
Radar Altimeter Database System (RADS): Towards a generic multi-satellite altimeter database system

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Executive Summary

Satellite altimetry is a technique whereby the global sea level is continuously monitored from space by a number of downward looking microwave radar systems. The measurements taken by the altimeter enable the height of the satellite over the surface, and the significant height of wind waves in a footprint with a diameter of approximately 5 to 10 kilometers to be derived. In addition it is possible to track over ice and land surfaces provided that they are sufficiently flat for the instrument.

The first satellite altimeter experiment ran on Skylab in the beginning of the seventies. The Skylab altimeter recorded a couple of tracks and revealed the existence of trenches in the marine geoid. GEOS-3 was the first dedicated altimeter mission in 1975 which allowed radar images of the sea level in the vicinity of ground tracking stations. It was soon followed up by the more accurate SEASAT mission in 1978 which provided the first real global radar image of the oceans thanks to (at that time) improved autonomous in-orbit data compression techniques, enabled by sequential trackers and the ability to store data on magnetic tape within the satellite allowing it to be down loaded after over flight over a ground terminal.

All newer missions were always significantly more accurate than previous ones. The GEOSAT altimeter, 1985-1989, is comparable in quality to modern altimeter missions such as ERS-2 and TOPEX/Poseidon whereby the global sea level variations are recorded with a typical accuracy of about 3 cm rms. Yet the systematic errors related to orbit determination and contamination of the GEOSAT data by ionospheric and tropospheric effects make it a different type of instrument than the modern altimeter projects.

Much can be said about the altimeter system accuracy, whether we are dealing with random or systematic errors and the origin of these errors. Dedicated filtering techniques allow elimination of many error sources and the 3 cm noise level can even be obtained from the historic altimeter data sets. A fact is that the technique itself is invaluable and one of its kind. After all it offers not only scientists but also the general public a unique capability to monitor height variations of all water and ice-like surfaces on our planet. Geophysical research is much helped by satellite altimetry, many examples of applications can be found in oceanography, meteorology, glaciology and geodesy which all have strongly benefited, or in some cases have made giant leaps forward as a result of satellite altimetry. There are also examples of operational applications of satellite altimetry, whereby activities such as towing, dredging, navigation and exploration at sea can, in principle, be helped by products that have benefited from satellite altimetry.

The long time span of satellite altimetry whereby measurements and corrections are recorded at a typical rate of about eighty bytes per second causes a problem of data storage and maintenance. This is the point where the contents of this

report come in the picture. It is all about the Radar Altimeter Database System (RADS) project, which purpose it is to maintain an on-line collection of all satellite altimeter measurements and corrections back to the GEOSAT mission.

Our initial expectations are to apply such a database for scientific research within the DEOS institute at the Delft University of Technology. The database itself is somehow an organized collection of 80 byte records. Each record refers to an altimeter measurement taken at a rate of 1 per second. The records themselves are referred to as Geophysical Data Records (GDRs). Our strategy is to store the complete GDR structure on-line instead of concentrating on a shortened version that for instance merely contains corrected sea level anomalies as an end product. We realize that this choice leads to a large allocation of disk space, however the benefit is that modifications to isolated fields on the GDRs, which concern newer versions of corrections to the measurements or auxiliary models, can be simply applied. This concept is applied to all satellite altimeters that have operated since GEOSAT including ERS-1, ERS-2, TOPEX and Poseidon. At the moment of writing the size of the database is about 30 Gb in the form of more than 200 thousand pass files whereby each pass consists of approximately 2 thousand altimeter measurements.

For daily use of the database higher level products come into the picture. In this report several of such products are mentioned. Noteworthy in the case of RADS are improved trajectory descriptions of the ERS-1 and ERS-2 satellites. This product is regularly posted on the Internet, see <http://www.deos.tudelft.nl/ers/precorbbs>. Experience over the years has shown that this product serves a large international community with applications beyond the field of satellite altimetry. Examples are for instance the use of precise orbits within interferometric synthetic aperture radar applications, and near real time ocean monitoring with satellite altimetry. The precise orbit calculation itself is a daily coordinated effort between the TU Delft and NOAA/NGS over the Internet. The aim is to provide the ERS altimeter community with precise trajectories compatible with those of the TOPEX/Poseidon ocean monitoring system.

In addition there are other higher level products derived from the core database. Noteworthy are sea level anomaly maps and movies, time longitude diagrams, tide models, and other essential updates necessary for some altimeter systems. Several examples are continuously updated at web pages and anonymous FTP servers within DEOS, see for instance <http://www.deos.tudelft.nl/altim>. Another entry point is the NEONET topical node at <http://pocus.geo.tudelft.nl:8080/> which contains various descriptions of data within RADS. The latter web address is the result of the coordinated effort between DEOS and NLR to establish a meta data exchange protocol within NEONET. The NEONET program contains a core facility (managed by the National Aerospace Laboratory, NLR) which is a focal point of the meta data received from the application facilities such as RADS, among several others.

In turn the RADS project is surrounded by a user community in the Netherlands. This user group was established during a user consolidation phase which ran in the summer of 1997. In a response to the RADS initiative DEOS was involved in several actions to keep the users involved in the project. The actions concerned individual meetings with the user groups and a questionnaire to the users which formed the basis for writing a user requirements document.

The RADS project was funded by the Netherlands Remote Sensing Board (BCRS) and the Space Research Organization in the Netherlands (SRON) and

started in December 1997. This report documents the way the base level database was set up and derived higher level products are defined including validation procedures of altimeter data. The latter topic is mostly concerned with the way ERS-1 and ERS-2 data are included in the generic database with an accuracy comparable to TOPEX/Poseidon. The interaction with the users and the involvement of the RADS project within the larger NEONET program is also described. The perspective of continuing RADS in view of newer satellite missions, such as JASON, ENVISAT and NPOESS are mentioned in the outlook section.

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Chapter 1

Introduction

The purpose of this document is to report the activities that resulted in a Radar Altimeter Database System, also known as RADS, that is presently the most complete and validated source of online geophysical data records for all altimeter systems available within the Delft institute for Earth Oriented Space research (DEOS). In the summer of 1997 the RADS project started with a contribution of DEOS to a user consolidation phase within the NEONET program. It resulted in the user consolidation report [Heppener *et al.*, 1997]. From this point on it was decided to submit a project proposal, listed in appendix A, which was honored in the autumn of 1997. The RADS project started on December 1, 1997 and ran until April 1, 2000 and was sponsored by the Netherlands Remote Sensing Board (BCRS) and the Space Research Organization Netherlands (SRON) in the framework of the GO-2 program for remote sensing user support in the Netherlands. The RADS project is formally labeled “application facility” (AF) within a larger project called NEONET which aims for the establishment of a national data infrastructure.

The original project proposal contains three work packages. Work package 1 is the management module which is a mandatory activity for all externally financed projects within the Delft University of Technology; work package 2 is all about database development; and work package 3 is concerned with communication to the RADS application facility users, other partners in NEONET and quality control of the developed products.

All activities in the RADS project were reported in steering group (in Dutch: stuurgroep) meetings convened by the BCRS and SRON, and in financial reports directly to the BCRS and SRON. The initial frequency of these meetings was set at a 3 monthly interval, later on in the project it was temporarily increased to once every 6 weeks. There were additional meetings with BCRS representatives and other BCRS and SRON related requests concerned with project presentations at the Ministry of Transport, Public Works, and Water Management (in Dutch: Rijkswaterstaat). In addition there were contributions from DEOS representatives at NEONET workshops organized by the National Aerospace Laboratory (NLR) and presentations at international congresses convened by the American Geophysical Union (AGU) the European Geophysical Society (EGS) and the Centre Nationale d’Etudes Spatiales (CNES).

This report is about the RADS project and the results obtained. Chapter 2 gives some insights into the way the project was set up and how we kept the users involved. In the data processing Chapter 3 we describe in greater detail the base and higher level products developed within the framework of RADS. Chapter 4 is about validation of the developed products and quality control. This Chapter

mostly describes the status of the ERS-1/2 altimeter systems. In Chapter 5 we discuss the communication part of the project. In Chapter 6 concluding remarks are made and perspectives of continuing the RADS project are highlighted.

Project proposal

2.1 Initiative

The original proposal can be found in appendix A. Still, it is worthwhile to highlight the expectations that we had (and still have) with regard to the RADS project. In itself the RADS concept is relatively straightforward. The goal is to build and maintain a research facility in the form of a publicly accessible database containing satellite altimeter data. This database should have a uniform character, namely that all altimeter systems dating back to GEOSAT should be treated in the same way. Certain key words such as "users", "publicly accessible", "satellite altimeter data", "uniform character" and "treated in the same way" need a better description. The purpose of this Chapter is to highlight these aspects in view of the submitted project proposal.

2.2 Altimeter data

We start with the phrase "satellite altimeter data". This means a downward looking satellite altimeter system operating on a microwave frequency such as the Ku or C band probing the face of the oceans. The altitude of the satellite over the ocean, significant wave height and strength of reflection are measured. Additional information, usually modeled in some way, is added as extra fields within the data records in order to be able to map height variations of the sea level in a footprint illuminated by the radar. Several of such systems operate today, namely the ERS-2 system of the European Space Agency (ESA), and the TOPEX/Poseidon system which is a cooperation between the US and French space agencies NASA and CNES. Somewhat older systems include ERS-1 and the US Navy satellite GEOSAT. Systems that operated before 1985, including SEASAT and GEOS-3, fall in the same category but are of less important due to relatively large instrument noise and other flaws. A number of new systems such as Jason-1 and Envisat-1 are planned for the near future. Altimetry itself is one of the success stories of remote sensing technology, a full discussion of all systems is not appropriate in this document, it can be found in literature such as [Cheney *et al.*, 1994].

Raw altimeter data that is used for most research purposes comes in the form of Geophysical Data Records (GDRs) which are provided as fixed length records containing binary integer data. The GDR records are normally generated every time the altimeter performs a measurement, whereby it should be mentioned that the sampling frequency is 10 or 20 measurements per second, depending on the

system. Normally only 1 measurement per second is used because there is probably little extra information in the 10 or 20 Hz data compared to 1 Hz data. Averaging the data over 1 Hz bins reduces the measurement noise. For the RADS project we came to the conclusion that all data can be compressed into 80 bytes, which is the base level data format described in appendix B.

Two other essential phrases in the original RADS concept are concerned with the words “uniform character” and “treated in the same way”. In our case “uniform character” means that a significant amount of time was spent to verify that the base level database records do contain all essential information to form a “generic radar altimeter database system”. Part of this problem is a mapping operation. Organizations that produce geophysical data records for individual altimeter systems such as AVISO/CLS contracted by CNES for TOPEX/Poseidon; ESA’s processing and archiving facilities (the PAFs) for ERS-1 and ERS-2; and NOAA for GEOSAT, provide GDRs which differ on various points. The source data need to be re-mapped into the generic format described in appendix B. More important is that, besides the formatting of the data, whenever possible unified algorithms should be used to build the base level database. Various issues related to both aspects are also described in appendix B.

It was mentioned before that we have chosen to compress all measurement data into 80 byte records which are generated at a rate of once per second. This results in 4.6 Mb of data per satellite per day, assuming that 70 percent of the data is recorded over ocean and ice-like surfaces. For a decade recorded by one altimeter system it means that approximately 16 Gb of hard disk storage is required.

Before RADS the storage problem was circumvented by focusing research on limited collections of altimeter data heterogeneously distributed within the individual groups forming DEOS. The other option was to concentrate on higher level data products such as the Pathfinder products generated by NASA/GSFC.¹

2.3 Required resources

One of the first activities within DEOS was to assess the feasibility of the RADS project. An internal study with regard to the estimated computer resources for all activities mentioned in the proposal was finished in October 1997. It was obvious that the existing infrastructure at both faculties forming DEOS was not sufficient. The bottlenecks were the availability of a dedicated file server capable of handling the voluminous radar altimeter database system. This facility was established in November 1997, since then several upgrades have been realized to keep the RADS server up to date with the current standards.

2.4 Users

Up to now a number of keywords in the original RADS initiative have been explained, the remaining two phrases “users” and “publicly accessible” now need further attention.

One of the conditions to receive project funding for the RADS project was to evaluate a common market for an altimeter database in the Netherlands. DEOS

¹DEOS participated in the making of these products. The ocean and load tide models on the Pathfinder database, see <http://neptune.gsfc.nasa.gov/ocean.html>, are the result of a cooperation between the Goddard Space Flight Center and the Delft University of Technology.

itself has been successfully involved in altimetry for many years and is therefore by definition a user. Extramural cooperation with users of the NEONET/RADS application facility within the Netherlands required further attention.

The first discussion within the framework of extramural cooperation with RADS users started with a user consolidation phase which ran prior to the approval of the RADS project. The structure of the application facility users group is mentioned in the project proposal. During the beginning of the project we got actively involved with users in separate meetings. Later during the project, near the completion of the base level database, we documented a summary of user remarks and wishes in the “user requirements document”, see also [Naeije *et al.*, 2000]. The bottom line is that a common national market does exist. It focuses on applied research and operations dealing with sea level.

The phrase “publicly accessible” is another concern. Besides technological constraints limiting the transfer of large volumes of data over public networks there is the issue of data ownership. Not all base level data can be provided directly to others without violation of signed license agreements. This problem applies in particular to the ERS data collection within RADS. What could be done is to provide value added data, in which case legal restrictions no longer hold. Higher level data products, level 1 and onwards, can be distributed more easily, though still under certain conditions, for instance by acknowledging the provider.

Whether it is essential to provide the base level data to others remains under investigation. Within the Netherlands the RADS users did not explicitly mention in Naeije *et al.* [2000] that there was a need for receiving such data. On an international level several requests can be expected.

2.4.1 User consolidation phase

Before the approval of the RADS project, DEOS was involved in a user consolidation phase in which part of the above mentioned problem was discussed. The actual user consolidation phase involved the entire NEONET program and all submitted application facility proposals. The findings of the users consolidation phase are not discussed here, for this purpose there is a separate user consolidation report, see also [Heppener *et al.*, 1997].

2.4.2 RADS and NEONET

Essential in the discussion of RADS in relation to NEONET is the difference between what is called Core Facility (CF) and Application Facilities (AFs). The RADS proposal was accepted and labeled as an application facility. The latter means that it was envisaged to exchange, yet to be specified, information with a CF. The CF is in turn maintained by the NLR and is part of INFEO which is concerned with an European data network for Earth observation data. The INFEO network is funded through the European CEO project and is part of the ECs fifth framework program.

The issue of information exchange often runs into legal problems because of the earlier mentioned data ownership issues which, for instance, prevent that DEOS provides base level data to arbitrary users. Within the NEONET project it was agreed that meta data, a term introduced by the NLR referring to descriptive information with regard to data products within an application facility, can be exchanged.

The problem of exchanging meta data for Earth observation data has an analogy with the exchange of library cards for which there is an internationally accepted standard in the form of a CIP protocol. Within NEONET the meta data standards were implemented as a XML protocol. (XML stands for eXtensible Markup Language meant for documents containing structured information, it is different from HTML in the sense that it provides arbitrary structure). In January 2000 dedicated software tools for meta data exchange developed by the NLR were delivered and installed on the RADS topical node server. Our findings with this method of meta data exchange within NEONET are discussed in Chapter 5.

2.5 Experience in satellite altimetry

In order to get the RADS proposal into a form that stood a reasonable chance of being selected within the GO-2 programme for user support in the Netherlands the subject of experience on the field of database building and management for altimeter applications had to be addressed. DEOS is a formalized cooperation between the Astrodynamics and Satellite Systems chair of the Faculty of Aerospace Engineering and the Physical Geometrical and Space Geodesy group at the department of Geodetic Engineering, both at the Delft University of Technology. There is a common research program in the area of Earth oriented space research whereby several scientists and students are involved in projects related to applications of satellite altimetry. Numerous articles were published in scientific journals and dissertations appeared on the subject of satellite altimetry. DEOS committed itself to cooperation with various organizations within the Netherlands. Noteworthy are the relations with the IMAU institute at the University of Utrecht, KNMI, NIOZ, Delft Hydraulics, RIKZ at Rijkswaterstaat and ARGOSS which were suggested as members for a user group of the RADS application facility, see appendix A.

2.6 Users in the RADS project proposal

The following remarks can be made with regard to the RADS users group:

- In the beginning of the project a commitment of the RADS users mentioned in the project proposal was required. This resulted in positive reactions from all involved groups, confirmed by written responses. The users presented their interest in RADS in a meeting organized in Utrecht in June 1998.
- RIKZ was forced to change their position in the RADS project, the response of other groups was positive.
- Contacts with Delft Hydraulics, ARGOSS and the KNMI resulted in new projects such as the SAT2SEA, MBISH, GWSAT, and an El Niño monitoring proposal, in which DEOS is currently involved.
- All AF groups in the project proposal are selected within the Netherlands. International contacts in the field of satellite altimeter applications are in a different category and are not mentioned as such in this report.

Data processing

3.1 Introduction

Data processing concerns all steps of transforming source data obtained from the providers into a base level database which is described in section 3.2. A stringent requirement is that the base level database is complete, in the sense that the original GDR source information is properly presented. Moreover its format and contents are as uniform as possible covering all known altimeter systems back to GEOSAT.

In the beginning of the project the use of the NASA Pathfinder products which are distributed on one CD-ROM per altimeter system was considered, see also <http://neptune.gsfc.nasa.gov/oceans.html>. The Pathfinder product does contain positions of the altimeter footprint and corrected sea level anomalies (SLAs) at this point including some editing information. In itself this is a useful product for many applications. Unfortunately it does not allow one to retrace all individual corrections that have been applied to the SLAs. With the RADS base level product one still has the possibility of replacing or isolating certain model corrections. This is an important research area within DEOS and a typical desired property of a database system to be used in a scientific environment.

Other properties of the base level database system are concerned with fast on-line access without having to reread archived data from external media. Moreover contemporary database users demand that the data is somehow validated and tested and that the most obvious sources of errors are documented. The user requirements document [Naeije *et al.*, 2000] provides further details regarding the users wishes. Yet it should be remarked that we started off with the base level specification before we officially consulted the RADS users, thereby relying on our own experience in the field of satellite altimetry and on our national and international contacts.

3.2 The base level database

3.2.1 Mapping the altimeter equation

The base level database is the core product of the RADS project and contains the 1 Hz geophysical data records which consists of measurements, corrections and auxiliary data. This database represents the altimeter observation equation such

as mentioned in *Naeije et al.* [1996]:

$$h_{dyn} = (H_o - H_a) - \sum_i e_i - H_g \quad (3.1)$$

where h_{dyn} is the sea level anomaly signal we are usually interested in, H_o is the orbital height with respect to the reference ellipsoid, H_a is the observed altimeter range, e_i are instrumental, environmental and geophysical corrections, H_g is the geoid. In the RADS project we mapped all essential variables in the altimeter equation onto a 80 byte record, more details on this procedure are explained in appendix B.

3.2.2 Pass files

The base level database typically allocates 4.6 Mb per satellite per day. The data are stored in separate pass files which are kept in a hierarchical directory structure. In the RADS project, passes (also called tracks) are defined as the data stream that start at one extreme inclination latitude, 66°N or 66°S for TOPEX/Poseidon, 72°N or 72°S for GEOSAT and 82°N or 82°S for ERS-1/2, ending at the opposite. Inside passes a time index relative to the equator transition point is defined. The pass files themselves are designed such that they can be read from a variety of programming environments such as C, C++, Fortran 77 and Fortran 90 and on multiple operating systems.

For a generic altimeter system each pass typically consists of 2000 measurements. Taken at a rate of 1 Hz they are roughly 160 Kb each whereby altimeter land reflections are not stored. In the database we also record log files for each pass that hold bookkeeping information such as the name and version of the program that modified the pass file contents and the date on which the file was made. The strategy is that each pass file can be retraced to its source which in practice means that all steps (read programs) and input are known.

For TOPEX/Poseidon the pass file generation is a two-step procedure, the **gdr2raw** program captures all data from the AVISO/CLS CD-ROMs and a **patch** program applies a variety of modifications to the captured data. For ERS-1 and ERS-2 it turned out that one data capture program and 4 patch programs are required. For GEOSAT it is a one-step procedure, since most of our specifications agree with those of the provider of the data, NOAA. Appendix B contains the base level database specification and shows the problems we encountered for different altimeter systems.

3.2.3 Directory structure

It is obvious that one pass only represents a relatively short part of the total mission duration and that several thousand of these pass files need to be recorded, see also table 3.1. We deliberately avoided any storage structure where multiple passes are stored in a bigger file as is done in the Goddard Space Flight Center (GSFC) altimeter database system. This particular choice is probably driven by the heritage of older operating systems that were not necessarily efficient in storing small files, although this problem does not play a role with contemporary Unix file systems.

The directory structure for storing the pass files is in our case hierarchically organized. Although the details are explained in appendix B we also want to explain some basic properties here. The top level entry point in the pass file struc-

System	# of passes	# of phases	Start date	Stop date
GEOSAT	45021	2	31-Mar-1985	29-Dec-1989
ERS-1	47869	7	1-Aug-1991	2-Jun-1996
TOPEX	61727	1	25-Sep-1992	21-Feb-2000
Poseidon	6323	1	1-Oct-1992	13-Dec-1999
ERS-2	51857	1	15-May-1995	13-Jul-2000

Table 3.1 An overview of the data available within RADS is presented in chronological order. The column labelled "# of passes" refers to the number of realized pass files, the column "# of phases" refers to the number of available mission phases, the start and stop dates reflect the time range spanned by each altimeter system.

ture is the name of the satellite, it is followed by the mission phase, and finally a pass number. The lowest level directories contain pass files for all cycles that occurred within a mission phase. In this discussion mission phases are defined by the satellite ground track sampling properties. The definition of pass numbers depends on the mission phase and is specific for each altimeter system and in particular whether the satellite is repeating or non-repeating for a specific mission phase.

For non-repeating ground tracks the pass numbers continuously increment throughout the mission phase. In the RADS database this only happened three times, namely GEOSAT's geodetic mapping mode and ERS-1 phases E and F (168 day repeating ground tracks). For non-repeating mission phases there is by definition only one cycle, which stems from the fact that ground tracks are not repetitively flown over. These parts of the base level database are particularly useful for studying, for instance, the fine structures of the marine gravity field [Sandwell and McAdoo, 1988], [Wisse *et al.*, 1994].

All other data within RADS is for altimeter systems with repeating ground tracks in which case the pass numbers start at 1 in a given cycle. For altimeter systems in RADS the following repeating ground track configurations exist:

- GEOSAT had a 17-day repeat cycle which consists of 244 orbits (or 488 passes). The 17 day repeat cycle mapping occurred between August 1986 until the end of 1989.
- ERS-1 had eight mission phases with three different repeat cycles lasting 3, 35 and 168 days. ERS-1 mission phase G is the 35 day mapping mode where 501 orbits, or 1002 passes were completed in one cycle. ERS-1 operated until very recently when its attitude control system failed.
- ERS-2 has only one mission phase which over flies the same ground track as the 35 day repeat cycle of ERS-1. The fact that ERS-1 and ERS-2 share a tandem mode, whereby the altimeter footprint ground track positions are separated by one day, is unique. This situation was in affect during the first year of the ERS-2 mission.
- Finally TOPEX/Poseidon has only one mission phase where 127 orbits or 254 passes are completed in a 10 day repeat cycle.

