NEW EARTH EXPLORER MISSIONS IN SUPPORT OF ATMOSPHERIC SCIENCE AND APPLICATION RECOMMENDED FOR IMPLEMENTATION

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ABSTRACT

The European Space Agency ‘Living Planet’ programme [http://www.esa.int/livingplanet] is ESA’s programme for observing the Earth. The programme represents a flexible and user-friendly approach to the whole concept of Earth observation from space. Within this programme various types of missions are considered including research and demonstration missions.

In autumn 2001 three candidate core missions were selected for Phase A study including an Earth radiation (i.e. cloud and aerosol) mission (EarthCARE) and a water vapour profiling mission (WALES). The primary objective of WALES is to overcome the shortcomings of radiosondes and passive satellite sensors. The former do not cover the globe uniformly and do not provide reliable water vapour observations in the upper troposphere and lower stratosphere, nor at low humidity and low temperature levels (e.g. polar regions). EarthCARE has been specifically defined with the scientific objectives of determining for the first time, in a radiatively consistent manner, the global distribution of vertical profiles of cloud and aerosol field characteristics to provide basic essential input data for numerical modelling and global studies.

In spring 2002 three candidate Earth Explorer Opportunity Missions (EEOM) were selected for Phase A study including an Atmospheric and Climate Explorer, ACE+ a mission targeted at demonstrating an innovative approach using radio occultations for globally measuring profiles of humidity and temperature throughout the troposphere and stratosphere and EGPM, the European contribution to the Global Precipitation Measurement (GPM) mission with the main objective to provide improvement of the rainfall retrieval accuracy and, in particular, the detection of light rain and snowfall crucial for a wide range of process studies and operational applications.

In May 2004 the decision has been made which out of the six candidate missions have been recommended for implementation. The paper focuses on the potential benefits of the selected missions for atmospheric science and application.

1. INTRODUCTION

The ‘ESA Living Planet Programme’ (http://www.esa.int/livingplanet) is gaining momentum. Four Earth Explorer missions are currently being implemented, namely GOCE, CRYOSAT, ADM-Aeolus and SMOS. Information about the four missions can be found at the same URL.

Based on a ‘Call for Ideas’ for Earth Explorer Core missions released in 2000 in autumn 2001 three candidate core missions were selected for Phase A study, namely SPECTRA, a Surface Processes and
Ecosystems Changes Through Response Analysis mission, EarthCARE, an Earth Clouds, Aerosols and Radiation Explorer, and a water vapour profiling mission (WALES).

In spring 2002 three candidate Earth Explorer Opportunity Missions (EEOM) were selected for Phase A study including an Atmospheric and Climate Explorer, ACE+ a mission targeted at demonstrating an innovative approach using radio occultations for globally measuring profiles of humidity and temperature throughout the troposphere and stratosphere and EGPM, the European contribution to the Global Precipitation Measurement (GPM) mission with the main objective to provide improvement of the rainfall retrieval accuracy and, in particular, the detection of light rain and snowfall crucial for a wide range of process studies and operational applications.

Based on a User Consultation Meeting held in April 2004 where the six candidate missions were presented to the user community a decision on those missions recommended for implementation has been taken. The recommendations are as follows:

- The full implementation of Swarm, a magnetospheric mission, as the next Earth Explorer Opportunity Mission,
- The selection of the next Earth Explorer Core Mission between EarthCARE and SPECTRA,
- The preparation of EGPM for a potential implementation as an Earth Watch mission1.

As EGPM had been addressed in a recent document (Ingmann, 2003) this mission will not addressed here. Focus will be on the EarthCARE mission, a mission which is process oriented but could also provide new tools which could proof very useful in an operational context.

2. THE EARTHCARE MISSION – BACKGROUND

Difficulties in representing aerosols, clouds, and convection in numerical models of the atmosphere seriously limit the ability to provide accurate weather forecasts and reliable predictions of future climate. These factors govern the radiation balance and hence the temperature of the Earth and are directly responsible for the production of precipitation and thus control the hydrological cycle. In summary:

**a) Aerosols**

Aerosols have a direct radiative impact by reflecting solar radiation back to space which leads to cooling. Absorbing aerosols, e.g. carbon from anthropogenic sources, can lead to local heating. Aerosols also control the radiative properties of clouds and their ability to produce precipitation. The low concentration of aerosol particles in marine air leads to water clouds with a small number of relatively large droplets. In contrast, the high concentration of aerosols in continental and polluted air results in water clouds with a much higher concentration of smaller droplets. Continental clouds therefore not only have a higher albedo and reflect more sunlight back to space but also are much more stable and long lived and less likely to produce precipitation. Aerosols also control the glaciation process, yet their effect on the properties of ice clouds is essentially unknown. There is a need to quantify the degree to which aerosols are responsible for the observed rapid reduction in the albedo of freshly fallen snow. Present observations of global aerosol properties are limited to optical depth and a crude estimate of particle size. This is very unsatisfactory, since we need to know their chemical composition, whether they scatter or absorb, and their vertical and geographical distribution.

