

On-orbit performance of the ACE-FTS Instrument

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ABSTRACT

The Atmospheric Chemistry Experiment (ACE) is the mission selected by the Canadian Space Agency (CSA) for its science satellite, SCISAT-1. ACE consists of a suite of instruments in which the primary element is an infrared Fourier Transform Spectrometer (FTS) coupled with an auxiliary 2-channel visible (525 nm) and near infrared imager (1020 nm). A secondary instrument, MAESTRO, provides spectrographic data from the near ultra-violet to the near infrared, including the visible spectral range. In combination the instrument payload covers the spectral range from 0.25 to 13.3 micron. A comprehensive set of simultaneous measurements of trace gases, thin clouds, aerosols and temperature are made by solar occultation from a satellite in low earth orbit. The ACE mission measures and analyses the chemical and dynamical processes that control the distribution of ozone in the upper troposphere and stratosphere. A high inclination (74 degrees), low earth orbit (650 km) allows coverage of tropical, mid-latitude and polar regions. The ACE/SciSat-1 spacecraft was launched by NASA on August 12th, 2003.

This paper presents the on-orbit performance of the ACE-FTS instrument. The commissioning activities allowed the activation of the various elements of the instrument and the optimization of several parameters such as gains, integration times, pointing offsets, etc. The performance validation was the last phase of the instrument hardware commissioning activities. The results of the performance validation are presented in terms of on-orbit instrument performance with respect to instrument requirements such as signal-to-noise ratio, transmittance accuracy, and spectral resolution. Results are also compared to ground validation tests performed during the thermal-vacuum campaigns. Performance is presented in terms of validation of instrument from an engineering perspective.

Keywords: ACE, FTS, SCISAT-1, Spectrometer, On-orbit, Performance

1. INTRODUCTION

The Atmospheric Chemistry Experiment (ACE) main scientific objective is to measure and understand the chemical and dynamical processes that control the distribution of ozone in the upper troposphere and stratosphere. The Canadian Space Agency selected this space science mission for the SciSat-1 scientific satellite. The mission scientist is Dr. Peter Bernath from the Department of Chemistry at the University of Waterloo. He heads a Science Team that includes Canadian scientists as well as scientists from the United States, Japan, France, Sweden and Belgium. ABB Bomem Inc. is the industrial prime contractor for the development of the ACE main instrument. Bristol Aerospace built the spacecraft bus.

The ACE-FTS instrument is the primary instrument mounted on the SciSat-1 spacecraft. The ACE-FTS instrument is composed of a Fourier Transform Spectrometer (FTS) and two imager detectors. The SciSat-1 spacecraft was launched by NASA on August 12th, 2003. The Launch and Early Operation Phase (LEOP) activities were conducted by the Canadian Space Agency's Mission Operation Center (MOC) located at St-Hubert in Canada. ABB Bomem Inc. provided commissioning planning and technical support for the on-orbit functional and performance validation of the ACE-FTS instrument. Performance evaluations were performed throughout the commissioning activities with most of the data recorded in December 2003 [3].

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2. ACE-FTS INSTRUMENT DESCRIPTION

2.1. Key Sensor Requirements

The science team, led by Prof. Peter Bernath, derived a set of key requirements for the sensor based on the accuracy of the retrieval needed for each of the trace gases. The Instrument Requirements Document (IRD) provided by the Canadian Space Agency covers the performance, the functionality and the reliability of the sensor. Some of the key performance requirements are described in this section.

To minimize the uncertainty in the concentration profiles retrieved from the spectra, a high level of signal-to-noise ratio (SNR) is required. The FTS instrument was therefore required to achieve a SNR of at least 100 over its entire spectral range when pointing towards a blackbody source at a temperature of 5800 K. This specification applies to the highest spectral resolution and for a 2-second measurement. This sensitivity requirement has driven the selection of the infrared detectors as well as most of the design specifications of the FTS.

During sunrises and sunsets, the instrument measures the visible and infrared signals that contain information on different atmospheric layers, which provide the vertical profiles of atmospheric components. Each sunrise and sunset event is called an occultation event. During an occultation event, the instrument makes a set of spectral measurements corresponding to science and to calibration data. While achieving a very good SNR, the FTS is also required to have a stable response transfer function during the time of the occultation. The nominal occultation event, including measurements of exo-atmospheric (solar references) and deep space measurements (radiometric offset), lasts 3 minutes. To meet the science objectives, the maximum deviation in the evaluation of the atmospheric transmittance has to be smaller 1 % (1σ). This challenging requirement has driven the specification on the temperature stability of the infrared detectors during the occultation. Note that for sunrise events, the instrument goes through a thermal transient which makes its temperature increase during the occultation. Thorough investigation using Finite Element Models and state-of-the-art design techniques were required to meet the performance requirements of the ACE-FTS instrument.

