

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

ACE-FTS instrument: after two years on-orbit

Francois Chateauneuf, Marc-Andre Soucy, Serge Fortin

Francois Chateauneuf, Marc-Andre Soucy, Serge Fortin, "ACE-FTS instrument: after two years on-orbit," Proc. SPIE 5883, Infrared Spaceborne Remote Sensing 2005, 58830F (29 August 2005); doi: 10.1117/12.617938

SPIE.

Event: Optics and Photonics 2005, 2005, San Diego, California, United States

ACE-FTS instrument: after two years on-orbit

François Châteauneuf, Marc-André Soucy*, and Serge Fortin
ABB, Remote Sensing Group
585 Charest Blvd. East, Suite 300, Québec, QC, Canada, G1K 9H4

ABSTRACT

The Atmospheric Chemistry Experiment (ACE) is the mission on-board Canadian Space Agency's 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 being made by solar occultation from this 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°), 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 status of the ACE-FTS instrument after two years on-orbit. On-orbit performances are also covered. The health and safety status of the instrument payload is discussed. Optimization of on-orbit performance is presented as well as operational aspects.

Keywords: ACE, FTS, SCISAT-1, Spectrometer, Fourier, 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 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. Performance evaluations were performed throughout the commissioning activities with most of the data recorded in December 2003 [4]. Science measurements started in February 2004 and atmospheric retrievals are conducted by the University of Waterloo [3].

2. ACE-FTS INSTRUMENT 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.

* Author to whom correspondence may be addressed: E-mail: marc-andre.a.soucy@ca.abb.com; phone 418 877-2944; fax 418 877-2834

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 a 5X magnification telescope primary mirror. A small bandpass filter, mounted on the primary telescope mirror, transmits the 1.52 μm to 1.59 μm spectral range to a quad cell (used as the feedback source for the suntracker module) and reflects the remaining spectrum to the VIS/NIR imager.

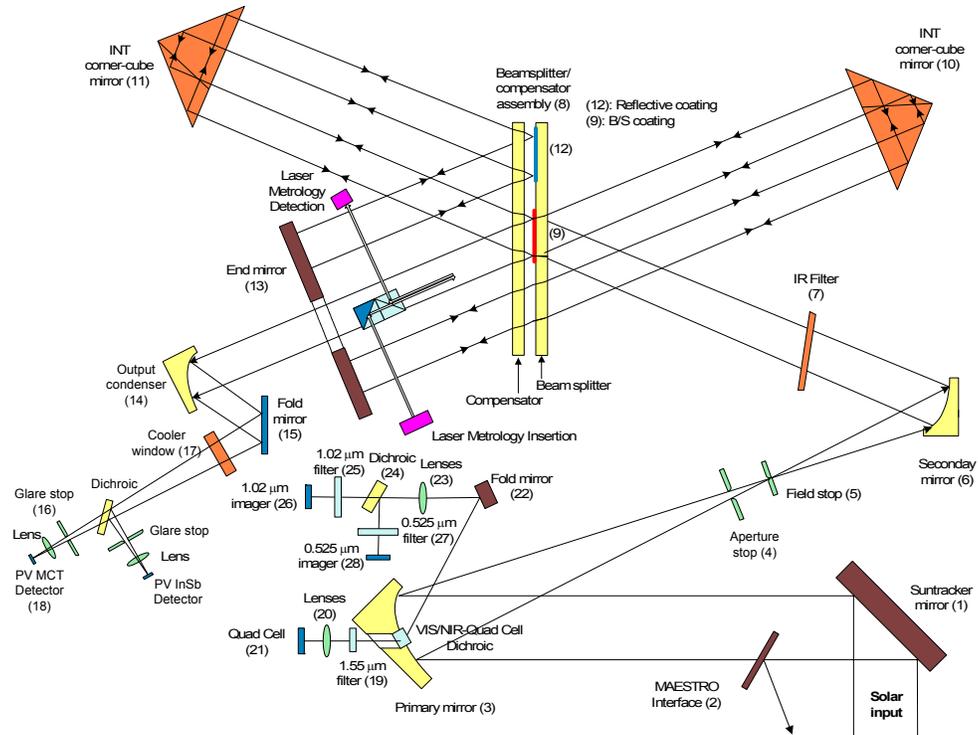


Figure 1: ACE-FTS instrument optical layout

The primary mirror then reflects the signals through the aperture and field stops to the secondary collimation 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].

