SP-1196 (4)

REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Atmospheric Dynamics Mission

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THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Atmospheric Dynamics Mission

ESA SP-1196 (4) – The Nine Candidate Earth Explorer Missions –
ATMOSPHERIC DYNAMICS MISSION

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1. Introduction

For the post-2000 time-frame two general classes of Earth Observation mission have been identified to address user requirements, namely:

Earth Explorer Missions – these are research/demonstration missions with the emphasis on advancing understanding of the different Earth system processes. The demonstration of specific new observing techniques also falls under this category.

Earth Watch Missions – these are pre-operational missions addressing the requirements of specific Earth Observation applications. The responsibility for this type of mission would eventually be transferred to operational (European) entities and the private sector.

Nine Earth Explorer missions have been identified as potential candidates for Phase A study. For each of these candidate missions Reports for Assessment have been produced.

This particular Report for Assessment is concerned with the Atmospheric Dynamics Earth Explorer Mission. It has been produced by one of the nine Mission Working Groups that have been established to produce these Reports for Assessment. The four (external) members of this particular group are D. Carson (Hadley Centre, Meteorological Office, Bracknell, UK), P. Flamant (Laboratoire de Meteorologie Dynamique, Palaiseau, France), A. Stoffelen (The Royal Netherlands Meteorological Institute, De Bilt, The Netherlands) and W. Wergen (Deutscher Wetterdienst, Offenbach, Germany). They were supported by members of the Agency who advised on technical aspects and took the lead in drafting technical/programmatic sections. This Report is, together with those of the other eight candidate Earth Explorer Missions, being circulated amongst the Earth Observation research community in anticipation of a Workshop which will be held in Spain in May 1996.

The aim of the Atmospheric Dynamics Earth Explorer Mission is to demonstrate the possibility of to providing observations of three-dimensional wind fields in clear air thereby helping to correct a major deficiency in the current (meteorological) operational observing network. Such data would be assimilated into numerical forecasting models. The mission would also provide data needed to address some of the key concerns of the World Climate Research Programme (WCRP) i.e. quantification of climate variability, validation and improvement of climate models and process studies relevant to climate change. The newly acquired data would also help realise some of the objectives of the Global Climate Observing System (GCOS). This would be achieved by a) contributing directly to the study of the Earth's global energy budget by measuring three-dimensional wind fields globally in clear air and b) providing data for the study of the global circulation and related features such as precipitation systems, the El Niño and the Southern Oscillation phenomena and stratospheric/tropospheric exchange.

All the Reports for Assessment follow a common structure comprising seven chapters. Each starts by addressing the scientific justification for a particular mission and moves on to detail its specific objectives. Then, following the specification of observational requirements and a listing of the various mission elements required to satisfy these, consideration is given to the implications of meeting the requirements in terms of both the space and ground segments as well as requisite advances in scientific algorithms and processing/assimilation techniques. Finally, programmatic aspects are considered.

2. Background and Scientific Justification

2.1. Introduction

Measurements of winds throughout the atmosphere are crucial for both Numerical Weather Prediction (NWP) and an increasing range of studies related to the global climate, its variability, predictability and change. Accurate and timely information on winds is central to, amongst other things, aviation flight planning and the prediction of the dispersal of atmospheric pollutants. Reliable instantaneous analyses and longer term climatologies of winds are also needed to improve our understanding of atmospheric dynamics and the global atmospheric transport and cycling of energy, water, aerosols, chemicals and other airborne materials.

After several decades of meteorological observations from space, direct measurements of the full global, three-dimensional wind field remain elusive. Deficiencies, including coverage and frequency of observations, in the current observing system are impeding progress in both operational weather forecasting and climate-related studies. In particular, improvements in the available wind data are needed urgently if we are to exploit fully the potential of recent advances in Numerical Weather Prediction and continue to make significant progress in this field.

There is a clear requirement for a high-resolution observing system for atmospheric winds with full global coverage. At present, our information on the wind field over the oceans, the tropics and the Southern Hemisphere is indirect. It is severely limited by having to rely mainly on space-borne observation of the mass field, and quasi-geostrophic adjustment processes. Although there are several ways of measuring wind from a satellite, only the active Doppler wind lidar has the potential to provide the requisite data in clear air (i.e. above or in the absence of thick cloud) globally. It is the only candidate so far that may provide direct observations of the three-dimensional structure of the global wind field. In addition, a laser Doppler instrument will not only provide wind data in clear air but also much needed ancillary information on cloud top heights, vertical distribution of cloud, aerosol properties, tropospheric height, and the height of the atmospheric boundary layer.

There is enormous synergy between advances in Numerical Weather Prediction and those in climate-related studies. Indeed, climate studies are increasingly using analyses of atmospheric (and other) fields from data assimilation systems designed originally to provide initial conditions for operational weather forecasting models. Our understanding of the atmosphere and its evolution is based to a large extent on the analysed fields from continuous data assimilation carried out at operational weather centres, so that progress in climate analysis is linked closely to corresponding progress in Numerical Weather Prediction. It is widely recognised therefore that the impact of a new global atmospheric observing system, such as a space-borne Doppler wind lidar, on our understanding of atmospheric dynamics should be evaluated primarily in the context of operational weather forecasting. This is the philosophy followed in this Report. In presenting the scientific justification for the requirement for better global measurements of atmospheric winds, we consider firstly their importance for Numerical Weather Prediction, followed by a discussion of the corresponding requirement for climate studies.

2.2. The Need for Atmospheric Wind Fields for Numerical Weather Prediction

2.2.1. Background

Numerical Weather Prediction is an initial value problem, which requires good knowledge of an initial state (primarily that of the atmosphere) before the forecast can be started. In meteorology, this initial state is usually called the 'analysis'. It gives a complete three-dimensional picture of the prognostic variables of the weather forecasting model at all its grid points for a particular starting time of a forecast. Medium-range forecasts, which predict the evolution of the global atmosphere from typically four to ten days ahead, are generally started twice a day, at 00 UTC and 12 UTC. Often embedded in the global models are high-resolution, limited-area models for short-range predictions up to 2 or 3 days ahead. They are started from initial times usually only 6 or 3 hours apart. The standard prognostic model variables are: the horizontal wind components, the temperature, the humidity and the surface pressure. Future models might require additional initial values for cloud water, cloud ice, cloud amount, turbulent kinetic energy and densities of various constituents, such as aerosol.

In order to obtain an appropriate description of the atmosphere, a composite operational observing system has been established under the auspices of the World Meteorological Organisation (WMO). It consists of a number of different observing platforms which either take observations at pre-specified times (synoptic hours) or quasi continuously. They can be grouped further into in-situ or remote-sensing measurements. They either provide information for one level only (surface or upper air) or give profiles for a number of levels in the vertical.

2.2.2. Data Deficiencies

In order to give an impression of the observations currently available, Figures 2.1 to 2.6 show the locations of the reports from the various systems for the period from 21 UTC, 6 March 1996 to 3 UTC on the following day. All the reports which were available at that time for use in the operational analysis of the global model at the Deutscher Wetterdienst (DWD) are indicated.

Single Level; Surface

Figure 2.1 shows the synoptic surface reports from land stations and ships. They report surface values for winds, temperature, humidity, pressure, cloud amount and a number of other parameters. Clearly, their distribution is very inhomogeneous with only a few values from the oceans and Africa. Coverage is best over Europe and China. In total 3,400 reports were used in this particular analysis.

Figure 2.2 gives the locations of the drifting buoys. They report surface values for temperature, humidity, pressure and sea surface temperature. Some of them also report winds. There were only 214 buoy reports available for this particular analysis. Superimposed are the bands with scatterometer winds from the ERS-1 satellite providing high-resolution surface winds over the oceans for the swath of the spacecraft. In total, 51,000 wind vectors were reported for this 6-hour time window.

In order to fill the data gaps, there are also attempts to use qualitative information. For example, the Australian Meteorological Service manually derives pressure 'observations' from satellite pictures over the Southern Hemisphere oceans and makes them available to other services.

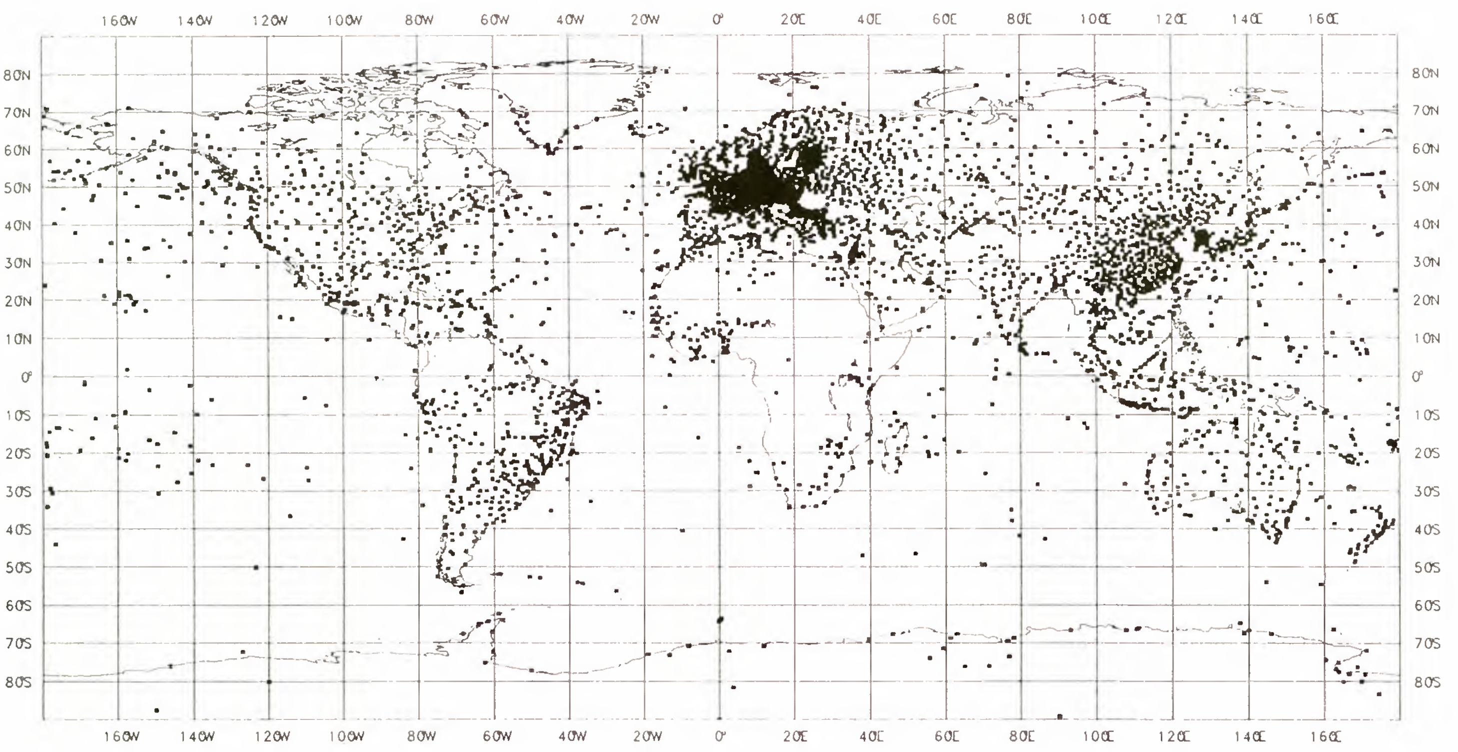


Figure 2.1. *Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from conventional land surface stations and ships.*

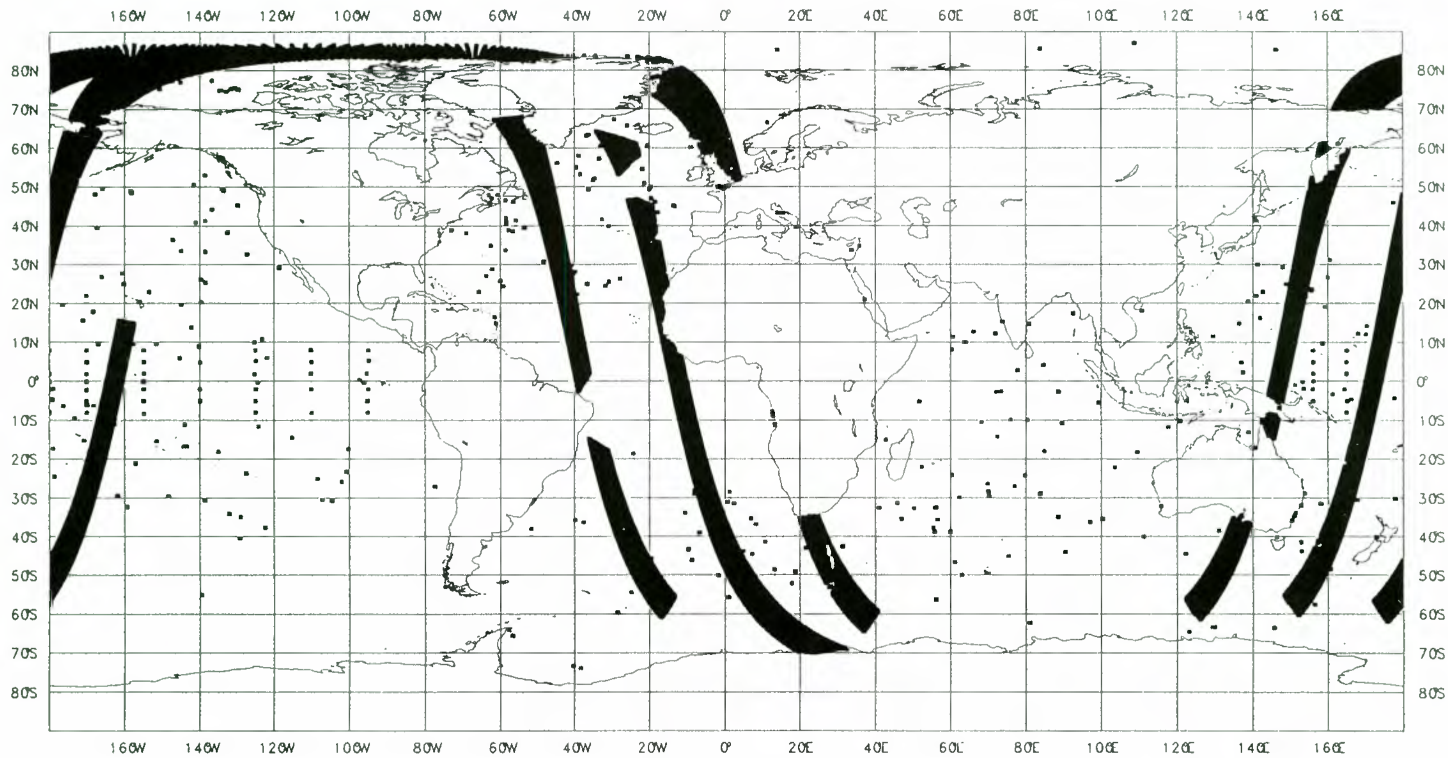


Figure 2.2. Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from drifting buoys (squares) and scatterometer winds from the ERS-1 satellite (bands).

Single Level; Upper Air

Another source of single level observations, but from higher up in the atmosphere are the aircraft reports (Figure 2.3). Aircraft either report at specified locations when having reached their flight level or send the observations continuously within the data stream being transmitted between the aircraft and its home base. The latter reports are available in very high resolution and include the takeoff and landing phases. Altogether 213 aircraft reports were used for this particular analysis. Information is dense along the traffic routes which are planned so as to avoid severe weather, but is sparse otherwise.

By tracking the cloud motions as observed by the geostationary satellites, wind vectors for the cloud top level can be obtained. As can be seen from Figure 2.4, wind information can be obtained between $\pm 50^\circ$ latitude. Of course, cloud motions winds can only be derived in cloudy areas. Also, there is some uncertainty in the height assignment for the winds.

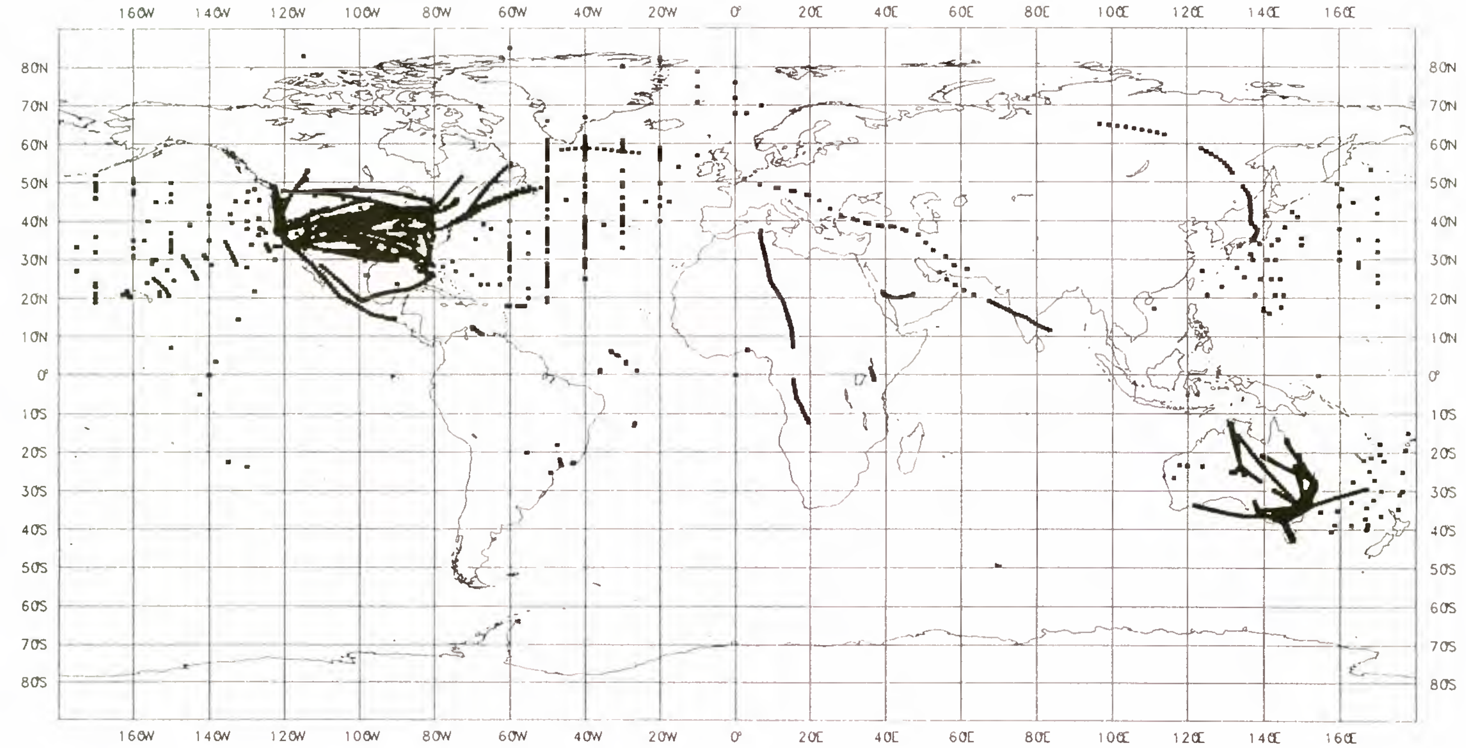


Figure 2.3. *Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from aircraft data.*

