Coastal Altimetry and Applications

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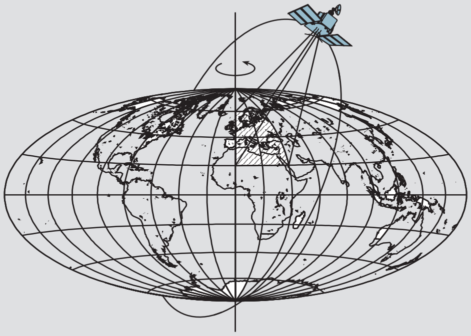

Report No. 464

Geodetic and GeoInformation Science
Department of Civil and Environmental Engineering and Geodetic Science
The Ohio State University
Columbus, Ohio 43210-1275

January 1999

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Acknowledgments

This report was prepared by Dr. Michael Anzenhofer of the Geo-Forschungs-Zentrum (GFZ) Potsdam, Germany, while visiting the Department of Civil and Environmental Engineering and Geodetic Science (CEEGS), Ohio State University, during 1997-1998. The visit was hosted by Prof. C.K. Shum of the Department of Civil and Environmental Engineering and Geodetic Science. This work was partially supported by NASA Grant No.735366, Improved Ocean Radar Altimeter and Scatterometer Data Products for Global Change Studies and Coastal Application, and by a grant from GFZ, Prof. Christoph Reigber, Director. We gratefully acknowledge Prof. Christoph Reigber's role for making this visit possible.

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1. Introduction

In open ocean areas highly accurate sea level measurements can be provided by satellite altimetry. Due to proper modeling of ocean state quantities, such as tides, and accurate measurements of atmospheric refraction the radial accuracy of altimeter data is in centimeter level. Recent investigations with long time series of altimeter data (Anzenhofer and Gruber, 1998, Nerem et al. 1997, Shum et al., 1995, Shum, 1998) have demonstrated that relative accuracies for drifts are better than 1 millimeter. Near the coasts, however, accuracy decreases dramatically. Ocean tidal models introduce errors in decimeter level. The altimeter range corrections become incorrect or are flagged 'not available' in the official products. Furthermore, 1 Hz measurements prohibit investigations close to the coasts. The problems can be overcome by the use of 20 Hz waveform data with individual signal analysis, called retracking. With this data, shallow water areas can be investigated with much more data and closer to the coast lines than the official products. However, the use of this data introduce new problems, such as a higher noise, and new processing strategies. One application is the determination of gravity anomalies, which are usually degraded in accuracy near the coast.

The first part of the report describes the generation of coastal altimeter data, which includes a detailed section of the retracking algorithms and their implementation. The second part shows the design and the structure of the intermediate ERS waveform format. The third part describes different analysis of the coastal altimeter data showing the quality and problems of retracked altimeter data. At last a summary of the problems with waveform data is given and future improvements are outlined.

2. Generation of Coastal Altimeter Data

2.1 Retracking System Design

The general purpose of the retracking system is to process non-ocean altimeter data in order to derive geophysical products and new insights into the system Earth that have fundamental impacts for geodesy, geophysics, oceanography, ice research, and climatology.

Usually, altimeter data are processed and used only over the oceans, as signal processing and corrections are well known. Over non-ocean surfaces, the return signals depend on the surface characteristics, which can alter in time and region. This means, that each single signal -they are called waveforms- must be specifically analyzed and processed. In general, altimeter data are delivered as 1 Hz products, known as GDR (geophysical data records). The waveforms, however, are 20 Hz measurements. Thus, the data amount and the special signal processing induce a complex and data intensive processing chain known as retracking. Furthermore, the processing and research in this topic has been done only piecewise and for restricted time periods in the past and present. The retracking system, which is developed within the value-adding work package Ocean/Ice for Envisat-1, is designed to

- process all (spatial and temporal) altimeter waveform data (past and present), especially for ERS-1/2 and Envisat-1,
- allow ice/land research in the same manner as done for the oceans, and
- enable coastal applications.

The latter, which is the topic of the report at hand, is an open issue, driven by new applications and need for further improvements of existing models. An incomplete list with applications of improved altimeter data in coastal regions should demonstrate their need:

- ship routing
- harbour dredging
- tidal model improvements
- extensions as close as possible to land for gravity anomalies, sea surface height models etc.

2.2 Retracking System Decomposition

Based on the experience of ERS altimeter data processing within the D-PAF, a retracking system has been designed, which will be fully implemented a few months before the launch of Envisat-1. 3 major requirements were found that set up the frame of the retracking system:

1. Allow a long-term processing of all altimeter waveforms, although they are extreme data-intensive and processing-time-consuming.
2. Allow the use of all developed and tested programs to process and analyze altimeter data, which were implemented within D-PAF activities, e.g. crossover generation, gridding etc..
3. Generate a mission independent data structure from waveform data, which allows the combined use of different mission data.

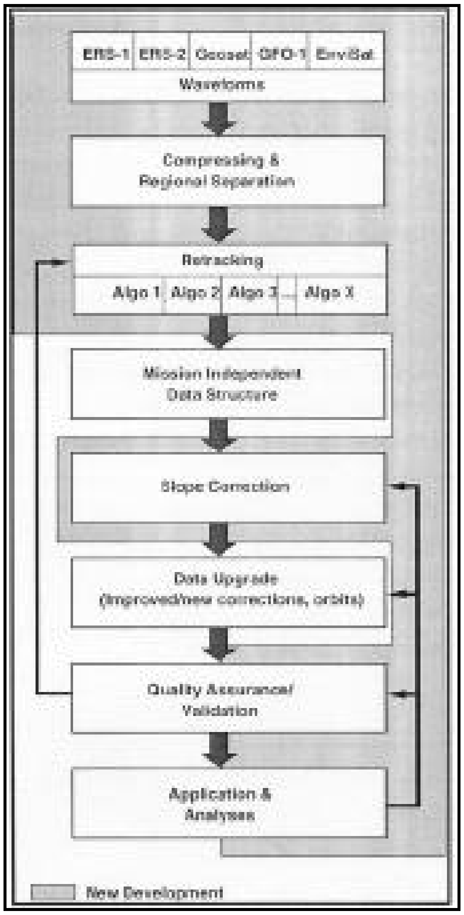

Fig. 1: Retracking System

The listed requirements led to a retracking system, which is displayed in figure 1. The retracking system, its specific components, and their relationship is described in brief in the following section.

The altimeter waveforms of past and present missions are distributed with different formats and data contents. Mostly, this implies a specific data access software, which sometimes is provided by the processing system. The data amount and additional information -if needed or not- is extremely high, e.g. as mentioned for ERS-1/2 up to 1000 Exabytes. The data distribution medium, logistic, and sizes do not allow a systematic or individual processing of altimeter waveform data. This requires a reasonable data compressing and transcription to another storage medium (CD or disk). The proposed data compression consists of 3 steps:

- data compressing, so that only record items remain that are needed for further processing, either for quality/editing or retracking,
- extraction of land and ice areas, because ocean waveform retracking is not necessary as validated ocean data are available, and
- regional separation in continents to allow continent-wise processing easily.

The regional separation is an important step in the retracking system, because it allows faster data processing and data extraction. Earlier waveform data investigations and processing have shown that the data were never globally processed. There has always been a regional separation and treatment of the data, because

- ocean data were mostly not needed,
- different surfaces (land/ice) need different retracking algorithms, and
- regional interest stood behind the analyses.

Having these reasons in mind, the waveforms data were split into continents. In table 1 the regional limits are presented. Furthermore, there are some constraints for waveforms to be processed:

- only waveforms are considered, with have water depths greater than -200 m, which allows also coastal applications
- all waveforms are processed with absolute geographical latitudes greater than 55 to include all possible ice and sea-ice areas.

Region	Longitude	Latitude
Europe	$-12^0 < \_ < +65^0$	$+28^0 < \_ < +90^0$
Greenland	$-80^0 < \_ < -12^0$	$+55^0 < \_ < +90^0$
Africa	$-20^0 < \_ < +65^0$	$-40^0 < \_ < +40^0$
North America	$-180^0 < \_ < -50^0$	$+5^0 < \_ < +90^0$
South America	$-90^0 < \_ < -30^0$	$-60^0 < \_ < +14^0$
Asia	$+65^0 < \_ < +180^0$	$+10^0 < \_ < +90^0$
Antarctica	$-180^0 < \_ < +180^0$	$-90^0 < \_ < -55^0$
Australia	$+65^0 < \_ < +180^0$	$-50^0 < \_ < +10^0$

Table 1: Regional Separation Limits

The next step is the retracking itself, which means the analysis and processing of waveforms in order to extract altimeter ranges. Therefore, a set of retracking algorithms (Anzenhofer, 1998) has been developed, which can handle waveforms of different shapes. This is the most critical and time-consuming part of the whole retracking system, as each 20 Hz waveform must be analyzed, processed, and validated, possibly in several iterations. The result of the retracking step is the generation of a mission independent data structure, which will be the same as for ocean GDR. This component allows the use of all programs, including quality control, generation of higher level products, and data exchange.

The technical note Retracking (Anzenhofer, 1998) has demonstrated that the slope correction is the most critical correction for land/ice altimeter data. The corrections highly depend on the surface slopes and, thus, require very good surface slope informations from digital terrain models. As 20 Hz altimeter data require a spatial resolution of 350 m, digital terrain models of that resolutions are in most cases not available. The slope information can be extracted from the along-track altimeter data itself by an iteration scheme (Anzenhofer, 1998). However, data gaps or data spikes make it very difficult to derive reasonable slope angles and, thus, corrections.

