A Forward Model for the Stratospheric Wind Interferometer for Transport studies

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ABSTRACT

The Stratospheric Wind Interferometer for Transport studies (SWIFT) is a Canadian satellite instrument designed to measure stratospheric winds and ozone in the 20-45km region. SWIFT is a field-widened imaging system similar, in principle, to the WINDII (WIND Imaging Interferometer) instrument but will operate in the infrared rather than the visible. An overview of the current instrument is described, followed by a description of a preliminary forward model to compute limb radiances for the Michelson interferometer imaging system of SWIFT. The model is a derivative of the Fast Line-by-Line Radiative Transfer model. This model, with the addition of a gradient model, will be initially tested in retrieval mode with the aim of eventual use by the Canadian data assimilation system. This paper will briefly describe the SWIFT instrument to be flown on the Canadian Space Agency's Chinook Mission in late 2010 followed by a description of the forward model.

Overall Objectives of SWIFT

To provide high resolution global measurements of horizontal wind vectors in the stratosphere under both daytime and night time conditions in order to study:

- Atmospheric dynamics in general
- Ozone transport from co-located wind and ozone measurements
- The potential of operational stratospheric wind measurements for medium range forecasting

Brief History and Current Status of SWIFT

- SWIFT originally proposed to ESA as an Earth Explorer Opportunity Mission in 1998 by a Canadian team led by Gordon Shepherd of York University. ESA short-listed SWIFT as one of the top 5 candidate missions out of 27 international proposals (SWIFT was the highest ranking atmospheric mission in this competition).
- Later, ESA and the CSA investigated an alternative mission for SWIFT
- In 2004 the CSA made SWIFT the primary instrument for their next SciSat mission.
- In 2005 the CSA selected ARGO (a GPS occultation experiment) to accompany SWIFT
- mission now named Chinook
- Chinook is in Mission Phase A/B stage
- scheduled launch in 2010 for a minimum 2 year mission.

Measurement Technique

A relatively isolated O_3 line ($\upsilon_o = 1133.4335$ cm⁻¹) in the IR region is separated from the complex limb spectrum of the stratosphere using a narrow-band filter system with a width of about .1(cm⁻¹). A field-widened Michelson interferometer placed in the beam is used to sample the interferogram of the Doppler wind shifted spectrum at 4 points (Fig 1, 2 & 3). The stratospheric wind and ozone density profiles are recovered from the 4-point measurement images.
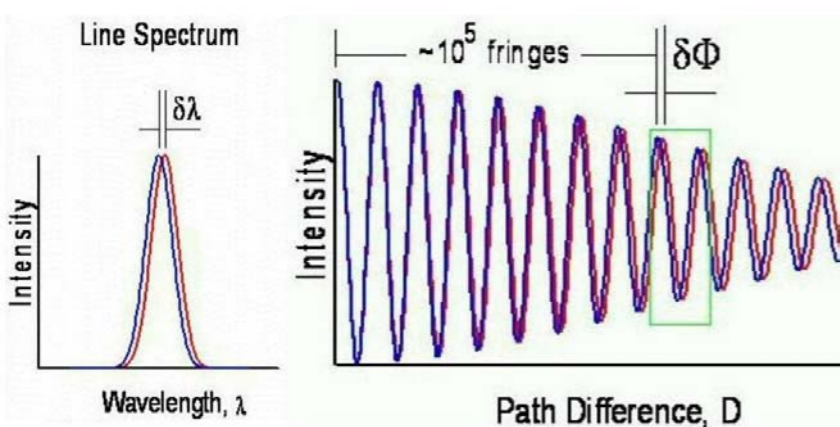

Fig 1: The impact of a Doppler shift of a line spectrum on its interferogram. The diagram on the left shows the narrow emission line (—) is Doppler shifted by δλ (—). Their corresponding interferograms are shown on the left.
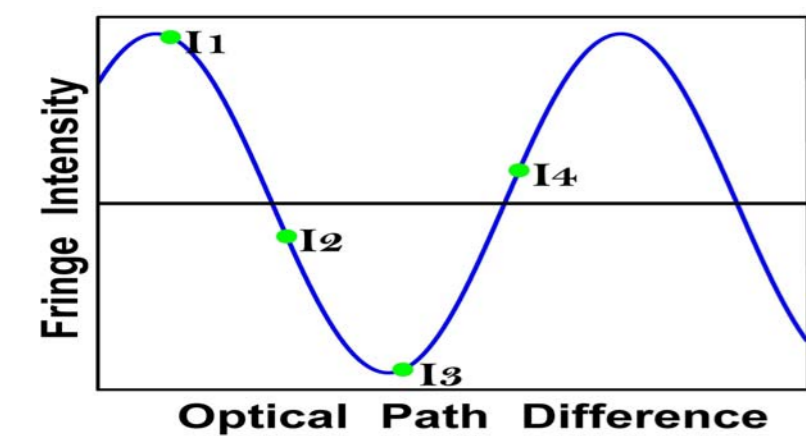

