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THE ES013 GRILLE SPECTROMETER : A FIRST SPACE FLIGHT

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INTRODUCTION

Limb sounding is an already ancient technique of atmospheric observation, it consists in the observation of the absorption of solar radiation by the atmosphere as the sun sets or rises, especially at zenith angles which are greater than 90°, which is commonly called below the horizon, the factor gained in optical depth is then about seventy compared to the value obtained at the vertical of the lowest point reached in the atmosphere (Fig. 1). The purpose of the ES013 experiment was to observe this absorption from a space-platform in order to be able to get a complete scan of the earth's atmosphere from the altitude of 20 km up to outer space. The same geometry was also planned to be tried in emission. The choice of an infrared instrument is due to the fact that the major gases, O_2 and N_2, do not present any absorptions in the near infrared and that all the absorption is due to the molecules able to present a permanent oscillating dipole moment which is the case for

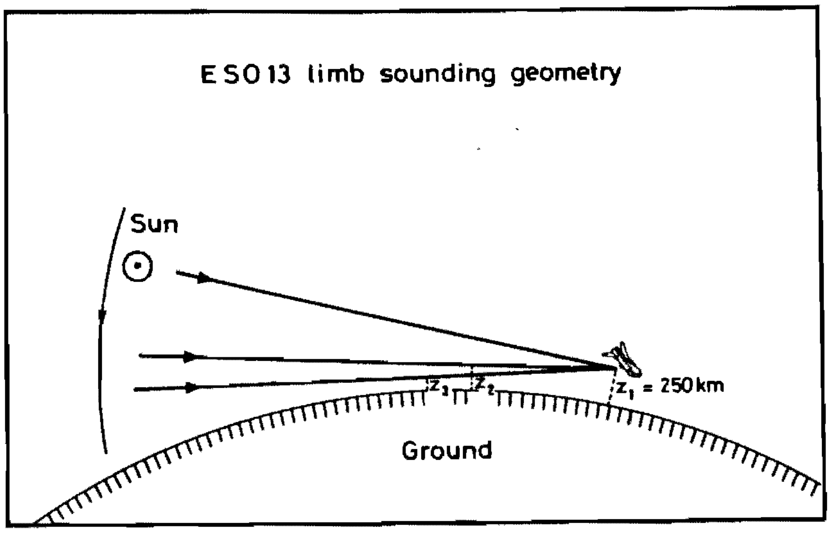

Fig. 1.- Observational geometry during a sunset. The spacecraft being at an altitude of 250 km, the spectrometer heliostat follows the sun as it goes down. At zenith angles greater than 90 degrees, the altitudes Z_2 and Z_3 where the rays are the closest to the earth surface are the zones of main absorption and will be referred as the altitudes of the observation.

all other atmospheric gases with the exception of the noble gases and molecular hydrogen. The targeted gases were : O_3, CO, CO_2, CH_4, NO, NO_2, N_2O, H_2O, HF and HCl. These constituents have been reliably observed in the last decades from balloons and planes in the lower stratosphere (12 to 40 km), and even stratospheric ozone has been routinely monitored for more than 30 years in several meteorological stations. The stratospheric balloon float altitude is rarely higher than 40 km (49 km obtained in 1982 by a team of the BISA supported by the French Space Agency CNES at Aire sur l'Adour being the European record), thus almost no data exists for the upper stratosphere (40 to 55 km), the mesosphere (55 to 90) is uncharted in terms of its composition and the thermosphere (above 90 km) is so poorly studied even in terms of theoretical modeling that we had to rely on educated guesses to decide which constituents to study in those altitude ranges.

Infrared observations, after complete interpretation, permit to obtain the composition of the gas layers as well as the physical state of the absorbing molecules. It is possible that, in the mesosphere, as the intervals between collisions diminish a significant number of molecules in vibrationally excited state could subsist and produce absorptions which could never be simulated in the laboratory.

To reach this level of observations, one has to have access to the individual lines and this could be attained only by a high or medium resolution instrument (better than 0.1 cm^{-1}), moreover this instrument must be able to scan rapidly in order to repeat the observed interval as the sun sets in the atmosphere. Our choice was the grille spectrometer which could be described as a classical grating spectrometer in which the entrance and exit slits are replaced by perfectly aligned hyperbolic grilles. Since its introduction twenty years ago (Girard, 1963), this principle has led to a family of laboratory and ground instruments and since 1971 to spectrometers which have been embarked on planes (Concorde, Caravelle, CV 990) and on balloons, leading to the first stratospheric observations of NO and HCl which ten years ago, contributed to settle the ozone layer depletion controversy. Other possible high resolution instruments are the Fourier transform interferometer and the heterodyne spectrometer, low resolution interferometers were successfull in the American Nimbus and Voyager projects and in the Interkosmos Meteor program. A higher resolution interferometer failed to function due to a mechanical problem during the third shuttle flight and the Nasa ATMOS interferometer will fly in November 1983 on the second Spacelab flight but is critically dependent on the status of the high data rate transmission between the Spacelab and the ground receiving station. Heterodyne spectrometers and Fabry-Perrot cavities have so far not been developped for comparable atmospheric studies because they have been previously very specialized instruments restraining their operations to extremely narrow spectral intervals.

