NINE MONTHS OF ATMOSPHERIC OBSERVATION FROM THE ORBITING EURECA PLATFORM

Didier Fussen, Etienne Arijs and Dennis Nevejans

The EURECA (EUropean REtrievable CArrier) has been launched by ESA on the 31th of July 1992 for a one year mission on a quasi-circular orbit of 508 km and 28° of inclination. The Belgian Institute for Space Aeronomy (BISA) had developed for this mission a simple UV-visible radiometer (named ORA for Occultation RAdiometer) capable of measuring atmospheric neutral density, ozone, nitrogen dioxide, water vapour, and aerosol altitude profiles. The experiment was combined with a companion infrared radiometer designed by the Department for Atmospheric, Oceanic and Planetary Physics of the University of Oxford to measure upper atmospheric water vapour.

Our Institute was given an exceptional opportunity to observe the above-mentioned stratospheric constituents over a long time scale with a global coverage ranging from 40°S to 40°N. During the mission more than 300 Mbytes of scientific data have been recorded and are presently under processing and investigation.

The purpose of the present article is to give a short survey of the occultation radiometry method used in space observation of the Earth's atmosphere, of the difficulties associated with the retrieval of the constituent concentration profiles and also to present very preliminary but promising results.

1. The occultation radiometry method

The ORA instrument has been described elsewhere(1). Briefly, it consists of 8 independent radiometers of similar design, each of them containing a quartz window, an interference filter, and a simple optics followed by a photodiode. Using the sun-pointing capabilities of the EURECA carrier, the instrument measures the attenuation of the solar radiation through the Earth's atmosphere during the orbital sunrises and sunsets (Figure 1).

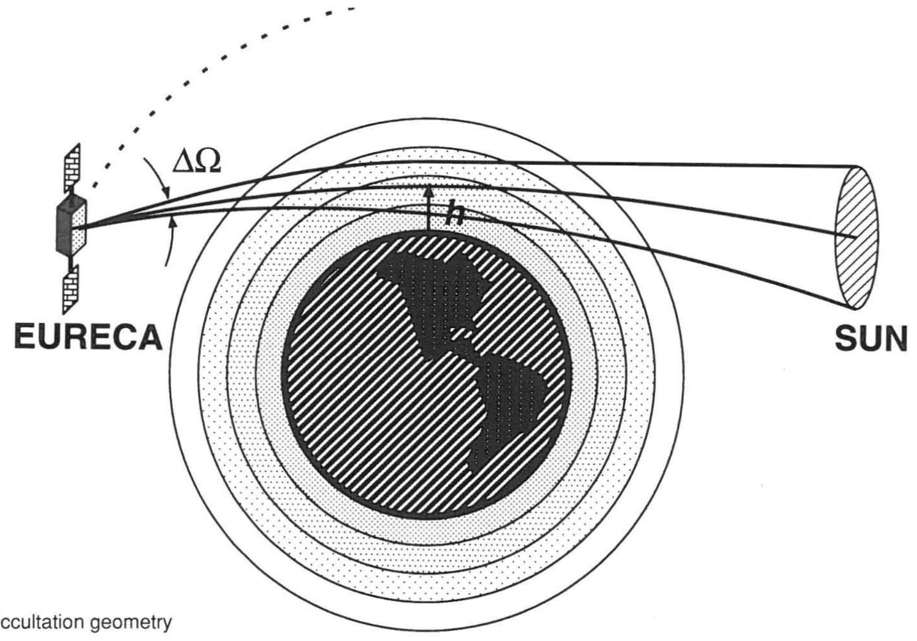

Figure 1 : Occultation geometry

During each solar occultation, the UV-vis unit of the ORA instrument has continuously recorded the relative attenuation of the solar rays in eight narrow wavelength domains (referred to hereafter as channels). This attenuation is caused by different mechanisms that can overlap in separate channels.