Fig 2: Four point measurement of a pixel interferogram. Every pixel on the detector array has a similar interferogram associated with it.
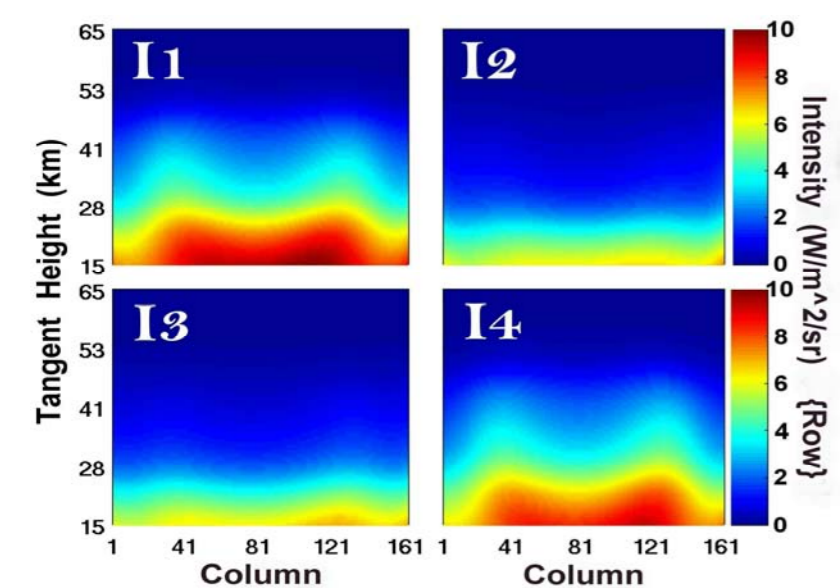

Fig 3: The Michelson modulates the radiances by stepping the movable mirror (ie it varies the optical path) thereby creating an interferogram for each pixel in the field of view. Each of the above images corresponds to one of the four points on the sample pixel inteferogram in figure 2.

SWIFT Instrument Concept

SWIFT measures the two near-orthogonal horizontal components of the wind by observing the limb to the side of the instruments forward direction; forward at 48º and aft at 132º wrt the spacecraft velocity (Fig 4). Each field of view (FOV) is defined by a reflecting telescope and a field stop in the fore & aft optical channels. Incoming light from both FOVs are redirected by the telescopes and pointing mirrors to a field combiner (Fig 5). The combined beams are passed through a set of Fabry-Perot etalons to spectrally isolate υo, and through a field widened Michelson interferometer before being projected onto a 2D array detector. The atmospheric emissions are modulated by stepping a mirror within the Michelson interferometer (4 steps at 0, λ/4, λ/2 & 3λ/2, as in fig 2). For more details, see Rahnama, 2006.
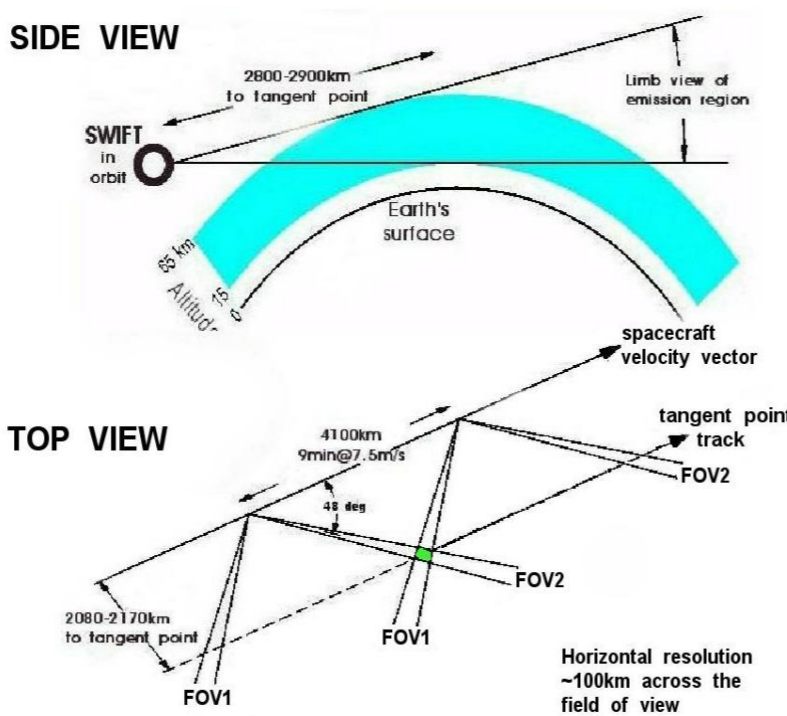

