On-orbit commissioning of the ACE-FTS instrument

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ABSTRACT

The Atmospheric Chemistry Experiment (ACE) is the mission selected by the Canadian Space Agency 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 will be made by solar occultation from a satellite in low earth orbit. The ACE mission will measure and analyze 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 commissioning of the ACE-FTS instrument. Various steps were required to safely and progressively activate each module and sub-system of the instrument. This paper describes each step and its relation with the health and safety of the instrument. The overall strategy and sequence of the commissioning activity is presented. Commissioning results are presented in terms of validation of instrument functionality from an engineering perspective. The characterization of the detector contamination is described as well as methods that were developed to mitigate this issue.

Keywords: ACE, FTS, SCISAT-1, Spectrometer, on-orbit

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. More information regarding the instrument design can be found in [1].

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.

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The commissioning phase activity was needed in preparation for the routine exploitation phase. Commissioning was conducted using a well-organized set of documents. The top-level commissioning plan [2] provided the general overview covering the high-level set-up, the necessary validation sequences, verification and characterization activities to be performed, the on-ground analysis steps, and ground processing configurations to optimize data product quality. Then, lower-level commissioning plans [3], [4], and [5] addressed in more detailed the commissioning of specific parts of the ACE-FTS instrument, that is: the interferometer and imager commissioning, the suntracker commissioning, and the characterization and performance assessment.

Each lower-level commissioning plan was conducted in a separate sequence. Each sequence was contained over a period of up to 5 consecutive days. The data validation was performed in near real time to detect any anomaly and to provide the Go/NoGo decision for the following steps. Data analyses and reporting were performed on site also in a near real time mode.

This commissioning covered the activities starting just after the LEOP phase and up to the assessment of readiness for the operational phase for the ACE-FTS instrument. Activities addressed in this paper cover the commissioning of the ACE-FTS instrument from a hardware/engineering perspective. It does not cover the science commissioning requirements.

2. COMMISSIONNING ACTIVITIES

The driving factor in planning commissioning activities is the safety of satellite equipment. In order to reduce as much as possible the risks associated with start-up and early operations, a sequence of gradual commissioning activities was conducted. The caging mechanism, used to lock the interferometer rotary arm during launch, was first released. Then, other ACE-FTS instrument mechanisms (interferometer rotary arm and suntracker) were operated in open-loop configuration to validate the quality of their feedback, prior using them for close-loop servo controls. Once validated, the mechanisms were commanded in closed-loop configuration at reduced operating ranges and for short durations. After analysis of the results, the mechanisms were then allowed to move across their full range and for their nominal durations. Many parameters of the instrument, such as preamplifier gains, exposure times and suntracker offsets, were then optimized and the instrument performance was characterized.

Some guidelines were established by the MOC and ABB before commissioning. First, commanding of parameters had to be limited to items needed for nominal operations. This implied that if it were judged that the operational heater was not needed to maintain temperature within limits, the commanding of the operational heater would never be exercised during commissioning phase, and thus, would not be commissioned. Similarly, if a functionality is backed-up with redundancy, the redundant assembly would not be exercised if the primary assembly is working nominally. For these reasons, the operational heater, the redundant power supply, and redundant metrology units were not commissioned. Special commissioning activities will be initiated if the need to use uncommissioned functionalities arises.

Commissioning plans were prepared by ABB, and the procedures produced and conducted by the MOC. ABB was on-site to check the procedures, to witness telemetry data for activities performed during ground-to-spacecraft direct contacts, and to process and analyze all data produced specifically for commissioning. In general, commissioning activities were performed using uploaded scripts to mitigate the risks associated with loss of ground to spacecraft transmissions. The next sub-sections describe the commissioning activity in details.

