Invited Paper

SciSat-1 mission overview and status

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ABSTRACT

SciSat-1, otherwise known as the Atmospheric Chemistry Experiment (ACE), is a satellite mission designed for remote sensing of the Earth's atmosphere using occultation spectroscopy. It has been developed under the auspices of the Canadian Space Agency and is scheduled for launch in August 2003. The suite of instruments on the satellite consists of a high-resolution (25 cm maximum path difference) Fourier Transform Spectrometer (FTS) operating in the infrared (2.4 to 13.3 microns), a UV/Visible Spectrometer operating between 0.285 and 1.03 microns with a resolution of 1 to 2 nm, and a pair of filtered imagers operating at 1.02 and 0.525 microns. The primary science goal of the ACE mission is to investigate the chemical and dynamical processes that govern ozone distribution in the stratosphere and upper troposphere. To this end, vertical profiles for trace gases, aerosols, temperature and pressure will be deduced from analysis of the solar occultation spectra. In particular, the role of heterogeneous reactions on ozone loss will be investigated, with a focus on the Arctic winter stratosphere.

Keywords: remote sensing, occultation spectroscopy, ozone

1. INTRODUCTION

The Atmospheric Chemistry Experiment (ACE) is the first in a planned series of small science satellites to be flown by the Canadian Space Agency. Scheduled for launch in August of 2003, ACE will perform remote sensing of the Earth's atmosphere from low Earth orbit (650 km altitude). The ACE mission will contribute to the investigation of ozone depletion mechanisms, with a focus on northern high-latitudes.

Ozone in the stratosphere and upper troposphere shields organisms on the Earth's surface from harmful solar ultraviolet radiation. Thinning of that shield in recent years is a serious and alarming issue. Detailed investigations are needed to clarify and quantify the reasons for the declines, so that contributions from human activity can be assessed

The distribution of atmospheric ozone is an extremely complex issue, involving an array of chemical and dynamical processes. Thus, an in-depth investigation of ozone requires much more than simply monitoring ozone itself. One must simultaneously measure temperature, pressure, and the concentrations of dozens of molecules (ideally as a function of altitude, geographical location, and time), as well as measure and quantify aerosols, including composition, size distribution, and shape.

The most dramatic atmospheric ozone-related issue is the large region of extreme ozone destruction that occurs every September/October (spring in the Southern Hemisphere) in the Antarctic, a phenomenon that has been dubbed the "ozone hole." The primary cause of the ozone hole is heterogeneous reactions.[1] During the polar winter, air descends and takes on a westerly circulation, known as the *polar vortex*. Air cannot easily move across the vortex boundary. Thus, the air inside the vortex is isolated from the air outside, and the vortex then serves as a crucible for destruction of the ozone contained within. In the Antarctic, stratospheric temperatures during the polar winter are typically cold enough (below about 195 K) to condense the small amount of water (in conjunction with other constituents such as nitric acid) into clouds, which are known as *polar stratospheric clouds* (PSCs). These cloud particles act as catalysts for

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reactions that release species such as Cl_2 and BrCl into the stratosphere. When the sun returns in the spring after the long polar night, these species photolyze into Br and Cl, both of which then proceed to rapidly deplete odd oxygen species such as ozone. The chemical processes behind ozone destruction during polar spring were described in more detail in a previous SPIE proceedings.[2]

No ozone hole occurs in the Arctic, although there is typically a thinning of the ozone layer in March (spring in the Northern Hemisphere), as seen in Fig. 1.

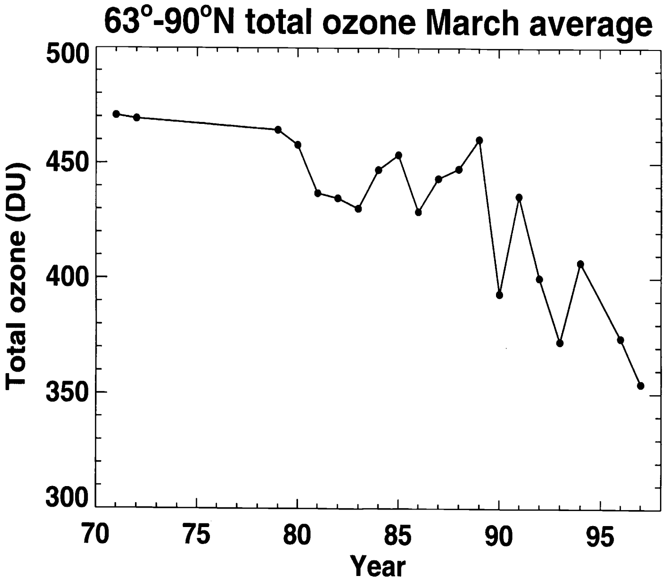


Fig. 1: Ozone column amounts averaged over the Arctic region and averaged over the month of March

