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Proposal in Response to the ERS Announcement of Opportunity

# Altimetry For Research In Climate And Resources (Project AFRICAR)

Copenhagen – Delft – Oslo
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## Project Theme

Investigate and exploit the use of ERS radar altimeter data and ancillary information for monitoring the climate and earth resources, through the mapping and monitoring of the topography of oceans and land ice; and, in support of this effort, provide precisely computed ERS orbits and PRARE station positions.

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## Abstract

The Project AFRICAR (Altimetry For Research In Climate And Resources) is a combined effort of several European and United States' research institutes with expertise in precise orbit computation, remote sensing, geodesy, geophysics, and oceanography, with emphasis on the application of radar altimeter data.

The project encompasses several proposed investigations into the use and exploitation of radar altimeter data for research in climate change and the detection of earth resources, through mapping and monitoring of the global and regional sea level, and land ice topography. For this research, ERS-2 altimeter data will be used in combination with ATSR sea surface temperatures and selected SAR images, remote-sensing data from other satellites, and in-situ measurements. A full list of required data is given in Table 1, Section 8.

This proposal is divided in three parts: precise orbit determination of ERS-2 and precise positioning of PRARE stations, applications of altimetry for research in oceanography on a global scale, and applications of altimetry in gravity field mapping and ice sheet monitoring.

# Contents

# 1 Introduction

Under the acronym AFRICAR (Altimetry For Research In Climate And Resources) several European and United States' research institutes have combined their expertise in orbit determination, geodesy, geophysics, oceanography, and remote sensing, to conduct a number of investigations into the use and exploitation of radar altimeter data for climate-related studies and detection of submarine earth resources. This includes the synergistic use of ERS–2 altimeter data with data from other ERS–2 instruments, as well as combination with ERS–1 and TOPEX/Poseidon remote sensing data and in-situ data.

The cooperating institutes have established an extensive record of publications in their respective fields of expertise, many of them with emphasis on the use of ERS–1 remote sensing data. After the Announcement of Opportunity for ERS–1 was issued, these groups have cooperated informally to combine some of their efforts in the use of ERS–1 radar altimeter data for oceanographic and geophysical research. With the Announcement of Opportunity for ERS, issued last year, the institutes have decided to draw up three focused proposals which are mutually supportive.

The AFRICAR Project consist of three parts, each on a different (though closely linked) theme:

PART I: Precise orbit determination of ERS satellites and ground positioning using PRARE.

PART II: Altimetry for global oceanographic research and tide model improvement.

PART III: Gravity field mapping and ice sheet monitoring.

Part I

# Precise orbit determination of ERS satellites and ground positioning using PRARE.

## 2 Objectives of the investigation

The objective is to establish a precise framework for the radar altimeter data, consistent with present and past radar altimeter missions. *i.e.*,

- compute precise orbits for ERS–1/2 based on PRARE. SLR, and RA measurements in support of altimetry applications
- ensure a continuation of the Geosat - ERS–1 - TOPEX/Poseidon - ERS–2 altimeter data set within the same JGM-2 reference frame
- orbit improvement through comparison between (simultaneous or near simultaneous) ERS–1, ERS–2, and TOPEX/Poseidon altimeter data
- reduce orbit error by gradual improvement of ERS surface force model and tailoring of the gravity field model.
- contribute to the calibration and geophysical validation of the PRARE system
- use a network of 4 to 5 PRARE stations for a precise positioning experiment
- provide precise orbital data for a near real time SAR interferometry experiment at Tromso Satellite Station
- contribute to global PRARE tracking of ERS–2

To achieve the above goals, the availability of ERS tracking by PRARE and SLR (preferably providing a global coverage) is essential. For off-line orbit determination and validation of the orbit precision, the availability of ERS radar altimeter data is required. In addition, to test the accuracy of the orbits, the generated orbits will have to be compared with available preliminary and precise orbits.

## 3 Experimental plan

A key role in the application of radar altimeter data is the availability of precise ephemerides of the satellite, typically better than 10 cm in the radial direction. The AFRICAR project proposes several investigations into precise orbit determination for ERS and will continue the operational orbit determination, currently set up for ERS–1, throughout the ERS–1/2 lifetime. Five PRARE ground stations are available to support the orbit determination effort. Precise positioning of PRARE station sites and verification of the data products of this new tracking system are envisioned.

Because of the availability of PRARE as well as laser tracking on ERS–2, the expected amount of ERS–2 tracking will be a significant improvement over ERS–1. Thus, ERS–2 will mark a step into a new era of precise orbit determination for low-earth orbiting (800-km altitude) satellites, expecting to cut the radial orbit error (presently in the order of 12 cm) down to a level of some 6 cm. This may require extensive force model re-evaluation.

The Section Space Research and Technology (SSR&T) at Delft University of Technology (DUT) has many years of operational experience with laser tracking and precise orbit determination (OD) of Earth resource satellites. SSR&T has adapted the Goddard OD software GEODYN II for the ERS–1 satellite for which an orbital accuracy of 10–15 cm in the radial direction is achieved on a regular basis [*Scharroo et al.*, 1994].

At the Norwegian Defence Research Establishment (NDRE), a software package named GEOSAT [*Andersen*, 1986] has been developed for high-precision analysis of satellite tracking and VLBI data for geodetic and geodynamic applications. The software has been gradually improved and extended during the last ten years and has also been installed on a fast workstation at the Institute of Theoretical Astrophysics (ITA), University of Oslo for applications to ERS–1. ERS–1 orbital accuracies obtained with the Geosat software are in good agreement with precise SSR&T and D-PAF orbits [*Andersen et al.*, 1994].