2.1. Post-Launch Health Monitoring

The ACE-FTS was switched ON ten hours after launch. The first activity was to monitor instrument temperatures and status while other spacecraft functions were initiated. At this stage the spacecraft was rolling four degrees per second and prevented the instrument to settle to its nominal predicted temperature. In particular the infrared (IR) detectors cryo-cooler was remaining warm. However, many parameters could be checked. First, once per spacecraft rotation, the Sun illuminated the IR detectors. Even with warm detectors, the effect on the detector DC offset was clearly visible and confirmed detectors were functioning. The suntracker quad cell sensor was also showing nominal signal levels. Other telemetry data, available in sleep mode, were also checked against data acquired during ground verifications. All housekeeping data were to their nominal value for sleep mode.

2.2. Interferometer Arm Caging Release

The objective of the following commissioning activity was the release of the interferometer arm caging mechanism. The caging mechanism was used to protect the rotary arm during launch. The caging release is based on volumetric expansion of paraffin that occurs during the solid-to-liquid phase change when heat is applied. Constraining the expansion within the actuator body generates significant static force. This force is transformed by the actuator to mechanical work in the form of linear shaft motion.

The caging release was activated in favorable conditions, at an instrument temperature in the upper range to optimize the efficiency of paraffin heating. The caging release script was executed during ground station overpass for real-time monitoring. Emergency scripts were ready for emergency stop in case of any anomaly. The caging release was performed successfully. Immediately after release, metrology laser fringes were observed.

2.3. Cryo-Cooler Decontamination

Since the IR detectors operate at colder temperatures than other parts of the instrument, they tend to trap contaminants. The primary source of contaminants is water vapor trapped in Multi Layer Insulation (MLI) blankets. Contaminants form ice on detectors and other optical component surfaces, which result in loss of optical transmission. This transmission loss is mainly observed between 750 cm^{-1} and 1000 cm^{-1}, between 2800 cm^{-1} and 3700 cm^{-1}, and to some less extent elsewhere in the spectra.

Loss of performance due to contamination was expected and decontamination heaters have been incorporated to the ACE-FTS instrument. Decontamination was performed twice during commissioning; first when the detectors were relatively warm (prior activation of satellite roll control), and a second time prior to performance verification. Figure 1 shows the signal recovery obtained during the second decontamination activity performed on December 13, 2003. The signal amplitude of the IR channels before (lower curve) and 24 hours after cryo-cooler decontamination (upper curve) is shown.

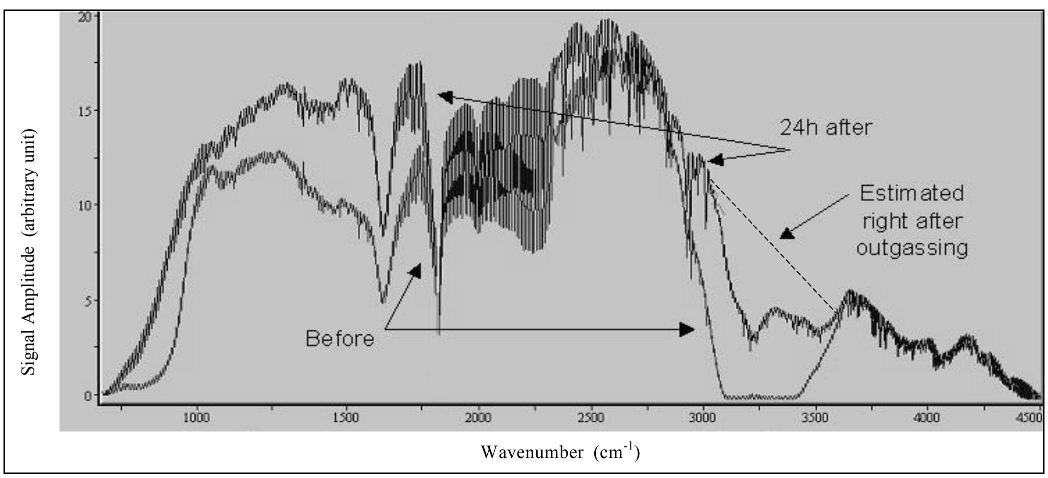

Figure 1. Signal amplitude of the IR channels before (lower curve) and 24 hours after cryo-cooler decontamination (upper curve)

2.4. Simplified Decontamination

After the second decontamination performed on December 13th 2003, four months after launch, it was found that the contamination rate was still significant. The baseline plan was to perform decontamination more frequently but this would have reduced significantly the duty cycle for science measurements, would have induced thermal stresses, and consequently, would have affected long-term reliability; an alternate approach for decontamination was therefore needed.