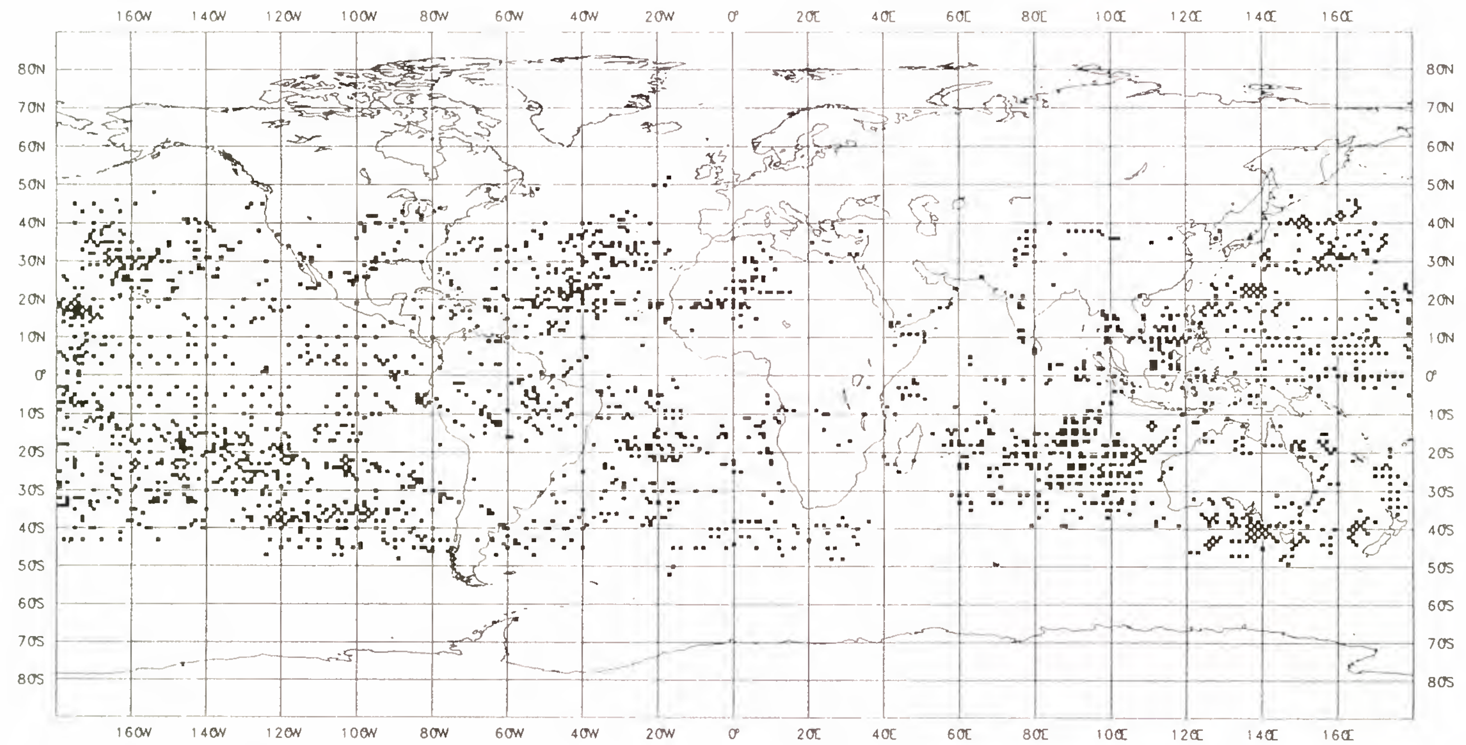


Figure 2.4. *Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from cloud motion winds from geostationary satellites.*

Multi Level

There are only two observing systems which provide profile information for a number of levels in the vertical. The first produces temperature and humidity retrievals from the polar orbiting satellites NOAA12 and NOAA14 (Figure 2.5). At the Deutscher Wetterdienst these profiles are used with a horizontal resolution of 500 km. Each retrieval contains 7 independent layer-mean temperatures and 3 values only for the humidity. The values are obtained from the measured radiances by inverting the radiative transfer equation. As there is no unique solution to this, additional information has to be used in order to obtain the most likely profiles. This additional 'background' information is to some extent reflected in the retrievals and so they are not an independent source of information. Within the six-hour window 1,090 profiles were used for the particular analysis illustrated here. These satellite soundings give a global coverage with mass field information, albeit with problems in their proper usage.

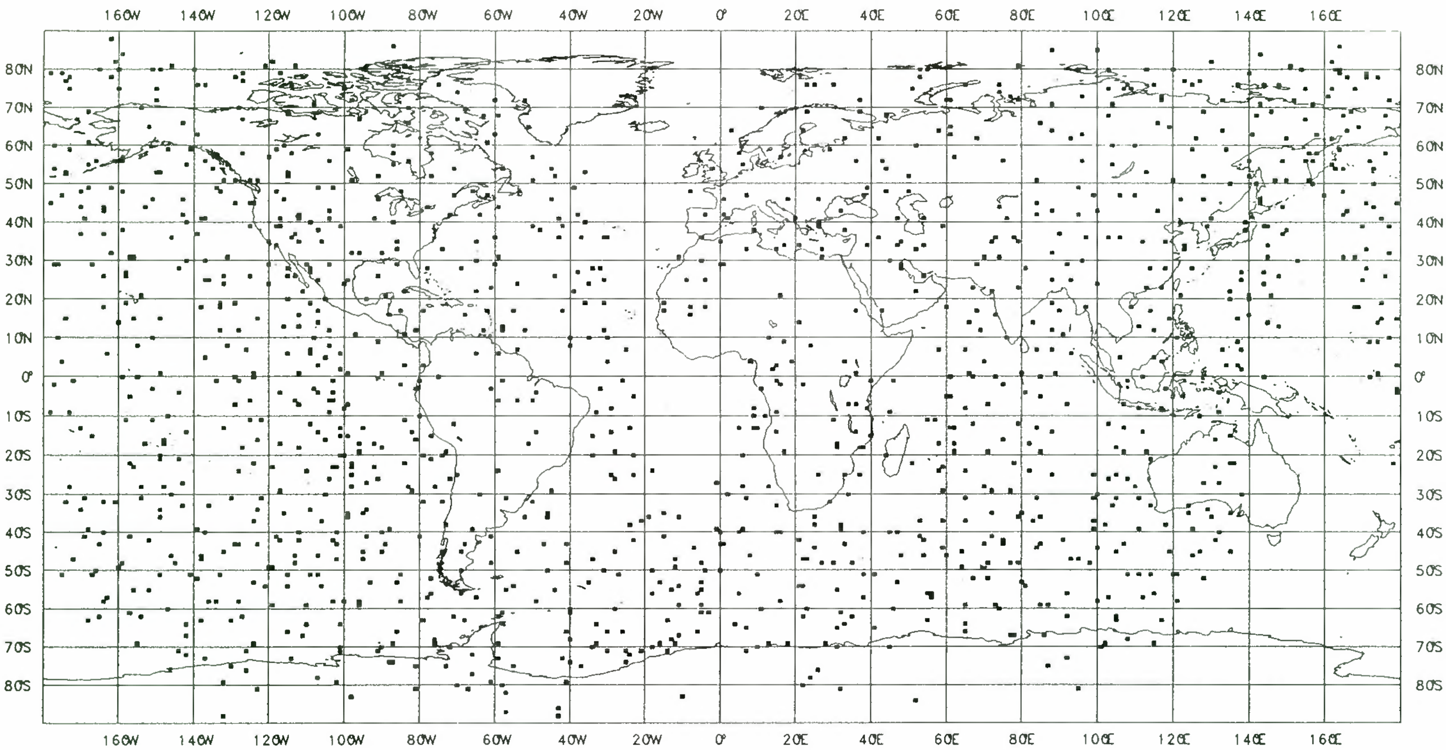


Figure 2.5. *Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from temperature and humidity soundings from the polar orbiting satellites NOAA12 and NOAA14.*

Radiosondes (Figure 2.6) constitute the only observing system providing profile data of the wind and mass fields. A balloon-borne sonde provides data for temperature, humidity and pressure. Wind vectors are derived by tracking the balloon by radar. A simplified version provides only the wind data. For the analysis in question 590 full profiles of the mass and wind fields and 120 wind-only profiles were used. Clearly, these observations are mostly from continental areas. Only a few island stations and some ships provide data from oceanic areas. Nonetheless, the radiosondes are still the backbone of the present observing system.

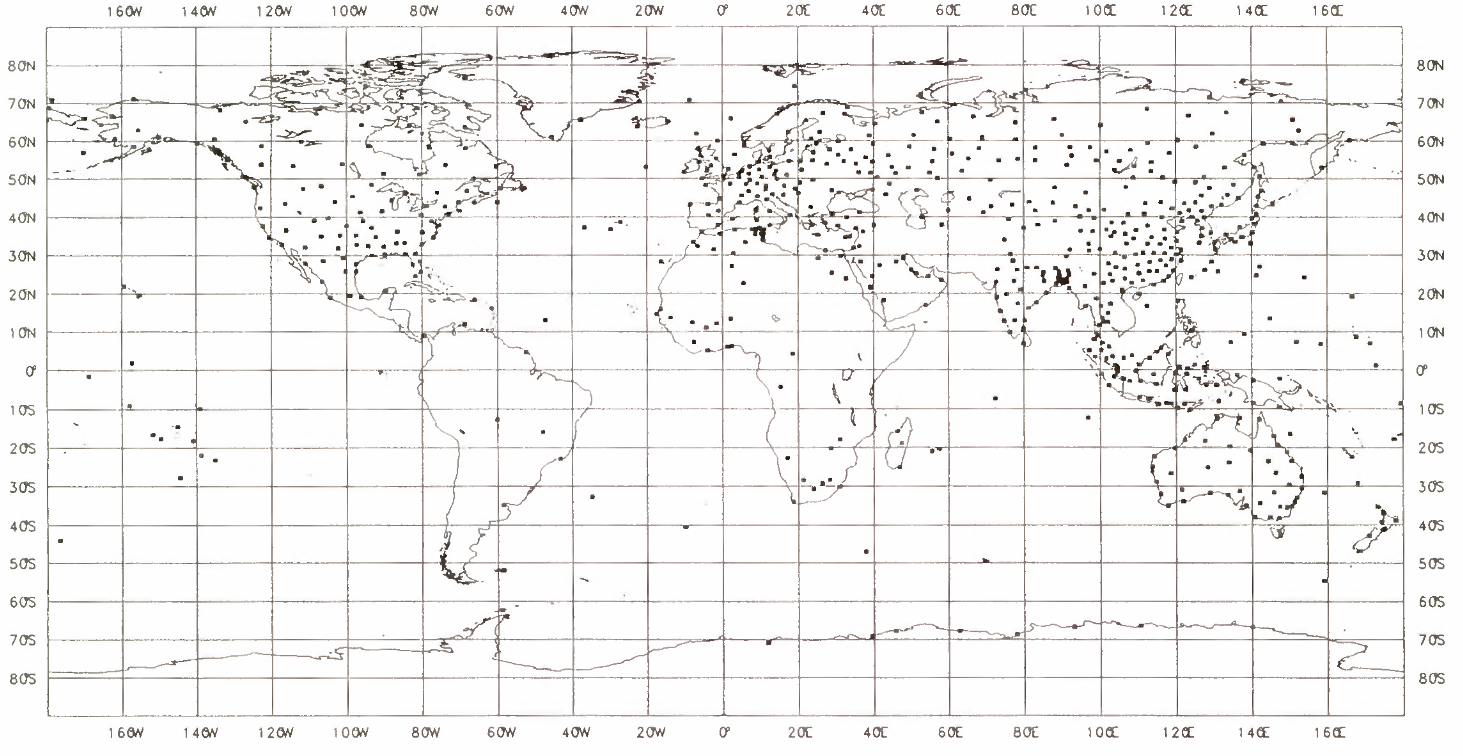


Figure 2.6. *Locations of the observations available at DWD for the 6-hour time window centred at 00 UTC, 7 March 1996 from radiosonde ascents.*

The present data deficiencies can be summarized as follows: the surface-based, conventional network shows large gaps in the Southern Hemisphere, in the tropics and over the oceans in the Northern Hemisphere. Satellite soundings provide global coverage with radiance data, which can only be used indirectly for the definition of the mass field. Radiosondes are the only observing system providing vertical profiles of the wind field. They are available mainly from the continents in the Northern Hemisphere. Very little information about the vertical profile of the wind field is available from the oceans, in the tropics and in the Southern Hemisphere. Cloud motion winds, aircraft reports, surface stations and scatterometer winds are single-level observations and these are more difficult to use than profile measurements because of the uncertainty of how to spread the information in the vertical.

2.2.3. Implications for Numerical Weather Prediction

The previous figures (2.4 to 2.6) indicate the locations of the various available reports. In general, each report contains a number of observations. For instance, radiosondes are supposed to report winds, temperature and humidities for at least 15 mandatory levels. In total, around 40,000 individual pieces of information were used in the analysis of the mass and wind fields for 00 UTC, 6 March 1996. Almost half of the data were provided by radiosondes, 60% of the observations were for the mass field, 40% for the wind field.

It is interesting to compare these Figures with the amount of information actually required to define the global mass and wind fields at every grid point of a model. Assuming, in future models, 50 km horizontal resolution and 50 vertical levels, a total of 10^7 initial values have to be set. These numbers can be even higher for limited area models with finer resolution. Compared with the 40,000 observations currently used, it is evident that Numerical Weather Prediction is a severely under-determined initial value problem. Therefore, data assimilation schemes have been developed which try to cope with this problem.

They do so by making use of the statistical knowledge we have about the spatial correlations that exist in the atmosphere. A variable at one grid point is not totally independent of the values at neighbouring grid points. Data assimilation also builds on the knowledge about the dynamics of the atmosphere. This is usually done by incorporating a forecast model into the process of defining the initial state. Thereby, dynamical relationships between the different variables as well as the temporal evolutions, implied by the spatial structures in the fields, can be accounted for. Thus, the time domain is incorporated into the analysis process, allowing information from previous observations to be extrapolated forward in time. This information is usually termed 'first guess' or 'background' in operational meteorology. In principle, the data assimilation system tries to translate temporal resolution into spatial resolution.

The second purpose of data assimilation is to combine the various sources of information, namely the background fields and the observations with their different error characteristics, in a statistically optimal way. This requires knowledge of the mean and random errors and the various correlations for the different sources of information. The innovation brought about by a new observing system thus depends on the accuracy of the new measurements compared with the accuracy of the background fields. The latter depends on the quality and the quantity of the previous observations and on the forecast model used to advance the information in time. Any improvement in one of these components leads automatically to more stringent demands on the new observing system.

The third important task is the quality control of the observations. Outliers in a distribution have to be identified and their impact on the final analysis reduced. Information about quality provided by the data producers can facilitate this process considerably.

The fourth task of a data assimilation scheme is to interpolate from the irregularly spaced locations of the observations to the regular grid points of a forecast model.

The concept of data assimilation is sketched in Figure 2.7. The full line shows the unknown true evolution of the atmosphere. At certain intervals, the sparse and infrequent observations are used to correct the background, which is usually a short-range forecast of 6 or 3 hours from a previous analysis. By this process, the evolution of the model atmosphere is adapted to the evolution of the true atmosphere as far as it is reported by the incoming observations.

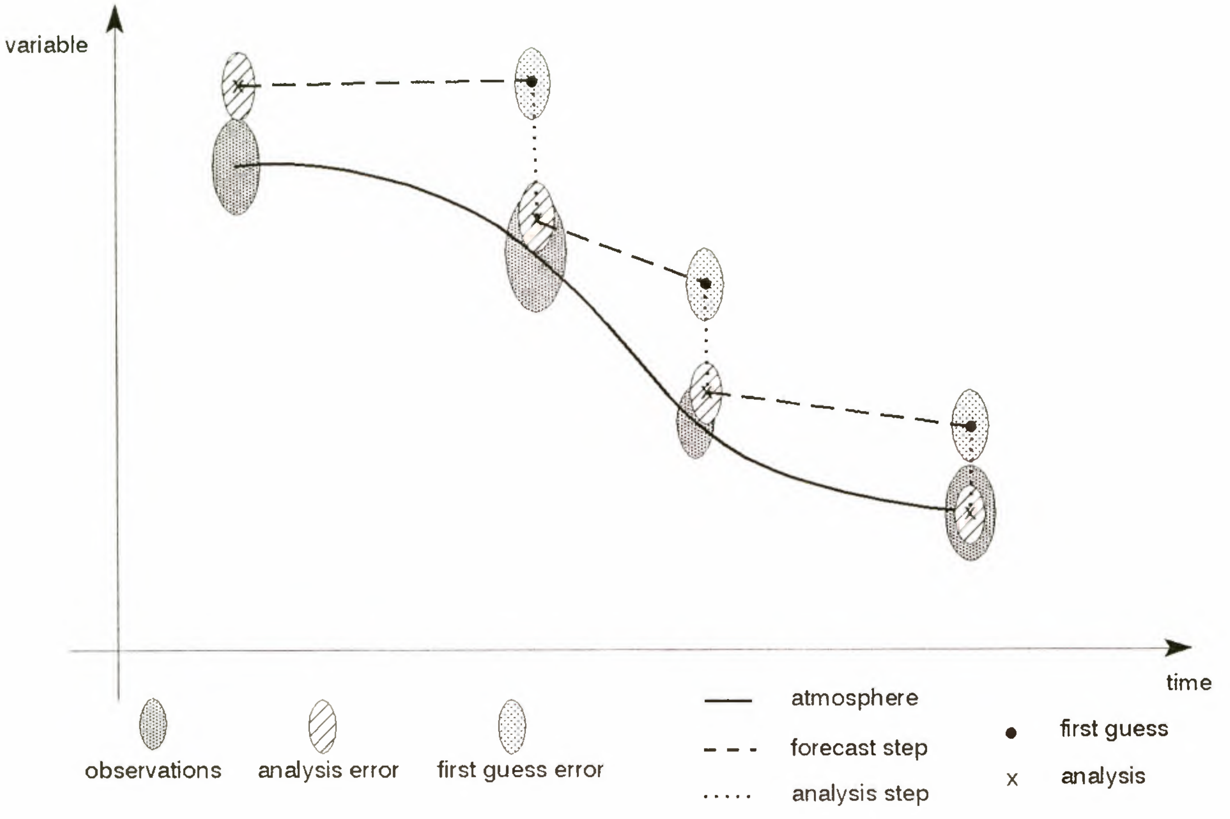


Figure 2.7. *Schematic diagram of the assimilation process (see text for details).*

Data assimilation is currently the subject of intensive research and development. Despite all past and expected future advances in this area, there will always be major uncertainties about the state of the atmosphere in data-void areas. As an example, Figure 2.8 shows the annual mean differences between 1980 and 1979 for the 'analysed' wind speed at 10m height for the Indian Ocean as emerging from a major re-analysis project being conducted by ECMWF. This effort was meant to provide consistent fields not influenced by changes in the assimilation system. However, Figure 2.8 shows up to 2 m/sec differences in the 'observed' annual mean speeds. Differences at any particular instant in time can be considerably larger. One explanation is that it could merely be due to the documentation of inter-annual atmospheric variability. There is, however, a caveat to this. During 1979 there was a geostationary satellite positioned over the Indian Ocean. It provided cloud track winds during the 'First GARP Global Experiment (FGGE)'. It was withdrawn from that position towards the end of 1979 so that the cloud track winds from the low level clouds in this area were no longer available. Without observations, we have no way to establish the true reason for the differences.

