ACE-FTS Instrument: After One Year On-orbit

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***Abstract*—The Atmospheric Chemistry Experiment (ACE) is the mission on-board the Canadian Space Agency's SciSat-1 science satellite. ACE consists of a suite of instruments in which the primary element is an infrared Fourier Transform Spectrometer (FTS) coupled with an auxiliary 2channel visible and near infrared imager. A secondary instrument, MAESTRO, provides spectrographic data from the near ultra-violet to the near infrared, including the visible spectral range. In combination, the two instruments cover the spectral range from 0.25 to 13.3 microns. A comprehensive set of simultaneous measurements of trace gases, thin clouds, aerosols, and temperature are made by solar occultation. A high inclination (74°), low earth orbit (650 km) allows coverage of tropical, mid-latitude and the polar regions. The ACE mission is intended to measure and analyze the chemical and dynamical processes that control the distribution of ozone in the upper troposphere and stratosphere. This paper presents the status of the ACE-FTS instrument after one year of on-orbit operations. The results of the commissioning phase and early science operations phase are presented.**

Keywords: ACE, SciSat-1, FTS, on-orbit

I. INTRODUCTION

The ACE-FTS instrument is composed of a Fourier Transform Spectrometer (FTS) and two imager detectors. More information regarding the instrument can be found in [1]. The Principal Investigator of the mission is Prof. 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, Belgium, Japan, France and Sweden. ABB-Bomem inc. is the industrial prime contractor of the ACE-FTS instrument. The spacecraft bus was built by Bristol Aerospace.

Average ozone declines have been measured over much of Canada using ground-based Brewer spectrophotometers [2]. Since 1980 all five long-term Canadian stations (including Toronto 44° N, 79° W) have found a statistically significant decrease of about 6% in the ozone column. Ozone sonde measurements show that most of the decline has occurred in the lower stratosphere and the current atmospheric models cannot account for these observations. The total ozone column obtained from satellite-based TOMS instruments shows that in March 1997, the ozone column was 21% less than normal and in a small region near the pole the decrease was 40% [3]. The only reasonable explanation for this data is chemical loss of ozone probably due to heterogeneous chemistry. The goal of ACE is to help explaining these losses.

The ACE/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 provided commissioning planning and technical support for the on-orbit functional and performance validation of the ACE-FTS instrument. The ACE-FTS instrument has started its scientific operational phase on February 27th, 2004.

II. COMMISSIONNING ACTIVITIES

The driving factor in planning commissioning activities is safety of satellite. 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 locking mechanism, used to lock the interferometer rotary arm during launch, was first activated. Then, other ACE-FTS instrument mechanisms (interferometer rotary arm and suntracker) were operated in open-loop configuration to validate the quality of their feedbacks, prior using them for close-loop servo controls. Once the feedbacks were validated, the mechanisms were commanded in closed-loop configuration at reduced operating ranges and short durations. After analysis of the results, the mechanisms were then allowed in their full range and 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, e.g., if it was 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.

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 main phases of the commissioning activity.

A. 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. 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.

B. 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 hydrostatic pressure. This pressure 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.

C. Cryo-Cooler Decontamination

Since the IR detectors operate at cryogenic temperatures, 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 components, 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 had 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.

D. 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. The simplified decontamination is now performed once every week with no impact on science operations.

E. 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 to 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.

F. Imager Commissioning

The imager commissioning was performed as part of the interferometer commissioning. The activity consisted mainly in validating the dynamic range and in setting the gain and exposure time. As for the IR channels the imager channels are not sensitive to transponder activity and the measurements can be performed with the transponder either ON or OFF.

The imager response was also characterized by varying the integration time from 20 to 260 units time (104.627 µs per unit). Non-linearity data was derived and the optimized exposure time was established. The SNR for the VIS and NIR imager are 8000 and 7500 respectively. The required SNR is 2000. Note that this SNR includes the source noise, but excludes systematic effects such as ghosts.

G. 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 closed-loop with transponder ON and OFF. The suntracker is not affected by the transponder. The pointing stability requirement of 15 µrad RMS is met. The standard deviation has been evaluated to 6.6 µrad RMS in elevation and 3.6 µrad RMS in Azimuth.

The co-registration between the IR channels and the Imager channels was established during suntracker commissioning. Following the co-registration validation, the imager readout was switched to the cropping mode, with cropping offsets to position the Sun 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 open loop, which also positioned the IR channels on the center of the Sun.

H. Radiometric Offset Characterization

The instrument self-emission contributes to the measured signal by adding an offset. This offset is easily evaluated by doing measurements while pointing at deep space, which provides negligible radiation. The measured signal is then produced by the instrument self-emission and can be subtracted from all measurements. Deep space measurements were performed for different elevation and azimuth offsets to validate if stray light (from Sun) could contaminate the deep space measurements. The results were essentially identical and deep space pointing offsets were selected; 45 mrad in elevation (above Earth horizon) and 64 mrad in azimuth (to further move away from the Sun).

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.

I. Thermal Performance

On-orbit instrument temperatures extend from 16°C to 27.5°C and are well within the thermal-vacuum qualification temperature range (-10°C to 40°C). The on-orbit average temperature is 22°C, which is very close to alignment temperature during ground integration. This very good thermal performance is close to the predictions from the finite-element model and are obtained without the use of the operational heater.