Based on the cryo-cooler manufacturer (Ball Aerospace) recommendations, the decontamination process was modified to apply heat only to the intermediate stage of the cryo-cooler. The cryo-cooler intermediate stage contains a window that isolates the warm instrument from the cold detector. As the contaminants are mainly produced on the instrument side and that the window is cooler than the instrument, most of the contaminants are trapped on the instrument side of the intermediate stage window.

The intermediate stage heater was activated for 35 minutes to obtain a temperature of 200K. The assumptions were confirmed and the simplified decontamination proved to be effective. Contaminants were removed 50 minutes after the simplified decontamination execution. The cold stage temperature increased by less than 10K and produced no significant effect on detector performances. Figure 2 shows the IR signal amplitude ratio of the signal taken 5 days after simplified decontamination over the signal measured just after simplified decontamination. The simplified decontamination is now performed once a week with no impact on science operations.

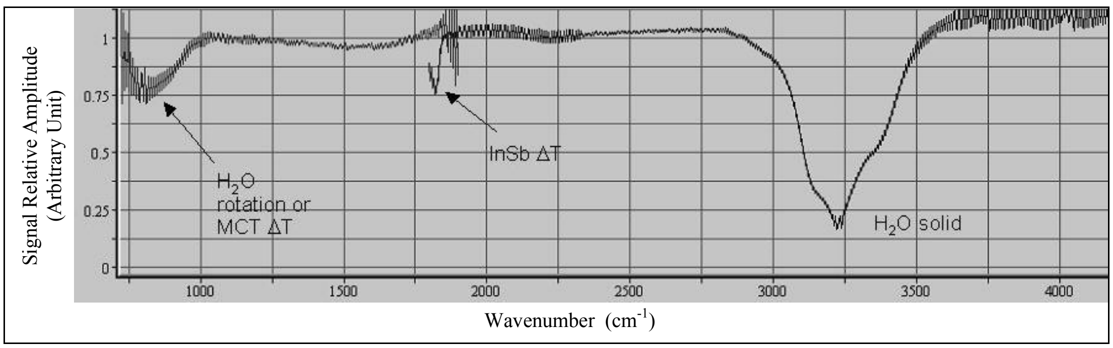

Figure 2. Ratio of the IR signal taken 5 days after simplified decontamination over the signal measured just after simplified decontamination

Some contaminations (here called residual contaminants) are not removed by the simplified decontamination. This is the case for the contaminant located on the cold side of the IR detector cryo-cooler. Figure 3 shows the IR signal amplitude right after the second full decontamination and the signal nearly four months later without additional full decontamination. Note that, on Figure 3, the Sun intensity variation has not be removed but has been taken into account in the contamination rate evaluation.

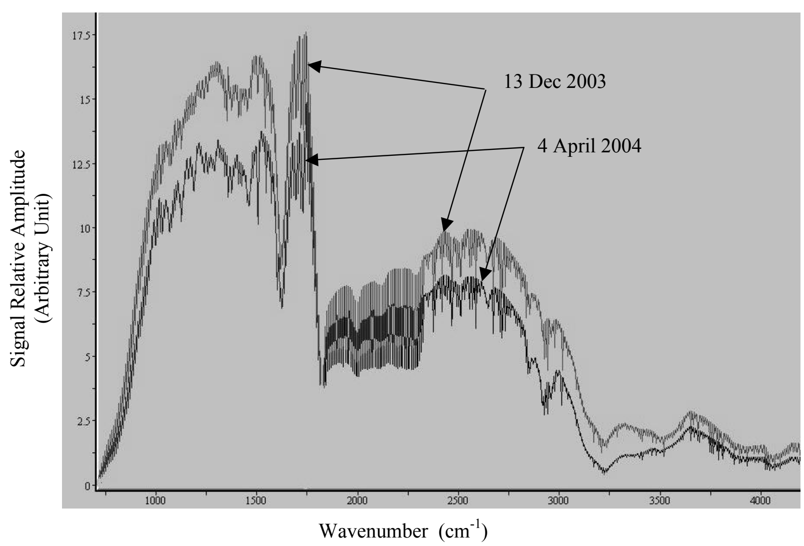

Figure 3. IR signal amplitude right after the second full decontamination and four months later (without additional full decontamination)