As the fields from data assimilation schemes are also used for diagnostic studies of the atmosphere, the differences in the wind fields lead to major uncertainties in diagnostic quantities, such as energy and water budgets as addressed in the Global Energy and Water Cycle Experiment (GEWEX) (see sub-section 2.3.7). Figure 2.9 shows the differences in the annual mean surface energy budget between 1980 and 1979. The differences in wind speeds lead to differences in evaporation with corresponding changes in the energy and water

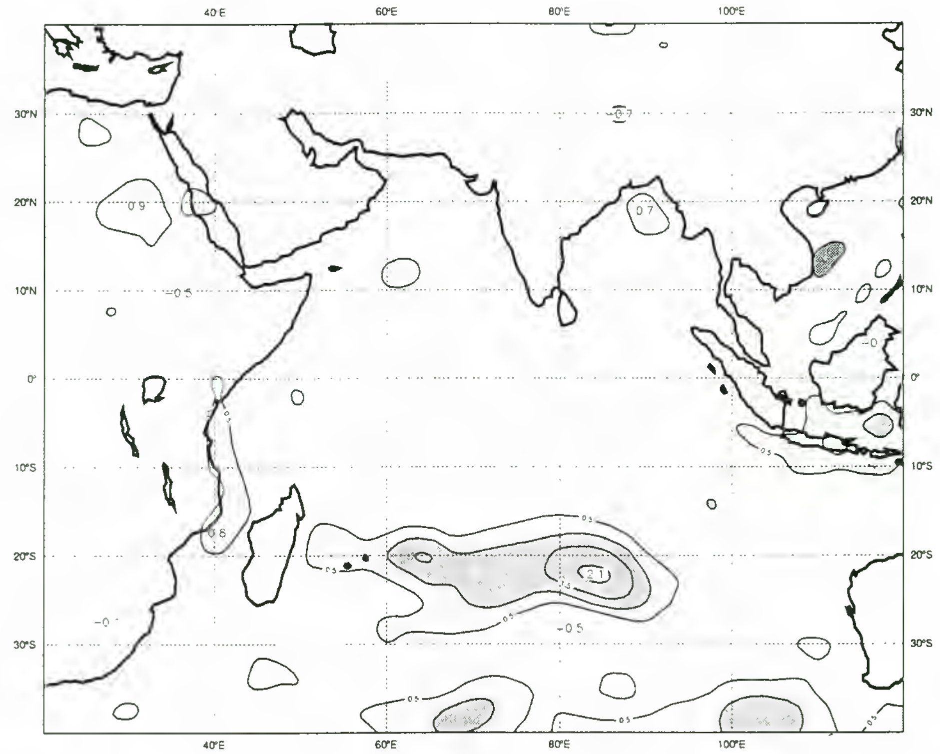


Figure 2.8. Differences in annual mean fields of wind speed at 10 m above ground between the year 1980 and 1979 as analysed in the ECMWF re-analysis project. Fields are valid for 00 UTC. Contour interval is 0.5 m/s.

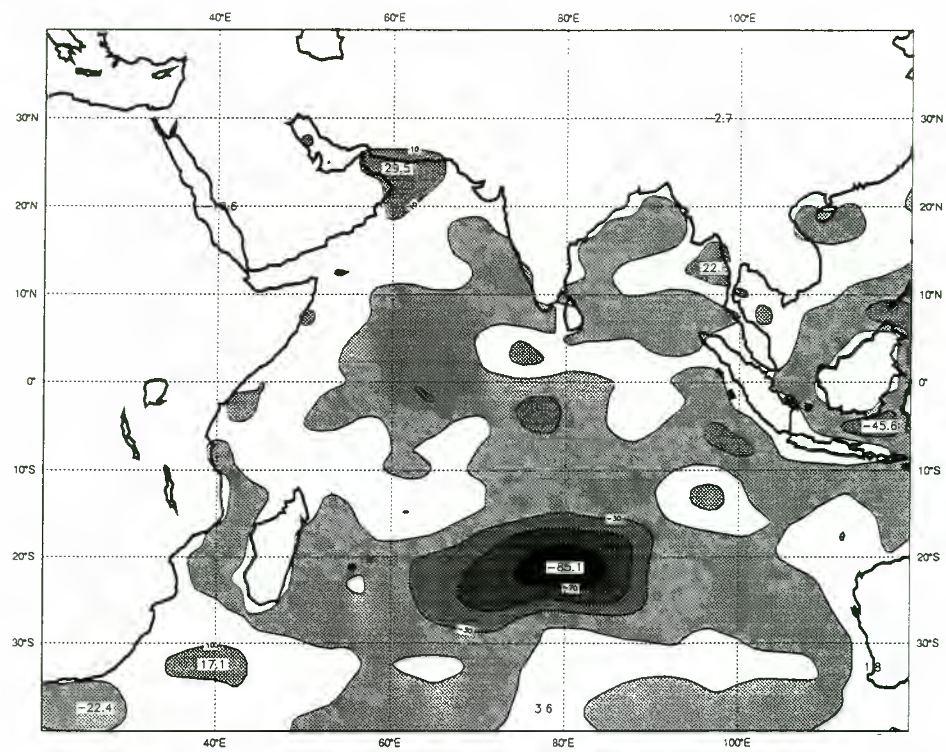


Figure 2.9. Differences in annual mean fields of net heat fluxes at the surface between the year 1980 and 1979 as analysed in the ECMWF re-analysis project. Fields are valid for 00 UTC. Contour interval is 30 W/m2.

budgets. These uncertainties, which in this case amount to 50% of the total budget, seriously impede progress not only in Numerical Weather Prediction but also in climate research (see section 2.3).

In summary, we can state that lack of observations makes Numerical Weather Prediction a seriously under-determined initial value problem. Data assimilation systems help to reduce this problem by bringing in additional statistical and dynamical information. However, there remain major uncertainties which obstruct further progress in weather forecasting and, as discussed later, in climate-related studies.

2.2.4. The Importance of Wind Data

In the following section, the relative importance of wind data as compared with mass data will be discussed. The arguments will be based on the linearized model equations which will allow important statements on the relationship of mass *and* wind information for controlling atmospheric dynamics.

The atmosphere can be regarded as an oscillating system. Just like a piano string, it has its own (eigen) oscillations. Each oscillation is associated with a particular frequency, the eigenfrequency. The oscillations are also referred to as 'modes'. Each mode describes a particular three-dimensional global structure of the mass and the wind fields. The modes can be ordered according to their horizontal and vertical scales.

The eigenfunctions of the atmosphere fall into two classes: the Rossby modes and the inertia-gravity modes. Rossby modes have low frequencies and they describe a characteristic relationship between the mass and the wind fields. In the extra-tropics, this balance can be approximated by the geostrophic relationship in which the pressure gradient force is balanced by the Coriolis force. Rossby modes describe most of the weather. They are the 'signal' we want to observe and to analyse.

Inertia-gravity modes have high frequencies. Their wind field is highly divergent and not coupled by a simple relationship to the mass field. Their amplitudes in the atmosphere are generally lower than those of Rossby modes. Inertia-gravity modes are sometimes called 'noise' in meteorology. Their analysis is very difficult and most assimilation schemes have special features included in order to prevent unrealistically high amplitudes of these waves.

Clearly, a new observing system is most useful if the additional data help to describe the 'signal' and do not generate 'noise'. That means that new measurements are easiest to use if they describe Rossby modes. Failing this, they might simply generate spurious inertia-gravity wave activity which will be dissipated quickly. The net effect would then be that the observations are 'rejected' by the model and all investment would be in vain.

With some further simplifications, the Rossby radius of deformation (R) can help to identify the conditions for exciting Rossby modes. For the extra-tropics it can be defined as:

$$R = \frac{\sqrt{gh}}{2\Omega \sin\Phi} \qquad (2.1)$$

where g is the acceleration due to gravity, h the equivalent depth of the fluid, Ω the angular velocity of the Earth and Φ latitude. R can be thought of as the length scale for which the mass and wind fields contribute equally in exciting Rossby modes. For length scales $L \gg R$, mass field information dominates and the wind field adjusts to the mass field. For $L \ll R$, wind field information is dominant and the mass field adjusts to it. R depends on the equivalent depth h and on the latitude. With decreasing latitude Φ, R increases and this leads to a higher weight of wind data. When approaching the equator, R goes to infinity and the winds become the all important variable. The equivalent height can range from 10^4 m for vertically uniform (barotropic) structures to over 10^3 m for vertically varying (baroclinic) structures such as developing disturbances to only a few metres for atmospheric boundary layer processes. It is clear from equation 2.1 that deep vertical structures have a higher sensitivity to wind data than shallow ones.

These findings are condensed in Figure 2.10 which shows the Rossby radius of deformation as a function of equivalent depth and horizontal scale for a latitude of 45°. Winds are the dominant component for exciting Rossby modes at large equivalent depth and small horizontal scale. By contrast, for large horizontal and shallow vertical scales, mass field information is more important. In between, there is a wide range where both mass and wind data are important. With decreasing latitude, the separation line moves to the right with more influence being given to wind observations.

Although the above discussion might seem theoretical, it is of immense practical importance, as the following two historical examples will highlight. Richardson in the 1920s first tried to calculate a numerical weather forecast. He did so by hand and although his approach was very similar in principle to what is done now with large computers, he failed. The reason was simply that the analysis he started his calculations from gave rise to very large amplitude inertia-gravity waves which completely ruined his forecast. A similar problem occurred with the advent of sounding data from polar orbiting satellites. Simply inserting this mass field information resulted in the excitation of large amplitude inertia-gravity modes, which quickly propagated the information away from the source region and were eventually dissipated. The observations thus got 'rejected' by the model. It was only after the addition of geostrophically derived winds that the observations were accepted by the model. It has become common practice in data assimilation to accompany mass data by geostrophic wind components in the extra-tropics. As will be discussed in the next section, this has a number of shortcomings which can only be overcome by the provision of independent wind data.

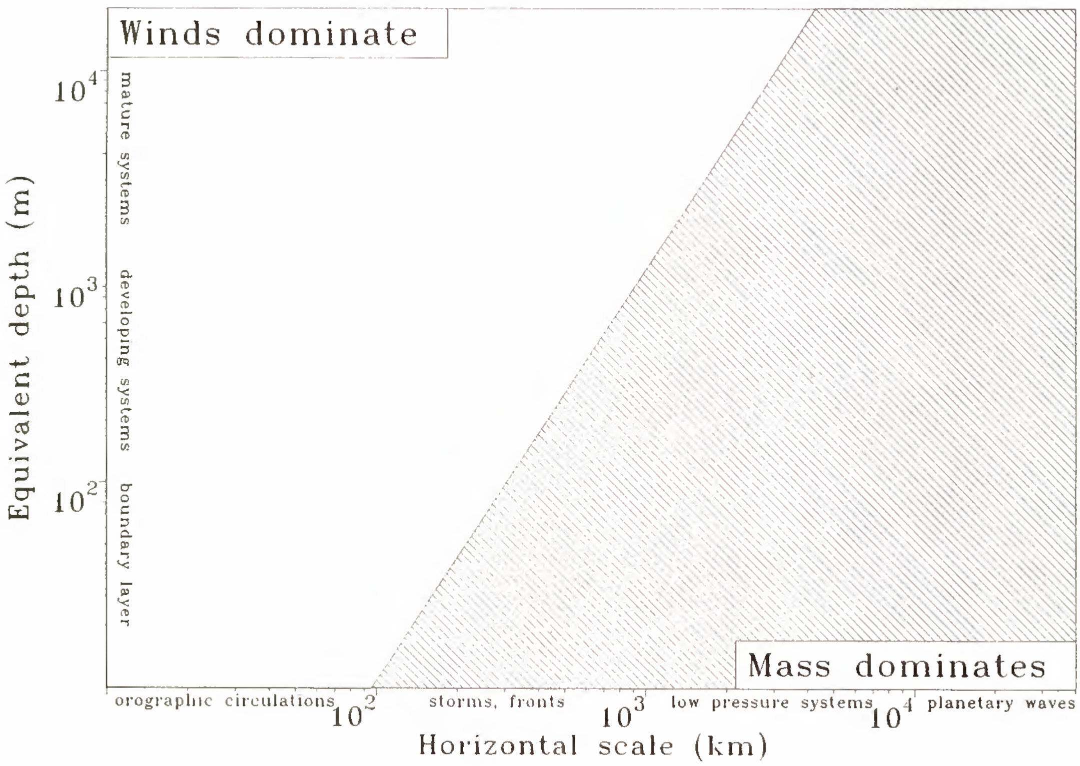


Figure 2.10. *Rossby radius of deformation for a latitude of 45⁰ as a function of horizontal scale and equivalent depth. Open area denotes the range within which the wind field dominates.*

In summary, we can state that observations are most useful if they directly influence the balanced component of that flow. In the tropics, winds are the dominant part of the flow. They govern the tropical dynamics. In the extra-tropics, they are the primary source of information for small horizontal scales and deep vertical structures. Mass field information is important for large horizontal scales and shallow vertical structures. Between these two extremes, there is a wide range where both mass and wind data are essential.

2.2.5. The Impact of Additional Wind Profiles

From the previous discussion it follows directly that reliable wind profile observations would have a major impact in the tropics. They would lead to a considerable step forward in our understanding of tropical dynamics. Furthermore, they would result in a much improved definition of the initial state for Numerical Weather Prediction which would lead, together with improved modelling made possible by a better understanding of tropical dynamics, to a major increase in the time range up to which useful forecasts, including warnings of tropical cyclones, can be issued for the tropics. This would have enormous social and economical consequences.

In the extra-tropics, the most important areas to cover are those of the storm tracks where most of the new cyclones develop. They are concentrated in a latitude band between 40° and 70°. It is important to capture the initial instabilities of the flow in order to be able to predict the subsequent intense developments.

While firm conclusions concerning the benefit of additional wind profiles for the tropics can easily be drawn, the arguments for the extra-tropics are somewhat more indirect. This is mainly due to the fact that, to zeroth order, there exists a relation between the mass and the wind fields which can be exploited. Given a global coverage with mass data from polar orbiting satellites, geostrophic winds can be derived from the geopotential height gradients. One could argue that there is a reduced need for wind data in middle and high latitudes. There are, however a number of problems with this approach.

Calculating geostrophic winds involves differences in neighbouring values of the heights of isobaric surfaces. This approach is therefore very sensitive to errors in these observations. For instance, a height observation error of 10 m (corresponding to a 1 K temperature error in the layer between 700 and 500 hPa) between two adjacent soundings 120 km apart translates into a geostrophic wind error of 10 m/s. As was discussed in sub-section 2.2.2, the retrievals from polar orbiting satellites are subject to various uncertainties. Deriving geostrophic winds from spurious height observations holds the danger of converting observational noise into Rossby modes. The opposite way, namely to calculate height fields from the observed winds, involves an integration and is therefore less prone to observational errors.

Therefore, additional wind profiles would allow a much needed calibration and verification of the sounding data from polar orbiters. Currently, the quality control for these data is very difficult, as there is little other information to check them against and they have the tendency to support each other. Once erroneous retrievals have found their way into a data assimilation system, it is very difficult to identify them as in error.

Apart from these general arguments, there are two more points which address specific additional problems at the extreme ends of the spectrum.

Firstly, as was shown in the previous section, at small scales the wind field is the dominant component of the flow. Deriving small scale winds from height field observations does not reflect the true dynamics. Additional reliable wind profile data might therefore be expected to lead to improvements in short-range forecasts of intense wind events, which frequently cause severe damage.

Secondly, at the other end of the spectrum, i.e. at the planetary scales, the geostrophic relation is not valid. Imposing local geostrophy results in an aliasing of Rossby modes on inertia-gravity modes. Therefore the geostrophic coupling between mass and wind has to be relaxed for the very large horizontal scales. Planetary-scale Rossby modes can only be analysed properly if both mass and wind data are available. With the availability of additional wind profiles one can envisage a better definition of the large-scale initial state, which will result in improved medium-range forecasts.

2.3. The Need for Atmospheric Wind Fields for Climate Studies

2.3.1. Background

A simple definition of climate is 'the average weather'. A description of the climate over a specified period (which, typically, may be from a few years to a few centuries) involves the averages of appropriate characteristics of the weather over that period, together with the statistical variations of those characteristics. As a result of natural processes, the climate fluctuates on many timescales and this intrinsic feature is often referred to as natural climate variability. In this report, the term 'climate change' refers to any change in climate over time, whether this is due to natural variability or human activity or, indeed, is a consequence of both these causes.

Although the climate varies over a vast range of timescales, from inter-annual to many thousands of years, two ranges are currently receiving particular attention. These are, firstly, the seasonal-to-interannual time-scale range and, secondly, the decadal-to-centennial time-scale range and these, particularly the latter, provide the focus for this section of the report. Following brief comments on the general data requirements for current studies involving these two ranges, this section discusses the particular needs for wind data for climate studies, with separate comments on tropospheric and stratospheric winds.

In the context of climate studies, one of the highest-priority concerns for better global wind measurements has been expressed by the Scientific Steering Group of the Global Energy and Water Cycle Experiment (GEWEX), a major component of the World Climate Research Programme (WCRP), and so this requirement is discussed specifically in sub-section 2.3.7.

2.3.2. Seasonal-to-Interannual Variability and Predictability

Recent research has achieved significant progress in making credible predictions for a few seasons ahead for certain regions of the globe. Success to date has been most evident for some tropical areas and has resulted from research conducted principally under the auspices of the WCRP, to understand the interaction of the Tropical Ocean/Global Atmosphere (TOGA) and the related large-scale ENSO (El Nino/Southern Oscillation) phenomenon.

The standard assimilated meteorological data sets are required for initialisation and validation purposes in relation to seasonal-to-interannual climate predictions. In this context, atmospheric wind is a key meteorological variable, particularly in the tropics where reliable wind observations are crucial as their inclusion in the Numerical Weather Prediction assimilation process strongly affects the large-scale features of the analysed tropical wind field (see section 2.2).

Whilst the evidence for seasonal predictability is strongest in the tropics, there is also growing evidence of some predictability in the extra-tropics. Global data, including atmospheric winds, are therefore required for a range of uses in connection with the investigation of seasonal variability and predictability, and the development and application of seasonal-to-interannual prediction techniques.

2.3.3. Decadal-to-Centennial Climate Variability and Predictability, Including Modelling and Detection of Anthropogenic Climate Change

The prospect that the global climate may be modified by human influence has led to international programmes to monitor and increase our understanding of climate and to detect, attribute and predict climate change. Comprehensive observations of the climate system are recognised as being an essential component of these programmes and so the Global Climate Observing System (GCOS) has been established to ensure that the observational needs for climate are met in a coordinated and systematic manner.

In the current debate about climate change, it is evident that adequate information is not available to answer fully the critical scientific questions. While many observational programmes are currently under way, systematic global observations of key variables, including atmospheric winds, are urgently needed to :

- monitor the climate and its variability at global, regional and more local scales, thereby enabling quantification of natural climatic fluctuations and extreme events on a range of temporal and spatial scales and the detection of climate change;
- establish 'fingerprints' of climate change, which will allow not only detection of change but also some attribution to its causes;
- conduct diagnostic studies to document and understand better the behaviour of the climate system and its component parts, including studies of the mechanisms of natural climate variability;
- model climate and predict climate change.

Model-related climate studies require global observations for a number of reasons. Atmospheric wind data are required principally for validation of the models, i.e. to assess the performance of models being used for climate simulation and prediction. Model behaviour is compared with that of the 'observed' climate, often leading to further development and improvement of the models. These particular model requirements apply not only to multi-decadal simulation and prediction but also to the seasonal-to-interannual studies discussed above.

The acquisition of systematic and comprehensive space-based global observations with adequate coverage in space and time are essential to meet the above aims. However, in addition to the requirements for continuous, systematic data collection, special data are also needed in support of detailed research studies of a wide variety of complex dynamical, physical and other processes which govern the state and evolution of the climate system. Such specialised data sets are likely to need to be highly resolved in time and space and therefore may be gathered for a limited period only. In particular, further progress in understanding and predicting global climate change is critically dependent upon improvements in our ability to model energetic processes, as detailed in the scientific plan for GEWEX (1990). The high priority attached to wind data in support of GEWEX is discussed in sub-section 2.3.7.

