring with a phase calibration accuracy of \(~10^{-3}\) radians are included in the data retrieval process (Rahnama et al. 2012; Rahnama 2010). The impact of thermal drift on random error is not considered here as this is negligible. It is assumed that the N\(_2\)O concentration is known to 95\% and 97\% for design options A and B, respectively. In the retrieval, two species are included versus nine species in the forward model. The species omitted are H\(_2\)O, CH\(_4\), NH\(_3\), HO\(_2\), HNO\(_3\), CFC-12, and CFC-22. Other retrieval limitations are due to short-cuts and approximations (e.g., a spectral radiance sampling interval of 0.0003 instead of 0.00017 cm\(^{-1}\) and a maximum line of sight integration path increment of 50 instead of 5 km). The applied wind profile was set to a constant value of zero (no wind) and hence any recovered nonzero wind value is a wind error. The two fields of view result in relatively similar performance (Rahnama 2010). The error analysis results are presented for only one of the two fields of view.

Figures 2, 3, and 4, respectively, show the random error standard deviation of ozone concentration, systematic error in ozone concentration for multiple systematic error sources, and the resultant ozone error profile from a realization with multiple systematic error sources and random errors for design options A and B. Note that the random error profile of ozone is the standard deviation of random error (measurement noise). Figures 5, 6, and 7, respectively, show the random error standard deviation of inverted wind, systematic error in inverted wind for multiple systematic error sources, and the resultant wind error profile from a realization with multiple systematic error sources and random errors for design options A and B. Note that the random error profile of inverted wind is the standard deviation of random error. Note that both the error profiles of wind and ozone due to the combined effect of random and systematic error sources are based on comparisons of the final iteration with the a priori (true) values.

As seen from the results presented in this section, achieving the desired target accuracy in wind profiles
implies satisfying the required ozone concentration target accuracy. The performance analysis results show that both design options A and B result in similar performance. The target and threshold wind and ozone accuracies are given in Table 1. As seen from Figs. 4 and 7, for design option A, the calculated inverted wind and ozone concentration errors are within the required threshold wind and ozone accuracies as specified in Table 1. For design option B, the wind accuracies for altitudes between 15 and 17 km do not meet the threshold requirements. For both design options, the wind accuracy for lower altitudes can be improved by including more than two species in the retrieval (currently two species are included in the retrieval versus nine species in the forward model). Instrument PSF will be characterized prior to launch and therefore the instrument PSF error will be reduced, which in turn would improve the wind error, in particular for the lower altitudes.

It is important to note that for the results presented in Figs. 2 to 7, it is assumed that the N$_2$O concentrations are known to 95% and 97% for design options A and B, respectively. The impact of insufficient knowledge of N$_2$O concentrations is discussed later in this paper.

To improve the instrument performance, some of the pixels at the corners of the FOV should be excluded in the data processing since the error in wind for the pixels at the corners of the FOV is noticeably larger compared to the other pixels. This is due to a number of factors. The pixels at the corner of the FOV are at larger off-axis angles compared to the other pixels of the FOV. Filter transmittance for pixels at larger off-axis angles is lower compared to pixels at lower off-axis angles. Lower filter transmittance means lower signal, which results in lower SNR and therefore higher random error for pixels at larger off-axis angles. Moreover, the atmospheric background is larger for pixels at larger off-axis angles (the filter system is tuned such that the optimum transmittance is obtained for the pixels at very small off-axis angles), which results in larger systematic errors due to filter thermal drift. And most importantly, Michelson phase resolution reduces significantly for the pixels at larger off-axis angles, which results in larger wind and ozone errors for pixels at larger off-axis angles. The very low random error for lower altitudes compensates for large systematic wind errors at the lower corners of the FOV. Therefore, pixels that should be excluded in the data processing are essentially most of the pixels at the two top corners. At higher and lower altitudes, as well as at the corners, both line visibility and ozone filter throughput are low, as seen from the image of filter transmittance at the ozone line (Rahnama 2003; Rahnama et al. 2006) and line visibility (Rahnama 2010; Rahnama et al. 2013). A threshold technique was developed in order to flag pixels that are more prone to high errors. The main criterion is due to the loss of phase resolution at large off-axis angles. If the phase
change across a pixel is more than 0.06 rad, the pixel is excluded from the data processing. These pixels can automatically be excluded from the data processing (Rahnama 2010).

The SWIFT instrument selects an ozone spectral region from 1132.5 to 1134.5 cm$^{-1}$, where a strong ozone line is least contaminated by its neighbors and by emissions from other atmospheric constituents. As a consequence, the success of the SWIFT instrument is critically dependent on the spectroscopic knowledge in the selected measurement region.