The residual contamination rate is reducing with time. The contamination rate observed in March 2004 is much lower than in last December 2003. Figure 4 shows the relative IR signal amplitude, on the MCT channel, for three measurements: one performed on 13 December 2003, on 3 March 2004, and on 4 April 2004. The contamination rate was evaluated at 21.6 % during the first three months and at 2.5 % during the 4^{th} month for one of the largest absorption features, located just above 1500 cm^{-1}.

The residual contaminant can be removed by the full decontamination. However, the full decontamination induces thermal stress and this stress should be minimized. Recommendations were given that the full decontamination should be performed only when required and, as for the simplified decontamination, the full decontamination should be performed at lower temperature than initially planned. Up to July 2004 no additional full decontamination was performed.

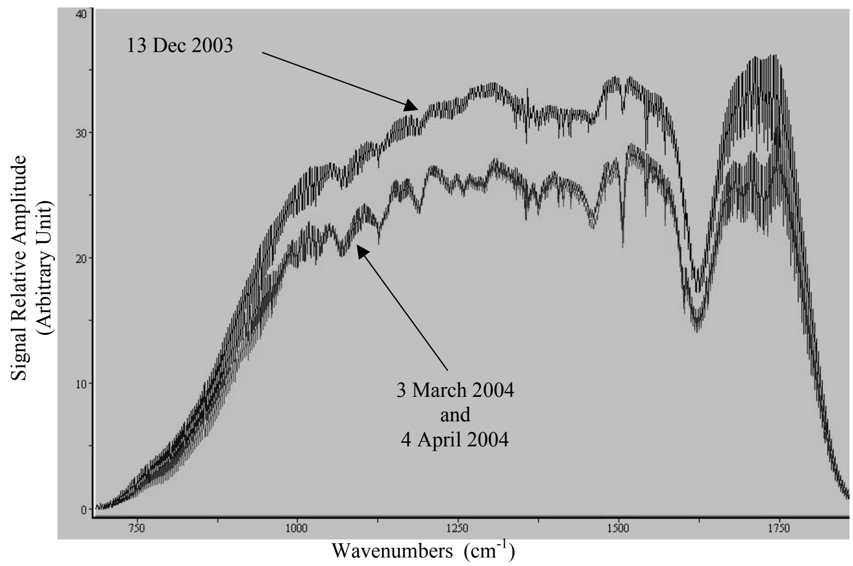

Figure 4. IR signal amplitude (long wave channel) right after, three months after, and four months after full decontamination

2.5. Interferometer Commissioning

Interferometer functional verification was performed to assess that the interferometer was functional in all configurations and modes. The interferometer functional verification was performed before the suntracker commissioning to allow spectra acquisition as early as possible, providing data for ground processing start-up. At this stage the suntracker was still OFF but the spacecraft attitude allowed Sun view for a portion of the orbits.

Interferometer rotary arm mechanism was first operated in open-loop which made the rotary arm move in a predefined angular position profile. This was performed in standby mode with the high-speed housekeeping mode enabled providing diagnostic data from the metrology detection. The metrology signals were analyzed and compared to the data recorded before launch during final verification. This verification was repeated with the spacecraft transponder ON while transmitting data to a ground station. All metrology signals were nominal (both AC and DC levels). Then, the interferometer rotary arm was operated in close-loop for short durations, with transponder ON and OFF, and the data validated. Finally, the rotary arm was commanded to perform the full stroke for a short duration, validated, and then activated for a nominal duration and validated again.

