ACE-FTS instrument: after four years on-orbit

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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 (74^0), 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 four years on-orbit. On-orbit performance is presented. The health and safety status of the instrument payload is discussed. Optimization of on-orbit performance is presented as well as operational aspects. Aspects related to reliability of FTS are discussed as well as potential future follow-on missions.

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 [1]. Science measurements started in February 2004 and atmospheric retrievals are conducted at the University of Waterloo [2].

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.

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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.

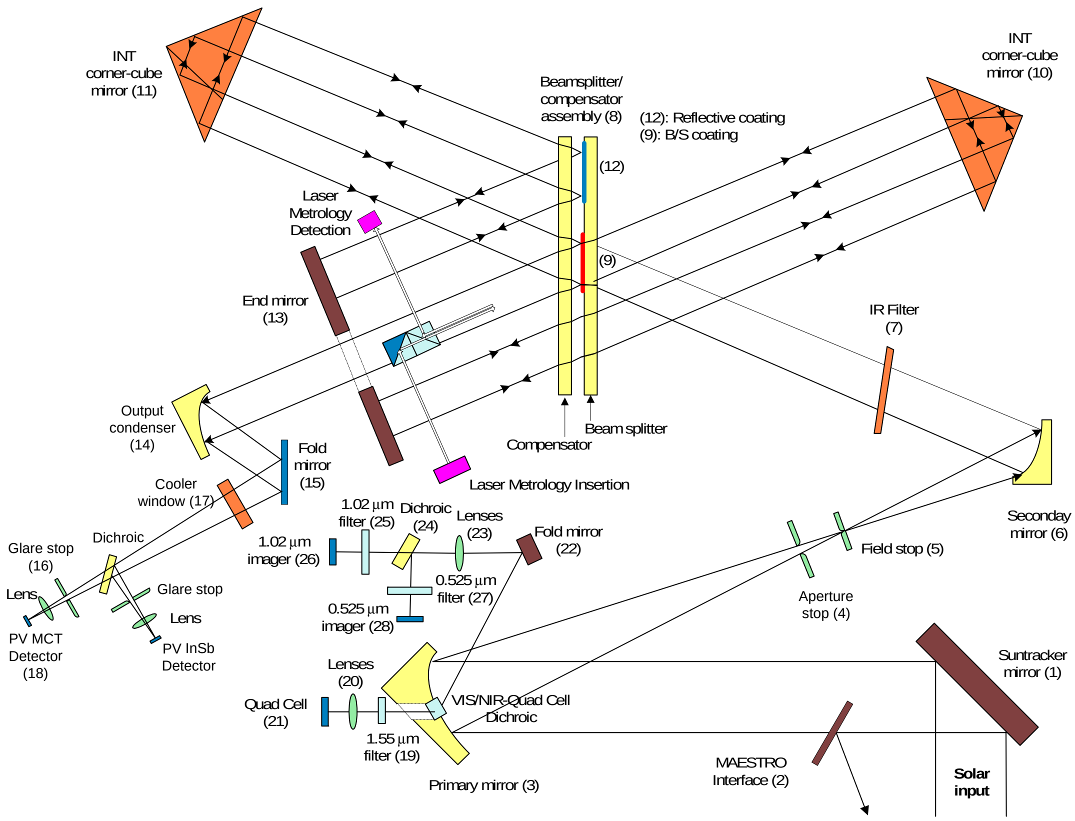


Figure 1: ACE-FTS instrument optical layout

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 interferometer uses a 1550 nm distributed feedback laser diode as the metrology source to provide feedback on the position and speed of the scanning mechanism. After three years of continuous operation, a decrease of less than 1.5 % in the laser power has been observed proving the high reliability of this kind of metrology source. Note that early during its mission life, the SciSat-1 spacecraft had to face a violent and severe Solar storm. No degradation or impact on the reliability has been observed yet. The exploded view of the instrument is shown in Figure 2. More information regarding the instrument design can be found in [3] and [4].