**b) Clouds**

Clouds are the principal modulators of the Earth’s radiation balance. Currently, there are global estimates of cloud cover but little information on their vertical extent or the condensed mass of ice or liquid cloud water. Low clouds cool the climate by reflecting short wave solar radiation back to space, whereas high clouds warm the climate because they are cold and emit less infrared radiation to space. In the present climate these two effects are large and have opposite signs. Any changes in the vertical distribution of clouds in a future warmer climate could lead to large changes in the net radiative forcing. Climate models disagree as to whether this attenuates

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1 Earth Watch missions are missions with a (pre-)operational character.
or amplifies the effect of the original direct greenhouse gas warming. Uncertainties in the vertical profiles of clouds are largely responsible for the current unacceptable spread in predictions of future global warming, and also limit the accuracy of numerical weather prediction. Models are able to produce the present observed top-of-the-atmosphere radiation but with very different vertical profiles of clouds and water content. To evaluate models, observations of cloud profiles are urgently required, so that the ability of models to provide reliable weather forecasts and predictions of future global warming can be improved.

**c) Convection and Precipitation Processes**

Clouds are the source of all precipitation, but details of this process are poorly understood. At present, models convert cloud condensate in a grid box to precipitation either by slow widespread ascent, or, for the more intense rainfall, by convection. Major difficulties include the large spread in model predictions of cloud condensate, the efficiency with which this is converted to precipitation, and the representation of sub-grid-scale convective motions. The extent to which vigorous tropical convection introduces moisture into the stratosphere is uncertain. It is also known that the modelled diurnal cycle of convection is incorrect. Understanding these processes is crucial for quantitative precipitation forecasting. The societal benefits in providing warning of flash flooding would be immense. Global observations of the probability distribution function of vertical motions within the grid box to constrain convective parameterisation schemes are needed.

The mission goal is to deliver observations of:

a) Vertical profiles on a global scale of aerosol properties such as extinction coefficient (optical depth per unit height increment) and an estimate of the size and chemical composition of the aerosol particles differentiating between absorbing and non-absorbing aerosols.

b) Vertical profiles on a global scale of cloud properties such as cloud cover, cloud overlap and the mass of liquid and ice water content condensed in the clouds, sub-grid-scale cloud inhomogeneity, and vertical velocities, cloud particle size and identification of the different types and shapes of ice particles present.

c) Probability distribution functions (PDFs) of the mass flux and vertical velocities within stratiform and convective clouds and how such PDF’s change with height, IWC and horizontal dimensions.

Such observations will enable the performance of current NWP models and GCMs to be evaluated so that the various proposed schemes for parameterising aerosols, clouds and convective precipitation can be compared, any biases and errors within such schemes can be identified, and ultimately such schemes can be improved.

### 3. RESEARCH OBJECTIVES

EarthCARE mission has been specifically defined with the basic objective of improving the understanding of cloud-aerosol-radiation-precipitation interactions so as to include them correctly and reliably in climate and numerical weather prediction models. Specifically, the scientific objectives are:

1. The observation of the vertical profiles of natural and anthropogenic aerosols on a global scale, their radiative properties and interaction with clouds.

2. The observation of the vertical distributions of atmospheric liquid water and ice on a global scale, their transport by clouds and their radiative impact.

3. The observation of cloud distribution (“cloud overlap”), cloud-precipitation interactions and the characteristics of vertical motions within clouds, and

4. The retrieval of profiles of atmospheric radiative heating and cooling through the combination of the retrieved aerosol and cloud properties

The key parameters determining the radiative properties of clouds and aerosols are:

- The extinction and absorption properties of aerosols.
- Large scale cloud structure, including cloud fraction and overlap.
- Cloud condensate content, particle size, shape and small scale cloud structure.
Note that macroscopic and microscopic cloud parameters depend in part on physical and chemical properties of aerosols acting as cloud condensation and/or freezing nuclei.