Interferometer commissioning showed that the instrument IR channels were not sensitive to transponder activity and that the measurements can be performed with either the transponder ON or OFF. Interferometer commissioning also confirmed that the functionalities have not been affected by launch.

2.6. Imager Commissioning

The imager commissioning was performed as part of the interferometer commissioning. The activity consisted mainly in validating the dynamic range, setting the gain and exposure time, and setting the cropping mode and cropping offsets. As for the IR channels, the imager channels were found to be insensitive to transponder activity and the measurements can thus be performed with the transponder either ON or OFF.

The imager response was also characterized by varying the integration time. Imager relative signal response is given in Figure 5 (the imager ADC dynamic range is 12288 arbitrary unit). Non-linearity data was derived and the optimized exposure time was established.

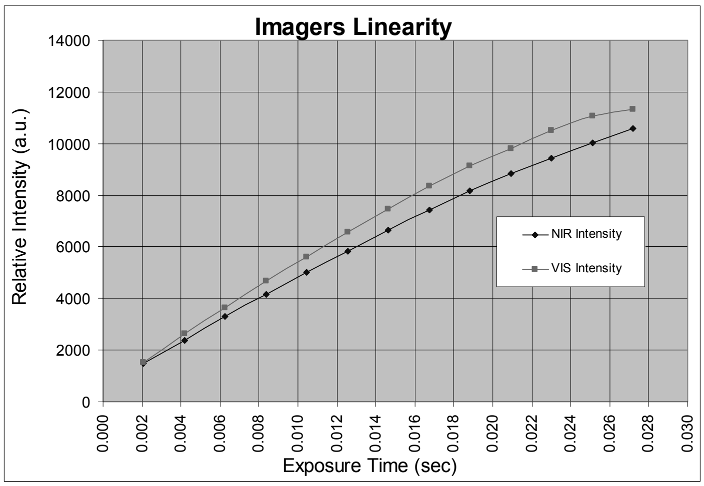

Figure 5. Imagers response vs. exposure time

2.7. Suntracker Commissioning

The suntracker, built by Ball Aerospace, was first operated in open-loop mode. Both azimuth and elevation axes were commanded and the suntracker position sensors were recorded and compared to characterization results in thermal-vacuum chamber. The suntracker was then commanded in close-loop with transponder ON and OFF. It was established that the suntracker is not affected by the transponder activity.

Then, the suntracker closed-loop mode was exercised and close-loop offsets were commanded. It was found that the close-loop offset range is limited in elevation and azimuth. Pointing instability occurs when exceeding the limits. However, these limits do not affect the nominal operations since optimum offset values were later established being close to the middle of the offset ranges available.

The co-registration between the IR channels and the imager channels was established during suntracker commissioning. The suntracker was commanded to point at the Sun with a sequence of offsets. At each pointing offset the intensity of the signal at the IR channels and the center of the Sun on the imagers were recorded. This sequence provided the pointing values where the IR channels were crossing the edges of the Sun. Repeating the experiment for both azimuth and elevation sequences allowed to derive the pointing for which the IR channels were pointing at the center of the Sun and thus the position of the IR channels registration on the Imagers. The sequences were performed in a short period of time for which the spacecraft attitude drift could be considered negligible compared to the pointing accuracy. The co-registration is presented in Figure 6. The IR channels co-registration on the imager is nearly centered and has not been altered by the launch.