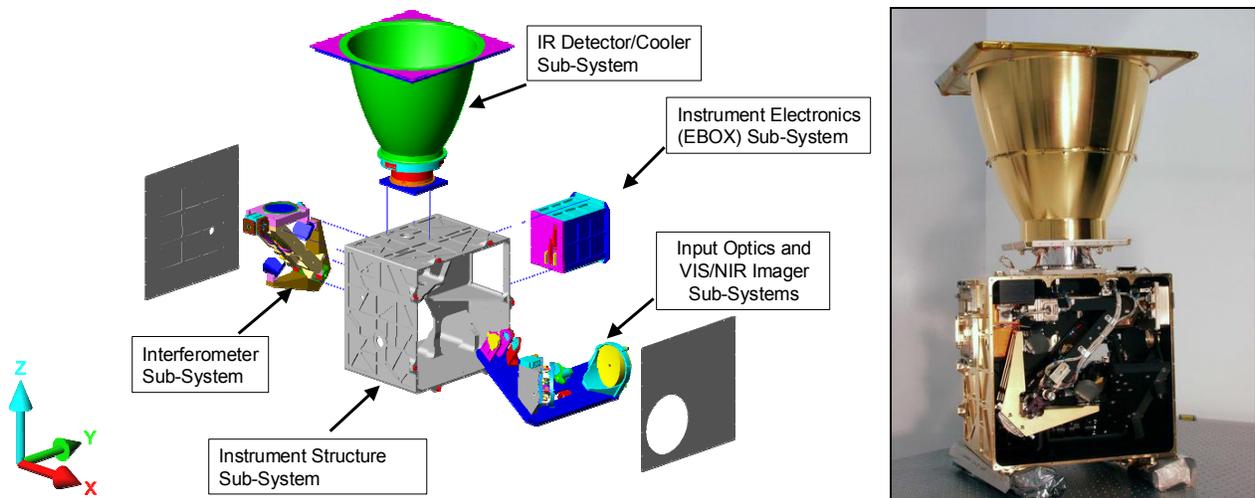


Figure 2: ACE-FTS architecture (left) and picture of the Flight Model (right)

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.

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. 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. The on-orbit instrument sensitivity shown in the left panel of Figure 3 is excellent and is more than three times the specification for the main part of the spectral coverage. The on-orbit SNR has been evaluated from an exo-atmospheric measurement taken on December 2, 2003.

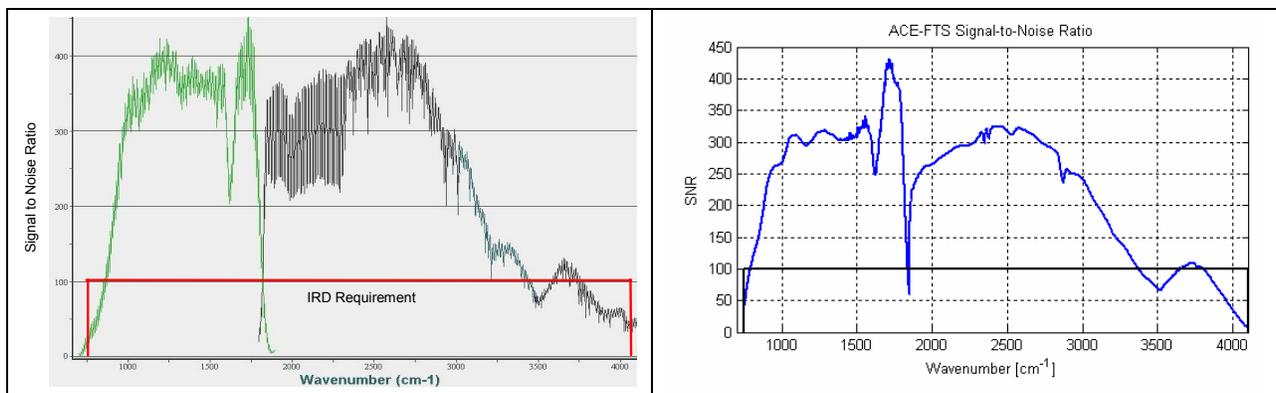


Figure 3: On-orbit SNR (left) and modeled SNR for scene at 5800 K (right)

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} .

