ACE-FTS instrument: After five years on-orbit

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ACE-FTS instrument: after five 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, a grating spectrometer named MAESTRO, provides spectrographic data from the near ultra-violet to the near infrared, including the visible spectral range. With all instruments combined, the 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 nearly five years on-orbit. On-orbit SNR and some telemetry signals are presented. The health status of the instrument is discussed.

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 [ref. 1]. Science measurements started in February 2004 and atmospheric retrievals are conducted at the University of Waterloo [ref. 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 5× 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.

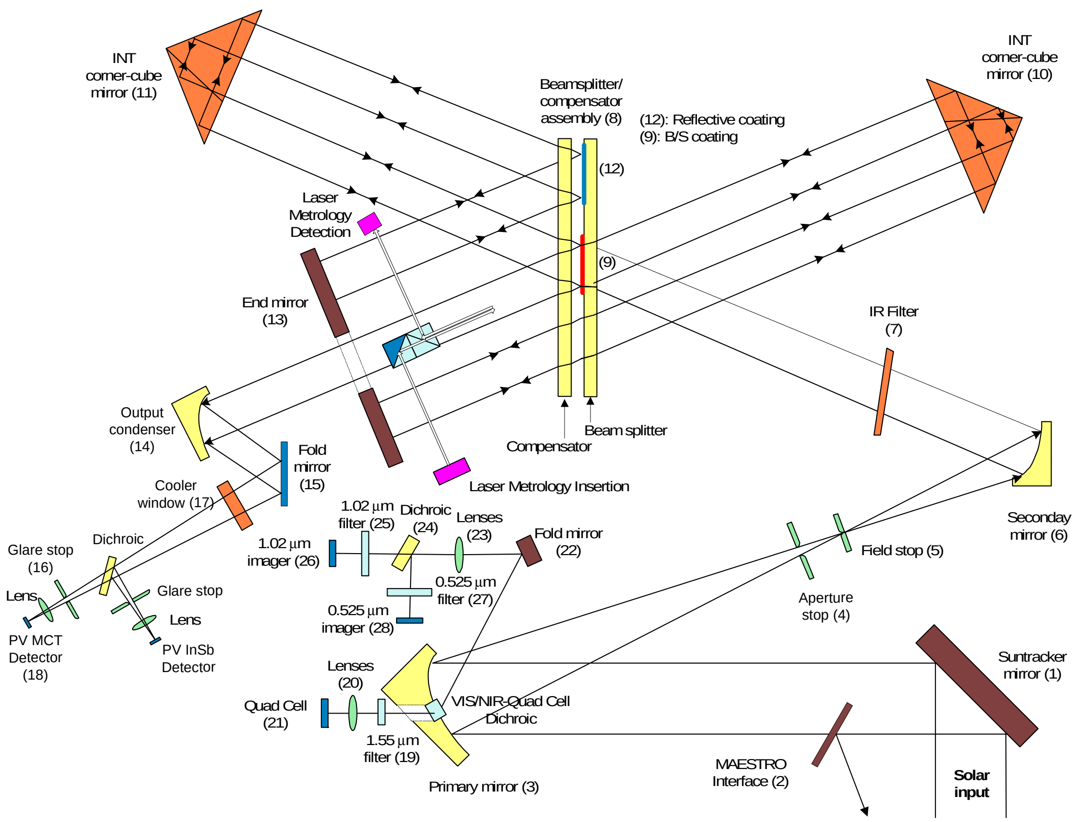

Figure 1: ACE-FTS instrument optical layout

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 real-time feedback on the position and speed for the servo-control of the scanning mechanism.

The ACE-FTS was designed for a 2-year mission. The choice of parts, the redundancy scheme, the shielding, the qualification and testing of some elements have all been done with a 2-year mission in mind. Note that early during its mission life, the SciSat-1 spacecraft had to face a violent and severe solar storm. No significant 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 [ref. 3] and [ref. 4].