More details on the data within the RADS base level database can be found in appendix B and Naeije *et al.* [2000]. Some database statistics are presented in table 3.1.

3.3 Level 1 products

A significant amount of work within the RADS project went into the definition of the level 0 product. It is the base level product from which higher level products can be derived. Level 1 is the first logical step, it is concerned with directly derived results from the base level product much in the way, for instance, the NASA Pathfinder products and similar products from other organizations are defined.

The level 1 products themselves are subdivided into several categories. They evolved from the use of altimeter data over the years, and can be found in applications as reported in the user requirements document. The remainder of this section is concerned with a summary of the individual products on level 1 without specific technical details on how they are realized in practice. Instead the level 1 and higher products are delivered in such a way that they are self explanatory.

3.3.1 Data dumps along a measured altimeter track, level 1a

When working with the base level database a question often received is whether a procedure exists to obtain a fully corrected variable. A standard procedure does not exist and a tool is required to trace the information flow starting at the original database to the desired answer. There is not much fantasy required for this product, a straightforward dump of the data stored in the database is often all that is needed.

In our case this product is labeled as level 1a. It is often concerned with along track altimeter height observations of the sea level which are corrected for all known effects. The purpose of such a product is often to be able map sea level anomalies which represent phenomena such as El Niño and western boundary current variability, but not the response of the sea level to atmospheric pressure changes or tidal forcing. The distinction between what is well-known and what is not, is often related to the research goals of the specific user.

Examples of an along track altimeter data dump are shown in figure 3.1 and in figure 3.2. Figures like 3.1 and 3.2 can be obtained directly from <http://pocus.geo.tudelft.nl/~schrama/Public/RADS-server/gtb.html> where the user is presented with a form on which a track and cycle number including and the variable to plot can be requested.

3.3.2 Collinear along track interpolation, level 1b

Strictly speaking a level 1a product is just an along track listing of altimeter data at epochs as they appear in the base level database. The aspect of time-wise interpolation between different cycles is not considered in this approach, instead the problem is that the user needs to gather data at coinciding along track positions for different cycles. The easiest step is to use the core database itself, product 1b is one abstraction level further than 1a. In this case, care is taken to interpolate corrected sea level anomalies at exact one second intervals relative to the equator transition time. During the RADS project several types of collinear files were developed, examples can be found on the RADS project anonymous FTP server which can be found on the web at <ftp://hocus.geo.tudelft.nl>.

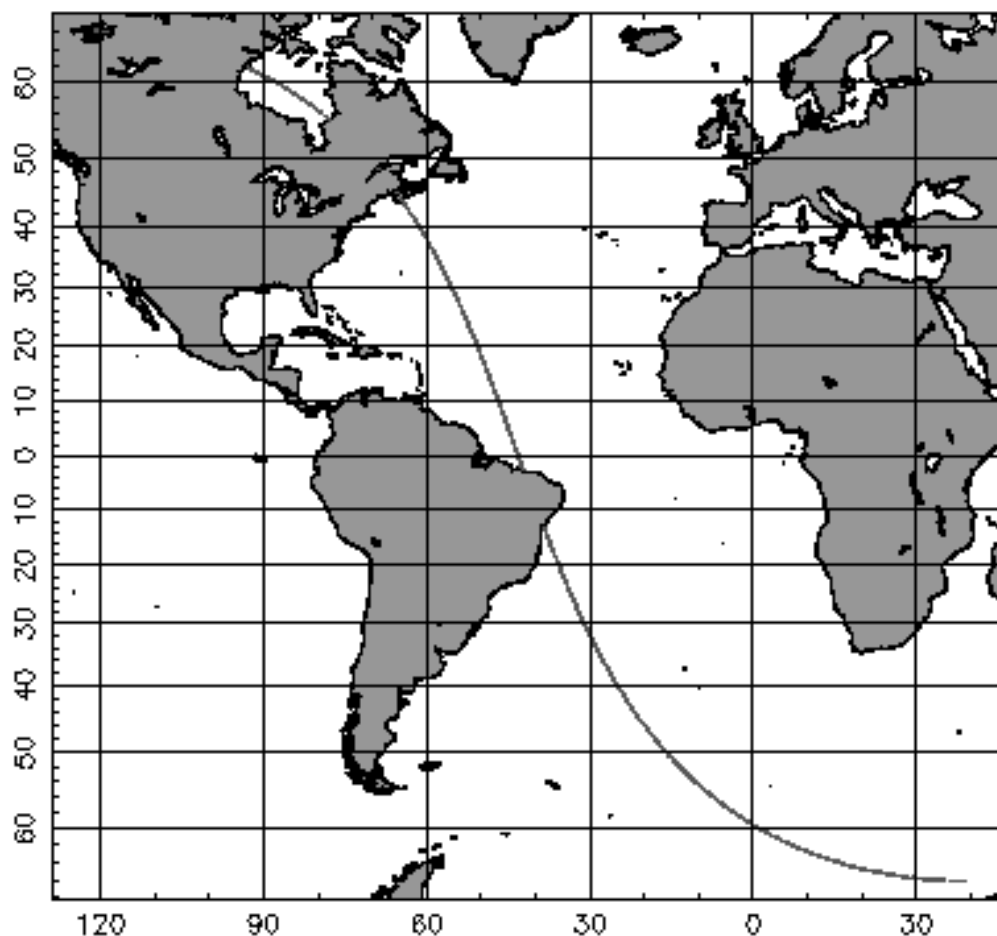


Figure 3.1 Part of the ground track for descending pass 100 cycle 100 by TOPEX/Poseidon.

3.3.3 Crossover data, level 1c

The use of crossover data is related to research activities which go back to the use of the first altimeter data. Crossover data is formed at the geographical positions where ground tracks intersect and can appear between any type of combination of ascending and descending ground tracks. This can be the case for one or more orbiting altimeter systems and for all tracks that appear in the RADS database. Crossover data adds an extra possibility to validate altimeter system information. The benefits of using crossover data are summarized as follows:

- Common errors or signals contained in either track forming the crossover disappear in the difference computed at the crossover. For example: errors in a geoid model are invisible in crossover differences referring to sea level anomalies. It is a convenient property when long wavelength orbit errors are to be estimated from altimeter data.
- Data from independent altimeter systems can be compared at crossover locations. Thereby there is a possibility to monitor SWH's etc.
- From a time-scale point of view, crossovers allow one to sample the data in a fashion that differs from the collinear sampling scheme which helps for instance in the extraction of tidal signals.

Drawbacks of crossover data are:

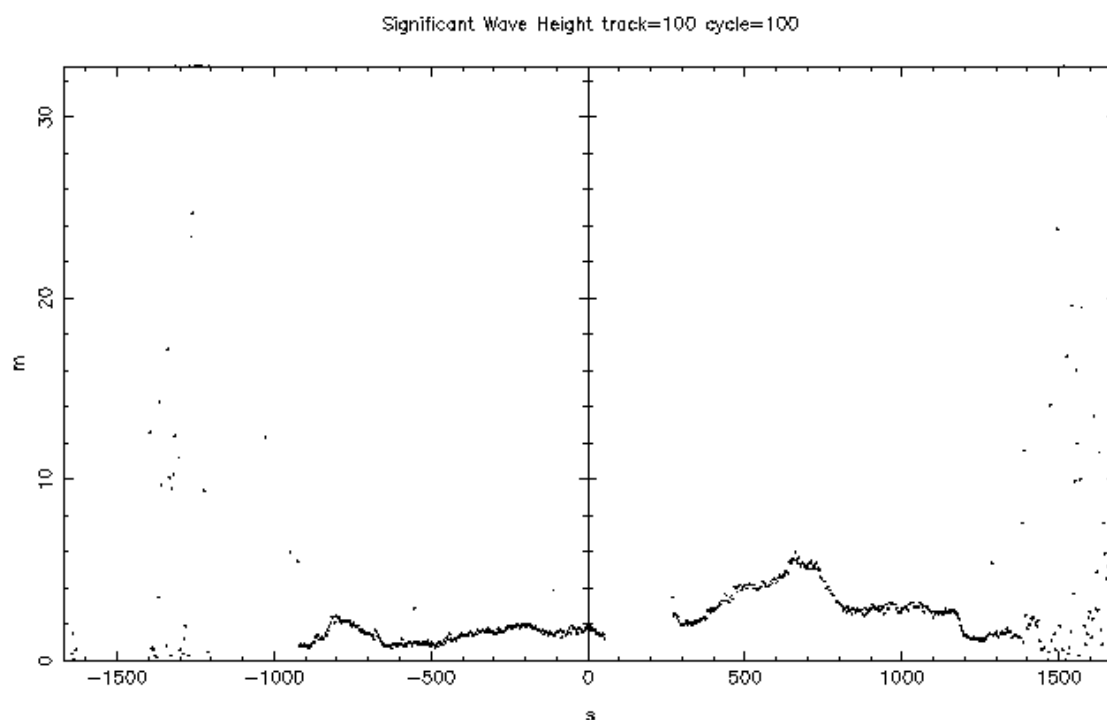


Figure 3.2 The significant wave height variable for the Ku band TOPEX altimeter as recorded in pass 100 within cycle 100.

- The normal matrices derived from certain least squares based estimation schemes are known to be rank deficient. This discussion is related to the existence of a geographically correlated orbit errors, [Schrama, 1989].
- The amount of crossover locations grows quadratically as time increases.

Within the RADS project tools were developed to compute crossover data for the general case where the data type is formed within two arbitrary cycles of the any altimeter system. The software tool developed for this purpose is called **xgen**. To simplify the generation of stacked crossover data for a satellite in a repeating ground track a separate tool **xclgen** was developed.

The GEOSAT data in RADS is still affected by a relatively large radial orbit error (10-15 cm), see <http://neptune.gsfc.nasa.gov/ocean.html>. To minimize this type of error crossover difference minimization algorithms can be adopted. However, it should be mentioned that this minimization problem relies on additional constraint equations to fix a datum problem.

3.4 Geographical interpolation, level 2

Sea level anomalies can also be interpolated directly in time and place by means of Gaussian or boxcar interpolation functions as described in *Nerem et al.* [1994]. This is probably the most convenient way of presenting altimeter observed sea level changes to users and this product is called level 2. At the RADS web site several of such products can be found in some convenient image form or even in movie format. It is interesting to recall the witnessing, by both ERS-2 and TOPEX/Poseidon, of the 1997-1998 El Niño phenomenon, which was one of the largest in the last century. Figure 3.3 shows the four characteristic phases that

were observed by TOPEX/Poseidon.

3.5 Level 3 products

3.5.1 Tide models, level 3a

In level 3a we define ocean and load tide models improved by satellite altimetry. These models are provided in the form of certain tidal constants on geographical grids (Figure 3.4). The subject of tidal modeling has seen some dramatical changes since the launch of TOPEX/Poseidon. A crucial point is the aliasing effect of tidal frequencies with respect to the repeat period. The method of retrieving the ocean tides from altimetry works best for an altimeter system that is not launched in a sun-synchronous orbit because of the in-phase sampling of solar tides. GEOSAT has shown the first improvements in the ocean tides, as reported by [Cartwright and Ray, 1990]. The most spectacular improvements are obtained by a direct analysis of T/P altimeter data combined with some a priori knowledge to solve the shallow water problem, see [Schrama and Ray, 1994]. The accuracy of tidal models is still of interest when working with modern altimeter data products. It turns out that it is difficult to get a global tide model that fulfills the requirement of reducing tidal errors as seen by the altimeter to less than 3 cm. There are a great number of technical details on this subject. The bottom line is that the most difficult challenge in obtaining this goal lies in the optimization of the ocean tide representation on the records. During the RADS project various activities focussed on the verification, and also accuracy assessment, of recent ocean tide models. A well known reference on this point is [Shum *et al.*, 1997]. A contribution of DEOS to the Keystone 1998 science working team meeting showed an initial result based on the RADS base level database, [Schrama and Naeije, 1998]. In Saint Raphaël in 1999 an update of this model was shown by [Schrama, 1999] and a contribution was made to the finite element modeling activities in the LEGOS group at the CNRS/GRGS laboratory in Toulouse.

3.5.2 Calibration models, level 3b

In level 3b we define model data related to the altimeter calibration parameters. The space agencies responsible for the altimeter systems usually have different policies of handling the calibration problem. Within the TOPEX/Poseidon project, as well as all other NASA/CNES projects on altimetry, there are science working team meetings where the calibration problem is put on the agenda. Within ESA similar procedures are implemented, although there are no regularly organized science working team meetings for the ERS altimeters, instead there are symposia organized by ESA.

Taking the NASA/CNES set-up as an example, the usual procedure is that the altimeter as an instrument is monitored on a regular basis by mission operations and that problems are reported to the project manager and the project scientists who in turn report their findings at the science working team meetings. Members of the science working team meetings are therefore stimulated to look into specific problems. Moreover French and American research groups are funded to carry out their research under the umbrella of a science investigation program sponsored by NASA and CNES.

Several actions ran for the TOPEX/Poseidon altimeter system. During the

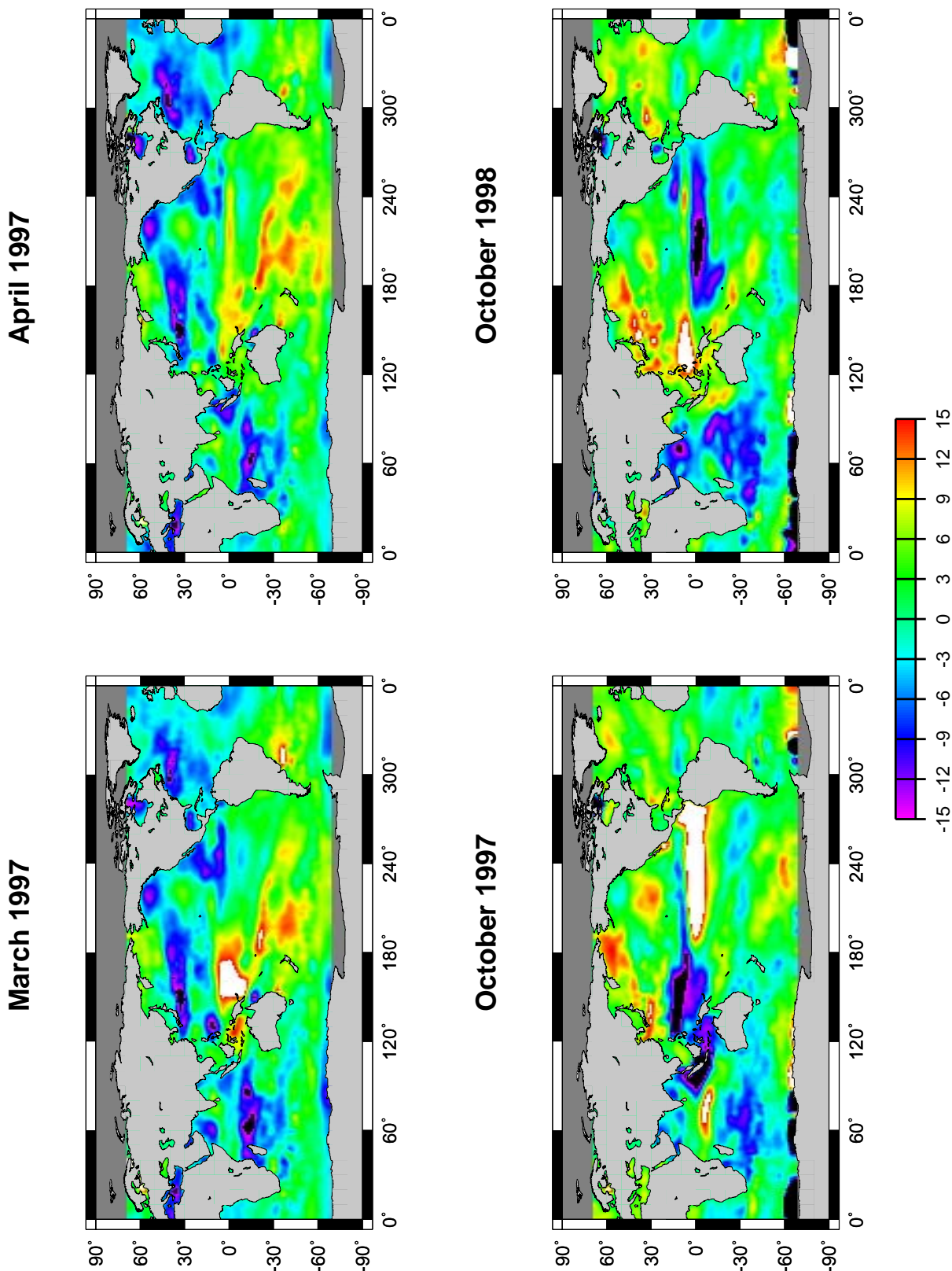


Figure 3.3 The 1997-1998 El Niño event as seen by TOPEX/Poseidon. Shown are monthly mean sea level anomalies relative to a mean over the entire TOPEX/Poseidon period, units: centimeters.

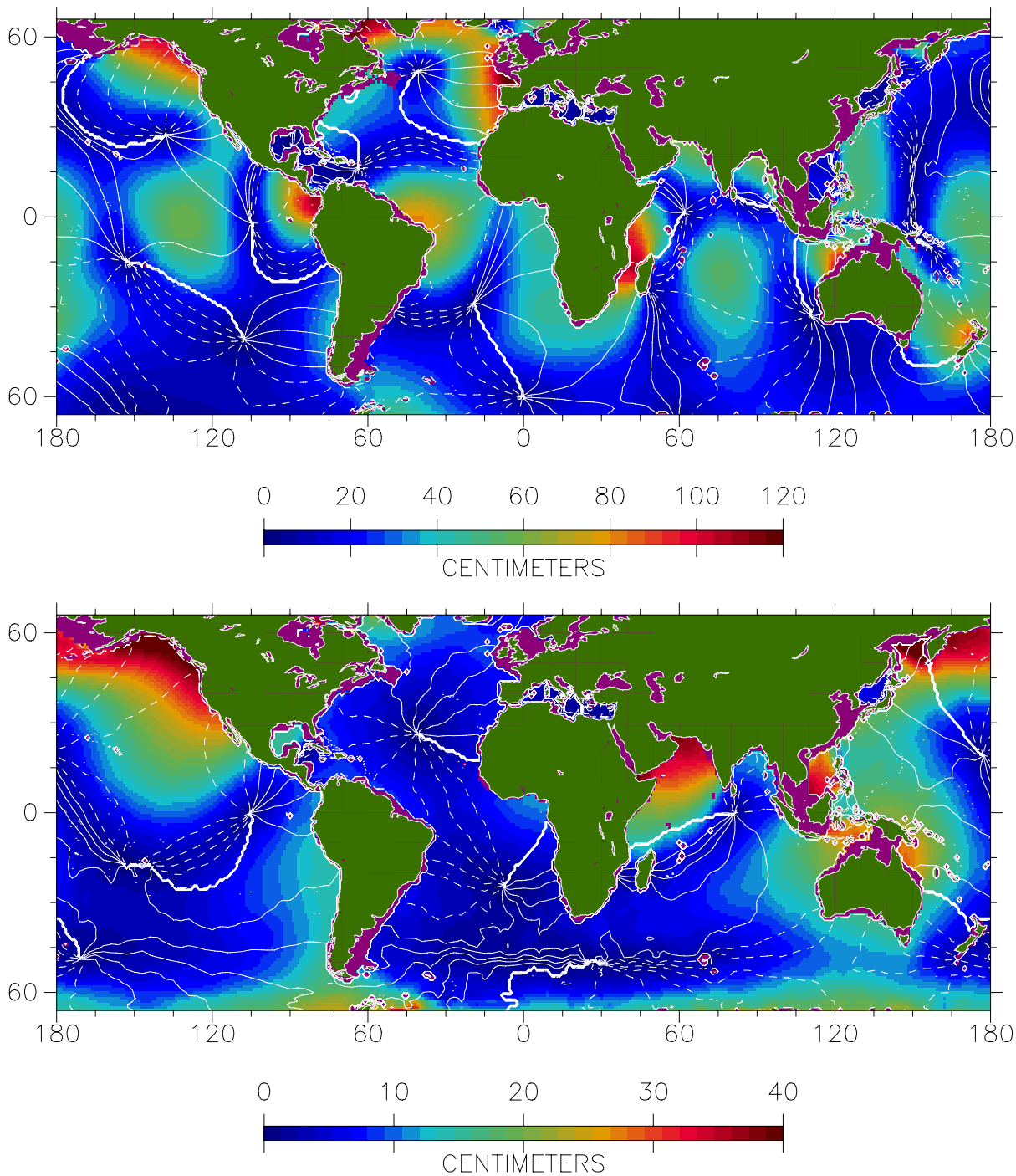


Figure 3.4 Cotidal charts of M_2 (top) and K_1 (bottom) from the TOPEX/Poseidon harmonic tidal solution [Smith, 1999]. The colors indicate the amplitude and the white lines the Greenwich phase lags (contour interval of 30°). Solid lines indicate lag $< 180^\circ$, dashed lines $> 180^\circ$, and thick lines 0° . The solutions are masked for depths less than 200m (purple color). Notice the different scales.

TOPEX/Poseidon project an obvious but essential flaw was discovered, it concerned an erroneous altimeter drift calibration algorithm detected in June 1995. The second action concerned a switch-over to the backup altimeter, also known as side B on TOPEX/Poseidon, as a result of performance degradation of the chirp generator within the side A altimeter. The switch-over was successfully realized in February 1999 during the first 68 passes in cycle 236.

Under these circumstances one may argue whether it is necessary to be involved in any altimeter instrument related discussions or whether the problem is solved by others. In fact, we decided to participate in the discussion and presented our results at the SWT in Keystone, CO (1998), the AGU meeting in San Francisco (1998), and the EGS meeting in The Hague (1999), [Scharroo *et al.*, 1999b]. Moreover, there were separate discussions in the EU Cost Action 40 program and some preliminary results were presented at Bidston, January 1999.

In addition it should be mentioned that DEOS is officially involved in the preparation of the GDRs for Jason-1 and Envisat-1.