THE INSTRUMENT

Several descriptions of the instrument have already been published, each introducing a new state of completion of the design, of the testing or the scientific programming of the spectrometer (Besson et al, 1978; Vercheval, 1978; Muller and Laurent, 1982; Lippens, 1982; Laurent et al, 1983). These previous papers are still correct, the main change to report is that the instrument and the Spacelab systems proved to be able to operate in non-nominal modes during the flight which had not shown a satisfactory result during preflight testing and simulations.

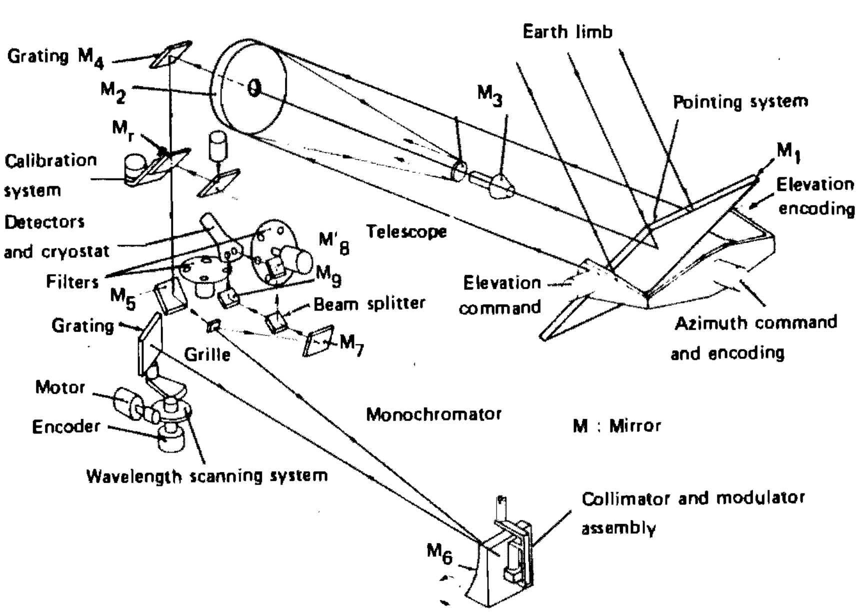

Fig. 2.- Optical diagram of the instrument. The characteristic parts of the grille spectrometer are the grille itself, used in transmission as entrance and in reflexion as exit slit and the vibrating parabolic mirror M6 which aligns the spectrometer once in each oscillation, defining a built in modulation.

The optical diagram of the instrument is presented on figure 2, the image of the Sun, absorbed through the terrestrial limb, is magnified in a 6 meter focal length Cassegrain telescope, its infrared part is then sent to the spectrometer itself, first to the entrance grille, then to the vibrating parabolic mirror, which ensures the modulation (the high resolution is achieved only, when this optical system aligns itself perfectly, which happens one in each oscillation) and then the solar image is diffracted by the grating and sent back to the parabola, and to the grille which this time acts in reflection and leads the signal to two filter wheels. The filters ensure that only one of the grating orders arrives at the two detectors, In Sb and Hg Cd Te. This configuration defines two channels which could be studied simultaneously and permits and optimal detectivity in the interval between 2.5 μm and 10.5 μm.

The detectors have to be cooled at liquid nitrogen temperature by the Joule-Thomson expansion of nitrogen contained in a pressurized bottle (220 bar), two titanium bottles contained in the instrument ensure it an autonomy of about 30 coolings during normal operations. A larger bottle was not possible because of weight restrictions and the necessity to use a system already qualified for space (in this case, on the Symphonie communication satellite).

The instrument gets its electrical power from Spacelab and controlled by several internal microprocessors. The possibility of operating in emission and in absorption had to lead to a completely programmable instrument. The first programming step is the definition of "spectral windows", these are characterized by the limiting positions of the grating, by the code numbers of the optical filters to be placed in front of the each detector and finally by the gains on both channels. The gains range from 1 to 624 and are coded from 0 to 15. The filters are coded from 0 to 7 and the grating angles are represented by a resolver code which is the integer part of $(6368-\gamma)x\ 30.79$ where γ is the grating angle expressed in hundredths of a degree.

