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Atmospheric Chemistry and Physics Discussions

Nadir measurements of the Earth's atmosphere with the ACE FTS: first results

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Abstract

The primary objective of the Canadian SCISAT mission is to investigate the processes that control the distribution of ozone in the stratosphere. The SCISAT satellite consists of two major science instruments; an Atmospheric Chemistry Experiment (ACE) high-resolution Fourier-transform spectrometer (FTS) and an ultraviolet/visible/near-infrared spectrograph. These instruments primarily function in occultation mode; however, during the dark portion of the orbit the Earth passes between the sun and the satellite. This configuration provides the opportunity to acquire some nadir-view FTIR spectra of the Earth. Nadir spectra obtained with the ACE FTS are presented and analyzed for methane, ozone and nitrous oxide. The measurements show that the instrument should have sufficient signal-to-noise ratio to determine column gas amounts of the major trace constituents in the atmosphere. Possible applications of these measurements to the study of global warming and air pollution monitoring are discussed.

1 Introduction

The SciSat satellite was launched successfully on 12 August 2003 carrying the Atmospheric Chemistry Experiment (ACE) (Bernath, 2006). The satellite consists primarily of two science instruments, the ACE Fourier-transform spectrometer (FTS) and an optical spectrograph for the Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO). SCISAT uses the occultation of the Sun by the Earth to make detailed determinations of the structure and chemistry of the atmosphere in heights ranging from 4 to 100 km above the Earth's surface. The satellite orbits the Earth 15 times each day providing an opportunity to observe sunlight which has passed through the Earth's atmosphere during 15 brief “sunrises” and “sunsets”, which results in 30 sets of observations each day.

However, in between the sunset and sunrise occultation the ACE FTS is pointed at the dark-side of the Earth, and therefore, is capable of acquiring and storing nadir spectra of the Earth's atmosphere. This could potentially result in the acquisition of another set of atmospheric gas measurements, i.e., column gas amounts, which can be made for each satellite orbit (Kobayashi et al., 1999). Thus, the nadir-view data could potentially contribute extra science to the ACE mission and provide complementary data to the IASI (Phulpin et al., 2007) and TES (Beer, 2006) missions. For example, radiative trapping or the absorption of upwelling thermal radiation by the atmosphere could be measured for several greenhouse gases. This type of information is important for verifying that climate models are correctly predicting the forcing function aspect of global warming (Evans and Puckrin, 2001; IPCC, 2001; Harries et al., 2001). In addition, column amounts are useful for determining the presence of localized sources of pollution (Reichle et al., 1990). The nadir data measured with the ACE instrument could be very useful for filling in spatial gaps between occultations in the measurement of several stratospheric gases, particularly ozone. The potential science for future nadir missions could be evaluated as well. In the past we have measured the radiative trapping from CFC11 and CFC12 from IMG spectra (Evans and Puckrin, 2002; Kobayashi et al., 1999). The radiative trapping and column amounts for ozone, methane, nitrous oxide and carbon dioxide also can be easily measured with good signal-to-noise (SNR) from the IMG spectra.

Previously, tests were performed on the ACE FTS instrument at the Space Instrument Calibration Facility at the University of Toronto in March 2003 (Puckrin et al., 2003), using gases in a cell and a radiative contrast of about 100 K to approximately simulate a nadir sensing scenario to determine if the ACE FTS instrument was, in principle, capable of measuring gases in a nadir configuration. Methane, ozone and carbon monoxide gases were used in the cell for the purpose of simulating the measurement characteristics of the ACE FTS instrument with respect to the nadir radiation emanating from the planet's surface and atmosphere over most of the thermal infrared region. These measurements indicated that the ACE FTS had a sufficient SNR to measure the column amounts of several trace gases in the atmosphere.

In this paper, we present initial results from a collection of nearly 1000 nadir spectra that were measured by the ACE FTS from orbit for a period of 2 min over South America on 6 May 2004 (Fig. 1). These spectra represent the first nadir measurements ever acquired with the ACE FTS. The ACE FTS operates at a resolution of 0.02 cm^{-1} for the occultation measurements; however, to reduce the noise in the nadir observations of the Earth's atmosphere the resolution was reduced to 0.4 cm^{-1} and measurements taken over approximately 16 s were coadded (100 spectra). The measurement modes of the ACE FTS are summarized in Table 1. This configuration results in the acquisition of column gas amounts that represent an average measurement over a horizontal spatial scale of about 100 km at the Earth's surface.