3.5.3 Time longitude diagrams, level 3c

Time longitude diagrams are a separate product class intended for studying wave propagation speeds. Examples of these Hövmöller diagrams generated from the base level data can be found either at <ftp://hocus.geo.tudelft.nl/pub/remko> or at <http://www.deos.tudelft.nl>. The diagram in figure 3.5 shows on the horizontal axis the longitude, and on the vertical axis a time index. The goal of these diagrams is to detect striped patterns which reveal the presence of large scale wave effects. The inclination of the striped effect is a direct measure of the propagation speed of the wave, of which two main types exist. The west to east traveling phenomena are the equatorial Kelvin waves which travel at roughly 2.8 meters per second. The presence of such waves coincides with the onset of an El Niño, a phenomenon widely reported. The RADS server holds samples of movies of the El Niño as seen by ERS-1/2 altimetry. Then, depending on the latitude there are secondary waves, called Rossby waves, which travel east to west at higher latitudes. The speed of Rossby waves depends on the latitude. At 40°N or 40°S slow wave propagation speeds have been detected with a propagation speed of a few centimeters per second. These waves can take up to a decade to traverse the world's largest ocean basin, the Pacific, and are remnants of El Niño Southern Oscillation (ENSO) phenomena that occurred in the preceding decade [Naeije, 1995].

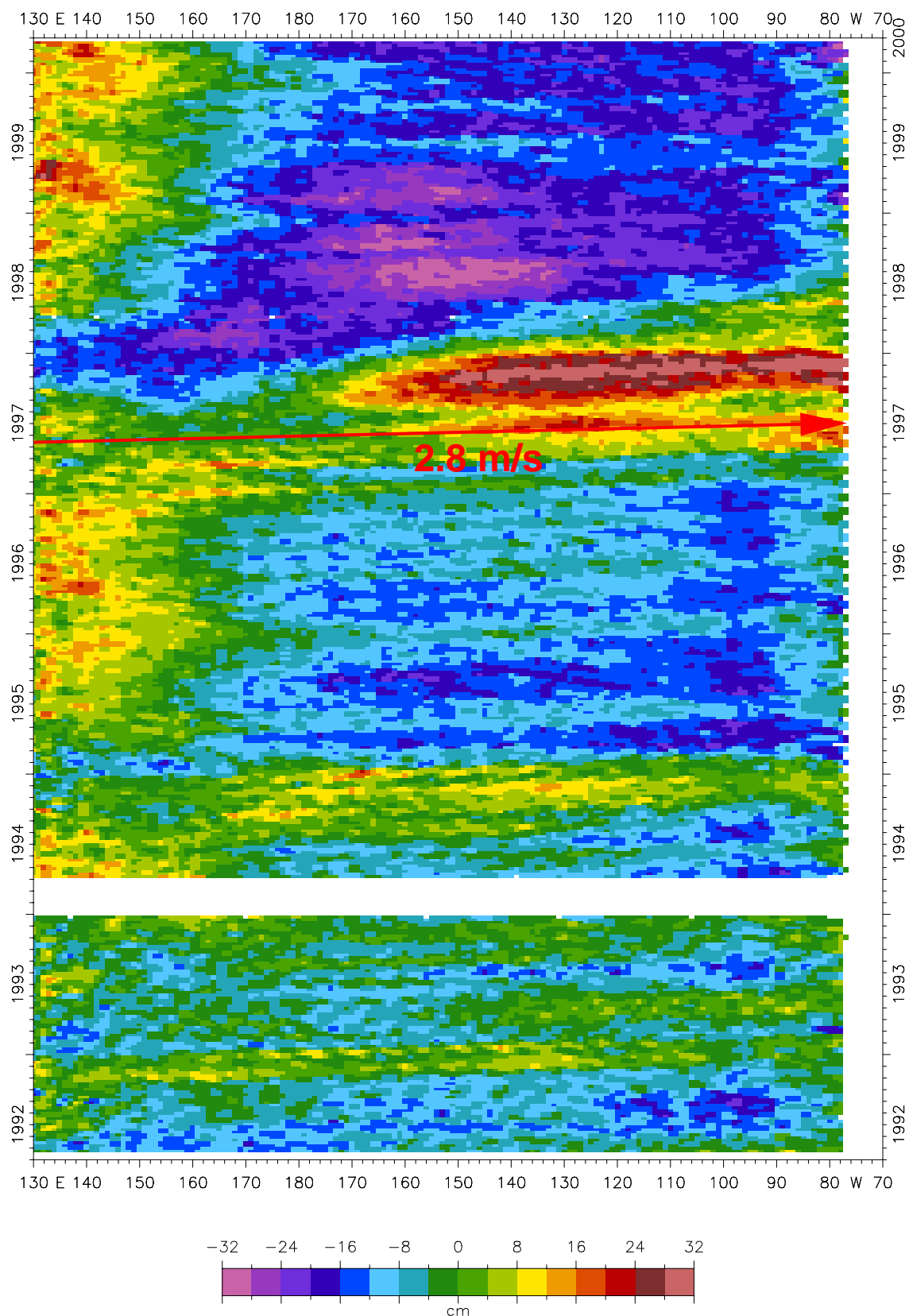


Figure 3.5 Time longitude diagram of the sea level anomalies observed by ERS altimetry along equator. The El Niño Southern Oscillation (ENSO), is clearly visible, including the latest 1997/1998 El Niño event. Equatorial waves can be seen propagating at a speed of approximately 2.8 m/s.

Validation of Altimeter Data

TOPEX/Poseidon data from AVISO/CLS [AVISO, 1996] is relatively easy to insert into the RADS data base. Most of the values on the original data records are up-to-date and properly validated.

The upgrading and merging of ERS-1 and ERS-2 altimeter data from the ESA Ocean Product (OPR) [CERSAT, 1996] into the RADS data base was more troublesome. A long list of adjustments to the measurements and geophysical corrections finally compiles an accurate and unified ERS data set that meets the standards required for research in geodesy, oceanography and climate change.

After all data was unified, some experiments were conducted to assess the value of the new data set. This includes cross-calibration of sea level height and significant wave height, sea ice detection, and tide gauge comparisons.

4.1 The upgrading of ERS data

ERS-1 altimeter data have a history of product and algorithm definitions dating back to 1990, and not surprisingly they were soon surpassed by TOPEX-aided knowledge and models. Upgrades were never made, but also the well-determined re-calibrations to the measurements were never applied. Only as late as 1995 was the altimeter product generation upgraded, with the drawback that no reprocessing of older ERS-1 data was envisaged.

A user of ERS altimeter data, unfamiliar with the products' heritage, but knowing that the measurements are made by two nearly identical satellites, in two identical orbits, with two identical altimeters, expects to deal with **one** altimeter product in which ERS-1 and ERS-2 data are nearly indistinguishable.

Few expectations could have a more disappointing outcome. In reality the user of ERS altimetry has to deal with **three** different data sets: ERS-1 prior to the Tandem Mission, ERS-1 during the Tandem Mission, and ERS-2.

A clear task for DEOS is to construct a unified multi-satellite Radar Altimeter Database System that also includes ERS-1 and -2. This includes the detailed validation and upgrading of the data to common formats and standards. A long list of re-calibration algorithms and updated geophysical corrections finally provides a unified and accurate ERS-1/2 altimeter data set that allows the reconstruction of many ocean parameters with equal efficiency as other altimeters, but with the denser 35-day coverage.

4.1.1 ERS OPR Version 3, Version 5, and Version 6

After the radar altimeter pulse has reflected off the ocean surface it is received back by the altimeter. The characteristic increase and flattening out of the power in course of time is called the *waveform*. The location of the point of maximum increase, the slope of the increase and the total received power are the three principle properties that are measured by a radar altimeter. This process is performed by an algorithm called *tracker*; in case this is done on-ground, we talk about *re-tracker*. From these properties of the waveform straightforward conversions determine the important physical measurements of *range*, *Significant Wave Height*, and *wind speed*.

The scientific datasets, or Ocean Products (OPRs), that are available for ERS-1 and ERS-2 differ in format, applied retracker, and/or ancillary data. ERS-1 data is released in two versions of OPR data: *Version 3 (V3)* for Phases A through F (July 1991 until March 1995) and *Version 6 (V6)* for Phase G. ERS-2 data was only released in OPR V6. The differences between the versions are:

Format: V3 conforms to the CEOS format and V6 to the CCSDS format

Retracker: V6 is based on a more accurate retracker, which means that all measurements of range, significant wave height (SWH) and wind speed are incompatible with V3

Propagation corrections: Data from the Microwave Radiometer (MWR) on V6 are processed with new calibration values in the algorithms to convert brightness temperatures to wet tropospheric delay. A new sea state bias model was introduced.

Orbit: V6 finally has a slightly more accurate orbit which at the same time introduces differences in geographically correlated orbit errors.

Geophysical corrections: V6 features newer models for ocean tides, load tides and mean sea surface.

Without significant adjustments, V3 and V6 data can not be merged together or with T/P data for accurate geodetic or oceanographic studies. Even between the data of ERS-1 and ERS-2 still some differences remain. The rest of this chapter describes the process of harmonization of V3 with V6 and how to upgrade them both to be more compatible with T/P data.

For the intercomparison of V3 and V6 we have used ERS-1 cycles 145–148 processed with Versions 5 (V5) and 6. In this case, V5 is identical to V3, except that the product format corresponds with V6. As a result, in the following V5 can be read as V3.

4.1.2 Significant Wave Height

As the latest OPR data version (V6) uses a retracker different from the original version for ERS-1 (V3), the registration of wave height will be different. In the end this will cause inaccurate registration of the sea level through the sea state bias. In fact, this is one of the main causes as to why two different sea state bias algorithms are proposed for V3 and V6 data [Gaspar and Ogor, 1996]. Figure 4.1 shows the scatter plot of SWH from V5 and V6. Clearly V5 underestimates all wave heights, but particularly the low wave heights which are often set to zero. The difference between V5 and V6 wave heights is shown in Figure 4.2. The line fit obtained by DEOS (black line in Figure 4.2) is determined through least-squares adjustment

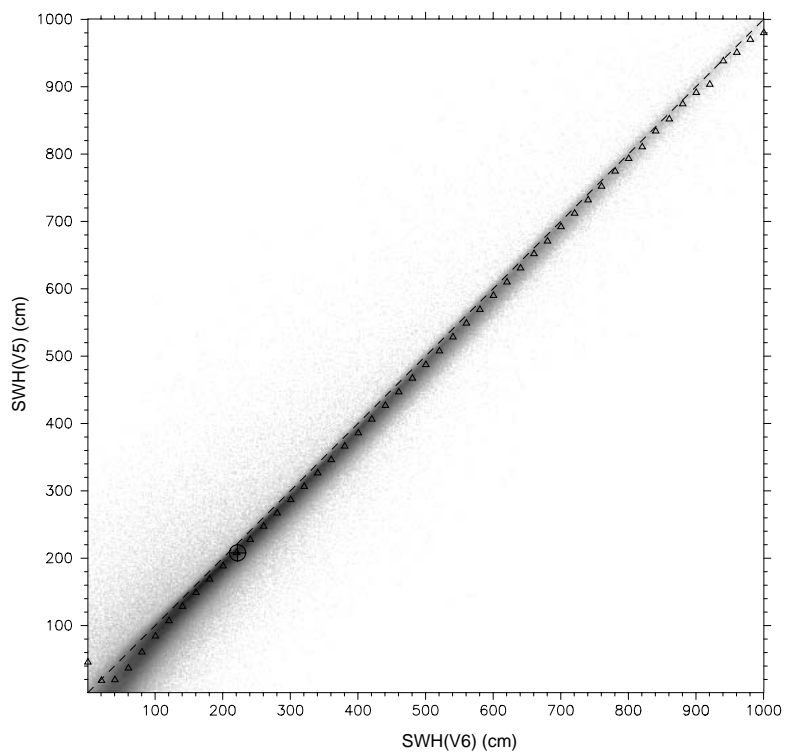


Figure 4.1 Comparison of ERS-1 wave heights according to software versions V5 and V6.

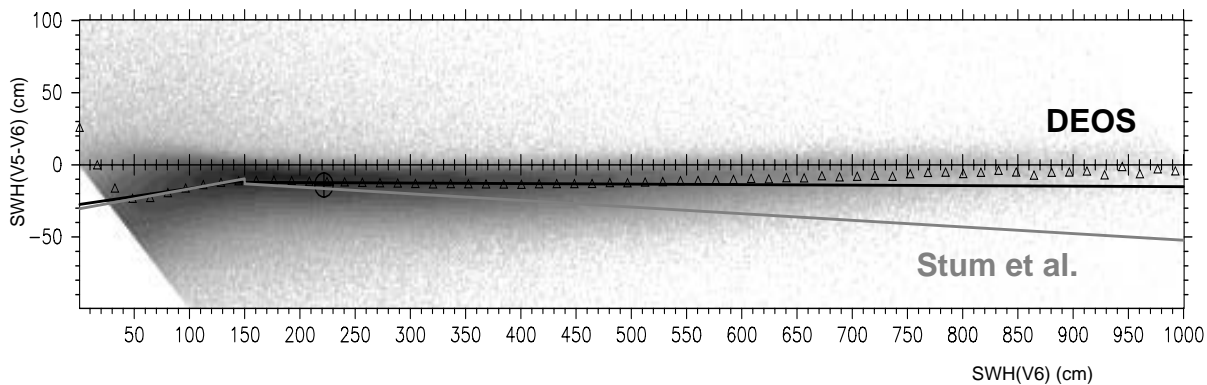


Figure 4.2 Difference between ERS-1 wave heights according to software versions V5 and V6, as a function of SWH. The grey line represents the correction to be applied to the V5 data according to [Stum et al., 1998]. The black line represents the DEOS correction that was applied.

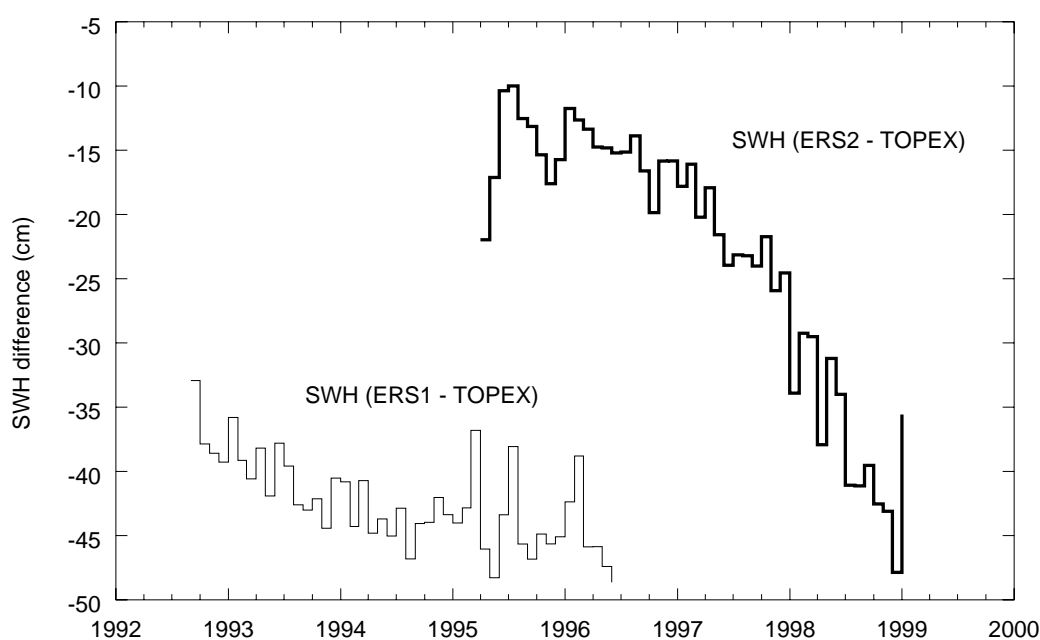


Figure 4.3 Comparison between ERS-1, ERS-2 and TOPEX wave heights at dual-satellite crossovers. The difference between ERS and TOPEX is plotted as a function of time.

of four parameters (two slopes and the location of the breaking point) and better represents the difference at higher wave heights than the (grey) line fit by *Stum et al.* [1998]: This fit leads to the correction algorithm (SWH in meters):

$$\begin{aligned} \text{SWH}(V5) < 1.256: & \text{SWH}(V6) = 0.900 \text{SWH}(V5) + 0.247 \\ \text{else:} & \text{SWH}(V6) = 1.003 \text{SWH}(V5) + 0.117 \end{aligned}$$

Note that the new correction differs from the one proposed to the user by several tens of centimetres at higher wave heights. Although at low wave heights the two corrections agree very well. It is hard to translate the V5 wave heights to V6 wave heights since they are cut off at low wave heights.

After the new correction has been applied to all V3 ERS-1 data, it is essential to compare wave height between ERS and TOPEX (Figure 4.3). The comparison shows that during the tandem mission ERS-1 and ERS-2 had a seemingly constant bias of about 30 cm between their respective SWH recordings despite our new correction. This is because ERS-1 is measuring systematically low at low wave heights for which no simple correction can be applied. Note also that wave heights measured by TOPEX exhibit a serious drift of as much as 40 cm, which, through the Sea State Bias (SSB) will affect the range stability. Although it has been shown that this effect is partly counterbalanced by an anomalous drift in the backscatter coefficient, it was decided in 1999 to switch the TOPEX altimeter to the redundant side B.

In the next version of the RADS data base we will attempt to correct the drift in the TOPEX SWH as well as the bias between the SWH recordings of ERS-1 and ERS-2.

4.1.3 Range and sea state bias

The change of retracker directly influences the measurement of range and significant wave height. Additionally, the influence of wave height on the range measurement, the so-called *tracker bias*, can change. Although the contribution of

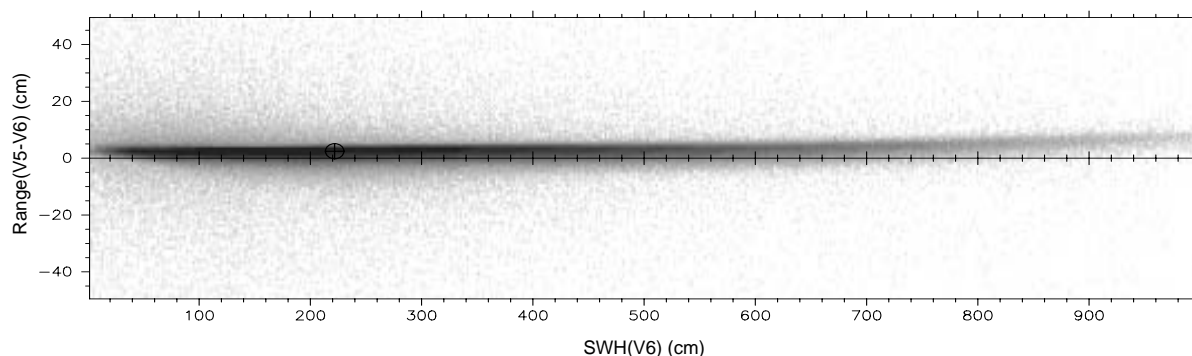


Figure 4.4 Difference between ERS-1 ranges according to software versions V5 and V6, as a function of SWH.

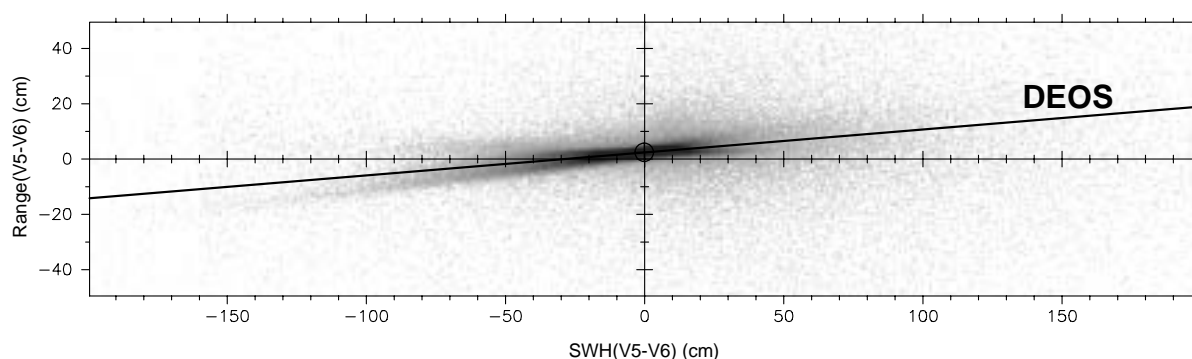


Figure 4.5 Difference between ERS-1 ranges according to software versions V5 and V6, as a function of the difference between V5 and V6 wave heights. The solid line gives the best fit through the data.

the retracker algorithm constitutes only part of the sea state bias, it is important to evaluate the whether the dependency of the range retrieval to wave height has changed from V5 to V6. Figure 4.4 investigates this dependency by plotting the difference between V5 and V6 ranges against wave height. There appears to be none from which we conclude that SSB is the same for V6 and V5' (after applying our SWH correction). With SWH in metres and wind speed U in m/s [Gaspar and Ogor, 1996]:

$$\text{ERS-1 (V5'+V6): } \text{SSB} = \text{SWH} (-0.047 - 0.0035 U + 0.000160 U^2)$$

$$\text{ERS-2: } \text{SSB} = \text{SWH} (-0.048 - 0.0026 U + 0.000126 U^2)$$

Note that we apply the correction to the V6 data *as well as* to the upgraded V5 data. In Figure 4.5 we show that the range difference V5-V6 depends mainly on SWH difference V5'-V6. This is largely undone when the range is corrected for sea state bias by the formulas above. A constant of 24 mm remains due to retracker change and an error in V3 processing.

$$\text{ERS-1 (V5): } \text{RANGE(V6)} = \text{RANGE(V5)} - 0.024 \text{ m}$$

4.1.4 Radiometric wet troposphere corrections

The 23.8 GHz channel of the ERS-2 radiometer suffered a power failure on 26 June 1996 at 16:00. The retrieval of the wet tropospheric delay correction from brightness temperature values had to be recalibrated. Algorithms are given in the Validation Reports [Calvez *et al.*, 1996] and by Eymard and Boukabara [1996],

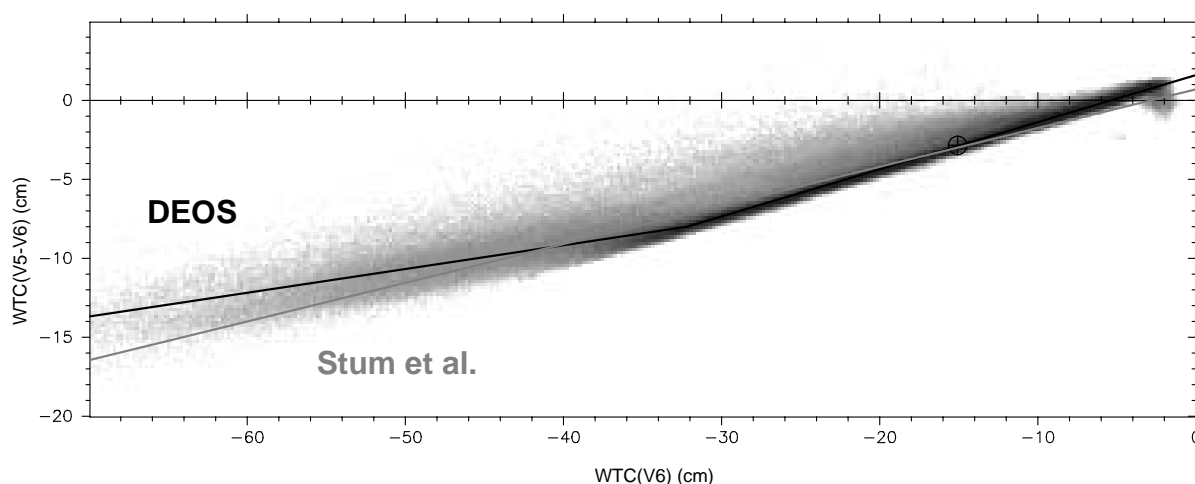


Figure 4.6 Comparison of the Wet Tropospheric Correction (WTC) according to software versions V5 and V6, as a function of the delay itself. The grey line indicates the correction proposed by *Stum et al.* [1998]. The solid line represents our own applied correction.

but we choose a later correction by *Eymard and Boukabara* [1997] because it provides a slightly lower crossover rms. First we have to correct the ERS-2 brightness temperature TB23 (K) after 26 June 1996, then recompute the radiometer wet tropospheric correction (WTC, negative in metres):

$$\begin{aligned} \text{TB23}' &= 0.93 \text{ TB23} + 19.18 \\ \text{WTC} &= -1.65435 + 0.54668 \log_{10}(280 - \text{TB23}') \\ &\quad - 0.22558 \log_{10}(280 - \text{TB36}) + 0.00137 (U-7) \end{aligned}$$

The parameters in the above algorithm are different from V3, but here no brightness temperatures are available. Our correction algorithm comes from the comparison of V5 and V6 wet tropospheric delays (Figure 4.6) and differs from the one in [*Stum et al.*, 1998] particularly at low and high numbers, our correction is:

$$\begin{aligned} \text{WTC}(V5) < -0.402: & \text{WTC}(V6) = 0.869 \text{ WTC}(V5) + 0.027 \\ \text{else:} & \text{WTC}(V6) = 0.770 \text{ WTC}(V5) - 0.012 \end{aligned}$$

4.1.5 Model wet tropospheric correction

An error was discovered in the computation of the model wet tropospheric delay. It makes an impact on all ERS-1 data (V3 and V6) and ERS-2 data until 1 December 1997 [*Calvez et al.*, 1996]. We have to apply the following correction (MWTC negative in meters):

$$\text{All data before 1 Dec 1997: MWTC}' = 0.850 \text{ MWTC} - 0.006$$

Comparison between model and radiometer wet tropospheric corrections of ERS-2 (1995-1998) (Figure 4.7) still shows large discrepancies, which are not yet explained.