Ozone destruction in the Arctic is less pronounced than what occurs in the Antarctic because downward transport of ozone-rich air masks the strong ozone depletion.[3] Additionally, Arctic stratospheric winter temperatures are generally warmer than those in the Antarctic because the vortex is often in sunlight. Colder temperatures lead to the formation of more polar stratospheric cloud particles, and consequently more severe ozone destruction. The degree of ozone depletion in Fig. 1 tracks very well the minimum temperature measured in March, consistent with heterogeneous PSC chemistry being the primary cause of stratospheric ozone losses for the Arctic polar spring.

Although there is currently no Arctic ozone hole, at least one model[4] predicts that the combination of increasing greenhouse gases and ozone-depleting halogens will cause an Arctic ozone hole in the 2010 to 2020 time frame. Greenhouse gases warm the Earth's surface, but lead to radiative cooling of the stratosphere. This could contribute to a more stable Arctic vortex, which would cool the Arctic winter stratosphere even further. A colder stratosphere means more PSCs and therefore more ozone depletion.

However, a recent compilation of long term predictions for Arctic ozone[5] shows a lack of consensus among the various models as to the future of Arctic ozone. Even the sign of the change in ozone levels during Arctic polar spring varies from one model to the next. There is a clear need for high quality measurements in northern regions to be assimilated into these models and thereby improve the clarity of the predictions.

In addition to the dramatic springtime ozone destruction events, there has been a steady decline in average ozone amounts observed by all five of Canada's long-term monitoring stations, as seen in Fig. 2. The measurements were taken using ground-based Brewer spectrophotometers.[6] Ozone sonde measurements show that most of the decline has occurred in the lower stratosphere. Similar declines have been observed over mid-latitudes in Europe. This thinning of the ozone layer over large population centres in Canada and Europe is certainly a cause for grave concern.

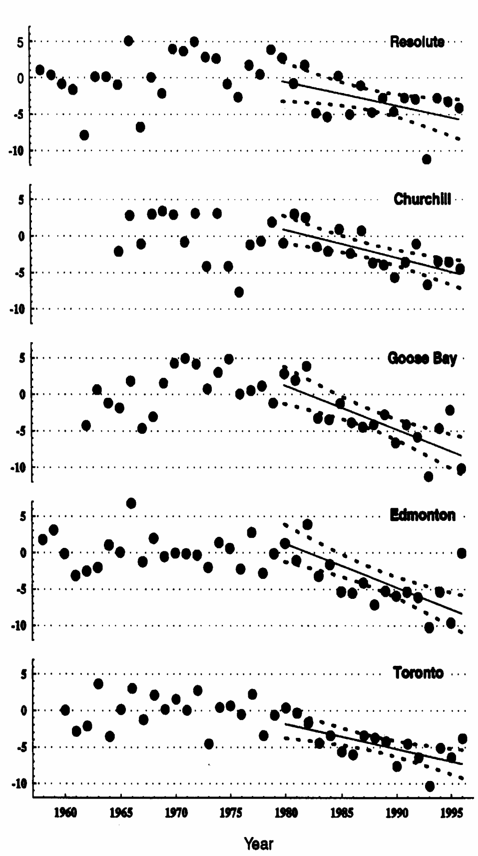


Fig. 2: Trends in mid-latitude ozone over Canadian monitoring stations.

These declines cannot be attributed to polar chemistry, although transport of ozone-depleted air following polar spring may contribute. It is important to be able to understand and model the processes that lead to ozone depletion, both for the polar spring events and for the mid-latitude declines. Only then could we understand best how to minimize the impact of human activity on this key component of our environment.

2. ACE Science Goals

ACE will focus primarily on one important and serious aspect of the atmospheric ozone problem, namely the decline of stratospheric ozone at northern mid-latitudes and in the Arctic described above. It will be important to quantify both chemical and dynamical contributions to ozone loss. To that end, models (from simple chemical box models to more elaborate atmospheric global circulation models) will play a major role in interpreting the data. It will also be important to quantify aerosols and PSCs, including density, size distribution, and composition.