The main processes involved are elastic scattering of light by small particles (including Rayleigh scattering by the atmospheric major neutral constituents N_2 and O_2 and Mie scattering by aerosols consisting of dust and supra-molecular clusters) and photo-absorption by trace gases such as ozone(O_3), nitrogen dioxide(NO_2) and water vapour(H_2O). Elastic scattering of light gives rise to little wavelength dependency of the extinction coefficient while photoabsorption total cross sections exhibit much more pronounced structures. The respective influences of these constituents can be summarized in table 1 :

Table 1 : Major light absorbers at the different UV-vis channels

λ [nm]	259	340	385	435	442	600	943	1013
predominant constituents	O_3 neutrals	neutrals aerosol	aerosol NO_2	aerosol NO2	aerosol NO2	O3 aerosol	aerosol H_2O	aerosol

The two channels at 435 and 442 nm, chosen for NO_2 detection, are lying close together because the NO_2 photoabsorption cross sections at those wavelengths, although not dominant, are quite different and well marked on the differential signal. Channels at 259 and 600 nm are more specific for ozone and 943 nm was selected for water vapour. The remaining channels are mainly devoted to the correlative measurement of elastic scattering processes at different wavelengths.

At any time during the occultation, the relative transmission of a solar ray, grazing the Earth at an altitude h, can be written as :

$$T_\lambda(h) = \exp(-\int_{s2}^{s1} \beta_\lambda(h)\, ds\,(h)) \qquad (1)$$

where β_λ (h) is the total attenuation coefficient along the optical path whose length element is described by the variable s(h). For any of the channels :

$$\beta_\lambda(h) = \beta_\lambda^{Rayleigh}(h) + \beta_\lambda^{Aerosol}(h) + \beta_\lambda^{O_3}(h) + \ldots \qquad (2)$$

where the superscript Rayleigh refers to the the light scattering by the neutrals. The relative signal (with respect to the full Sun) measured by ORA reads :

$$S_\lambda(h) = \int_{\Delta\Omega} W(\Omega)\, T_\lambda(h(\Omega))\, d\Omega \qquad (3)$$

because the instrument observes the whole solar disk within the solid angle $\Delta\Omega$ spanning more than 25 km along the grazing plane. The angular function $W(\Omega)$ expresses the relative light distribution across the Sun including area and solar limb darkening dependencies. The attenuation coefficient can be expressed as :

$$\beta_{ij} = \alpha_i\, n_j(h) \qquad (4)$$

for a particular absorber j where α_i represents the attenuation cross section in the channel i, and n_j (h) the concentration profile.

2. The inverse problem

Starting from the measured signal to get a good estimation of the n_j (h) profiles is called the inversion problem, which is at the first glance obscured by three mathematical obstacles :

– the measured signal results from a double integration leading to a loss of spatial resolution;

– the relation between S_λ (h) and n_j (h) is mostly highly non-linear and the uniqueness of the solution is often questionable;

– overlapping contributions between channels require a constrained retrieval algorithm.

The set of tasks required for a complete data analysis can be divided into 7 groups, namely :

1. flight data preprocessing;
2. optical segment generation;
3. total cross section compilation;
4. synthetic spectrum production;
5. development of the inversion algorithm itself;
6. data analysis automation;
7 error estimation, data validation and spatio-temporal interpretation.

2.1. Flight data preprocessing

Throughout the flight a database was built up by regularly extracting scientific as well as technological housekeeping data from the EURECA Data Disposition system with a software developed at BISA. The scientific data represent a subset of this ORA database. A systematic extraction of the relevant data including the signal in the different channels as a function of universal time together with the measured position of the satellite expressed in an Earth-fixed frame was performed. Combining these with routines giving the astronomical ephemerides, enabled us to determine the geometrical grazing height of any solar ray hitting the satellite as well as the geographical spreading of the sites where the occultations were measured.

2.2. Optical segment generation

The atmosphere of the Earth is an inhomogeneous medium causing non-negligible refraction effects, especially below 35 km and for a large field-of-view instrument. In order to divide the atmosphere into a set of quasi-homogeneous layers we wrote a complete code to solve this problem, taking into account the angular size of the Sun, solar limb darkening and the differential refraction attenuation. The results have been validated by comparison with similar calculations performed by other authors(3) and by inspecting the agreement between the predicted occultation time and the observed one.