The SSR&T, NDRE, and ITA groups complement one another in terms of expertise, experience, and tools. The availability of two independent OD software packages makes orbit quality assessment safer and gives added flexibility in processing a variety of tracking data (SLR, PRARE, altimeter height residuals, single and dual satellite crossovers). GEODYN II is best suited for operational use on account of its higher speed and efficiency, while GEOSAT offers more flexibility for experimental purposes because of its modular design and the fact that the designer is a co-investigator.

GEODYN II uses the least squares method for parameter estimation, while GEOSAT can use either the least squares or the Kalman filter method. Kalman estimation is particularly useful in OD cases involving 'reduced dynamics' [*Melbourne et al.*, 1993] by which is meant that the orbital dynamics is geometrically constrained. One obtains a hybrid solution lying between two extremes: a purely geometric and a purely dynamic solution. The Kalman method achieves this by estimating at every time step a 3-D stochastic force, each component of which is being constrained by an a priori variance and correlation time.

The reduced dynamics method seems very well suited for handling combined PRARE, SLR, and also RA data. Simultaneous range measurements from at least three PRARE stations, in the local network described below, can be used for a purely geometric OD (trilateration) over a short orbital arc outside of which the satellite dynamics and other tracking data will gradually come more and more into play.

Since the short-arc orbit, in the limited region where it applies, is essentially free from force model errors, it is hoped that it will be more precise than the global long-arc orbit. This will benefit especially local altimetry applications, PRARE calibration, point positioning, and SAR interferometry. The precision of the short-arc orbits, however, depends heavily on the availability of sufficient PRARE and SLR tracking data.

Operational precise long-arc orbits for ERS–2 will be produced at SSR&T based on the JGM-2 gravity model and any later improvements. This will ensure a continuous data set of altimetry from Geosat, ERS–1, TOPEX/Poseidon, and ERS–2.

## 3.1 Operational orbit determination

**Continuing the JGM-2 based data set.** Comparison of radar altimeter data acquired from several satellites can only be performed with sufficient confidence when all orbits are computed in the same reference frame with similar force models. Therefore, the operational orbit determination for ERS, based on the JGM-2 gravity model, will be continued throughout the ERS–1 and ERS–2 lifetime in order to have a continuous Geosat - ERS–1 - TOPEX/Poseidon - ERS–2 sea level time series within the same reference frame. These orbits will be generated within three days after the end of a 5.5-day period for which the orbit is to be determined, and can then be combined with fast delivery altimeter data to obtain precise sea level information within a week after acquisition [*Scharroo et al.*, 1993]. Obviously, this demands the availability of global SLR, PRARE, and altimeter data within few days after the measurements are made.

## 3.2 Off-line orbit improvement

**Combined use of tracking data.** The applicability of different types of tracking data (SLR, PRARE, altimeter height residuals, single and dual satellite crossover height differences) will be investigated. The various orbit solutions based on the different types of tracking data (and their combinations) will be compared.

**Non-dynamic orbit solutions.** Because of the expected abundance of tracking data, with both SLR and PRARE operational, reduced-dynamic orbit solutions (applying advanced filtering techniques) may be achievable. This kind of orbit determination process will possibly enable us to investigate and reduce the geographically correlated orbit error which is inherent in the classical dynamic solution.

**Non-gravitational force model improvement.** The non-gravitational forces (drag and solar radiation pressure) are the main error sources in the orbit determination. Part of these errors are due to imperfections in the modelling of the satellite's shape and surface properties (macro model). Tuning of the macro model for ERS-2 will be performed to improve the precision of the orbit determination of ERS-2 as well as (in retrospect) ERS-1.

**ERS tandem experiment.** The tandem operation of ERS-1 and ERS-2 (flying in similar orbits with the same local solar time of the ascending node) provides a unique opportunity to link the solved-for empirical drag force parameters for ERS-1 and ERS-2. Since ERS-1 and ERS-2 have near-identical shapes, orientations, and orbits, both satellites will experience a very similar evolution of the atmospheric drag along the orbit, but slightly shifted in time. Any mismodelling of atmospheric conditions will thus affect the orbits of the to satellites in a similar way.

The estimation of drag scaling parameters absorbs a major part of the drag mismodelling but also makes the solution less stable, especially when few tracking data are available. Because the satellites experience the same conditions, drag scaling parameters ought to be identical for both satellites, and can be solved for simultaneously in the OD. Linking the parameters between both satellites will stabilise the solution and improve the precision of both orbits.

Both tandem mission alternatives, with a one-day or eight-day separation, are suitable for this purpose.

**Gravity field model improvement.** Additional orbit improvement is expected from improvement and tailoring of the gravity field model, using the abundance of ERS-2 tracking data. Tailoring of some of the gravity field model parameters to ERS-2 will be performed once sufficient SLR and PRARE tracking data is available (*i.e.*, after 6 to 12 months).

**Software comparison.** A comparison study between different orbit determination software packages (*e.g.*, GEOSAT and GEODYN II) with different estimation techniques (filtering and Bayesian) will be performed.

## 3.3 Short-arc orbit determination

**OD support for altimeter applications.** For many applications (such as regional tide model improvement) high precision orbits are required over a limited area. In the case that a sufficient amount of SLR and PRARE tracking data is available, short-arc orbit determination techniques can be applied that minimise the dynamical force model errors and reduce the radial orbit error to some 2–4 cm. For ERS-2 these techniques can be improved for special applications over the North Sea and Greenland-Iceland-Norwegian Sea because of the dense tracking support by PRARE in the area and the regular tracking by the established SLR stations. Comparison of techniques, precisions, and softwares will be performed.