4.1.6 Geophysical corrections and orbits

Here follows a list of upgrades that we have applied to the ancillary data, such as ocean tide models, pole tide, orbits, etc.:

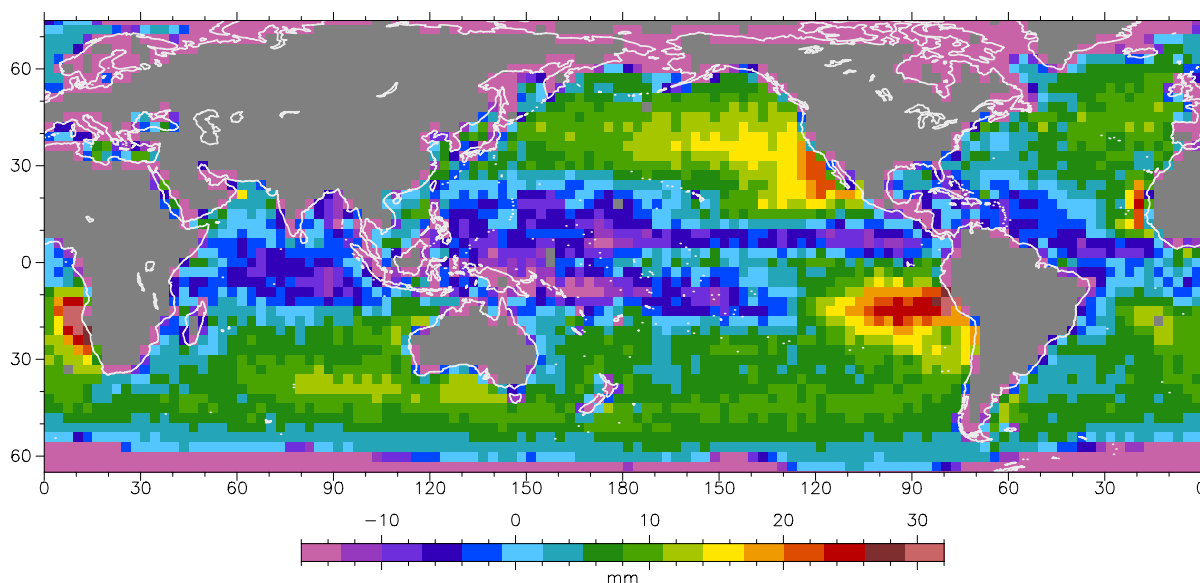


Figure 4.7 Mean difference between wet tropospheric delay corrections determined by the ERS-2 radiometer and the ECMWF model. The model generally predicts a wetter troposphere, except in the tropics.

Ocean tide models: currently favoured are FES95.2.1 and a slightly more accurate CSR 3.0.

Pole tide: This correction is not included on ERS OPR data. A subroutine and a table with IERS pole positions are required to calculate this value on each data record.

Mean sea surface: OSU MSS95 is significantly better than the mean sea surface featuring on OPR V3. It is provided in RADS for all ERS data.

Geoid: Models have improved since OSU91A and JGM-3 that are provided on ERS OPR versions V3 and V6. We use EGM96 instead.

Orbits: The orbits featuring on V3 and V6 have a radial accuracy of approximately 14 and 10 cm, while current state-of-the-art is 5 cm. DEOS provides accurate orbits for the entire ERS-1 and ERS-2 missions, computed with an improved JGM-3-derived gravity model (DGM-E04).

Reference ellipsoids: They differ between ERS and TOPEX products. The above geoid and mean sea surface models are referenced to the TOPEX ellipsoid (GRS80 minus 70 cm). We added 70 cm to the DEOS orbital altitudes to bring them in line with TOPEX.

4.1.7 Time tagging

The satellite altitude may change as much as 25 m/s (Figure 4.8), and thus accurate time tagging (better than 1 ms) is required. The error in the time tagging can be determined from crossover height differences, especially around the mid-latitudes where the effect is the largest. The solid line in Figure 4.9 represents a time tag bias of 1.5 ms for ERS-1. For ERS-2 it appears to be 1.3 ms; the difference is explained by an error in the OPR processing [Stum *et al.*, 1998]. Before interpolating the DEOS orbits, we correct the time tag:

$$\begin{aligned} \text{ERS-1 (V5 and V6): } & \text{TIME}' = \text{TIME} + 1.5 \text{ ms} \\ \text{ERS-2: } & \text{TIME}' = \text{TIME} + 1.3 \text{ ms} \end{aligned}$$

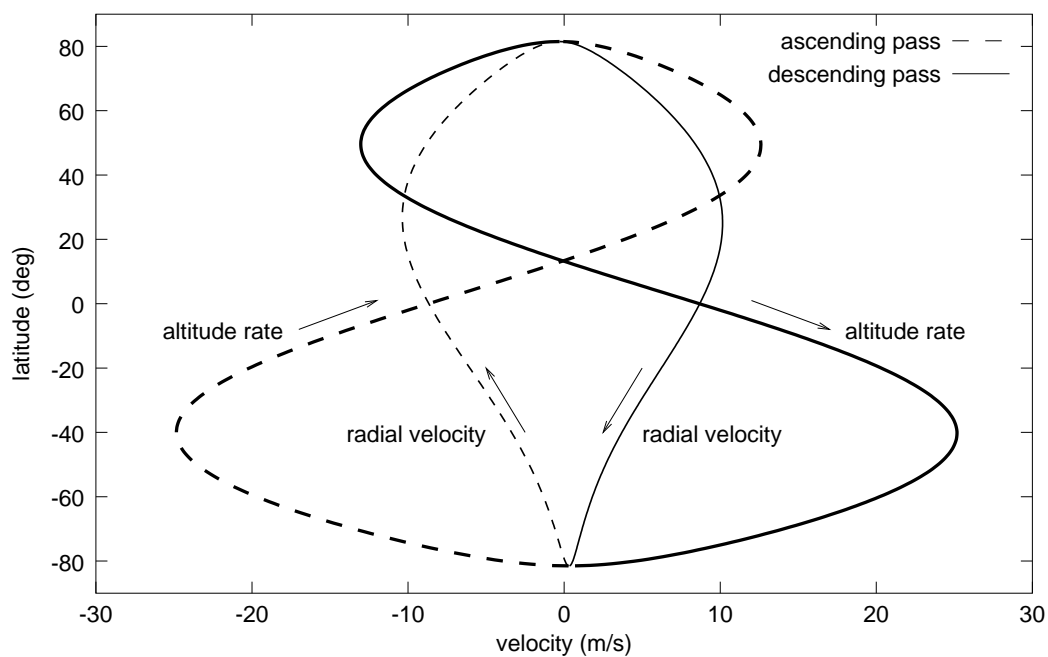


Figure 4.8 Radial and vertical velocity of the ERS satellites

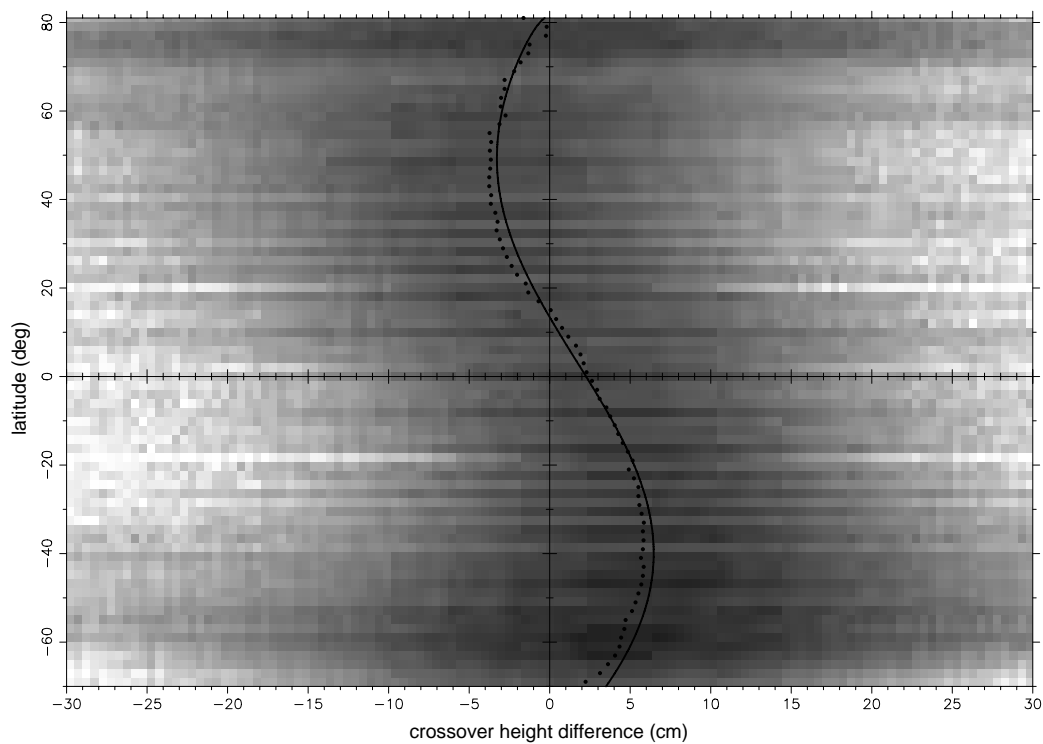


Figure 4.9 Crossover height difference as a function of latitude. The dots represent the mean crossover height difference for each latitude band. The solid line indicates the theoretical latitude to crossover height difference relation for a time tag error of 1.5 ms.

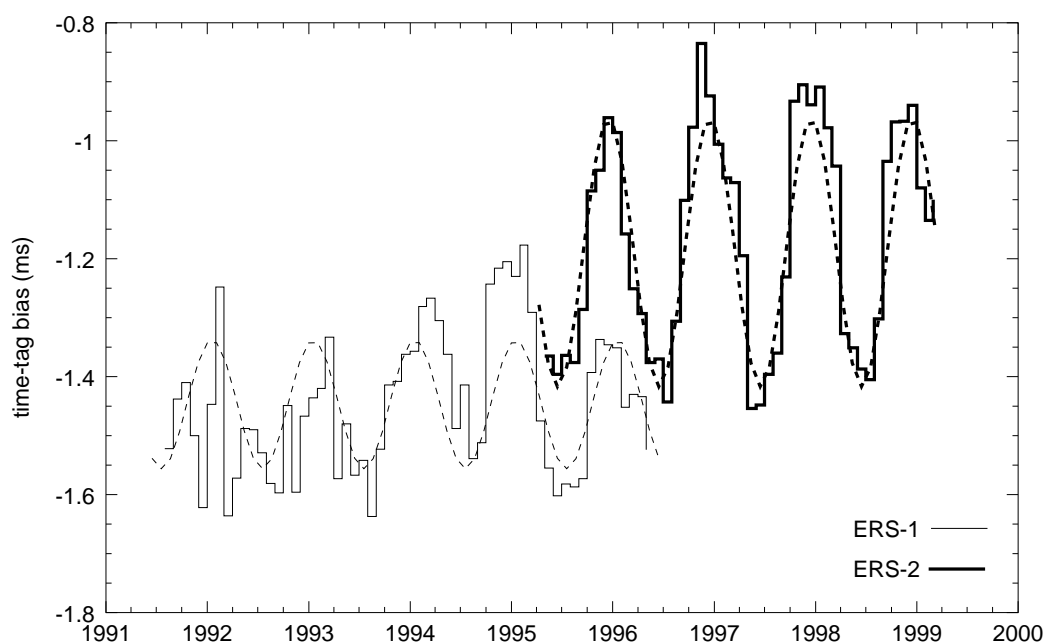


Figure 4.10 ERS-1 and ERS-2 time tag biases estimated from crossover height differences. The dashed lines are the best fitting annual cycles in the data.

It is relatively simple to estimate time tag biases for each month of data. The results show a statistically significant temporal variation with a clear annual cycle (Figure 4.10). The cause of this is not yet fully understood, but we suspect it is related to temperature variations around the orbit changing the clock frequency of the on-board oscillator (Figure 4.11).

4.1.8 Altimeter biases and drifts

Although it can not be assessed now, we assume that altimeters of ERS-1 and ERS-2 have the same range bias of 40.92 cm, as was measured on ERS-2 in laboratory environment. This is close to the *Venice Calibration* value of 41.5 cm.

Both ERS-1 and ERS-2 altimeters suffer from rather unfortunate jumps in the range bias when the instruments are temporarily switched off. A correction for this effect (known as the Single Point Target Response or the *SPTR* bias correction) could be determined from on-board calibration data. Although the correction takes away most of the effect, improvements of this correction are in progress.

Furthermore, the frequency of the oscillators (USO) in the altimeters slowly change with age, which leads to a drift in the retrieved altimeter range unless it is accounted for. One should apply both SPTR and USO corrections from the tables at <ftp://ftp.estec.esa.nl/pub/RA> (Figure 4.12).

$$\text{ERS-1: RANGE} = \text{RANGE} + \text{SPTR_bias} + \text{OSU_drift} + 0.4092$$

$$\text{ERS-2: RANGE} = \text{RANGE} + \text{SPTR_bias} + \text{OSU_drift}$$

4.2 The upgrading of TOPEX/Poseidon data

The processing of the data from the TOPEX and Poseidon altimeters required much less effort. Most of the data entries are based on the most recent knowledge and models. This is not only due to the fact that a lot of advanced data users

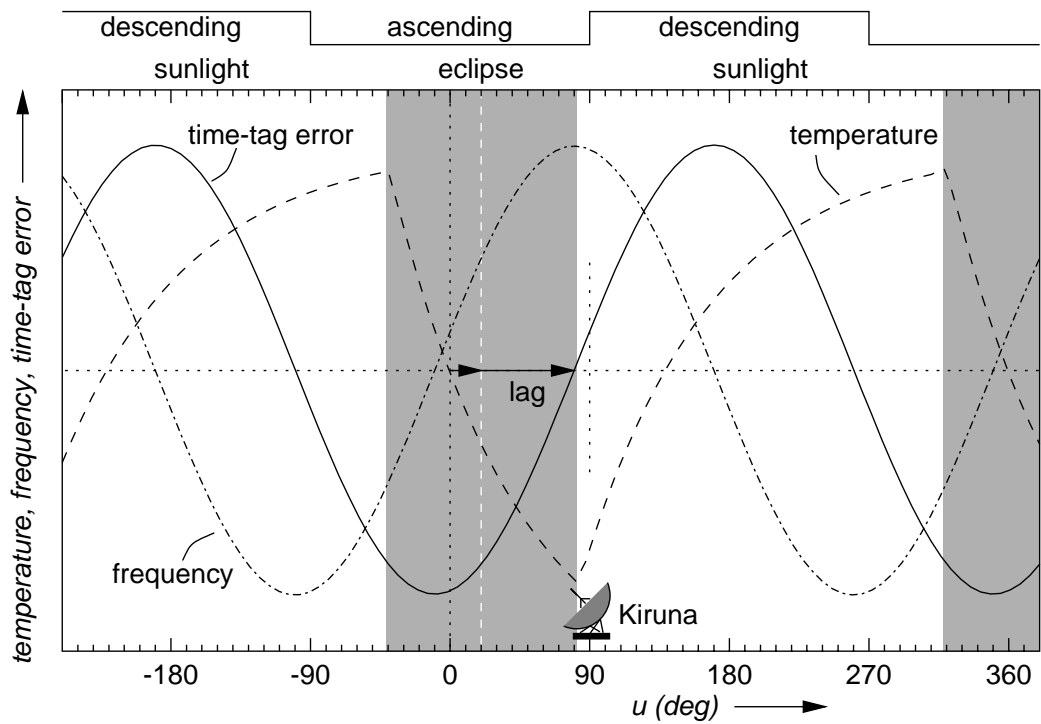


Figure 4.11 Impression of the evolution of temperature, clock frequency, and time tag bias around the orbit.

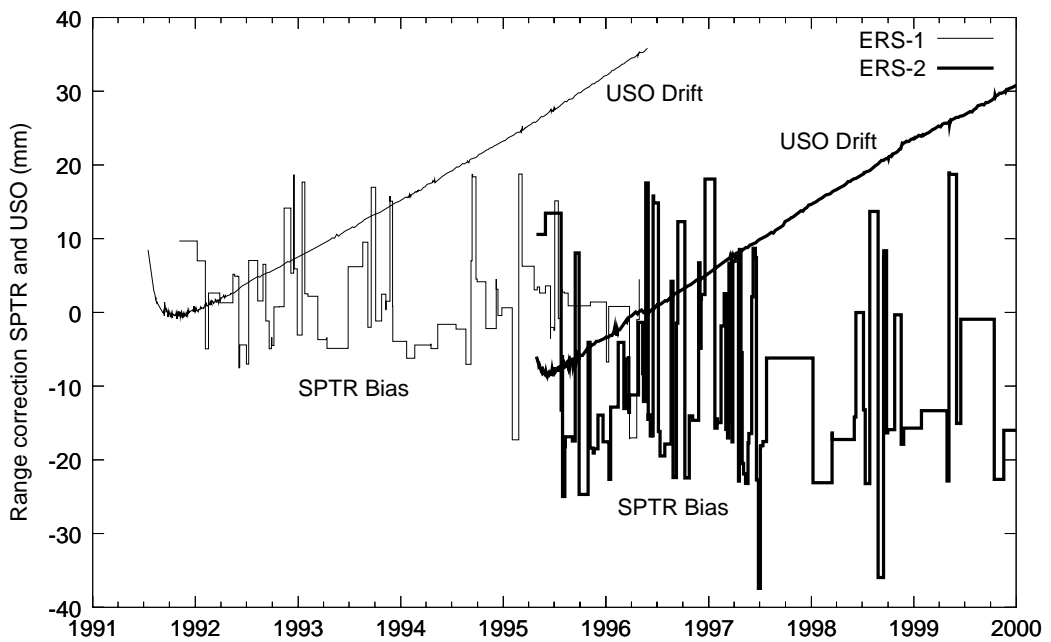


Figure 4.12 SPTR and USO biases for ERS-1 and ERS-2. Source: ESA/ESRIN.

were involved in the validation of the AVISO/CLS data product, but also because the algorithms involved in the production of the data sets have been regularly updated and the data redistributed. As a result many of the altimeter data users have put much more confidence in the TOPEX/Poseidon products, rather than the ERS products, often ignoring the latter entirely.

Still, apart from a format change that significantly reduced the data volume, a few corrections have been made to the data itself.

4.2.1 Geophysical corrections

Just like with the ERS data we shortly summarise the geophysical corrections and ancillary data that have been changed with respect to the AVISO/CLS data sets.

Ocean and load tide: These quantities had to be disentangled. The ocean tide no longer includes the loading contribution.

Ionospheric corrections: The differential delay of the two frequencies of the TOPEX altimeter provides a more accurate ionospheric correction, but it is much more noisy than corrections obtained from models. Although not yet included in the RADS data base, experiments have shown that a smoothed version of the dual-frequency ionospheric corrections provided better results.

Mean sea surface: OSU MSS95 is interpolated from an off-line grid, consistent with the ERS data.

Geoid: Models have improved since the OSU91A/JGM-3 clone that is provided on the AVISO/CLS data. We use EGM96 instead.

4.2.2 Web links

What to get	and where?
Ocean tides	ftp://ftp.csr.utexas.edu/pub/tide/
Pole tide	http://www.deos.tudelft.nl/altim/rads/
Sea surface	ftp://helmert.eng.ohio-state.edu/pub/osumss95/
Geoid	http://cddisa.gsfc.nasa.gov/926/egm96/egm96.html
Orbits	http://www.deos.tudelft.nl/ers/precorbs/

4.3 Data flagging and editing

Although much effort has been put into providing the most accurate ancillary data, and into correcting the principle altimeter measurements for offsets, tilts and drifts, rogue measurements will still exist in the data base. Instead of eliminating those data points, making it impossible to later correct for yet unknown errors, we have flagged data whenever they are conspicuous. These flags include warnings for degraded orbit precision, measurements taken over land, possible contamination of the wet tropospheric delay measurements by land in the microwave radiometer footprint, etc.

Especially, the application of a required land mask was studied in detail. It was discovered that a significant portion of the T/P as well as the ERS data could be originally flagged “over ocean”, where in fact the measurements were taken over inland lakes or even over dry continents or ice shelves. We devised a land mask that properly distinguishes between ocean, land and lake surfaces.