2.3. Total cross section compilation

The extinction coefficients have been computed for the directly exploitable channels including Rayleigh scattering, O_3, NO_2, H_2O and aerosol absorptions. A convolution of the best up-to-date absorption data with solar irradiance, detector wavelength sensitivity and transmission function has been performed. For water vapour absorption, the broad-band model of Pierluissi (5) has been modified for weak absorptions and optimized with respect to the FASCODE package(6).

2.4. Synthetic signal production

For the retrieval scheme validation, we generated synthetic signals using the US Standard Atmosphere 1976(4) and the low aerosol level compiled for the SAGE experiment data during the years 1986-1990(2). Comparison with the ORA signal shows :

– a general good agreement validating astronomical, optical and extinction coefficient computations;

– the signature of an important supplementary absorption (probably due to aerosols from the Pinatubo eruption);

– the low apparent spatial resolution compensated by a high instrument sensitivity (NO_2 and H_2O signatures).

2.5. Development of the inversion algorithm itself

As it appears from the mathematical expression of the signal, the occultation method leads to a non-linear inversion problem. The first difficulty lies in the choice of an inversion method of high performance for the extinction coefficient profile (there are about 6000 events x 8 channels to retrieve) which is at the same time robust, i.e. quite insensitive to the profile analytical properties.

This method has to face with the inherent degeneracy of the problem which can only be solved by an adequate regularization criterion. More subtle is the question of the maximal information content that we can extract from a given signal to get the maximal spatial resolution with a low retrieval error.

From the obtained extinction profiles another inversion problem (fortunately linear) must then be solved to capture the relevant contributions embedded in an extinction profile. This is of course a constrained problem due to the correlative effects of one constituent among several channels.

2.6. Data analysis automation

When the whole retrieval algorithm is ready as a framework of independent optimized modules, it will then be necessary to define the best strategy for the data analysis concerning the possible necessity to work on averaged (latitude, longitude and time) data. Large storage capacities will be required and the use of a powerful graphical interface is desirable.

2.7. Error estimation, validation and interpretation

A forward-backward error prediction scheme has to be developed to estimate the retrieval error as a function of constituent and altitude. This step will be a prerequisite for the validations of the ORA results with other space – or ground – based experiments. Cooperative programs and data exchange with other scientific teams will be highly profitable.

Last but not least, the retrieved density profiles n_j (h) must be interpreted and compared with other results such as global 3-D models, optical properties of aerosols and other studies.

3. Data analysis status and preliminary results

3.1. The β_λ (h) retrieval

The purpose of the inversion algorithm is to follow a robust and efficient process to retrieve the total absorbing profile along the zenith of the tangential point.

As expressed by equations (1) and (3) the signal results from a double integration across the Earth's atmosphere and depends on the infinitesimal optical thicknesses in an highly non-linear way. For instance, trajectories coming from distinct angular directions and crossing different absorbing layers can contribute equally to the total signal.

There don't exist general methods nor convergence theorems concerning this kind of inverse problems. We tested several published semi-empirical algorithms such as : the onion peeling method, the Chahine's and Mill's methods. All of them, while giving valid results for high angular resolution instruments, suffered from the following defects :

- a slow convergence to a solution sensitive to the method direction(upwards or downwards);

- no clear optimization criterium for the solution;

- spontaneous generation of spurious oscillations in the solution as a consequence of the algorithm locality.

We therefore developed an original method to solve these problems by inspecting the information content embedded within an unknown profile. This technique, referred to as NOPE (Natural Orthogonal Profile Expansion) consists of expressing the solution profile with respect to a truncated basis of orthogonal polynomials using a generic standard profile as a measure for the scalar product. The coefficients defining the monic polynomials have been computed in a Stieltjes recurrence for each channel. Finally, the optimal solution profile is determined by a Levenberg-Marquardt minimization for a X^2 merit function

$$X^2 = \sum_{i=1}^{n}\left(\frac{y_i - S_\lambda^{bf}\,(\beta_\lambda^{bf}\,(h))}{\sigma_i}\right)^2$$

where y_i stands for the observed signal at n independent measurements, S_λ^{bf} is the best fit signal computed from the best fit profile $\beta_\lambda^{bf}(h)$ and σ_i is the estimated experimental error on y_i.