**OD support for SAR interferometry.** NDRE has developed a very fast SAR processor which has been operating at Tromsø Satellite Station (SST) for the entire ERS-1 mission. The main interest is surveillance of ships, sea ice, and structures on land. Experiments with interferometry on ERS-1 SAR scenes which repeat at 3-day intervals have shown promise of detecting small structural changes.

For surveillance the time factor is important. NDRE has already demonstrated detection in near real time with conventional SAR processing which does not demand very precise knowledge of the orbit. For SAR interferometry, on the other hand, the orbital accuracy is critical, and it is a challenge to provide a precise orbit in near real time. This can be done, however, by relying on the short-arc OD technique discussed before.

A SAR interferometry experiment is proposed for a limited period to be agreed on later, with ERS-1/2 SAR data acquired at Tromsø and PRARE data for real-time OD coming from the local network of PRARE stations.

## 3.4 PRARE calibration, validation, and operation.

The proposers have at their disposal 5 PRARE stations; 3 to be operated by Statens Kartverk (SK), 1 by the University of Copenhagen and Kort- og Matrikelstyrelsen (KMS), and 1 by SSR&T. These stations have been built by Dornier but the owners will not take delivery until the units have

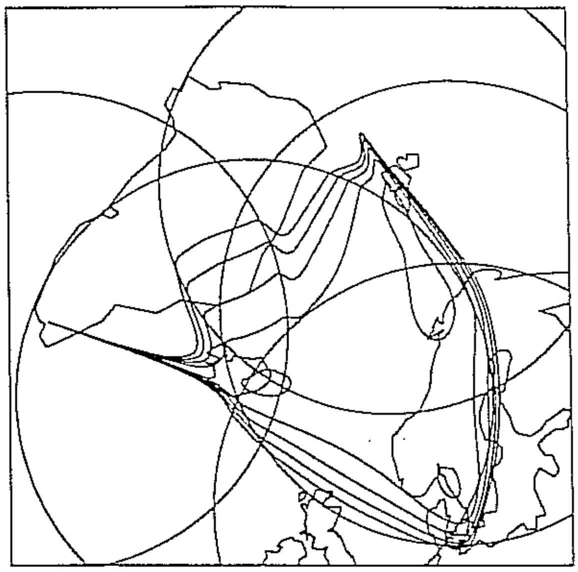

Figure 1: Visibility circles and VDOP contours for PRARE stations

been checked out by Dornier against the PRARE space segment on the Russian satellite Meteor 3 which was successfully launched at the end of January 1994. By early March the PRARE system has to a large extent been checked out and about 10 PRARE stations have been activated. Preliminary information about the ranging accuracy is very promising.

SK is planning to activate one PRARE station, probably at Ny Alesund, in the second half of 1994 to gain experience with PRARE operations ahead of the ERS-2 launch.

PRARE sites have been prepared or are under preparation at Stavanger, Trysil, and Tromsø in Norway, Ny Alesund on Svalbard, Onsala in Sweden, Höfn on Iceland, and Narsarsuaq on Greenland. These sites have had their locations precisely measured by means of GPS, SLR, or VLBI. During the three-month commissioning phase of ERS-2, PRARE stations at these sites will be made available to ESA for a calibration/validation campaign to be coordinated with the German PRARE campaign.

In order to get a rough idea about the short-arc OD accuracy to be expected during a single ERS-1/2 pass over a local network of PRARE stations, a covariance analysis has been performed based on simulated PRARE ranges. As an example, we assume that stations are located at Onsala, Tromsø, Ny Alesund, Narsarsuaq, and Höfn. In Figure 1 visibility circles with a cut-off elevation of 15° are drawn around each site. It is assumed that the tropospheric error increases as the cosec of satellite elevation and that the site coordinates are perfectly known. The five closed contours (other than those marking geographical areas) represent the so-called VDOP (vertical dilution of precision) running from 1 to 3 in steps of 0.5. The VDOP value at a given geographical location multiplied by the range error at zenith is an estimate of the radial orbit error for a pass directly above that location.

One can conclude from Figure 1 that inside the polygon with corners at the five sites, the radial orbit error is roughly 1.5 times the range error at zenith. With the assumed measurement accuracy of the PRARE system, that amounts to a radial error of 5–10 cm. This polygon includes the Norwegian Sea, the Greenland Sea and part of the Barents Sea, areas which are all interesting targets for altimetric studies.

We also intend to deploy an RA transponder in a suitable position beneath the ERS ground track in western Norway. This can be used both to enhance the orbit determination and to validate the RA.

**PRARE point positioning.** Absolute point positioning with a single PRARE station will not be very accurate on account of the uncertainty in the position of ERS-2 as derived from a long-arc dynamical orbit. Of more interest is relative positioning with two or more PRARE stations. Simulations have shown that one station may be located relative to the other(s) some kilometres away with errors of about $10^{-6}$ and $10^{-7}$ times the length of the baseline, using long-arc and short-arc techniques, respectively.

We propose a positioning experiment with four PRARE stations operating in a nearly simultaneous mode. The PRARE system is capable of making range measurements to up to four stations simultaneously. Three of the stations will be located at well surveyed points, *e.g.* at Onsala, Tromso, and Höfn, and used for short-arc orbit determination by trilateration. With the orbit precisely known, the fourth PRARE station can then be used for positioning, *e.g.* of an oil platform. If the technique proves sufficiently accurate, it is desirable to use it in combination with differential GPS to position the tide gauges along the Norwegian coastline. In this way the mean sea level derived from tidal data can be determined in the ERS reference frame for direct comparison with the ERS altimetric geoid.

**PRARE tracking support.** With the precondition that a global tracking plan will be developed, several of the PRARE transponders will be deployed in permanent sites, which will be maintained by the national authorities. It is recommended that at least one ground station should be placed in Höfn on Iceland to fill in the North Atlantic gap in the PRARE coverage.