The cryo-cooler thermal performance has also been characterized and the performance is very close to predictions from model (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.

J. SNR Performance

The required Signal to Noise ratio (SNR) was 100 for a 0.02 cm^{-1} spectral interval and single sweep measurement. The on-orbit instrument sensitivity is excellent and is more than three times the design requirement for the main part of the spectral coverage. The on-orbit SNR for an exo-atmospheric measurement is presented in Fig. 1. The results are consistent with ground-level testing.

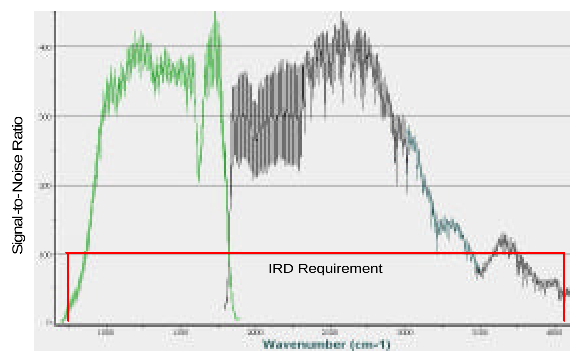

Figure 1. On-orbit FTS signal to noise ratio

K. Transmittance Accuracy

The transmittance accuracy is also very good, with little non-linearity effects, very good metrology stability and good cancellation of channel spectrum and Doppler effects. The 1% accuracy is met over the spectral range with better than 0.3% above 850 cm^{-1} and better than 0.2% on average. The transmittance accuracy is presented in Fig. 2.

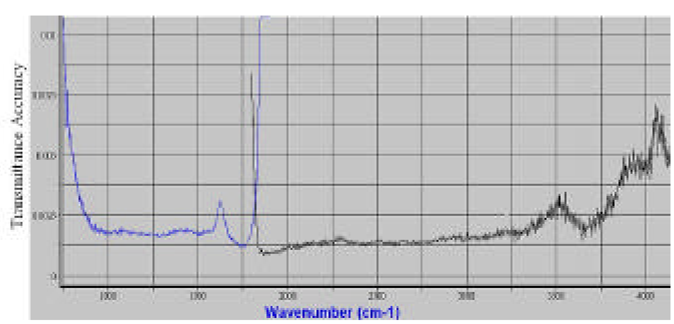

Figure 2. On-orbit FTS transmittance accuracy

L. Spectral Resolution

The on-orbit spectral resolution specification (0.028 cm^{-1} ILS FWHM) is met over the spectral range. The table 1 shows the ILS Full Width at Half Maximum (FWHM) for high altitude gas line measurements.

TABLE I. 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

III. NOMINAL ON-ORBIT OPERATIONS

The ACE-FTS Instrument has started its scientific operational phase on February 27th, 2004. The ACE raw data volume is about 1 GByte per day. The data are sent to ground using a minimum of 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. In the case of the FTS, the raw interferograms (level 0) are transformed into corrected atmospheric spectra (level 1). Computation of transmittance then follows.

Due to limited download throughput capabilities, the early operations mainly consisted of sunset occultations with additional characterization and special events led by the SOC. The sunset occultations were selected since they are located on the northern hemisphere and were very critical for monitoring the Artic vortex event.

A. Temperature Monitoring

In support to the nominal operations, the performance and functionality of the ACE-FTS instrument is monitored regularly by validating the instrument telemetry against predefined limits. Temperatures are monitored closely as they are related to safety of the instrument.

B. Suntracker Instabilities

Suntracker instabilities were observed at some occasions during commissioning when operating outside the nominal mirror travel range. Also, suntracker pointing instabilities were observed during the early operational phase for sunrise occultations. Special commissioning was undertaken at the end of May and early June 2004 to optimize initial suntracker pointing during sunrise events. During sunrise events, the suntracker is automatically set in open-loop mode when the Sun intensity is below a specified threshold. If the open-loop offsets are set at values too far from the rest position of the mechanism, the suntracker is gaining too much speed when searching for the Sun once the intensity is over the minimum intensity threshold. The problem was resolved by setting the open-loop offsets to zero and a number of short duration sunrises (30) were monitored and successfully completed. No instabilities were observed since the implementation of the settings, and the suntracker can be operated in all viewing geometry modes.

C. Transit of Venus

A special set of measurements was acquired during the transit of Venus in early June 2004. The objective was to measure the spectral signature of the Venus planet when it was aligned with the Sun. At the time of writing this paper, no scientific results were available regarding this special measurement campaign.

IV. 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.

ACKNOWLEDGMENT

The authors would like to thank the Canadian Space Agency, the ACE science team (in particular Dr. Kaley Walker) and the Mission Operation Center at St-Hubert. The authors would like to thank all the persons involved in the design, manufacturing, testing, commissioning 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. Chateauneuf, C. Deutsch, N. Étienne, ABB Bomem Inc., Radiometry Division, “ACE-FTS Instrument Detailed Design”, Proceedings of SPIE 2002, Vol. 4814.

[2] D. I. Wardle, J. B. Kerr, C. T. McElroy, and D. R. Francis, “Ozone Science: A Canadian Perspective on the Changing Ozone Layer”, Environment Canada, 1997.

[3] P. A. Newman, J. F. Gleason, R. D. McPeters, and R. S. Stolarski, Geophys. Rev. Lett., 24, 2689, 1997.