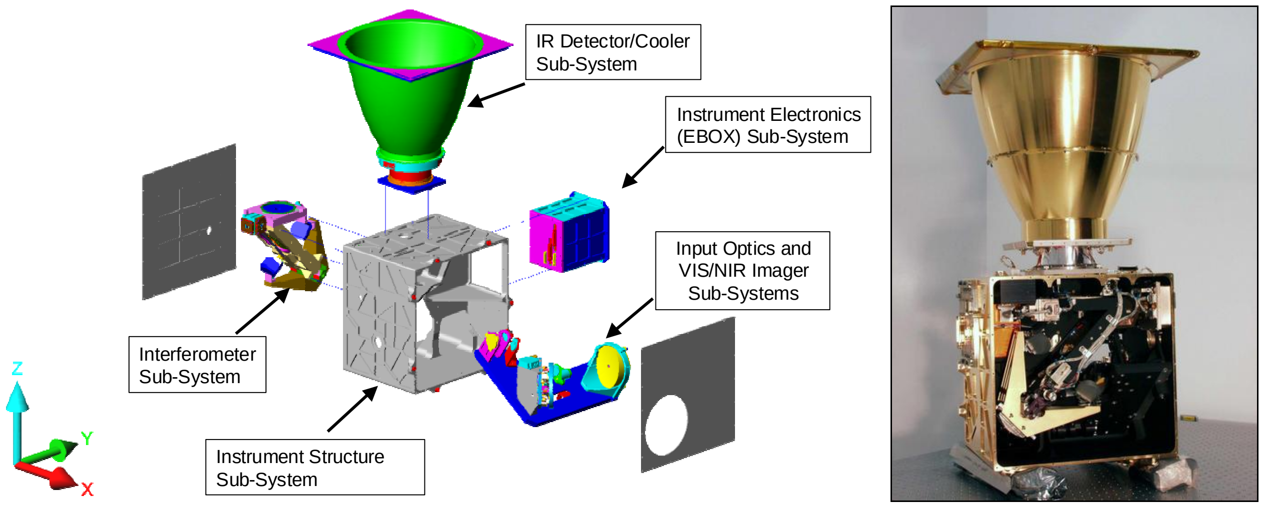

Figure 2: ACE-FTS architecture (left) and picture of the Flight Model (right)

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 5800 K blackbody as the input. However, such a hot blackbody was not available for testing. 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.

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 SNR estimated from exo-atmospheric measurements is shown on the same figure. The agreement between the prediction and the measurements is good except when the instrument suffered from periodic icing in its early life in space. Ice reduced the transmittance in some spectral region, in particular near 3250 cm^{-1}.

The icing problem has been attributed 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. 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. Figure 4 shows the frequency of occultations with ice between January 2004 and January 2007.

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}.

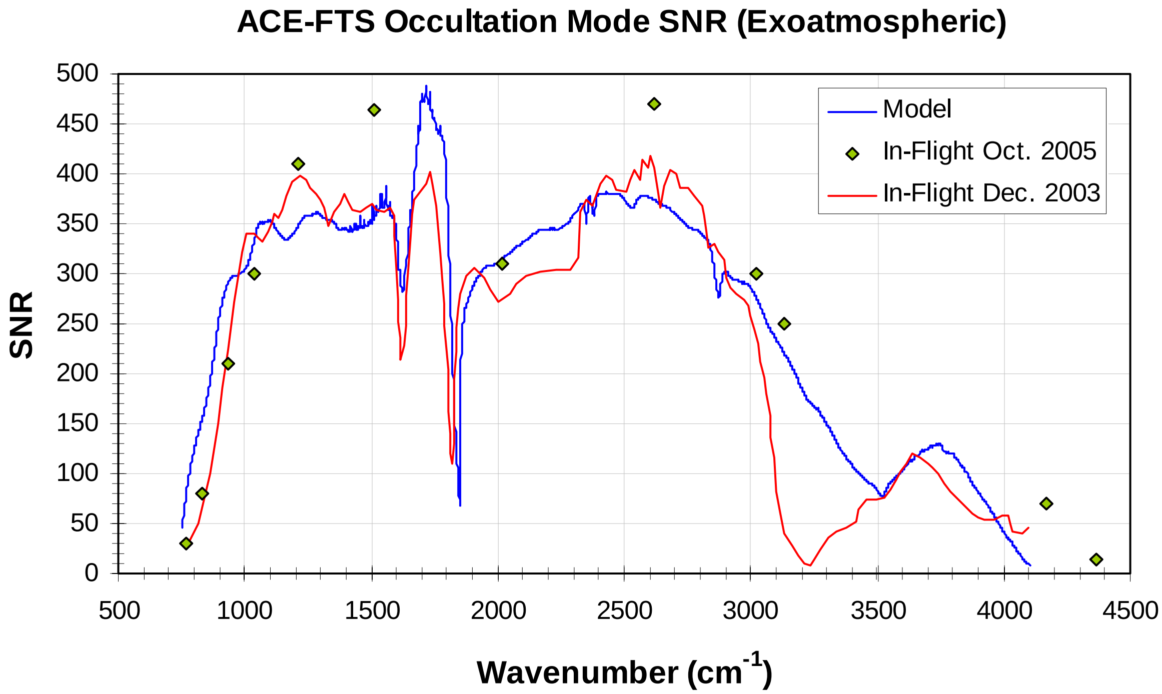

Figure 3: Comparison of SNR model prediction (blue) and in-flight measurements in 2003 (red) when there was ice before deicing and in 2005 (green).