**Estimation of tropospheric range correction.** The Onsala site will be equipped with a water vapour radiometer (WVR) and a ground based total pressure sensor which makes it possible to estimate the propagation delay caused by the neutral atmosphere of the PRARE signals with an rms accuracy better than 1 cm during more than 90% of the time. (The accuracy is worse during rainy conditions.) This will be a very important part of the PRARE calibration, since the expected error in modelling the wet propagation delay in general is in the range 2–7 cm even though the expected modelling error at the Onsala site is 2–3 cm rms without the WVR.

Post-processing of VLBI and GPS data acquired at Onsala and Ny Alesund will also give valuable tropospheric information to be applied in the PRARE data analysis. A Mark III VLBI with a 20 m dish is now under construction in Ny Alesund and is expected to be operational in mid 1994.

In addition, it will be investigated whether global tropospheric range corrections can be estimated from the PRARE tracking data simultaneously with the orbit determination. Because the wet and dry troposphere do not significantly affect the range-rate measurements, these will provide sufficient information together with the range measurements to solve for a tropospheric bias correction for each pass.

# Part II
# Altimetry for global oceanographic research and tide model improvement.

## 4 Objectives of the investigation

The objective is to further exploit the application of radar altimeter data for the mapping and monitoring of the oceans, with emphasis on climate related research, *i.e.*,

- determination of the global and regional ocean topography for the extraction of the small scale geoid features, related to the mass distribution in the earth's crust. and the extraction of the large scale ocean dynamics
- development and improvement of techniques to separate the geoid and ocean topography component in the mean sea level *at all wavelengths*
- combination of historical and contemporary radar altimeter data over the oceans to obtain long-duration time series of sea level change
- development and improvement of time-space interpolation techniques to provide correct identification of meso-scale ocean phenomena, exploiting the synergy of several satellites and instruments (ERS, ATSR and SAR)
- utilisation of sea level time series for better understanding of meso-scale ocean processes, for tide model improvement, and to extract global and regional secular sea level change
- integration of conventional oceanographic measurements (buoy and ship-borne current, salinity, and temperature data) into altimeter data analysis and exploitation of the synergy of the two data types to study volume and heat transport on basin-wide scale

Some of these studies will closely liaise with the World Ocean Circulation Experiment (WOCE).

To achieve the above goals, the availability of ERS radar altimeter data (both fast delivery and off-line), ATSR sea surface temperatures throughout the ERS-1 and ERS-2 missions, and selected SAR images is essential. Since the use of altimetry requires accurate sea level determination, precise models and orbits are required.

## 5 Experimental plan

The instantaneous sea level (as derived from altimeter data, precise orbits, propagation and engineering corrections) consists of various components:

**Tides:** elevation of the sea level due to the attraction of sun and moon. This term is usually provided by astronomical tide models.

**Dynamic topography:** part of the sea elevation caused merely by ocean currents, consisting of a stationary part (background currents) and non-stationary part (meso-scale variability, eddies, current meanders).

**Geoid:** part of the sea elevation caused by the gravity field of the earth. This term is near-stationary and reflects the mass distribution of the earth.

**Sea level change:** various contributions, such as wind forcing, bottom friction, and regional or global sea level rise due to climate change.

A fundamental problem in oceanography as well as geodesy is the separation of the sea surface height into geoid height and stationary dynamic topography. It seems impossible to separate the one from the other from altimeter measurements only. But since the error in the present geoid models is highest at the shorter wavelengths, in which the dynamic topography has little power, both components can often be resolved. In areas of strong currents, however neither of the components is properly modelled and large errors remain in geoid as well as the dynamic topography models.

Research into this problem using combined analyses of altimetry from ERS satellites as well as others (Geosat and TOPEX/Poseidon) together with marine (and land) gravity will continue. The use of ocean circulation models as constraints in the separation will be attempted in regions of strong currents and ocean variability. These studies will also require tide model improvement.

For regional areas current velocities can be converted into volume and heat transport. In order to obtain estimates for these quantities from altimetry, it is necessary to have an idea of the sub-surface profiles of water properties (current, temperature, salinity). Only to a limited extent, climatological estimates are available from conventional measurements, but this data base will be greatly enhanced by the WOCE campaigns. Altimetry can help to fill areas that are not well sampled by conventional data. Hence, the combination of the two data types will be profitable to both regimes. The integration of buoy and ship-borne data in altimeter processing should thus be a major effort.

## 5.1 Oceanographic studies

**Global ocean circulation and sea level time series.** The long-wavelength dynamic ocean topography (reflecting the large scale ocean circulation) can be extracted from global radar altimeter measurements, by subtracting existing global geoid model heights from the altimetric sea level heights. Provided the applied satellite orbit is accurate up to sub-decimetre level, and the geoid model is sufficiently accurate at the longer wavelengths, the global ocean circulation can be mapped from altimeter measurements covering a period of some 10 days.

Currently, time series of global dynamic topography solutions are generated from Geosat, TOPEX/Poseidon, and ERS–1 data separately. Evaluation of the time series shows the seasonal, annual, and interannual evolution of the large-scale ocean circulation and global or regional secular sea level change [*Naeije et al.*, 1993, 1994].

A major drawback in using ERS–1 data is the lack of a sub-decimetre orbit precision. To be able to create a topography solution still, the effect of the orbit error is reduced by extending the measurement period for each solution. This limits the time series' temporal resolution to some 35 days.

With the ERS–2 mission an uninterrupted period of some seven years of ERS radar altimeter data and precise PRARE orbits will be in reach. The establishment and investigation of a continued ERS time series, combined with TOPEX/Poseidon time series, is a valuable contribution to the monitoring of global climate change.