It should be mentioned that the slope correction is needed only for absolute height differences. Relative investigations can be performed without the slope correction. This implies only errors, if surface slopes vary in time. The slope correction is a correction which can be estimated after the retracking procedure and generation of the data structure. This is a big advantage, because these corrections can be exchanged afterwards, i.e. when better digital terrain models are available. The slope correction is not necessary for applications over ocean.

Having set up the mission independent data structure, data upgrades and improvements can be done. As shown in the GFZ's sea level study (Anzenhofer and Gruber, 1998), a data upgrade of all past and present altimeter missions is absolutely necessary, as improved models and corrections sometimes are first available long after data delivery. One critical point for data harmonization is the satellite orbit. With every new gravity model from CHAMP and GRACE (Reigber, 1996) a reprocessing of the satellite ephemerides must be performed, which means a step-by-step improvement of the data.

A major task in the retracking system is the quality assurance of the retracked altimeter data. The quality assurance can be separated in 2 parts, the quality checks of the retracking results (slope correction and retracked range) and of all the other GDR parameters, i.e. orbit. There are formal quality checks, comparisons with external and validated internal results, statistical properties, and checks against empirically determined limits. Having validated the mission independent altimeter data structure over different surfaces, applications and analyses can be performed. This data processing can be taken as part of the quality control, because it provides comparable quantities or physical properties of the Earth's surface. The retracking system is a closed-loop chain with the possibilities to step back to a distinct processing level and iterate from there on. Application and analyses results may show that the slope correction is wrong, or some altimeter corrections are too bad. Then, an iteration with new information can be initiated. The quality assurance may show that the retracking procedures produced unreasonable ranges. Then, a step back to the waveform analyses can be done.

2.3 Altimeter Waveform Analysis - Retracking

At time $\mathbf{t_e}$ the satellite emits a radar pulse with a spherical wavefront which reflects at the surface and is received at time $\mathbf{t_r}$. The range-to-surface or altimeter range measurement is then calculated:

$$range = c\,(t_r - t_e)\,/\,2 \tag{1}$$

where c = the speed of light.

The range, however, must be corrected for the atmospheric refraction, before it can be used for scientific investigations.

The altimeter product of primary interest to scientists is the altimeter range measurement, which, when subtracted from a precise satellite orbit referenced to a reference ellipsoid, gives a measure of the surface height above that ellipsoid. Subtracting the geoid height yields the sea surface topography which is caused by ocean currents and, thus, can be used to compute their geostrophic velocities.

The altimeter measures the range using an on-board tracker. This instrument receives and filters the return signal into time bins of varying resolution. The output from the filter, referred to as the waveform, gives information on the surface characteristics within the range window. The altimeter maintains acquisition by keeping the signal within the range window. The tracker predicts the range by centering the waveform at the pre-designated tracking gate. The on-board system can predict precise ranges for the normally-distributed ocean surfaces. Typical ocean waveforms have a sharp ramp and slowly declining trailing edge, where the mid-point of the ramp is centered at the tracking gate.

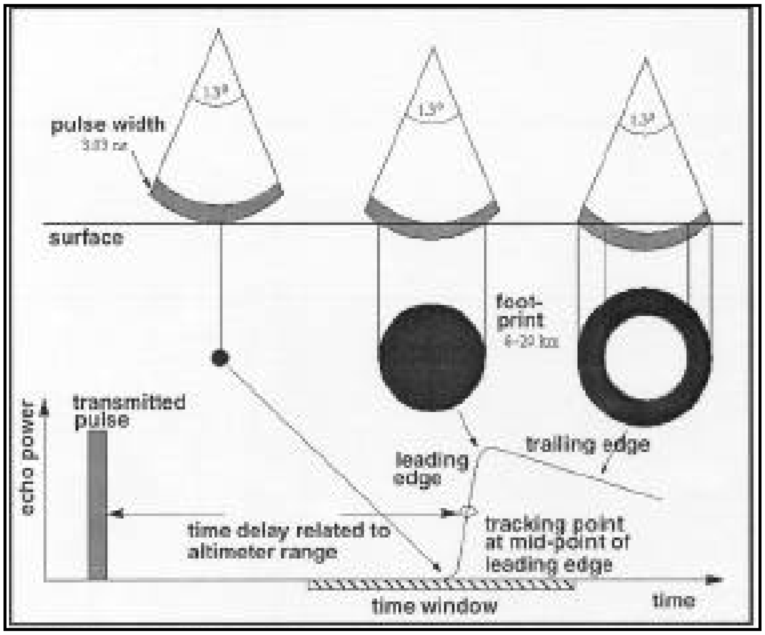

Fig. 2: Altimeter Pulse and Profile of Return Waveform

Over non-ocean surfaces, such as ice, sea ice, or land, the performance of the radar altimeter differs significantly from the performance over oceans due to the higher slopes of the ice surface, variations in the surface reflection and penetration of the radar signal in the surface, and generally irregular surface geometry. Thus, waveforms over non-ocean surfaces are not comparable with the typical ocean waveforms. Information about the ice sheet surface properties can be obtained by examination of the waveforms. The range correction, which is typically in the range of a few meters, accounts for variations of the waveform shape and positioning of the waveform in the window of range gates. This range correction is obtained by a procedure known as retracking.

Beside the range correction from the waveform analysis, the range must be corrected, if the surface at the reflection area is sloped and not planar. Some sub-degree variations of surface slopes may cause range variations up to 100 meters. The number indicates that the slope correction is the most critical part in the waveform processing chain, when keeping a requested centimeter or decimeter accuracy level in mind.

The key principle behind any altimeter is that the information required is in the shape and timing of the returned altimeter pulse. Figure 2 shows a pulse being reflected from a flat surface. As the pulse advances, the illuminated area grows rapidly from a point to a disc, and becomes an annulus growing in size as the pulse vanishes. The annulus area remains approximately constant. The return signal level, which is proportional to the reflecting area, grows rapidly until the annulus is formed, and remains constant until the annulus reaches the edge of the radar beam, where it starts to diminish. If the surface is not flat but is composed of scatter points with elevation normally distributed, then the echo rise time is longer as the pulse needs more time to hit all the scatterers.

Applying this concept to the ocean surface, one can consider that the echo slope is directly related to the significant wave height. The slope mid marks the surface elevation and the total echo power is proportional to the backscatter coefficient, in turn related to the small scale surface roughness ultimately related to wind speed.

Real echoes are composed of the sums of return signals from many scatter points, each with random phase and amplitude. The individual echoes are therefore affected by statistical fluctuations. Echoes are averaged to reduce the statistical fluctuations and perform real time tracking (i.e. to maintain the signal inside an analysis window as far as range and power are concerned).

For ERS altimeter geophysical data records the situation is as follows. The fast delivery altimeter range measurements are generated from the on-board tracker. No post-processing is done at the receiving ground stations Kiruna, Maspalomas, Gatineau, and Prince Albert. The on-board tracker itself is destinated to provide accurate range measurements over ocean. As land, ice, and sea-ice waveforms exhibit anomalies towards ocean waveforms, the on-board processing leads to incorrect ranges. Mostly, this data is not provided in the fast delivery products. The precise altimeter data, the so-called OPR2 are post-processed data with retracked waveforms. However, the OPR2 are ocean-products; land and ice data are removed from the products. This means, that there is no data for land, sea-ice, and ice investigations from ERS altimeter data. Only with the ERS waveform product 'ERS.ALT.WAP' the processing of these areas is possible (Mansley, 1996; NRSC, 1995).

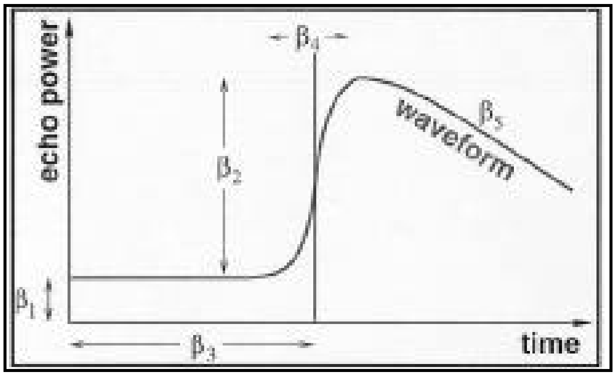

Fig. 3: Waveform Approximation with Beta Retracker

For the processing of the ERS and later for ENVISAT waveforms, a set of retracking algorithms has been considered (Martin et al., 1983; Rodriguez et al., 1994; Wingham et al., 1986). The idea of the following retrackers is to approximate the altimeter waveforms with a functional model. All the various retracking algorithms have their own unique advantages and drawbacks, and it is generally accepted that no single algorithm can meet the diverse needs of all altimeter applications. Thus, several algorithms -at present 5- were developed from which 3 are described in the following sections.

2.3.1 Beta Retracker

The idea of the beta retracker single ramp is to approximate return signals with a distinct sharp rise in power indicative of normal-distributed elevations within the footprint (figure 3). The mathematical formulation is as follows.

$$y = \beta_1 + \beta_2 (1 + \beta_5 Q)\, P\left(\frac{t - \beta_3}{\beta_4}\right) \tag{2}$$

where

$$P(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{q^2}{2}}\, dq \quad \text{with substitution} \quad q = \frac{t - \beta_3}{\beta_4} \tag{3}$$

$$\begin{aligned} Q &= 0 \ \text{ if } \ t < \beta_3 + 1/2\, \beta_4 \\ Q &= t - (\beta_3 + 1/2\, \beta_4) \ \text{ if } \ t \geq \beta_3 + 1/2\, \beta_4 \end{aligned} \tag{4}$$

P is the the error function

For each waveform 5 beta coefficients must be estimated. For altimeter processing 3 beta parameter are of special interest:

- ß$_3$: marks the time delay related to the altimeter range which is the tracking point at mid-point of leading edge
- ß$_4$: determines the slope of the leading edge and, thus, gives information about the significant wave heights at the footprint
- ß$_5$: determines the trailing edge and, thus, is related to the scattering at the footprint and in turn is related to wind speed

With ß$_3$ surface properties, i.e. penetration depth or canopies, can be estimated. The parameter ß$_4$ determines the echo power which gives clues about the kind of surface the altimeter measures, i.e. high value indicates sea-ice.