The science priorities for the ACE mission are summarized below.

Priority 1:
a) Measurement of regional polar O_3 budget to determine the extent of O_3 loss. This will require measurements of O_3, tracers (CH_4 and N_2O), and meteorological variables (pressure and temperature).

b) Measurement / inference of details of O_3 budget by detailed species measurements and modeling.
c) Measurement of composition, size distribution, and density of aerosols and polar stratospheric clouds in the visible, near infrared, and mid infrared.
d) Comparison of measurements in the Arctic and Antarctic with models to provide insight into the differences, and with emphasis on the chlorine budget and denitrification.

Priority 2:
a) Mid-latitude O_3 budget.
b) Measurement of Arctic vortex descent.

Priority 3:
a) Study of upper troposphere chemistry.
b) Monitoring of CFCs (chlorofluorocarbons), CFC substitutes, and greenhouse gases.

3. Mission Design

SciSat-1 was designed as a low weight, low power, and low cost (relative to typical satellite missions) platform for remote monitoring of the Earth's atmosphere. The baseline duration of the mission is two years, but with no on-board consumables and few moving parts, the satellite has the potential to operate for a long time. It was patterned after the successful ATMOS series of missions[7] that flew four times on the space shuttle but has a much broader range of frequency measurements, a necessary feature for the detailed study of aerosols.

An artist's depiction of the ACE satellite in orbit is shown in Fig. 3. The satellite is essentially a pair of plates with instruments bolted to the back of the rear plate. Attached to the front plate (the side always facing the sun) are solar cells that will provide power to the satellite. An aperture on the front plate allows sunlight through to the instruments. The primary instrument is a high-resolution (25 cm maximum path difference) infrared Fourier Transform Spectrometer (FTS), operating from 2.4 to 13.3 microns (750 to 4100 cm^{-1}). A passive cooler will maintain the FTS detectors at a temperature below 95 K (typically the order of 80 K) in order to achieve the required signal-to-noise. Also on board is an ultraviolet/visible/near infrared spectrometer known as MAESTRO (Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation), operating between 285 and 1030 nm, with a resolution of approximately 1-2 nm. Extinction of solar radiation at 1.02 and 0.525 microns will be measured by a pair of filtered imagers. A suntracker will be used at the input aperture to ensure the instruments point at the radiometric centre of the sun. A startracker will provide accurate determination of spacecraft orientation and will be used for feedback control of spacecraft roll, in order to keep the MAESTRO input slit aligned horizontal to Earth horizon during measurements.

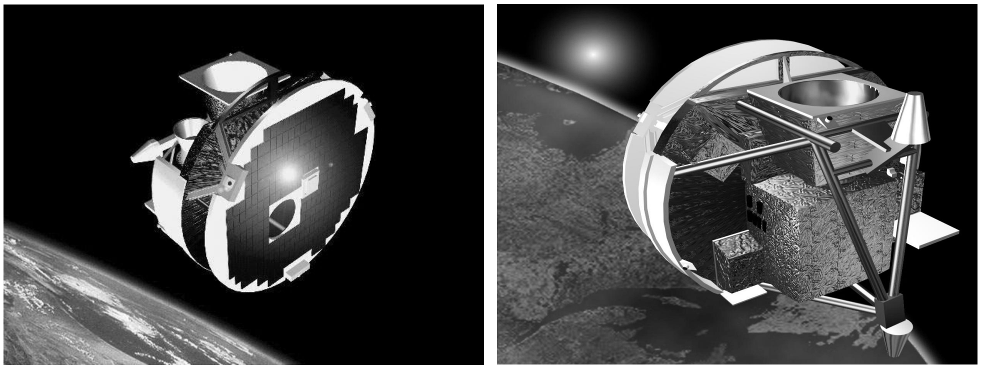


Fig. 3: ACE in orbit (from Tom Doherty 2002). The front view is on the left and the rear view is on the right. The image on the right is more up-to-date, reflecting a 90 degree rotation of the antenna in the satellite design.