EarthCARE will meet these objectives by measuring simultaneously the vertical structure and horizontal distribution of cloud and aerosol fields together with outgoing radiation over all climate zones. More specifically, EarthCARE will measure:

1. Properties of aerosol layers:
   a) The occurrence of aerosols layers, their profile of extinction coefficient and boundary layer height and
   b) The presence of absorbing and non-absorbing aerosols from anthropogenic or natural sources.

2. Properties of cloud fields:
   a) Cloud boundaries (top and base height) including multi-layer clouds
   b) Height resolved fractional cloud cover and cloud overlap
   c) The occurrence of ice and liquid and of super-cooled cloud layers.
   d) Vertical profiles of ice water content and effective ice particle size and shape.
   e) Vertical profiles of liquid water content and effective droplet size.
   f) Small scale (1km or less) fluctuations in these cloud properties.

3. Vertical velocities to characterise cloud convective motions and ice sedimentation.


5. Narrow-band and broad-band reflected solar and emitted thermal radiances at the top of the atmosphere.

4. THE MISSION CONCEPT

The scope of the EarthCARE mission is shown in Figure 1. The objective is to retrieve vertical profiles of cloud and aerosol, and characteristics of the radiative and microphysical properties so as to determine flux gradients within the atmosphere and fluxes at the Earth’s surface, as well as to measure directly the fluxes at the top of the atmosphere and also to clarify the processes involved in aerosol/cloud and cloud, precipitation, convection interactions. Guideline here is to measure with an instantaneous accuracy of 10 W m\(^{-2}\).

![Figure 1: the Scope of the EarthCARE Mission](image-url)
The accuracy requirements are based on typical values of the geophysical quantities provided by EarthCARE and on sensitivity calculations which provide estimates of “radiatively significant” changes of about 10 Wm$^{-2}$, given the measurement capability of instantaneous radiances at the top of the atmosphere, which leads to the need to detect and measure clouds and aerosols with an extinction coefficient of 0.05 per km. Table 1 summarises the requirements for clouds, based in part on the work of Slingo (1990) for liquid water clouds and Kristanjsson et al. (2000) for ice clouds and calculations performed in earlier EarthCARE studies.

<table>
<thead>
<tr>
<th>Property</th>
<th>Detectability threshold</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice cloud top/base and profile</td>
<td>N/a</td>
<td>500m</td>
</tr>
<tr>
<td>Ice water content (IWC)</td>
<td>0.001gm$^{-3}$</td>
<td>± 30%</td>
</tr>
<tr>
<td>Ice crystal effective size</td>
<td>N/a</td>
<td>± 30%</td>
</tr>
<tr>
<td>Water cloud top/base and profile</td>
<td>N/a</td>
<td>300m</td>
</tr>
<tr>
<td>Liquid water content (LWC)</td>
<td>0.1 gm$^{-3}$</td>
<td>±15-20 %</td>
</tr>
<tr>
<td>Water droplet effective radius</td>
<td>N/a</td>
<td>± 1-2 µm</td>
</tr>
<tr>
<td>Fractional cloud cover</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Ice Cloud optical depth</td>
<td>0.05</td>
<td>15%</td>
</tr>
<tr>
<td>Vertical velocity within clouds</td>
<td>0.2ms$^{-1}$</td>
<td>± 0.2ms$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1: Accuracy requirements for cloud properties

The overlap of cloud layers in the vertical is an important parameter which is usually assumed in model parameterisations. The information on the cloud profiles in Table 1 will enable the overlap to be determined. The vertical velocity within clouds is presently also either assumed or modelled, as is the fall speed, or sedimentation rate, of ice crystals. Information on drizzle rates in boundary layer stratocumulus would be extremely valuable as this makes a significant contribution to the water budget of these clouds. Estimates of heavier rain rates would also be valuable.

**Measurement principles**

The observational requirements discussed above indicate the need for measurements from a single satellite platform of the vertical structure of aerosols and clouds, plus complementary information on cloud-scale vertical velocities and precipitation, and of the corresponding broad-band and narrow-band radiances at the top of the atmosphere. The profile information can only be provided by active instruments, a lidar for aerosols and thin clouds and a high frequency (94GHz) Doppler radar for clouds. These instruments can also provide the additional information required on discriminating absorbing from non-absorbing aerosols, on cloud-scale vertical velocities and precipitation (mainly drizzle) rates. A multi-spectral imager is required to provide additional geographical coverage of aerosol and cloud optical property retrievals and a broad-band radiometer is required to measure radiances and to derive fluxes. These measurements need to be made for the whole globe and for a period long enough to ensure that all of the important climatic regimes are represented with the necessary statistical significance. This leads to the requirement for a single satellite mission with a lifetime of several years, in a sun-synchronous polar orbit with as low an altitude as possible to optimise the performance of the two active instruments (lidar and cloud radar), which are supplemented by a multi-spectral imager providing cross-track observations and a broad-band radiometer for determining incoming and outgoing radiation simultaneously.