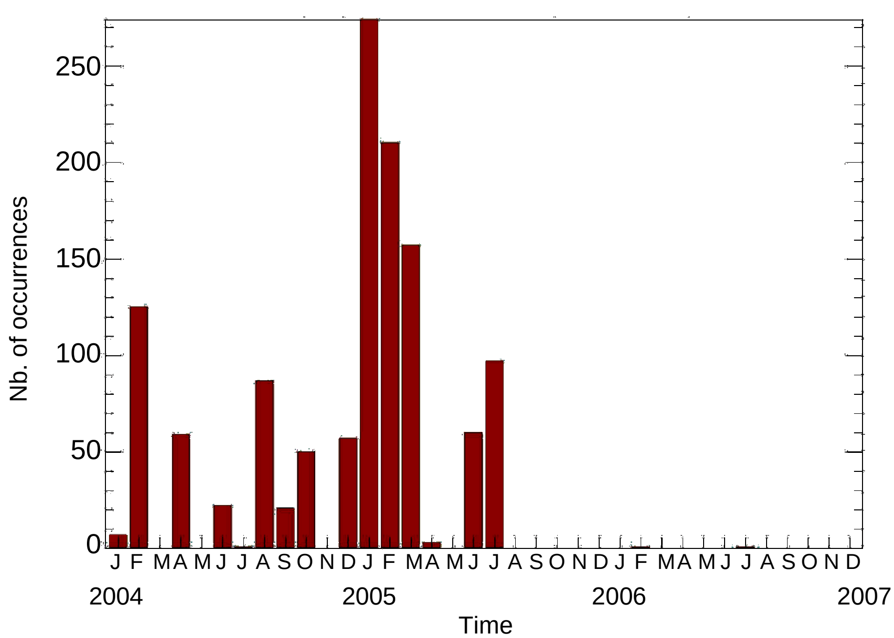

Figure 4: Frequency of occultations with ice (January 2004 to January 2007)

The next figure illustrates an SNR comparison between 2004 and 2008. Each SNR curve was built using exoatmopsheric measurements during five occulations at beta angle near 0°. Both curves are nearly identical. Figure 6 shows the SNR as function of the year for some selected frequencies. For each year, the calculated SNR is an average of five SNR measurements (in spectral bins of 0.5 cm^{-1}) made at low beta angles during the year. The error bars are the standard deviations of the five data sets for each year. For most frequencies, there is no significant trend. However, a systematic decrease of SNR is apparent near 1710 to 1740 cm^{-1} and near 2840 to 2980 cm^{-1}. The exact reason for that decrease has not been found yet but progressive contamination by organic molecules is suspected (see the "signature" on Figure 7).