As mentioned above, the 5 parameter approximation determines the point related to the altimeter range. The correction from the retracking algorithm dr is obtained by the difference between the mid-point of the leading edge and the time window mid-point, multiplied by the distance ds which is related to a single bin. If the abscissas of the time window range from 1 to 64 then the window mid-point is 32.5.

$$ds = t_k * c/2 = 0.4542 \text{ m} \qquad (5)$$

where: t_k is pulse width (3.03 ns for ERS); c = velocity of light (299792458 m/s)

$$dr = (ß_3 - 32.5) * ds = (ß_3 - 32.5) * 0.4542 \text{ m} \qquad (6)$$

$$\text{corrected range} = \text{range} + dr$$

The retracker is suitable for waveform processing over ocean surfaces, thus, preferable for coastal studies.

2.3.2 E-Retracker

Especially for ERS processing, new retracker algorithms have been developed as the form of a typical waveform altered. The linear trailing edge was replaced by an exponential decay term, which simulates the antenna attenuation as the pulse expands on the surface beyond the pulse-limited footprint. The E-Retracker fits the fast-decaying returns very well, which happen especially over sea-ice.

$$y = \beta_1 + \beta_2 e^{-\beta_5 Q_1} P\left(\frac{t - \beta_3}{\beta_4}\right) \qquad (7)$$

where

$$\begin{aligned} Q_1 &= 0 \quad if \quad t < \beta_3 + k\,\beta_4 \\ Q_1 &= t - (\beta_3 + k\,\beta_4) \quad if \quad t \geq \beta_3 + k\,\beta_4 \end{aligned} \qquad (8)$$

k is set to +2, however, it is a weighting factor that can be changed to get perfect fits of the return echo.

2.3.3 Offset Center of Gravity Retracker

To achieve robust retracking, a retracking algorithm has been developed called offset center of gravity (OCOG) (MSSL, 1987). It was originally designed to provide continuous altimeter ranges of topographic surfaces. As the mathematical formulation is rather simple, the OCOG algorithm is a proper tool to provide

- retracking correction,
- classification of waveform,
- determination of waveform shape, and
- estimation of waveform quality.

The fundamental idea is to find the center of gravity of each waveform as it is shown in figure 4. Then, waveform describing parameters like the leading edge position can easily determined. The mathematical formulation is as follows.

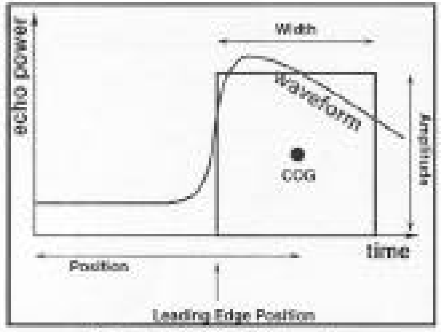

Fig. 4: OCOG Retracker

The OCOG retracker is a robust and simple algorithm to extract the leading-edge position of the waveforms. However, the beta and the E-retracker are more accurate. The OCOG retracker provides very good a-priori parameters for the least squares solution as described in the following section.

$$Position = \sum_{n=1}^{n=64} n\, R^2(n) \,/ \sum_{n=1}^{n=64} R^2(n) \qquad (9)$$

$$Amplitude = \sqrt{\sum_{n=1}^{n=64} R^4(n) \,/ \sum_{n=1}^{n=64} R^2(n)} \qquad (10)$$

$$width = \Big(\sum_{n=1}^{64} R^2(n)\Big)^2 \Big/ \sum_{n=1}^{64} R^4(n) \qquad (11)$$

Leading-edge position = Position - 1/2 * Width (12)

2.3.4 Least Squares Adjustment and Solution

The last three sections described algorithms that approximate the radar altimeter return signal by empirical curves. The backscattered signals are available as a discrete function with time intervals and corresponding backscattered energy. Each signal consists of at least 60 pairs of discrete points, eg. 64 for ERS satellites.backscattered signals are approximated by empirical functions with 5 to 9 variables. This means, an overestimated system is available for each signal, which can be solved by least squares adjustment.

$$y_i = F_i(x) \quad i = 1,..,n \tag{13}$$

y is the ordinate of a discrete time series with abszissa x, which is approximated by a functional model F. The least squares adjustment is as follows:

$$\Delta\hat{x} = [\, A^T\, P\, A\,]^{-1}\, [\, A^T\, P\, L] \tag{14}$$

A is called design matrix, P is the weighting matrix and L contains the observations. L is determined by the difference 'observation minus approximation (index 0)'.

$$L_i = F_i(x) - F_i(\, x_0\,) \quad i = 1,...,n \tag{15}$$

The weighting matrix determines the weighting of the observations. The experiences with waveform retracking had shown that it is very important to have a proper weighting, because the retracking algorithms are very sensitive for different weights, ie. different weighting schemes are necessary for the three quantities (range, significant wave height, wind speed), which can be derived from waveform analysis.

$$A_{n,m} = \begin{vmatrix} \frac{\partial F_1(\, x_0\,)}{\partial x_1} & \frac{\partial F_1(\, x_0\,)}{\partial x_2} & \cdots & \frac{\partial F_1(\, x_0\,)}{\partial x_m} \\ . & . & . & . \\ . & . & . & . \\ \frac{\partial F_n(\, x_0\,)}{\partial x_1} & \frac{\partial F_n(\, x_0\,)}{\partial x_2} & \cdots & \frac{\partial F_n(\, x_0\,)}{\partial x_m} \end{vmatrix} \tag{16}$$

The design matrix A is built up by the partial derivatives of the functional model by their unknowns. The number of unknowns (e.g. 5 for the beta retracker) determines the number of columns and the number of observations the number of rows, respectively.

$$\hat{x}_j = x_{0j} + \Delta x_j \quad j = 1,...,m \tag{17}$$

Then the least squares system is solved. The unknown Δx are added to the a-priori values. From

$$v = A\, x - L \tag{18}$$

the standard deviations of the unknown are determined by

$$K_{\hat{x}} = \sigma_0^2 \_ A^T P A \_^{-1} \quad with \quad \sigma_0^2 = \frac{\hat{v}^T P \hat{v}}{n - m} \qquad (19)$$

Different criteria (standard deviation of unknowns, convergence), determine whether the procedure must be iterated or not. Then new a-priori values, ie. the results from the preceding solution, are introduced and the system is solved again.

The following two paragraphs show the design matrices for the retrackers used for the study.

Least Squares Adjustment for Beta Retracker

$$y = \beta_1 + \beta_2 (1 + \beta_5 Q) P(\frac{t - \beta_3}{\beta_4}) \qquad (20)$$

$$P(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{q^2}{2}} dq \quad ; \quad q = \frac{t - \beta_3}{\beta_4} \qquad (21)$$

$$\begin{array}{r} Q = 0 \;\; if \;\; t < \beta_3 + 0.5\, \beta_4 \\ Q = t - (\beta_3 + 0.5\, \beta_4) \;\; if \;\; t \geq \beta_3 + 0.5\, \beta_4 \end{array} \qquad (22)$$

The partial derivatives are as follows:

$$\frac{\partial P}{\partial \beta_3} = - \frac{1}{\beta_4 \sqrt{2\pi}} e^{-\frac{q^2}{2}} \quad ; \quad \frac{\partial P}{\partial \beta_4} = - \frac{t - \beta_3}{\beta_4^2 \sqrt{2\pi}} e^{-\frac{q^2}{2}} \qquad (23)$$

$$\frac{\partial y}{\partial \beta_1} = 1 \qquad (24)$$

$$\frac{\partial y}{\partial \beta_2} = (1 + \beta_5 Q) P \qquad (25)$$

$$\frac{\partial y}{\partial \beta_3} = \beta_2 \frac{\partial P}{\partial \beta_3} + W \beta_2 \beta_5 (t \frac{\partial P}{\partial \beta_3} - (P + \beta_3 \frac{\partial P}{\partial \beta_3}) - 0.5\, \beta_4 \frac{\partial P}{\partial \beta_3})) \qquad (26)$$

$$\frac{\partial y}{\partial \beta_4} = \beta_2 \frac{\partial P}{\partial \beta_4} + W\, \beta_2\, \beta_5 \left(t \frac{\partial P}{\partial \beta_4} - \beta_3 \frac{\partial P}{\partial \beta_4} - 0.5\left(P + \beta_4 \frac{\partial P}{\partial \beta_4} \right) \right) \tag{27}$$

$$\frac{\partial y}{\partial \beta_5} = \beta_2\, Q\, P \tag{28}$$

Having set up the design matrix, the least squares adjustment can start to solve for the 5 unknown. The approach determines the mid-point of the leading edge. The retracking correction is then the difference between the mid of the time window and the estimated mid-point of the leading edge. This difference must be multiplied by a distance, which accounts for 2 adjacent bin pairs.