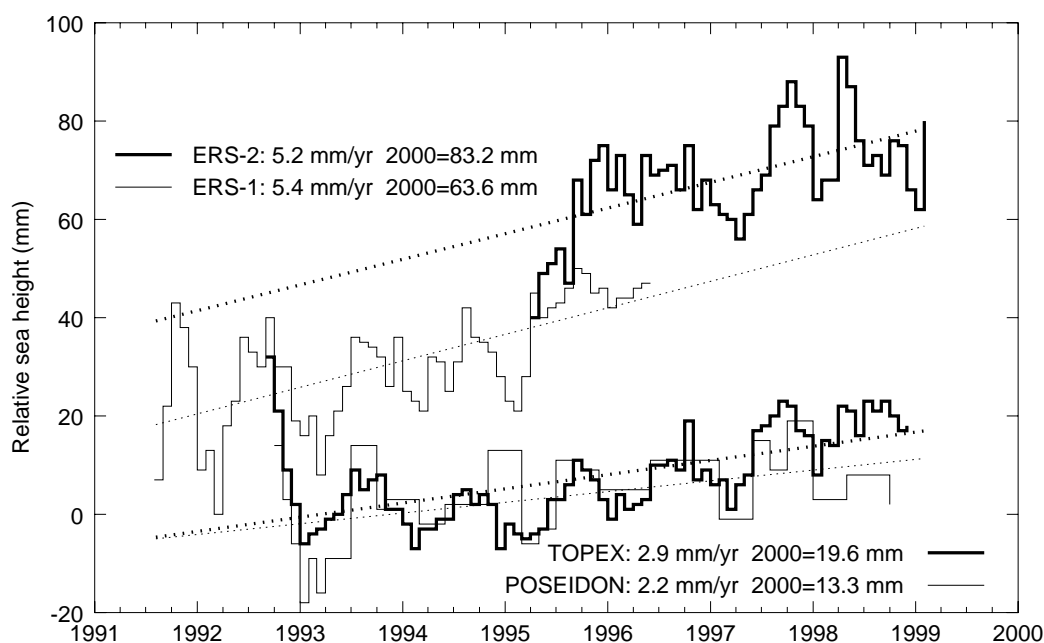


Figure 4.13 Monthly mean sea level height above the OSU MSS96 mean sea surface model. Different colours indicate the different altimeters: ERS-1, ERS-2, TOPEX and Poseidon. Best fitting linear trends are indicated by the dotted lines.

Even after flagging the data, we are still left with some conspicuous or low-accuracy measurements. These data can be identified by checking the principle measurements (wave height, backscatter coefficient, range, and their standard deviation over a 1-second period) against pre-described limits. On top of that the so-called sea level anomaly, the difference between the altimeter-derived sea level and a static model, may exceed a certain limit, indicating a bad data record. These can occur either because the range measurement itself is incorrect, or because the geophysical corrections are inaccurate. This data editing is done *on the fly* by the subroutine `getdata` that reads the data records and transforms the values to SI units.

4.4 Sea level trends

After all data have been unified sea level trends according to the ERS, TOPEX and Poseidon altimeters are computed in two ways

Figure 4.13 Monthly mean height differences with the OSU MSS96 mean sea surface model (actually of pass-by-pass one cycle per revolution fits). The difference in sea level trends may be due to drifts in the radiometers.

Figure 4.14 ERS-1/TOPEX and ERS-2/TOPEX crossover height differences. The latter seem to indicate no significant difference in the sea level trends.

The fact that the mean sea level (Figure 4.13) indicates a different relative trend between ERS-2 and TOPEX than the crossovers (Figure 4.13) could be due to data beyond 66° latitude.

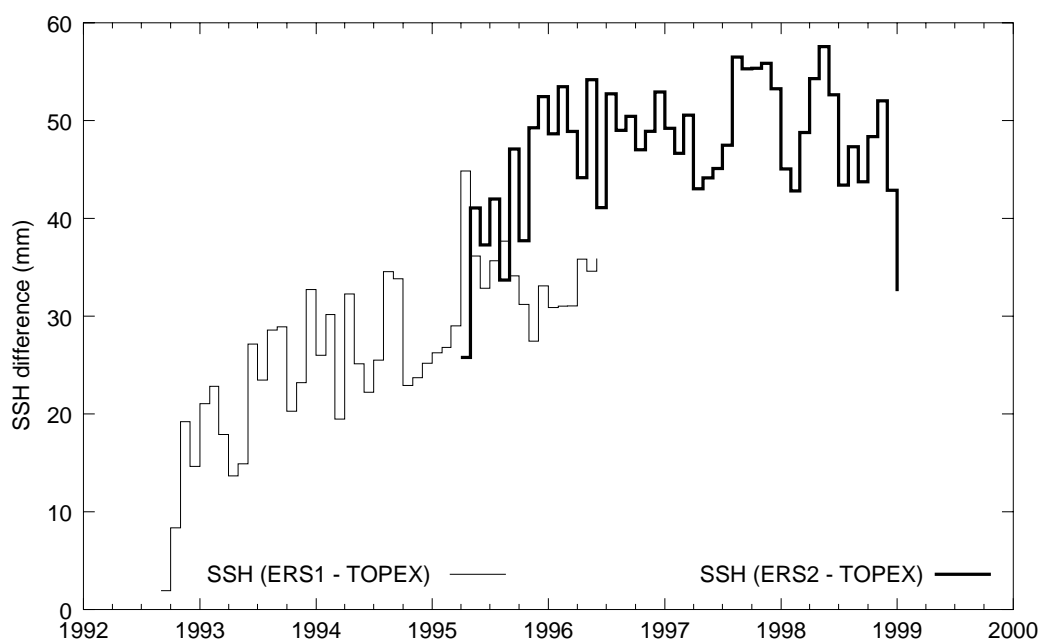


Figure 4.14 ERS-1/TOPEX and ERS-2/TOPEX crossover height differences as a function of time.

4.5 Testing the data set

The data set itself has undergone some further scrutiny by various external users. Their comments resulted in several upgrades to the data set and more wishes ended up on the *to-do* list (See Section 4.6).

- Students used RADS for graduation projects, practical work and case studies.
- An excerpt of the RADS data base has been sent to smaller groups doing geophysical and oceanographic studies in the Mediterranean Sea (Politecnico Milano and University of Darmstadt). These groups are not able to handle the vast amount of altimeter data and are very much helped by the provision of fully-corrected and unified altimetric sea level measurements.
- Colleagues at KNMI use the data to study El Niño and other climate related issues.

4.6 Wishlist

Still, numerous smaller and bigger items have not been completely resolved:

- Orbit precision should be quantified and added as additional field.
- All ancillary fields should be flagged on the data records and not require additional checks during data retrieval.
- More additional geophysical corrections could be added, such as an IRI95 ionosphere model.
- There is a difference in sea level trend between T/P and ERS: Is it due to the altimeters? Or due to radiometer differences?
- ERS-1 and ERS-2 sea surface heights differ by approximately 2 cm: This could be a bias difference or still caused by SPTR.

- SPTR correction tables are still being upgraded, this should remove part of the variations in the ERS bias.
- What is the impact of the apparent SWH drift in TOPEX on its range and sea level trends?
- Harmonize TOPEX side A and B data.
- What is the real cause of the time tag bias in ERS-1 and ERS-2? How can the temporal variation be modeled in an optimal way?

Communication

In this Chapter we discuss a number of issues related to work package 3 and in particular were it concerned the communication with the RADS AF users and the integration of RADS within NEONET. Finally in the section NEONET Core software, we briefly mention some experiences with this NLR developed software product.

5.1 RADS users group

A first request by the BCRS was to establish a RADS AF users group, we recognized two versions these being the solicited and unsolicited user groups.

5.1.1 Solicited user groups

This group of users is mentioned in our proposal and was one of the initiatives to start the discussion on an altimeter data service. All users were contacted individually and positive responses were received. Meetings were organized at which the users interest in the project was discussed. Questionnaires were sent out which formed the basis for constructing a user requirements document [Naeije *et al.*, 2000]. This document is now approved by the BCRS for official publication.

The main goal of the study presented in Naeije *et al.* [2000] was to obtain a set of requirements that can be used in the design of the RADS system, fulfilling the need of highly accurate altimeter data. The questionnaire itself contained questions on a) user profile (nature of projects, organization, and computer infrastructure); b) data requirements (which parameters, level, resolution, and what meta data); c) general requirements (format, software, and on-line browsing); and d) suggestions, (continuation, shortcomings, funding, etc). A preliminary breakdown showed that the complete field ranging from pure science to operational work is covered; that all parties have direct access to computers and the Internet; and that predominantly sea level is required in a level 1 product form. Obviously tags like time and position are needed but the most important one is the accuracy of the measurement: this is especially true for those cases in which altimeter data is to be assimilated in ocean models. More general requirements concern 'highest resolution', global coverage, 'binary integers', and disclosure through HTTP/FTP (URLs) and CD-ROM. Furthermore it is suggested, or actually strongly recommended, that the RADS service will be continued for a period well beyond 2000. This is not only vital for research on decadal variability and global change, but will also contribute to better statistics on the dynamic behavior of sea level in

general.

The requirements from the user group were merged with the requirements set by DEOS and those from the RADS usage test cases by WL-Delft Hydraulics in the frame of the BCRS' SAT2SEA project, by the KNMI in the frame of the ALW proposals, and by NIOZ in the frame of a CLIVARNET proposal concerning sea level variability in the North-east Atlantic Ocean.

Not only was the common denominator in the retrieved requirements compatible with DEOS' requirements, it also fitted the more general requirements that came out of a survey taken in the frame of a CEO contract called 'Collect User Requirements from Experimental User Community on Marine Altimetry' conducted by CLS, CNES, ECMWF, GFZ, GRGS, MSSL, POL, Oceanor, Space Tec Ltd., and DEOS, in 1995. Therefore, no further requirements had to be retrieved. Problems and new needs concerning RADS are processed during the evaluation and use of the data base by the users group and in the future by new users.

5.1.2 Unsolicited user groups

Besides the officially reported AF user contacts there have been many contacts with international users. The fact that we were asked to define a national application facility users group was a request by BCRS and SRON. As a result users had to commit themselves, sending formal letters of compliance, filling out questionnaires, etc.

As is well known and reported to BCRS/SRON, general users on the Internet do not want to see such strict commitments. Such users are not readily going to fill out questionnaires, or may not even intend to reveal their identity. Their interest is more in the direction of easy access to results that DEOS presents on the web.

5.2 Integration of RADS within NEONET

A second request by the BCRS/SRON financiers was to synchronize our meta data information with the NLR NEONET Core software system. The NEONET Core software system is concerned with the topic of meta data exchange on the Internet. The discussion continues with the effort DEOS invested in helping to set-up and maintain a meta data information exchange mechanism with the NLR within the framework of NEONET.

5.2.1 Search robots

In earlier versions of NEONET the NLR set up a search robot service that scans Internet sites in the Netherlands related to Earth remote sensing information. In the current version of NEONET the NLR took the initiative to set up a more enhanced meta data information exchange mechanism that requires more effort of the application facilities than just to provide their information services on the web.

5.2.2 NEONET core software

The NEONET Core Software (NCS) version 1 was delivered by the NLR. Their last version was released at the end of December 1999 and was installed on a SGI

O2 machine at the disposal of the RADS project within DEOS. Although we were not asked to give a technical evaluation of this software system (it is not part of our contract) we briefly mention some implications of installing and maintaining NCS.

Installation

The installation of the NCS version 1 did not run flawlessly and required intervention by the NLR, apparently because it was still in an experimental stage. There was not a central configuration script to install the entire product, instead there were several configuration scripts that relied on the availability of software packages above an unspecified release number. Noteworthy is a JAVA engine embedded within the IRIX operating system on the O2.

Maintenance

The overhead imposed by NCS version 1 on the IRIX operating system is relatively marginal but noticeable. The overhead imposed on the users of the system is substantial, we have tried several options to test NCS. In a manual set-up the user can add meta data information on a form on a web page. Such tests are successful but not practical. For example in a case where maintenance of a large set of meta data descriptors is desired.

In the case of RADS processing of large volumes of meta data may be desired. We strive towards an automated way of updating the meta data description files (the XMLs) on the topical node from our anonymous FTP area. Moreover we want to leave the meta data descriptors in local directories in the anonymous FTP oriented file system without having to map the XMLs into one single directory as is the case with the current version of NCS.

From our experience with NCS installed in January 2000 we concluded that the software itself is still in an experimental stage and that it still requires several modifications to become of practical use.

Conclusions and Outlook

6.1 The present

Today, research and applications in geosciences are dependent on space-borne techniques that require a global approach. Some of these techniques have become successful, with the establishment of internationally coordinated (free) services that handle the generation of standard products, recommendations, standards, coordinated analysis, data collection, and product and software distribution. A good example of such a service is the IGS, the International GPS Service. Gradually, the need for coordinated global approaches and global observation systems for other space techniques are also being recognized. On a European level, the Centre for Earth Observation (CEO) programme works on an observation system for (public) access to all sorts of remotely sensed data. It has built the Internet infrastructure called INFEO which stands for Information on Earth Observation. As a logical consequence, on national levels initiatives are also being developed to take advantage of the need of such data bases and services. In this respect NEONET is worth mentioning as the Dutch answer to INFEO. In the NEONET frame DEOS thought it not only appropriate, but also mandatory, to build a satellite altimetry service. Many investigations have demonstrated and proven that altimetry is extremely important for geosciences, in particular geodesy, oceanography and geophysics, and as such deserves a place within NEONET and INFEO.

DEOS' anticipation of the need for altimeter services has started the RADS project: "The Radar Altimeter Database System", of which the findings have been documented here. It began with the definition of a level 0 data base that consists of validated and calibrated altimeter data (sea level, wave height, wind, models and corrections) not only internally consistent, but also consistent from mission to mission and phase. Consistency here meant, if possible, similar models for media and geophysical corrections, equivalent orbit information and identical reference systems. Now, at the end of the project the data base has been filled with almost 15 years worth of value-added altimetry products, occupying over 30 Gb of disk space. It is being updated and validated whenever new data or new knowledge on models come in. From the level 0 or base level data base we started building higher level products in correspondence with user defined needs. These products have been used and published by us for our own research, and also by others, for instance by the KNMI and Delft Hydraulics. There was also a strong interest in RADS by foreign institutes and universities. Plans exist to incorporate the RADS service in the outreach service of JPL (NASA). The RADS concept has been adopted by SCOMMSA, the sub-commission on Multi-Mission Satellite Al-

timetry, part of the CSTG, Commission for International Coordination on Space Techniques for Geodesy and Geodynamics. SCOMMSA provides a platform for discussions on this topic and is open to collect and disseminate information on all aspects of multi-mission satellite altimetry. In addition, the intensive cooperation with potential users and partners (national AND international) already initiated new projects and new funds.

All in all it can be concluded that RADS, viewed apart, is a big success, of which this document only gives minor reflections. It is a bit harder to indicate the success of RADS as integrated part of the NEONET infrastructure. In Chapter 5 it was concluded that the current version of the NEONET Core Software (NCS version 1.2) is not capable of fulfilling most of DEOS'/RADS' needs. On a modest level meta data has been made exchangeable through the NCS-XML interface. This was already promising but needs further work and falls beyond the conclusions of the RADS project.

6.2 The future

Referring to the summary of the User Requirements Document, it is strongly recommended that the altimeter data base, as DEOS provides through RADS, should be continued for years to come. This would especially provide a framework for research on the climate such as decadal variability, ENSO events, and global change (think of the CLIVAR programme), because it requires decades of calibrated and validated data to come to useful conclusions. Also: more data will definitely contribute to improving the statistics on the dynamic behavior of sea level in general. The success of RADS not just depends on the present state of the data, but even more on the continuation of the service: important for DEOS and all of its present and future research partners.

On a global scale the accuracy of estimates of sea level change will continue to improve by insertion of Jason- and Envisat-1 observations into the altimeter database. On regional scales, the combination of TOPEX/Poseidon with ERS-data and/or *in situ* data demonstrated the separability between altimeter instrument drift and sea level change. Synergy of Jason- and Envisat-1 and existing altimeter missions and other *in situ* ocean monitoring techniques will help in solving the calibration problem. The inclusion of new data will enhance the sampling characteristics of the altimeter data. Inter-satellite calibration will play a significant role in these studies.

In addition, the current accuracy of altimeter data and the proposed accuracy of both the Jason- and Envisat-1 systems enables incorporation of altimetry in operational sea level observing systems. This is an important step towards a precise regional sea-land monitoring system based upon various terrestrial and satellite observation techniques.

We would like in the future to address some of the standing issues:

- Coordinate and harmonize efforts for a precise and continuous calibration of ALL missions, because sea level rise studies can only be successful with a consistent, long-term record of altimetry.
- Cross-calibration of missions operating simultaneously appears to be very precise, but how can the connection back to GEOSAT be built? Instrumental drifts (of oscillators, radiometers, etc) prohibit the absolute calibration by a chain of independent cross-calibrations.

- How can we best take advantage of the synergy of missions operating simultaneously? With the Path-finder project and the AVISO/CLS products we have good examples, but it appears to be more accidental that the orbit configurations of ERS- (and Envisat-1) and of TOPEX/Poseidon (and Jason-) are complementary. Will we have a similar well suited situation after Jason- and Envisat-1?
- There are new techniques like *e.g.* laser altimeters to map ice sheets and thereby derive mass balance. Do we already know how to calibrate laser altimeters and cross-calibrate them with radar technology?

More detailed standing issues can be found at the end of Chapter 4

Summarizing, for RADS we definitely strive for continuation, extension (not only new altimeter data but also new higher level products), improvement of quality control, linkage with other programmes, and intensification of national and international contacts. We see this only as the beginning!

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Appendix A

Original proposal

The following concerns the text of the original proposal submitted to the BCRS which was accepted for the indicated period. A minor organization point of view was the splitting up of work package 2 which was, as an alternative, partly funded by the BCRS and partly funded by the Stichting Ruimteonderzoek Nederland (SRON).

Satellite altimetry is one of the long standing activities within the Delft institute of Earth-Oriented Space research, DEOS. The activities have focussed on the processing of satellite altimeter observations and improvement of various correction models that accompany these data. Numerous altimeter missions have been studied, noteworthy are the data of GEOS-3 which operated from 1975-1978, SEASAT in the summer of 1978, GEOSAT: 1985-1990 and ERS-1 1991-1995. Ongoing altimeter missions are those of TOPEX/Poseidon and ERS-2 which were initiated in respectively 1992 and 1995. Moreover there are plans that DEOS will be involved in follow-on projects of existing altimeter projects such as GEOSAT follow-on (GFO), TOPEX follow-on (JASON), and Envisat.

The above summary indicates that satellite altimetry data easily spans a period of more than 20 years. Radar altimeter measurements in heterogeneous formats with, oftentimes, outdated corrections are in principle available within DEOS and sea level variations, including specialized products derived from such information, can be analyzed. As was mentioned before, altimeter measurements do require the presence of a number of environmental and instrumental corrections and part of the scientific activities within DEOS is to continuously improve such information. An example is the problem of modeling ocean and load tides that are normally removed from the sea level profiles observed by the altimeter. Our current understanding of this phenomenon outperforms models available only 5 years ago. Application of modern ocean and load tide models to older altimeter data will therefore clean up previously thought data errors in for instance SEASAT and GEOSAT data thereby enabling scientists to study past sea level changes with unprecedented accuracies. The above example should not just be mentioned in the context of the ocean tide problem, the same situation is true for marine gravity data, radial orbit consistency and a number of other corrections essential for radar altimetry.

Products derived from satellite altimeter data are classified at three levels. The level 0 product is what is closest to raw data and corrections as they are received from various organisations including orbit corrections computed within DEOS. The level 1 product comes in the form of geographical maps containing sea level anomalies relative to a mean sea level or a geoid which in some cases can be the result of the combination of different altimeter sensors. The level 2

product are more dedicated products derived from level 0 and 1, intended for more specialized purposes. One could imagine derived amplitude and phase maps of selected ocean and or load tide constituents, time longitude maps to study wave propagation effects, seasonal amplitude and phase maps to study steric heating of the top-layer of the oceans, and so on.

Our proposal towards the BCRS will be discussed in more detail in part B and will strive towards an implementation of level 0, 1 and 2 altimeter products in the form of a public database. Special attention will be paid towards maintaining data integrity and consistency among the various altimeter missions. This might for instance mean that level 2 products derived from more recent altimeter data sources could be used to enhance level 0 altimeter data from earlier sensors.

Users of such a public altimeter database should in our opinion be sought in the direction of the various contacts established by DEOS on a national and international level. A few examples: DEOS has participated within the BCRS project MOCUR, is sponsored by SRON for ERS-1 and -2 and TOPEX/Poseidon data processing activities and initiated the DATUM-1 and 2 projects with the RWS/RIKZ. However, for this proposal a total of 7 user groups have been approached; the contact persons of institutes and companies involved as users in this proposal are listed below:

RIKZ: Rijksinstituut voor Kust en Zee, drs. M.E. Philippart, Tel: 070-3114311 Fax: 070-3114321, e-mail: m.e.philippart@rikz.rws.minvenw.nl

IMAU: Instituut voor Marien en Atmosferisch Onderzoek Utrecht, dr. P.J. van Leeuwen. Tel: 030-533275, Fax: 030-543163, e-mail: leeuwen@fys.ruu.nl

NIOZ: Netherlands Institute for Sea Research, dr. L.R.M. Maas, Tel: 0222-369300 (or /419) Fax: 0222-319674, e-mail: maas@nioz.nl

KNMI: Koninklijk Nederlands Meteorologisch Instituut, dr. G.J.H. Burgers, Tel: 030-2206682, Fax: 030-2210407

ARGOSS: Advisory and Research Group on Geo Observation Systems and Services, dr. C. Mastenbroek, Tel: 0527-242299, Fax: 0527-242016, e-mail: info@argoss.nl

TU Delft/DIOC: Prof. Dr. Ir. A.W. Heemink, Tel: 015-2785813, Fax: 015-2787209, e-mail: a.w.heemink@math.tudelft.nl

Delft Hydraulics: dr. H. Gerritsen, Tel: 015-2858585, Fax: 015-2858582, e-mail: info@wldelft.nl

We have also sought contact with two other national activities in the framework of GOOS, global ocean observing system, and its european branch EUROGOOS. We have spoken to dr. J Stel (NWO/GOA) and dr. L. Droppert (RIKZ) who both confirmed the close relationship to the current RADS activities although it should be admitted that GOOS and EUROGOOS are concerned with a wider scope in the sense of operational oceanography, see also the report "The strategy for EUROGOOS", published by the Southampton Oceanography Centre, ISBN 0-904175-22-7. Our proposal is that we keep both mentioned representatives informed about our activities and that the RIKZ user group is used as a primary point of contact.

Description of the technical approach adopted to tackle the problem

Currently there exist no dedicated altimeter databases within DEOS that do fulfill all necessary requirements for public querying and most important of all, data integrity among various altimeter data sources. The foreseen system called RADS, Radar Altimetry Database System, will at the end of this project contain the essential data and meet the integrity and quality assurance specifications. During the project we anticipate that parts of the existing altimetry data sources will be merged into RADS so that scientists in the field of oceanography and geodesy within the Netherlands will be relieved from maintaining large complex scientific databases.