In order to resolve the spectral lines of the Earth atmosphere and increase the probability of detecting low concentration trace gases, a spectral sampling interval of 0.02 cm^{-1} is required. This spectral sampling interval corresponds to an unapodized resolution of about 0.024 cm^{-1} . Adding the effect of the interferometer self-apodization results into a full-width at half the maximum (FWHM) of about 0.028 cm^{-1} at the highest wavenumber.

Apart from the key requirements derived for the FTS, the monitoring of aerosols during the occultation requires a high sensitivity on the auxiliary 2-channel visible and near infrared imager. A SNR as high as 2000, for a 2-second measurement, is required on each channel of the imager.

Finally, to obtain an accurate tangent altitude value and a precise location of the monitored atmospheric layer with respect to Earth coordinates, a very good pointing accuracy of 0.5 milliradian is required. The instrument pointing is also required to be stable up to 0.015 milliradian during the 2-second measurement.

2.2. Sensor Design Overview

The ACE-FTS instrument is an infrared Fourier Transform Spectrometer (FTS) coupled with an auxiliary 2-channel visible and near infrared imager. The FTS, operating from 2.4 to 13.3 microns, measures at high resolution (0.02 cm^{-1}) the infrared absorption at different altitudes. The atmospheric absorption provides information on vertical profiles of atmospheric constituents, temperature, and pressure. The imager monitors aerosols based on the extinction of solar radiation using two filtered detectors at 1.02 and 0.525 microns.

The spectrometer is an adapted version of the classical Michelson interferometer using an optimized optical layout and moving cubes corner. The instrument has a field-of-view (FOV) of 1.25 mrad and an aperture diameter of 100 mm. The instrument includes a suntracker, which provides fine pointing toward the radiometric center of the Sun.

The instrument optical layout is based on a highly folded design and results in a very compact high performance instrument. The instrument optical layout is presented in Figure 1. The first optical component is the suntracker module that tracks the radiometric center of the Sun. The infrared and visible signals are then directed to the 5X magnification telescope primary mirror. A small bandpass filter, mounted on the primary telescope mirror, transmits the $1.52 \text{ }\mu\text{m}$ to $1.59 \text{ }\mu\text{m}$ spectral range to the quad cell (used as the feedback source for the suntracker module) and reflects the remaining spectrum to the VIS/NIR imager.

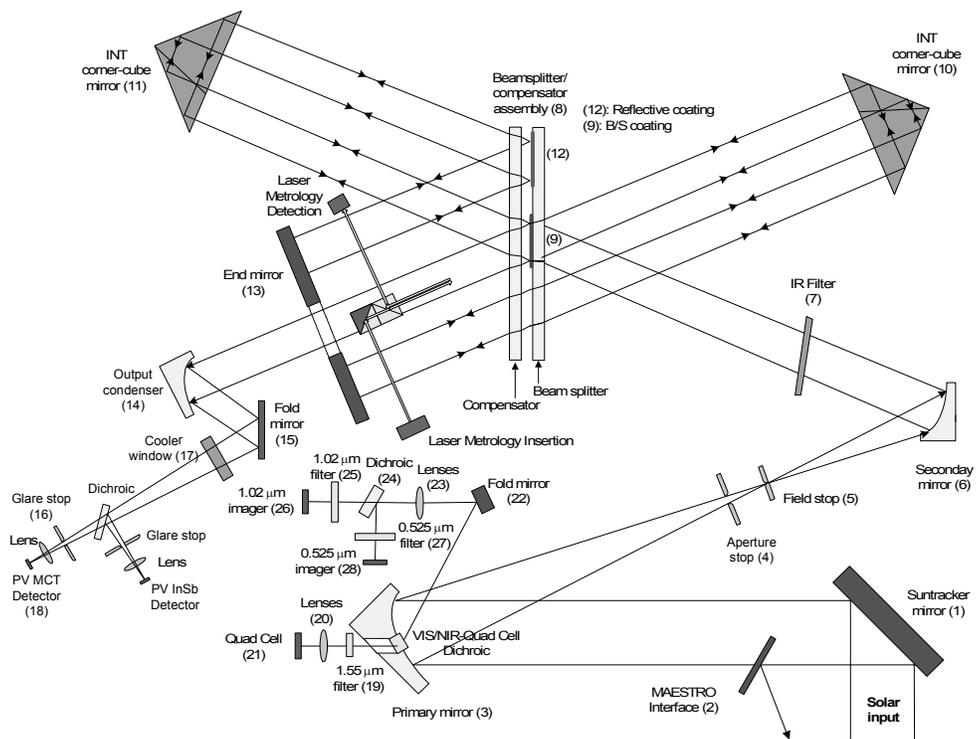


Figure 1: ACE-FTS instrument optical layout

The primary mirror then reflects the signals through the aperture and field stops to the collimator mirror. Then, the collimated beam is directed towards the interferometer. A filter is installed between the input optics and the interferometer to minimize the thermal load on the interferometer. The output of the interferometer is then condensed to the InSb/MCT detector assembly using another off-axis parabola. The exploded view of the instrument is shown in Figure 2. More information regarding the instrument design can be found in [1] and [2].