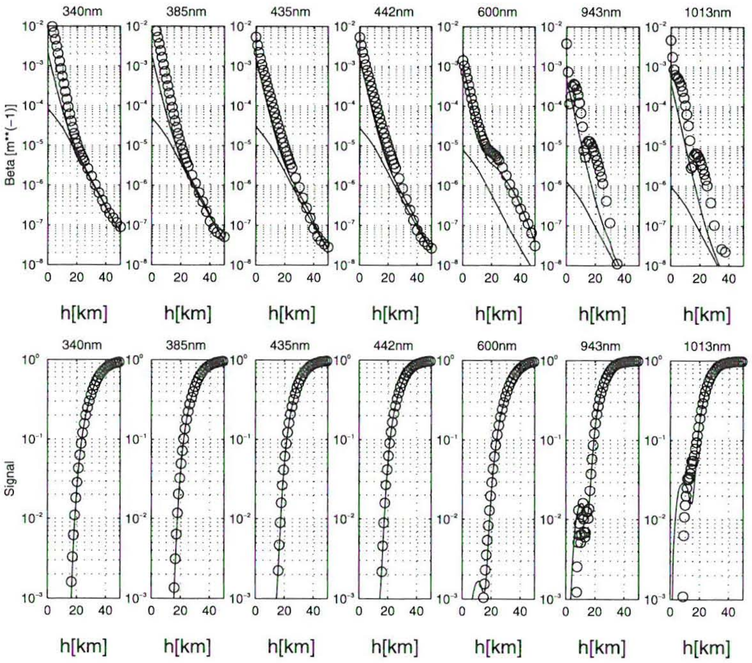

Figure 2 : Top : Retrieved total absorption profile for 7 UV- visible channels (open circles); total absorption profile for Standard Atmosphere (US76) and non-volcanic aerosol conditions (upper full line); Rayleigh scattering only (lower full line). Bottom : best fit signal obtained for the retrieval; total absorption (open circles) compared to observed signal (full line)