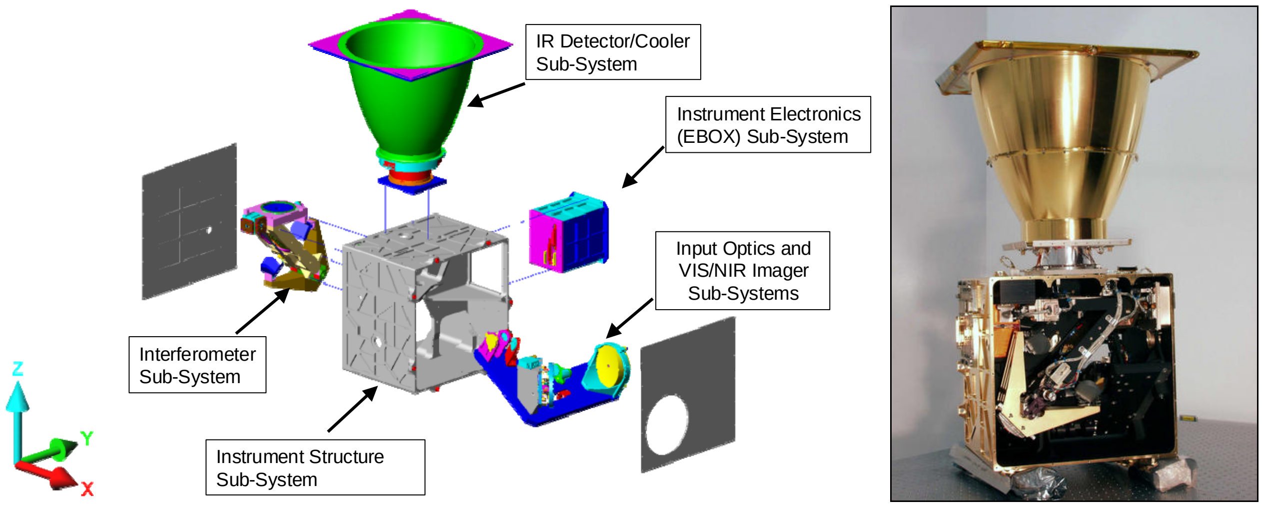


Figure 2: ACE-FTS architecture (left) and picture of the Flight Model (right)

3. ON-ORBIT PERFORMANCE

3.1. FTS SNR Performance

The Signal-to-Noise Ratio (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 a thermal vacuum chamber. The SNR is specified for a radiance of a blackbody at 5800 K as the input. However, such a hot blackbody was not available. A characterization of the SNR with a colder source has therefore been performed to validate the model. Once validated the model was 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 initial on-orbit SNR has been evaluated from an exo-atmospheric measurement taken on December 2, 2003.

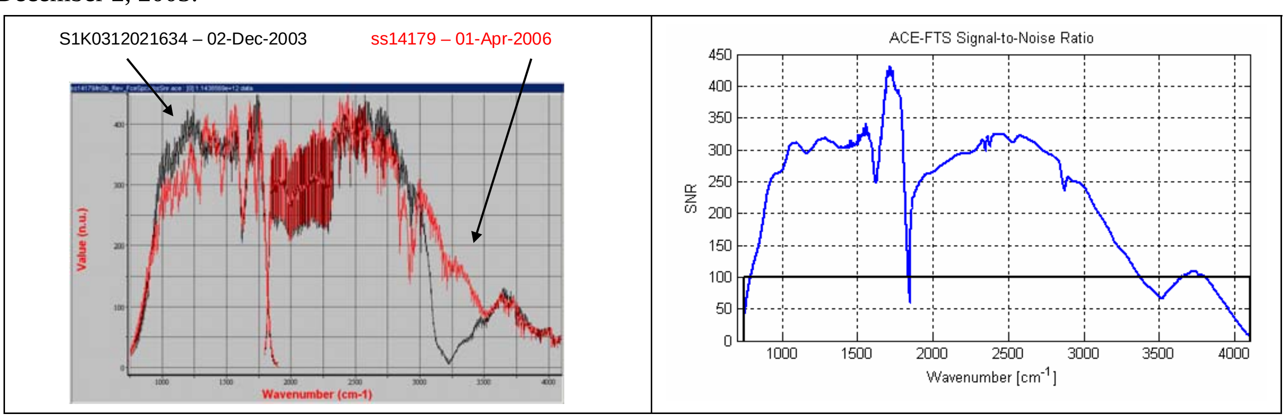


Figure 3: Validation of SNR model: on-orbit SNR (left) and modeled SNR for scene at 5800 K (right)

The dip in SNR around 1850 cm^{-1} is due to the cut-off in the response of the InSb detector where the MCT detector 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}. The next figure illustrates an SNR comparison between Feb. 28, 2004 and Feb. 28, 2007. Although the SNR comparison shows an improvement of the SNR over time, such conclusion would require further analyses, and the authors conclude at this point that no degradation of SNR occured since the launch of the ACE-FTS instrument.