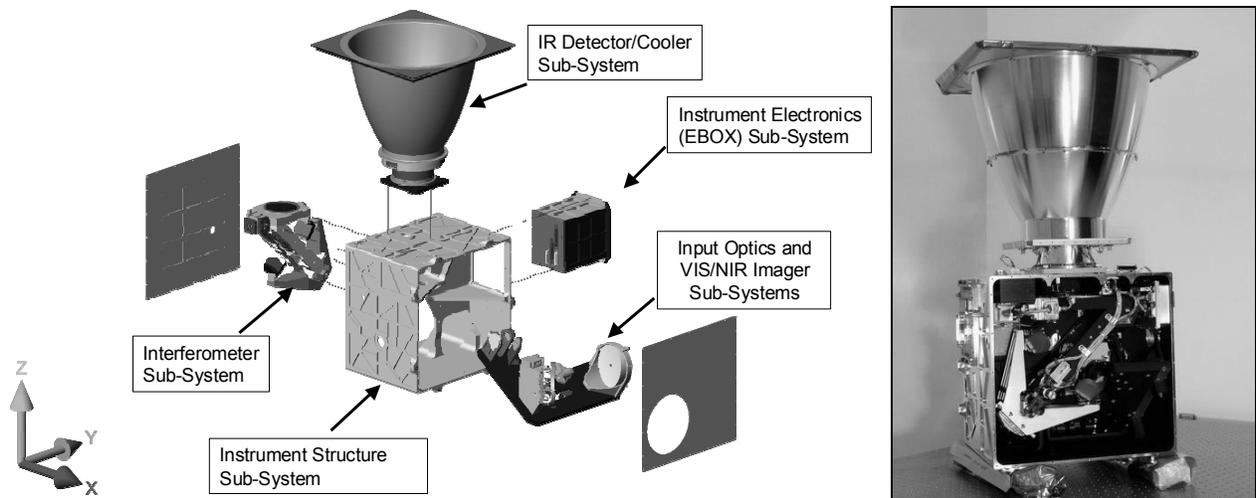


Figure 2: ACE-FTS architecture (left) and picture of the Flight Model (right)

3. ON-ORBIT PERFORMANCE

3.1. FTS SNR Performance

The SNR is a measure of the sensitivity. SNR performance was modeled to optimize the instrument design. This model includes the shot noise from the scene and the background, the detector and electronics noise, the quantification noise, noise from the sampling jitters, and noise due to drive non-linearity as well as other parameters. In order to feed the performance model, many key parameters of the ACE-FTS instrument were characterized or estimated. The throughput, the transmittance of every optical component, the modulation efficiency, the detectivity of the infrared detectors, the metrology signal-to-noise ratio, and the speed stability of the scanning mechanism are examples of these parameters.

Some of the parameters were characterized at the sub-system or even at the component level. The signal-to-noise ratio of the metrology signal is higher than 65 dB where the requirement has been set to 51 dB. The speed stability has been measured in the laboratory environment and is better than 99.95% while the requirement is 99 %. Manufacturers have measured the transmittances of optical components. All these parameters were used in the model to assess the performance of the instrument.

The SNR was first verified during ground verification in thermal vacuum chamber. The SNR is specified for a radiance of a blackbody at 5800 K as the input. However, such a hot blackbody is not available. A characterization of the SNR with a colder source has therefore been performed to validate the model. The left panel of Figure 3 presents the wavenumber dependence of the SNR when the scene is a blackbody radiator at 2929 °C seen through an atmospheric absorption path of about 4 meters.

Once validated the model is then run for a theoretical source set at 5800K. The right panel of Figure 3 shows the estimated SNR with a 5800 K blackbody radiator. The design complies with the sensitivity requirement on the whole wavenumber range except for a small spectral region at the lower end of the long-wave band and at the upper end of the short waveband.

In the long-wave band, a considerable effort has been made to bring the detector and electronics noise at the same level of the shot noise level. Note that this SNR evaluation takes into account a 10 % transmittance degradation due to contamination accumulated during integration and test of the FTS as well as a further 5 % transmittance degradation due to on-orbit contamination for a 2-year mission which corresponds to an end-of-life evaluation.