2 Results and discussion

An example of the raw nadir spectra collected over South America is presented in Fig. 2a. In each figure the average uncalibrated radiance of approximately 100 individual scans collected over a period of 16 s are presented, along with the maximum and minimum spectra in each collection of 100 scans. In Fig. 2b an indication of the uniformity of each set of 100 spectra is presented in which the spectral radiance of each scan has been integrated over wavenumber. It is apparent that typically there is a variation of about 2% in the integrated radiance which is likely attributed to changes in surface scene and possibly the instrument self emission.

In order to calibrate the radiance spectra shown in Fig. 2a, exoatmospheric measurements of the Sun and deep space were also obtained with the ACE FTS, as shown in Figs. 3 and 4, respectively. The Sun spectra were used to represent a hot blackbody calibration source, and they were obtained in occultation at very high altitude above the Earth's surface to avoid atmospheric absorption. The time series integrated spectra show that these measurements are very uniform and have an rms noise value of 0.2%. The deep space spectra were measured approximately 1.5 degrees off the Sun, and these spectra represent a cold source for characterizing the instrument self-emission. The cooling effect on the optics after pointing away from the Sun is evident in the time series integrated spectra.

The FTS spectra of the hot source (Sun) and cold source (deep space) were used to calibrate the average nadir spectrum, as shown in Fig. 5a. The deep space and nadir spectra have been expanded by a factor of 20 in order to compare more readily the differences between them. The two measurements are very close in intensity. In fact the deep space measurement (cold source) appears more intense than the nadir measurement. This effect can be attributed to the fact that the temperature of the ACE-FTS field-stop was decreasing between the time of the nadir measurements and the deep space measurements. The calibration result for a resolution of $0.4\,\text{cm}^{-1}$ is shown by the blue curve in Fig. 5b. As expected, the calibrated spectrum is negative due to the temperature impact on the deep space and nadir spectra. However, atmospheric features can still be easily identified in the spectrum, particularly the ozone band at $1050\,\text{cm}^{-1}$. An attempt was made to correct for the variable temperature effect of the FTS field stop. The cold source measurement (i.e., deep space) was corrected (gray curve) by accounting for the maximum field-stop temperature difference of 3°C that existed between the nadir and deep space measurements (Fig. 6). Implementing the corrected deep space measurement in the calibration procedure yields a more realistic nadir radiance (red curve), which approximately corresponds to an Earth surface temperature of 273 K. This is likely too low for this geographical region in May; however, it's possible that some cloud cover may have been present which would have resulted in a lower temperature than expected. It is probable that other optical components (e.g., beamsplitter) must also be considered to account correctly for the total temperature change. In order to verify the temperature-related impact from other optical components it will be necessary to compare ACE nadir measurements with another space-based sensor or some ground-truth measurements. This would help to confirm the full thermal impact on the nadir measurements and lead to a possible method to model the effect and account for it more accurately in the calibration procedure.

A nadir spectrum of the US standard (USS) atmosphere (Anderson et al., 1986) was simulated using the line-by-line radiative transfer model (LBLRTM) (Clough et al.,

2005) and incorporated line parameters from the HITRAN 2000 database (Rothman et al., 2003), and this result is compared in Fig. 7 to the nadir radiance measured by ACE over South America. The qualitative comparison shows that absorption features relating to ozone, methane and water vapour are clearly evident, but less so for nitrous oxide. The noise equivalent spectral radiance (NESR) of the ACE measurement was estimated to be about 3.4×10^{-7} W/(cm^2 sr cm^{-1}), resulting in a SNR of about 12:1 for ozone. A similar comparison is shown in Fig. 8 between the ACE measurement at 0.4 cm^{-1} and an IMG measurement at 0.1 cm^{-1} obtained with a higher SNR.