On-orbit contamination impacts the signal-to-noise performance of the instrument. As can be seen from Figure 4, contamination is mainly due to water condensing and freezing on the cold window separating the warm side of the instrument from the cold detector side. A complete decontamination sequence has been performed in April 2005 where the temperature of the entire instrument was raised to evacuate water in the vicinity of the cold optics.

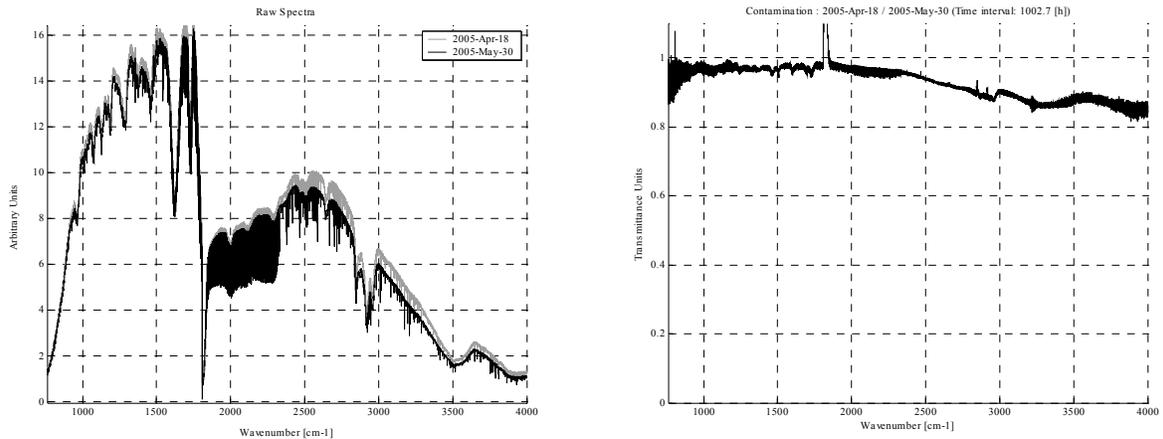


Figure 4: Raw spectra before and after decontamination sequence (left) and ratio of before and after spectra (right)

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. 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.

A moving average of 100 data point is then applied to reduce the noise. The transmittance accuracy is presented in Figure 5. 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.

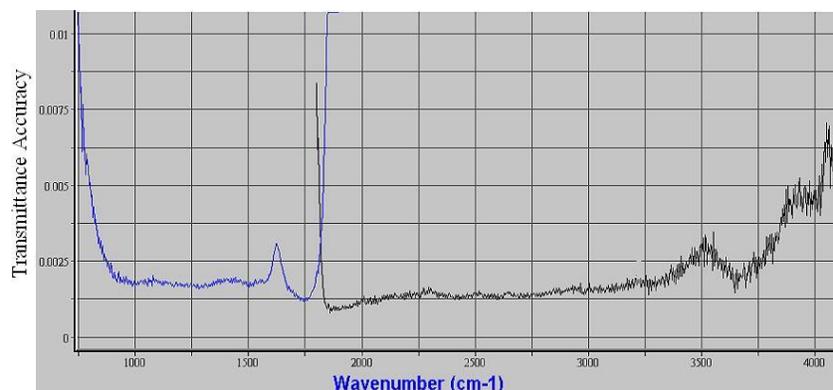


Figure 5: On-orbit FTS transmittance accuracy

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. 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} .

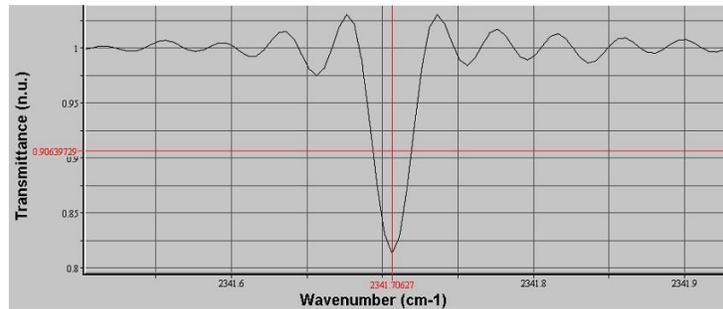


Figure 6: On-orbit FTS instrument line shape

Figure 6 shows a high altitude CO lines taken from a southern hemisphere sunset recorded on 17 January 2004. Complete retrieval and characterization of the instrument line shape can be found in Ref [3]. 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 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 7 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.