2.3.4. The Importance of Wind Data for Climate Studies

Climate research is highly dependent upon reliable operational global analyses of standard atmospheric variables, including *winds throughout the atmosphere*. These constitute the basic data needed to infer more complicated quantities, such as the properties of atmospheric transport and the surface fluxes of momentum, energy and mass, which are not measured directly or routinely. Global coverage with optimal vertical resolution and representative horizontal spacing are the crucial requirements for many climate activities and so, as in the case of Numerical Weather Prediction (section 2.2), space-based observations are particularly important in this context. Earlier expert studies have already stressed the great importance of accurate vertical profiles for wind and temperature which largely determine the quality of many of the other important meteorological fields.

Atmospheric data, including winds, are required to understand better the dynamics of the climate system and its natural variability. In particular, as implied above, atmospheric data are needed to monitor the current state of the climate, to detect change and to validate the models which are used for seasonal forecasting, simulating climate and providing projections of climate change due to human activities. Related research, such as studies of the serious depletions of stratospheric ozone over the Arctic and Antarctic would also be much better served by the availability of global wind data.

The main requirement is for long term, consistent and representative global data sets but there is also a need for shorter-period data sets to improve understanding of the climate system through process and diagnostic studies. Better information is needed on the atmospheric circulation for the purpose of trying to establish attribution of climate change to particular causes. A comprehensive view of the observed climate change must be pursued by analysing all climate variables and accounting for relationships among them wherever possible. The fundamental atmospheric variables needed are principally those measured routinely for weather forecasting, including wind velocities throughout the troposphere. Current accuracy and coverage are inadequate for many such studies and improvements are needed.

Changes in the atmospheric circulation are potentially very important because it forms the main link between regional changes in wind, temperatures, and precipitation in the atmosphere and other climatic variables such as ocean currents and sea-surface temperatures through changes in surface fluxes of heat, moisture and momentum. Internal consistency among analysed changes in the variables can add substantial confidence to results and provides the physical setting for understanding the changes taking place. A strong case can be made that local climate change can only be understood if the changes in the global atmospheric circulation have been fully taken into account.

Note that an Atmospheric Dynamics Mission has already been recognised as one of the seven 'missions' defined as necessary to meet the requirements of the Global Climate Observing System (GCOS) from space programmes and the provision of wind profiles is one of the principal observations listed for such a mission (GCOS, 1995). Indeed, GCOS is giving close attention to achieving more comprehensive and complete analyses of the full three-dimensional structures of both the atmosphere and the oceans.

2.3.5. Tropospheric Winds

The current deficiencies in coverage and consistency of in-situ measurements of atmospheric winds throughout the troposphere are similar in character but generally worse in extent to the problems experienced with the corresponding data for temperature and humidity. These make in-situ data sets largely inadequate for climate purposes through a combination of sparse coverage and poor quality. Coverage is particularly poor over the oceans and it is here that satellite data have much to offer. In particular, wind observations in the tropics are crucial as their inclusion/exclusion in Numerical Weather Prediction data assimilation schemes determines the analysis of large-scale features of the tropical wind field, as has been explained already in section 2.2.

Existing sensors only allow winds in the tropics and extra-tropics to be inferred (from cloud motion vectors) at one or two vertical levels and only when trackable features are imaged. Winds derived in this way have suffered from time-varying biases (which have gradually decreased over the past 10 years) which limit their usefulness for climatological purposes. For all satellite measurements it is vital that a period of overlapping, independent (in situ) observations exists for intercomparison purposes. Note that there are very few observational wind measurements south of 30°S to act as an independent in-situ reference set.

Although assimilated wind fields are highly desirable for climate purposes, it is also vital that high-quality, single-source data sets are also available. To this end it is important to promote and support missions which seek to demonstrate new and potentially valuable technology. In this case the main such development is the possible addition of active sounders on satellite payloads including Doppler wind lidars. Such instruments are needed to provide measurements of tropospheric wind profiles with higher accuracy and better vertical resolution than we have now.

2.3.6. Stratospheric Winds

Although the more pressing immediate need is for tropospheric winds, there is also a strong climate requirement for stratospheric winds. In addition to its important role in the climate change debate, the stratosphere is being studied increasingly in its own right. In particular, it is necessary to establish if the stratosphere will continue to be perturbed by changing atmospheric composition and chemistry resulting in severe stratospheric ozone depletion, particularly in the polar regions, and, if so, how long will this continue for and with what consequences.

Accurate determination of stratospheric winds is likely to become an increasingly important issue in addressing such problems and as models increase in vertical resolution and begin to resolve more realistically climate perturbations, such as 'sudden warming' events. As in the case of tropospheric winds, the assimilated wind product is vital for climate purposes, although single-source data sets are also important. Increased observational accuracy and spatial resolution are desirable, though not essential, for future missions. Improvement in vertical resolution is needed for monitoring of 'sudden warming' events, which have a vertical scale of typically several kilometres, and for studying the processes involved.

2.3.7. The Global Energy and Water Cycle Experiment

Process research is needed to improve our understanding of the climate system and our capabilities to model climate and detect, attribute and predict climate change on decadal (and longer) timescales. This is addressed by the WCRP whose overall objectives are to observe, understand, model and ultimately predict climatic variations and climate change. In particular, through GEWEX, the WCRP places a high priority on achieving accurate computations, and therefore a better understanding of energy and water fluxes on the global scale which determine the current state and the future evolution of the climate. In addition to progress in understanding and predicting global (climate) change, further progress in weather forecasting beyond a few days, and seasonal-to-interannual forecasting are also critically dependent upon improvements in our ability to model energetic processes, as shown in the scientific plan for GEWEX (1990).

The need for accurate global measurements of tropospheric winds for numerical weather forecasting and climate studies has been highlighted as a serious issue by the GEWEX Scientific Steering Group. Indeed, it has identified inadequate tropospheric wind measurements as one of the three global data areas of most concern for GEWEX studies (the other two being, cloud, aerosol and radiation measurements, and soil moisture measurements) and therefore deserving the highest scientific priority and more attention in the planning of future satellite programmes.

The WCRP in general, and GEWEX in particular, require basic meteorological variables for estimating energy and water transformation in the atmosphere and fluxes at the air-sea interface, but tropospheric winds remain a weak point. This deficiency poses a considerable limitation for scientific diagnostics of large-scale diabatic processes from the divergent component of the wind field. The problem is most serious in the tropics where the wind field is a critical dynamical variable. As noted several times previously in this chapter, tropical winds in particular are currently very poorly determined because of the almost complete lack of direct observations. In addition, low level winds are not observed everywhere with the required spatial and temporal resolution for the type of climate-related studies being carried out in GEWEX.

The regular provision of global wind profiles is regarded as an important requirement for many aspects of GEWEX science and climate research in general. As discussed earlier, accurate global wind data are also essential for initialisation of Numerical Weather Prediction models so as to define the transport of water vapour and other atmospheric constituents such as ozone and aerosols. It is recognised, therefore, that the greatest impact of such measurements will most likely come from within the framework of operational meteorology. A global wind mapping system would advance the operational analyses upon which climate monitoring and climate studies rely. The GEWEX Scientific Steering Group is in no doubt therefore that experimental Doppler wind lidar demonstration missions should be given serious consideration as a means of proving and advancing the technology in this area.

GEWEX has also identified humidity as a major variable in the assessment of climate change. Research (sponsored by ECMWF and EUMETSAT, see McNally and Vesperini (1995)) has already indicated a marked sensitivity of humidity analyses to the inclusion or omission of satellite radiances. In turn the humidity adjustments caused by the assimilation of radiance data are accompanied by significant changes in the model dynamics, especially the description of the tropical Hadley circulation. This result has important implications for the observational strategy planned for GEWEX and other WCRP programmes. In particular, it has been demonstrated at ECMWF that analyses of the mean meridional circulation in the Atlantic and Eastern Pacific have substantial systematic errors when no radiance data are assimilated. The Inter-Tropical Convergence Zone in the Atlantic has a wider region of moist ascent when radiance data are assimilated, as opposed to a rather weaker and narrower maximum when they are excluded. The strength and details of the meridional circulation, and the corresponding mean humidity structure, are therefore significantly different with and without the assimilation of the radiances.

In one documented case (McNally and Vesperini (1995)), moistening of the tropics and drying of the sub-tropics resulted in a stronger mean analysed meridional circulation in the Atlantic. These improvements to the analyses have also been shown to improve the medium-range forecasting of humidity, together with some associated benefit in the corresponding predictions of cloud and precipitation. Given the status of model development, these results suggest that current wind and temperature measurements alone cannot be relied on to provide a good description of the Hadley circulation (i.e. humidity data are also necessary). There is an urgent need, therefore, for good quality wind data which are essential in order to reduce such uncertainties.

2.4. Conclusion

In the context of atmospheric data, we have argued that progress in climate analysis is dependent to a large extent on progress in Numerical Weather Prediction; the two cannot be separated. Indeed, operational and extended-range weather prediction offer an ideal opportunity for detailed verification and improvement of model physics, at least for the so-called 'fast' atmospheric processes. Furthermore, climate research depends on the products of operational, meteorological analyses for much of the basic climatological information, including many second-order quantities which cannot be determined directly from observations on the global scale (e.g. momentum, heat and water fluxes). For this reason, both weather forecasting and climate research place the highest priority on improving the basic meteorological fields. These are required not only for initialising operational weather forecasts and for estimating global climatological quantities, but also for the formulations of physical processes in weather prediction and climate models, which are essential for both successful extended-range forecasts and meaningful assessments and predictions of climate change. Filling the gaps in existing wind observations, especially in the tropics, is regarded as being one of the first priorities to achieve these objectives.

Modern data assimilation systems with their ability to incorporate all available observations for the atmosphere and the surface are now the most reliable sources of analysed data for a number of applications. Indeed, in all likelihood, comprehensive analyses of global atmospheric fields, based on four-dimensional assimilation of meteorological and marine data, will constitute the main source of information on the Earth's budgets for energy, momentum and water. For this reason, further improvements in the analysis of the global atmospheric circulation and the computation of budgets and fluxes are essential for both weather forecasting and to meet the objectives of major international climate research projects such as GEWEX.

Reliable measurements of the tropospheric, three-dimensional wind field are therefore of the utmost importance for Numerical Weather Prediction, seasonal-to-interannual forecasting and for studying atmospheric dynamics, energetics and the water, chemical and aerosol cycles associated with the current state of the climate and its future evolution.

Space-borne Doppler wind lidars are the only candidates for providing the required direct, accurate, global sampling of the wind field in clear air (as defined in section 2.1). In addition to its primary role as a wind-finding system, the Doppler wind lidar could also prove valuable as a backscatter lidar providing sorely needed information on cloud top heights, vertical distribution of cloud, aerosol properties, tropospheric height, and height of the atmospheric boundary layer. In particular, the capacity of a space-borne wind lidar to provide sampling of the wind structure in the atmospheric boundary layer should have strong impacts on our understanding of atmosphere-ocean and atmosphere-land interactions. For these reasons, a very high priority should be given to the implementation of an Earth observing mission which demonstrates and tests the capabilities of the Doppler wind lidar.

3. Research Objectives

3.1. Introduction

The primary aim of the Earth Explorer Atmospheric Dynamics Mission is to provide observations of three-dimensional wind fields in clear air (i.e. above or in the absence of thick cloud) thereby helping to correct a major deficiency in the current (meteorological) operational observing network. Such data would be assimilated into numerical weather prediction models leading to an improvement in objective analyses and hence in Numerical Weather Prediction.

The mission would also provide data needed to address some of the key concerns of the World Climate Research Programme (WCRP) i.e. quantification of climate variability, validation and improvement of climate models and process studies relevant to climate change. The newly acquired data would also help realise some of the objectives of the Global Climate Observing System (GCOS) by:

a) contributing directly to the study of the Earth's global energy budget (by measuring three-dimensional wind fields globally in clear air); and
b) providing data for the study of the global atmospheric circulation and related features such as precipitation systems, the El Niño and the Southern Oscillation phenomena and stratospheric/tropospheric exchange.

3.2. Numerical Weather Prediction

From the discussion in chapter 2 it is clear that a space-borne atmospheric wind lidar is expected to provide the following benefits of direct value to Numerical Weather Prediction:

a) A major improvement in our understanding and modelling of tropical dynamics through the provision of observations of the essential component of the flow.
b) A significant increase in the usefulness of tropical forecasts through a more precise definition of the initial state and through better modelling.
c) Improvements in short-range forecasts of intense wind events through proper definition of the wind field for the small scales.
d) An increase in the usefulness of medium-range forecasts for the extra-tropical region through a better definition of the planetary-scale waves.
e) A much needed quality control standard for the thickness retrievals from polar orbiters, which will lead indirectly to improvement in forecasting skill, particularly in the Southern Hemisphere, where remote sensing data are the primary source of information.

These data may also help to validate observations of wind from other sources.

In summary, the primary objective of this mission will be to contribute to Numerical Weather Prediction, in the areas detailed above, by the provision of three-dimensional wind information. The mission should demonstrate the potential of Doppler wind lidar for operational meteorology.

3.3. Climate

The mission should provide data sets suitable for the validation of climate models, i.e. to assess the performance of models being used for climate simulation and prediction, with a view to their improvement. These particular model requirements apply not only to multi-decadal simulation and prediction but also to seasonal-to-interannual studies, including predictions of climate evolution. Although assimilated wind fields are highly desirable for climate purposes, it is also important to remember that high quality, single source data sets are also required.

Reliable short-period wind 'climatologies' are also needed to improve our understanding of atmospheric dynamics and the global atmospheric transport and cycling of energy, water, aerosols, chemicals and other airborne materials. In particular, the proposed mission should also produce data sets for use in detailed research studies of a wide variety of complex dynamical, physical and other processes which govern the state and evolution of the climate system. Further progress in understanding and predicting global climate change are critically dependent upon improvements in our ability to model energetic processes, as detailed in the scientific plan for the Global Energy and Water Cycle Experiment (GEWEX, 1990) of the World Climate Research Programme. GEWEX requires wind data suitable for estimating energy and water transformation in the atmosphere and fluxes at the air-sea interface.

The Doppler wind lidar should not only provide wind data in clear air but also much needed ancillary information on cloud top heights, vertical distribution of cloud, aerosol properties, tropospheric height, and the height of the atmospheric boundary layer. Global winds are required for a range of uses in connection with the investigation of seasonal variability and predictability, and the development and application of seasonal-to-interannual prediction techniques.

4. Observational Requirements

4.1. Introduction

In chapter 2 the need for three-dimensional wind information for numerical weather prediction and climate studies was highlighted. There are still significant data void areas especially over the tropics, the Southern Hemisphere and the Northern Hemisphere oceans. Surface-based observations do provide wind profile information but mainly over the continents in the Northern Hemisphere. Single-level data sources, such as the scatterometer, aircraft reports and (cloud) feature tracked winds are not adequate to describe the atmospheric circulation in sufficient detail. In order to meet the numerical weather prediction and climate objectives put forward in chapter 3, a supplementary system is needed that provides three-dimensional winds over a large part of the globe. This means that it is essential to put significant effort into the development of a space-based system. Only a Doppler wind lidar (DWL) has the potential to provide the three-dimensional wind fields in clear air (see section 2.1), by measuring profiles of the line-of-sight (LOS) wind components. The scientific principles underlying the Doppler wind lidar and the observational requirements for such a system are discussed in this chapter.

4.2. Geophysical Element

4.2.1. Wind

The Earth Explorer Atmospheric Dynamics Mission will provide profiles of line-of-sight winds. The synoptic-scale (i.e. 500-1000 km) component of the vertical wind is generally very small in the atmosphere. A line-of-sight wind is thus effectively the projection of the horizontal wind onto the direction of the laser beam. Therefore, the essential information in a line-of-sight wind is one of the two components of the horizontal wind, here called horizontal line-of-sight (HLOS). Most numerical weather prediction data assimilation systems analyse the mass and humidity fields and the two horizontal wind components. The two independent wind components are usually decomposed into a North-South and an East-West component. However, decomposition relative to any other direction can be made with a straightforward linear operator. The horizontal line-of-sight component wind is thus easily matched by an equivalent numerical weather prediction background value, and the difference of both interpreted in the analysis. Figure 4.1 illustrates that the assimilation of a wind vector is equivalent to the assimilation of two component winds at a different location. In general, measurements that are linearly related to the background variables may be assimilated in conventional data assimilation models. In variational schemes, it is also possible to assimilate measurements that relate non- or quasi-linearly to the background.

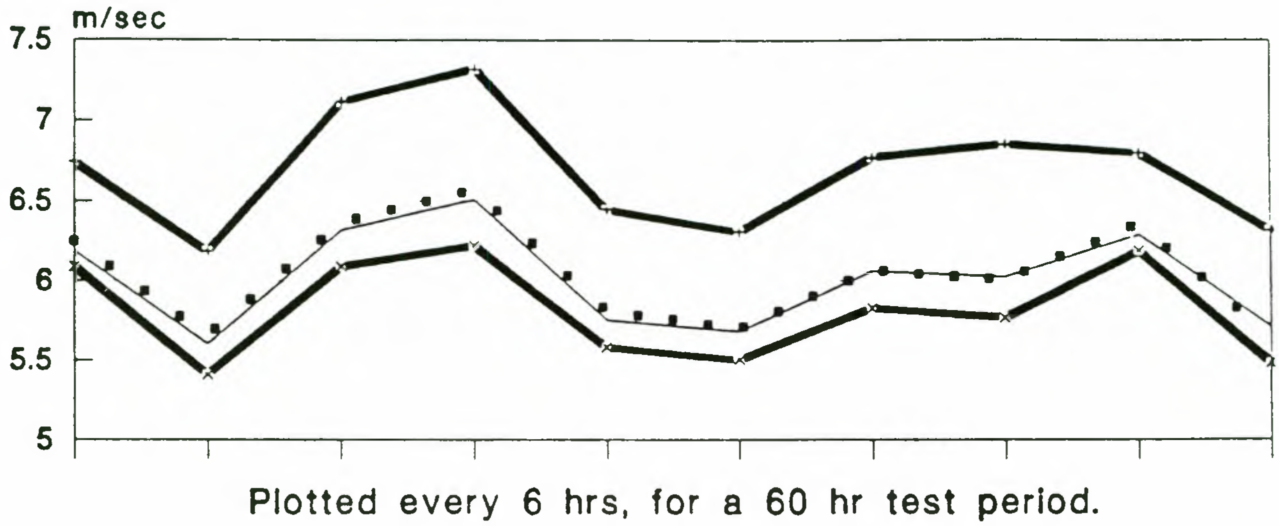


Figure 4.1. Root mean square fit of 6-hour forecasts to wind observations in the tropics. Thick lines show results from control assimilations, using none and all of the single level wind observations. Dots show results using a single component from each wind. The thin line shows results using the same number of wind components as for the dots, but presented as wind vector observations at half the number of locations (cf. Lorenc et al., 1992).

At very small scales (e.g. the footprint of a Doppler wind lidar) and in extreme cases (thunderstorms) the vertical component of the wind may be quite substantial. The assumption to neglect vertical motion is strictly not valid in such situations. However, current numerical weather prediction models cannot represent these small scales and as such the vertical motion should be regarded as an unwanted component of the measurement and treated as part of the so-called representativeness error. The representativeness error will be further discussed below. It will be no problem to assimilate the vertical wind in future high resolution atmospheric models.

By their very nature, Doppler wind lidar line-of-sight winds have spatially variable accuracy, reliability and coverage though atmospheric data assimilation systems are designed to cope with such data. However, the direct interpretation of line-of-sight winds would not be expected to be particularly useful for climate studies, as discussed in chapter 2. On the other hand, improved numerical weather prediction analyses will be very useful for studying circulation and transport phenomena relevant to climate studies. Further, the numerical weather prediction fields do provide consistent atmospheric data sets of wind, humidity and temperature. The monitoring of the quality of numerical weather prediction output is done operationally by comparing it with the wide range of real-time meteorological observations, complemented by off-line validation studies.