The measurement technique to be used is known as solar occultation, the geometry for which is depicted in Fig. 4. The satellite always points at the sun, and measurements are taken just after the sun rises or just before it sets over the horizon. As the satellite progresses in its orbit, a set of measurements is taken for different paths of sunlight through the atmosphere. This approach allows variations as a function of altitude (e.g., in temperature or molecular concentration) to be inferred from the measurements. A set of pure solar measurements with no intervening atmosphere (denoted exoatmosphere in Fig. 4) are used as reference spectra in the calculation of transmittances, making the ACE instruments self-calibrating.

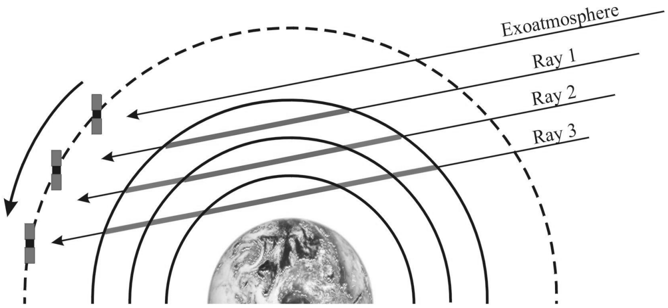


Fig. 4: Solar occultation geometry

The high inclination (74°), circular low Earth orbit (650 km altitude) selected for ACE gives a degree of global coverage, but with a strong weighting towards occultations in the polar regions. The right ascension of the ascending node for the orbit was tuned to provide polar coverage during the times of year when ozone depletion is most severe.

3.1 ACE-FTS

ABB Bomem Inc. in Quebec City constructed the SciSat-1 FTS, a custom design to meet the needs of the mission. It is a Michelson interferometer with a folding mirror inside the interferometer to provide high resolution in a compact instrument, and with full compensation for both tilt and shear in both the moving and stationary optics. Other papers in these proceedings provide more detail on the FTS design.

The signal-to-noise ratio (SNR) requirement for the FTS was 100:1 over the majority of the measurement range (750 – 4100 cm^{-1}), with a goal of 200:1 SNR. The SNR goal is easily met for much of the frequency range, but contamination of the cryogenic detectors with water ice leads to significant signal losses within the ACE-FTS frequency range. Of particular concern is the region 780 cm^{-1}, the region with spectral features for chlorine nitrate, an important molecule in the chemistry of polar ozone loss. Signal losses due to absorption by the ice contamination drops the SNR to well below the requirements at this wavenumber. More details on these contamination effects will be provided in another paper in these proceedings.[8] In order to derive information on the important chlorine nitrate molecule from ACE measurements, much priority will be placed on decontaminating the detectors during early orbit operations, and likely throughout the mission.

The scan time at maximum spectral resolution (~0.02 cm^{-1}, unapodized) for ACE-FTS is two seconds. The resulting vertical resolution of solar occultation measurements will be 3 to 4 km. There are also lower resolution settings for the instrument (0.04, 0.08, and 0.4 cm^{-1}) that use shorter scan times, but these lower resolutions will not be used on an operational basis.

In addition to the normal occultation measurements, the ACE-FTS will be used occasionally to make nadir measurements. Because the SNR of a single scan would not be high for such measurements, a rapid series of short scans would be recorded and co-added on the ground.

More than thirty molecules will be monitored on a regular basis using the ACE-FTS, including but not limited to: O_3, H_2O, N_2O, CH_4, CO, NO, NO_2, HNO_3, HCl, HF, $ClONO_2$, N_2O_5, CCl_3F, CCl_2F_2, ClO, HCN, and hydrocarbons associated with biomass burning. CO_2 spectral features will be used to derive pressure and temperature information from ACE-FTS measurements.

Because we are working at high resolution, contributions to the spectrum from different molecules can often be considered separately, thereby simplifying the analysis. There will also be a concerted effort to determine information on aerosols (and particularly polar stratospheric cloud particles) from the infrared. Structure in aerosol spectra in the infrared gives information on composition that cannot be derived from other frequency regions, and plans are in place to exploit that spectral information.

3.2 MAESTRO

MAESTRO was built in a partnership among the Meteorological Service of Canada, the University of Toronto, and the Ottawa-based company EMS Technologies. The design is a simple concave grating with no moving parts, divided into two overlapping spectrographs (280-550 nm and 500-1030 nm) to improve the stray light performance. The detectors are linear EG&G Reticon photodiode arrays with 1024 elements. MAESTRO's entrance slit will be maintained horizontal to the horizon during occultation measurements by controlling spacecraft roll using a momentum wheel on the satellite. Other papers in these proceedings provide more detail on the design of MAESTRO.