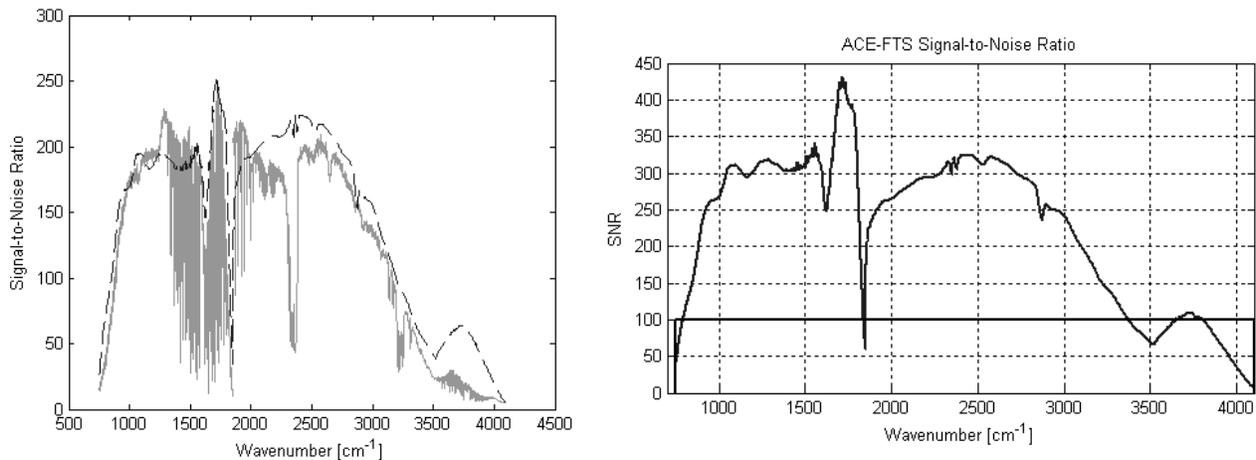


Figure 3: Ground level measured SNR for a 2929 °C blackbody (left) and extrapolated SNR for scene at 5800 K (right)

The dip in SNR around 1850 cm^{-1} is due to the cut-off in the response of the InSb detector where the MCT one takes over at long wavelengths. By an appropriate combination of signals, weighted according to their respective SNR, the discontinuity is smoothed out with a SNR higher than 100 at 1850 cm^{-1} . However, the actual SNR remains lower than optimum due to detector dichroic wavenumber cutoff being too low.

The on-orbit instrument sensitivity is excellent and is more than three times the specification for the main part of the spectral coverage. The actual on-orbit SNR for an exo-atmospheric measurement taken on December 2, 2003 is presented in Figure 4. Note that the noise equivalent spectral transmittance decreases during the occultation on the short wave channel. This suggests that the short wave channel is scene shot noise limited.

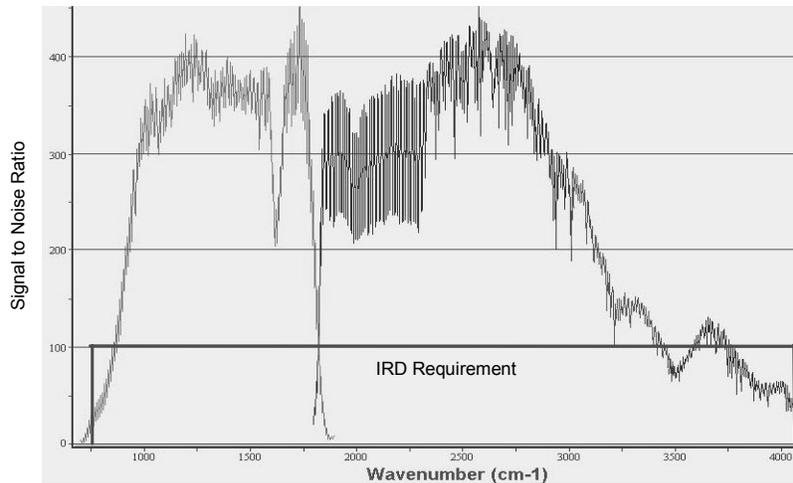


Figure 4: On-orbit FTS SNR

3.2. FTS Transmittance Accuracy

In solar occultation measurements, the transmittance of the atmosphere is usually evaluated as the ratio of the occultation measurement by the exo-atmospheric measurement. In a Fourier transform spectrometer, the outcome of a measurement is

$$S^M = G(L^M \star ILS + O) \quad (1)$$

where G is the instrument gain, L^M is the true radiance from the scene, ILS is the instrument line shape, and O is the instrument offset. Assuming the offset is negligible, the gain is the same for the exo-atmospheric and the solar occultation measurements, and the radiance of the Sun is constant over the range of the instrument line shape function, the atmospheric transmittance may be given by

$$\frac{S^{Atm}}{S^{Sun}} = \frac{G((L^{Sun} T^{Atm}) \star ILS + O)}{G(L^{Sun} \star ILS + O)} \cong T^{Atm} \star ILS \quad (2)$$

However, the offset is different from zero, the gain is not constant, and the measurements are noisy. All deviations from the assumptions mentioned above are considered in a transmittance accuracy budget.