**Lidar**

Lidar is analogous to radar but uses short pulses of light. The backscatter signal, $\beta$, at 355nm has two components: a molecular (or “Rayleigh”) component from the air molecules which is proportional to air density and a “Mie” component from the aerosol or cloud particles. The return from cloud particles is approximately proportional to their surface area and so $\beta \propto N D^2$ in units of m$^{-1}$ sr$^{-1}$ where $N$ is the concentration of particles of size $D$ and the sum is over all values of $D$. Figure 2 (lower panel) from a ground based vertically pointing lidar shows the low values of $\beta$ from aerosol in the boundary layer, the very large $\beta$ but rapid extinction associated with liquid water clouds, and the moderate values of $\beta$ and lower attenuation produced by ice clouds.
To detect an extinction $0.05 \text{ km}^{-1}$ requires a sensitivity of $\beta = 8 \times 10^{-7} \text{(m sr)}^{-1}$ if a ratio of the extinction to backscatter, $\alpha / \beta$, of the lidar signal, $S$, of 60 has been assumed. Quantitative interpretation of the lidar signal, $\beta$, is difficult because of i) attenuation in clouds, ii) a variable and unknown value of $S$, and iii) multiple scattering. For ice clouds the radar signal can be used to correct for the lidar attenuation and derive the profile of the extinction coefficient to within 15%, independently of $S$. The ratio of the radar return ($Z \propto D^6$) to the corrected lidar backscatter then provides a measure of the mean ice particle size, and when combined with the radar return, the IWC and particle size can be estimated to an accuracy of 30%.

In the case of aerosol no useful radar return is available thus, the lidar results alone must be relied upon. Conventional lidar designs can only measure the total aerosol and molecular return signals, but because the extinction-to-backscatter ratio of aerosol ($S$) is quite variable, it is difficult to estimate aerosol extinction. The EarthCARE lidar will separate the narrow band return from the slowly moving aerosol/cloud particles from the thermally Doppler broadened molecular signal. This "High-Spectral Resolution" (HSR) technique uses any reduction in the molecular return to directly determine the extinction, $\alpha$, of aerosols and thin clouds, which is then used to correct $\beta$ in the Mie channel for attenuation, and find $S$. The HSR technique is similar in principle to Raman lidar approach in which the total Rayleigh and Mie return is separated from the wavelength shifted Raman scattered light from molecules.

Radar

The magnitude of the backscattered signal, or radar reflectivity, $Z$, is given by $\Sigma N D^6$, and is usually expressed in dBZ, that is in dB relative to the backscatter from a single mm raindrop in a cubic metre. The EarthCARE cloud radar will operate at 94 GHz frequency to maximise sensitivity and provide a narrow beamwidth even with a small antenna. Aerosol particles are very small and cannot be detected by radar. Liquid cloud droplets are typically of size 10 $\mu$m and are close to the threshold of detectability unless occasional drizzle drops are present (Figure 2). Ice particles with generally larger size have a much larger value of $Z$ (figure 2). Calculations using ice particle size spectra observed by aircraft show that a radar with a threshold of $-36$dBZ will detect 98% of "radiatively significant" ice clouds. The accuracy of the conversion of $Z$ to IWC is limited to about 50-100% by the variability of the ice particle spectra; additional temperature information reduces this uncertainty to around 50%; more accurate size information can be obtained from the ratio of the radar signal to the attenuation corrected lidar signal. The smaller drops in liquid clouds makes them more difficult to detect. A year’s climatology of radar observations indicates that only about 50% of stratocumulus clouds will be detected with a threshold of $-36$dBZ; derivation of liquid water content from $Z$ is difficult because $Z$ is dominated by occasional larger sized drizzle drops; however when drizzle is present the $Z$ is related to the drizzle rainfall rate.

The EarthCARE CPR will be the first space-borne radar with a Doppler capability. There are two scientific requirements: firstly to characterise convective motions an accuracy of 1 m s$^{-1}$ with a horizontal resolution of...
1 km is necessary; and secondly to estimate the sedimentation of ice particles in cirrus. An accuracy of 0.2 ms\(^{-1}\) is desirable at the expense of 10 km horizontal resolution.