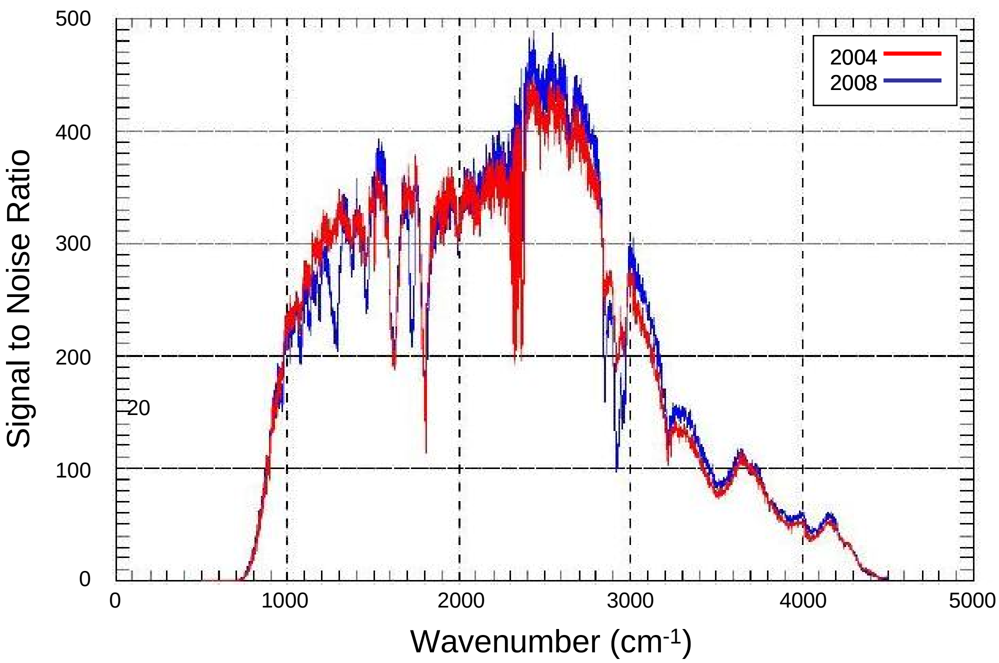

Figure 5: On-orbit SNR comparison of 2004 (blue) and 2008 (red). Each curve was built with exoatmopsheric measurements during five occultations at beta angle near 0°