The spectroscopic line parameter values used for the analyses presented in this paper are from the high-resolution transmission (HITRAN) database for use with the Voigt line profile (Rothman et al. 2003). For the analyses presented in this paper, the atmospheric
The radiance model used for the SWIFT simulations and analyses assumes a value of \(-0.003 \text{ cm}^{-1} \text{ atm}^{-1}\) for pressure-shifting coefficients for most of the lines in the SWIFT spectral region of interest (about \(\pm 1 \text{ cm}^{-1}\) about the vibration–rotation ozone line at 1133.4335 cm\(^{-1}\)). The spectral region consists of many thermal emission lines of more than 16 species, with the most important ones due to ozone and nitrous oxide. The assumed value of \(0.003 \text{ cm}^{-1} \text{ atm}^{-1}\) for pressure-shifting coefficients has to be verified by laboratory measurements. There is a lack of knowledge on pressure-shifting parameters and the uncertainty of the pressure broadening parameters for the SWIFT spectral region of interest. These parameters are important for accurately simulating the expected observations of the SWIFT instrument and assessing the instrument performance accordingly. High-resolution laboratory measurements have to be carried out to accurately determine spectroscopic parameters in the selected measurement region, such as the pressure-shifting parameters and uncertainty of the pressure broadening parameters for the SWIFT spectral region of interest. This research should also include the deviation of the ozone lines in the spectral region of interest from the Voigt profile.

A study involving laboratory measurements of the relevant spectroscopic parameters including the
pressure-shifting parameter was conducted by the Laboratoire de Physique Moléculaire pour l’Atmosphère et l’Astrophysique (LPMA) of Université Pierre et Marie Curie (Paris, France). The results of this study were not incorporated in SWIFT’s atmospheric radiance model. However, in a joint effort, Environment Canada and the CSA conducted an assessment of the impact of the new laboratory measurements on the current SWIFT design (Y. Rochon and S. Melo 2011, personal communication). The assessment shows that wind errors are sensitive to changes, uncertainty, and knowledge in the line spectra and therefore accurate spectroscopic measurements will be required for SWIFT in order to achieve the desired overall wind accuracies.

Use of a narrow spectral filter significantly reduces but does not eliminate the contribution from other lines and other constituents. The contribution from other ozone lines can be accounted for through knowledge of the line parameters as the ozone concentration is retrieved in tandem with the wind. Ideally, one would want the contribution from the other interfering constituents to be negligible. The main interfering species is N$_2$O. The performance analyses presented assume that the N$_2$O concentration is known to a degree that results in meeting the threshold wind and ozone accuracies.

The presence of N$_2$O as an interfering species decreases the SWIFT performance at all altitudes with the largest impact, especially for altitudes below 25–30 km. This effect would be reduced provided that fairly accurate collocated information of N$_2$O concentrations is available. In particular, the performance of design option B is strongly dependent on the knowledge of atmospheric N$_2$O concentration. An alternative solution is to exclude from the data processing pixels that are more strongly affected by N$_2$O, as first employed by the first author in 2005 and as described in detail in Rahnama (2010). Another option is to retrieve N$_2$O concentration. While this option might potentially improve N$_2$O concentration knowledge to a very limited degree (depending on the uncertainty of the initial guess), resulting N$_2$O concentration error will also be introduced by the retrieval to compensate for other error sources that are not well accounted for. Both of these effects may contribute to reducing wind error.

In general, the molecular species in SWIFT’s selected spectral range of $\sim$1132.5–1134.5 cm$^{-1}$ other than ozone can affect SWIFT’s measurements through absorption and emission. Their mixing ratios either cannot be retrieved from the SWIFT measurements or, if retrieved, will not be reliable. The uncertainty in their mixing ratios will usually contribute to increased wind and ozone errors, in particular for altitudes below 25 km. Other than N$_2$O, CFC-12 and HCFC-22 are the most important interfering constituents for SWIFT followed by CH$_4$ (excluding any aerosol contribution). The degree of knowledge of these species is important for SWIFT retrieval. The largest wind errors are obtained when not accounting for N$_2$O in the retrievals (in addition to not accounting for the contribution of other interfering species).

The wind error due to omitting the presence of nitrous oxide is 5–20 m s$^{-1}$ for altitudes below 25 km, reducing from 5 to 1 m s$^{-1}$ as the altitude increases from 25 to 55 km. The sensitivity of wind retrieval is weaker in the upper levels due to lower N$_2$O concentration levels. When N$_2$O concentration is known to 80%, the wind error is 1–8 m s$^{-1}$ for the altitude range of 30–15 km. For N$_2$O knowledge of 50%, the wind error increases to 2–14 m s$^{-1}$ for the altitude range of 30–15 km (Y. Rochon and S. Melo 2011, personal communication).

To bring down the wind error due to imperfect knowledge of N$_2$O concentration to an acceptable level, N$_2$O concentration knowledge of 95% and 97% is needed for design options A and B, respectively. Figure 8 shows the random error standard deviation of inverted wind for design option B with perfect knowledge of N$_2$O concentration (solid curve) and 97% N$_2$O knowledge (dotted curve).