In support of the ocean circulation study, the same time series will be used to improve global (astronomical) tide models. The modelling is primarily aimed at open oceans, where the dynamics are important. In coastal zones the meteorological and boundary conditions are to be considered as well.

**Monitoring of meso-scale ocean phenomena.** Meso-scale ocean phenomena, like current meanders and eddies, have a typical scale of 100–200 km. Since the current geoid models are generally insufficiently accurate at these wavelengths, meso-scale phenomena can not be determined directly by subtracting a suitable geoid model. At these wavelengths meso-scale oceanic variability (reflecting eddy shedding processes, eddy transport, and evolution of current meanders) shows up as changes in the sea level with respect to the mean ocean topography determined from the same time series [*Samuel*, 1990; *Naeije et al.*, 1992; *Feron*, 1992].

Even though these eddies transport huge amounts of warm or cold water across the oceans, they sometimes remain unobserved by infra-red imaging, because the view is often obstructed by clouds, or because the eddies do not extend to the sea surface, but remain hidden under a thin layer of (in this case usually warmer) surrounding water. Monitoring of eddies, which play a key role in the ocean-wide energy transport and regional fish stock, is a first step towards apprehension of the yet insufficiently understood meso-scale ocean phenomena.

Research in this field will not only pertain to the extension of historical time series of altimetric sea level determination, but also the development of adequate time-space interpolation procedures to monitor sea level changes within the 35-day ERS baseline repeat period. The ERS tandem mission with an eight day separation can be used in this respect to verify the effectiveness of the interpolation procedures. Because of their temperature signature, being warmer or colder than the surrounding water, eddies show up in infra-red ATSR data, as long as the view is unobstructed by clouds and the eddies are not submerged. Also, the temperature and salinity difference may be visible in SAR images, or are available from conventional measurements. Hence, ATSR data, low resolution SAR images, and conventional current information will be used to enhance and verify the detection of eddies and other meso-scale currents.

Models will be verified in the area between Norway, Greenland, and the United Kingdom where the precise orbit will be available due to PRARE tracking and where sufficient sea gravity information is available for precise geoid determination. A similar test can be performed in the Mediterranean depending on the availability of precise orbits.

**Assimilation of radar altimeter data into ocean models.** The research into the application of global altimetric sea level measurements in ocean circulation modelling will be continued. Previous studies have indicated the value of altimeter data to verify current models [*e.g., Feron*, 1993*a*] and as supplement to conventional buoy and ship-borne data [*e.g., Samuel*, 1993]. Detailed study of volume and heat transport on a basin-wide scale from conventional current, salinity, and temperature data is practically impossible due to the relatively sparse temporal and spatial sampling of the ocean along ship and buoy tracks and at a restricted number of fixed buoy locations. Extending this data set is very costly.

Here, altimeter data can provide the link between various observations, as it provides a boundary condition for the interpolation and integration of the current information. At the same time the conventional data will provide the down-ward information that the altimeter data itself are not able to provide.

Further exploration, combining ERS data with TOPEX/Poseidon data, is proposed. These studies are intended to demonstrate and exploit the application of radar altimeter data in modelling and understanding of meso-scale oceanic activity, volume, and heat transport, and go beyond the mere monitoring of the processes.

## 5.2 Local tides

The improvement of tide models in coastal areas is of great importance to hazard forecasting, particularly when closing of storm surge barriers are in order (*e.g.*, Oosterscheldekering in the Netherlands). The assimilation of altimeter data in addition to conventional tide gauge data in regional tide models, will be further investigated.

**Tide model improvement around North Sea.** Current investigations on the assimilation of ERS–1 altimeter data in tide models developed for the European Continental Shelf area, as a supplement to conventional tide gauge measurements have demonstrated the applicability of the altimeter data for this purpose. Further investigations will focus on the extension of the altimeter data set, adjustment of tide model parameters for some major tidal components [*Andersen*, 1993; *Mortensen and Andersen*, 1994], storm surge monitoring and forecasting, and the use of an altimeter transponder to provide a well-defined reference for the altimetric profile obtained along the satellite's pass.

The tandem mission of ERS will provide a large amount of altimeter data (ERS–1, ERS–2, and TOPEX/Poseidon) within a relatively short period. This will be a unique opportunity for the tide model improvement, since at that moment the amount of altimeter data start to be significant with respect to the conventional tide gauge data.

**Tides in closed seas.** Using the RA transponder, tide gauge measurements, laser and PRARE tracking, and RA measurements we can verify the consistence of the various measurements. With a transponder on a precisely positioned shore location, co-located with the tide gauge, laser and PRARE station by means of GPS, altimeter data can be used directly as sea level measurements over a limited area, even when the orbit and atmospheric corrections are not accurately known. Hence, altimeter data in coastal areas can be used in addition to tide gauge data to extrapolate this data to open sea.

An additional study will aim at the use of the Mediterranean Sea precise geoid and tidal model for orbit calibration (GEOMED follow-on). Since the geoid and tides in the Mediterranean Sea are accurately modelled, altimeter data can be used as nearly error free tracking data for the orbit. Comparison of the measured and computed height of the satellite above the sea level is a good measure for the orbit and tropospheric correction error.

Part III

# Gravity field mapping and ice sheet monitoring.

## 6 Objectives of the investigation

The objective is to further exploit the application of radar altimeter data for the modelling of the gravity field and the monitoring of the land ice sheets, with emphasis on climate related research and earth resource detection, *i.e.*,

- determination of the global and regional ocean dynamic topography for the extraction of the small scale geoid features, related to the mass distribution in the earth's crust
- development and improvement of techniques to separate the geoid and ocean topography component in the mean sea level *at all wavelengths*
- development and improvement of techniques to invert gravity field quantities into mass distribution of the earth crust
- use of transponders and precise positioning to investigate the reflection of the radar signal on ice under several ice conditions
- develop topography maps for the Greenland and Antarctic ice sheet from altimeter data
- monitor evolution of ice topography (from ERS-1 and ERS-2 data) to identify the mass balance.