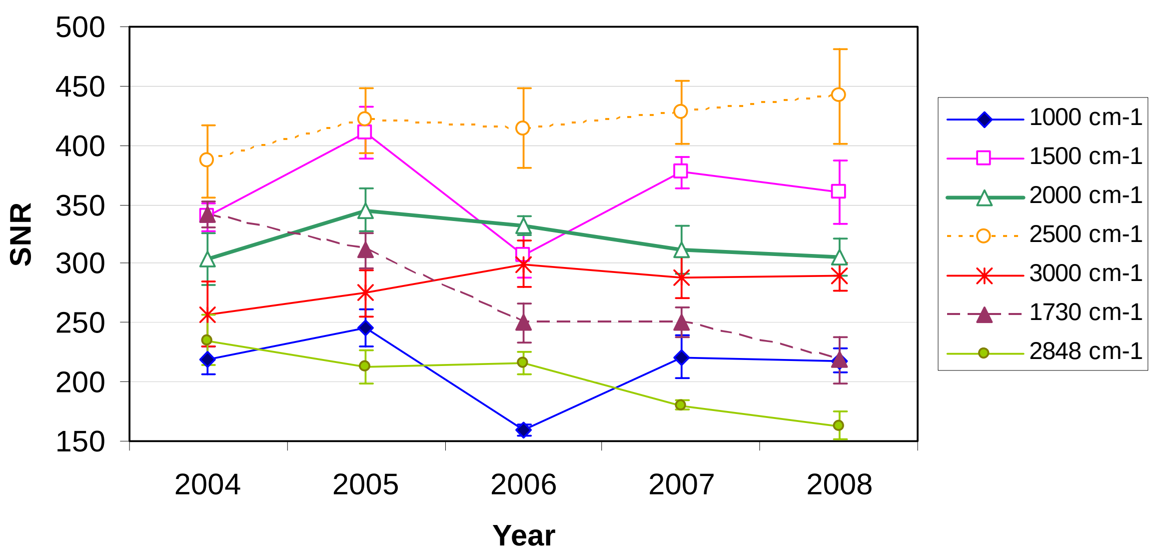

Figure 6: SNR trend lines for a few wavenumber

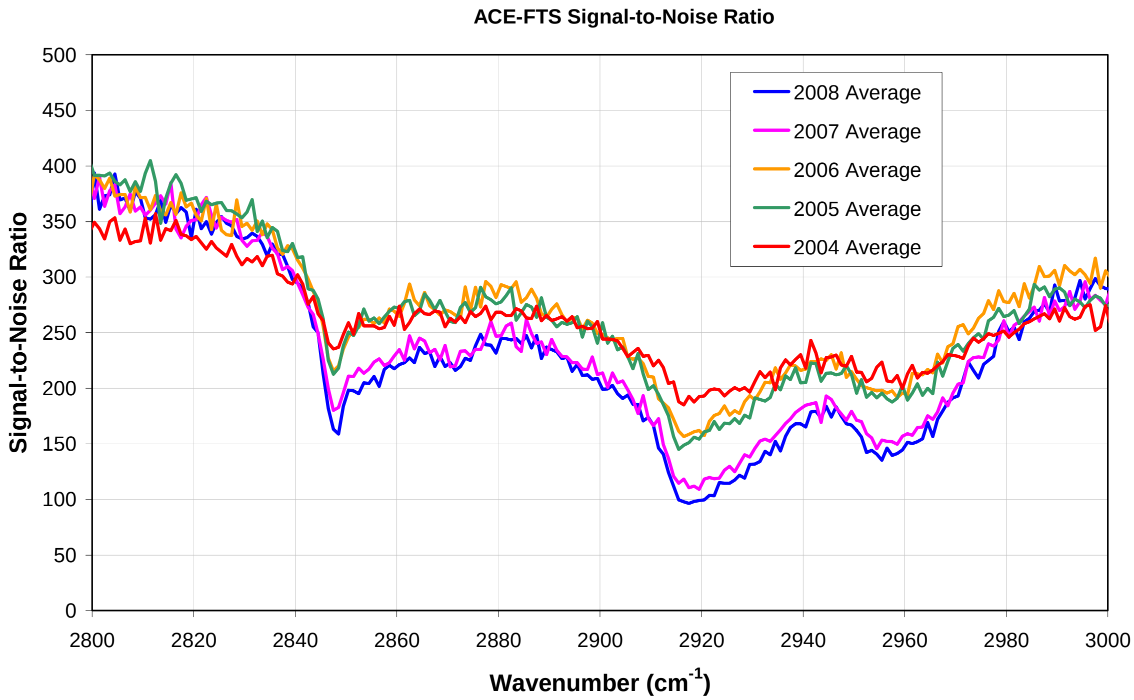

Figure 7: SNR decrease between 2820 and 2980 cm^{-1}

3.2. On orbit status and evolution of instrument

The telemetry data of the ACE-FTS contains information such as the temperature of thermistors placed at key locations in the instrument and the DC signal of the infrared detectors. These parameters are used to infer the overall health of the instrument.

The next series of figures are built with elements within the telemetry data gathered since the ACE-FTS became operational after the end of the commissioning phase in February 2004. The figures show, respectively,

- The temperature of the control electronics box that contains all the circuit cards controlling the ACE-FTS;
- The temperature of a thermistor placed on the structure of the interferometer near the beamsplitter;
- The temperature of a thermistor placed on the startracker mirror;
- The temperature of a thermistor placed near the aperture stop of the instrument;
- The temperature of the cold stage of the passive cooler that cools the infrared detectors. The cold stage is placed at the base of the IR Detector passive cooler;
- The temperature of a thermistor placed near the top of the IR Detector passive cooler;
- The DC signal of the MCT detector;
- The DC signal of the InSb detector.

The temperature of the electronics control box has risen by about 5°C since the instrument since February 2004. The temperature of the star-tracker mirror has risen by about 11°C. The star-tracker mirror being the first component in the optical path, it is also the most exposed to the Sun and the warmest component. The temperatures of the beamsplitter and of the aperture stop have both risen by about 5°C. The oscillations of the temperature are due to variations of the orbit beta angle and to decontamination heating. The drop of temperature in February 2006 is due to a shut-down of the instrument when there was an issue related to the spacecraft gyrowheels.

According to ACRIM data (ref. 8), the solar constant has been slightly decreasing since 2001. The rise of the instrument temperature cannot be attributed to a rising of the solar irradiance. The duty cycle of the satellite has increased and its temperature has increased by about 1°C per year. Most likely, the temperature of the instrument is simply following the temperature of the bus. There is still room for further temperature increase as the instrument was qualified during TVAC for temperatures from 0°C to 40°C.

The average temperature of the cold stage, of the upper portion of the passive cooler and the average DC levels of both detectors have remained relatively constant. The passive cooler used for the two infrared detectors is still showing very good performance and 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 100 K, and consequently SNR is positively impacted.