An improvement in NESR can be realized by degrading the resolution of the measurement by truncating the ACE-FTS interferogram and re-calculating the spectrum, as shown in Fig. 9. Degrading the resolution to 1 cm^{-1} decreases the NESR to about 2.2×10^{-7} W/(cm^2 sr cm^{-1}) and increases the SNR to 18:1 for ozone (Fig. 9a). Further degradation of the resolution to 2 cm^{-1}, as shown in Fig. 9b, results in an NESR of 1.2×10^{-7} W/(cm^2 sr cm^{-1}) and a SNR of 33:1 for ozone. It is interesting to note that this resolution is approximately equivalent to the 2.8 cm^{-1} that was used by the Infrared Interferometric Spectrometer (IRIS) in 1970–1971 to make global measurements of atmospheric gases from orbit. Recently, it has been demonstrated that IRIS data at this resolution can be compared with current satellite measurements in order to study the change in the radiative forcing of greenhouse gases over a period of more than 30 years (Harries et al., 2001). This could present another possible application of ACE nadir measurements. However, it should be noted that an occultation measurement is lost every time a nadir measurement is acquired. Figure 9c displays the nadir spectrum at a resolution of 4 cm^{-1}. The resulting NESR has improved to 6.8×10^{-8} W/(cm^2 sr cm^{-1}) and the ozone SNR is now about 60:1. The final degradation to a resolution of 8 cm^{-1} is shown in Fig. 9d. The NESR is 2.9×10^{-8} W/(cm^2 sr cm^{-1}), which results in a corresponding SNR of better than 130:1 for ozone. These nadir spectra, obtained by manually degrading the ACE-FTS spectra, exhibit ozone SNRs of greater than 50:1 may provide an important method for monitoring air pollution on a global basis. Nadir spectra, which represent the total atmospheric ozone column,

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may potentially be combined with occultation spectra, which represent primarily the stratospheric ozone contribution. This may provide a possible method to recover the tropospheric ozone component, which would be useful for the global mapping of urban air pollution.

3 Conclusions

Example results from the first nadir spectral measurements ever obtained with the ACE FTS have been presented in this paper. The measurements were obtained at a resolution of 0.4 cm^{-1} over South America on 6 May 2004. Average nadir spectra consisting of 100 co-additions have been analyzed to determine if atmospheric absorption features are present. It has been shown that the integrated radiance can change by as much as 4% over a measurement period of 16 s; it is, therefore, necessary to choose sequential spectra that are relatively uniform in order to achieve a higher SNR.

It has also been shown that calibration difficulties exist due to the thermal drift of the FTS optics. However, a pseudo-calibration that takes into consideration the changing temperature of the FTS field stop during the calibration and nadir measurements has permitted an analysis of ACE nadir spectra to show sufficiently that ozone and methane features are readily visible. Future work incorporating a comparison of measurements with other sensors or ground truth may lead to a satisfactory method of modelling the optics' temperature that will address the temperature variation impact on the calibration procedure.

Degrading the resolution of the nadir spectra (by truncating the ACE-FTS interferograms) also resulted in much higher SNR values for ozone which should be sufficient to extract total column amounts of this gas. This resolution is approximately the same that was used by the IRIS instrument in the early 1970s to measure atmospheric gas columns. Hence, the ACE FTS could potentially provide a useful database that may be compared to the earlier radiative forcing results obtained by the IRIS instrument. This could provide one of the very few experimental determinations of the increase in

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global warming from greenhouse gases such as carbon dioxide and methane. In addition, a comparison of occultation measurements with nadir measurements obtained with the ACE FTS may potentially be useful for monitoring air pollution sources on a global basis.

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Table 1. ACE FTS Instrument settings for Occultation and Nadir Measurements.