To achieve the above goals, the availability of ERS radar altimeter data (fast-delivery, off-line, and wave form products), and selected SAR images is essential. Since the use of altimetry requires accurate sea level determination, precise models and orbits are required.

Altimeter data will be combined with ground-truth (sea gravity, GPS positioning) and derived products will be compared to available ice topography maps, geoid models, and bottom topography.

## 7 Experimental plan

### 7.1 Gravity studies

**Geoid modelling.** Employing radar altimeter data along the ERS-1/2 collinear passes in their respective 35-day repeat cycles and integrating radar altimeter data from several missions (Geosat, TOPEX/Poseidon, ERS-1/2) will provide highly detailed mean sea surface models. In oceanographically quiet areas without significant currents (like closed seas) the mean sea surface equals the geoid, otherwise at least the short-wavelength part of the mean sea surface directly relates to the geoid. Therefore, radar altimeter data from these various missions can be used to improve the accuracy and spatial resolution of the geoid in closed seas and at the short wavelengths. Investigations in the Mediterranean, Baltic Sea, North Sea, and Norwegian Sea will continue, using an ever increasing amount of altimeter data.

**Gravity inversion.** For geodynamical and geological studies, information of the regional gravity field is presented as gravity anomalies rather than geoid heights, since gravity anomalies are exceptionally suited to reflect the sea bottom topography and sub-bottom structures (mainly variations in crust density relating to change of rock composition). The translation of the mean sea level (or geoid) determined along the collinear tracks into gravity anomalies is a rather straightforward process, but the unambiguous inversion of sea bottom topography and sub-bottom structures can not be obtained without extra information [*Arabelos and Tziavos*, 1993].

The modelling of the 'fingerprint' of known regional structures in the gravity field will help to provide the a priori information needed in the gravity inversion to distinguish, qualify, and properly quantify sea bottom and sub-bottom geological features. This information will be very helpful for geodynamical and geological studies, as well as for resource monitoring, and is of major interested to oil companies.

## 7.2 Ice studies

The mapping of the global land ice sheets is an important issue in climatological studies. Not only is the accuracy of contemporary topographic maps of both Greenland and Antarctica very poor, the rate of change of the ice thickness is completely unknown. Since the mass balance of the land ice sheets is an important parameter in the estimation of the sea level rise, monitoring of the ice cover is beneficiary to climate change studies.

**Altimeter - ice interaction.** An important factor in the calibration of ice sheet related altimetry is the penetration depth of the radar signal into the ice. It is expected that the location of the surface of reflection is below the actual ice-air boundary and that the penetration depth varies with the ice characteristics (age, density, temperature). At least four locations on Greenland are to be selected to investigate the penetration depth by comparing the altimetric range from the satellite to the ice surface and to an altimeter transponder located on the ice beneath the satellite's path. Preliminary tests have at least demonstrated the feasibility of such a setup [*Tscherning et al.*, 1993; *Mortensen and Andersen*, 1994], but further investigation are required.

This investigation includes a comparison with SAR imaging to verify the geographical extend of various ice types.

**Greenland and Antarctic ice sheet topography modelling.** The modelling of the Greenland ice sheet topography will be completed, employing increased insight in matters of penetration depth and general calibration of ice-based altimetry. Through monitoring of the ice topography (from ERS-1 and ERS-2 data) the mass balance of the Greenland ice sheet will be identified, [*Keller et al.*, 1993; *Ekholm et al.*, 1993].

Also the ice topography modelling of a 100×100 km area around the Finnish Antarctic base of Aboa will be performed.

Part IV

# Organisation overview

## 8 Data requirements

The investigations described above are all based on the availability of global altimeter data and orbits.

Orbit computation requires SLR and PRARE tracking while for improvements through different types of altimeter data, both fast delivery and refined altimeter data sets are necessary.

The synergic use of altimeter data with infra-red information requires the availability of ATSR sea surface temperature information. Also, for comparison purposes, the availability of preliminary or precise orbits, and off-line geoid and ocean topography models is valuable. Selected SAR images are requested for eddy detection and identifying land ice properties and their evolution. A full list of required ESA products is given in Table 1.

Altimeter data will be processed together with conventional oceanographic measurements (tide gauges, buoys, and ship-born data) to be provided by third parties.

Table 1: Required data products

| Name | Product (and observation frequency and region) |
|---|---|
| ERS-n.ALT.FDC | ALT FD Product |
| ERS-n.ALT.QLOPR | ALT Quick Look Ocean Product |
| ERS-n.ALT.OPR | ALT Ocean Product |
| ERS-n.ALT.LIR | ALT Land Ice Product (All land-ice regions) |
| ERS-n.ALT.SSH | Sea surface height |
| ERS-n.ALT.TOP | Sea surface topography |
| ERS-n.ALT.OGE | Oceanic Geoid Model |
| ERS-n.ATS.SST | ATSR Sea Surface Temperature Map (At weekly intervals, North and South Atlantic Ocean |
| ERS-n.SAR.UILR | Quick-look SAR images (Regions of interest in North and South Atlantic, at weekly intervals) |
| ERS-n.ORB.PRL | Preliminary Orbit |
| ERS-n.ORB.PRC | Precise Orbit |
| ERS-n.ORB.EGM | ERS-n Gravity Model |
| (PRARE MCS) | ERS-2 PRARE Tracking Data |
| (EUROLAS) | ERS-1/2 SLR Tracking Data |

## 9 Management plan

The cooperation between the institutes involved started a few years ago as an informal agreement between Danish, Dutch, and Norwegian groups to combine their efforts in the use of ERS–1 radar altimeter data for oceanographic and geophysical research. Regular meetings have been held in Copenhagen (1989), Delft (1991 and 1993), and Oslo (1994). In addition, an e-mail discussion group was established in 1992. The investigators in the AFRICAR project will meet regularly to coordinate the investigations, exchange results, and plan future activities. The next (pre-launch) meeting is to be held in October 1994.