The vertical resolution of MAESTRO measurements will be about 1 km, and the signal-to-noise ratio will be in excess of 1000 to 1. Gain settings and integration times will be varied dynamically over the course of an occultation for this instrument.

Although MAESTRO will operate primarily in occultation mode, it will also be able to make some near-nadir solar backscatter measurements like the GOME instrument on the European ERS-2 satellite.[10]

Molecules to be monitored with MAESTRO include O_3, NO_2, H_2O, $(O_2)_2$, SO_2, OClO, BrO, and HCHO. Aerosol information will also routinely be derived from MAESTRO measurements. For the molecules in common with the ACE-FTS, MAESTRO's higher vertical resolution will permit observation of smaller scale structure in the altitude profiles. O_2 spectral features will be used to derive temperature information from the MAESTRO measurements.

3.3 Imagers

The Imager has two filtered channels at 0.525 and 1.02 microns, chosen to match two of the wavelengths monitored by the SAGE II satellite instrument.[10] These two channels are useful for the study of clouds and aerosols because they are relatively free of absorption by atmospheric molecules. The Imager will also be used to refine pointing knowledge and to determine the co-registration of ACE-FTS and MAESTRO.

The detectors are 256 × 256 active pixel sensors from Fill Factory, a Belgian company. Imagers have field of view 30 mrad, much larger than the 9 mrad extent of the sun in order to avoid clipping the solar image. The signal-to-noise will be greater than 1000 to 1. Images will be generated at a frequency of 4 Hz.

3.4 Ground Segment

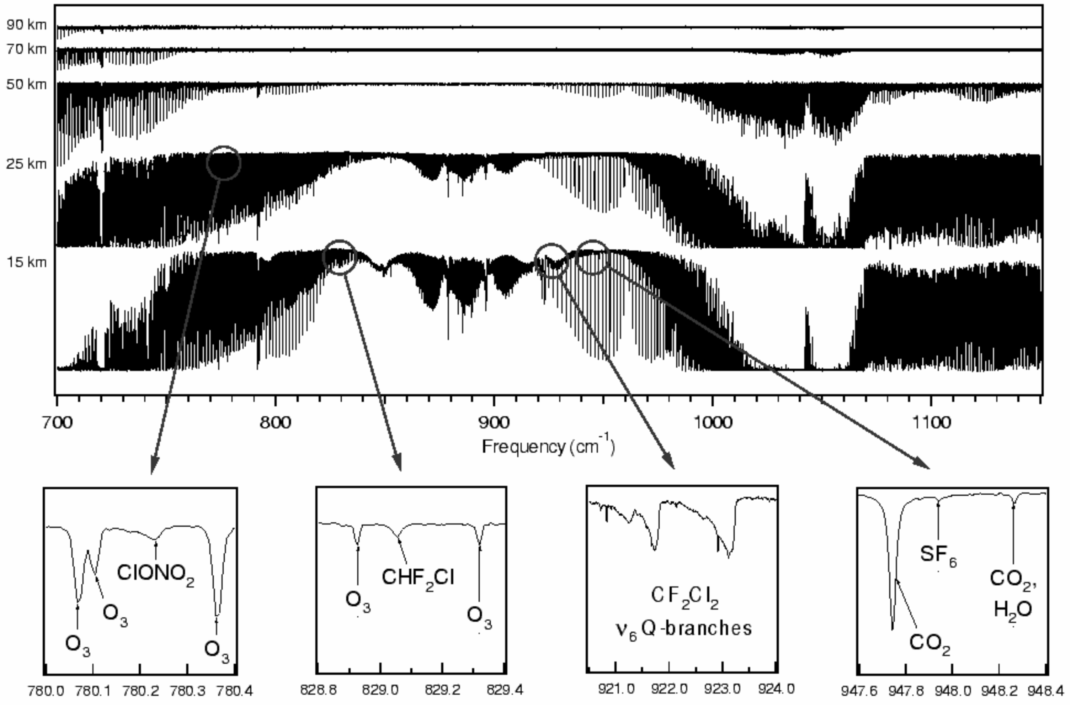
The raw ACE data will be sent to the ground using a combination of two ground stations, one located in St. Hubert, Quebec, and the other in Saskatoon, Saskatchewan. The data volume will be about 1 GB per day. All data collected will be routed to the Mission Operations Centre (MOC) located in St. Hubert. Uplink commands to the satellite will also originate from the MOC. Data will be transferred over the internet from the MOC to the Science Operations Centre (SOC) located at the University of Waterloo in Waterloo, Ontario. The SOC will oversee archiving and analysis of the data, and the distribution of data products to members of the ACE Science Team will occur from this facility.