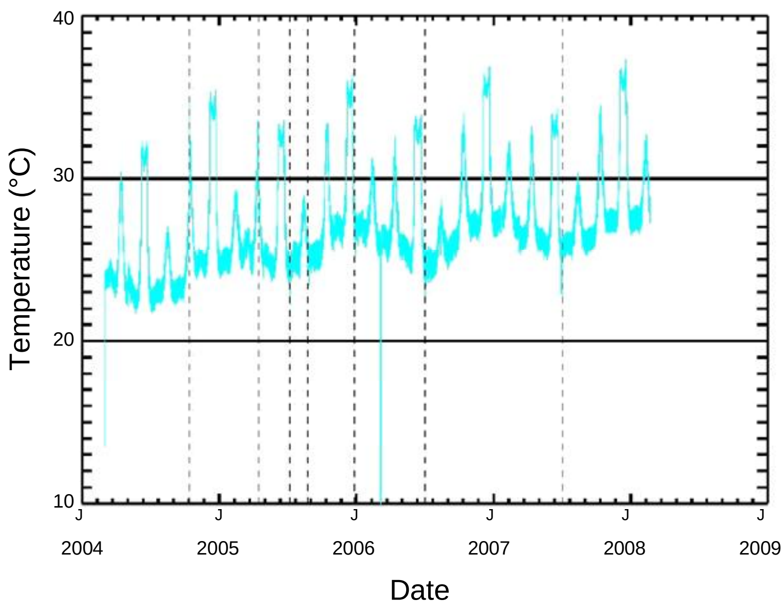

Figure 8: Evolution of the temperature of the control electronics box with time

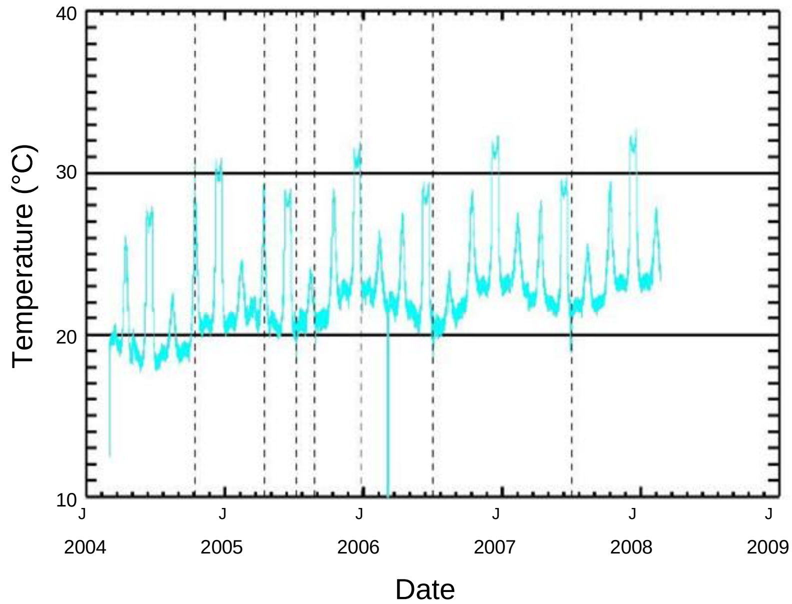

Figure 9: Evolution of the temperature near the beamsplitter with time

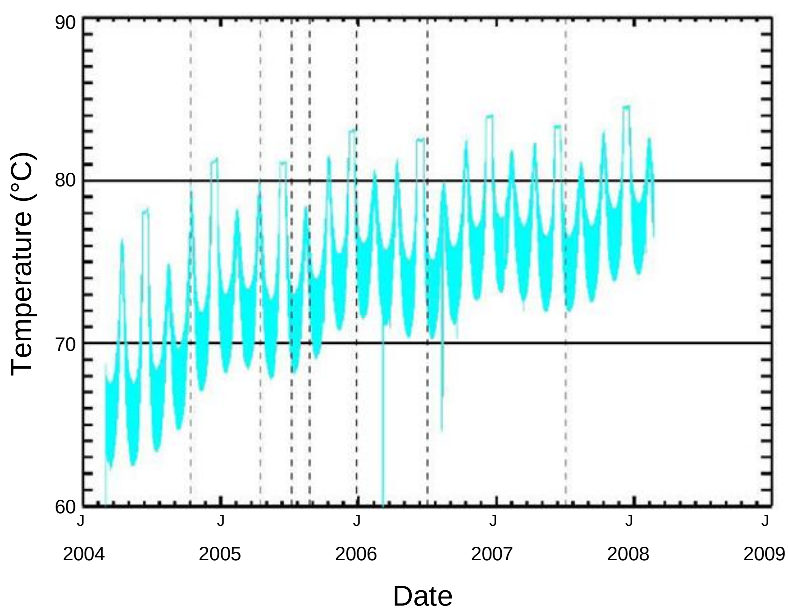

Figure 10: Evolution of the temperature of the sun-tracker mirror with time

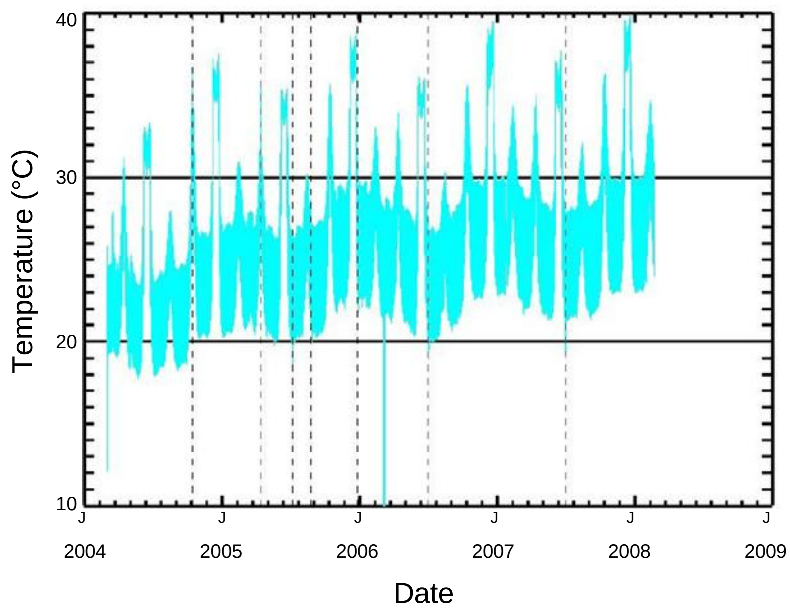

Figure 11: Evolution of the temperature of the aperture stop with time

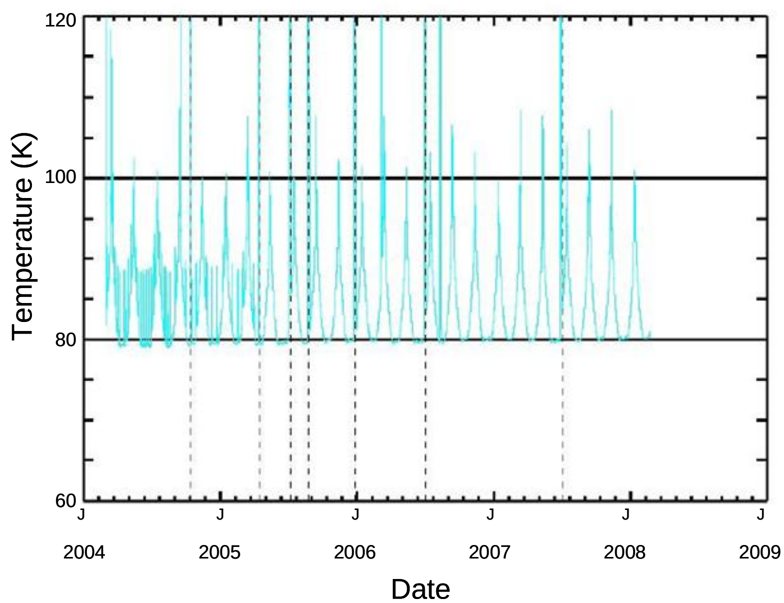

Figure 12: Evolution of the cold stage temperature with time

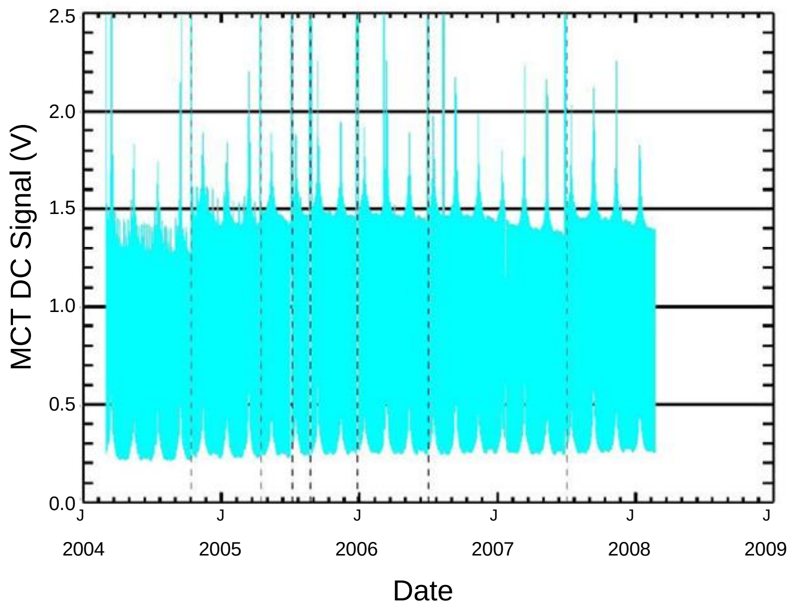

Figure 13: Evolution of the DC signal level of the MCT detector with time

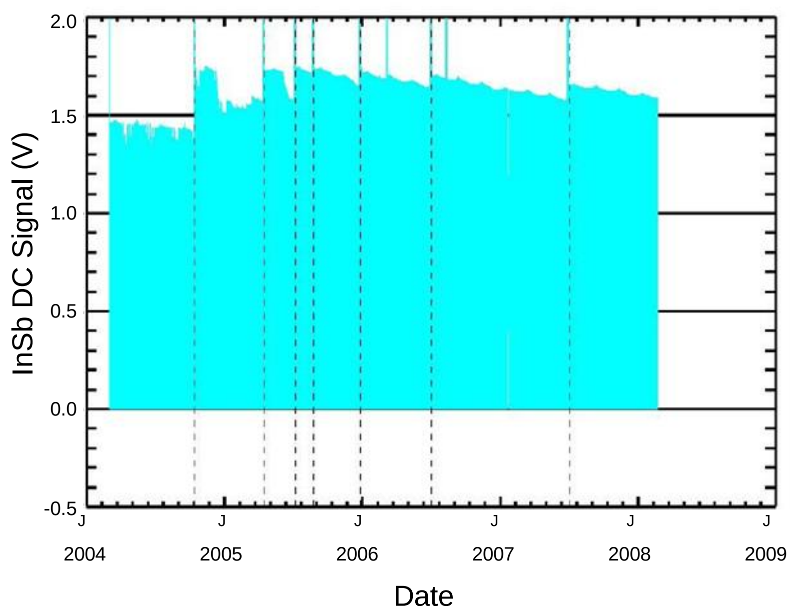

Figure 14: Evolution of the DC signal level of the InSb detector with time

3.3. 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 Mission Operation Centre (MOC) to the Science Operation Centre (SOC). The SOC for ACE is operated by the University of Waterloo, in Canada. The SOC is responsible for the scientific operations of the satellite, the collection and archiving of mission data, the collection of auxiliary data (climatology, orbit information, solar activity, etc.), the processing of the data, the development of official data processing and the distribution of data products. The University of Waterloo maintains a web site (http://www.ace.uwaterloo.ca) with information about the mission, the satellite and its instruments, ACE related publications, description of data products and how to have access to the ACE data.