Least Squares Adjustment for E-Retracker

The E-retracker is an algorithm for waveforms with high energy peaks. It is also a 5 parameter function which approximates the waveforms.

$$y = \beta_1 + \beta_2\, e^{-\beta_5 Q_1}\, P\left(\frac{t - \beta_3}{\beta_4} \right) \tag{29}$$

$$P(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{q^2}{2}}\, dq \quad ; \quad q = \frac{t - \beta_3}{\beta_4} \tag{30}$$

$$\begin{aligned} Q_1 &= 0 \;\; if \;\; t < \beta_3 + k\,\beta_4 \\ Q_1 &= t - (\beta_3 + k\,\beta_4) \;\; if \;\; t \geq \beta_3 + k\,\beta_4 \\ w &= -\beta_5\, Q_1 \end{aligned} \tag{31}$$

$$\begin{gathered} \frac{\partial P}{\partial \beta_3} = -\frac{1}{\beta_4 \sqrt{2\pi}}\, e^{-\frac{q^2}{2}} \quad ; \quad \frac{\partial P}{\partial \beta_4} = -\frac{t - \beta_3}{\beta_4^{\,2} \sqrt{2\pi}}\, e^{-\frac{q^2}{2}} \\ \frac{\partial e^w}{\partial \beta_3} = \beta_5\, e^w \;\; ; \;\; \frac{\partial e^w}{\partial \beta_4} = -k\, \beta_5\, e^w \;\; ; \;\; \frac{\partial e^w}{\partial \beta_5} = -Q_1\, e^w \\ if \quad t < \beta_3 + k\,\beta_4 \;\; => \;\; e^w = 1 \qquad \frac{\partial e^w}{\partial \beta_i} = 0 \end{gathered} \tag{32}$$

$$
\begin{aligned}
\frac{\partial y}{\partial \beta_1} &= 1 \\
\frac{\partial y}{\partial \beta_2} &= e^w P \\
\frac{\partial y}{\partial \beta_3} &= \beta_2 \left(\frac{\partial e^w}{\partial \beta_3} P + e^w \frac{\partial P}{\partial \beta_3} \right) \\
\frac{\partial y}{\partial \beta_4} &= \beta_2 \left(\frac{\partial e^w}{\partial \beta_4} P + e^w \frac{\partial P}{\partial \beta_4} \right) \\
\frac{\partial y}{\partial \beta_5} &= \beta_2 \frac{\partial e^w}{\partial \beta_5} P
\end{aligned}
\qquad (33)
$$

Weighting Scheme and A-priori Parameter

Altimeter waveforms highly depend on the reflecting surface properties. Flat surfaces, for example over lakes or ice, produce waveforms with high and narrow energy peaks, while ocean surfaces lead to slowly declining trailing edges and lower energy levels. Different height levels within the altimeter footprint may produce 2 or more ramps in the waveforms. Thus, usually the waveforms must be classified before the retracking procedure, ie. proper retracking algorithms must be chosen. For the coastal study at hand, however, no classification is necessary, because only ocean waveforms are used. This means that either the beta retracker or the E-retracker can be chosen. The experience with the least squares approximation, however, has shown, that very good a-priori knowledge of the retracking unknowns is needed for a successful solution. This implies also a proper weighting scheme for the observations as defined in formula 2.

For proper a-priori values and for the weighting scheme the OCOG retracker is performed, because it is an easy and fast algorithm for waveform processing as it does not need a least squares approach. The leading edge a-priori value _$_3$ is taken from the OCOG retracker result. _$_1$ is set to zero. _$_2$ accounts for the maximal amplitude of the waveform and can easily be found by looking for the extreme energy level. The time interval of the leading edge is defined by the parameter _$_4$ and is constantly set to 1.3, which is found out empirically. The slope of the trailing edge (_$_5$) can be set to zero.

The experience with ERS-1 waveform processing has clearly demonstrated that a proper weighting scheme is important for the iterative least squares process. The iterations are very sensitive to different weights especially over non-ocean surfaces, ie. no solutions are achieved by wrong weighting and, thus, data loss.
The weighting scheme chosen for the coastal altimetry study is empirically found. From

- begin of waveform to (leading edge position - 1 bin): weights are 100
- from (leading edge position - 1 bin) to (leading edge position + 2 bins): weights are 50
- from (leading edge position + 2 bins) to end of waveform: weights are 30

It was found out that a strong weighting to the leading edge position is needed. Otherwise the least squares approach does not converge. The weighting scheme is special for the leading edge mid-ramp identification. For the extraction of sigma naught and significant wave heights another weighting is needed.

Test of Beta Retracker on Arbitrarily Chosen Ocean Waveforms

Figure 5 shows the result of a quality investigation for the Beta Retracker. For the test, 30 arbitrarily, but consecutive waveforms were chosen. The original waveforms are plotted in the middle of figure 5. It is obvious that there are distinct differences in their shapes. The retracking correction calculated from the Beta Retracker is shown in the image at the bottom of figure 5. The correction ranges between a few centimeters and 0.8 m (for waveform number 25). The statistics reveal a bias and an rms of 17 cm (further details in section 4.1.1). 6 individual waveforms were selected to demonstrate the the iterative procedure of the Beta Retracking. With # the waveform numbers are described. The original waveforms are plotted in black color, the different iteration steps are in grey. In each single image an horizontal and vertical line mark the mid-point of the leading edge estimated from the Beta Retracker. The thin dotted lines define the middle of the time window and, thus, the pre-defined point for the raw range. It is obvious that there are differences between the middle of the time window and the estimated mid-point. In the image of waveform 25 the reason for the 0.8 m retracking correction is apparent: there is a small bump in the middle of the leading edge, which points to a small height change within the altimeter footprint (for example land included). However, it seems that the Beta Retracker is able to approximate the original waveforms very well.

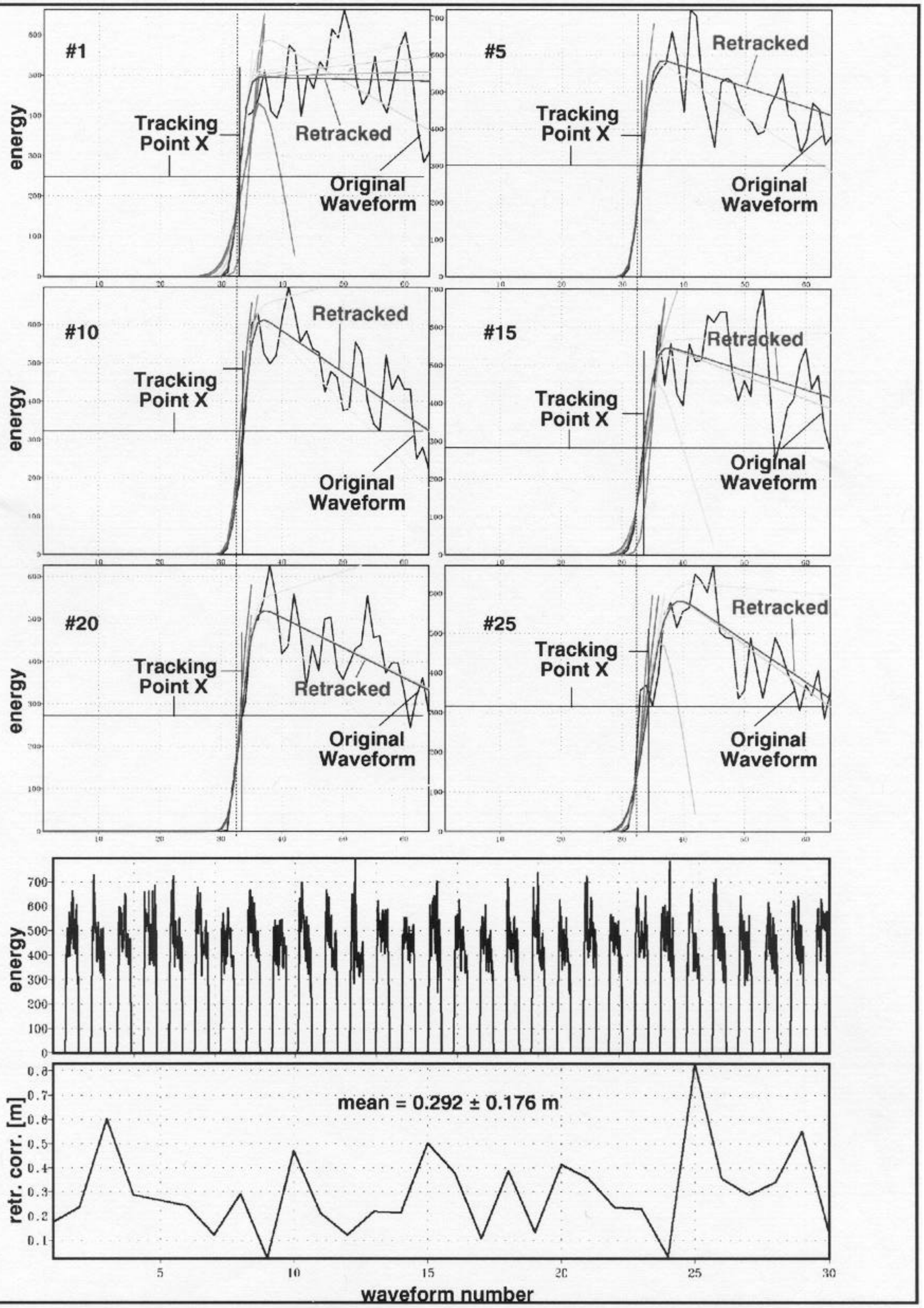

Fig. 5: Test of Beta Retracking on Real Waveforms

3. ERS Waveform Data and Intermediate Format

ERS waveforms are sensor altimeter data of the ERS-1 and ERS-2 missions flown from 1991 until 2000 (end is still in discussion). Sensor altimeter data means, that the range and range related parameters, wind speed and wave heights, are available as raw quantities. Instead, they are provided in a set of energy bins with respect to time, the so-called waveforms. From this bins (ERS: 64 bins) the altimeter signal (Anzenhofer, 1998) can be reconstructed by empirical approaches (Anzenhofer, 1998).