Averaging

The observations should be representative of averages over a volume of the atmosphere, to be used in numerical weather prediction. The lower limit of the volume is a grid box of the numerical weather prediction forecast model, since this is the smallest spatial dimension that can be resolved by the assimilation system. The upper limit is the spatial resolution of the background (see chapter 2 for definition) since this may be improved by inserting the new observations. The resolution of the background is verified by computing the background error covariance structure. For the wind field the horizontal resolution is on average about 200-250 km for models with a grid spacing smaller than 100 km. The vertical resolution is around 1 km. Detailed wind information in the horizontal, needed to improve the numerical weather prediction model resolution, is most welcome (see chapter 2). A sensible requirement for the dimensions of the Doppler wind lidar observation resolution cell in the troposphere (< 15 km height) is therefore 50 km × 50 km × 1 km. In the stratosphere the requirement on the vertical and horizontal resolution may be relaxed. It is anticipated that 50 km will be the typical grid distance of global numerical weather prediction models in about ten years' time. Without increasing the density of the meteorological observational network, the average resolution of data assimilation systems is not expected to gain much in the coming years.

Quality

The quality of observations is determined by their accuracy and reliability. The accuracy in turn consists of contributions from both the measurement error and the representativeness error. The measurement error is the difference between the measurement and the true average of the measurement variable over the measurement volume. The representativeness error is the difference between the true average over the measurement volume, and the time average over the numerical weather prediction model grid cell, provided the latter is larger.

The errors and their correlations need to be available to the assimilation system, and are usually approximated by their expected root-mean-square (RMS) values (see also section 2.2.3). However, this is done on the premise that the systematic error (bias), as opposed to the random component of the error, is negligible. Data assimilation systems are designed to account for random error, but have great difficulty in dealing with unknown systematic, or unknown spatially correlated error. Systematic errors should be removed by the data producer.

Observational accuracy and background accuracy are used to determine the weight of an observation over the background. Improper prior specification of the observational error will therefore lead to a wrong assessment of the value of the observation, and consequently to an inferior analysis. Doppler wind lidar winds have variable accuracy and it is thus important to develop algorithms that are able to define their accuracy prior to assimilation. Given the experience in numerical weather prediction, radiosonde wind observations are considered an important element of the operational meteorological observational network. Their accuracy varies from 3 m/sec close to the surface to 5 m/sec around the tropopause level. Over data sparse areas this accuracy is expected to be sufficient to provide a beneficial impact on numerical weather prediction analyses. However, it is noted that the requirement of the World Meteorological Organisation (WMO) for the accuracy of tropospheric wind observations is

1-2 m/s.This requirement was justified by anticipated future developments in numerical weather prediction modelling which would lead to tighter user requirements.

Data assimilation systems always possess a quality control procedure to prevent measurements which are grossly in error having an effect on the analysis. When a gross error occurs the observation does not relate to the (model) atmospheric state and is therefore potentially damaging. For conventional systems gross errors are usually due to transmission or instrument failure, or to unrepresentative measurements. A classic example of the latter is the release of a radiosonde through a thunderstorm. Generally, gross error rates are below 5% for conventional wind data. The forecast is known to be sensitive to gross error elimination procedures in critical atmospheric conditions, as is illustrated in Figure 4.2, which shows the forecast impact of one wind observation (AIREP) in a so-called Hovmöller diagram (see the Figure caption for an explanation). The inclusion of this wind observation on the date line in the analysis improved the forecast over Europe substantially after 5 days. Further it is an example of what effect wind data can have on the weather forecasts in a situation of baroclinic development.

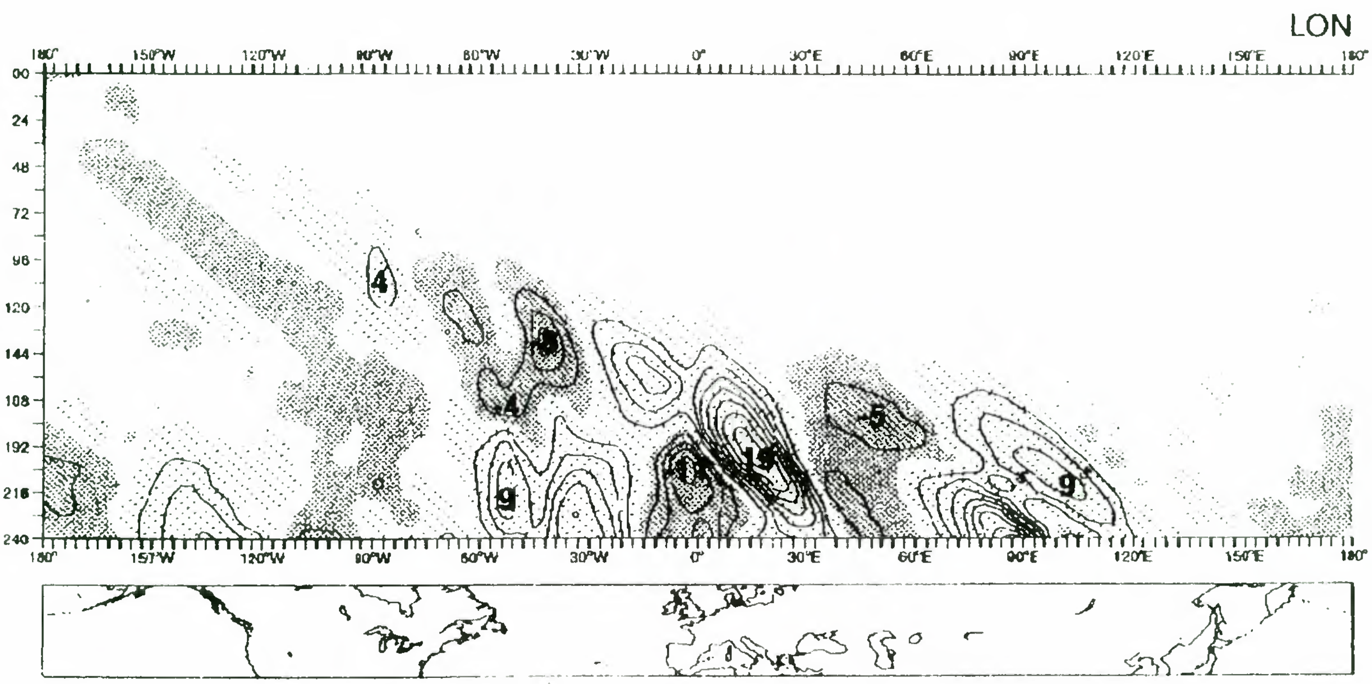


Figure 4.2. *The upper panel shows the difference between two forecast series as a function of longitude (horizontal) and time (vertical) in a so-called Hovmöller diagram. The difference in the height of the 300 hPa pressure surface averaged over the latitude band 35-60°N, as shown in the lower parcel, is contoured. The only difference between the forecast series is that in the analysis (time=00) of one of them, one additional AIREP wind report located on the date line has been used. It illustrates the potential sensitivity to wind data and the critical role of quality control (courtesy A. Person, ECMWF).*

For Doppler wind lidar data the reliability is strongly related to the atmospheric aerosol loading and the speckle effect (see chapter 6). Unreliable data should be flagged and not presented to the data assimilation system. In line with the experience with conventional data, a gross error rate of 5% may be allowed for the line-of-sight winds that are presented to the data assimilation system, provided that the gross error occurrence is not correlated spatially.

Delivery

Data should be disseminated as rapidly as possible to meteorological centres assimilating the Doppler wind data to carry out routine operational weather forecasting. Delivery could, ideally, be as fast as one hour for regional applications and should be no more than 3 hours for global applications (from observation from space). Systematic delays or lack of continuity of the service will limit the utility of the data. A data delivery strategy similar to that planned for METOP would be appropriate. It should be stressed that the real-time operational evaluation of experimental systems is a prerequisite for the development of fully operational observing systems.

Timing

The local overpass time may not be critical, although a morning or evening pass will result in lower cloud amounts and therefore more line-of-sight returns. Since the atmosphere is a moving target there is no requirement on local revisit time.

Coverage

Single-level winds are less satisfactory than wind profiles though such data, if of high quality (i.e. accurate), would be a useful complement to multi-level systems.

For a mission set out to demonstrate the feasibility of a full-scale Doppler wind lidar system, the horizontal density of observations is a lower priority amongst the requirements mentioned so far. The requirements on accuracy and reliability will be the most difficult and most important to achieve. However, the higher the density of wind component profiles in the demonstration mission, the more confidence can be put in a full-scale Doppler wind lidar mission afterwards. As explained in chapter 2 the meteorological impact in the tropics is the most certain and, from a climate point of view, also the most useful. However, for numerical weather prediction in Europe it may be more relevant to demonstrate the impact of Doppler lidar winds at high latitudes.

The feasibility of a full-scale Doppler wind lidar system can be studied through the launch of a demonstrator instrument fulfilling the requirements discussed above. Scientific questions regarding clear air lidar returns, multiple scattering and cloud returns and blocking would be addressed much more effectively with a Doppler wind lidar in space. Further, the development of tailor-made processing algorithms would be accelerated and considerably enhance the feasibility of a full-scale Doppler wind lidar system measuring the three-dimensional winds.

The analysis of the atmospheric dynamics in the tropics will improve. For numerical weather prediction, insight will be gained on the feasibility of detecting baroclinic structures (e.g. vertical wind shear) with a Doppler wind lidar. The improved analyses will benefit both tropical and extra-tropical weather forecasts. Improved information on transport and circulation will be of benefit for climate studies. In particular, improved advection of tracers would benefit the Earth Explorer Atmospheric Chemistry Mission, and the enhanced analysis of humidity convergence would contribute to the Earth Explorer Precipitation (ESA, 1996 a) and Earth Radiation Missions (ESA, 1996 b).

4.2.2. Other Elements

In addition to line-of-sight velocity measurements, a space-based Doppler wind lidar will provide information on cloud and aerosol measurements over the depth of the atmosphere. These include cloud top heights (notably cirrus top and base), cloud cover, cloud and aerosol extinction and optical thickness, identification of multi-layer clouds, aerosol stratification, height of the tropopause, height of the atmospheric boundary layer, etc.

The properties of these secondary products will be determined by the requirements for the wind profile product. As such, the vertical resolution of the secondary products will be the same or better than the one used for the velocity measurements, depending on the signal-to-noise ratio (SNR). The horizontal resolution will vary with the backscatter properties, ranging from 25 m (a single shot) to 50 km (a shot cluster). Since the priority was put on the line-of-sight wind measurements, only a little effort has so far been put into the retrieval of the secondary products so the above list will need further study.

Given the spatial resolution of winds in the current data assimilation systems (i.e. 200-250 km) it is convenient to manage the distribution of a given number of wind profiles such that they are at least separated by this distance. Then each profile will provide essentially new information to the data assimilation system.

The cloud products are relevant for the validation of atmospheric model parametrisations, both for numerical weather prediction and climate. It is expected that cloud and aerosol will be prognostic variables in most atmospheric models by the year 2005. In a four-dimensional variational data assimilation scheme some of these products may be assimilated directly by the numerical weather prediction analyses. The cloud information is relevant for radiative transfer calculations in the model. Tropopause and atmospheric boundary layer height may also be validated against forecast models. Cloud top heights may further be used to improve the height assignment procedure for cloud-tracked winds. Numerical weather prediction models currently use a fixed aerosol profile. The aerosol products may be inserted as passive tracers in the data assimilation system, again to benefit radiative transfer calculations, but also, in addition, chemistry computations. It may further improve the ALADIN processing.

5. Mission Elements

5.1. Introduction

The main element provided by the Earth Explorer Atmospheric Dynamics Mission will be tropospheric wind component profiles. These will be distributed to Numerical Weather Prediction centres to improve their weather analyses and forecasts. The improved analyses of the atmospheric circulation and transport will also be valuable for climate studies. In particular, improved advection of tracers would benefit the Earth Explorer Atmospheric Chemistry Mission (ESA, 1996 c), and the enhanced analysis of humidity convergence would contribute to the Earth Explorer Precipitation (ESA, 1996 a) and Earth Radiation Missions (ESA, 1996 b).

This chapter describes the Earth Explorer Atmospheric Dynamics core space mission, complementary space and ground elements and ancillary data needed for the processing on ground (for reference the various facets are summarised in table 5.1). Both the space and ground segments are described briefly.

Mission Element	**Instruments**	**Observations**
Core space mission	Doppler Wind Lidar (i.e. ALADIN see below)	Wind profiles (clear air)
Space complement	SATOB Scatterometer (METOP) Earth Explorer Atmospheric Profiling Mission	Cloud top winds Ocean surface winds Temperature, humidity
Ground complement	Surface-based observations	Wind, temperature, humidity
Auxiliary data	Numerical Weather Prediction (NWP)	Wind, aerosol

Table 5.1: *The Earth Explorer Atmospheric Dynamics instruments and data.*

5.2. Instruments and Data

5.2.1. Core Space Elements

The core space element of the Earth Explorer Atmospheric Dynamics Mission is ALADIN. This is a Doppler wind lidar concept intended to provide profiles of tropospheric wind in clear air (i.e. above or in the absence of thick cloud). Another element carried by the space segment will be the GRAS receiver (ESA, 1996, d) to be used for position and velocity determination as well as for atmospheric temperature profiling. The inclusion of the latter would provide a contribution to the Earth Explorer Atmospheric Profiling Mission (ibid.).

5.2.2. Complementary Space Elements

SATOB observations have been discussed in chapter 2. These wind observations obtained by tracking cloud features in satellite images may be compared with the strong returns of the Doppler wind lidar at cloud tops and help interpret these. On the other hand, the cloud top height information from ALADIN may be very useful for the height assignment of SATOB winds. Also, cirrus detection by ALADIN may result in better height assignments.

The scatterometer provides all-weather ocean surface wind information. The combination of these data with a Doppler wind lidar is potentially very powerful to resolve the so-called Ekman spiral in the atmospheric boundary layer. This is important for detecting instabilities in the lower troposphere and for a proper estimation of fluxes across the atmosphere-ocean interface.

The Earth Explorer Atmospheric Profiling Mission would provide temperature and humidity information in the troposphere. As discussed in chapter 2 this information is useful to define the geostrophic component of the flow and complements the Earth Explorer Atmospheric Dynamics Mission which provides also the ageostrophic flow component. The relative importance of each component depends on latitude, where the wind information is most relevant in the tropics. The two missions would also complement each other by providing additional data for monitoring, validation and quality control.

5.2.3. In-Situ Complement

The wide range of in-situ observations and their limitations have been discussed in chapter 2. It is considered that these could contribute to the monitoring and calibration of the Earth Explorer Atmospheric Dynamics Mission.

5.2.4. Auxiliary Data

Numerical Weather Prediction background or short-range forecast winds may provide a good prior estimate for the strength of the Doppler wind lidar line-of-sight component strength. This information may then be used to limit the search window (bandwidth) for the Doppler shifted frequency, thereby increasing the signal-to-noise ratio. Furthermore, aerosol information obtained from sounding instruments or ALADIN may be used in Numerical Weather Prediction assimilation systems. As such, aerosol forecasts could be issued that may be of help in the line-of-sight wind processing.

5.3. Space Segment

Chapter 6 describes the space segment in detail.

The baseline solution will be to fly a Doppler wind lidar, plus GRAS, on a satellite flying in a polar, dawn-dusk, sun-synchronous orbit with an altitude of 479 km. The dawn-dusk orbit allows the combination of a low altitude with a standard platform. The required mission duration is 3 years, which allows time for an optimisation of the real-time ALADIN products, their operational monitoring and validation as well as introduction into the operational data assimilation system and evaluation of impact.

The alternative solution would be to attach ALADIN to the International Space Station Alpha. However, the more limited geographic coverage (at higher latitudes) would limit the demonstration of the potential usefulness of a Doppler wind lidar. Also, the continuity of the data flow would be interrupted occasionally by servicing, orbit restitution, etc. However, the lifetime could be quite long, in excess of 3 years, so more time would be available to assess the usefulness of these data, assuming that in-orbit servicing is possible.

5.4. Ground Segment

The ground segment, providing near real-time data delivery, is discussed in detail in section 6.5. It is proposed that it should consist of two ground stations to cover each orbit. At these stations the data will be partly pre-processed to produce a corrected and calibrated, but not scientifically interpreted, output. A second process will produce the scientific outputs. Both data reduction processes are time critical. The timeliness requirement has been established as 3 hours (or less from the actual observation from space) for operational meteorology. In addition to this near real-time provision, it is proposed to archive the data for a period of 10 years and to make it available to users on request.

5.5. Relation with Other Earth Explorer Missions

In section 5.2.2 we discussed the synergy of the Atmospheric Dynamics Mission and the Atmospheric Profiling Mission. Both should contribute to improved Numerical Weather Prediction mass and wind analyses. Improved information on transport and circulation will be of benefit for climate studies. In particular, improved advection of tracers should benefit the Earth Explorer Atmospheric Chemistry Mission and the enhanced analysis of humidity convergence should contribute to the Earth Explorer Precipitation and Earth Radiation Missions (ESA,1996 c; ESA 1996 b). The secondary products, on aerosol and cloud, may further complement the Earth Explorer Atmospheric Chemistry and Earth Radiation Missions (ESA 1996 c; ESA 1996 b).

6. System Concept

6.1. General

Taking into account the requirement for wind measurements in clear-air areas discussed in previous chapters, it is clear that a Doppler wind lidar is the only instrument which has sufficient sensitivity to fulfil the requirements of accuracy and reliability. There exist various Doppler wind lidar concepts but presently the CO_2 coherent Doppler wind lidar technology is the most mature for space. Accordingly, ESA has conducted two parallel industrial studies to assess the feasibility of ALADIN with CO_2 laser technology. Their output has been used to arrive at the definition of the instruments discussed in section 6.2. Another study has defined the system and mission aspects. This is the source of the information contained in sections 6.3 and 6.4. Finally, two supplementary studies have addressed the accommodation of ALADIN on the International Space Station Alpha. These results are reported in section 6.7.

6.2. Payload

6.2.1. ALADIN

Operating Principle

The ALADIN concept is intended to measure radial wind speed components (i.e. line-of-sight winds). The principle used is to observe the Doppler shift of laser light scattered from atmospheric aerosols. A laser emits powerful pulses of monochromatic light to the atmosphere. As the pulse propagates through the atmospheric layers, part of its energy is backscattered to the instrument by particles (typically aerosols generated by anthropogenic, volcanic and wind erosion activities) moving at the same velocity as the ambient wind. The particle velocity relative to the instrument induces a frequency shift Δf (i.e. a wavelength shift) into the backscattered radiation (Doppler effect) which is directly proportional to the radial speed V_R (i.e. the projection along the line-of-sight of the velocity of particles relative to the instrument reference frame) and inversely proportional to the emitted wavelength λ of the light :

$$V_R = -\frac{\lambda}{2}\Delta f$$

The factor 2 takes into account the round-trip of the pulse whereas the minus sign results from the convention that a particle approaching the instrument has a negative radial velocity.

The mean velocity of the line-of-sight wind component in a 'slice' of the atmosphere and its actual range from the instrument, are measured by evaluating the frequency shift and the time-of-flight between the emitted pulse and the part of the return signal backscattered in that atmospheric slice (range gate). As a consequence the instrument's line-of-sight must be directed off nadir to get information on the horizontal wind component. Satellite motion and the varying azimuth of the line-of-sight direction generate a horizontal sampling pattern while the range gating determines the vertical sampling and hence the spatial resolution in the vertical of the measurements. Figure 6.1 illustrates the instrument's operating principle.