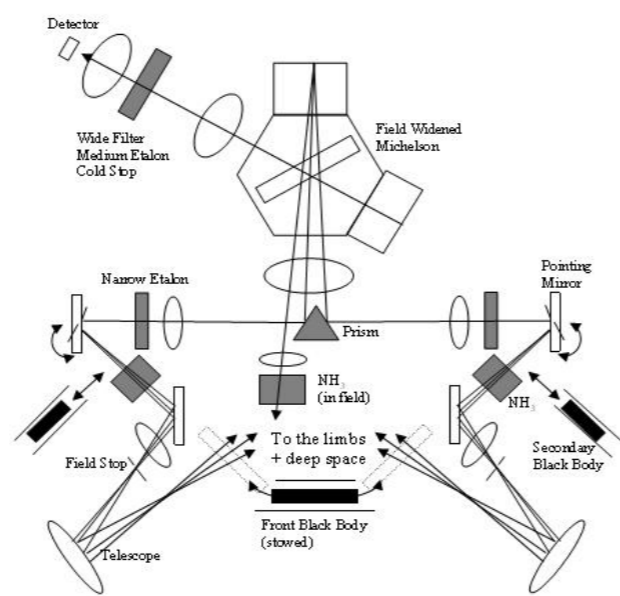Fig 4: SWIFT fields of view as seen from the side (upper) and from above (lower) the satellite.

Fig 5: Schematic drawing of an earlier optical concept for SWIFT

Line of Sight Wind Recovery

The relative velocity of the source and instrument is determined by a combination of Earth rotation, satellite motion and line of sight (LOS) wind. Each of these causes a shift in the phase of the interferogram. The intensity, I_{ijk}, for each pixel i,j and each mirror step, k, can be written as

$$I_{ijk} = I_{ij}^{mean}\left(1 + U_{ij}V_{ij}\cos(\Phi_{ij}+\varphi_{ijk})\right)$$

In practice, the Michelson mirror may not step in exactly λ/4 steps, thus I_{ijk} is fitted with a 3-term Fourier series. The 3 Fourier coefficients (J_1, J_2, J_3) are determined by fitting the four I_{ijk} for each pixel. The phase is obtained from the coefficients, and hence the line of sight wind, V_{ij}

$$V_{ij} = \frac{c\,(\tan^{-1}(J_{3ij}/J_{2ij}) - \varphi_{rij} - \varphi_{sij} - \varphi_{0ij})}{2\pi\tilde{v}_o\Delta_{ij}^{eff}}$$

Forward Model

SWIFT interferograms are simulated by the intergral of limb emission, $\Re$, convoluted with a complex instrument function, $\Im$, that is—

$$I_{ijk} = \int_{\Delta\tilde{v}}\Re_{ij}(\tilde{v}_w)\,\Im_{ijk}(\tilde{v}_s)\,d\tilde{v}$$

where $\Im_{ijk}(\tilde{v}_s) = R_{ij}(\tilde{v}_s)f_{ij}(\tilde{v}_s)\left[1+U_{ij}(\tilde{v}_s)\cos(\Phi_{ij}(\tilde{v}_s)+\varphi_{ijk}(\tilde{v}_s))\right]$

$$\Re_j(\tilde{v}_w) = \int_{\Delta x}B(\tilde{v}_w,T(x))\,d\Im(\tilde{v}_w,x)$$

$$\Im(\tilde{v},x) = EXP\left(-\sum_{i=1}^{N}\int_{u_{space}}^{u_{SWIFT}}k_i(\tilde{v},p(x),T(x)u(x))\,du(x)\right)$$