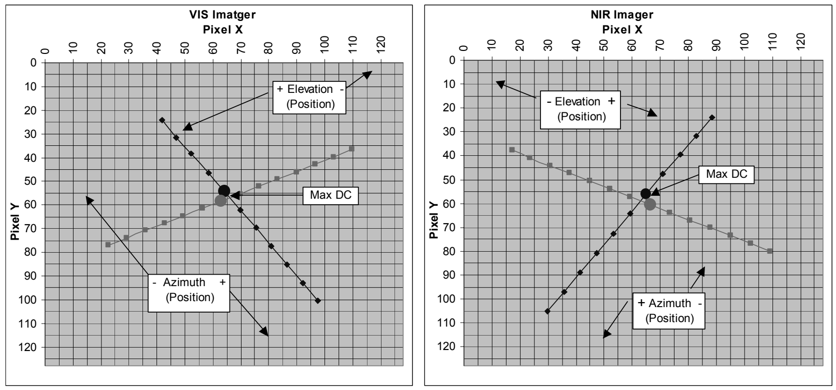

Figure 6. On-orbit co-registration of the IR channels and the imager

Following the co-registration validation, the imager readout was switched to the cropping mode, with cropping offsets to position the IR channel co-registration at the center of the cropped image. Imager cropping reduces the imager data rate by a factor of four. Finally the suntracker closed-loop offsets were adjusted to center the Sun on the cropped image when operated in close-loop.

Suntracker instabilities were observed at some occasions during commissioning when operating outside nominal mirror travel range. Also, suntracker pointing instabilities were observed during the early operational phase for sunrise occultations. Essentially, for sunrise event, the suntracker is automatically set in open-loop mode when the Sun intensity is below a specified threshold. If the open-loop offsets were set at values away from the rest position the suntracker was gaining too much speed reaching for the Sun. Special commissioning was undertaken at the end of May and early June 2004 to optimize initial suntracker pointing during sunrise events. The problem was resolved by setting the open-loop offsets to zero and a number of short duration sunrises (30) were monitored. No instability was observed.

2.8. Radiometric Offset Characterization

The instrument self-emission contributes to the measured IR signal. This contribution is easily evaluated by doing measurements when pointing at deep space, which produces negligible radiation. The measured signal is then only due to the instrument self-emission and can be subtracted from all measurements. Deep space measurements were performed for different elevation and azimuth offsets to check if any Sun stray light could contaminate the deep space measurement. The results were essentially identical and open-loop offsets, corresponding to pointing offset from the Sun center of 45 mrad in elevation (above Earth horizon) and 64 mrad in azimuth (to further move away from the Sun), were selected.

The Figure 7 present the relative radiometric offset compared to exo-atmospheric measurements. The radiometric offset is close to 10% of the exo-atmospheric measurement at 750 cm^{-1} and must be taken into account in the transmittance computation for the MCT channel. No radiometric-offset subtraction is needed for the InSb channel. The radiometric offset results also show that high-resolution spectral features are negligible and thus allows some flexibility in processing the exo-atmospheric and atmospheric measurements, e.g., the radiometric offset measurement can be acquired at lower spectral resolution, can be truncated to use only the center part of the interferogram, and can be acquired less frequently.

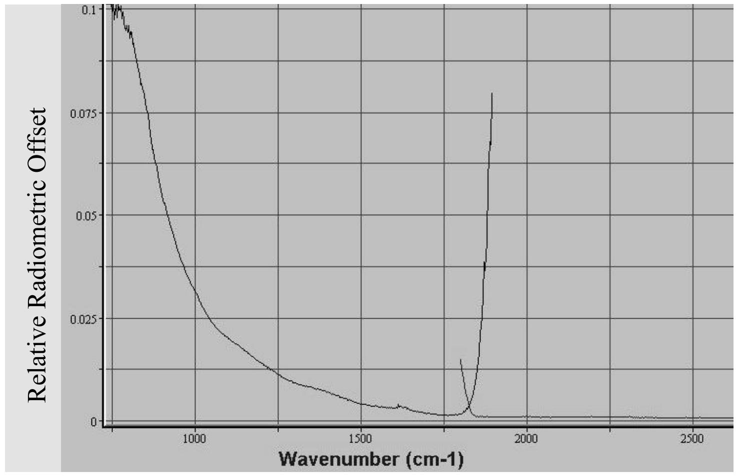

Figure 7. Radiometric offset compared to exo-atmospheric measurement

The radiometric offset variation was also characterized. Radiometric offset variation was estimated to 1% of the exo-atmospheric signal at 750 cm^{-1}. This variation was due to the aperture stop temperature variations (from 294.5K to 302.0K) caused by the spacecraft attitude variations. The spacecraft attitude variations would allow the Sun image on the aperture stop to move away from the center gold coated portion and illuminate the aperture stop holder, which is painted black (Aeroglaze). These variations were observed before the spacecraft attitude control was fully implemented and these radiometric-offset variations are not seen during nominal operations.