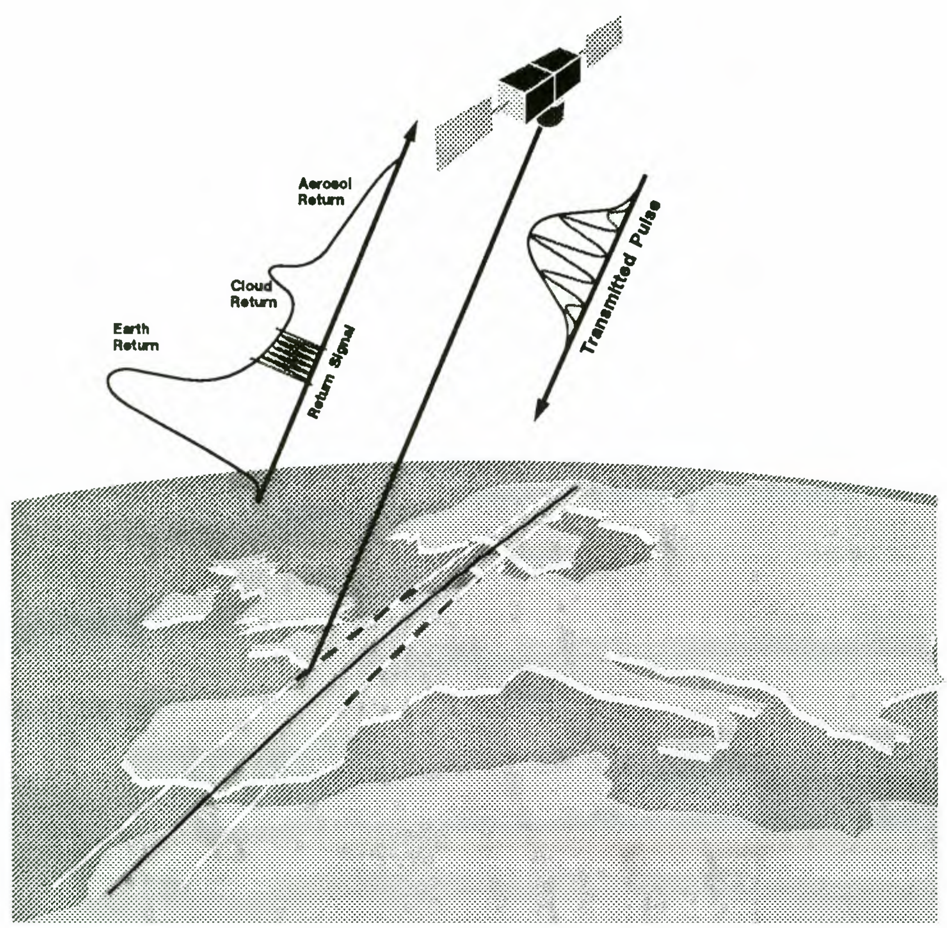


Figure 6.1. *Principle of measurement of 3-dimensional wind field by a space based Doppler wind lidar (ALADIN): A short light pulse is emitted at a frequency f. Backscattered energy by wind carried particles is shifted in frequency. The signal is temporally sliced to retrieve the mean LOS wind in a range gate whose location is determined by the pulse return time.*

For an orbiting instrument like ALADIN, the frequency shift of the backscattered signal is not only due to the velocity of the wind-carried particles (0 to 100 m/s) but also to the spacecraft's velocity (7 km/s) and the Earth's rotational velocity (460 m/s maximum at the equator). Each of the latter two velocities produces a much larger frequency shift than the wind and so they need to be properly estimated to be properly compensated. This requires accurate knowledge of the line-of-sight pointing (to better than 35 μrad corresponding to 0.2 m/s for 30° nadir angle) and can be achieved with the aid of star sensors and accurate knowledge of the velocity of the spacecraft (better than 0.1 m/s); obtainable with a GPS receiver. The ground return signal, when present, is also useful for this compensation.

The Doppler shift is measured by comparing the optical frequency of the return signal with a reference signal provided by a local oscillator. This comparison is done by mixing the two signals on a detector which generates an electrical signal at the frequency difference. This technique is called heterodyne detection or, more generally, coherent detection.

The sensitivity of the measurement is characterised by the number of photons (N_P) in the return signal which are coherently detected over a range gate. This parameter (N_P) may be written as:

$$N_P = K \cdot \gamma \frac{E \cdot A \cdot \Delta R}{R^2} \beta \cdot T^2 \cdot \lambda$$

where, K is a parameter which represents the physical constants and optical losses of the instrument, γ is the heterodyne efficiency, E is the pulse energy, A is the area of the receiver aperture, ΔR is the range resolution, R is the range to the target, β is the backscatter coefficient of the atmosphere, T is the one-way transmission of the atmosphere and λ is the wavelength of the laser.

An analysis of the above equation shows that, apart from the atmospheric parameters β and T (discussed later), there are a few system parameters which can be varied to achieve the required sensitivity and consequently the required accuracy and reliability. Thus, pulse energy E, receiver area A and range resolution ΔR must be as high as practical and range R as low as practical. Any increase of the pulse energy E is limited by the available electrical resources on the satellite and lifetime issues. The increase in receiver aperture A is limited by the volume available on the satellite and the increased sensitivity of the heterodyne efficiency γ to misalignment in the range of a few microradians. The range resolution ΔR is set by the vertical resolution given by the users. The decrease of the target range R is limited by the increased mass of propellant needed to fly the satellite at low altitude. This last point is discussed in more detail in section 6.4.

A peculiarity of coherent detection is temporal speckle noise which is linked to the statistical properties of the return signal. It is due to the differential motion of particles within the sensing volume and to the laser pulse illuminating different particles at different locations within the sensing volume. It causes fading on the return signal which has a typical time scale of about one microsecond. The fading effect can be reduced by estimating the frequency shift over a range gate larger than the time scale of the temporal speckle and by accumulating (along a fixed line-of-sight) shots whose individual return signals are uncorrelated.

The performance of Doppler wind lidar in space is critically dependent on the presence of aerosol particles. Moreover, dense clouds will obstruct a significant part of return signals so on average only 40% of the shots generated in space by a Doppler wind lidar will actually reach the Earth's surface (though 60% of the shots will reach an altitude of 2 km). The variability of cloud and aerosol makes it difficult to accurately estimate the performance of a Doppler wind lidar in space.

Figure 6.2 shows some models of backscattering from the atmosphere derived from measurement campaigns. Although they vary in detail all show drops in the backscatter coefficient, β, of about four orders of magnitude between the ground and an altitude of 15 km. This means that the quality of wind measurements will vary with altitude. In particular, the low backscatter coefficient above the atmospheric boundary layer will be associated with low return signals, precluding high quality wind retrieval on a single shot basis. One way to reduce this problem is to use shot accumulation. In this (as discussed in section 4.2.1 and termed 'averaging') a number of shots are emitted along a fixed line-of-sight direction. The corresponding return signals are stored and sent to the ground segment to be combined (in the spectral domain at the signal processing level) to retrieve the wind information.

Shot accumulation can be used to reduce the wind estimation error by a factor equal to the square root of the number of accumulated shots. It also improves measurement reliability. To achieve this wind measurements must be derived from a number of accumulated shots spread over a restricted area in which there is limited wind velocity variability (35 km horizontal distance is deemed to be acceptable, except in the atmospheric boundary layer and areas of clear air turbulence, since it corresponds typically to less than 2 m/s wind variability).

However, for low backscatter coefficient regions, even with the accumulation technique, wind estimation will be based on signals containing very low numbers of photons (coherently detected in each range gate). This will lead to the appearance of bad estimates randomly distributed over the wind speed 'search window'. These bad estimates (also called gross errors) manifest themselves as powerful noise features which mimic the wind signal. The good estimates are spread in a Gaussian distribution around the true wind speed. The standard deviation of the Gaussian distribution represents the error in the wind estimate while the percentage of estimates within the Gaussian distribution provides an indication of measurement reliability. An additional error due to the non-perfect compensation of satellite and Earth rotation velocities must be added to the wind estimation error to obtain the instrumental measurement accuracy.

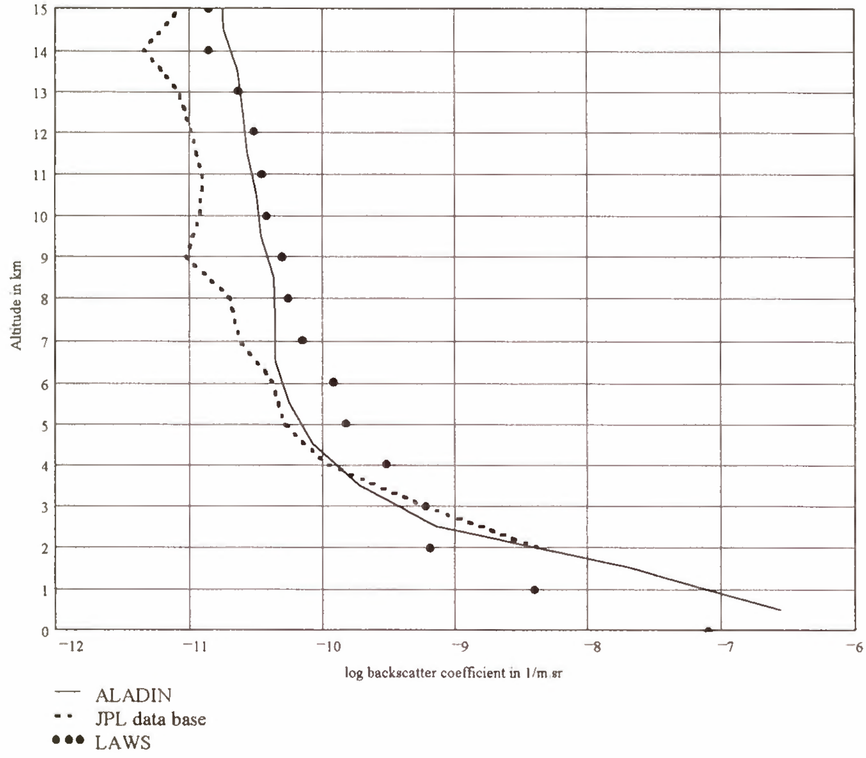


Figure 6.2. *The ALADIN backscatter coefficient model is the median of profiles at 10.6 µm collected over the Atlantic during the relatively clean period 1988-1990 before the Mount Pinatubo volcano-eruption. These airborne measurements were made by Defence Research Agency (UK). For the sake of comparison, the LAWS model (the NASA Doppler wind lidar concept) and the Jet Propulsion Laboratory (USA) data base geometrical mean profile taken over the period 1984-1992 are displayed.*

In the ALADIN concept the raw data is the time history of the backscattered return from each shot as it traverses the troposphere. These data will be transmitted to the ground where the line-of-sight wind estimates will be computed from the information contained within each range gate of the clustered shots. To further reduce the errors associated with low signal levels, it is anticipated that a priori wind information from a short range forecast model will be used. This may narrow the range of the wind search window from 100 m/s to 25 m/s for one component of the horizontal wind.

Different frequency estimators can be used to extract wind information from raw data. These have different characteristics and behave differently depending on the characteristics of the return signal (i.e. signal-to-noise ratio, spectral width of the return signal, etc.). For instance, the pulse-pair estimator technique is quite effective when the spectral width of the return signal is large, but its performance is rather poor when it is narrow. The adaptive notch filter, Levin and Capon estimators behave in the opposite way. This means that a decision algorithm is needed to choose the 'optimal' estimator. In addition the retrieved line-of-sight wind speeds must be tagged with a quality index for use in the data assimilation process.

Figure 6.3 illustrates the principal subsystems of the ALADIN instrument concept.

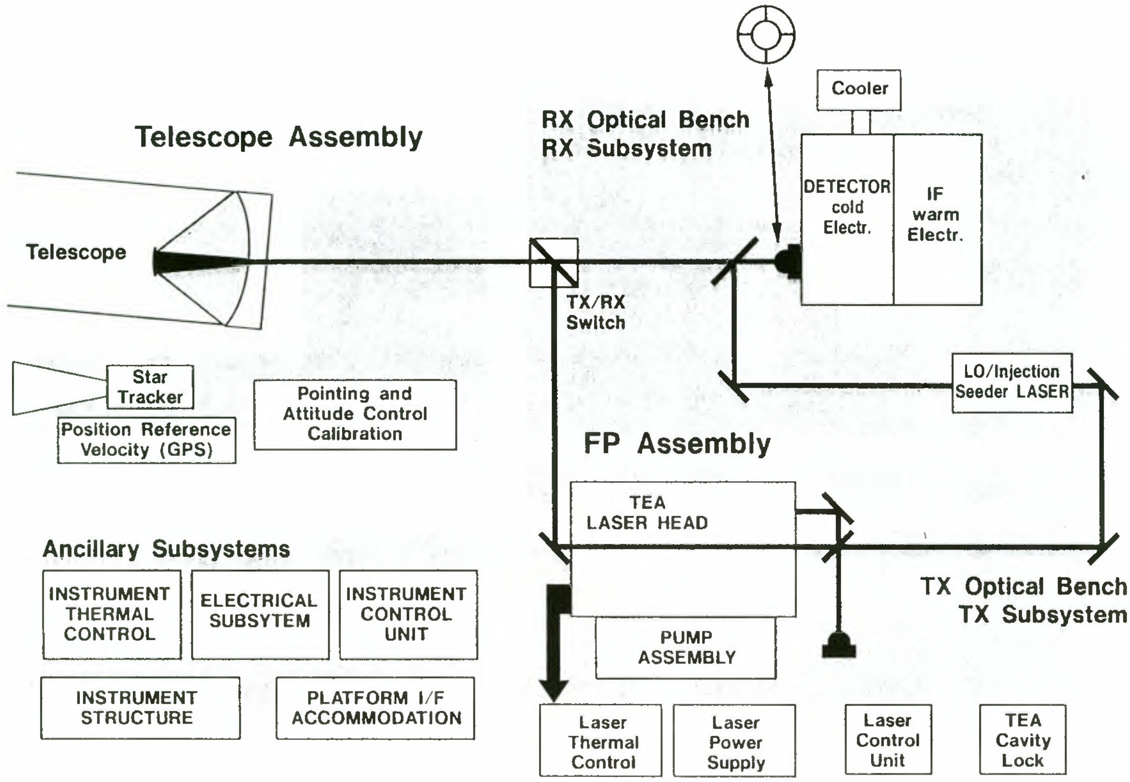


Figure 6.3. *ALADIN sub-system breakdown.*

The laser is a pulsed CO_2 laser with output at 10.6 micron which emits 15 J energy pulses at a maximum repetition rate of 10 Hz. It must satisfy stringent requirements on pulse width, spectral and spatial beam quality. To lock its transmitted mean frequency the high energy laser is injection-seeded by a very stable low power CO_2 laser. To meet lifetime requirements it must operate for more than 10^8 shots without failure (corresponding to 3 years lifetime). Also it must have a control system to periodically align the laser cavity mirrors. The laser is expected to be about 5% efficient and most of the power it uses ends up as heat that must be evacuated through a thermal control subsystem to the satellite radiators.

The light from the laser is transmitted through a telescope of 80 cm aperture whose line-of-sight is pointed towards the Earth. Each shot probes an elementary cylindrical volume of the atmosphere of 25 metre diameter. Part of the backscattered light is collected by this telescope. During light emission and reception, the telescope's line-of-sight is fixed in the satellite's frame of reference allowing shot accumulation. With this approach, called step-scanning, the instrument's line-of-sight is switched between a few fixed directions for each of which the receiver's field-of-view and return signal are aligned. This avoids the need for a dedicated complex dynamic alignment unit (lag-angle compensator).

The return beam is directed to the detection chain via a transmitter/receiver switch which geometrically decouples the transmitter optical path from the receiver one. It is superimposed on the local oscillator beam and the two beams are focused on a mercury cadmium telluride detector for heterodyne detection. The detector is a five-element array cooled at 80 K by Stirling cycle coolers to achieve the required sensitivity. The central element of the array is used for heterodyning and operates at high electrical bandwidth; compatible with the frequency shift due to the satellite and Earth rotation radial velocities. The four ring elements are used for alignment monitoring and operate at lower electrical bandwidths. To obtain efficient heterodyne detection, the local oscillator frequency must be as close as possible to the frequency of the return signal (< 400 MHz) and the return beam must be nearly diffraction limited, properly overlapped and well aligned with the local oscillator beam. Since the diffraction limited beamwidth is about 16 μrad, the return beam must be kept aligned to a small fraction of this angle or to about 3 μrad during the round trip time of the pulse (~ 4 ms).

The electrical signal at the output of the detector is down-converted in frequency in order to reduce the noise bandwidth, by compensating for the spacecraft and Earth rotation induced frequency shifts. The signal is then digitized and formatted by the on-board data handling system to be stored and sent to Earth.

The two opto-mechanical scanning concepts resulting from the two feasibility studies are shown in Figures 6.4 and 6.5.

Instrument Performance

Wind measurement quality is expressed in terms of the accuracy and reliability of the horizontal line of sight wind. Figure 6.6 shows a simulation of these two parameters with the working assumptions for mission and instrument that can be seen in table 6.1. The ALADIN atmospheric backscatter model at 10.6 micron is used. Figure 6.7 shows the sampling pattern on ground.

Such an instrument should provide up to 15,000 reliable line-of-sight wind profiles every 12 hours. This figure has to be compared to about 800 reliable wind velocity profiles reported every 12 hours by the TEMP and PILOT observing systems. The measurements will be clustered on 50 km long zones. This will reduce the representativeness error of the measurement since there are about 17 line-of-sight wind measurements per cluster. The limitation on the number of profiles results from both the power available to the instrument (1200 W including 20% margin) and the laser lifetime. The sampling strategy shown in Figure 6.7 can be scaled-up by increasing the laser shot pulse repetition frequency but at the cost of a reduction in laser lifetime.