Mode	Resolution (cm^{-1})	Single Scan Duration (s)	Total Measurement Duration (s)	Spectral Range (cm^{-1})	Footprint (km)
ACE Occultation Measurement (high resolution)	0.02	2	2	700–4100	n/a
ACE Nadir Measurement (low resolution)	0.4	0.1	16 (100 scans)	700–4100	100×1
IMG Nadir Measurement	0.1	10	10 (1 scan)	714–3030	8×8

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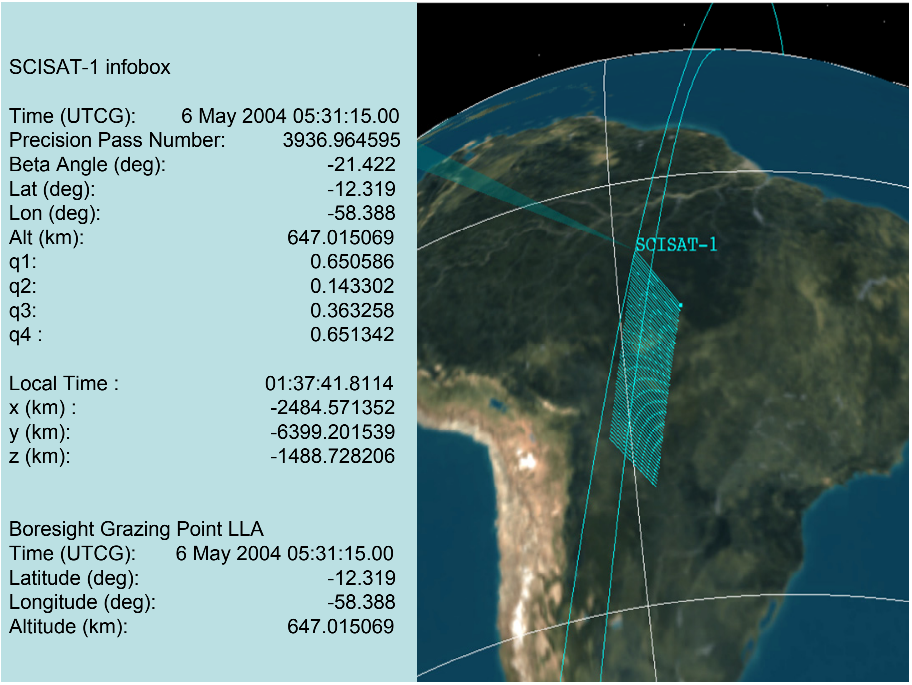

Fig. 1. Schematic diagram showing the path of SCISAT-1 over South America during the acquisition of 1000 nadir spectra on 6 May 2004.

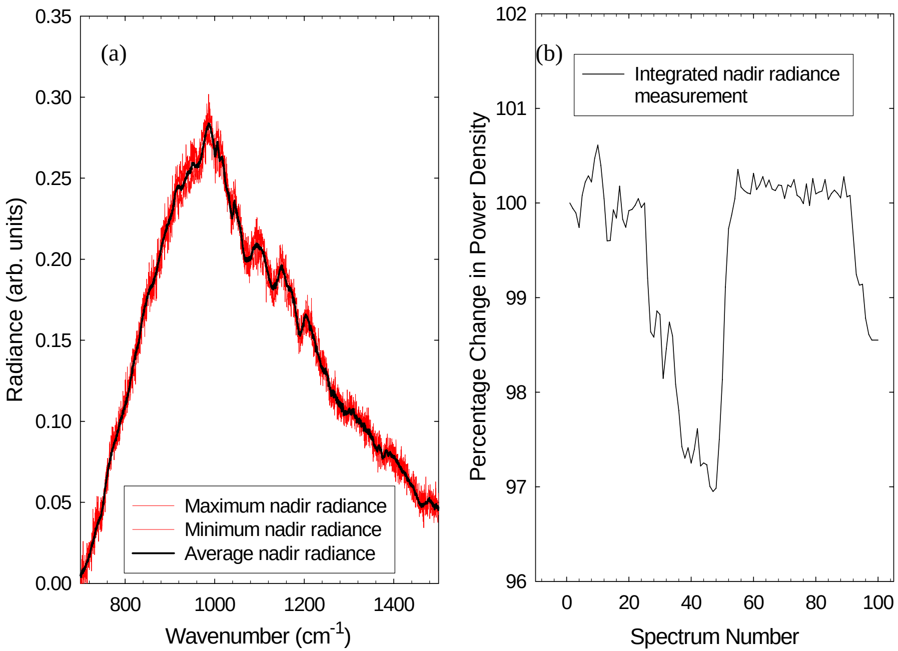

Fig. 2. (**a**) Raw nadir radiance spectra of the Earth showing the average of 100 scans, acquired over a time of 16 s, and the upper and lower limits. (**b**) Time sequence showing the variation in the radiance of the 100 spectra. These variations may be associated with the presence of cloud cover or changes in surface reflectivity.