The atmospheric model, for the moment, is assumed to be locally spherically homogenous, refracting, and that there are no significant sources outside the atmosphere. Refraction pulls the tangent point down, by as much as a ½ km in the 1133(cm-1) region. The layering of the atmosphere is designed such that each tangent point, after adjusting for refraction, is situated on a level. There are 81 pixels in the vertical direction, i, that map to 81 tangent heights from 15 to 65km in the atmosphere. The distance between tangent heights is about 630m. An additional 24 layers extend the atmosphere to the top of the atmosphere. The number of cells in a LOS path varies from 49 to 209 for tangent heights of 65 and 15 km respectively. For convenience the tangent layer is split into two at the tangent point. The mean layer pressure and temperature used to evaluate the layer's absorption coefficient, and the absorber amount used to calculate the layer optical depth are calculated by sub-dividing a layer into sublayers and calculating the weighted quantity with respect to absorber amount along the path within the layer. The absorbers H_2O, O_3, N_2O, CH_4, NH_3, CFC_{12} & CFC_{22} were identified as the potentially significant gases to include in the model. More details of the general FLBL model can be found in Turner, 2005.

Each pixel on the interferogram is, in effect, a separate channel, meaning that SWIFT has potentially 162x81 channels per FOV. The difference between any adjacent pixel is small. For operational purposes a highly accurate forward model is required. A line-by-line (LBL) radiative transfer model would be ideal, but they are generally too slow for operational purposes. Usually a parameterized model such as RTTOVS. (Saunders et al, 1999) is used.

The FLBL (Turner, 2005) was chosen to test the feasibility of assimilating SWIFT winds, as it is accurate & fast. It has the advantage of accounting for wavenumber dependencies explicitly and does not need to operate on a preordained vertical grid. Unlike a regression model, it can be implemented now since its implementation does not require a search for appropriate parameters for the wind as would a regression model. Studies with the FLBL will also aid in determining parameters for any future parameterized model, should the need arise.

Impact Studies

Ideally a high resolution model is better than a low resolution model. However better resolution requires more computational resources. A balance must be found between high accuracy and available resources. Since the end product are the winds, the bounds of the FLBL are best determined by examining how the winds will be affected by various parameters, such as spectral resolution. For this study the object is to maintain an error less than .2m/s relative to a high resolution model.

Figure 6 illustrates the impact on derived winds when spectral resolution is decreased. At .002(cm-1) differences over 1m/s just start to appear in the upper corners. At .003(cm-1) the corners are solidly over 1m/s and the central field is in error of near .2m/s. Resolutions over .004 are unacceptable.
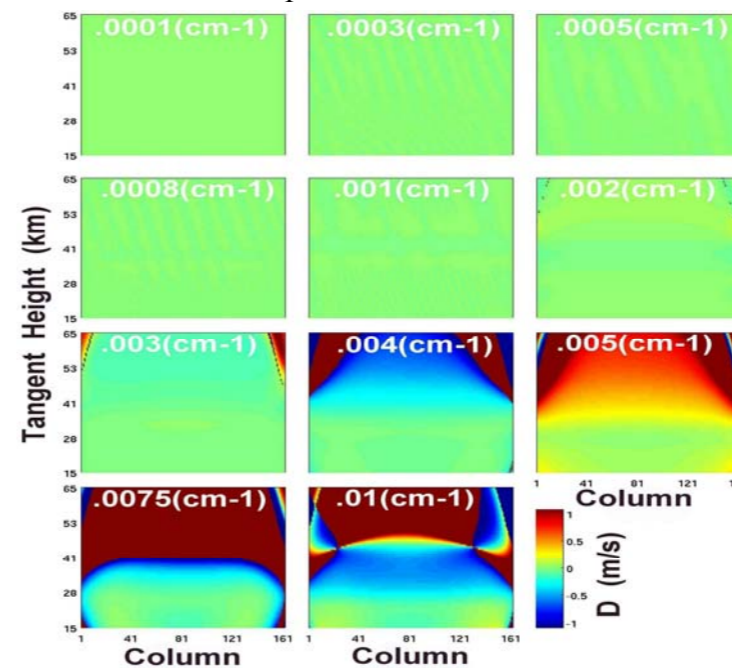

Fig 6: Difference between winds derived using a .0001 (cm-1) model and ones of lower resolution.