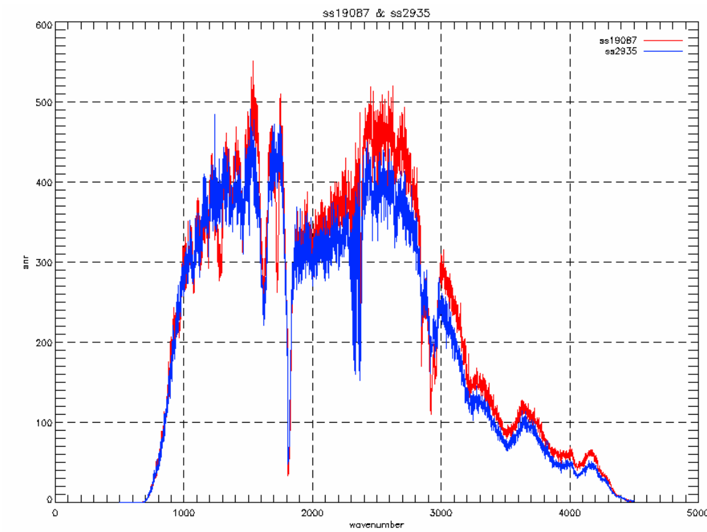


Figure 4: On-orbit SNR comparison Feb. 28, 2004 (ss2935) and Feb. 28, 2007 (ss19087)

On-orbit contamination impacts the signal-to-noise performance of the instrument. As can be seen on the left panel of Figure 3, 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. Since its launch in August 2003, a total of seven full decontamination sequences have been performed where the temperature of both the cold and intermediate stages of the passive cooler were raised to evacuate water in the vicinity of the cold optics. As shown by the April 2006 curve in the left panel of Figure 3, impacts of ice contamination have disappeared. A total of 44 partial decontaminations, where only the intermediate stage heater is warmed, were performed from launch up to April 2005. Since contamination rate has greatly reduced since launch, the science team recommended in May 2007 to no longer perform partial decontaminations and to limit decontamination cycles to one full decontamination (where the cold stage heater is warmed) per year, to be performed after the high beta angle period in summer. The next figure shows the frequency of occultations with ice between January 2004 and January 2007.

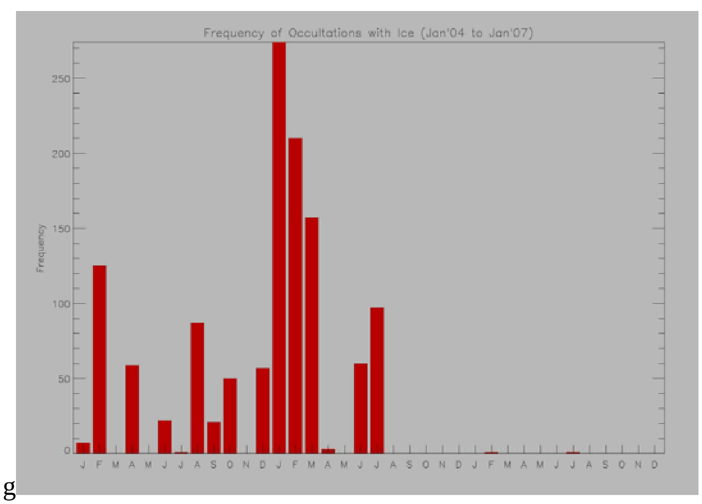
g 

Figure 5: Frequency of occultations with ice (January 2004 to January 2007)

The passive cooler used for the two infrared detectors is still showing very good performance as shown in Figure 6 as there are no signs of degradation in the cold stage/detector temperature. The temperatures follow the orbit beta angle evolution as predicted. Except during decontamination cycles, the detector temperature is almost always better than the maximum allowed temperature of 100K, and consequently SNR is positively impacted (more significant in the long wave range of the spectra).