The transmittance accuracy budget tree was modeled and the contributors are plotted in Figure 5. The targeted design margin was 20 % of the entire allowed budget, i.e. 0.2 % of uncertainty.

The transmittance accuracy is very good with little non-linearity effects, very good metrology stability, and good cancellation of channel spectrum. Transmittance is computed by dividing a single raw spectrum, taken from an exo-atmospheric measurement sequence (covering 3 minutes), by the average raw spectrum (computed over the same sequence). The standard deviation is then computed over the transmittance sequence.

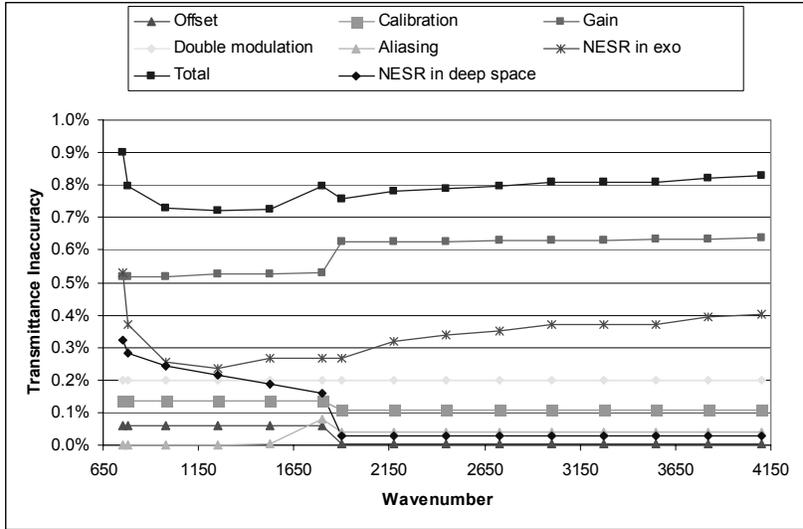


Figure 5: Uncertainty in the evaluation of atmospheric transmittance

A moving average of 100 data point is then applied to reduce the noise. The transmittance accuracy is presented in Figure 6. The result includes some residual noise and spectral drift contributions from the Doppler effects. The transmittance inaccuracy is less than 1% for the specified spectral range and is lower than 0.25% on average.

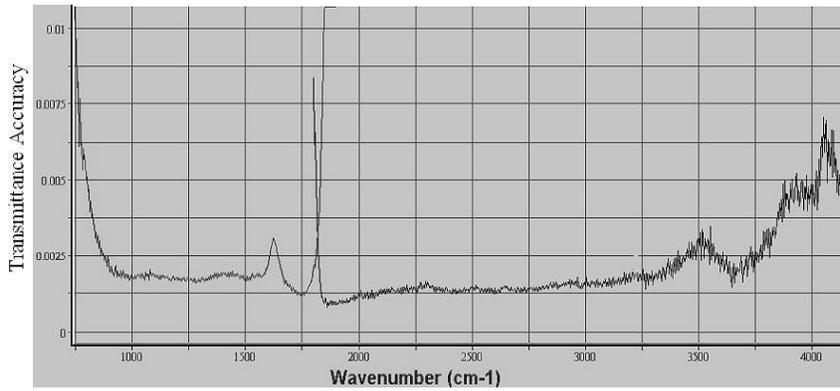


Figure 6: On-orbit FTS transmittance accuracy

3.3. FTS Spectral Resolution

In order to meet all science objectives, the instrument line width of the ACE-FTS has to be smaller than 0.028 cm^{-1} at 4100 cm^{-1} . However, there are different contributors affecting the spectral lines of a spectrum which are due to effects inherent to the instrument. Starting from an elementary line contribution, e.g., emission from a single gas molecule, interactions between the molecules, expressed as temperature and pressure, produce a line broadening ($C0$ in Figure 7). This physical effect cannot be removed and reflects some of the gas properties to be retrieved. The first instrument contribution illustrated here ($C1$) is due to self-apodization [4]. As the emitted energy enters the interferometer, different angles for the different positions in the fields of view produce different apparent spectral frequencies. A monochromatic signal thus produces a continuum of frequencies. The shape of this continuum is a function of the field-of-view (FOV) geometry, the FOV position with respect to the optical axis, and the spectral frequency of the signal. The corresponding line shape is indicated by *Beam Divergence* in Figure 7. The second effect ($C2$) is due to perturbations like shear and tilt on the interfering beam, which may fluctuate, causing distortions on the measured lines. The corresponding line shape is indicated by *Modulation Degradation* in Figure 7. The third contribution ($C3$) is due to acquisition of interferograms,

which are of finite length. This third effect introduces the Sinc “dressing”. The corresponding line shape is indicated by *Sampling Window* in Figure 7.