This initiative towards the BCRS in this area of database development and user support calls for a 2 year funding period. It should be mentioned however that there are strong intentions within DEOS to submit a follow-up proposal, not included in this text, where we want to continue and possibly slightly extend the activities described here. Issues as commercial exploitation where private companies will get access to RADS derived products will therefore get a more important role in the follow-up proposal where it concerns an additional funding request after 1/12/99.

In work package 2 we ask for one full time technical support staff which should be employed for a period of 2 years. The activities of this technical support staff are shortly described in work package 2. Purpose of a technical support staff should be: a) to develop an on-line public altimeter database, b) to feed heterogeneous altimeter sources into a uniform database structure, c) to merge (that is interpolate and test) alternative corrections from other data sources, and d) to maintain documentation.

A second activity in our proposal will be to hire in a temporary technical support staff on the subject communication and quality control. This activity is described in work package 3, purpose of this activity is: a) to help altimeter database users to access RADS and b) to maintain a world wide web interface consisting of browsers and specialized query programs to access level 0, 1 and 2 products.

A third activity in our proposal is a management work package which DEOS and the Delft University of Technology currently demand for temporary projects such as this proposal submitted to the BCRS. Purpose of the management work package is to take care of the over-all progress of this project including a number of other tasks as mentioned under work package 1 on the forms.

Level 0 data description

This appendix is a separate section that deals with the full description of the level 0 data records for all platforms. It is included as a reference for those who have access to the level 0 database. The appendix starts with a section on the use of conventions throughout the level 0 records. It is followed by a section on the structure of an individual pass file. Some field items on the records are common for all altimeters, so their descriptions do not need to be repeated as such and can be found in the section called "common field names". The header record descriptions and the data record descriptions follow for all altimeter systems in the data base.

B.1 Conventions

In order to avoid confusion in the discussion of altimeter measurements and corrections we will first define a number of terms that are consistently used throughout this Chapter.

Range is the distance between the satellite center-of-mass and the (ocean) surface as measured by the altimeter.

Altitude is the distance from the satellite center-of-mass to the reference ellipsoid as derived from precise orbit computations.

Height is the distance from the sea surface to the reference ellipsoid. It is computed by subtracting the altimeter range from the satellite orbital altitude.

Reference ellipsoid is the ellipsoid adopted by the TOPEX Science Working Team. It is defined by an equatorial radius of 6 378 136.3 m and an inverse flattening of 298.257. This ellipsoid is the reference for height elements (orbital altitude, geoid, etc.). The flattening also plays a role in the computation of the geodetic latitude.

Time is measured in UTC seconds starting on 1 January 1985 at 00:00:00.

Longitude is referenced to the Greenwich meridian counting positively eastward. It is restricted to the range $[0^\circ, 360^\circ]$.

Latitude is referenced to the equator and is positive for Northern latitudes or negative for Southern latitudes. It is restricted to the range $[-90^\circ, 90^\circ]$.

Corrections have to be *added* to the quantity to be corrected to revise the value to the truth. In other words:

$$\text{Corrected quantity} = \text{Measured value} + \text{Correction}$$

This means that signal path delays through the atmosphere are generally negative. Thus, adding the negative values to the altimeter range reduces the measured value to the corrected value.

For some corrections two versions are provided, one based on in-situ measurements, one based on a global model. For example, the wet tropospheric delay correction can be based on the microwave radiometer measurement (**wettrop1**) or a meteorological model (**wettrop2**).

In some other cases the user can choose between various alternative models. This is the case for the orbital altitude and for the ocean tide.

“Ocean” returns are the measurements that, based on the shape of waveform, look like returns from an ocean surface. This might just as well be from a sea or large enough lake, or from any surface that reflects like ocean (e.g. shallow land ice). The land flag may help distinguish between *real* ocean returns and *apparent* “ocean” returns.

Fully corrected sea level anomaly is a term used for the instantaneous sea level referenced to a long-term mean sea surface, corrected for any modeled height variation. Using the elements in the RADS Level 0 data base, the preferred way to determine this fully corrected sea level anomaly (SSH in mm) from ERS data is:

$$SSH = \text{alt2} - \text{altrng} - \text{drytrop} - \text{wettrop1} - \text{iono2} - \\ \text{ssb1} - \text{invbaro} - \text{otide1} - \text{ltide} - \text{stide} - \text{ptide} - \\ \text{geoid} - \text{mssh}$$

Flagging. Data not over water surfaces and data without a valid range measurement have already been discarded. When a measurement component is flagged ‘bad’ in the sense of ‘unusable’ the corresponding data value is set to ‘invalid’ (see below). If a flag indicates an out-of-range value, it is not set to ‘invalid’ but the value obtained from the source data is reported. There are also flags that do not relate to the measurements or corrections but indicate the surface condition (land, deep ocean, shallow sea)

Editing of the measurement values and data corrections can be applied based on the ‘minimum value’ and ‘maximum value’ given for each data element in the following Sections. Therefore, these minimum and maximum values are to be considered ‘sensible’ values, rather than physically possible values.

Binary data All fields of measurements and corrections are recorded as *signed* 2- or 4-byte integer words. In this convention the most significant bit is the first (left most) bit in each of the bytes and the most significant byte is also the first (left most) byte in the word. This representation of integers is used on most workstation computers. Notorious exceptions are VAX, DEC and PC; for these systems one should reverse the bytes (but not the bits) before determining the value of the I2 or I4 word.

“Invalid” values are $2^{15}-1$ (32 767) for 2-byte integer words and $2^{31}-1$ (2 147 483 647) for 4-byte integer words. Some fields will never contain an ‘invalid’ value because it can always be determined. In such a case the invalid value is specified as ‘N/A’ (not applicable).

Bit numbering in the I2 word **flags** is from 0 to 15, bit 0 being the least significant bit (right most bit of the right most byte) and 15 the most significant bit (left most bit of the left most byte).

B.2 Pass files

Pass files are stored in 80 byte length records that start with a header record followed by as many data records as can be found in that pass. The pass files are grouped together for identical passes of one altimeter in a specific mission phase. There is separate software available on the file server to read and access pass files.

B.3 Common variables

In the header and data records some variables always follow the same description. These variables are described in the following sub-sections.

B.3.1 Time tags

The UTC time elapsed between the reference epoch (1 January 1985, 00:00:00) and the time of the 1-Hz altimeter measurement, corresponding to the center of the footprint.

The time tag is normally provided as two 4-byte integers. The first word contains the number of entire UTC seconds elapsed since 1 January 1985, the second word contains an additional microsecond portion. Hence:

$$time(s) = sec + usec \times 10^{-6}$$

The definition of time is such that leap seconds are accounted for. This means that each day starts on a multiple of 86400, irrespective of the amount of leap seconds passed. For example, on 1 January 2000 00:00:00 `sec` equals 473299200.

B.3.2 Latitude and Longitude

Both variables represent the geodetic latitude and longitude on the reference ellipsoid, all coordinate descriptions on the base level data records used in the RADS project are taken according to the NASA/CNES TOPEX/Poseidon reference ellipsoid, see also [AVISO, 1996].

To compress the latitude and longitude variables into integer 4 words the variables are multiplied by 10^6 so that the representation is given in μ deg.

B.3.3 Geoid

The geoid is an equipotential surface of the Earth's gravity field that is closely associated with the location of the mean sea surface. As a reference for the geoid height the reference ellipsoid (with its center determined by the origin of the satellite orbit reference frame) is used. It is implicitly assumed that this origin coincides with the Earth's center-of-mass, but this is not necessarily true.

The geoid height varies between about -83 and 106 meters and includes contributions from the very large wavelengths associated with the general shape of the Earth up to high frequency variations related to ocean trenches, sea mounts, etc. Depending on the degree and order expansion of the gravitational potential, higher frequencies may be cut off.

The value representing the geoid height is computed by means of bi-cubic polynomial interpolation in the $0.25^\circ \times 0.25^\circ$ grid of the NIMA/GSFC EGM96 geoid model. This geoid model is a representation of the EGM96 geopotential

model [Lemoine *et al.*, 1997] that is based on a combination of satellite tracking, altimetry and surface gravity data. The model extends up to degree and order 360, which implies that the shortest resolved wavelength is 1° .

B.3.4 Mean sea surface

The mean sea surface height on the data records is represented relative to the geoid and is stored in a variable called **mssh**.

The mean sea surface is the position of the ocean surface averaged over a long time period. The period should be sufficiently long to average out any annual, semi-annual and seasonal sea height variations. In addition the contribution of mesoscale ocean circulation and spurious height signals associated with altimeter correction errors should be removed. The hardest signals to account for are signals with time scales of several years, like the El Niño Southern Oscillation.

The mean sea surface undulation (**mssh**) is based on a grid of the OSU MSS95 mean sea surface model [Yi, 1995] that is derived from one year of GEOSAT (JGM-2) GDRs, one year of ERS-1 NOAA IGDRs from Phase C, the first Geodetic Phase cycle of ERS-1 NOAA IGDRs, and one-year of TOPEX (JGM-2) GDRs.

In order to reduce the required memory, the original $3.75' \times 3.75'$ grid was sub-sampled at $7.5' \times 7.5'$ after which the values are interpolated using a bi-cubic polynomial interpolation. This procedure introduces no substantial reduction of accuracy over the bi-cubic spline interpolation in the original grid.

For ERS-1 and 2 a shift of 14.5 cm was applied to account for the anomalous bias in TOPEX that was absorbed into the MSS95 model.

The value in this field is the height of the mean sea surface above the geoid. Therefore, it contains a combination of the permanent ocean dynamic topography and short-wavelength features in the ocean surface related to sea mounts, sharp trenches, etc. To get the full height of the mean sea surface above the reference ellipsoid **mssh** should be added to **geoid**.

B.3.5 Dry tropospheric correction

The correction for the (one-way) delay of the radar altimeter pulse through the dry atmosphere is given by the [Saastamoinen, 1972] equation:

$$\text{drytrop} = -2.277 \cdot P_s \cdot (1 + 0.0026 \cos 2\phi)$$

where P_s is the atmospheric surface pressure in hPa and ϕ the latitude at the footprint.

Surface pressure is based on interpolation of $0.5^\circ \times 0.5^\circ$ grids of surface pressure provided by the French Meteorological office every 6 hours, derived from ECMWF model outputs.

B.3.6 Inverse barometer correction

The inverse barometer correction accounts for the *presumed* hydrostatic response of the sea surface to changes in atmospheric pressure. A 1 hPa increase in atmospheric pressure depresses the sea surface by about 1 cm.

The instantaneous correction to sea level is based on the surface pressure (P_s in hPa) which in turn is inferred from the dry tropospheric correction (**drytrop** in mm):

$$P_s = \frac{\text{drytrop}}{-2.277(1 + 0.0026 \cos 2\phi)}$$

The inverse barometer correction (**invbaro** in mm) is then:

$$\text{invbaro} = -9.948(P_s - 1013.3)$$

Note: The physical model behind the IB correction equation is that of a local hydrostatic response. Although at longer time scales most of the world's oceans do respond like an inverse barometer, this is not the case at short time scales or at some certain locations.

B.3.7 Solid Earth tide correction

The solid Earth tide is the response of the solid Earth to gravitational forces of Sun and Moon. As the response is fast enough to be considered in equilibrium with the tide generating forces, the tidal elevation is proportional to the tidal potential. The proportionality is determined by the Love numbers.

The solid Earth tide is computed as described by *Cartwright and Taylor* [1971] and *Cartwright and Edden* [1973] and includes a free core nutation resonance term near K_1 . The permanent tide is explicitly *excluded* since the solid earth tide correction only deals with temporal height variations.

B.3.8 Ocean Earth tide correction version 1

The ocean tide is the response of the ocean water column to the gravitational attraction of Sun and Moon. The value **otide1** models the so-called elastic (or bottom-referenced) ocean tidal elevation.

The ocean tide model CSR 3.0 (University of Texas at Austin, Center for Space Research) relies on the Grenoble hydrodynamical model FES94.1 [*Le Provost et al.*, 1994] for the shallow water regions and is enhanced with 89 cycles of TOPEX/Poseidon altimetry. The model is based on the orthotide approach in the diurnal band and in the semi-diurnal band. The classical equilibrium model for long period tides [*Cartwright and Taylor*, 1971; *Cartwright and Edden*, 1973] have been added. The spatial resolution of the model is $0.5^\circ \times 0.5^\circ$.

B.3.9 Ocean Earth tide correction version 2

The **otide2** field is derived from the ocean tide model FES95.2.1 by *Le Provost et al.* [1998] which is a purely hydrodynamical solution on basis of finite element modelling. The model simulates the eight major tidal constituents (M2, S2, N2, K2, 2N2, K1, O1, and Q1) plus an additional 19 (L2, T2, P1, ν_2 , μ_2 , ϵ_2 , λ_2 , η_2 , 2Q1, σ_1 , ρ_1 , M11, M12, χ_1 , π_1 , ϕ_1 , θ_1 , J1, and OO1) determined by admittance from these eight major constituents. The classical equilibrium model for long period tides [*Cartwright and Taylor*, 1971; *Cartwright and Edden*, 1973] have been added. The resolution of the model is $0.5^\circ \times 0.5^\circ$.

B.3.10 Load tide correction

The load tide is the compression of the ocean bottom (and the land masses surrounding the oceans) to changes in the ocean column as a result of ocean tides. The load tide can be considered the convolution of the ocean tide and the response of the upper lithosphere to ocean loading. This load tide model is derived from the CSR 3.0 ocean tide model.

B.3.11 Pole tide correction

In contrast to the solid Earth tide, ocean tide, and load tide, the pole tide has nothing to do with the gravitational attraction of the Sun and Moon. Instead, the pole tide is the response of the solid Earth to the oscillating behaviour of the direction of Earth's polar axis, or polar motion. Part of the response is the direct effect of the displacement of the reference ellipsoid with respect to the conventional reference pole. Secondly, the additional centrifugal force creates another displacement of the surface. For this a proportionality factor, the Love number k_2 is applied.

The pole tide is thus expressed by *Wahr* [1985] as:

$$ptide = -69.435 \sin 2\phi[(x - x_0) \cos \lambda - (y - y_0) \sin \lambda]$$

where x and y denote the instantaneous location of the IERS pole and x_0 (=0.042) and y_0 (=0.293) denote the mean location of the IERS pole (all in arcsec). The x-axis is towards Greenwich, the y-axis in the direction of 90° W longitude. ϕ and λ are latitude and longitude, respectively.

B.4 ERS-1/2 altimeter header records

Bytes	Type	Symbol	Unit	Description
1-4	char	iden	N/A	File type identifier
5-8	char	version	N/A	File version number
9-16	char	satel	N/A	Name of the satellite
17-20	char	mission	N/A	Mission identifier
21-24	int	sec_s	sec	Start time pass
25-28	int	sec_e	sec	End time pass
29-32	int	sec_n	sec	Time of nodal passage (sec part)
33-36	int	usec_n	usec	Time of nodal passage (usec part)
37-40	int	lon_n	udeg	Longitude of the node
41-44	int	orbnr	N/A	Absolute orbit number
45-48	int	cycnr	N/A	Cycle number
49-52	int	passnr	N/A	Pass number
53-56	int	datanr	N/A	Number of data records
57-76	char	cdate	N/A	Creation date and time
77-80	int	hspare	N/A	Spare header field

B.4.1 iden – File type identifier

Data type : char
Byte range : 1-4
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The file identifier is a character string of 4 bytes: "@RAW".

B.4.2 version – File version number

Data type : char
Byte range : 5-8
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The file version number is a character string of 4 bytes in the form "M.PP" where "M" is the major revision number and "PP" is the patch-level.

B.4.3 satel – Name of the satellite

Data type : char
Byte range : 9-16
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The name of the altimeter or the satellite is stored in an 8-byte character string with capitals only. Current values are "ERS-1" and "ERS-2".

B.4.4 mission – Mission identifier

Data type : char
Byte range : 17-20
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Identification of the phase of the satellite mission. For ERS-1 this 4-byte character may contain the letter "A" (followed by 3 spaces) through "G", see table below. For ERS-2 the phase is always "A".

Phase	Repeat	Name
A	3-day*	Commissioning Phase
B	3-day	First Ice Phase
C	35-day	Multi-disciplinary Phase
D	3-day	Second Ice Phase
E	168-day [†]	First Geodetic Phase
F	168-day [†]	Second Geodetic Phase
G	35-day	Tandem Phase

*The Commissioning Phase orbit is *not* collinear with the other 3-day repeat orbits

[†]The two Geodetic Phase orbits are *not* collinear; they interleave.

B.4.5 orbnr – Absolute orbit number

Data type : int
Byte range : 41-44
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The absolute orbit number is defined by ESA as 1 starting at launch and increasing by 1 at every ascending node. For ascending passes we store the number corresponding to the second half of the pass. This value is provided for reference only.

B.4.6 cycnr – Cycle number

Data type : int
Byte range : 45-48
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The ESA cycle numbering scheme is used. At launch we are somewhere in Cycle 0. The cycle number increases by one when pass number 1 is revisited. Pass 1 is the ascending pass that crosses the equator closest to the Greenwich meridian, counting eastward. Also, in the case of phase transitions, the cycle number is increased by 1. Note that under this definition the 18 Cycles in ERS-1 Phase C are spread over 19 Cycles (83 to 101), the first and last being incomplete.

B.4.7 passnr – Pass number

Data type : int
Byte range : 49-52
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The RADS data base is split up into passes. A pass extends half an orbit (half a revolution) and starts and ends at the ‘turnover point’ closest to the geographical North and South pole. Pass number 1 is the first pass in a cycle. This is the ascending pass that crosses the equator closest to the Greenwich meridian, counting eastward. In other words, pass number 1 is the pass in a cycle for which **lon_n** is the smallest. Every next pass obtains a number that is one higher than the previous. Hence, ascending passes are odd numbers, descending passes even numbers. There are 86 passes in an ERS 3-day repeat, 1002 in a 35-day repeat and 4822 in a 168-day repeat.

B.4.8 datanr – Number of data records

Data type : int
Byte range : 53-56
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Number of data records that follow the header.

B.4.9 cdate – Creation date and time

Data type : char
Byte range : 57-76
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Date and time on which the pass file was created. The format of this 20-byte string is "DD-MMM-YYYY HH:MM:SS", where "DD" is the day number, "MMM" is the month as a string (e.g. "Apr"), "YYYY" is the four-digit year number (e.g. "2000"), "HH" is the hour (e.g. "23"), "MM" are minutes and "SS" seconds.

B.4.10 hspare – Spare header field

Data type : int
Byte range : 77-80
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

In the current implementation this spare field is always zero.

B.5 TOPEX and Poseidon altimeter header records

B.5.1 iden – File type identifier

Data type : char
Byte range : 1-4
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Currently (as for all pass file header records) a value of "@RAW" is assigned to this variable.

Bytes	Type	Symbol	Unit	Description
1-4	char	iden	N/A	File type identifier
5-8	char	version	N/A	File version number
9-16	char	satel	N/A	Name of the satellite
17-20	char	mission	N/A	Mission identifier
21-24	int	sec_s	sec	Start time pass
25-28	int	sec_e	sec	End time pass
29-32	int	sec_n	sec	Time of nodal passage
33-36	int	usec_n	usec	Time of nodal passage (usec part)
37-40	int	lon_n	udeg	Longitude of the node
41-44	int	orbnr	N/A	Absolute orbit number
45-48	int	cycnr	N/A	Cycle number
49-52	int	passnr	N/A	Pass number (odd=asc,even=des)
53-56	int	datanr	N/A	Number of data records
57-76	char	cdate	N/A	Creation date as 'XX-YYY-ZZZZ 00:00:00'
77-80	int	hspare	N/A	Spare follow-up header record descriptor

B.5.2 version – File version number

Data type : char
Byte range : 5-8
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Version number of the pass file unique for the TOPEX/Poseidon part of RADS.

B.5.3 satel – Name of the satellite

Data type : char
Byte range : 9-16
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

This variable is set to "TOPEX" or "POSEIDON".

B.5.4 mission – Mission identifier

Data type : char
Byte range : 17-20
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

This variable is set to "ERM" since TOPEX/Poseidon is designed to fly over an

exactly repeating ground track.

B.5.5 orbnr – Absolute orbit number

Data type : int
Byte range : 41-44
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The orbit numbers used in the TOPEX/Poseidon data and header records correspond to the Rec_Number variable on page 28 in [AVISO, 1996]. Orbit number 680 coincides with pass 254 in cycle 1. This pass transits the equator at longitude 294.1°E on 3-oct-1992 01:08:37 UTC.

B.5.6 cycnr – Cycle number

Data type : int
Byte range : 45-48
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

In the TOPEX/Poseidon project cycle numbers are defined as consecutive time windows of 9.9156 days in length that correspond to the repeat period of the nominal TOPEX/Poseidon orbit. Within RADS the first pass in cycle 4 transits the equator on 22-oct-1992 22:01:51 UTC, and the first pass in cycle 5 transits the equator on 1-nov-1992 20:00:23 UTC.

B.5.7 passnr – Pass number (odd=asc,even=des)

Data type : int
Byte range : 49-52
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The TOPEX/Poseidon pass numbering scheme is explained in [AVISO, 1996] on pages 15 and 17. Pass number 1 is a south to north going or ascending track that intersects the equator at longitude 99.92 in the baseline orbit.

B.5.8 datanr – Number of data records

Data type : int
Byte range : 53-56
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **datanr** word gives the number of records that follow the header record in the pass file.

B.5.9 cdate – Creation date as 'XX-YYY-ZZZZ 00:00:00'

Data type : char
Byte range : 57-76
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

This variable represents the pass file creation date and time. It is written in the header record by the program that created the pass file for the first time.

B.5.10 hspare – Spare follow-up header record descriptor

Data type : int
Byte range : 77-80
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **hspare** word in the header record is usually assigned a value of 0 meaning that no follow-up header records exist. Values other than zero may be used for future versions to indicate that follow-up header records exist.

B.6 GEOSAT altimeter header records

Bytes	Type	Symbol	Unit	Description
1-4	char	iden	N/A	File type identifier
5-8	char	version	N/A	File version number
9-16	char	satel	N/A	Name of the satellite
17-20	char	mission	N/A	Mission identifier
21-24	int	sec_s	sec	Start time pass
25-28	int	sec_e	sec	End time pass
29-32	int	sec_n	sec	Time of nodal passage
33-36	int	usec_n	usec	Time of nodal passage (usec part)
37-40	int	lon_n	udeg	Longitude of the node
41-44	int	orbnr	N/A	Absolute orbit number
45-48	int	cycnr	N/A	Cycle number
49-52	int	passnr	N/A	Pass number (odd=asc,even=des)
53-56	int	datanr	N/A	Number of data records
57-76	char	ctime	N/A	Creation date as 'XX-YYY-ZZZZ 00:00:00'
77-80	int	hspare	N/A	Spare follow-up header record descriptor

B.6.1 iden – File type identifier

Data type : char
Byte range : 1-4
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Currently set to @RAW.

B.6.2 version – File version number

Data type : char
Byte range : 5-8
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Currently set to 1.0.