The SOC features a dedicated processing system for the ACE mission. It includes a Sun Fire 3800 server with 4 GB of RAM, 4 processors, and 650 GB of online storage. There is also a Tape Robot with 2100 GB (native) storage capacity. Prior to launch, the system has been used for development of analysis software for the mission.

Data management at the SOC will make use of relational SQL databases, providing standardized access to the data and greatly enhancing our ability to manage the large volume of data to be generated during the mission. The SOC will use *postgres*. Because this is an open source engine, allowing Science Team members access to the data becomes much more cost effective. The SOC will also provide Science Team members a library of highly portable C and FORTRAN routines for accessing the ACE data, including the ability to access the data remotely over the network.

4. Data Analysis

Fig. 5 shows a series of measurements taken by the ATMOS mission. The labels on the left of the spectra are the *tangent heights*, i.e., how close the solar rays being measured came to the Earth's surface. The ACE-FTS instrument will measure similar sets of spectra.



Infrared transmission at tangent altitudes between 15 and 90 km and between frequencies of 700 and 1100 cm^{-1} (recorded using the ATMOS interferometer onboard the space shuttle, Feb. 1992)

Fig. 5: ATMOS spectra (from Curtis Rinsland)

As can be seen from the insets in Figure 5, it is possible to isolate spectral features primarily due to a single molecule. We therefore analyse small (~ 1 cm^{-1} wide) portions of the spectrum (termed *microwindows*) containing spectral features primarily from the molecules of interest, rather than analysing the entire spectrum.

The ACE-FTS data is analysed in several stages. First, the raw FTS interferograms need to be transformed into corrected atmospheric transmittance spectra using software to be supplied by the instrument contractor, ABB Bomem. Next, the pressure and temperature profiles as a function of altitude are determined. This will be done using a Global Fit type approach[11] to the analysis of a set of CO_2 microwindows, using a fixed volume mixing ratio profile for CO_2. The volume mixing ratio profiles for the molecules of interest are then determined, also using a Global Fit approach. These retrieval procedures were described in more detail in the SPIE proceedings from last year.[12]

Fig. 6 shows a series of synthetic spectra describing what MAESTRO will measure from orbit. Note particularly the significant absorption at short wavelengths by ozone that shows just how effectively the molecule absorbs UV radiation.

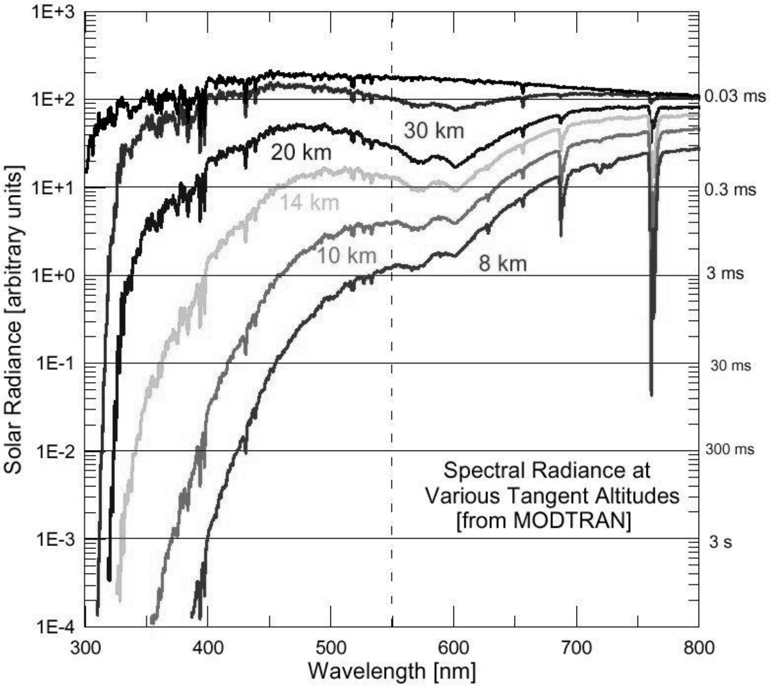


Fig. 6: MAESTRO synthetic spectra (from Tom McElroy)

The MAESTRO algorithms will draw on previous work by McElroy and co-workers with a variety of UV/visible spectrographs that have been deployed, e.g., on the NASA ER-2 aircraft.[13] Because of the low resolution, analysis of MAESTRO data does not employ microwindows.