Content: The ERS altimeter waveforms are generated from UK-PAF and represent the official ESA product ERS.ALT.WAP. The ERS.ALT.WAP is a so-called level 1.5 product. It contains all relevant informations from telemetry of the altimeter together with their corrections. A set of calibration values and orbit ephemerides are provided. Thus, a complete content is given to produce so-called altimeter GDR (geophysical data records).

Structure: The ERS.ALT.WAP are structured following the CEOS format. It is unformatted, binary, direct access and with fixed record lengths.

Format: The CEOS format (described in an unreadable document (NRSC, 1995)), is very complex and
contains, because of it's ambition to be a common format for all remote sensing data, a lot of headers and useless informations that are not proper for altimeter data processing. Thus, a data compressing and removal of useless informations are absolutely necessary. Therefore software and documentation of UCL/MSSL (Mansley, 1996) was acquired to handle the reading of the CEOS format. This software compresses 5 GByte of ERS.ALT.WAP to 1 GByte. It should be noted that the data compression is done without any loss of information needed for waveform processing.

The software processes the ERS.ALT.WAP to the so-called EAC format, described in Mansley (1996). It will not be further specified here. However, the structure and content of the EAC products is given:

- each satellite revolution is stored in one file, the naming convention is: the name of the ExaByte (e.g. UP517240) and the number of revolutions (e.g. 02); this leads to file names like UP517240_02
- each EAC file contains more than 20 MBytes
- on every ERS.ALT.WAP ExaByte there are 42 revolutions, that means 3 days of observations

The EAC products are the base for the retracking system. They are the intermediate waveform data from which a new and further compressed format is generated, the so-called AWF (AIDA waveform format). The AWF contains only the relevant items in order to produce altimeter GDR.
One major point in the AWF is, that each 20 Hz waveform is treated as one single altimeter GDR. Furthermore, there is a regional and temporal separation of the EAC products to allow fast and easy data identification and subsequent processing.

Number	Typ	Position	Description	Unit
1	si4	1	data degraded flag	.
2	si4	5	utc, since 01-01-1990	secs
3	si4	9	utc fraction	1.e-6 secs
4	si2	13	mode identifier	.
5	si2	15	peakiness	1.e+3
6	si2	17	bin count for bin 0 in waveform	counts
7	si2	19	bin count for bin 1 in waveform	counts
...	...	...	...	...
69	si2	143	bin count for bin 63 in waveform	counts
70	si4	145	slope from telemetry	1.e-2 slope
71	si4	149	automatic gain control (agc)	1.e-2 dB
72	si4	153	latitude	1.e-6 deg
73	si4	157	longitude	1.e-6 deg
74	si4	161	satellite height above reference ellipsoid	mm
75	si4	165	(not retracked) range	mm
76	si2	167	significant wave height	mm
77	si2	171	sigma naught	1.e-2 dB
78	si4	173	internal range correction	mm
79	si2	177	internal agc correction	1.e-2 dB
80	si2	179	doppler range correction	mm
81	si2	181	range sigma naught correction	1.e-6 dB
82	si2	183	ionospheric correction	mm
83	si2	185	PRARE delta correction	mm
84	si2	187	dry tropospheric correction	mm
85	si2	189	wet tropospheric correction (1)	mm
86	si2	191	wet tropospheric correction (2)	mm
87	si2	193	liquid water range correction	mm
88	si2	195	solid Earth tide	mm
89	si2	197	ocean tide	mm
90	si2	199	ocean loading	mm

Table 2: Intermediate Waveform Format

Looking at table 2, one can see that a single waveform record needs exactly 200 bytes. That means, a single 20 Hz package needs 4 kBytes disk space.

Naming Convention: The original names of ERS waveforms are not considered. The intermediate file names will be ERS?_YYYY_DOY_HH_region.

ERS? = ERS identifier
= ERS1 for ERS-1 mission
= ERS2 for ERS-2 mission
YYYY = year of data
DOY = day of year of data
HH = hour of day
region = regional subset (see chapter 4 for further information),
Africa = Africa
antarctica = Antarctica
europa = Europa
greenland = Greenland
n_america = North America
s_america = South America
asia = Asia
australia = Australia

They will be stored in directories with names ERS?_YYY_DO1_DO2.
ERS? = ERS identifier
= ERS1 for ERS-1 mission
= ERS2 for ERS-2 mission
YYYY = year of data
DO1 = start day of year of data
DO2 = start day of year of data

Sample contents of AWF CD-ROM:

ERS2_1996_240_243/ERS2_1996_240_13_antarctica
ERS2_1996_240_243/ERS2_1996_240_13_asia
ERS2_1996_240_243/ERS2_1996_240_13_australia
ERS2_1996_240_243/ERS2_1996_240_13_europa
ERS2_1996_240_243/ERS2_1996_240_13_greenland
ERS2_1996_240_243/ERS2_1996_240_13_s_america
...

Volume: The intermediate ERS waveforms written in AWF are stored on CD-ROM. The AWF lead to a further data reduction from 1 GByte to about 550 MByte for each 3 days data set. This means that each CD-ROM contains 3 days of ERS data.

Remarks: ERS waveforms are most valuable data for medium- and long-term investigations of land and ice surfaces with a high spatial resolution. Furthermore, ERS satellites are near polar-orbiting, enabling a very good polar ice cap mapping. With the extension of Envisat-1 waveform data flying the same repeat cycle as ERS, temporal and spatial variations of ice and land surfaces can be analyzed with a consistent 14 years time series. ERS waveforms serve as input and demonstration data for the Envisat-1 mission.

4. Application: Chinese Sea

The coastal study with altimeter waveforms was performed in the Chinese sea. Figure 6 shows the bathymetry in this region. It is apparent that the ocean surface is over the continental shelf which means, that it is a perfect area for waveform data because of tidal inaccuracies and data loss.

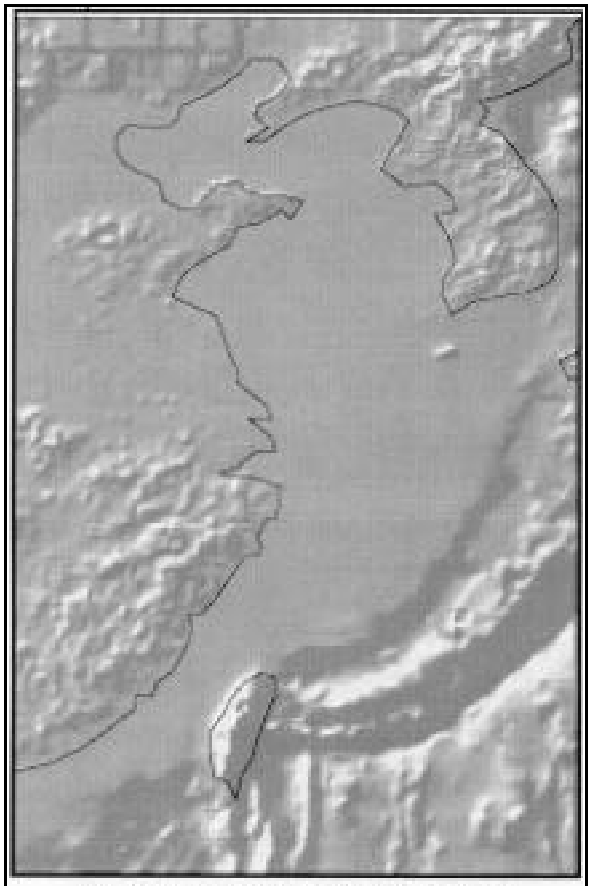

Fig. 6: Bathymerty in the Chinese Sea

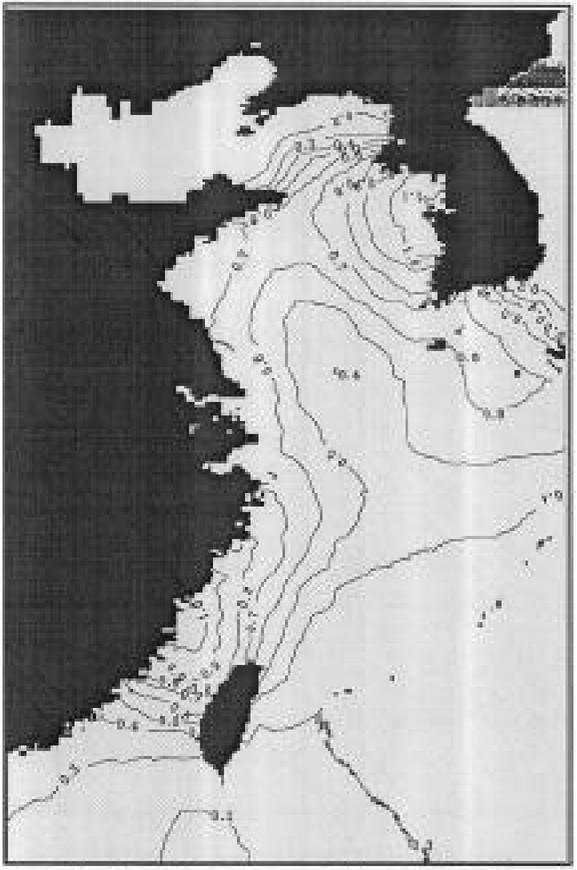

Fig. 7: RMS of Ocean Tides (FES95.2)

It could have been done anywhere on the globe, but the area was chosen, because there are some on-going studies (Pearlman, 1998) and detailed gravity anomalies maps and bathymetric maps from them are available (Hwang, 1997). Furthermore, it is a region with high tidal amplitudes in shallow water, which allows the comparisons of different tidal models in this for tidal modeling problematic zone.