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.

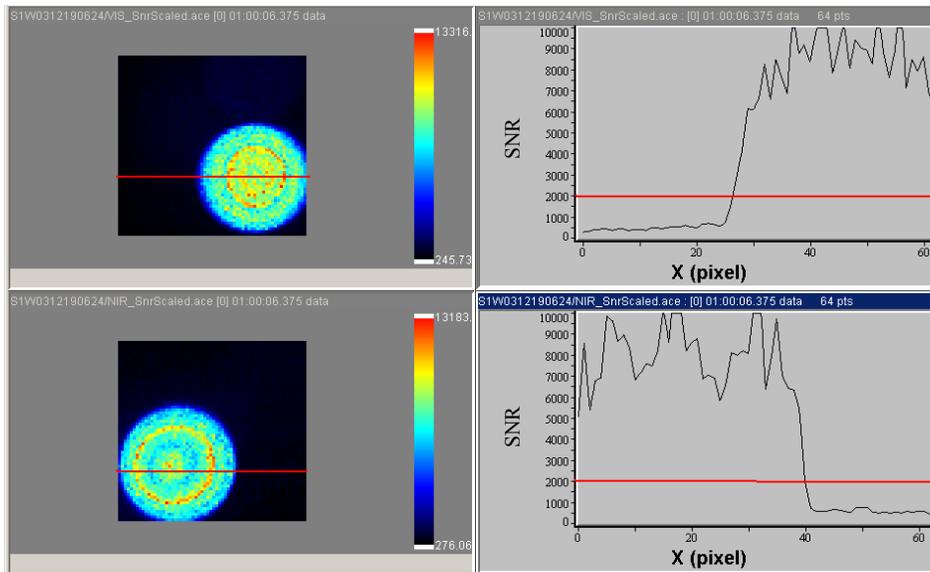


Figure 7: On-orbit Visible/Near-infrared Imager sensitivity

Ghosts are presented in Figure 8. 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.

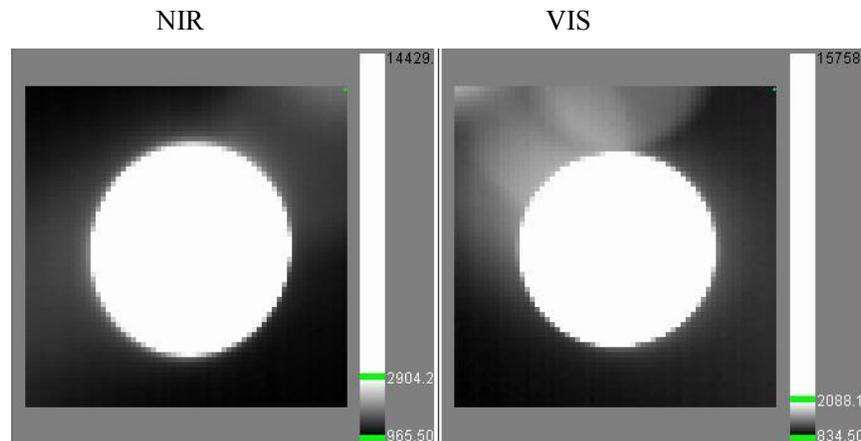


Figure 8: On-orbit VNI ghosts (magnified contrast)

3.5. 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. A typical occultation sequence is shown in Figure 9.

Since the beginning of the science phase of the mission, about 800 Gb of data has been collected and stored which corresponds to more than 5,330 occultations. More than 200,000 transmittance spectra of the atmosphere have been computed. About 370,000 high sun exo-atmospheric spectra have been recorded and could be used for solar research and 50 Nadir scans have also been recorded.