Data products from the Imager will be SAGE-like atmospheric extinction profiles[14]. In the analysis, pressure and temperature, as well as contributions to the signal from gas phase molecules, will be taken from the ACE-FTS and MAESTRO results.

5. Recent Activities

The various components and instruments associated with SciSat-1 have gone through several rounds of testing. Fig. 7 shows the instruments in the process of integration to the spacecraft baseplate in preparation for environmental and compatibility testing at David Florida Laboratories in Ottawa. Most recently, in mid-February through March of 2003, science instruments underwent calibration and characterization testing at the University of Toronto. The results of that campaign are described in a separate paper in these proceedings.[8]

Following science testing of the instruments, the satellite was assembled at David Florida Laboratories and underwent a final round of whole-satellite testing. From there, it was shipped to Vandenberg Air Force Base at the end of June 2003, and is undergoing preparations for launch, currently scheduled for August 12, 2003.

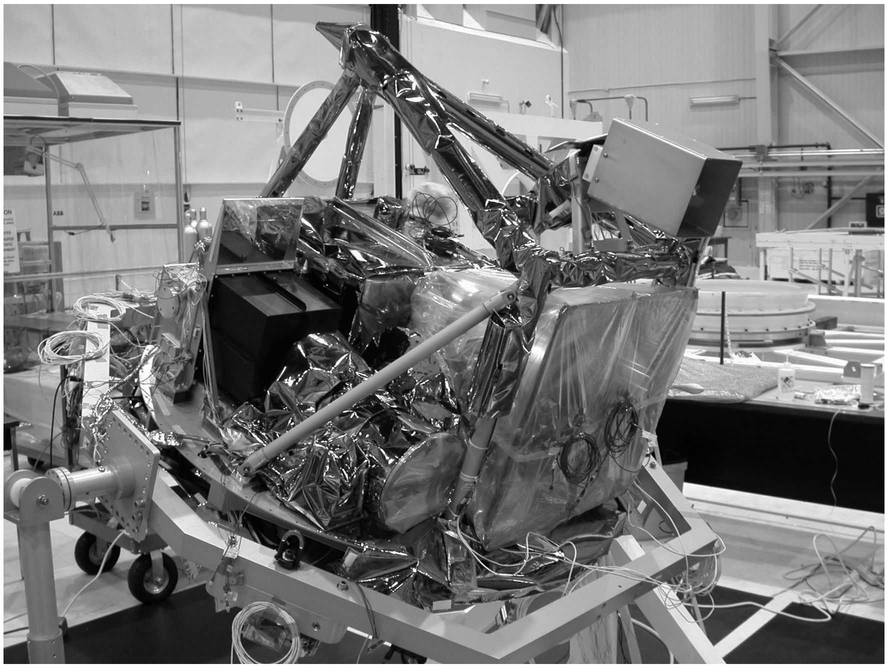


Fig. 7: Instrument integration to spacecraft at David Florida Laboratories.

6. Conclusions

ACE is well suited for the detailed investigation of ozone. The long path lengths in the solar occultation method allow the measurement of trace atmospheric constituents. The geometry allows the measurement of variations as a function of altitude. The ACE orbit provides global coverage, and a continuous data set over the course of the two-year mission will allow the inference of variations as a function of time. The chosen orbit will also permit a detailed study of processes within the polar vortex. The broad spectral range (from the infrared to the UV) not only allows many molecules of interest to be monitored, but also provides a unique opportunity to obtain quantitative information on the aerosols that are so important to atmospheric ozone chemistry.

The possibility of an Arctic ozone hole is a very disturbing development with strong political and social implications. In contrast to the Antarctic ozone hole, an Arctic ozone hole would affect heavily populated parts of the Northern Hemisphere. Our experimental and theoretical understanding of Arctic chemistry is still in a primitive state, a need that will be addressed by the ACE mission

Assimilation of ACE results into models should elucidate the underlying physics and chemistry. A number of scientists affiliated with the mission are prepared to perform this task.

ACKNOWLEDGMENTS

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