Figure 7 shows the RMS of the ocean tides based on FES95.2. The RMS of the ocean tides was calculated for each 1 degree box by simply looking at the mean and its variance for all measurements, which fall into the box within one year. Globally, the procedure produced RMS of up to ±2.5 m. Regions with RMS greater than ±1 m, however are outliers. It can be seen that the chosen region in the Chinese sea has highly variable tides and, thus, seems to be an appropriate region for coastal altimetry.

Only data from the second geodetic phase of ERS-1 were processed in that region. Data from other ERS phases were neglected. However, due to available preprocessed waveform data the data span did not cover the whole second geodetic phase (28. September, 1994 to 21. March, 1995).

In order to test the retracking algorithms over coastal ocean and to study the usefulness of retracked data for geophysical applications, different investigations were performed,

- single track analysis,
- collinear analysis,
- crossover comparisons, and
- sea surface height residuals,

which are described in following sections.

4.1 Single Track Analysis

Before using retracked data for geophysical applications, their quality must be known. As the truth is unknown, the quality can only be checked by intercomparison between existing off-line data products, such as QLOPR and OPR2. This means that the data differences must be analyzed point by point. For the first analysis only one track was extracted from the data base. Its' geographical distribution is shown in figure 8.

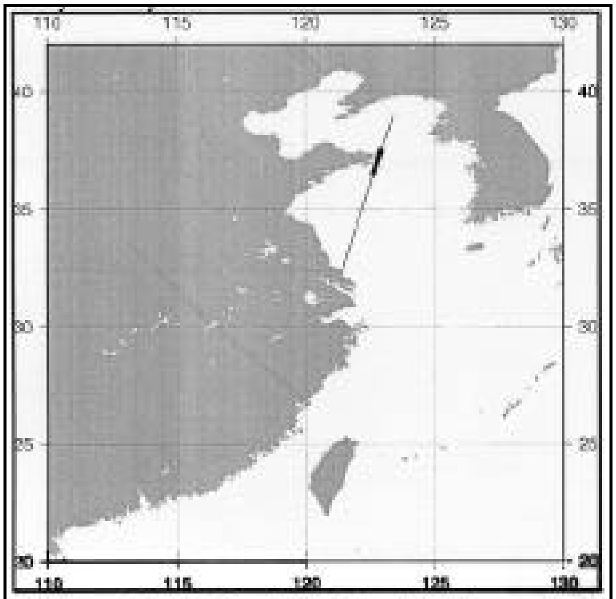

Fig. 8: Single Analyzed Track

The thin line indicates the considered track of the waveform data base. With thick circles the small zone is marked which is investigated in more detail. The latitudinal extension lies between 36^0 30' and 37^0 30'. This zone was chosen because of its' close vicinity to peninsula of Shan-dong. It is therefore an appropriate area to study the usefulness of altimeter waveforms.

For that particular track 4 different altimeter data types were available:

- ERS-1 OPR2, which are the official ERS-1 GDR available about 6 month after measurements (ESA, 1993)
- ERS-1 QLOPR, which are the official ERS-1 quick-look GDR available about 10 days after measurements (Gruber et al., 1994)
- ERS-1 waveform data with the raw range (means without retracking), the range is calculated with respect to the center of the waveform window (Mansley, 1996)
- ERS-1 waveform data with retracked range

The media corrections to the range and satellite height are quite different, too, and are shown in table 3.

	OPR2	**QLOPR**	**Waveforms**
Sat. Height	GFZ/1.2 orbit based on PGM055 gravity field	GFZ/1.2 preliminary orbit based on PGM055 gravity field	GFZ/1.2 orbit based on PGM055 gravity field
Ocean Tides	FES95	FES95	CSR3.0
Ocean Loading	FES95	FES95	CSR3.0
Solid Earth Tides	Wahr	Wahr	Cartwright Edden Taylor
Ionosphere	IRI95	IRI95	IRI90
Dry Troposphere	French Met. Office	ECMWF	ECMWF
Wet Troposphere	Radiometer	ECMWF	ECMWF

Table 3: Media Corrections

To avoid non-consistence by media corrections, first so-called raw sea surface heights are calculated by

$$\text{ssh(raw)} = \text{hsat} - (\text{range} + \text{no corrections}) \qquad (34)$$

This means that media corrections and sea surface corrections like the tides are not applied.

Te figure 9 shows the 4 different raw sea surface heights. The sea surface heights from waveforms are averaged to 0.5 second values by a box-mean procedure, which averages 10 consecutive measurements to one single value. It is obvious that there are different biases between them. The bias between the OPR2 and the raw range waveforms are the 41.6 cm from the absolute calibration at the Venice site (Francis, 1992), which are not applied. Between the OPR2 and the QLOPR a bias of about 26 cm exists. The reason for this bias must be caused by the coarse retracking of the fast delivery ranges. The retracking correction itself should not lead to a bias, but it seems that there is a shift in the center of the waveform window, ie. the center is not 32.5 if the the bins are counted from 1 to 64. The reason for this shift is unknown up to now.

What is much more important are the different features along the track with amplitudes up to 10 to 20 cm. As the truth is unknown one can only speculate which track shows the reality. In general the gradient of the sea surface is about 2.5 cm/km. This means all the shown features could be real. QLOPR and OPR2 seem to be quite consistent, however the OPR2 show more signal. Between the raw waveform

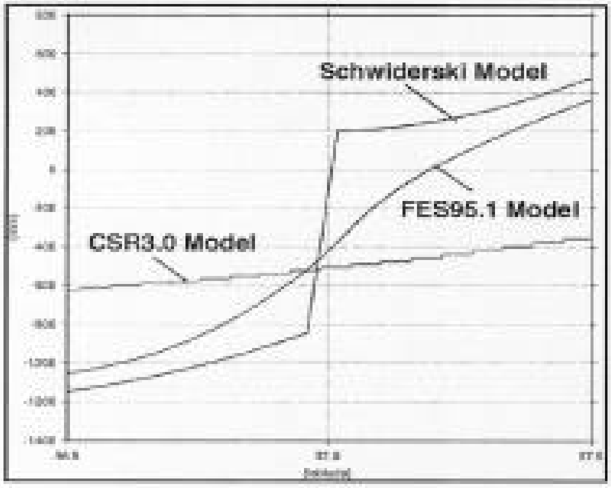

Fig. 9: Comparison of Different Ocean Tide Models

range and OPR2 there is one obvious area around latitude 7.2, where the raw waveform ranges has some strange features. This is also the area with bigger differences between QLOPR and OPR2. This area seems to be strongly affected by the vicinity of land (see figure 6). In this area the effect of waveform retracking can be seen; the bumps in the sea surface disappeared and are displaced by a smoothed sea surface. Over the whole area the retracked sea surface heights shows less signal and sharp peaks than the other data. It seems that the retracked sea surface heights reflect the unknown truth.

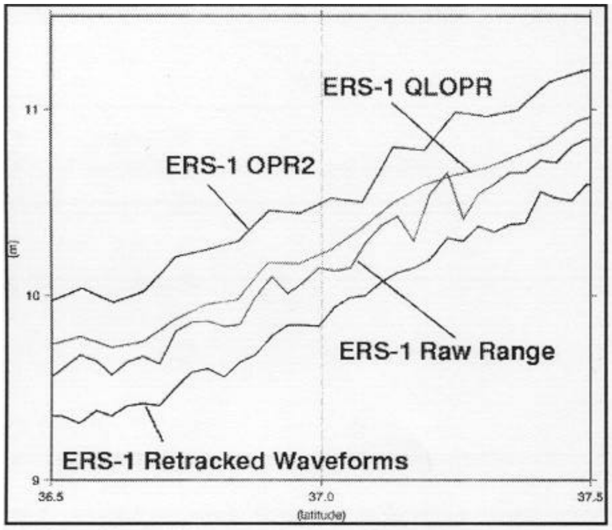

Fig. 10: Different Ranges of the Same Track

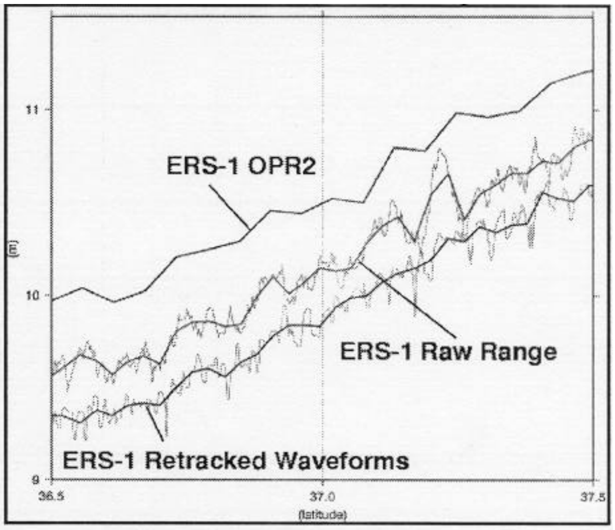

Fig. 11: Comparison of Ranges Including 20 Hz Data

A closer look at the 20Hz ranges is needed to extract the differences between the raw and the retracked ranges. Figure 9 shows the result. The thin lines around the box-filtered sea surface heights reflect the 20 Hz measurements. It seems that the retracked 20 Hz data are more noisy, ie. has more short-wave length signal than the raw data. However, longer wave length features are found in the raw data with no corresponding signal in the OPR2. It is questionable whether all 20 Hz measurements show useful data contents for further geophysical applications. A large portion of this scattering likely reflects the instruments characteristics of ±4 cm for a single measurement (ESA, 1993).