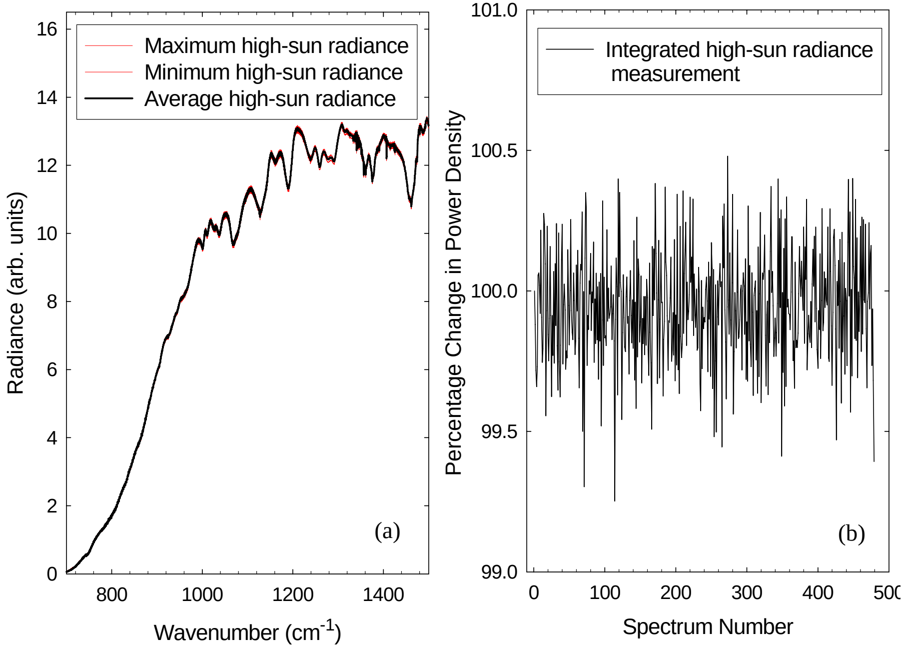

Fig. 3. (**a**) Radiance measurements of the Sun at high altitude above Earths surface. (**b**) Time sequence of 500 Sun spectra showing stability of measurements.

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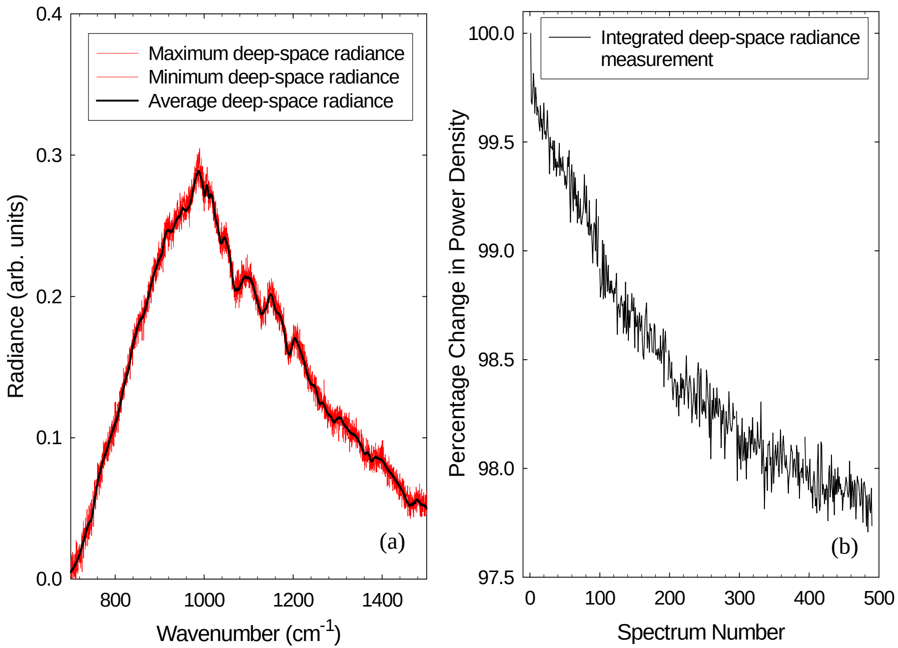

Fig. 4. (**a**) Radiance measurements of deep space at high altitude above Earths surface. (**b**) Time sequence of 500 deep-space spectra showing relative change of measurements due to the decreasing temperature of the FTS optics.