A steering committee of the three Principal Investigators and their secretaries (Kaare Aksnes, Hilde Erlandsen (ITA); Karel Wakker, Remko Scharroo (SSR&T); Christian Tscherning (KU), Per Knudsen (KMS)) will coordinate the investigations in the framework of each of the partial three proposals and will coordinate data distribution. Remko Scharroo will be responsible for communication. Contact point is Karel Wakker.

Funding of the research will be accomplished through national research councils and sponsoring by industry or external science institutes.

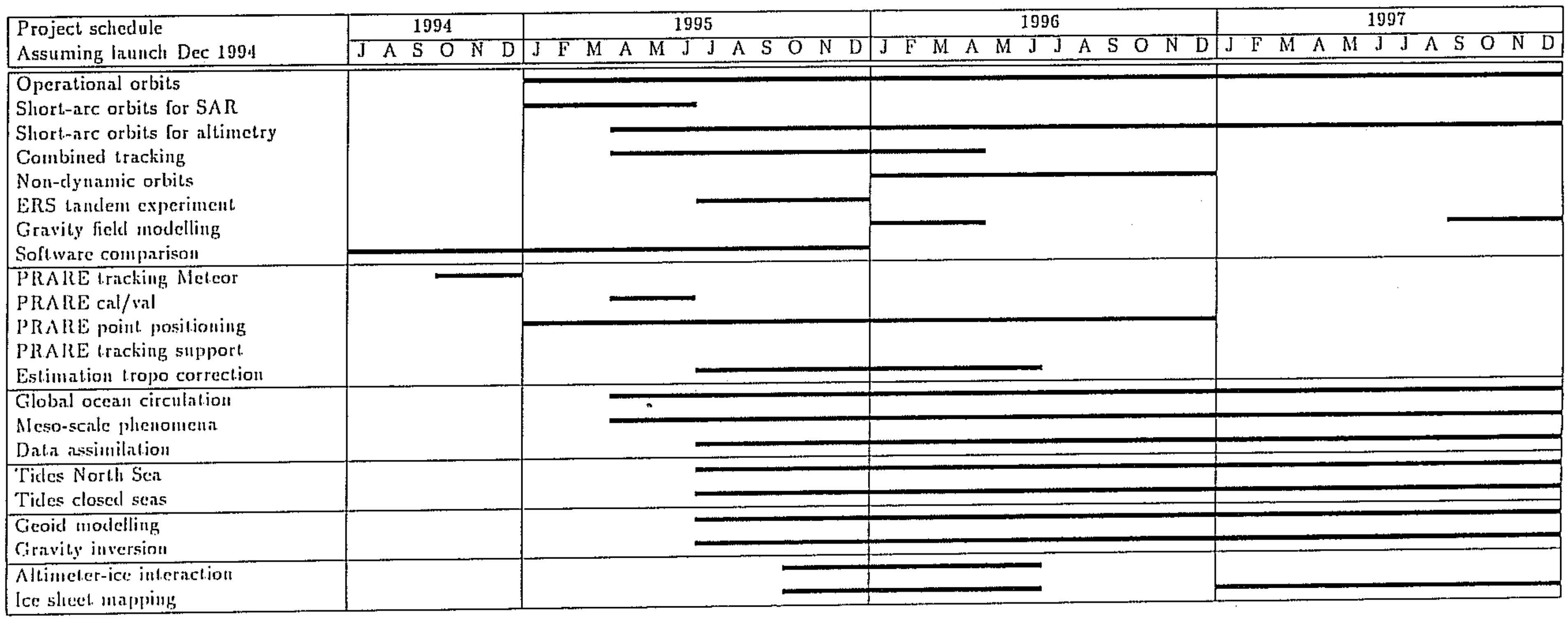


Figure 2: Time schedule of the proposed investigations

## 10 Time schedule

A tentative time schedule, based on a launch of ERS-2 in December 1994 or January 1995 and an active lifetime of the satellite of three years is presented in Figure 2.

## 11 Facilities and equipment

**PRARE.** Five PRARE ground stations are available for ERS-2 tracking, validation of the altimeter and PRARE products and station positioning. These stations are owned by Statens Kartverk (three stations), University of Copenhagen and KMS (one station), and SSR&T (one station).

**Transponders.** Two ultra-mobile radar altimeter transponder, build by RAL, are owned University of Copenhagen and Technical University of Graz, and one of them was successfully operated on ERS-1 in various locations during the last year.

**Radiometer.** The Water Vapour Radiometer (WVR) is designed, constructed and own by the Onsala Space Observatory, Chalmers University of Technology, Sweden.

**GPS receivers.** Four Trimble dual frequency P-code receivers owned by the University of Copenhagen and KMS. Two Turbo Rogues SNR-8000, one fixed Rogue SNR-8 (Kootwijk) and two dual-frequency Trimble 4000-SST owned by DUT. Several receivers owned by SK.