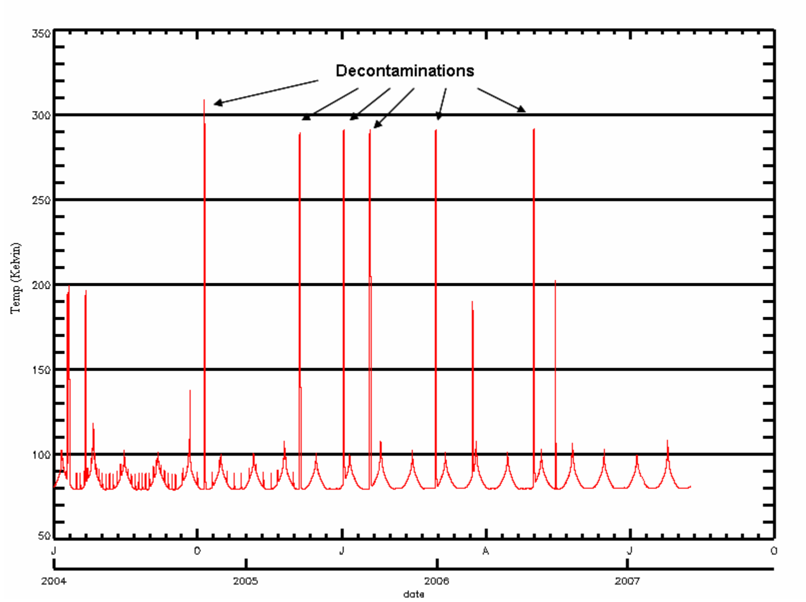


Figure 6: Evolution of the cold stage temperature with time

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 points is applied to reduce the noise.

The transmittance accuracy is presented in Figure 7. 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. Latest estimation of the instrument stability shows that the errors in the evaluation of the atmospheric transmittance are below 0.35% after 3 years of operation.

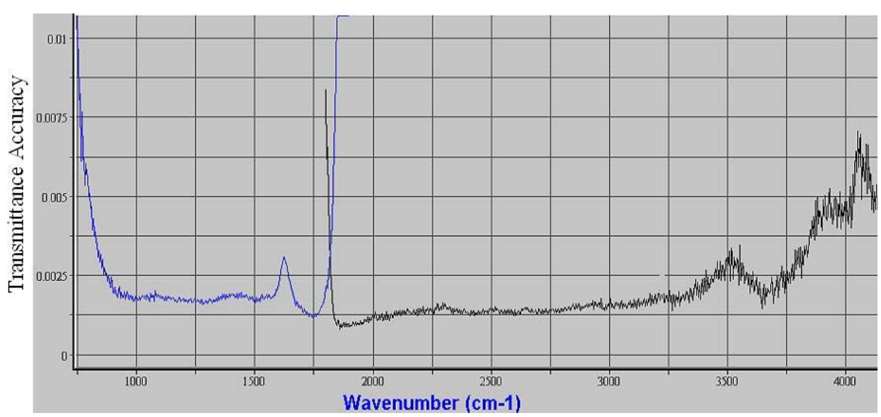


Figure 7: On-orbit FTS transmittance accuracy

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}.