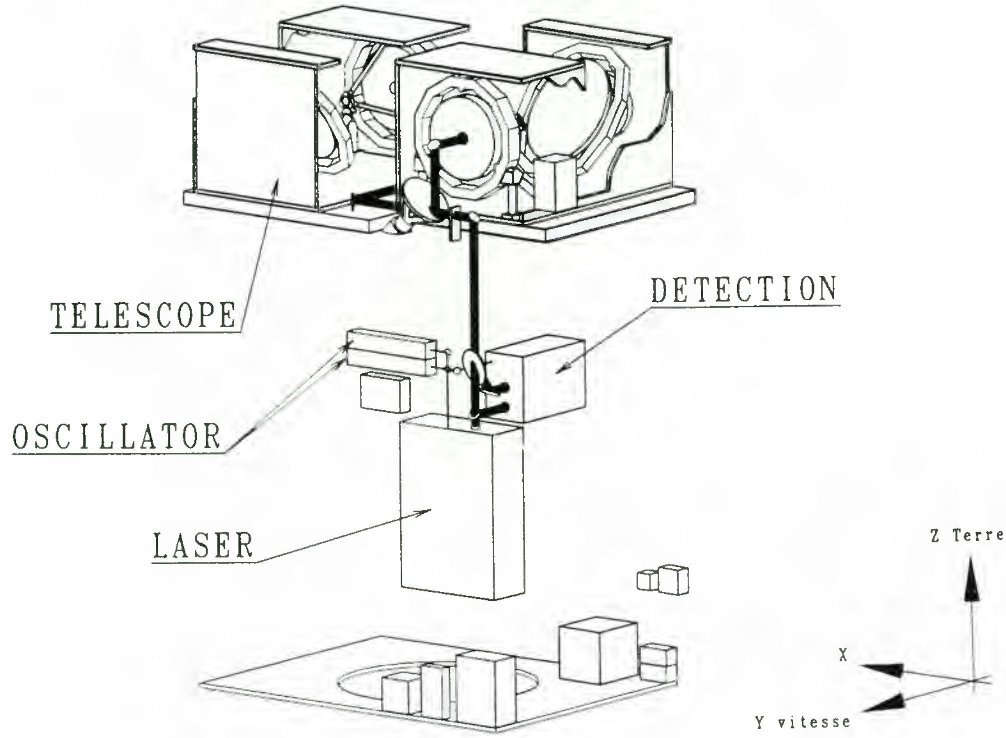
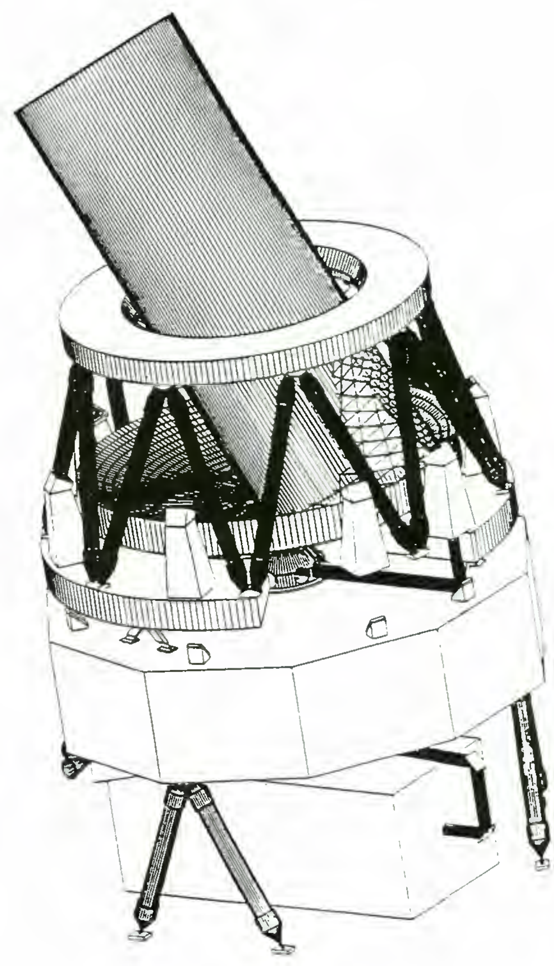
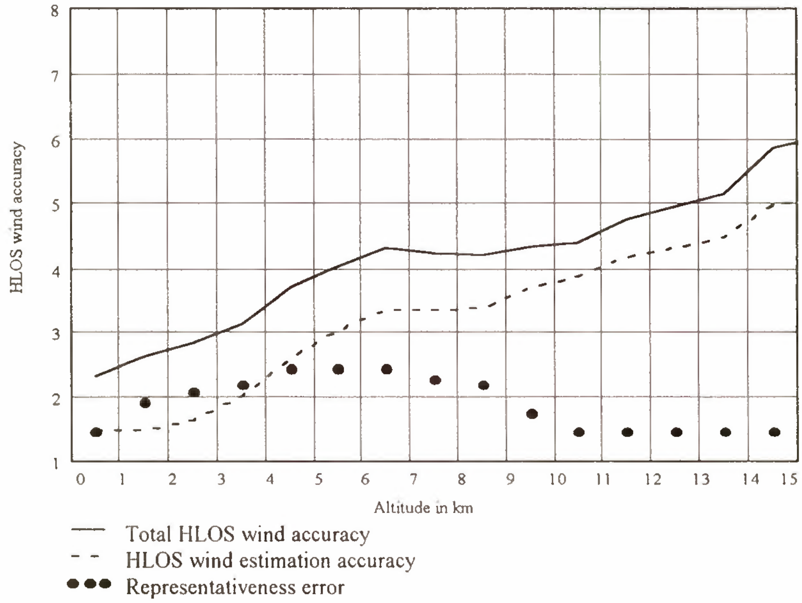


Figure 6.4. *This concept uses two identical telescopes with step rotating pointing mirrors. Rotation of the LOS occurs around the spacecraft velocity. This keeps the spacecraft induced Doppler shift constant but the range to a target at a given altitude varies over the swath.*

Figure 6.5. *This concept uses a single oversized primary mirror with a number of secondary mirrors on a ring. Scanning is achieved with a step rotating mirror located near the focal plane of the telescope. Rotation of the LOS occurs around nadir. This keeps the range to a target at a given altitude constant but the spacecraft induced Doppler shift varies over the swath.*





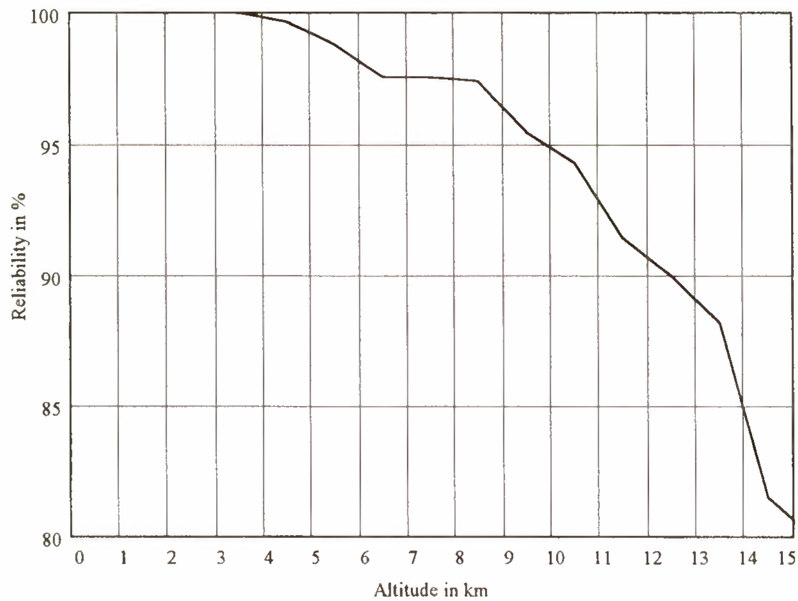


Figure 6.6: *Horizontal LOS wind accuracy and reliability versus altitude for reference parameters.*

Platform	
Altitude	480 km
Nadir angle	30°
Instrument power	1.2 kW (mean)
Transmitter	
Wavelength	10.6 μm
Pulse energy	15 J
Pulse spectral width	750 KHz
Repetition frequency	8 Hz (typical)
Duty cycle	0.26
Receiver	
Diameter	80 cm
Mis-alignment	3 μrad
Detector bandwidth	400 MHz (max)
Overall efficiency	0.095
Signal processing	
vertical resolution	820 m
Observation range	0-15 km altitude
accumulated shots	40
Processing bandwidth	10 MHz
Frequency estimator	Capon

***Table 6.1**: Design requirements for ALADIN*

The table below gives a typical instrument budget in mass, power and data rate.

Mass	~ 700 kg
Power	~ 1.2 kW
Data rate	~ 1 MBits/s

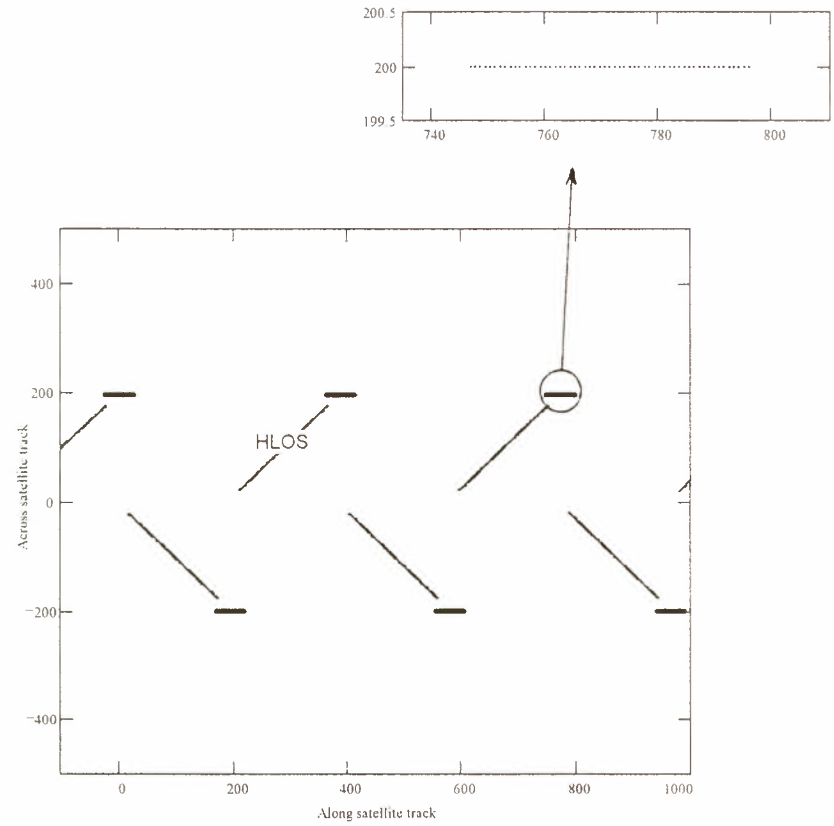


Figure 6.7. *Ground sampling pattern showing 50 km long cluster areas(bold) on a total swath of 400 km. There is only one perspective per cluster area and there is a 90° angle between the HLOS(thin lines) symmetrically oriented on both sides of the sub-satellite ground track. In each cluster area, 57 shots are uniformly distributed along the 50 km long line parallel to the satellite ground track. One LOS wind measurement requires 40 adjacent shots spread over 35 km. 17 LOS wind measurements are performed per cluster area.*

Heritage

The 10.6 μm laser technology has been supported over more than 2 decades for numerous applications in the USA and in Europe. It has reached a high level of technological maturity for ground and airborne applications but has never been flown in space.

In 1988 CNES initiated a phase A for a space mission named BEST (Bilan Energétique du Système Tropical) which included studies on a DWL. At that time, an instrument concept with four fixed telescopes using shot accumulation was selected. A technological programme followed the Phase A study and focused on the development of the receiver chain with the development of a high-bandwidth mercury-cadmium-telluride array detector.

In 1987 ESA initiated the development of a 10 J CO_2 laser transmitter operating at a 10 Hz pulse repetition frequency, with pulse length and frequency stability commensurate with 1 m/sec wind velocity accuracy. The laser was specified to operate efficiently either at 9.11 or

9.25 μm, according to the isotopic composition of the gas medium. The challenge consisted of meeting simultaneously a set of performance requirements which had only previously been demonstrated separately. Electron-beam sustained technology was chosen for the pulsed CO_2 laser as it provides good discharge stability at the relatively long pulse length required and operates at inherently high efficiency.

A highly engineered laser bread-board has been produced which met (or exceeded) all performance targets. It delivered output at 10 Hz pulse repetition frequency with a main discharge optical efficiency of 5% at a wavelength of 9.25 μm. The pulse length of 6.5 μsec yielded a measured bandwidth at half-height of 190 KHz, with a pointing stability of 25 μrad. The life tests achieved 6.5×10^7 pulses in catalyst-free operation.

As a result of study a pulse-sustained discharge technology has been base-lined for the ALADIN feasibility studies. Most aspects of the electron-beam sustained bread-board, with the exception of the pre-ionizer, are applicable to this base-line. In parallel with the laser bread-boarding several studies on signal processing have been carried out since any enhancements in this field could relax the demands on the technology.

It should also be noted that the airborne experience gained in Europe is quite advanced. DRA has performed quite a lot of measurement campaigns with an airborne continuous CO_2 coherent DWL which are at the origin of the ALADIN backscatter atmospheric model. DLR and CNES/CNRS are presently developing a pulsed CO_2 coherent DWL called WIND to be flown on the DLR Falcon aircraft. WIND will be available in 1998 to perform tests on a moving platform and perform measurement campaigns which will prefigure a spaceborne pulsed coherent DWL.

6.2.2. GRAS

GRAS is a GPS/GNSS receiver design of geodetic quality, i.e. it provides measurements at two frequencies (for ionospheric corrections to be feasible) with random noise in the signal carrier phase measurements below 1 mm, as required for precise positioning and atmospheric sounding. It has been tested at bread-board level. The receiver is capable of on-board operational use as a real-time position and velocity sensor. More information can be found in the description of the Earth Explorer Atmospheric Profiling Mission (ESA, 1996 d). The main characteristics of the GRAS electronics are as follows:

Mass (kg)	Power (W)	Data Rate (Kbps)
3	15	10

This instrument has a double function:

- It provides autonomous position and velocity information.
- It performs atmospheric temperature and humidity soundings.

For autonomous position and velocity determination, an antenna looking in the zenith direction is needed. The baseline is to use a helix antenna located at the edge of the anti-Earth solar wing. This configuration will minimise errors and maximise visibility. For atmospheric profiling a flat-patched antenna would be used which would be limb pointing, looking in the anti-velocity direction . The key figures of the antennae are:

	Volume (m^3)	Mass (kg)
Helix Antenna	$0.1 \times 0.1 \times 0.3$	3
Flat Antenna	$0.7 \times 0.7 \times 0.05$	5

6.3. Mission and Operations Profile

The drivers for the definition of the mission profile are:

- The minimum altitude compatible with a standard attitude and orbit control system on a conventional satellite. This simplifies the instrument.
- A dawn-dusk orbit for satellite simplicity

The base-line orbit is 479 km altitude. With this orbit and with a ±30 degrees half-cone scan-angle instrument around 30% of the Earth is covered in 12 hours and 50% in 24 hours. The coverage pattern after 24 hours can be seen in Figure 6.8.

Revisit requirements have not been considered as drivers (see chapter 4), but the mean revisit time is around 60 hours.

The altitude is a reasonable compromise between ground swath, laser power and satellite complexity. The dawn-dusk orbit allows the use of a fixed solar array. This not only simplifies the satellite but also reduces aerodynamic forces and torques.

6.4. Spacecraft

A life time of 3 years is assumed but fuel has been budgeted for 4 years.

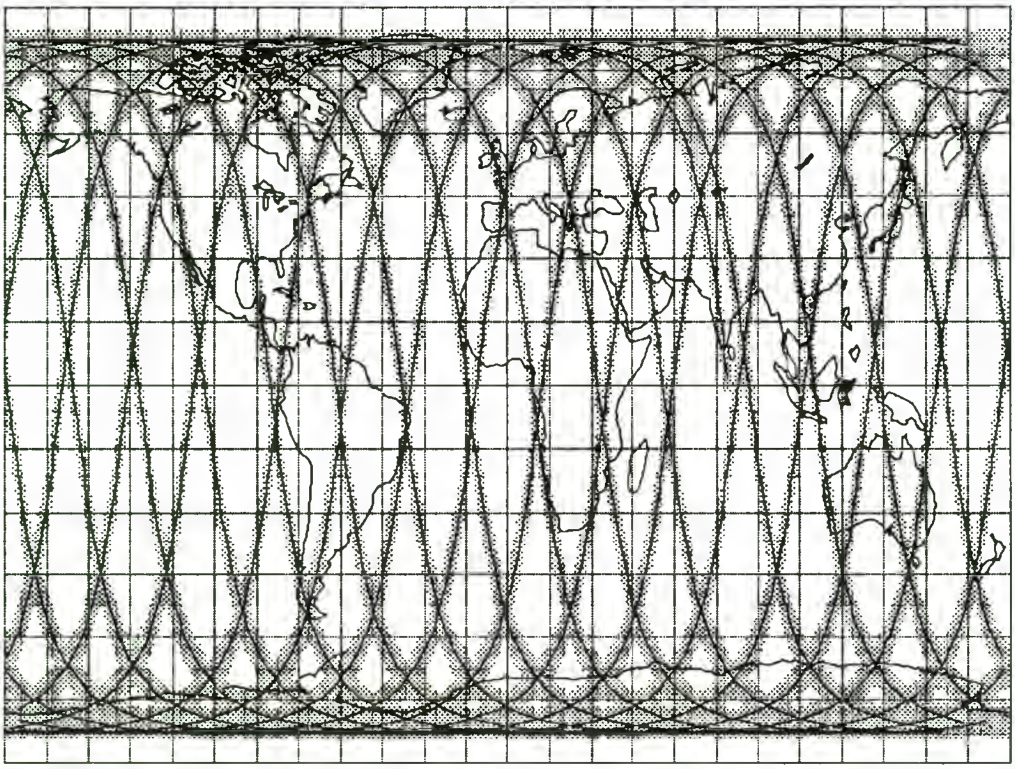


Figure 6.8. *Earth coverage in 24 hours.*

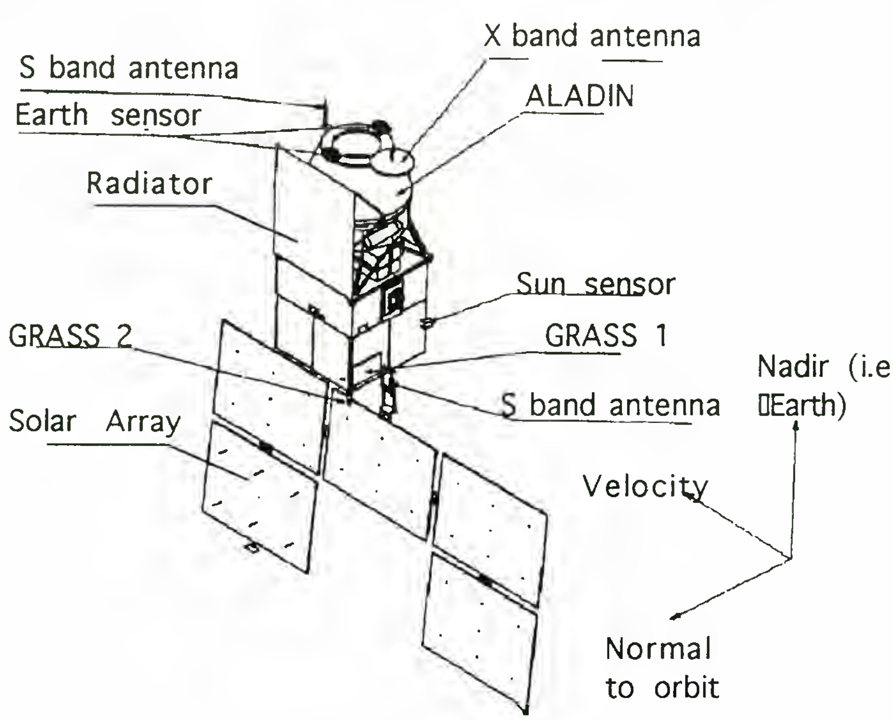


Figure 6.9. *Earth Explorer Atmospheric Dynamics satellite flying ALADIN.*

6.4.1. Configuration and Mechanical Design

The key assumption under-lying the design concept of the satellite is the assumption that the orbit is sun-synchronous dawn-dusk (6:00 hours local time descending node). In this orbit the sun and the solar array have a constant geometry and solar array rotation is unnecessary. The resulting solar array plane is parallel to the velocity, so minimising transversal area. This minimises perturbing aerodynamic forces and moments and allows the use of a fully conventional Mk-II (Spot-4) bus (with a simplified fixed solar array).

Although this bus selection is not the result of a thorough optimisation study, nevertheless it permits a 'reasonable' characterization of the mission. The configuration can be seen in Figure 6.9. The thermal design of the bus is also fully conventional, but the high thermal dissipation of the laser requires the use of advanced technology. It is proposed to use a large radiator on the anti-sun face. The radiator can be seen in Figure 6.9. A fluid loop is needed to drain the power from the laser transmitter to the radiator. Three to four square metres will be needed to dissipate the power generated by the satellite. This is perfectly compatible with the configuration.