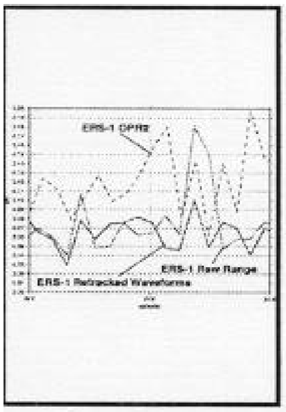

Fig. 12: Range Standard Deviations

Fig. 13: Comaprison of Wet Tropospheric Correction

The next question is on the quality of corrected sea surface heights in coastal areas. Are media-corrections already good enough for geophysical applications?

The most urgent questions relates to the ocean tides, because one can anticipate that there should be the largest deviations caused by mismodeling. The altimeter data at hand offered a good possibility to study different models in coastal areas. The CSR3.0 model included in the waveform data was compared with the old-fashioned Schwiderski model (Schwiderski, 1980) and the FES95.1 model, which are included in our 1 Hz data base (it should be noted that they will be exchanged by the new FES98 model). Figure 10 shows the result, which clearly demonstrates that the ocean tide models in coastal areas are far from being accurate. Differences of ± 50 cm appear between the models. It should be noted that the visible step-function in the CSR3.0 is an artifact of the waveform data. Each 20 Hz package has only one 1 Hz corrections. This implies a post-processing of corrections and orbital heights before further applications. The wet tropospheric correction is another critical part for the altimeter data. Usually it is measured by on-board radiometers. The official products also contain this correction from meteorological fields for example from ECMWF. Two problems arise with the wet tropospheric correction. Firstly, it is highly de-correlated in time and space, which means that one needs highly resolved meteorological fields for a proper modeling. Secondly, the radiometer does not work correctly in the vicinity of land, thus, it it mostly switched off or the data are flagged near and over land. The comparison of both show some systematic shifts with a bias of one centimeter and a drift of 1 cm / 100 km for this track. The result is not encouraging for further analysis. Furthermore, a mixing of both data should be avoided in case of missing radiometer data. Recent investigations have shown drifts of radiometers and other differences between different radiometers and/or in-situ data. The effect shown in figure 11, however, can not be attributed to these differences; their wave length is too small and the amplitudes of the differences are too big.

Ocean tides and the wet tropospheric effect are the most critical corrections for altimeter data. Other corrections such as ocean loading or Earth tides have less amplitudes and are less affected by shallow water conditions.

Data	Mean (cm)	RMS (cm)
OPR2	12.1	3.6
Raw Range	7.5	3.6
Retr. Range	6.5	1.7

Table 4: Range Standard Deviations

Another quality indicator are the standard deviations of the ranges. The result for the single track is shown in figure 12. Between the three quantities markable differences exist. The standard deviation of the range from the OPR2 seems to be a little higher than the waveform standard deviations. The OPR2 data show some bumps especially very close to land, i.e. near latitudes greater than 37^0. The same holds for the raw ranges, which have slightly higher rms than the retracked waveforms. It seems that the retracking leads to smoother standard deviations of the range, also close to the coast. This fact could be taken as an indicator for data improvement and, thus, encouraging retracking. The statistics of the different data are in table 4.

In general it seems that the retracked waveform data leads to an improvement in quality and data amount especially in coastal regions. However, problems remain such as tidal mismodeling, range corrections, data filtering and compression.

4.2 Collinear Analysis

Usually the collinear analysis of repeated altimeter data is a proper tool to extract the meso-scale variability of the sea surface (Cheney and Marsh, 1983, Sandwell and McAdoo, 1990). The method deals only with the time-variable effect of the sea surface and, thus, is independent of static features such as geoid. The method itself was initiated because of the radial orbit error problem at that time (Cheney and Marsh, 1983). The errors could easily be separated because the orbit related error has long wave length character, i.e. one or 2 sine waves per revolution. The sea surface features, however, have much shorter wave lengths. Therefore, the reduction of a low-degree polynominal from the differences between collinear arcs eliminates the orbit errors without removing sea surface variability. During the tandem mission of ERS-1 and ERS-2 a relative calibration of the ERS-2 altimeter with respect to the corresponding ERS-1 instrument was performed by several European groups (Benveniste, 1996). The collinear analysis has proven to be the most powerful and accurate technique for this purpose (Anzenhofer et al., 1996). For the intercomparison between different data sets of the same altimeter measurements the collinear analysis is much more effective, because there is no time lag between the data. However, there is one problem with the collinear analysis: the collinear analysis requires comparable data points, which means, measurements at the same geographical location and time. Usually this is achieved by a normal point program. The one, which is used for this study, was developed by Cheney and Marsh (1983). The normal points are obtained by a iterative polynominal representation of adjacent measurements including editing of bad quality data. For the comparison of different data types 1-second normal points were generated. The same normal point routine was used for all data types, which means, that 8 consecutive measurements are taken to calculate one 1 second normal point. This corresponds with the time tagging of the official data products OPR2 and QLOPR, where the time difference between consecutive measurements is about 0.98 seconds. Waveform data, however, are 20 Hz data. This means, for the OPR2 and QLOPR 1-second normal points are generated from 8-second blocks, the waveform 1-second normal points are generated from 0.4-second blocks (8 points in 20 Hz data). This inhomogeneous processing leads to a comparison of data with different spectral content and, thus, to a higher RMS in the differences.

The collinear analysis was used to obtain 2 important quantities for the retracking validation, the

- data amount, and
- differences between OPR2, QLOPR, waveforms.

Table 5 summarizes the results of the collinear analysis. The analysis was performed with data from July, 1995, a period arbitrarily chosen. It should be noted that only the ranges had been compared without any range correction such as atmospheric refraction or tides.
OPR2-QLOPR: There is a markable bias of 27 cm between both data. The reason for this is unknown and can only be introduced by the off-line retracking for OPR2. A detailed investigation of the differences (not shown in this report) reflected a dependence on the backscatter coefficient, an additional indicator of differences in the retracking algorithms. The RMS of 7 cm is pretty high and reflects partly the dependence on the backscatter coefficient.
OPR2-Waveform Raw Range: The bias reflects the absolute calibration bias (Francis, 1992) from the Venice Tower calibration. The value 40.6 cm is not applied for the wave form data. The RMS is twice the value of the comparison QPR2-QLPOR. Again, parts of the RMS is caused by the inhomogeneous normal point generation for both data.
OPR2-Waveform Beta-Retracked: The bias of 66.4 cm is 27 cm higher than the previous one. The 27 cm are the result from the retracking, which means that in general the waveform mid-point is shifted about 1.5 gates. Up to now there is no explanation for this phenomena. However, in ocean waveforms there is usually a bump at the beginning of the time window (Anzenhofer, 1998). Theoretically the waveform energy should be very small (about 0) from the beginning of the time window to the leading edge. This is not the case indicating to some problems with the ERS waveforms. The most interesting value is the RMS of the differences, which is smaller than the previous one. This is very promising and shows that there is an improvement by the retracking procedure. Also, the number of normal points is slightly higher, which means that there are less outliers (limit: absolute maximal difference between normal point greater than 1.5 m) than before.
OPR2-Waveform-E-Retracked: The E-retracked differences show almost the same bias to the OPR2 as the Beta retracker. However, a small bias of 1.2 cm between both retrackers exists. For local investigations this value should not be too critical, but for long time series and climate research mixed retracked waveforms cannot be taken. Otherwise, they produce artificial drifts. The reason for this bias must be further investigated. The RMS is slightly higher than the corresponding from the Beta Retracker, which means, the improvement of retracking is worse.
QLOPR-Waveform Raw Range: The bias of 8 cm cannot be explained at the moment, because there exists only little information about the range generation for the fast delivery data, the base for the QLOPR. The RMS is twice as high as for the corresponding OPR2 comparison. This means that the OPR2 data match much better the waveforms. The number of normal points is 25% less than for the OPR2 comparison indicating either less QLOPR data for comparison or more normal point outliers. For that specific region of the world it was found out that there are less QLOPR than OPR2 data, which is unusual, because QLOPR data come closer to the coast than the OPR2 before they are flagged out.

Data	OPR2 mean±RMS (m) no. of points	QLOPR mean±RMS (m) no. of points	Raw range mean±RMS (m) no. of points	Beta-retr. range mean±RMS (m) no. of points
OPR2				
QLOPR	-0.270±0.069			
Raw range	-0.394±0.131 2152	-0.082±0.223 1622		
Beta-retr. range	-0.664±0.107 2159	-0.352±0.153 1588	-0.261±0.214 2657	
E-retr. range	-0.675±0.114 2160	-0.365±0.155 1582	-0.274±0.190 2636	0.013±0.108 2700

Table 5: Results of Collinear Analysis

QLOPR-Waveform Beta-Retracked: For the bias, the above mentioned 27 cm because of the retracking appear, too. However, there is a distinct reduction of the RMS of 7 cm, which is twice the value as the RMS reduction of the OPR2 comparisons. This is very promising, again, demonstrating the necessity of retracking.

QLOPR-Waveform-E-Retracked: There is the same bias difference of about 1.2 cm as for the OPR2 comparison. Again, the RMS is worse than the above mentioned one. It seems that the Beta-retracking provides better results than the E-retracking.

Waveform Raw Range-Waveform Beta-Retracked: This comparison shows the above mentioned bias, which is the result from retracking and accounts for a shift of 1.5 bins in the waveform's time window. The RMS of 20 cm is rather high and shows the data changes by retracking. The most important figure in this field, however, is the amount of data. Almost 25% more 1 Hz data can be used when one takes retracked data instead of OPR2. This additional data is close to the coasts and, thus, a real improvement when investigating in these areas.