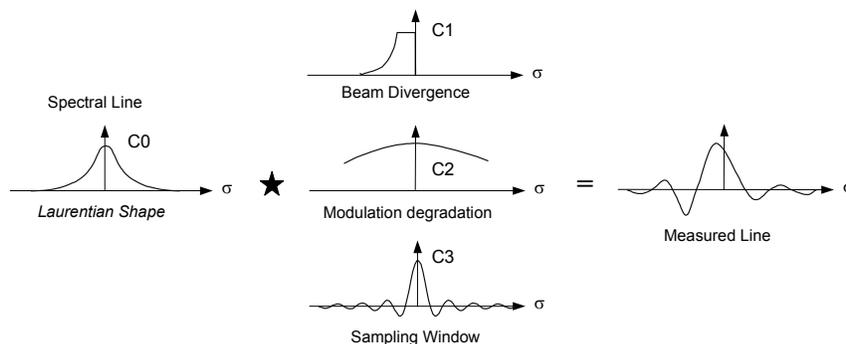


Figure 7: Instrument function contributors.

The mathematical operation for applying the contributions *C2* and *C3* to the gas line is expressed either by multiplication when considering the interferogram domain or by convolution when considering the spectral domain. However, the first contribution *C1*, i.e. self-apodization, cannot be treated as a simple convolution in either domain since this effect is non-local in both domains.

As mentioned above, only contributions *C1*, *C2* and *C3* can be controlled during the instrument design. The contribution *C0* is an intrinsic property of the scene. For the ACE-FTS, the maximum optical path difference was fixed at 25 cm defining a sampling window of 50 cm and therefore limiting the full width at half maximum (FWHM) of the instrument line shape (ILS) to 0.0242 cm^{-1} . The field of view of the ACE-FTS is 1.25 mrad and with a telescope magnification factor of 5, the maximum angle of a ray inside the interferometer for a perfectly aligned instrument is 6.25 mrad. The effects of sampling window and field of view contribution would give a line width of 0.0259 cm^{-1} at the smallest wavelength, i.e. at 4100 cm^{-1} .

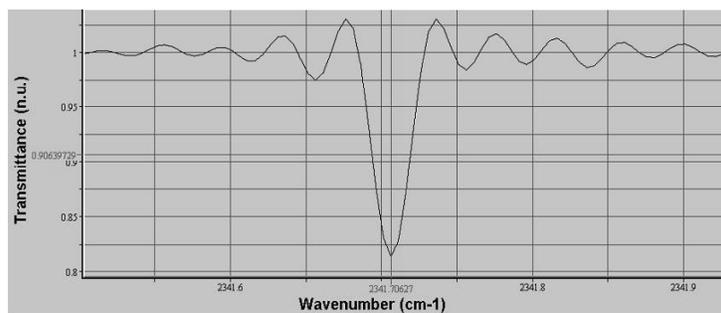


Figure 8: On-orbit FTS instrument line shape

The Figure 8 shows a high altitude CO lines taken from a southern hemisphere sunset recorded on 17 January 2004. The Table 1 gives the ILS FWHM estimated from various high altitude atmospheric absorption lines covering the spectral range. The spectral resolution specification (0.028 cm^{-1}) is met over the entire spectral range.

Table 1: On-Orbit FTS Spectral Resolution

Spectral Resolution (cm^{-1})	Spectral Frequency (cm^{-1})
0.0252	1032
0.0245	1576
0.0261	2364
0.0273	3722

3.4. Imager Sensitivity

The SNR requirement for the imager is specified as 0.05% of the radiance emitted by a blackbody radiator at 5800 K for a 2-second measurement duration. This corresponds to a SNR of 2000. The Visible/Near-infrared Imager signals are digitized with 10-bit analog-to-digital converters. This coarse digitalization does not seem to be adequate to obtain a SNR of 2000. However, the design approach was to acquire multiple frames during the 2-second measurement and to average them to increase the dynamic range. As a matter of fact, the integration time on each pixel is a few tens of milliseconds per frame and the shot noise on each frame is at least 3 times larger than the digitalization resolution. Therefore, the averaging of the frames effectively improves the SNR to provide a dynamic range equivalent to a 13-bit digitalization.