Laboratory measurements may be needed, if nothing else, to provide more precise knowledge of the actual uncertainty levels of N$_2$O spectroscopic parameters. However, benefiting from more accurate line parameters would have to be accompanied by comparatively good knowledge of the N$_2$O concentrations (given or retrieved) and of the other constituents besides ozone.

Line parameter uncertainty levels as identified in the HITRAN 2008 database (Rothman et al. 2009) for nitrous oxide near the target ozone line are 0.0001–0.001 cm$^{-1}$ for the line position, 2%–5% for intensity offset, and 0.001–0.01 cm$^{-1}$ atm$^{-1}$ for the air pressure shift coefficient. The impact of applying the upper bound of these uncertainty levels on wind error is investigated by Environment Canada (Y. Rochon and S. Melo 2011, personal communication). Wind errors due to 0.001 cm$^{-1}$ line position offset are 1–3 m s$^{-1}$ for 15–45 km and negligible for altitudes above 45 km. An offset of 5% in line intensity results in wind error of less than 1 m s$^{-1}$ for 15–45 km with negligible error for altitudes above 45 km. The wind error due to 0.01 cm$^{-1}$ atm$^{-1}$ for the air pressure shift coefficient is 1–2 m s$^{-1}$ for altitudes below 30 km and negligible for altitudes above 30 km.

Reliable N$_2$O concentrations from a source other than the SWIFT measurements would be required to benefit from improved line parameter values (Y. Rochon and S. Melo 2011, personal communication).
10. Conclusions

The feasibility of achieving the threshold wind and ozone accuracies using the SWIFT instrument has been investigated. The combined effect of the main error sources on wind measurements with monitoring and calibrations included have been evaluated. SWIFT wind and ozone error levels are quantified. An in-depth performance assessment was undertaken and the suitability of the method of Doppler Michelson interferometry for the measurement of stratospheric wind and ozone is investigated. Meeting wind and ozone accuracies with the two main design options discussed in this paper imposes tight requirements on instrument thermal stability, filter monitoring, and the determination of reference phase calibration. Achieving the required thermal stability of $10^{-3}$ K s$^{-1}$ even from a sun synchronous orbit is challenging.

The presence of N$_2$O as an interfering species decreases the SWIFT performance at all altitudes with the largest impact especially for altitudes below 30 km. The need for new laboratory measurements of N$_2$O spectroscopic parameters specifically to account for the atmospheric N$_2$O would rely on having accurate N$_2$O concentrations from another source and, at altitudes below ~25 km, also having accurate concentrations of other constituents, in particular CFCs and CH$_4$ if not also aerosols. Very accurate N$_2$O concentrations (uncertainty level of ~5% or better) are required to help meet the wind accuracy requirements using any of the two instrument designs presented in this paper.

SWIFT is a complex and technically demanding instrument. There are a number of technical risks associated with the knowledge and stability of the system filter function, thermal stability of the filters and the Michelson interferometer, and the determination of the reference phase. These critical issues need to be further investigated. The feasibility of meeting the required calibration and monitoring phase accuracies need to be proven.

Suitability of alternative measurement techniques for the observation of stratospheric winds such as the Doppler Asymmetric Spatial Heterodyne (DASH) technique (Harlander et al. 2010) should be investigated, and this work is currently in progress (Shepherd et al. 2012a).

There is a need for global accurate observations of stratospheric wind. The SWIFT instrument could fill this gap. SWIFT has the capability to address the link between dynamics and chemistry in the stratosphere that occurs through transport of ozone. The SWIFT data would advance our knowledge and understanding of our atmosphere, air quality issues, climate change, and weather forecast and would provide a scientific foundation for a sound policy needed to protect the future health of our planet.

Acknowledgments. SWIFT is an international project that involved a number of organizations. The authors acknowledge the support of the Canadian Space Agency (CSA), the European Space Agency (ESA), the Natural Sciences and Engineering Research Council of Canada (NSERC), Environment Canada, COM DEV Ltd., York University, and the Ontario Centre of Excellence (OCE) for Earth and Environmental Technologies (E-Tech; formerly the Centre for Research in Earth and Space Technology; CRESTTech). COM DEV Ltd. led the development of the instrument configuration, which is largely based on the WINDII instrument. This includes ray tracing analyses, thermal analyses, and mechanical design. The authors acknowledge the contributions of...
Neil Rowlands and Alan Scott from COM DEV as well as COM DEV’s engineering team in developing the instrument configuration. The authors acknowledge Yves J. Rochon of Environment Canada for providing the atmospheric radiance model and for his contributions to SWIFT’s data retrieval model; they would also like to thank him for his contributions to the SWIFT project during the phase A study.

REFERENCES