## 12 Personnel

### Principal Investigators

**Prof. Kaare Aksnes:** Born: 1938. Nationality: Norwegian.
Education: M.Sc. 1963 in astronomy, University of Oslo, Norway. Ph.D. 1969 in astronomy, Yale University, USA.
Experience: 1961-64: Observer, Baker-Nunn satellite tracking station at Harestua, Norway. 1965-67: Mathematician, Smithsonian Astrophysical Observatory, USA. 1967-69: Research assistant, Yale University Observatory, USA. 1969-71: Senior Engineer, Jet Propulsion Laboratory, USA. 1971-78: Celestial Mechanician, Harvard-Smithsonian Center for Astrophysics, USA. 1978-88: Scientist and head (1980-88) of Mathemetics Section, Norwegian Defence Research Establishment. Professor II (1980-88) in astrophysics, University of Tromso, Norway. 1989-: Professor in astronomy, University of Oslo, Norway. PI ESA ERS-1 project (N6). More than 75 publications.
Rewards: 1968: NATO Science Fellowship. 1969: Dirk Brouwer Memorial Prize. 1976: Japan Society for Promotion of Science Fellowship. 1978: Asteroid 2067 named Aksnes. 1981: NASA Group Achievement Award.

**Prof. Carl Christian Tscherning:** Born: 1942. Nationality: Danish.
Education: M.Sc. 1970 in geodesy, University of Copenhagen, Denmark. Experience: 1970-1988: employed at the Geodetic Institute of Denmark, 1975-1988: deputy manager computer section, 1988: State Geodesist. 1989-: Professor of geodesy University of Copenhagen and director of Geophysical Department. More than 125 publications. PI ESA ERS-1 project (DK2). Co-I on several ESA, EU and NATO projects.
Rewards: 1976: W. A. Heiskanen Senior Award (Ohio State University). 1992: Fellow AGU 1992.

**Prof. Karel Wakker:** Born: 1944. Nationality: Dutch.
Education: M.Sc. 1967 Faculty of Aerospace Engineering, Delft University of Technology (DUT), The Netherlands. Experience: 1967-: Research scientist and lector. 1975-: Head of Section Space Research and Technology (DUT). 1985-: Full professor in space research and technology DUT. 1993-: Rector Magnificus of DUT. More than 100 publications. PI ESA ERS-1 project (NL11), Co-I and PI on several ESA and NASA projects.
Rewards: Two NASA Group Achievement Awards (Crustal Dynamics and TOPEX/Poseidon).

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European Space Agency
ERS Announcement of Opportunity
c/o Dr. C. J. Readings (OEE/VR)
Head of the Earth Sciences Division
The European Space Research and Technology Centre (ESTEC)
P.O. Box 299
2200 AG Noordwijk, The Netherlands

| Your reference and date | Our reference | Office telephone | Date |
|---|---|---|---|
| | | +31 1578 5176 | 11 March 1994 |

Subject: Proposal in response to the ERS Announcement of Opportunity

Sub-division

Dear Dr. Readings,

Please find enclosed fifteen copies of the proposal drawn up in the framework of the AFRICAR project in response to the ERS Announcement of Opportunity.

The aim of the project is to investigate and exploit the use of ERS radar altimeter data and ancillary information (both provided by the ERS satellites and other equipment) for monitoring the climate and earth resources, through the mapping and monitoring of the topography of oceans and land ice; and, in support of this effort, provide precisely computed ERS orbits and PRARE station positions. This encompasses several investigations in the fields of orbit determination, geodesy, geophysics, oceanography, and glaciology.

The AFRICAR project (Altimetry For Research In Climate And Resources) is a joint effort of a number of European and United States' research institutes: University of Copenhagen, Kort- og Matrikelstyrelsen (Denmark), University of Oslo, Norwegian Defence Research Establishment, Statens Kartverk, Nansen Environmental and Remote Sensing Centre, Statoil's Research Centre (Norway), Finnish Geodetic Institute (Finland), Chalmers University of Technology (Sweden), Delft University of Technology, University of Utrecht (The Netherlands), University of Thessaloniki (Greece), Politecnico di Milano (Italy), Universidad Complutense de Madrid (Spain), Technical University at Graz (Austria), Technical University of Munich (Germany), Ohio State University, Defence Mapping Agency (USA).

The proposal enclosed provides detailed information on the experiments to be performed in the framework of the AFRICAR project, the time schedule of activities, and on the investigators involved in the AFRICAR project.

Also on behalf of the other two PI's, Prof. K. Aksnes (Univ. of Oslo) and Prof. C. C. Tscherning (Univ. of Copenhagen),

Yours sincerely,

Prof. K. F. Wakker (PI)

For your archives

encl: AFRICAR proposal in response to the ERS AO

When responding please quote our reference.

TU Delft

Delft University of Technology

Faculty of Aerospace Engineering

14 March 1994

Dear Chistian

I've mailed out the fifteen copies of the ERS proposal today by DHL, so it will be perfectly on time. Note we have been able to stick to the 2 + 20 pages limit.

We can be proud of such a fine combined effort! But now we have to make our promisses true.

With sunny, springish greetings,

Remko

PS: Can you take care of distributing copies to those who may not have received the PS version by e-mail in the Danish + Geomod communities?

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**Remko Scharroo:** M.Sc. 1989 Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands. Research associate. Preparing Ph.D. Research fields: orbit determination, altimetry, altimeter calibration.

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**Frank T. Tveter:** Ph.D. student at the Institute of Theoretical Astrophysics, University of Oslo, Norway. Research field: Orbit determination.

**Martin Vermeer:** PhD. 1985 University of Helsinki, Finland. Professor and head of the Department of Geodesy, Finnish Geodetic Institute. Research fields: Geoid determination, geopotential inversion, sea level studies, GPS interferometry, geodynamics.

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