The estimated mass budget without margins is as follows:

Mech & Therm.	Attitude Control	Power	OBDH & TTC	Payload	Fuel	Total
320 kg	239 kg	339 kg	134 kg	705 kg	300 kg	2037 kg

6.4.2. Attitude and Orbit Control

The attitude and orbit control system (AOCS) of the concept is driven by the pointing requirements of the instrument and by the internal and external perturbing forces and moments. Absolute pointing is not very demanding but attitude restitution is. This requires the implementation of star-trackers on the instrument. The exacting attitude rate stability requirements will require careful control of all perturbations as the AOCS cannot handle these. The summary of mission requirements is as follows:

Absolute pointing	2 mrad
Attitude restitution	35 µrad
Attitude rate stability	1 µrad in 3 ms
Orbital position restitution	50 m in radial direction
Orbital velocity restitution	0.1 m/s

The resulting system should be compatible with an AOCS identical to Mark-II of Spot-4. Gyros provide attitude measurements on the three axes. They are updated by an Earth sensor in roll and pitch and by a sun sensor in yaw. Torques are compensated by the reaction wheels which are in turn off-loaded by magneto-torquers. A 45 Nms wheel per axis and two 300 Am^2 magneto-torquers on roll and pitch are enough. The severe attitude restitution requirements will be met by star-sensors.

6.4.3. Data Handling and Communications

The data rates generated by this mission are moderate. Total data rate is 1000 Kbps. Instruments are continuously operating and, including overheads and Reed Solomon coding, 5.4 Gbits per orbit are produced. The telecommunication system (TTC) structure would be conventional 4 Kbps S-band for telecommand and housekeeping telemetry and 100 Mbps X band for downlinking of the payload data stream. The on board data handling system (OBDH) will be centred around a solid state mass memory. If two ground stations are provided (see chapter 6.5), the mass memory does not need to be larger than 5.4 Gbits.

A standard HRPT, "High Resolution Picture Transmission", system could provide local users with the data collected by the satellite during the overflight. The 1 Mbps data rate is well within its capabilities.

6.4.4. Electrical Design

Mk-II Spot-IV standard electrical subsystem, batteries and a simplified solar array are fully compatible with the mission as described here. The power budget estimates are as follows:

Thermal	Power	Attitude Control	Data Handling & TTC	Payload	Total
50 W	85W	213 W	140 W	1000 W	1488 W

6.5. Ground Segment and Data Dissemination

This mission is characterised by its pre-operational objectives which ask for:

- near real time data delivery requirements (3 hours from observation);
- high demand on communication link capacity;
- continuous 24 hour operational attendance.

These requirements are similar to those proposed for METOP so the resulting ground segment architecture is likely to be almost identical. At least one contact every orbit will be ensured. This requires two ground stations because due to the low orbital altitude even a station as far north as Svalbard is not able to provide contact every orbit. Direct and fast delivery to multiple users is assumed, but the derivation of winds is entrusted to a 'Processing Centre' that will disseminate this information to the general users. A ground segment overview is shown in Figure 6.10.

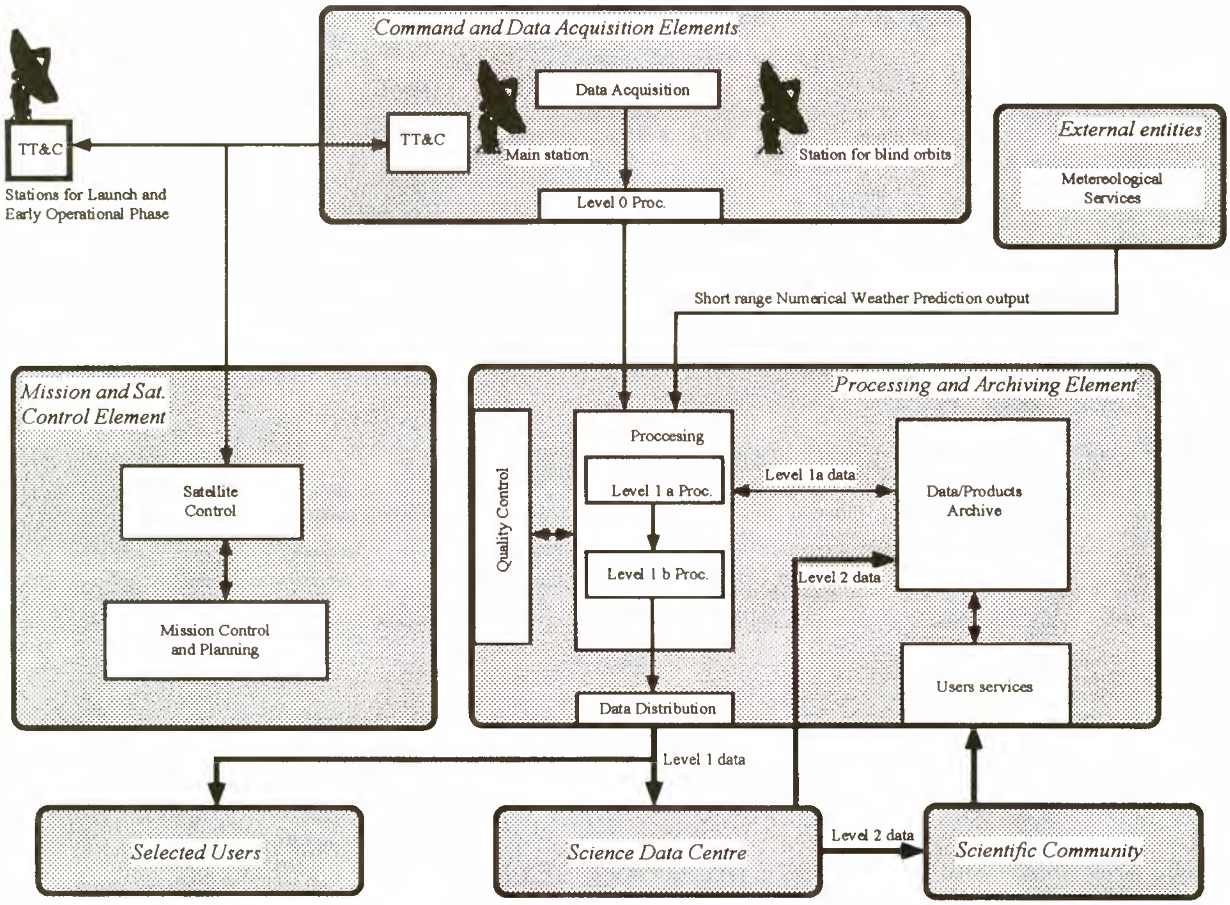


Figure 6.10. *Ground Segment.*

6.5.1. Command and Data Acquisition

As no single ground station could provide complete data acquisition, ideally, two stations are required. At the ground station the data will be processed to level 0 and forwarded to the Data Processing Element.

A centre similar to that used for the ERS satellitse can be assumed for command and control.

6.5.2. Data Products

The levels of data produced would as follows:

- Level 0 – raw data as telemetered from Atmospheric Dynamics Explorer.
- Level 1a – data 'depacketised' and sorted in files with calibration data attached but not applied. This level is reversible with respect to Level 0.
- Level 1b – calibrated and corrected line-of-sight wind with a quality tag attached.
- Level 2 – wind field output from assimilation models.

After validation of the satellite data, the scientific data would be pre-processed to Level 1a data. This consists of channel decommutation and reformatting. These data would contain the readouts from the instruments together with calibration data time attitude and other housekeeping information as needed.

Data would be calibrated and corrected to provide the Level 1b products. The output would be line-of-sight wind with associated quality tags. This task would be done by a Processing and Archiving Element. Level 1 data will be required to be delivered in near real-time in parallel to selected users. The needs of the scientific community would be met by a Science Data Centre which would perform the Level 1 to Level 2 scientific data reduction. Level 2 products would be wind fields. They also would be available in near real-time to selected users.

During the mission the Processing and Archiving Element should archive the data normally at Level 1a. Within one month data could be directly accessible on a rolling archive. After this the data would be stored on appropriate media in an off-line archives. Once a mission is completed it is proposed to transfer the complete mission data set to a 'post mission' archive. The type of data to be archived should be Level 1a and Level 2. Non real time users will access directly the rolling archive and will need specific request to the operator to access the off line archives. If the mission lasts for 4 years the overall archive size is estimated to be 252 Tbytes.

6.5.3. Data Validation and Monitoring

The aim of data validation is to check the quality of ALADIN wind data against independent reliable wind information. Experience with current satellite instruments used in numerical weather prediction, e.g. ERS or NOAA data, has shown the large potential for validation and monitoring of such data within the data assimilation system.

In a data assimilation system all operational meteorological observations are used. Further, past observations are projected forward in time during the forecasting step. Observations of temperature and pressure will influence the wind analysis (see chapter 2). Thus, the assimilation system provides an equivalent for the measurement of wind, at any location and time, making use of all available observations. This allows each observation of ALADIN to be checked by passing it through the data assimilation system. The average systematic bias, random error, and quality control statistics can be computed and monitored in time. In addition, such statistics can be easily provided as a function of several system parameters, such as signal strength, orbit position, etc., thereby providing detailed validation and monitoring.

In turn, the quality of the numerical weather prediction fields is operationally monitored by the real time observational systems as given in chapter 2, and bias, accuracy and spatial error characteristics are well known. This means that the conventional observations generally provide the reference for the validation and monitoring effort of satellite data with numerical weather prediction fields.

Direct comparison of ground-based observations and satellite data is very inefficient, given the relatively remote occasion where both observation types provide a collocation in space and time. In addition, both data types often represent different spatial or temporal scales, i.e. the comparison is not governed by the measurement accuracy, but by the difference in representativeness (see also section 4.2).

6.6. Launcher

The mass and volume of the proposed Earth Explorer Atmospheric Dynamics Mission makes it compatible with a number of medium and light launchers, e.g. the existing Delta-II or the LLV-3 project.

The requirements of the Earth Explorer Atmospheric Dynamics Mission are compatible with Ariane-5, either with a dedicated launch or shared. However, sharing appears to be a little problematic because it will be difficult to identify a co-passenger going to a similar orbit.

6.7. Implementation Option

This alternative is based on the use of the International Space Station Alpha. It has been investigated in parallel industrial contracts studying the two ALADIN concepts. The conclusion of both contracts was that the accommodation of ALADIN was feasible.

The preferred attachment places (see Figure 6.11) are:

- One of the three nadir oriented truss payload attachment sites. The figure indicates the position of the location reserved for European payloads.
- The Japanese Exposed Facility. ALADIN would take the place of one or two of the small boxes that appear in the figure.

The Japanese Exposed Facility provides better visibility and thermal accommodation but the standard volume allocated to each payload is limited and is insufficient for the present ALADIN concepts. The accommodation will be feasible only if two docking ports are made available. JEM-EF has a dedicated robotic arm that could be used for servicing. This could lessen the issue of laser reliability.

The International Space Station Alpha flies at a lower altitude than the baseline satellite; so the signal to noise ratio increases e.g by 40% at 400 km, and the data quality is improved. On the other hand the utilisation time and resulting coverage are reduced by International Space Station Alpha generated limitations.

International Space Station Alpha's orbit varies. Depending on solar activity the actual orbit varies from 460 and 335 km forcing an orbit correction phase every 70 days. This phase includes 20 days for service and maintenance and 2 days more for reboosting. No data production during these 22 days is possible. Interference from solar arrays and safety constraints will also limit the time available for observation.

Currently the International Space Station Alpha's orbit inclination is 51.6°. Although this means that high latitude regions will not be covered mid-European latitudes will be observable (see Figure 6.12). Also, as this orbit is not sun-synchronous, the local time of the observations will drift making it possible to provide the variations of the winds with the local time. The local time drift will be altitude dependent; in the case of orbit altitude equal to 400 km, it will be 16 minutes per day.

Another limitation to the experiment is the capability of the International Space Station Alpha and associated ground segments to provide near real-time data in 3 hours. The International Space Station Alpha uses the TDRSS data relay system which cannot guarantee near real-time delivery. However, this would still be compatible with a demonstration mission.

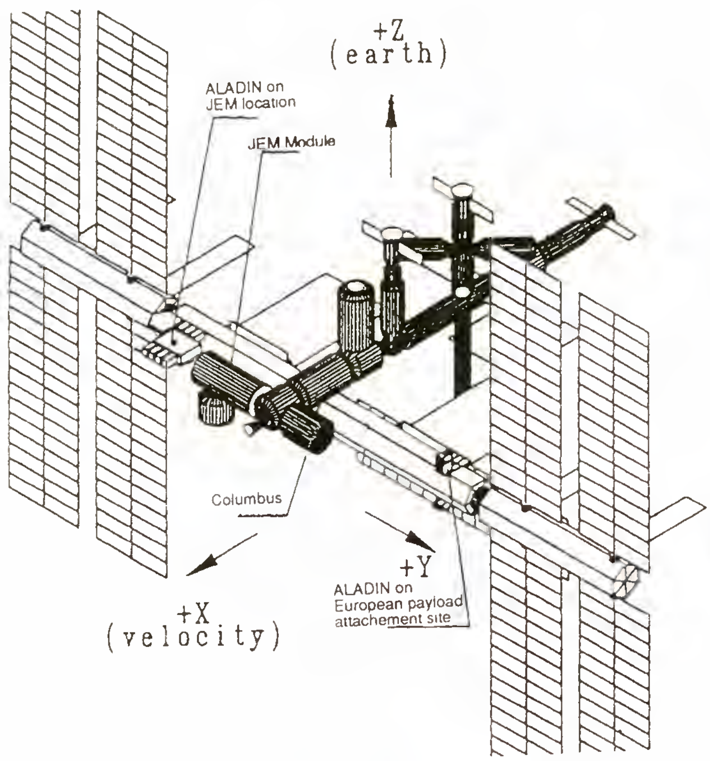


Figure 6.11. *ALADIN in the Space Station.*

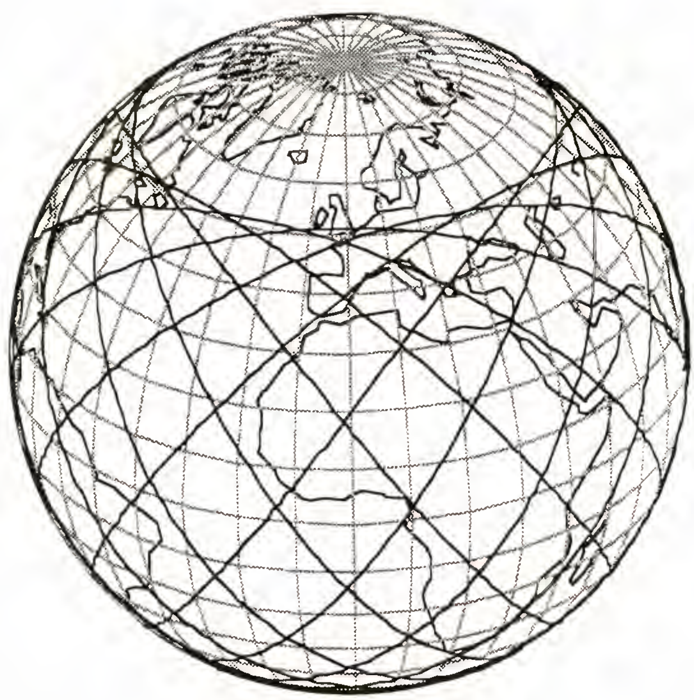


Figure 6.12. *Pattern of One Day of Orbits of the Space Station.*

7. Programmatics

7.1. General

The Atmospheric Dynamics Explorer would be implemented in the framework of the ESA Earth Explorer Programme of research missions if selected after phase A studies carried out within the framework of the Agency's Earth Observation Preparatory Programme.

7.2. Critical Areas and Open Issues

ALADIN is undoubtedly a complex and demanding instrument. However, the development effort devoted so far has already permitted the definition of a reasonable instrument concept.

The significant technological effort devoted towards the realisation of ALADIN in general, and on lasers in particular, should provide a good basis for the completion of the development. Continuation of this technological effort is presently proposed in the critical areas of receiver and transmitter technologies.

The major critical area is the lifetime of the laser as the three years mission duration still exceeds the lifetime of state-of-the art lasers. However, it is expected that this issue will be solved within an appropriate development time.

The near real-time requirement for data delivery would impose strict constraints on the ground segment though its implementation would prepare the way for potential operational utilisation.

7.3. Related Missions and Timeliness

Though there have been several attempts in the past to realise such a mission by national European and foreign agencies, currently no similar mission concept is planned. NASDA is considering a JLAWS experiment on the International Space Station Alpha for around the year 2004.

The Earth Explorer Atmospheric Dynamics Mission has a large and clear application potential. This long awaited mission should therefore be implemented as soon as possible to provide the results needed to demonstrate the related technologies and the utility of the data. Ideally the results of this Earth Explorer should be available before the middle of the next decade when studies of the next generation of meteorological satellites should be started.

7.4. International Cooperation

The absence of similar missions in the world does not mean lack of interest but rather the nature of the challenge posed by the realisation of this mission. There is widespread international interest in it and, therefore ample room for international cooperation. Such a possibility could be envisaged for instance within the frame of an experiment on the International Space Station Alpha where the international partners could, for example, provide transportation and accommodation possibilities.

The operational potential of the mission offers also possibilities for cooperation with operational Agencies.

7.5. Enhancements of European Capabilities and Applications Potential

In 1991 the WMO Executive Council Panel of Experts on Meteorological Satellites established the need for three dimensional wind measurements as the highest priority long term development for operational meteorology as reported at the 1991 Earth Observation User Consultation meeting (ESA, 1991).

Clearly, the observation, modelling, analysis and assimilation capabilities to be developed in the framework of this mission have a strong potential for operational application.

Observations made by ALADIN would also provide new insights for interpretation of cloud track winds as currently derived from geostationary satellites. In addition, the leading position of Europe in surface wind determination with scatterometers would be strengthened.

References

ESA, 1991: Report on the Earth Observation User Consultation Meeting, *SP-1186*

ESA, 1996 a): Earth Explorer Precipitation Mission, *SP-1196 (8)*

ESA, 1996 b): Earth Explorer Earth Radiation Mission, *SP-1196 (3)*

ESA, 1996 c): Earth Explorer Atmospheric Chemistry Mission, *SP-1196 (6)*

ESA, 1996 d): Earth Explorer Atmospheric Profiling Mission, *SP-1196 (7)*

GCOS (1995): GCOS plan for Space-based Observations, *Version 1.0, GCOS-15, WMO/TD No. 684*

GEWEX (1990): Scientific plan for the Global Energy and Water Cycle Experiment, *WCRP - 40, WMO/TD No. 376*

Lorenc A.C., R.J. Graham, I. Dharssi, B. Macpherson, N.B. Ingleby and R.W. Lunnon, (1992): Preparation for the use of Doppler wind lidar information in meteorological data assimilation systems, *ESA Contract Report No. 9063/90/HGE-1*

McNally A.P. and M. Vesperini (1995): Variational analysis of humidity information from TOVS radiometer, *Eumetsat/ECMWF Fellowship Programme, Research Report No. 1*, ECMWF, Reading

List of Acronyms

AIRS	Atmospheric InfraRed Sounder
ALADIN	Atmospheric LAser Doppler INstrument
AOCS	Attitude and Orbit Control System
CNES	Centre National d'Etudes Spatiale
CNRS	Centre National de la Recherche Scientifique
DLR	German Aerospace Research Establishment
DRA	Defence Research Agency
DWD	Deutscher Wetterdienst
DWL	Doppler Wind Lidar
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
ERS-1	The first European Remote Sensing Satellite
EUMETSAT	European Meteorological Satellite organisation
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Experiment
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Cycle Experiment
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	GPS/GNASS Radio Occultation Atmospheric Sounder
HLOS	Horizontal component of the LOS
IASI	Infrared Atmospheric Sounding Instrument
ITCZ	Inter-Tropical Convergence Zone
JLAWS	Japanese Doppler wind lidar concept
LOS	Wind component along the Line Of Sight
METOP	METeorological Operational Polar satellite
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction

OBDH	On-Board Data Handling
SYNOP	SYNoptic OPerational observations
TDRSS	Telecommunications and Data Relay Satellite System
TOGA	Tropical Ocean/Global Atmosphere
TTC	Telecommunications
UARS	Upper Atmosphere Research Satellite
UTC	Universal Time Coordinated
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation

European Space Agency
Agence spatiale européenne

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