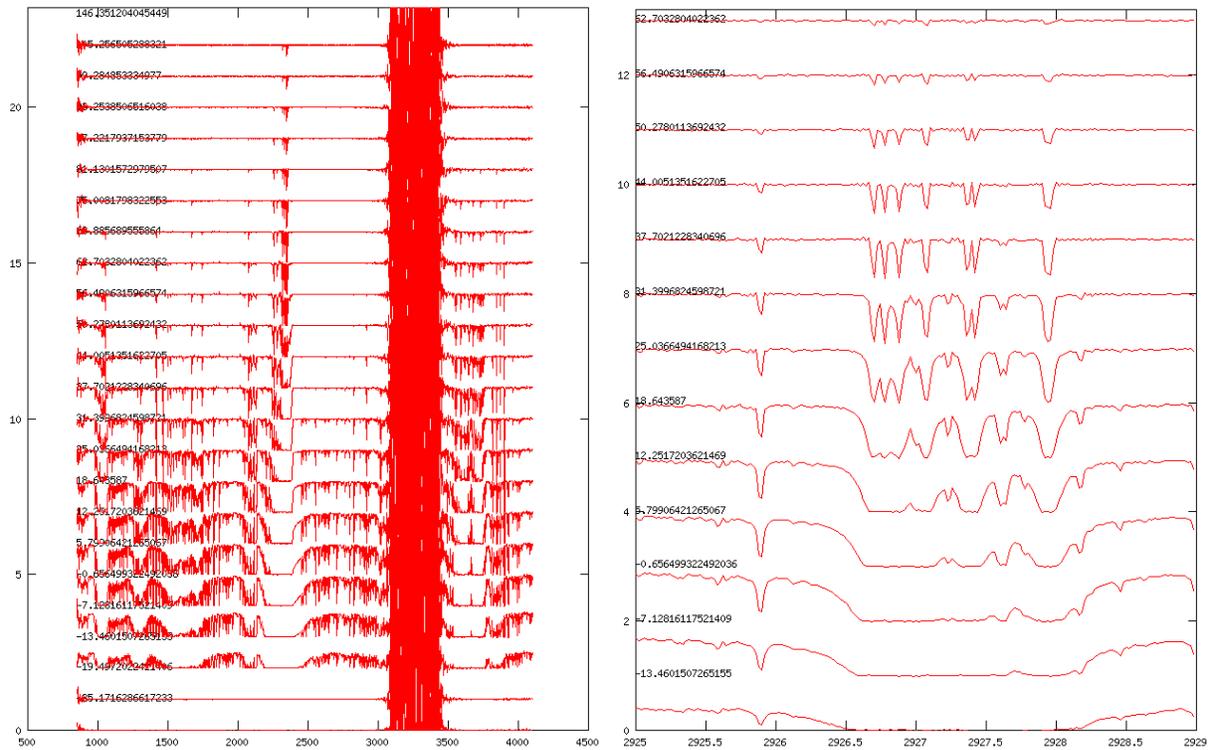


Figure 9: Typical occultation sequence over the entire spectral range (left panel) and showing HCl R(0) and CH₄ P(9) lines (right panel)

As described in [5], the molecules retrieved on a routine basis for version 1.0 of the ACE retrieval software were the following: H₂O, O₃, N₂O, CO, CH₄, NO, NO₂, HNO₃, HF, HCl, N₂O₅, ClONO₂, CFC-11, CFC-12, COF₂, HCFC-22, HDO, and SF₆. Version 2.0 and high added the following molecules to routine processing: HCN, CH₃Cl, CF₄, C₂H₂, C₂H₆, and N₂ (for diagnostic purposes). For version 2.1 processing during the perturbed polar spring season, ClO retrievals were added. Future planned additions to ACE-FTS processing include the following: HO₂NO₂, H₂O₂, HOCl, H₂CO, HCOOH, CFC-113, and HCFC142b.

4. POTENTIAL FUTURE USE FOR ACE-FTS

Currently, the temperature sounding for weather forecasting is done primarily by Nadir looking thermal infrared sounder. Infrared sounders on future polar-orbiting weather satellites (IASI and CrIS) are based on the FTS technology and the use precisely calibrated blackbody sources as the radiometric reference. However, the calibration blackbodies of these thermal infrared sounders are considered not stable enough so that the retrievals from these sensors can be used for global climate and temperature trends.

Because it operates in solar occultation, the ACE-FTS provides a more reproducible evaluation of the temperature profile. In fact, since the radiance of the Sun is used as the radiometric reference for the ACE-FTS, the temperature sounding is much less sensitive to manufacturing variability from one unit to the other or to the ageing of the hardware. This is a key advantage for global climatology where trends over decades must be accurately measured.