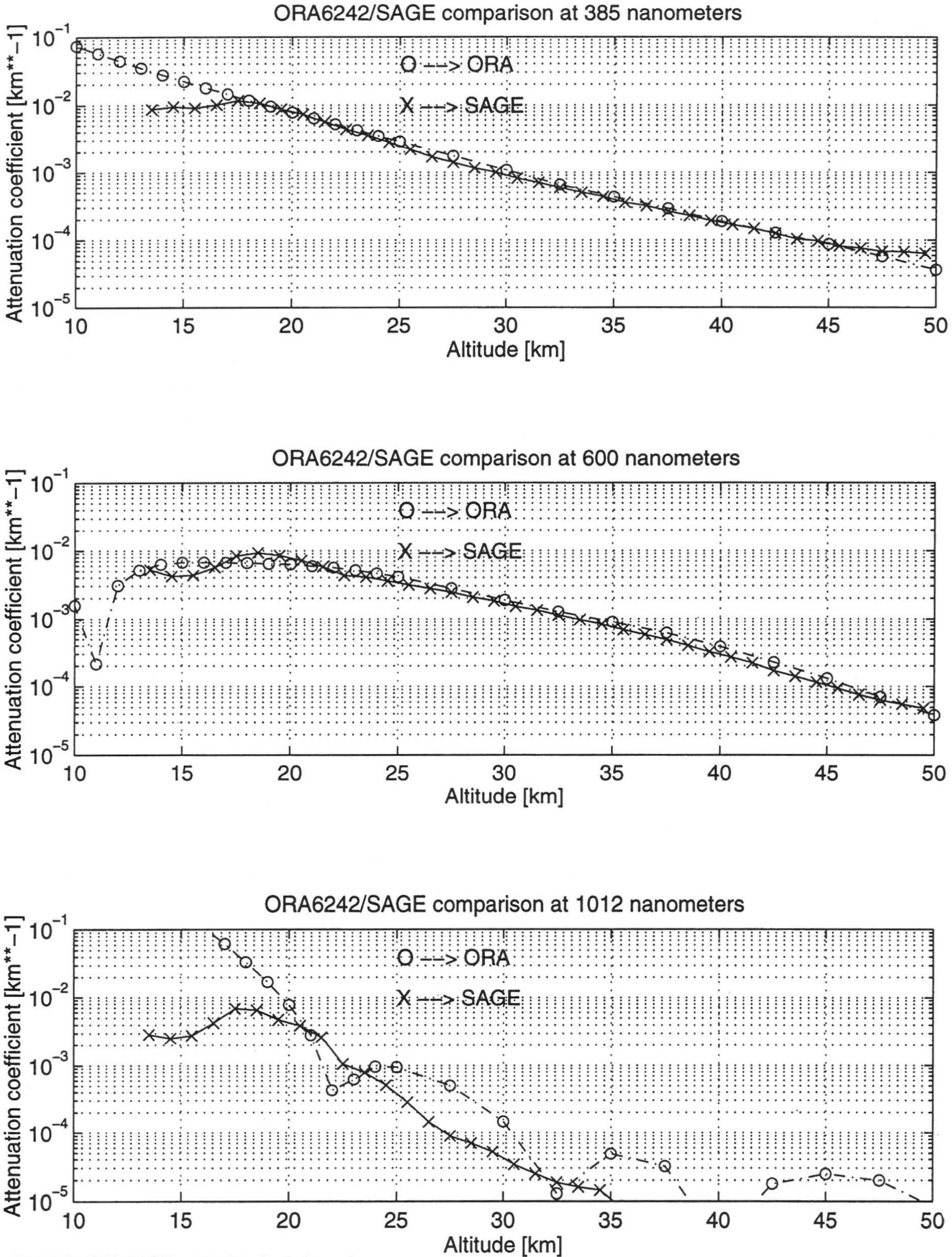

Figure 3 : ORA-SAGE comparison for 3 channels

The results obtained for the inversion for 7 channels are presented on figure 2.

These results show the validity of the method, which generated naturally smooth profiles, with a preserved information content (see the ozone signature in channel 5) over a large dynamic range. It is worth noting the important increase between 0 and 25 km (a factor of 10 or 20) which seems an evident signature of the Pinatubo aerosol.

Before starting a systematic inversion procedure, it was very interesting to compare our total attenuation profiles with the ones observed by the SAGE experiment at a common grazing site during the same period. Therefore we contacted the Laboratoire d'Optique Atmosphérique (LOA) in Lille (F) where J. Lenoble, C. Brogniez and P. Pruvost(2) developed a validated algorithm to invert the SAGE data. Four equivalent events have been found and compared for March and April 1993, the typical results of which being presented on figure 3. A very fair agreement is observed above 20 km in all channels while the divergence at lower altitudes is still under investigation.

3.2. The constituent separation

We are now looking for a possible random contamination of the measured absorption signal between 0 and 15 km (see figure 2) which tends to mislay the algorithm to optimized but spurious solutions i.e. solutions describing a "normal" atmosphere perturbed by a meteorological situation. A preliminary analysis indicates that some bumps in the raw signal would be due to low altitude clouds (stratus) leading to possible reflections or intensity modulation. A systematic statistical analysis of these events and a cross-comparison with synchronous meteorological satellite pictures will have to be performed to answer this question.

It is of crucial importance to control numerically the effect of this phenomenon because of the low spatial resolution of ORA which integrates low altitude ($h \leq 20$km) information up to a nominal altitude of ≈ 30km.

Due to the Pinatubo effect, the constituent separation (see equation 2) turns out to be much more difficult than foreseen. Indeed the aerosol contribution was by far the most important one in all channels, giving an excellent opportunity to characterize its time evolution and its spectral properties but obscuring the relative contributions of the other constituents, in particular NO_2 and H_2O. First attempts using brute force algorithms led to exotic and unstable solutions. This is presently under investigation.

Conclusions

The ORA experiment may be considered as a success because it furnished a huge amount of information over the status of the Earth's atmosphere in 1992 and 1993. This information has now been proved to be retrievable and valid after processing, stratification and inversion of the data.

Independently of the scientific results this would also mean that our low resolution, simple design and low cost instrument is a valid challenger with respect to more sophisticated space experiments.

The final step of the constituent separation is more delicate then expected not by the conception of the separation algorithm but by the selection (altitude dependent) process of discernible constituents.

Nevertheless, there seems to be no doubt that this ultimate difficulty will be surmounted within the next months.

References

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