Another consideration is how many sublayers are required to estimate the layer properties before an impact on winds appears. Figure 7 illustrates the differences between a 20 sublayer model at .001(cm-1) and 4 other values. At least 6 or 7 layers are required to minimize the impact on derived winds.

All possible combinations of gases were tested in order determine if the list may be reduced. Figure 8 shows the

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samples where a single absorber has been dropped off the list. It appears that at least H2O and NH4 could be ignored, as could CFC12 if one wished to exclude winds below 20km.
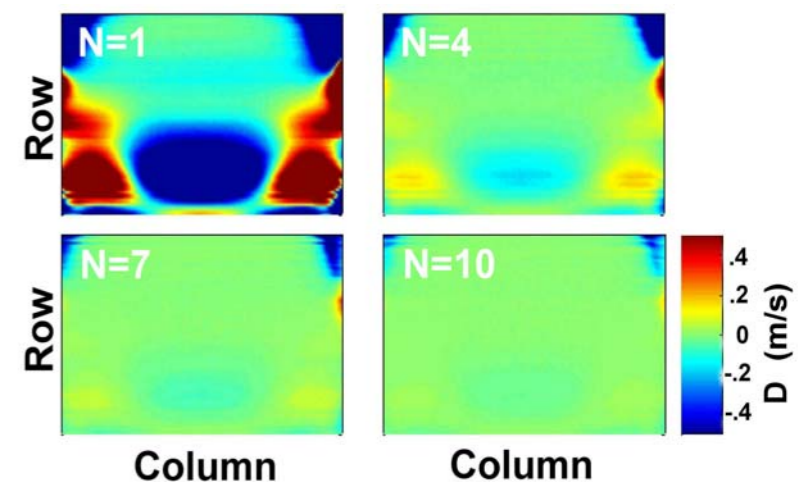

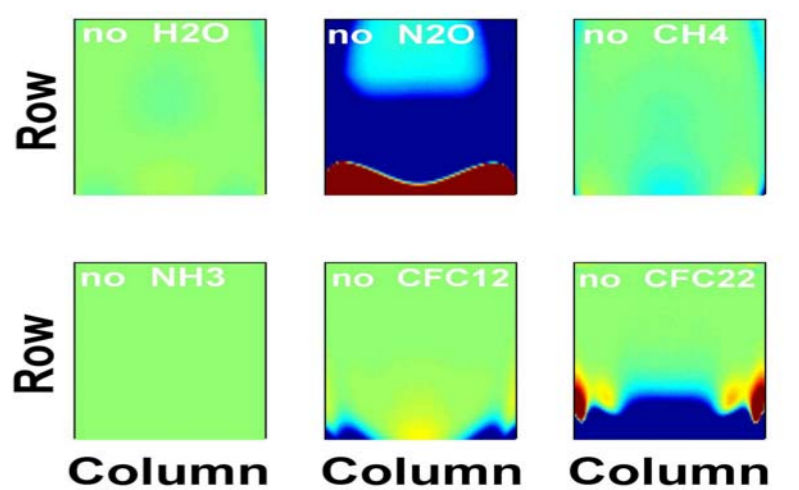Fig 7: Impact of the number of sublayers on the derived winds

Fig 8: Impact on wind upon removing an absorbers from the current list. (scales are the same as in figure 6 & 7)

Disscussion

A preliminary forward model for SWIFT has been chosen. To date it has been optimized to execute as on a LINUX within Intel architecture. One complete interferogram (.002 (cm-1)) takes about 40CPUsec. It remains to be seen if the FLBL is suitable on ASTD's IBM cluster of p690s.

The preliminary wind impact studies indicate that discarding the outer 20 columns of the interferogram then a lower resolution and fewer sub layers can be used, resulting in a speed up of 3 or 4 times. One or more absorbers may be potentially omitted, however more testing is required assuming other atmospheres before any decision on omitting gases is made.

The testing and optimizing the FLBL is incomplete. In addition, the gradient portion remains to be completed, tested and integrated into a data assimilation system in order test the feasibility for assimilating SWIFT into an NWP. If the FLBL is too slow on the IBM cluster, then efforts will turn to a more parameterized model.

The final instrument architecture is not finalized, as it still has to be optimized. Thus, the algorithm may have to be refined in order to reduce the wind errors to better than 3 m/s for 20 to 45 km and to better than 5 m/s for the extended range of 15 to 55 km through the entire life of the mission

Acknowledgements

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SWIFT web page

http://swift.yorku.ca

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