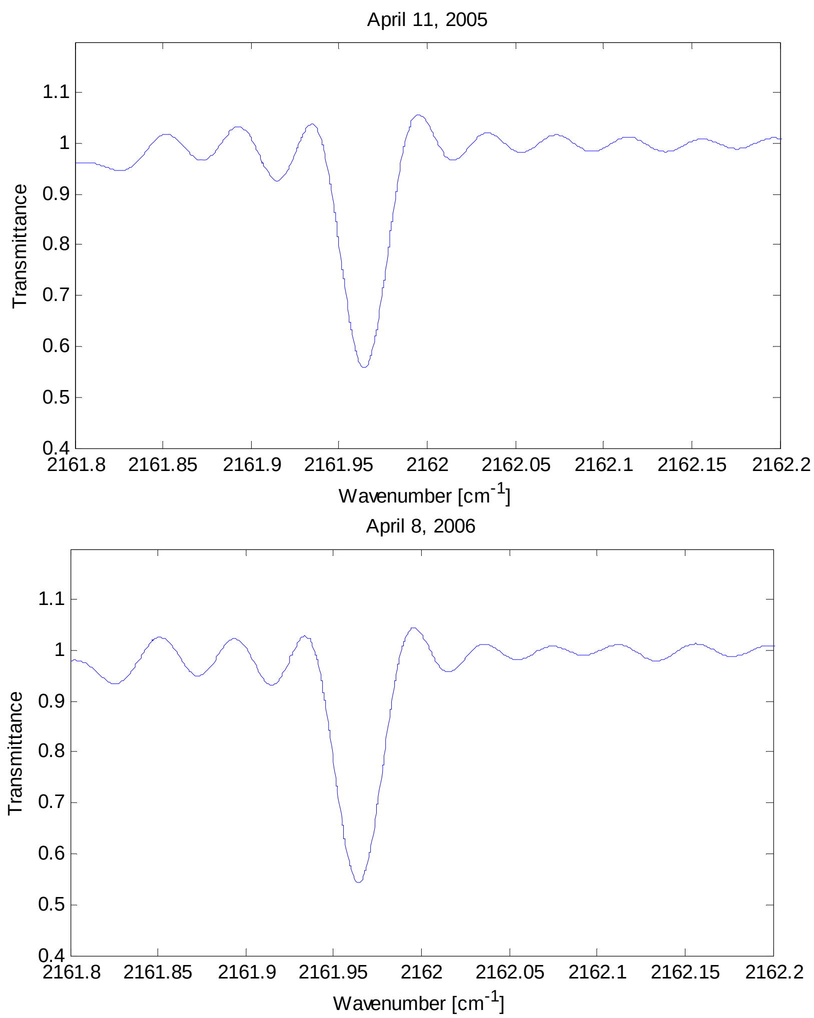


Figure 8: On-orbit FTS instrument line shape taken

Figure 8 shows a high altitude (40 km) CO line taken from two occultation sequences separated by a one year interval. The right wing of the line is very similar in both panels which shows that the alignment has been preserved. The left wing of the line shows some differences which are due to the overlap with neighbour lines. Complete retrieval and characterization of the instrument line shape can be found in Ref [3].

3.4. Nominal Operations

The ACE-FTS Instrument has started its scientific operational phase on February 21, 2004. Current station availability supports approximately 85 min/day of Science On-Time, i.e. 3.0 GByte/day of science data. Stations are located in Saint-Hubert, Saskatoon, Alaska and Kiruna. 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.

Since the beginning of the science phase of the mission, and up to May 1st 2007, about 2.5 Tb of data has been collected and stored which corresponds to more than 16,000 occultations. More than 645,000 transmittance spectra of the atmosphere have been computed over 21,200 orbits. Over the 16,000 occultations, only 5 were labelled ˝do not use˝, and 219 were labelled ˝use with caution˝ from known issues.

Since the end of its commissioning phase in February 2004, no serious anomaly resulted from the ACE-FTS instrument. The instrument operations are very stable, and no interruption resulted from instrument problems such as single event upsets. The interferometer and suntracker mechanisms have shown very high reliability, this being illustrated by the fact the instrument has been operated for more than 4 years, even though its original design lifetime was required for 2 years. The health and safety status of the instrument has always been nominal since the end of its commissioning phase. No sign of loss of optical transmission was observed, despite the fact that some optical components, such as the suntracker mirror, are directly exposed to the space environment in the velocity vector of the spacecraft. Moreover, the significant thermal cycling inherent to the solar occultation technique has not impacted the reliability of the instrument. Figure 10 shows the temperature of the instrument as measured at the beamsplitter of the interferometer, the heart of the instrument. Since the end of the commissioning phase, an increase of about 1 degree Celcius per year was observed. The overall spacecraft temperature is slightly increasing over time (as for most spacecrafts), but also the instrument duty cycle is higher than the beginning of the mission (heat from electrical power). Since the beginning of 2007, the temperature of the instrument is 24 degrees Celcius in average; there is still room for further temperature increase as the instrument was qualified during TVAC for temperatures from 0 to 40 degrees Celcius.