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. The generation of Level 2 data products (concentration of molecules vs. altitude) is handled by the SOC.

The scientific returns of the ACE mission are beyond what was initially expected. Since 2004, more than 104 scientific papers with review committee have been published on the ACE-FTS itself or on research performed with the ACE-FTS.

The official data processing will soon be in its fifth version (version 3.0). New molecules have been added to the initial set of molecules concentration profiles retrieved on a routine basis with each new release. The vertical concentrations of even more molecules are retrieved “non-officially” (e.g. HBr, SO_2, PAN, CH_3COCH_3, C_2H_4, etc.) by various scientific teams around the world.

Table 1: Molecules retrieved by the ACE-FTS data processing

Version 1.0	Version 2.0	Version 2.1	Version 2.2	Version 3.0 (tentative)
H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, HDO, SF_6	H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N2O5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, SF_6, OCS, HCN, CF_4, CH_3Cl, C_2H_2, C_2H_6, N_2	H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, SF_6, OCS, HCN, CF_4, CH_3Cl, C_2H_2, C_2H_6, N_2, ClO	H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, HDO, SF_6, OCS, HCN, CF_4, CH_3Cl, C_2H_2, C_2H_6, N_2, ClO, as well as isotopologues for some of these molecules	H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, HDO, SF_6, OCS, HCN, CF_4, CH_3Cl, C_2H_2, C_2H_6, N_2, ClO,HCOOH, CH_3OH, CCl_4, CFC-113, HCFC-142b, $COCl_2$, COClF, H_2CO, HFC-134a, as well as isotopologues for some of these molecules

Since the beginning of the science phase of the mission, and up to July 2007, about 3.2 TB of data has been collected and stored which corresponds to more than 20,000 occultations. More than 800,000 transmittance spectra of the atmosphere have been computed over 26, 000 orbits. Of the 20,000 occultations, only 11 were labelled ˝do not use˝, and 286 were labelled ˝use with caution˝ from known issues.

4. SUMMARY

The ACE-FTS instrument performance and functionality are fully nominal. The performance is consistent with ground level testing and no significant post-launch degradation of performance was observed. The FTS signal-to-noise ratio is more than three times the requirement over a large portion of the spectral range. No significant trend of the SNR has been observed over most of the spectral range of the instrument. The spectral resolution is consistent with theoretical models and with ground measurements taken during the verification campaign. Alignment has therefore been preserved after launch (Ref. 9).

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 significantly exceeding its original 2-year lifetime requirement and no degradation of performance or functionality has been 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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Several of the figures presented in this document were prepared by Ryan Hughes of the University of Waterloo in Ontario, Canada (Ref. 7).

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