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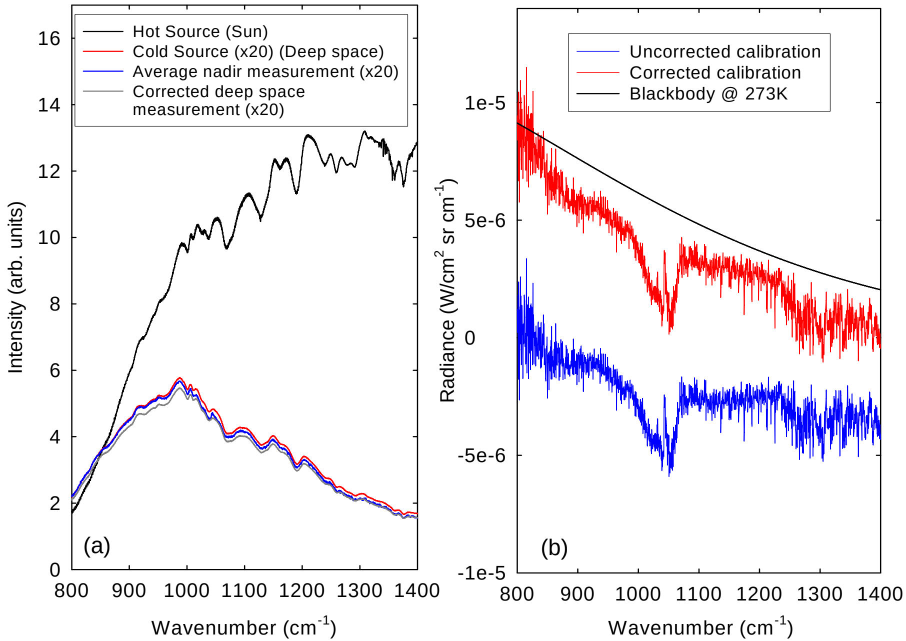

Fig. 5. (**a**) Raw ACE spectra used to calibrate nadir measurements. The cold source measurement (i.e., deep space) was corrected (gray curve) by accounting for the maximum field-stop temperature difference of 3°C that existed between the nadir and deep space measurements (Fig. 6). (**b**) The uncorrected calibration results in a negative nadir radiance (blue curve). Accounting for the change in the field-stop temperature between the nadir and deep space measurements yields a more realistic nadir radiance (red curve), which approximately corresponds to an Earth surface temperature of 273 K.