The program itself will be a sequence of windows. In the case of a sunset or sunrise, 12 successive altitude zones in which only two successive windows might be scanned are defined. The altitude is computed during the flight by the Spacelab computer and the transitions between zones are managed by the experiment processor. Figure 1 shows the limb sounding geometry, the referred altitudes are in fact the altitudes where the light rays are tangent to a surface parallel to the earth's surface. The nominal flight altitude was 250 km and is the upper limit of the first zone, the next ones are 200, 160, 120, 100, 80, 60, 50, 40, 30, 20 and 10 km. For the first flight, in order to minimize the mechanical operation of the filter wheel and of the fast grating drive, it has been decided to actually change spectral windows only at the transitions of 200, 100 and 50 km. Also, the option of scanning two successive windows in the same zone was avoided, although this procedure would be useful to study two relatively distant lines of the same constituent in the same scan, rotating the grating fast from one region to the other. A change of filters would be too slow in most cases to permit the retrieval of a profile. In emission, the altitude zones are also determined by the Spacelab computer using several horizon sensors and correspond to the altitudes assigned for absorption.

The total number of spectral windows is 64 of which 40, numbered 24 to 63 are fixed and definitively encoded in the instrument "Read Only Memory"; 24, numbered from 0 to 23 are programmable for use during the test period and later, to accomodate new scientific requirements during the flight. This option permits the payload specialist aboard the spacecraft to enter new parameters upon request of scientists or even, has allowed ground team to enter new data directly. There are 20 sunset and 20 sunrise programs numbered respectively from 20 to 39 and from 40 to 59 in which number 20 and 40 are programmable. The emission programs range from 60 to 79, sequence 60 being programmable.

Finally, 9 sets of programmable programs, each containing a sunset, a sunrise, an emission and 24 windows were implemented on a mass memory unit of the Spacelab computer, in fact a data tape. Three similar files of data were kept on the ground and have been directly uplinked to the instrument during the flight.

The signal treatment was more complex than anything we had on our previous optical experiments : after preamplification the detector signals are synchronously demodulated by two reference signals, 90 degrees out of phase at the modulating frequency. They deliver the sine and cosine components of both detector signal intensities. After digitizing each of these four signals to 12 bits they form together with the 18 bit grating encoder value a scientific data point. Two hundred such data points are taken per second. A single data point with a synchronization pattern, an experiment identification pattern and a frame counter form a frame for the experiment's dedicated HRM input channel. The frame counter counts from zero to seventy-nine. At frame count zero the whole frame is replaced by a status frame. At frame count forty, the frame is replaced by a status + GMT frame. A microprocessor controls the operation of the whole spectrometer, which is installed on the pallet.

A second box of electronics (EMOD) is installed in the module. This box controls the pallet instrument and is equipped with two microprocessors. EMOD communicates with EPAL - the pallet electronics by two dedicated asynchronous PCM lines. Two other lines bring the HRM clock and HRM data to EMOD.

EMOD picks out the status information frame and status + GMT frame (a total of 5 per second) and transmits this information to the experiment computer via the PCM data line. Upon request from the experiment computer during calibration or absorption mode a small 250 data point slice will be taken out of the HRM measurement data stream by EMOD, stored in its internal memory and transmitted to the experiment computer at the General Measurement Loop (GML) rate of 5 messages per second. Each message contains one actual status message and three measurement messages from the EMOD buffer. Graphics application software in the experiment computer will display this spectrum slice on the DDU for crew interaction and has been used for the attended calibration : a slice containing a typical methane doublet is sent to the experiment computer for graphic display. The crew introduces an encoder value offset to compensate the shift if the doublet is not in the middle of the screen. This encoder offset is sent to EMOD which will apply this correction to all the spectral windows. At the end of an operation sequence it will be stored on the MMU for later used.

The transmission of data from the orbiter to the White Sands (New Mexico) ground station has to go for such a complex mission through the Tracking Data and Relay Satellite System, which will ultimately number 14 satellites and will permit to phase out all the previous ground control station. Unhappily, due to an explosion which occured during its launch, in November of 1983, only one TDRS satellite at 41° West is available and it is operating in a degraded mode with a reduced command capability and a possibility of acquisition of only 20 to 40 minutes in each orbit. Outside of these periods, the data for all experiments was recorded on the Spacelab High Rate Data Recorder which was dumped to White Sands at the first good transmission available. As the data rate of the grille spectrometer was only 51.2 kbit/sec an alternate way was to record data on the much less efficient Payload Data Recorder and dump it also at the best opportunity.