The imager sensitivity was evaluated using 65 frames of a Sun measurement sequence and 144 frames of a deep space measurement sequence. First, the average and standard deviation of the Sun measurement sequence were computed. Then, the deep space average was computed and subtracted from the Sun average. Finally, the average and standard deviation were scaled for a 2-second observation time and the SNR computed. The SNR is evaluated to be 8000 for the VIS imager and 7500 for the NIR imager.

The Figure 9 shows the two imagers (VIS imager on the top and the NIR imager on the bottom). The circle appearing is attributed to quantification noise being more predominant than the source noise. The pattern of the quantification noise also indicates some non-uniformity on the quantification levels. Increasing the integration time and acquiring fewer frames for each image can remove these circles because this increases the source noise with respect to the quantification noise.

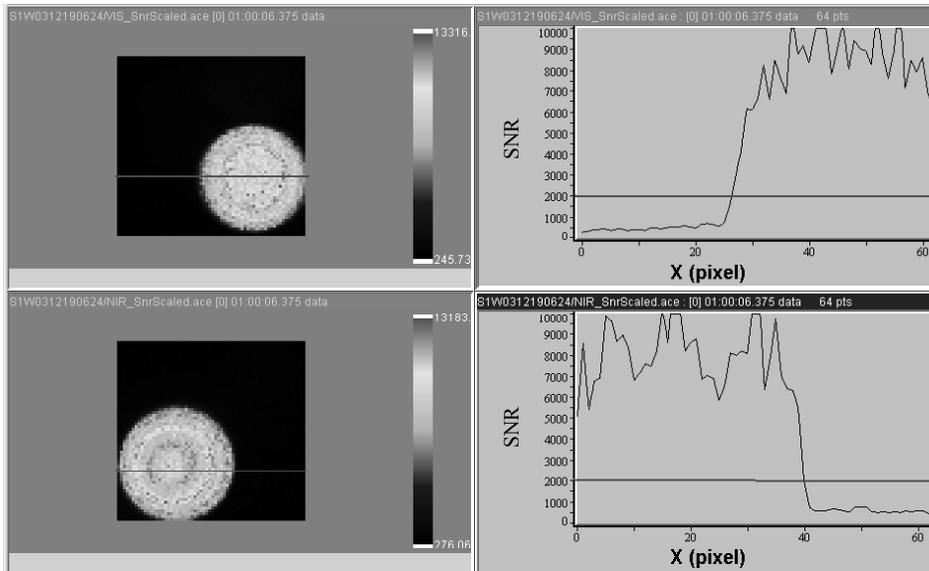


Figure 9: On-orbit Visible/Near-infrared Imager sensitivity

3.5. Imager Ghosts

Ghosts were observed from on-orbit data and are consistent with ghost observed during ground testing. Ghosts are produced from internal reflections between the neutral density filter, dichroics, bandpass filters, and the imager sensor surfaces. Two types of ghost were observed, the first type of ghosts moves opposite of the primary image and have been identified to be caused by the neutral density filter reflections, the second type of ghosts moves with the primary image and are typically caused by wedged optics.

Ghosts are presented in Figure 10. The worst case is for the second type of ghosts for the VIS imager for which the ghost have been evaluated to 4%. Ground processing is being developed to minimize the effect of ghosts.

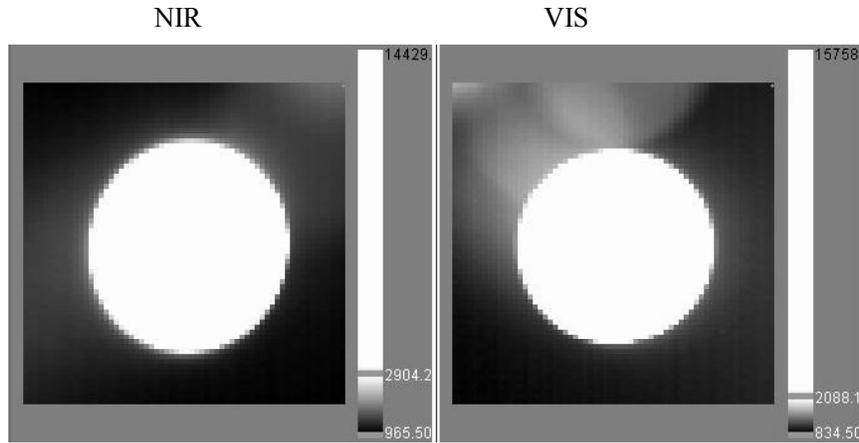


Figure 10: On-orbit VNI ghosts (magnified contrast)

3.6. Nominal Operation

The ACE-FTS Instrument has started its scientific operational phase on February 27, 2004. The ACE raw data volume is about 1 GByte per day. The data is sent to ground using at least 2 ground stations. This data is transferred from the MOC to the Science Operation Center (SOC) at the University of Waterloo. At the SOC the data is archived and transformed into data products for distribution to the science team members. In the case of the FTS, the raw interferograms (level 0) need to be transformed into corrected atmospheric spectra (level 1) by software supplied by the instrument contractor, ABB Bomem inc. A typical occultation sequence is shown in Figure 11.