Of course, the solar occultation technique does not offer a global coverage of the Earth and one must assess the drawbacks of these limited occultation observations. But overall, it is believed that solar occultation missions with an instrument offering the same high performance as the ACE-FTS can set the standard for monitoring global climate trends.

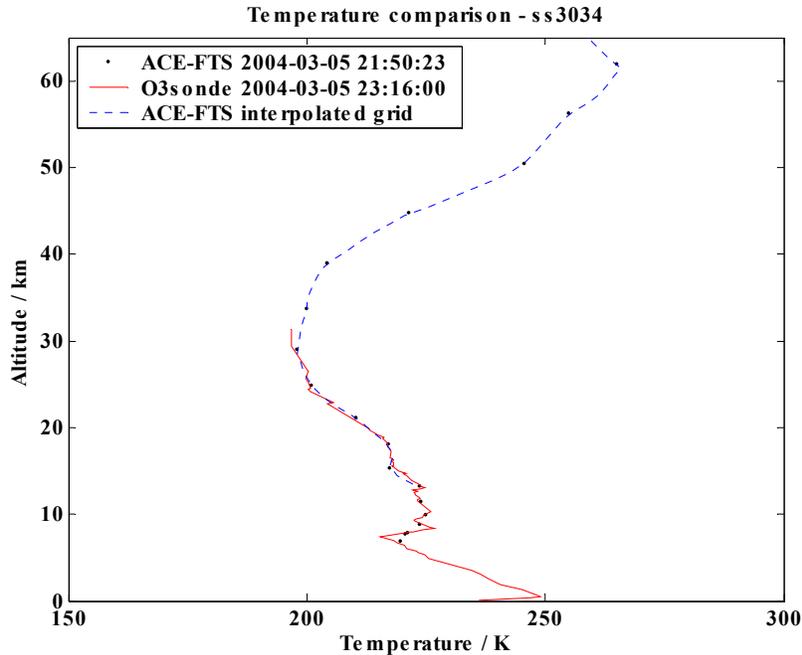


Figure 10: Intercomparison of the temperature profile retrieved from an ACE-FTS occultation and the measured profile from an Ozone radiosonde (figure taken from [5])

5. 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.

After the launch in August 2003, the ACE-FTS instrument commissioning has been conducted successfully. The instrument started its scientific operational phase on February 27th, 2004 and the mission has already delivered high quality results of high scientific value. The instrument is exceeding its original 2-year lifetime requirement and no degradation of performance or functionality was observed since launch.

The ACE-FTS has proven to be a highly reliable instrument for a space mission and will continue to deliver valuable information on the chemistry of the atmosphere. This instrument design, well adapted for a solar occultation mission concept, is a perfect candidate for long-term global climate change monitoring.

ACKNOWLEDGMENT

The authors would like to thank the Canadian Space Agency, the ACE science team and the Mission Operation Center at St-Hubert. The authors would like to thank all the persons involved in the design, manufacturing, testing, operations and management of the ACE-FTS instrument. Over 150 people have contributed to the realization of this instrument; we are indebted to all of them.

REFERENCES

1. M.-A. Soucy, F. Châteauneuf, C. Deutsch, N. Étienne, “*ACE-FTS Instrument Detailed Design*”, Proceedings of SPIE 2002, Vol. 4814.
2. F. Châteauneuf, M.-A. Soucy, C. Deutsch, N. Blanchard, J. Giroux, “*Recent Developments on ACE-FTS Instrument*”, Proceedings of SPIE 2002, Vol. 4814.
3. C. Boone, R. Nassar, S. McLeod, K. Walker, and P. Bernath, “*SciSat-1 Retrieval Results*”, Proceedings of SPIE 2004, Vol. 5542, pp 184-194.
4. S. Fortin, M.-A. Soucy, C. Deutsch, “On-Orbit Commissioning of the ACE-FTS Instrument”. Proceedings of SPIE 2002, Vol. 4814
5. C. D. Boone, C. P. Rinsland, R. Nassar, K. A. Walker, Y. Rochon, S. D. McLeod, and P. F. Bernath, “Retrievals for the Atmospheric Chemistry Experiment Fourier Transform Spectrometer”. Accepted for publication in Appl. Optics