From White Sands, the data was transmitted to Goddard Space Flight Center (Maryland) where it was recorded for post-flight treatment and to Johnson Space Center (Texas) where the experimenters could interact with their data. The data was available in three ways : direct transmission, playback of dumped data and near real time. This last option was a possibility for the experimenter to retrieve low data rate parameters from a disk file using a Nasa provided console. In our case we used two computer systems, one for data monitoring and recording and the other off line, for analysis of data quality and scientific re-programming of the instrument. These operations did necessitate 24 hours continuous monitoring.

Before the flight, after having been tested at ETCA (Belgium) and at ONERA (France), the instrument was qualified for flight by the

CNES in Toulouse in 1981, it was integrated to Spacelab systems at ERNO (Bremen, Germany), and delivered to Kennedy Space Center in Florida in June of 1982. A functional test was performed on the Spacelab pallet in September of 1982, followed by a first Mission Sequence Test in October and November; in March 1982, a second Mission Sequence Test was again performed, flight preparation was completed in late August and the last operation to be performed was a transmission test through the entire communication system in September of 1983. Five members of the experimenter team participated in four flight simulations and achieved the qualification of flight operation engineer which enabled them to send commands to the instrument during the flight and to interact with the Nasa system by voice loop communication and by use of Johnson Space Center computer consoles.

INSTRUMENT OPERATIONS

Spacelab was launched on November 28, 16:00 TU, the grille spectrometer was severally impacted by this date which meant that for an inelination of 57.1° of the orbit, the Spacelab would be constantly in the daylight after the fifth day, the orbit being quasi parallel to the terminator. So, the nominal operations had to be rushed in a shorter interval than expected and did not correspond to the requested latitude and longitude coverage. About three hours after launch, the first TV transmission proved that the TDRS satellite was functionning and when, 13 hours after launch, the calibration of the grille spectrometer was performed, the experimenters knew that the instrument was in nominal condition. On the second day, an incredible error was discovered : the times transmitted by the Orbiter to the Spacelab were wrong by one day and caused the Spacelab computer to put the instrument in standby and not perform its operation. We changed our nominal operation by trying to perform without using our own Experiment Computer Application software and scanning the same window in all the atmosphere. The uplink of the modification was successfully performed twice and the quality of the spectra was beyond expectation, the instrument performing in conditions where it could never have been tested on the ground. The error was finally corrected and the instrument had two nominal operations on the third day. On the fourth day, four operations had to be cancelled or were lost due to system problems in the Spacelab. The fifth day was marked by attempts to get back all lost operations on this last possible day using all the available options to operate the instrument. The sunsets and sunrises becoming longer and closer, the instrument overheated and we decided to operate it beyond its limits arriving finally at a situation where the cooling gas exhausted itself. Afterwards, tests were performed which showed that the instrument was still in sound condition, it was then put to rest until its refurbishment beginning in March of 1984.

Finally, the total number of operations was thirty plus the attended calibration; eighteen of these operations yield scientific data, 4 were as preplanned, all the other ones were modified during the flight. The quality of the data has maintained itself until the very last operations where the detector cooling was competing with the general overheating of the instrument and where the entire payload was impacted by system problems, originating in the complexity of the mission and its degraded communication situation. This good data quality has two causes : first cryogenic systems operate much better in a vacuum environment than in the test conditions where we always had to use pressurized gas lines and where convective warming of the cryostat was present; secondly, weightlessness affects favorably the operation of a mechanically complex instrument. Finally, these operations were the first ones using the sun as a source and provided an optimal signal. The first atmospheric spectrum to have been plotted during the flight is shown on figure 3, the high signal to noise ratio is evident from the intensity which instead of ranging, as usual in spectroscopy from zero transmission to maximum ranges from minimum to maximum.