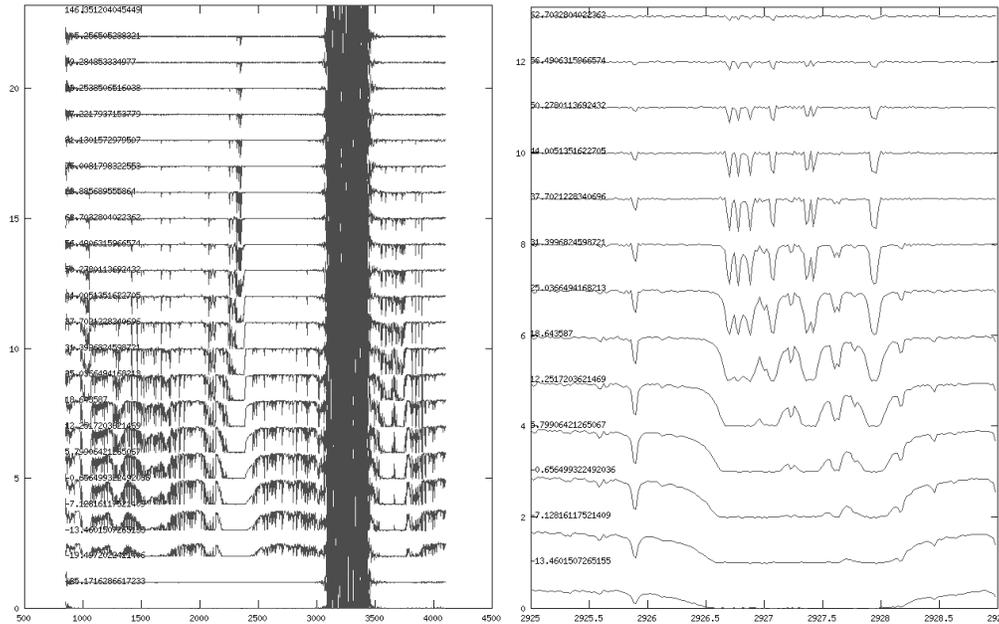


Figure 11: Typical occultation sequence over the entire spectral range (left panel) and showing HCl R(0) and CH₄ P(9) lines (right panel)

Due to limited download throughput the early operation mainly consisted of sunset occultations with additional characterization and special events led by the Science Operation Center (SOC). The sunset occultation was selected because they were located on the northern hemisphere and was of particular interest for monitoring the arctic vortex event. Also, the PARIS instrument was also measuring the arctic vortex from a ground site located at Eureka in the Arctic.

3.7. Suntracker Pointing Stability

During the commissioning phase, the pointing stability of the ACE-FTS instrument has been estimated by monitoring the short term variations of the drive signals sent to the suntracker mirror. The pointing jitters were then estimated to 0.0066 milliradian in elevation and 0.0036 milliradian in azimuth for a total value of 0.0075 milliradian. These jitters are two times smaller than what has been required by the science team.

To meet the accuracy requirement, a mapping of the shape of the Sun has been performed during the commissioning and with the help of the VNI, the FTS line-of-sight was repositioned on the radiometric center of the Sun by applying an offset on the suntracker mirror.

4. SUMMARY

The ACE-FTS instrument functionality is fully nominal. The performance is consistent with ground level testing and no post-launch degradation of performance were observed. The FTS signal-to-noise ratio is more than three times the requirement over a large portion of the spectral range. The instrument is very stable and the channeling observed on raw spectra cancels out with the computation of the transmittance. The spectral resolution is consistent with theoretical models and with ground measurements taken during the verification campaign. Alignment has therefore been preserved after launch. The ACE-FTS line-of-sight is pointing towards the Sun with the required accuracy. The pointing jitters of the instrument are two times smaller than what is required. Also, the imager has a signal-to-noise ratio 4 times above the requirement. The ghosts observed on the raw images are removed with ground processing.

Finally, the ACE-FTS instrument commissioning has been conducted successfully. The instrument started its scientific operational phase on February 27th, 2004 and the mission promises to deliver high quality results of high scientific value.

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