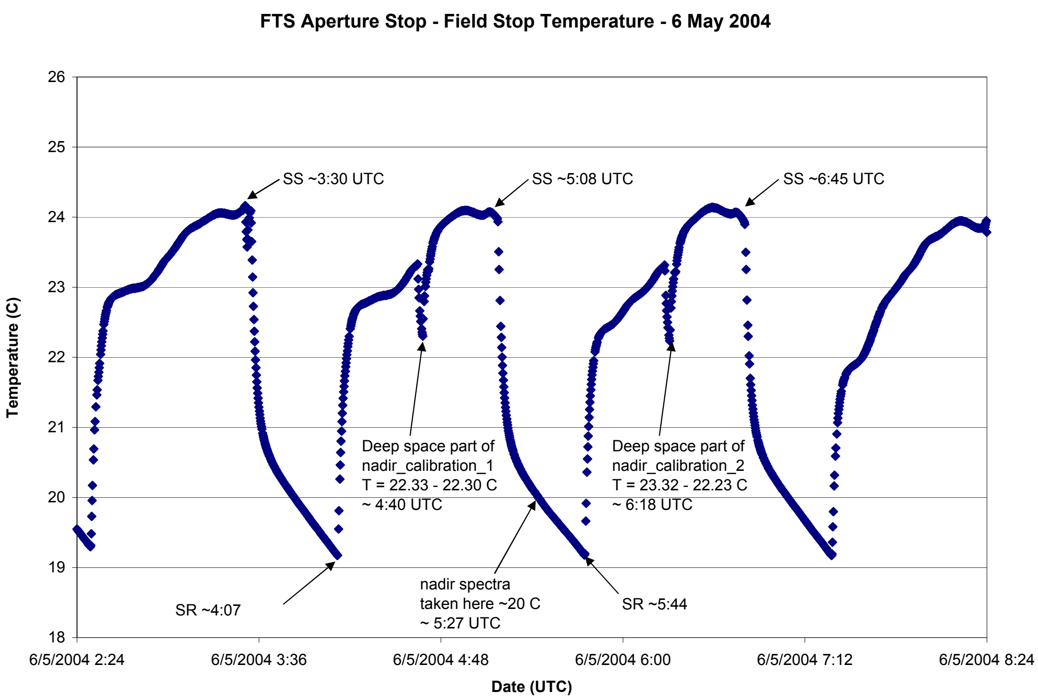

Fig. 6. Temperature behaviour of the ACE FTS field stop. The plot shows that the temperature of the stop changes by about 2°C between the time of the deep space cold measurements and the nadir measurements. The temperatures of other optical components will be necessary to consider in the calibration procedure of the nadir spectra. SR represents sunrise and SS represents sunset.

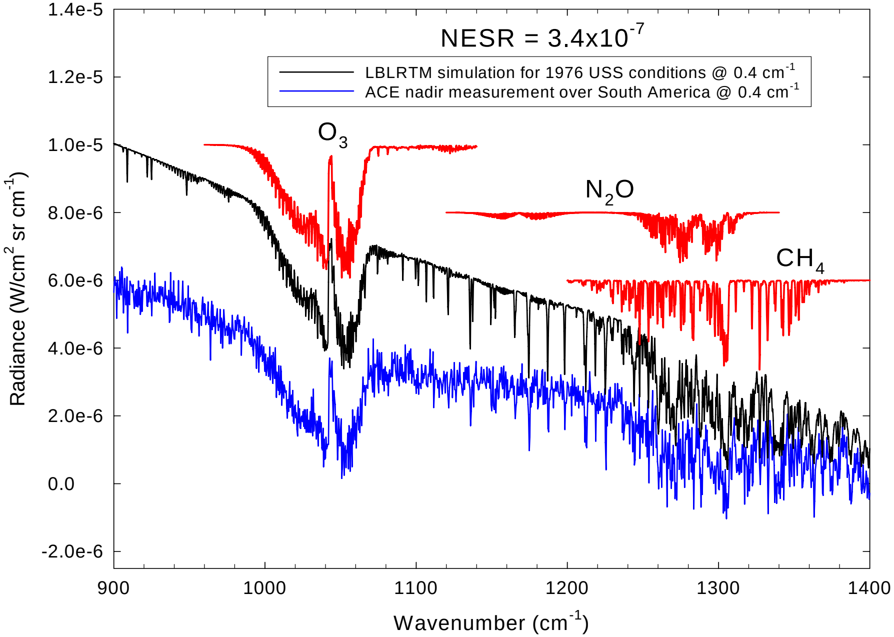

Fig. 7. Nadir radiance spectra of the Earth measured by the ACE FTS at a resolution of $0.4\,cm^{-1}$ and compared to the radiance for a USS atmosphere simulated by the LBLRTM model. Important absorption features of significance are shown in red.