These active instruments will be complemented by two passive instruments, namely the multi-spectral imager (MSI) which will provide spectral information of radiances or apparent reflectance depending on optical characteristics of atmospheric suspended particles, aerosol and cloud particles and the surface across-track. The broad-band radiometer (BBR) will be used to derive accurate instantaneous broadband top-of-the-atmosphere (TOA) fluxes (reflected short-wave and emitted long-wave) corresponding as much as possible to the small areas for which the radar, lidar, and MSI provide data.

5. THE IMPLEMENTATION CONCEPT

The EarthCARE mission architecture comprises the space segment with the single satellite carrying a multi-instrument payload, the launch vehicle and the ground segment. Two satellite concepts are depicted in Figure 3.

The EarthCARE mission is centred on the synergetic use of the data provided by the instrument suite. All instruments observe the same volume of the atmosphere, although at slightly different times, with the imager providing in addition across-track information. This principle allows not only micro- and macro-level cloud and aerosol measurements to be taken as a vertical profile along the flight track, but also horizontal two-dimensional information by means of the across-track observations of the multi-spectral imager.

The payload is accommodated on the satellite in a way satisfying the viewing and alignment requirement. The platform provides service functions like electrical power supply, data interfaces, attitude control and thermal control. Two design concepts have been developed which are shown Figure 3.

The EarthCARE satellite resource requirements lead to a mass of about 1.2 to 1.3 tons, a power requirement of between 1 and 1.1 kW and data rate of between 1 and 1.5 Mb s\(^{-1}\).

6. CONCLUSIONS

Using the satellite designs end-to-end simulations have been carried out for a number of idealized cases as well as scenes derived from cloud resolving models. In these end-to-end trials the combined lidar/radar and nadir pixel MSI data has been used to construct optimal estimates of the profiles of the nadir cloud optical and microphysical properties. Then the information in the nadir profiles was propagated outwards to fill-out the nadir BBR 10x10 km pixel using the non-nadir long-wave MSI pixel radiances. In essence, for a given non-nadir pixel, the closest match (in terms of measured LW radiances) nadir pixel was determined, then the derived cloud and aerosol properties corresponding to this pixel were assigned to the non-nadir pixel in question.

After the reconstructed 3-dimensional cloud property fields were created, they were fed back into the 3-D long-wave and short wave Monte-Carlo radiation codes in order to calculate the TOA fluxes and the BBR radiances. Finally, the reconstructed TOA fluxes and broadband radiances were compared with the ‘true’ values. For these idealized cases the combined short and long-wave TOA flux error is well within the 10 W m\(^{-2}\) instantaneous accuracy goal.

Other simulations have been conducted using data from cloud resolving models with explicit microphysics. An example of the model ‘true’ 355 nm optical depth field corresponding to a mid-level cirrus cloud compared with the reconstructed field is shown in Figure 4. For this scene, the TOA short-wave albedo can be reconstructed within a 5 to 6 % error for a range of solar zenith angles between 20° and 50°.
Figure 4: (Left) True 355 nm cloud optical thickness for a mid-level cirrus generated by a cloud resolving model with explicit microphysics. (Right) Reconstructed optical thickness.

The idea of the end-to-end simulations that have been carried out as part of the Phase-A studies for EarthCARE will also be applied in a similar manner to the operational data. That is, the comparison between the observed broad-band BRDF’s and the retrieved BRDF will serve as an important test of the accuracy of the overall retrievals. If the retrieved and observed BRDFs match then a high level of confidence can be assigned to the inferred TOA fluxes.

The simulations that have been conducted show that the combined EarthCARE sensors will enable the retrieval of a radiatively complete picture of a wide range of cloud and aerosol scenes at the 10 km scale. An important component of the envisioned EarthCARE retrieval procedures will be the ability to check the self-consistency of the retrieval products. More details can be found in ESA (2004).

Not only the climate modelling but also the numerical weather prediction community is preparing for the use of EarthCARE observations. This would imply that, if the mission is successful, there might be an operational follow mission. This could have a similar basis or, from the experience gained with Cloudsat/Calipso and EarthCARE and possibly other missions, be, for example, related to precipitation with a slightly different payload composition.

REFERENCES

European Space Agency (ESA), 2004: The Earth Cloud, Aerosol and Radiation Explorer (EarthCARE), ESA SP-1279(1), 60p, the report can also be found as an Adobe Acrobat file at http://www.esa.int/export/esaLP/AESMYNW9SC_earthcare_0.html