B.6.3 satel – Name of the satellite

Data type : char
Byte range : 9-16
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

Currently set to GEOSAT.

B.6.4 mission – Mission identifier

Data type : char
Byte range : 17-20
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

In the **mission** variable either the string ERM (exact repeat mission) or GM (geodetic mission) appears. The GM phase is associated with the first part of the mission, it is also denoted as **phase.a**. The ERM is associated with the second part of the mission, it is also denoted as **phase.b**.

B.6.5 **orbnr** – Absolute orbit number

Data type : int
Byte range : 41-44
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **orbnr** word in the Geosat level 0 header records is derived from the computed arc numbers provided in the **orb_epoc.dat** file on the Geosat altimeter JGM-3 GDRs on CD-ROM, cf. [*Lillibridge and Cheney, 1997*].

B.6.6 **cycnr** – Cycle number

Data type : int
Byte range : 45-48
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **cycnr** word in the Geosat level 0 header records is derived from the computed cycle numbers provided in either the **erm_eqc.txt** or the **gm_eqc.txt** file on the Geosat altimeter JGM-3 GDRs CD-ROMs, cf. [*Lillibridge and Cheney, 1997*].

B.6.7 **passnr** – Pass number (odd=asc,even=des)

Data type : int
Byte range : 49-52
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **passnr** word in the Geosat level 0 header records is derived from the computed pass numbers provided in either the **erm_eqc.txt** or the **gm_eqc.txt** file on the Geosat altimeter JGM-3 GDRs on CD-rom, cf. [*Lillibridge and Cheney, 1997*].

B.6.8 **datanr** – Number of data records

Data type : int
Byte range : 53-56
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **datanr** word gives the number of records that follow the header record in the pass file.

B.6.9 cdate – Creation date as 'XX-YYY-ZZZZ 00:00:00'

Data type : char
Byte range : 57-76
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

This variable represents the pass file creation date and time. It is written in the header record by the program that created the pass file for the first time.

B.6.10 hspare – Spare follow-up header record descriptor

Data type : int
Byte range : 77-80
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **hspare** word in the header record is usually assigned a value of 0 meaning that no follow-up header records exist. Values other than zero may be used in future versions to indicate that follow-up header records exist.

B.7 ERS-1/2 altimeter data records

B.7.1 alt1 – Orbit altitude version 1

Data type : int
Byte range : 17-20
Units : mm
Minimum value: 750000000
Maximum value: 850000000
Invalid value : 7FFFFFFF

This element contains the orbital altitude based on the DUT/DEOS JGM-3 precise orbits [Scharroo and Visser, 1998]. The orbital altitude is defined as the location of the nominal center of mass of the satellite above the TOPEX reference ellipsoid. Alternative orbit altitude models are given by **alt2** and **dalt3**.

B.7.2 alt2 – Orbit altitude version 2

Data type : int
Byte range : 21-24
Units : mm
Minimum value: 750000000
Maximum value: 850000000
Invalid value : 7FFFFFFF

This element contains the orbital altitude based on the DUT/DEOS DGM-E04 precise orbits [Scharroo and Visser, 1998]. These are the most precise orbits for

Bytes	Type	Symbol	Unit	Description
1-4	int	sec	sec	Time tag (seconds part)
5-8	int	usec	usec	Time tag (microseconds part)
9-12	int	lat	udeg	Latitude
13-16	int	lon	udeg	Longitude
17-20	int	alt1	mm	Orbit altitude version 1
21-24	int	alt2	mm	Orbit altitude version 2
25-28	int	altrng	mm	Observed range by altimeter
29-32	int	geoid	mm	Geoid height
33-34	int	drytrop	mm	Dry tropospheric range correction
35-36	int	wettrop1	mm	Wet tropospheric range correction version 1
37-38	int	wettrop2	mm	Wet tropospheric range correction version 2
39-40	int	iono1	mm	Ionospheric range correction version 1
41-42	int	iono2	mm	Ionospheric range correction version 2
43-44	int	invbaro	mm	Inverse barometric correction
45-46	int	stide	mm	Solid Earth tide correction
47-48	int	otide1	mm	Ocean Earth tide correction version 1
49-50	int	otide2	mm	Ocean Earth tide correction version 2
51-52	int	ltide	mm	Ocean Loading tide correction
53-54	int	ptide	mm	Pole tide correction
55-56	int	ssb1	mm	Sea State Bias correction version 1
57-58	int	ssb2	mm	Sea State Bias correction version 2
59-60	int	sigrng	mm	Sigma of the altimeter range
61-62	int	nrval	N/A	Number of valid measurements
63-64	int	swh	mm	Significant wave height
65-66	int	sigma0	cdb	Radar backscatter coefficient
67-68	int	dalt3	mm	Orbit altitude difference
69-70	int	tb23	ck	Brightness temperature at 21 GHz
71-72	int	tb36	ck	Brightness temperature at 36.5 GHz
73-74	flag	flags	N/A	Editing flags
75-76	int	speed	cms	Wind speed
77-78	int	altdot	mms	Orbit altitude rate
79-80	int	mssh	mm	Mean sea surface height relative to geoid

ERS available to date. The orbital altitude is defined as the location of the nominal center-of-mass of the satellite above the TOPEX reference ellipsoid. Alternative orbit altitude models are given by **alt1** and **dalt3**.

B.7.3 altrng – Observed range by altimeter

Data type : int
Byte range : 25-28
Units : mm
Minimum value: 750000000
Maximum value: 850000000
Invalid value : 7FFFFFFF

The 1-Hz altimeter range corrected for instrumental effects is the sum of the raw estimate and the instrumental corrections (look-up table correction, Doppler cor-

rection, internal calibration corrections, distance antenna to center-of-mass and external calibration correction). The instrumental corrections include the effect on of the drift of the Ultra-Stable Oscillator (USO) and the so-called SPTR jumps associated with a variable delay in the internal calibration determination. A 40.92 cm bias has been added to the ERS-1 ranges so that they conform to ERS-2 ranges.

B.7.4 wettrop1 – Wet tropospheric range correction version 1

Data type : int
Byte range : 35-36
Units : mm
Minimum value: -500
Maximum value: 0
Invalid value : 7FFF

The correction for the (one-way) delay of the radar altimeter pulse due to water vapor. **wettrop1** is based on the microwave radiometer brightness temperatures and the altimeter wind speed:

$$\text{wettrop1} = a + b \ln(280 - T_{23}) + c \ln(280 - T_{36}) + d(U - 7)$$

where T_{23} and T_{36} are the microwave brightness temperatures (in K) of the 23.8 GHz and 36.5 GHz channels and U is the altimeter wind speed in m/s.

The parameters a , b , c , and d are based on regression of simulated brightness temperatures against statistically representative sets of a atmospheric conditions from which they are derived:

$$a = 1654.35 \quad b = -546.68 \quad c = 225.58 \quad d = -1.37$$

In the generation of the ERS-1 OPR V3 product other values of a , b , c , and d have been used. On top of that the value d was wrongly applied with the opposite sign. To reverse the error made by the inversion of the sign of d we first apply a correction to all ERS-1 OPR V3 values (W_{OPR} in mm):

$$W = W_{OPR} + 3.04(U - 7)$$

As the brightness temperatures are not available on OPR V3, we can not recompute **wettrop1** with the proper parameters. We reside to a linear regression determined from the comparison of V6 and V3 data [Scharroo *et al.*, 1999b, 1999c]:

$$\begin{aligned} \text{wettrop1} &= 0.869 W + 27 \quad \text{for } W < -402 \\ \text{wettrop1} &= 0.770 W - 12 \quad \text{for } W \geq -402 \end{aligned}$$

After a gain fall in the 23.8 GHz channel of the ERS-2 microwave radiometer on 26 June 1996 at 16:00, a re-calibration algorithm is needed to unify the brightness temperatures with the ones before the event [Eymard and Boukabara, 1997]:

$$\text{tb23} = 0.93 T + 19.18$$

where T is the recorded brightness temperature in 0.01 K. After applying this correction, **wettrop1** is recomputed. In case the radiometer wet tropospheric correction is not available, the modelled value (**wettrop2**) can be used. It is strongly discouraged, however, to mix the two corrections.

B.7.5 **wettrop2 – Wet tropospheric range correction version 2**

Data type : int
Byte range : 37-38
Units : mm
Minimum value: -500
Maximum value: 0
Invalid value : 7FFF

The correction for the (one-way) delay of the radar altimeter pulse due to water vapor. **wettrop2** is based on interpolation in space and time of meteorological fields with a spatial resolution of $0.5^\circ \times 0.5^\circ$ and a temporal resolution of 6 hours. The fields are computed by the French Meteorological Office (FMO) based on ECMWF model outputs for temperature and humidity. Due to an error at FMO in the creation of the fields from the ECMWF data, all values for the model wet tropospheric delay (W in mm) prior to 1 December 1997 had to be corrected, *i.e.* for both ERS-1 and ERS-2:

$$\text{wettrop2} = 0.85 W - 6$$

The this field served as an alternative to the radiometer wet tropospheric correction **wettrop2**. Radiometric tropospheric corrections like **wettrop1** are generally preferred over meteorological equivalents like **wettrop2**. It is strongly discouraged, however, to mix the two corrections.

B.7.6 **iono1 – Ionospheric range correction version 1**

Data type : int
Byte range : 39-40
Units : mm
Minimum value: -250
Maximum value: 0
Invalid value : 7FFF

Since ERS-1 and ERS-2 carry single-frequency altimeters, there is no directly measured ionospheric correction available. Currently this field contains a copy of **iono2**. In the future we may include IRI95 or DORIS ionospheric corrections.

B.7.7 **iono2 – Ionospheric range correction version 2**

Data type : int
Byte range : 41-42
Units : mm
Minimum value: -250
Maximum value: 0
Invalid value : 7FFF

The ionospheric delay correction is based on modeled values of the total electron content (TEC, in electrons/m²) and the altimeter frequency f (13.8 GHz):

$$\text{iono2} = -40250 \cdot \text{TEC} / f^2$$

The Bent model [Llewellyn and Bent, 1973] is used to calculate the TEC values integrated to the satellite altitude of about 790 km. Predictions for the 12-month

running-average of the monthly averages of the sunspot number R12, published by CCIR are input to the model. The monthly median values of the critical frequency of the F2 layer are derived from these. Since for ERS there is no equivalent to the dual frequency ionospheric correction, the alternative field **iono1** is a copy of **iono2**.

B.7.8 **ssb1 – Sea State Bias correction version 1**

Data type : int
Byte range : 55-56
Units : mm
Minimum value: -1500
Maximum value: 1500
Invalid value : 7FFF

Due to the size of the altimeter footprint, the radar receives returns from a combination of wave crests and wave troughs. However, these scatterers do not contribute equally to the reflected pulse: wave troughs reflect better than wave crests, thus shifting the sea level measurement towards the troughs. The sea state bias is the overall offset between the centroid of the mean reflecting sea surface and the actual mean sea level averaged over the altimeter footprint. This bias is nearly linearly dependent on wave height. Small modifications for higher powers of wave height and wind speed make the sea state bias correction more accurate.

In addition to this physical effect, the so-called electromagnetic bias, there is also a contribution that is due to the instrument, or more precisely to the tracker that determines the altimeter range from the shape of the returned echo. At present, this instrument bias is indistinguishable from the electromagnetic bias. Hence, both contributions are combined in the sea state bias.

After applying a correction to the significant wave height (See **swh**) it appeared that the BM3 sea state bias algorithms by *Gaspar and Ogor* [1996] are equally applicable to the data originating from OPR versions 3 and 6. The algorithm for ERS-1 is:

$$\text{ssb1} = \text{swh}(-0.047 - 0.0035 U + 0.000160 U^2)$$

and for ERS-2:

$$\text{ssb1} = \text{swh}(-0.048 - 0.0026 U + 0.000126 U^2)$$

where **ssb1** is the Sea State Bias in mm, **swh** is the Significant Wave Height in mm, and U the wind speed in m/s.

B.7.9 **ssb2 – Sea State Bias correction version 2**

Data type : int
Byte range : 57-58
Units : mm
Minimum value: -1500
Maximum value: 1500
Invalid value : 7FFF

The sea state bias provided on the ERS OPR is simply 5.5% of the significant wave height. This (BM1) algorithm by *Gaspar and Ogor* [1994] has long been surpassed by a more accurate model, the use of which is strongly recommended. See **ssb1**.

B.7.10 sigrng – Sigma of the altimeter range

Data type : int
Byte range : 59-60
Units : mm
Minimum value: 1
Maximum value: 1000
Invalid value : 7FFF

The value **sigrng** is the standard deviation of the elementary (20-Hz) range estimates. Only “ocean” returns are taken into account. To get an estimate of the noise level of the 1-Hz range measurement, **sigrng** should be divided by $\sqrt{\text{nrval} - 2}$, where **nrval** is the number of 20-Hz measurements on which the 1-Hz range measurement is based.

B.7.11 nrval – Number of valid measurements

Data type : int
Byte range : 61-62
Units : N/A
Minimum value: 16
Maximum value: 20
Invalid value : 7FFF

The number of elementary (20-Hz) measurements that are considered to be valid “ocean” returns. This number of measurements has been used to compute the 1-Hz measurements of range, significant wave height and backscatter coefficient.

B.7.12 swh – Significant wave height

Data type : int
Byte range : 63-64
Units : mm
Minimum value: 0
Maximum value: 10000
Invalid value : 7FFF

1-Hz estimate of the significant wave height corrected for instrumental effects. ERS-1 wave heights from OPR Version 3 have been re-calibrated in order to unify the OPR Version 3 and Version 6 data [*Scharroo et al.*, 1999a]:

$$\text{swh} = 0.900 S + 247 \quad \text{for } S \leq 1256$$

$$\text{swh} = 1.003 S + 117 \quad \text{for } S > 1256$$

where S is the significant wave height (in mm) recorded on OPR Version 3. Unfortunately, in the production of the OPR V3 data it was decided to set negative values for the significant wave height to zero. This has the effect that the corresponding **swh** now start at 247 mm instead of at zero.

B.7.13 sigma0 – Radar backscatter coefficient

Data type : int
Byte range : 65-66
Units : cdb
Minimum value: 600
Maximum value: 3000
Invalid value : 7FFF

The 1 Hz backscatter coefficient (σ_0) corrected for instrumental effects.

B.7.14 dalt3 – Orbit altitude difference

Data type : int
Byte range : 67-68
Units : mm
Minimum value: N/A
Maximum value: N/A
Invalid value : 7FFF

In order to reconstruct the original D-PAF orbits (**H_Sat** on the ERS OPRs [CER-SAT, 1994, 1996]), this element is provided.

$$\mathbf{H_Sat} = \mathbf{alt2} + \mathbf{dalt3}$$

The D-PAF orbits for ERS-1 are based on SLR and crossover tracking data and the GFZ PGM035 gravity model. ERS-2 orbits are based on SLR and PRARE tracking data and the GFZ PGM055 gravity model. The D-PAF orbits are first corrected for the effect of time tag biases and are transformed to refer to the TOPEX ellipsoid. Alternative orbital altitude models are given by **alt1** and **alt2**.

B.7.15 tb23 – Brightness temperature at 21 GHz

Data type : int
Byte range : 69-70
Units : ck
Minimum value: 0
Maximum value: 28000
Invalid value : 7FFF

The brightness temperatures for both channels (23.8 GHz and 36.5 GHz) are computed using the processing scheme developed by *Bernard et al.* [1993]. The brightness temperatures are nadir viewing and have the same (radiometer) footprint of about 21 km in diameter. This field contains the brightness temperature for the 23.8 GHz channel. There are no values available for ERS-1 prior to Phase G. For Phase G the values include re-calibrations suggested by *Eymard et al.* [1996]. After a gain fall in the 23.8 GHz channel of the ERS-2 microwave radiometer on 26 June 1996 at 16:00, a re-calibration algorithm is needed to unify the brightness temperatures with the ones before the event [*Eymard and Boukabara, 1997*]:

$$\mathbf{tb23} = 0.93 T + 19.18$$

where T is the recorded brightness temperature in 0.01 K. Note that the radiometer wet tropospheric correction **wettrop1** depends on **tb23** and has to be recomputed using the recalibrated value for **tb23**.

B.7.16 tb36 – Brightness temperature at 36.5 GHz

Data type : int
Byte range : 71-72
Units : ck
Minimum value: 0
Maximum value: 28000
Invalid value : 7FFF

The brightness temperatures for both channels (23.8 GHz and 36.5 GHz) are computed using the processing scheme developed by *Bernard et al.* [1993]. The brightness temperatures are nadir viewing and have the same footprint of about 21 km in diameter. This field contains the brightness temperature for the 36.5 GHz channel. There are no values available for ERS-1 prior to Phase G. For Phase G the values include re-calibrations suggested by *Eymard et al.* [1996].

B.7.17 flags – Editing flags

Data type : flag
Byte range : 73-74
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The flags word **flags** on the ERS data records contains 16 bits. The meaning of each of the bits is defined in the following Table. In case the flags are copied from the original OPR Version 3 (v3) or Version 6 (v6) data, the relevant bits of the MCD (Measurement Confidence Data) word are mentioned (numbering of bits according to the OPR documentations [*CERSAT*, 1994, 1996]). In some cases, flags were not available on either v3 or v6 data, and the bit is not set (0).

When a flag related to a measurement is set, this does not mean that the corresponding data field is set to the ‘invalid’ value. Therefore, one should check the range of the data field and consider additional editing on certain data flags.

B.7.18 speed – Wind speed

Data type : int
Byte range : 75-76
Units : cms
Minimum value: 1
Maximum value: 2015
Invalid value : 7FFF

The wind speed is calculated using an empirical relation between the backscatter coefficient (σ_0) and the wind speed proposed by *Witter and Chelton* [1991]. As the limit is set to the range of σ_0 values to which this empirical relation applies, the effective range of wind speeds is 0.01 to 20.15 m/s.

Bit	Description
0	Altimeter flag: 1=ERS-1, 0=ERS-2
1	Satellite on track: 0=ok, 1=out of dead band around nominal track Based on OPR data (OPR v3: Bit 8; OPR v6: not set)
2	Not used, always 0
3	Not used, always 0
4	Depth indicator: 1=shallow water, 0=deep water. Based on $1^\circ \times 1^\circ$ mask generated at NOAA. Threshold depth is 2251 m.
5	Altimeter land flag: 1=land, 0=water Based on $5' \times 5'$ mask generated at NOAA.
6	Radiometer land flag: 1=land, 0=water Based on OPR data (OPR v3: Bit 10; OPR v6: Bit 20)
7	Not used, always 0
8	Corruption radiometer measurement: 0=ok, 1=rain or ice Based on OPR data (OPR v3: Bit 11; OPR v6: not set)
9	Quality of the 23.8 GHz brightness temperature: 0=ok, 1=out of range Based on OPR data (OPR v3: Bit 12; OPR v6: Bit 18)
10	Quality of the 36.5 GHz brightness temperature: 0=ok, 1=out of range Based on OPR data (OPR v3: Bit 13; OPR v6: Bit 19)
11	Quality of the range estimate: 0=ok, 1=bad (fatal) Based on OPR data (OPR v3: Bits 4 or 13; OPR v6: Bits 4, 5, or 6)
12	Quality of the wave height estimate: 0=ok, 1=bad Based on OPR data (OPR v3: Bit 6; OPR v6: Bit 7)
13	Quality of the backscatter coefficient estimate: 0=ok, 1=bad Based on OPR data (OPR v3: Bits 5 or 14; OPR v6: Bits 8 or 9)
14	Tracking mode: 0=normal, 1=preset Based on OPR data (OPR v3: not set; OPR v6: Bit 14)
15	Quality of the orbit: 0=ok, 1=degraded Based on OPR data (OPR v3: Bit 18; OPR v6: Bit 23)

B.7.19 altdot – Orbit altitude rate

Data type : int
Byte range : 77-78
Units : mms
Minimum value: -28000
Maximum value: 28000
Invalid value : 7FFF

The orbital altitude rate is the time derivative of the orbital altitude. This value can be used to estimate the effect of time tag errors. Due to the small difference in the orbital models this time derivative is the same for all these models.

Bytes	Type	Symbol	Unit	Description
1-4	int	sec	sec	seconds since 1.0 Jan 1985
5-8	int	usec	usec	microsecond correction
9-12	int	lat	udeg	Latitude
13-16	int	lon	udeg	Longitude
17-20	int	alt1	mm	Orbit altitude version 1
21-24	int	alt2	mm	Orbit altitude version 2
25-28	int	altrng	mm	Observed range by altimeter
29-32	int	geoid	mm	Geoid height
33-34	int	drytrop	mm	Dry tropospheric range correction
35-36	int	wettrop1	mm	Wet tropospheric range correction version 1
37-38	int	wettrop2	mm	Wet tropospheric range correction version 2
39-40	int	iono1	mm	Ionospheric range correction version 1
41-42	int	iono2	mm	Ionospheric range correction version 2
43-44	int	invbaro	mm	Inverse barometric correction
45-46	int	stide	mm	Solid Earth tide correction
47-48	int	otide1	mm	Ocean Earth tide correction version 1
49-50	int	otide2	mm	Ocean Earth tide correction version 2
51-52	int	ltide	mm	Ocean Loading tide correction
53-54	int	ptide	mm	Pole tide correction
55-56	int	ssb1	mm	Sea State Bias correction version 1
57-58	int	ssb2	mm	Sea State Bias correction version 2
59-60	int	sigrng	mm	Sigma of the altimeter range
61-62	int	nrval	N/A	Number of valid measurements
63-64	int	swh	mm	Significant wave height
65-66	int	sigma0	cdb	Radar backscatter coefficient
67-68	int	tb18	ck	Brightness temperature at 18 GHz
69-70	int	tb21	ck	Brightness temperature at 21 GHz
71-72	int	tb37	ck	Brightness temperature at 37 GHz
73-74	flag	flags	N/A	Editing flags
75-76	int	speed	cms	Wind speed
77-78	int	depth	m	Ocean depth
79-80	int	mssh	mm	Mean sea surface height relative to the geoid

B.8 TOPEX and Poseidon altimeter data records

B.8.1 alt1 – Orbit altitude version 1

Data type : int
Byte range : 17-20
Units : mm
Minimum value: 1200000000
Maximum value: 1400000000
Invalid value : 7FFFFFFF

The orbital altitude represented by the **alt1** variable is the NASA/GSFC computed orbital height based upon the JGM-3 orbit. It is taken from the **Sat_Alt** variable described on page 124 in [AVISO, 1996] whereby a default value is as-

signed in the case where the orbital height represented by **alt1** is below 1200 km or above 1400 km.

B.8.2 alt2 – Orbit altitude version 2

Data type : int
Byte range : 21-24
Units : mm
Minimum value: 1200000000
Maximum value: 1400000000
Invalid value : 7FFFFFFF

The orbital altitude represented by the **alt2** variable is the CNES computed orbital height. It is taken from the **HP_Sat** variable described on page 110 in [AVISO, 1996] whereby a default value is assigned in the case where the orbital height represented by **HP_Sat** is below 1200 km or above 1400 km.