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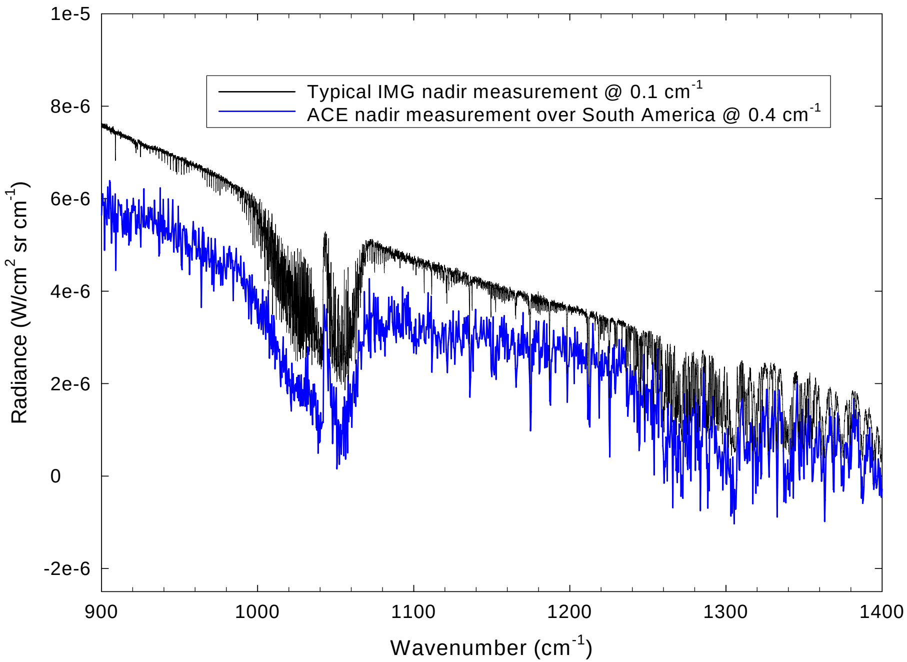

Fig. 8. A qualitative comparison between the nadir spectra measured by the ACE and IMG FTS systems. The ACE measurement is at a resolution of 0.4 cm^{-1}, and the IMG measurement is at 0.1 cm^{-1}.

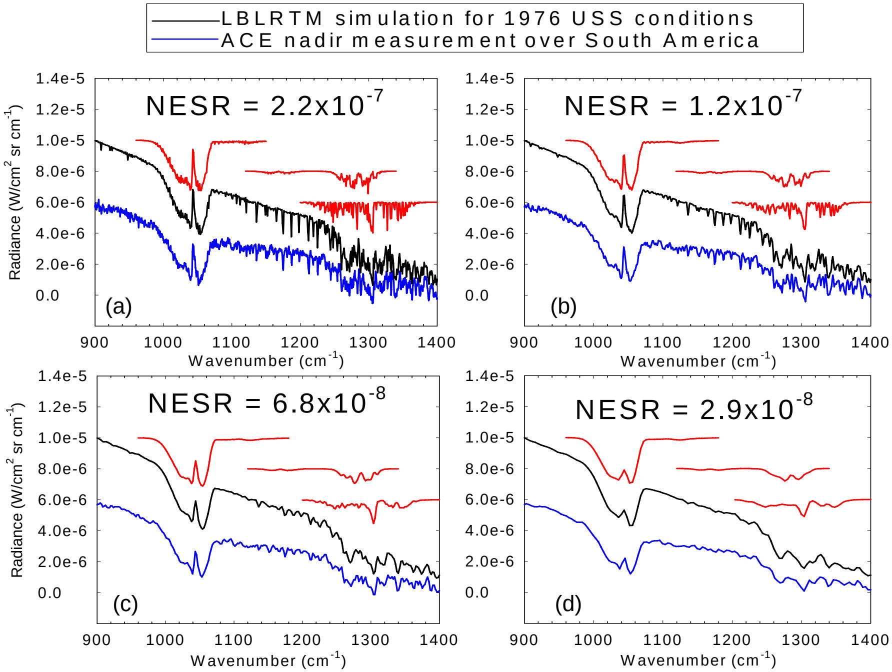

Fig. 9. Nadir radiance spectra of the Earth measured by the ACE FTS at a resolution of (**a**) 1 cm^{-1}, (**b**) 2 cm^{-1}, (**c**) 4 cm^{-1} and (**d**) 8 cm^{-1}. The spectra of three trace gases (in red), ozone, nitrous oxide and methane, have been simulated with the LBLRTM radiative transfer model for comparison.

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