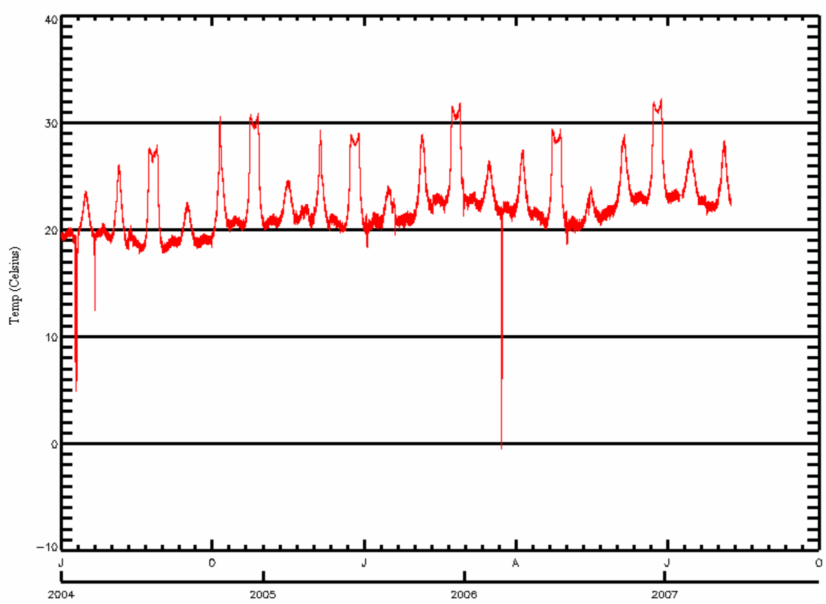


Figure 9: On-orbit FTS temperature (interferometer beamspliter) 2004-2007

As described in [5], the molecules retrieved on a routine basis for version 1.0 of the ACE retrieval software were the following: H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CFC-11, CFC-12, COF_2, HCFC-22, HDO, and SF_6. Version 2.0 and high added the following molecules to routine processing: HCN, CH_3Cl, CF_4, C_2H_2, C_2H_6, and N_2 (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: HO_2NO_2, H_2O_2, HOCl, H_2CO, 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 sounders. Infrared sounders on future polar-orbiting weather satellites (IASI and CrIS) are based on the FTS technology and they 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.

In 2005, an ESA report [6] suggested that solar occultation missions should be planned for the near future in order to maintain the highly valuable data collection that instruments like the ACE-FTS can provide. In fact:

> "Stratospheric measurements by ir and uv/vis solar occultation instruments offer intrinsically high precision, vertical resolution and long-term stability and have arguably provided the most valuable satellite contributions (e.g. SAGE-II, HALOE) to the quantification and attribution of height-resolved, long term trends in ozone and other stratospheric constituents. Solar occultation data have also been assimilated into chemical transport models for research purposes although, due to the very sparse geographical sampling of O_3 and H_2O by comparison to other data sources, their impact is not sufficient to justify assimilation into forecast models by the operational centres.
>
> There are currently no planned missions of this kind to follow ACE and MAESTRO on SCISAT, and these are unlikely to function beyond 2010. Instruments of this kind on a Sentinel mission could therefore be of great value to the "scientific assessment" user categories in the ozone/uv and climate applications…"

One of the final recommendations of the report states that to serve the observation needs in the future, ESA should seek cooperation with US, Canada and Japan where solar occultation mission heritage is strong.

Canadian scientists have shown a very strong interest in developing an ACE followen-on mission. Discussions have already started on potential improvements to the existing ACE design: extend spectral range, especially in the short wave, increase SNR at spectral ends, design a cooler that does not contaminate, adjustable FOVs and higher optical transmission.

Also, a strong interest has been expressed in China for a potential ACE follow-on mission. A ground-based breadboard model similar to the PARIS instrument is currently being built and will be delivered in December 2007 to allow scientific validations by Chinese authorities.

Finally, the use of atmospheric observation using solar occultation should not be limited to the Earth atmosphere. There is a growing interest for a ACE like mission around the planet Mars where the detection of Methane is targeted.

5. SUMMARY

The ACE-FTS instrument performance and 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.

After its launch in August 2003, the ACE-FTS instrument commissioning has been conducted successfully. The instrument started its scientific operational phase on February 21st, 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.

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