A few thousand spectra have been obtained, and their analysis has just began, the scale of the interpretation work being given by the

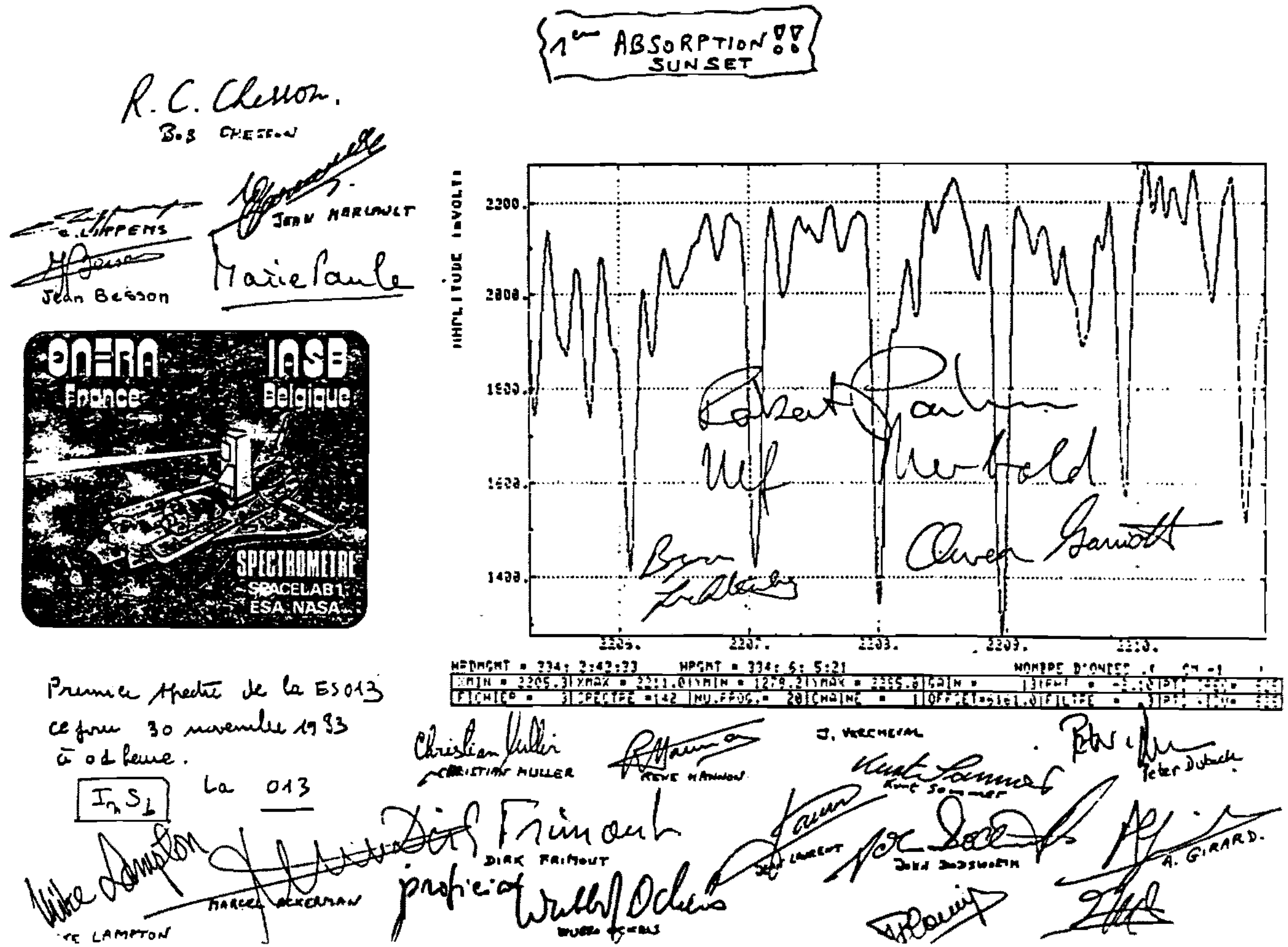

Fig. 3.- First atmospheric spectrum to have been plotted during flight operations, the large lines are mainly N_2O absorptions. This copy has been signed by the four Spacelab crew members who managed the instruments, other signatures belong to people having participated in the grille spectrometer flight operations in Houston. Line positions are slightly shifted due to grating realignment during the attended calibration.

fact that most publications of stratospheric composition using balloon obtained spectra have been made with less than ten spectra. The main missing point was that, due to Spacelab horizon sensor failure, the emission mode could not be tested. Data concerning all targeted molecules have been obtained, first preliminary results will be published after having thoroughly checked inside the experiment team, simultaneous effort being accomplished to present aeronomical explanation of the obtained vertical distributions.

The next flight of the instrument is scheduled for the EOM flight (Earth Observation Mission) in June of 1985, on the basis of the results, new spectral intervals will be choosen and, this time a completely preplanned geophysical program will be followed, hopefully, without disruptions.

We thank all the people, too numerous to be named here, who participated in this first space flight, at BISA, ONERA, ETCA (Space division of ACEC), ESA and NASA. Really special thanks go to the ESA Operational Engineers who saved our operations in real time and to the Spacelab crew who performed several contingency operations to protect the instrument from system problems.

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