B.8.3 altrng – Observed range by altimeter

Data type : int
Byte range : 25-28
Units : mm
Minimum value: 1200000000
Maximum value: 1400000000
Invalid value : 7FFFFFFF

The once per second altimeter range represented by the **altrng** variable is the measured range by the TOPEX or the Poseidon altimeter. Instrumental effects such as antenna offsets and instrumental drifts are taken into account. It is taken from the **H_Alt** variable described on page 106 in [AVISO, 1996] whereby a default value is assigned in the case where the observed range is below 1200 km or above 1400 km.

B.8.4 wettrop1 – Wet tropospheric range correction version 1

Data type : int
Byte range : 35-36
Units : mm
Minimum value: -1000
Maximum value: 100
Invalid value : 7FFF

The value represented by the **wettrop1** variable is a correction to the range observed by the altimeter. It is taken from the **Wet_H_Rad** variable described on page 135 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -1000 mm or above 100 mm. In order to obtain a corrected altimeter range the value of **wettrop1** needs to be added to the uncorrected altimeter range.

The **wettrop1** variable represents an radiometric wet tropospheric correction obtained by the Topex Microwave Radiometer TMR. The radiometer itself performs vertical brightness temperature observations of the Earth which acts as a black body radiating its power over the electromagnetic spectrum. The temperatures

are observed at three frequencies (18, 21 and 37 GHz whereby the 21 GHz channel corresponds to the water vapor absorption line. An estimation algorithm then transforms the three temperatures into columnar water vapor estimates which in turn are converted into the desired wet tropospheric range delay.

B.8.5 **wetrop2 – Wet tropospheric range correction version 2**

Data type : int
Byte range : 37-38
Units : mm
Minimum value: -1000
Maximum value: 100
Invalid value : 7FFF

The value represented by the **wetrop2** variable is a correction to the range observed by the altimeter. It is taken from the **Wet_Corr** variable described on page 132 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -1000 mm or above 100 mm. In order to obtain a corrected altimeter range the value of **wetrop2** needs to be added to the uncorrected altimeter range.

The **wetrop2** variable is the interpolated wet meteorological tropospheric range correction. It is derived from six hourly provided meteorological data received from the European Centre for Medium Range Weather Forecasting (ECMWF). In reality the range correction is between 6 and 30 cm, it can be used independently or as a backup to support the records there where the TMR failed.

B.8.6 **iono1 – Ionospheric range correction version 1**

Data type : int
Byte range : 39-40
Units : mm
Minimum value: -500
Maximum value: 40
Invalid value : 7FFF

For TOPEX the value represented by the **iono1** variable is a correction to the range observed by the altimeter. It is taken from the **Iono_Cor** variable described on page 116 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -500 mm or above 40 mm. In order to obtain a corrected altimeter range the value of **iono1** needs to be added to the uncorrected altimeter range. The **iono1** variable represents ionospheric range delay observed by a two frequency measurement of the TOPEX altimeter. The variable itself should be smoothed in the spatial domain prior to application. The smoother should be designed such that a moving average is computed over a window of 10 to 15 one Hertz measurements. Care should be taken to avoid noise contamination at the higher latitudes, a prefiltering method using a median filter or likewise might be advisable. An undefined value is assigned to the **iono1** variable when the Poseidon altimeter is on.

B.8.7 **iono2 – Ionospheric range correction version 2**

Data type : int
Byte range : 41-42
Units : mm
Minimum value: -1000
Maximum value: 0
Invalid value : 7FFF

The value represented by the **iono2** variable is a correction to the range observed by the altimeter. It is taken from the **Iono_Dor** variable described on page 116 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -1000 mm or above 0 mm. In order to obtain a corrected altimeter range the value of **iono2** needs to be added to the uncorrected altimeter range. The **iono2** variable represents ionospheric range delay observed by a two frequency measurement of the Doris tracking beacons. The variable itself is already smoothed in the spatial domain and should not be further processed as is the case with **iono1**. In general one can state that **iono2** appears to be less noisy. It is less representative of the vertical ionospheric range delay as seen by the altimeter since **iono2** is constructed from oblique observations. Its accuracy, therefore depends on predictive techniques which must assume something about the global structure of the ionosphere.

B.8.8 **ssb1 – Sea State Bias correction version 1**

Data type : int
Byte range : 55-56
Units : mm
Minimum value: -1200
Maximum value: 0
Invalid value : 7FFF

The value represented by the **ssb1** variable is a correction to the range observed by the altimeter. It is taken from the **SSB_Corr_K1** variable described on page 125 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -1200 mm or above 0 mm. In order to obtain a corrected altimeter range the value of **ssb1** needs to be added to the uncorrected altimeter range. The **ssb1** variable represents the Ku band one-per-frame range correction for the Sea State Bias. It relies on the so-called BM4 formulation of the sea state bias as is described in [Gaspar and Ogor, 1996]. For more details see pages 45 and 46 in [AVISO, 1996].

B.8.9 **ssb2 – Sea State Bias correction version 2**

Data type : int
Byte range : 57-58
Units : mm
Minimum value: -1200
Maximum value: 0
Invalid value : 7FFF

The value represented by the **ssb2** variable is a correction to the range observed by the TOPEX altimeter. It is taken from the **SSB_Corr_K2** variable described on

page 126 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below -1200 mm or above 0 mm. In order to obtain a corrected altimeter range the value of **ssb2** needs to be added to the uncorrected altimeter range. The **ssb2** variable represents the Ku band one-per-frame range correction for the Sea State Bias. It relies on the NASA project team formulation of the sea state bias as is described on page 46 in [AVISO, 1996]. An undefined value is assigned to the **ssb2** if the Poseidon altimeter is on.

B.8.10 **sigrng** – Sigma of the altimeter range

Data type : int
Byte range : 59-60
Units : mm
Minimum value: 0
Maximum value: 10000
Invalid value : 7FFF

The **sigrng** variable represents the root mean square of the high rate altimeter range relative to the 1 Hz data measured by the TOPEX altimeter. For Poseidon the **sigrng** variable represents the root mean square of the high rate (20 Hz) altimeter range relative to the 1 Hz data measured by that altimeter. The variable is taken from the **RMS_H_Alt** variable described on page 123 in [AVISO, 1996] whereby a default value is assigned in the case where the rms value gets below 0 or above 10000 mm.

B.8.11 **nrval** – Number of valid measurements

Data type : int
Byte range : 61-62
Units : N/A
Minimum value: 0
Maximum value: 10
Invalid value : 7FFF

The value represented by the **nrval** refers to the number of valid ranges seen by the TOPEX or the Poseidon altimeter. It is taken from the **Nval_H_Alt** variable described on page 121 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 or above 10 for TOPEX, or above 20 for Poseidon.

B.8.12 **swh** – Significant wave height

Data type : int
Byte range : 63-64
Units : mm
Minimum value: 0
Maximum value: 25000
Invalid value : 7FFF

The value represented by the **swh** is observed by the altimeter. It is taken from the **SWH_K** variable described on page 127 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 mm or

above 25000 mm. The **swh** variable is meant to indicate the Significant Wave Height observed from the return radar pulse recorded as a waveform sample. For the TOPEX altimeter it was confirmed during the RADS project that the **swh** slowly drifts away. It is related to an altimeter chirp generator aging effect and caused the TOPEX/Poseidon project management to initiate a switch over to the backup altimeter, also known as side B. For the Poseidon altimeter no drift effects have been reported in the **swh** variable.

B.8.13 **sigma0** – Radar backscatter coefficient

Data type : int
Byte range : 65-66
Units : cdb
Minimum value: 0
Maximum value: 30000
Invalid value : 7FFF

The value represented by the **sigma0** is observed by the altimeter. It is taken from the **Sigma0_K** variable described on page 125 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 dB or above 30 dB. The **sigma0** variable represents the backscatter coefficient observed by the altimeter, it is a measure for the automatic gain control value on the Ku band which is corrected by an algorithm.

B.8.14 **tb18** – Brightness temperature at 18 GHz

Data type : int
Byte range : 67-68
Units : ck
Minimum value: 0
Maximum value: 22000
Invalid value : 7FFF

The value represented by the **tb18** is observed by the Topex microwave radiometer. It is taken from the **Tb_18** variable described on page 129 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 or above 220 Kelvin. The **tb18** variable is meant to represent a brightness temperature of the Earth at 18 GHz. (Brightness temperatures are obtained by measuring the noise caused by thermal radiation within a given radio frequency band. To prevent that the thermal noise of the amplifiers within the radiometer are determining the outcome of this experiment a differential mode is used whereby the cold space noise and the hot object noise are observed. Cancellation of the amplifier noise is obtained by taking the difference of the “cold” and the “hot” noise observations.)

B.8.15 tb21 – Brightness temperature at 21 GHz

Data type : int
Byte range : 69-70
Units : ck
Minimum value: 0
Maximum value: 25000
Invalid value : 7FFF

The value represented by the **tb21** is observed by the Topex microwave radiometer. It is taken from the **Tb_21** variable described on page 129 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 or above 250 Kelvin. The **tb21** variable is meant to represent a brightness temperature of the Earth at 21 GHz.

B.8.16 tb37 – Brightness temperature at 37 GHz

Data type : int
Byte range : 71-72
Units : ck
Minimum value: 0
Maximum value: 27000
Invalid value : 7FFF

The value represented by the **tb37** is observed by the Topex microwave radiometer. It is taken from the **Tb_37** variable described on page 129 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 or above 250 Kelvin. The value of 250 Kelvin is too low and the lower limit should have been 270 K, this is caused by a bug in the **gdr2raw** program. The **tb37** variable is meant to represent a so-called brightness temperature of the Earth at 37 GHz.

B.8.17 flags – Editing flags

Data type : flag
Byte range : 73-74
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **flags** variable is a 16 bit integer which can be used to test the following conditions.

- bit 0 is set when TOPEX is on, otherwise Poseidon is on.
- bit 1 is set when the ionosphere is ok
- bit 2 is set when TMR channel 21a is on
- bit 3 is set when TMR channel 21b is on
- bit 4 is set when the altimeter footprint is over shallow water, otherwise it is over deep water with depths greater than 200 meters.
- bit 5 is set when the altimeter footprint is over land otherwise it is over water

- bit 6 is set when it is land for the TMR, otherwise it is water for the TMR
- bit 7 is set for ice otherwise it is water
- bit 8 is set when a rain cell is suspected
- bit 9 is part of the **TMR_BAD** word
- bit 10 is part of the **TMR_BAD** word
- bit 11 is set when there is a TOPEX hardware problem
- bit 12 is set when there is a Poseidon hardware problem
- bit 13 is set when the attitude is out of range
- bit 14 is set when the altimeter is in fine tracking mode
- bit 15 is not used

whereby it should be noted that:

- bit 5 is overwritten by the GMT landsea mask and not taken from the AVISO/CLS source data which relies on the terrain base dataset and an elevation test (which is obviously wrong for land below sea level).
- bit 7 is unreliable in the tropics, and perhaps also at other places, it was never seriously investigated.
- bits 9 and 10 are the same as bits 0 and 1 in the **TMR_BAD** word [AVISO, 1996] on page 131. '00' means that the TMR works fine.
- bit 11 reports a problem with both the Ku and C bands on TOPEX, do not use when set.
- bit 12 reports a possible problem with Poseidon.
- bit 13 is only true for Poseidon, it was never verified.
- bit 14 is true for both altimeters. For some reason, bit 14 (0x4000) is not properly set when the Poseidon altimeter is on, this can only be the result of the **Current_Mode_1** or **2** word on the GDR's, (a problem yet to fix in the **gdr2raw** program). It is perfectly safe to test bit 14 for TOPEX.
- bit 15 is a spare bit.

B.8.18 speed – Wind speed

Data type : int
Byte range : 75-76
Units : cms
Minimum value: 0
Maximum value: 2500
Invalid value : 7FFF

The value represented by the **speed** is indirectly derived from the altimeter data. It is taken from the **Wind_Sp** variable described on page 135 in [AVISO, 1996] whereby a default value is assigned in the case where the variable in question is below 0 m/s or above 25 m/s. The **speed** variable is meant to indicate the wind speed which in turn is derived from the return radar pulse recorded as a waveform sample. Although the value itself is represented in cm/s the resolution is no better than 0.1 m/s according to [AVISO, 1996].

B.8.19 depth – Ocean depth

Data type : int
Byte range : 77-78
Units : m
Minimum value: -30000
Maximum value: 30000
Invalid value : 7FFF

The value represented by the **depth** variable is the bathymetric or topographic height at the altimeter footprint. It is derived from the ETOPO5 dataset smoothed at 30 minute resolution.

B.9 GEOSAT altimeter data records

B.9.1 alt1 – Orbit altitude version 1

Data type : int
Byte range : 17-20
Units : mm
Minimum value: N/A
Maximum value: N/A
Invalid value : 7FFFFFFF

The orbital altitude represented by the **alt1** variable is the NASA/GSFC computed value based upon the JGM-3 orbit. It is taken from the **ORB** variable described on page 8 in [Lillibridge and Cheney, 1997].

B.9.2 alt2 – Orbit altitude version 2

Data type : int
Byte range : 21-24
Units : mm
Minimum value: N/A
Maximum value: N/A
Invalid value : 7FFFFFFF

The **alt2** variable not used and assigned a undefined value.

B.9.3 altrng – Observed range by altimeter

Data type : int
Byte range : 25-28
Units : mm
Minimum value: N/A
Maximum value: N/A
Invalid value : 7FFFFFFF

The once-per-second altimeter range represented by the **altrng** variable is measured range by the Geosat altimeter. Instrumental effects such as antenna offsets and instrumental drifts are taken into account. It means that the ultra stable oscillator correction and the internal calibration correction as described on page 14 in [Lillibridge and Cheney, 1997] are applied.

Bytes	Type	Symbol	Unit	Description
1-4	int	sec	sec	seconds since 1 Jan 1985
5-8	int	usec	usec	microsecond correction
9-12	int	lat	udeg	Latitude
13-16	int	lon	udeg	Longitude
17-20	int	alt1	mm	Orbit altitude version 1
21-24	int	alt2	mm	Orbit altitude version 2
25-28	int	altrng	mm	Observed range by altimeter
29-32	int	geoid	mm	Geoid height
33-34	int	drytrop	mm	Dry tropospheric range correction
35-36	int	wettrop1	mm	Wet tropospheric range correction version 1
37-38	int	wettrop2	mm	Wet tropospheric range correction version 2
39-40	int	iono1	mm	Ionospheric range correction version 1
41-42	int	iono2	mm	Ionospheric range correction version 2
43-44	int	invbaro	mm	Inverse barometric correction
45-46	int	stide	mm	Solid Earth tide correction
47-48	int	otide1	mm	Ocean Earth tide correction version 1
49-50	int	otide2	mm	Ocean Earth tide correction version 2
51-52	int	ltide	mm	Ocean Loading tide correction
53-54	int	ptide	mm	Pole tide correction
55-56	int	ssb1	mm	Sea State Bias correction version 1
57-58	int	ssb2	mm	Sea State Bias correction version 2
59-60	int	sigrng	mm	Sigma of the altimeter range
61-62	int	nrval	N/A	Number of valid measurements
63-64	int	swh	mm	Significant wave height
65-66	int	sigma0	cdb	Radar backscatter coefficient
67-68	int	wet_nvap	mm	wet troposphere from climatology
69-70	int	dry_ecmwf	mm	dry troposphere from ECMWF model
71-72	int	att	cdeg	spacecraft attitude (off-nadir cone angle)
73-74	flag	flags	N/A	Editing flags
75-76	int	speed	cms	Wind speed
77-78	int	depth	m	Ocean depth
79-80	int	mssh	mm	Mean sea surface height relative to geoid

B.9.4 wettrop1 – Wet tropospheric range correction version 1

Data type : int
Byte range : 35-36
Units : mm
Minimum value: -1000
Maximum value: 100
Invalid value : 7FFF

The value represented by the **wettrop1** variable is a correction to the range observed by the altimeter. It is taken from the **WET_T/S** variable described on page 8 in [Lillibridge and Cheney, 1997]. In order to obtain a corrected altimeter range the value of **wettrop1** needs to be added to the uncorrected altimeter range. The **wettrop1** variable represents an radiometric wet tropospheric correction derived from the TOVS/SSMI radiometric observations.

B.9.5 wettrop2 – Wet tropospheric range correction version 2

Data type : int
Byte range : 37-38
Units : mm
Minimum value: -1000
Maximum value: 100
Invalid value : 7FFF

The value represented by the **wettrop2** variable is a correction to the range observed by the altimeter. It is taken from the **WET_NCEP** variable described on page 8 in [Lillibridge and Cheney, 1997]. In order to obtain a corrected altimeter range the value of **wettrop2** needs to be added to the uncorrected altimeter range. The **wettrop2** variable is the interpolated wet meteorological tropospheric range correction. It is derived from daily meteorological data received from NCEP/NCAR. In reality the range correction is between 6 and 30 cm, it can be used independently or as a backup to support the records there where **wettrop1** is unavailable.

B.9.6 iono1 – Ionospheric range correction version 1

Data type : int
Byte range : 39-40
Units : mm
Minimum value: -500
Maximum value: 40
Invalid value : 7FFF

The value represented by the **iono1** variable is a correction to the range observed by the altimeter. It is taken from the **IONO** variable described on page 8 in [Lillibridge and Cheney, 1997]. In order to obtain a corrected altimeter range the value of **iono1** needs to be added to the uncorrected altimeter range. The **iono1** variable represents ionospheric range delay as derived from the IRI95 model [Lillibridge and Cheney, 1997].

B.9.7 iono2 – Ionospheric range correction version 2

Data type : int
Byte range : 41-42
Units : mm
Minimum value: -1000
Maximum value: 0
Invalid value : 7FFF

The **iono2** variable is not used and assigned an undefined value.

B.9.8 ssb1 – Sea State Bias correction version 1

Data type : int
Byte range : 55-56
Units : mm
Minimum value: -1200
Maximum value: 0
Invalid value : 7FFF

The value represented by the **ssb1** variable is a correction to the range observed by the altimeter. It is taken from the **SSB** variable described on page 8 in [Lillibridge and Cheney, 1997]. In order to obtain a corrected altimeter range the value of **ssb1** needs to be added to the uncorrected altimeter range. The **ssb1** variable represents the sea state bias as is described in [Gaspar and Ogor, 1996].

B.9.9 ssb2 – Sea State Bias correction version 2

Data type : int
Byte range : 57-58
Units : mm
Minimum value: -1200
Maximum value: 0
Invalid value : 7FFF

The **ssb2** variable is not used and assigned a undefined value.

B.9.10 sigrng – Sigma of the altimeter range

Data type : int
Byte range : 59-60
Units : mm
Minimum value: 0
Maximum value: 10000
Invalid value : 7FFF

The **sigrng** variable represents the root mean square of the high rate altimeter range relative to the 1 Hz data measured by the Geosat altimeter. It is taken from the **SIG_H** variable described on page 8 in [Lillibridge and Cheney, 1997].

B.9.11 nrval – Number of valid measurements

Data type : int
Byte range : 61-62
Units : N/A
Minimum value: 0
Maximum value: 10
Invalid value : 7FFF

The value represented by the **nrval** refers to the number of valid ranges seen by the Geosat altimeter. It is taken from the **H1-H10** variables mentioned on page 8 in [Lillibridge and Cheney, 1997].

B.9.12 swh – Significant wave height

Data type : int
Byte range : 63-64
Units : mm
Minimum value: 0
Maximum value: 25000
Invalid value : 7FFF

The value represented by the **swh** is observed by the altimeter. It is taken from the **SWH** variable described on page 8 in [Lillibridge and Cheney, 1997]. The **swh** variable indicates the Significant Wave Height observed from the return radar pulse recorded as a waveform sample. The **swh** value has been increased by 13% [Lillibridge and Cheney, 1997].

B.9.13 sigma0 – Radar backscatter coefficient

Data type : int
Byte range : 65-66
Units : cdb
Minimum value: 0
Maximum value: 30000
Invalid value : 7FFF

The value represented by the **sigma0** is observed by the altimeter. It is taken from the **SIG_00** variable described on page 8 in [Lillibridge and Cheney, 1997]. The **sigma0** variable represents the backscatter coefficient observed by the altimeter.

B.9.14 wet_nvap – wet troposphere from climatology

Data type : int
Byte range : 67-68
Units : mm
Minimum value: -1000
Maximum value: 100
Invalid value : 7FFF

The value represented by the **wet_nvap** variable is a correction to the range observed by the altimeter. It is taken from the **WET_NVAP** variable described on page 8 in [Lillibridge and Cheney, 1997]. In order to obtain a corrected altimeter range the value of **wet_nvap** needs to be added to the uncorrected altimeter range. This model may be used as an alternative for **wettrop1** or **wettrop2**. The **wet_nvap** variable represents a climatological wet tropospheric correction derived from NASA NVAP.

B.9.15 dry_ecmwf – dry troposphere from ECMWF model

Data type : int
Byte range : 69-70
Units : mm
Minimum value: -3000
Maximum value: -2000
Invalid value : 7FFF

The value represented by the **dry_ecmwf** variable is a correction to the range observed by the altimeter. It is taken from the **DRY_ECMWF** variable described on page 8 in [Lillibridge and Cheney, 1997]. This variable corresponds to the dry tropospheric correction derived from the ECMWF data. In order to obtain a corrected altimeter range the value of **dry_ecmwf** needs to be added to the uncorrected altimeter range.

B.9.16 att – spacecraft attitude (off-nadir cone angle)

Data type : int
Byte range : 71-72
Units : cdeg
Minimum value: N/A
Maximum value: N/A
Invalid value : 7FFF

The value represented by the **att** variable is derived from the altimeter waveform sample. It is taken from the **ATT** variable described on page 8 in [Lillibridge and Cheney, 1997]. The **att** variable indicates the off-nadir spacecraft orientation.

B.9.17 flags – Editing flags

Data type : flag
Byte range : 73-74
Units : N/A
Minimum value: N/A
Maximum value: N/A
Invalid value : N/A

The **flags** variable is a 16 bit status word where the bits are taken from the **FLAGS** variable described on page 8 in [Lillibridge and Cheney, 1997].

B.9.18 speed – Wind speed

Data type : int
Byte range : 75-76
Units : cms
Minimum value: 0
Maximum value: 2500
Invalid value : 7FFF

The value represented by the **speed** is indirectly derived from the altimeter data. It is taken from the **WS** variable described on page 8 in [Lillibridge and Cheney, 1997]. The **speed** variable is meant to indicate the wind speed which in turn is derived from the return radar pulse recorded as a waveform sample.

B.9.19 depth – Ocean depth

Data type : int
Byte range : 77-78
Units : m
Minimum value: -30000
Maximum value: 30000
Invalid value : 7FFF

The value represented by the **depth** variable is the bathymetric or topographic height at the altimeter footprint. It is derived from a 5 minute commercial dataset obtained from the GETECH company, Leeds, UK.

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