2.9. Thermal Characterization

On-orbit instrument temperature extends from 16 ^{o}C to 27.5 ^{o}C and is well within the ground thermal-vacuum qualification temperature range (–10 ^{o}C to 40 ^{o}C). The On-orbit average temperature is 22 ^{o}C, which is very close to alignment temperature during ground integration. Temperature profile of the instrument fro the first orbit beta angle cycle, measured at the beam-splitter level, is shown in Figure 7.

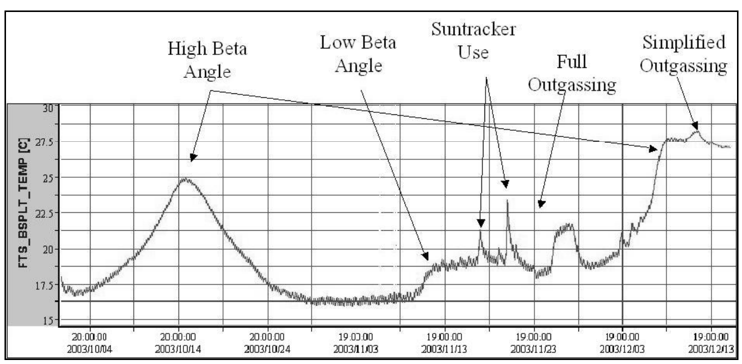

Figure 8. On-orbit ACE-FTS instrument thermal profile

The IR detectors cryo-cooler has also been characterized and the performance is as predicted (78K at high beta angle and 100K at low beta angle). Cryo-cooler temperature variations through the orbit beta angle cycles do not affect IR performances. The on-orbit IR detectors cryo-cooler thermal profile is presented in Figure 8.

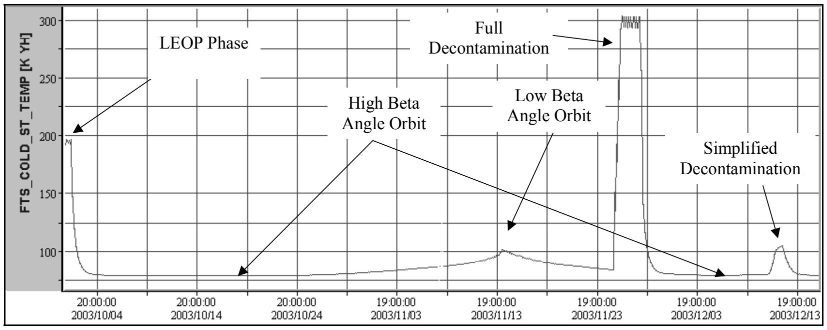

Figure 9. On-orbit IR detectors cryo-cooler thermal profile

2.10. Nominal Operations

The ACE-FTS Instrument started its scientific operational phase on February 27th, 2004. The ACE raw data volume is about 1 GByte per day. The data is sent to ground using at least 2 ground stations. These data are 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.

Due to limited download throughput, the early operations 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 Artic vortex event and to compare results with the PARIS instrument, which was performing simultaneous measurements from a ground site located at Eureka in Artic. The instrument telemetry is monitored and temperatures are checked more closely as they are related to safety issues. Up to now no major incident has been declared.

3. SUMMARY

The ACE-FTS instrument functionality and performance is fully nominal and on-orbit results are consistent with ground-level testing. In particular, the SNR quality is excellent. No post-launch degradation of performance was observed. The instrument data quality is not sensitive to transponder activity. The FTS transmittances show neither significant channeling nor significant effects of detector non-linearity. Instrument performance was initially strongly affected by contamination (mainly ice); however, a simplified decontamination procedure was developed to reduce the effects on science measurements and maintain good duty cycle of the instrument. No safety issues were found during the commissioning of the instruments. The commissioning of the instrument is completed and the system is operational.

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