Waveform Raw Range-Waveform-E-Retracked: The comparison shows similar results as the previous one. The RMS is better indicating less changes because of retracking.

Waveform Beta-Retracked-Waveform-E-Retracked: The comparison reflects the mentioned bias of 1.2 cm between the different retracking algorithms. The number of normal point is the maximum value for all the collinear analyses done here, which is encouraging for further applications.

The collinear analysis has clearly demonstrated that differences between the official ERS-1 GDR and retracked altimeter waveforms exist. Much more data can be used for geophysical application when taking retracked waveforms, which means that for example accurate altimeter derived gravity anomalies can be computed much closer to the shorelines. Furthermore, different retracking algorithms lead to biases in the data and sometimes large differences in the retracked correction, especially very close to land. The problem is, that the truth is not known and the collinear analysis can not give some clues about it. However, several preliminary conclusions can be made:

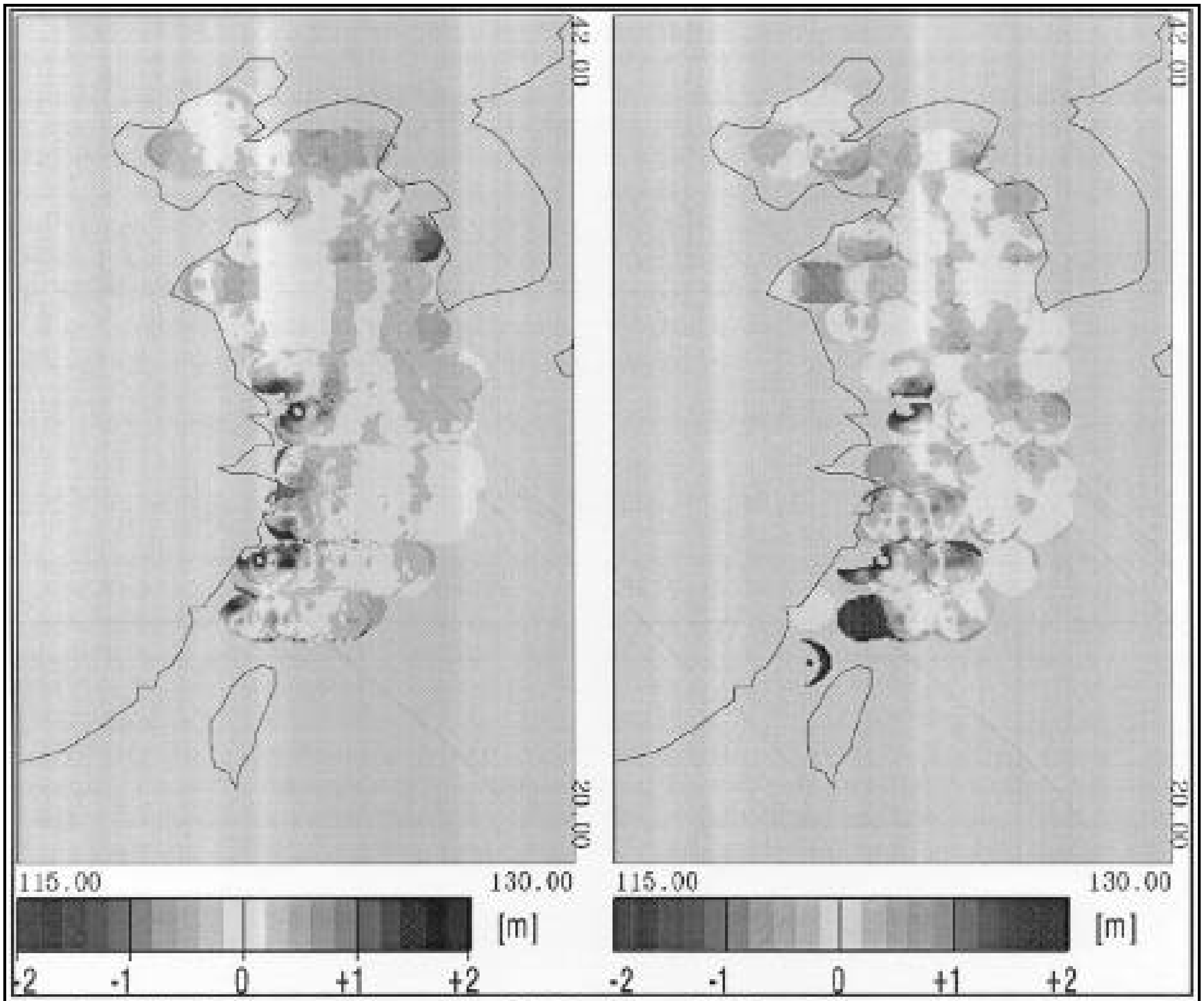

Fig. 14: Gridded Crossover Differences for OPR2 and Retracked Data Base

- retracked altimeter waveforms show differences to official GDR,
- different retracking algorithms lead to biases, thus, retracking algorithms should not be mixed when investigating temporal changes,
- much more data are available when using waveform data, and
- the correction from retracking leads to better consistence between official GDR and waveform data.

4.3 Crossover Statistics

Crossover statistics are an appropriate tool to qualify altimeter data. However, they are affected by the choice of data editing, temporal variability of the ocean surface, number of crossovers, and errors in models for the correction of altimeter data, such as tides. Having this in mind, a data upgrade was performed for the retracked data base in order to have comparable altimeter data.

	Waveforms	**Improved Waveforms**
Sat. Height	GFZ/1.2 orbit based on PGM055 gravity field	DUT/DEOS Orbits based on DGM04 gravity field
Ocean Tides	CSR3.0	FES95
Ocean Loading	CSR3.0	FES95
Solid Earth Tides	Cartwright Edden Taylor	Wahr
Ionosphere	IRI90	IRI95
Dry Troposphere	ECMWF	ECMWF remained
Wet Troposphere	ECMWF	ECMWF remained
Additional		SPTR correction oscillator drift
Bathymetric Heights		TUG87 (Wieser, 1990)
Geoid Heights		GFZ93A (Gruber and Anzenhofer, 1993)
Mean Sea Surface		MSS93A (Anzenhofer and Gruber, 1995)

Table 6: Waveform Upgrade

The upgrade procedure is described in detail in Anzenhofer and Gruber (1998). The upgraded waveform data base is now to a high extent comparable to the OPR2 data. Only the corrections for the troposphere varies a little, the OPR2 include the tropospheric corrections from the French meteorological office (ESA, 1993). The French meteorological data base, however, are based on the ECMWF fields, which are included in the waveform data. Thus, only minor differences should be apparent. For the crossover generation coarse data editing criteria were used, which are described in table 7.

This editing leads to a removal of altimeter data with suspicious quality. The result for the time period 10. October 1994 to 22. March, 1995 is compiled in table 8.
The numbers of calculated crossovers indicate that more than twice as much could be computed from OPR2. The reasons are missing waveform data in this time period. Furthermore, it was found out that for several retracked data arcs the tropospheric correction was set to zero, a value which is not possible over ocean surfaces. Hence, a zero value indicates that tropospheric data were missing. For crossovers a zero mean difference would be expected. Thus, mean values not equal to zero indicate systematic shifts between ascending and descending arcs. Usually this means errors in the satellite

Criteria	**Limit**
Bathymetry	> 0 m
|Difference to Mean Sea Surface|	> 3 m
RMS Range	> ±0.4 m
Sig. Wave Heights	> 12 m
Wind Speed	> 15 m/s
Max. Time Difference Between Crossing Arcs	> 35 days

Table 7: Editing Criteria for Crossovers

	OPR2	Retracked Data Base
No. of XO	442	210
Mean	-10.4 cm	-3.4 cm
RMS	±65.9 cm	±58.2 cm

Table 8: Result of Crossover Analysis

a smaller RMS than the OPR2. The difference between both RMS is small and could also be the result from different numbers of crossovers. The high RMS of about ±60 cm itself is huge compared to the global RMS of about ±10 cm. To a large extent this is caused by the vicinity of land and inaccurate ocean tidal modeling in shallow water regions and not from orbital errors.

The gridded crossover differences as seen in figure 14 show higher variability for the retracked data base than for OPR2. Some of the bumps in the retracked data image, however, are caused by missing crossovers. In both images a correlation to the areas of high tidal variability (see figure 6) is apparent. Also visible is the Jangtse estuary with high crossover differences.

In general, the statistics of crossover differences for OPR2 and retracked data are very promising. They indicate that similar quality of retracked altimeter data with respect to OPR2 can be achieved.

4.4 Sea Surface Height Residuals

	OPR2	Retracked Data Base
No. of SSH Residuals	8340	129028
Mean	-8.3 cm	-82.5 cm
RMS	±54.6 cm	±55.8 cm

Table 9: Result of SSH Residual Analysis

Sea surface height residuals are the second appropriate tool to investigate the overall quality of retracked altimeter data. But first to the definition of sea surface height residuals: With this method along track altimeter data are compared with gridded sea surface heights (sea surface height models). For each along track altimeter measurement the gridded sea surface height is bilinear interpolated with longitude and latitude of the footprint. Then, the along track sea surface height is subtracted from the corresponding interpolated sea surface height.

This quantity is called sea surface height residual. It can be used to detect biases, drifts, and other systematics in the along track data. Additionally, it can be used to quantify the quality of the gridded model by the so-called gradient test (Anzenhofer and Gruber, 1997). In this investigation the sea surface residuals are taken to look at systematics in the along track data. Therefore, a long term mean of the gridded sea surface is

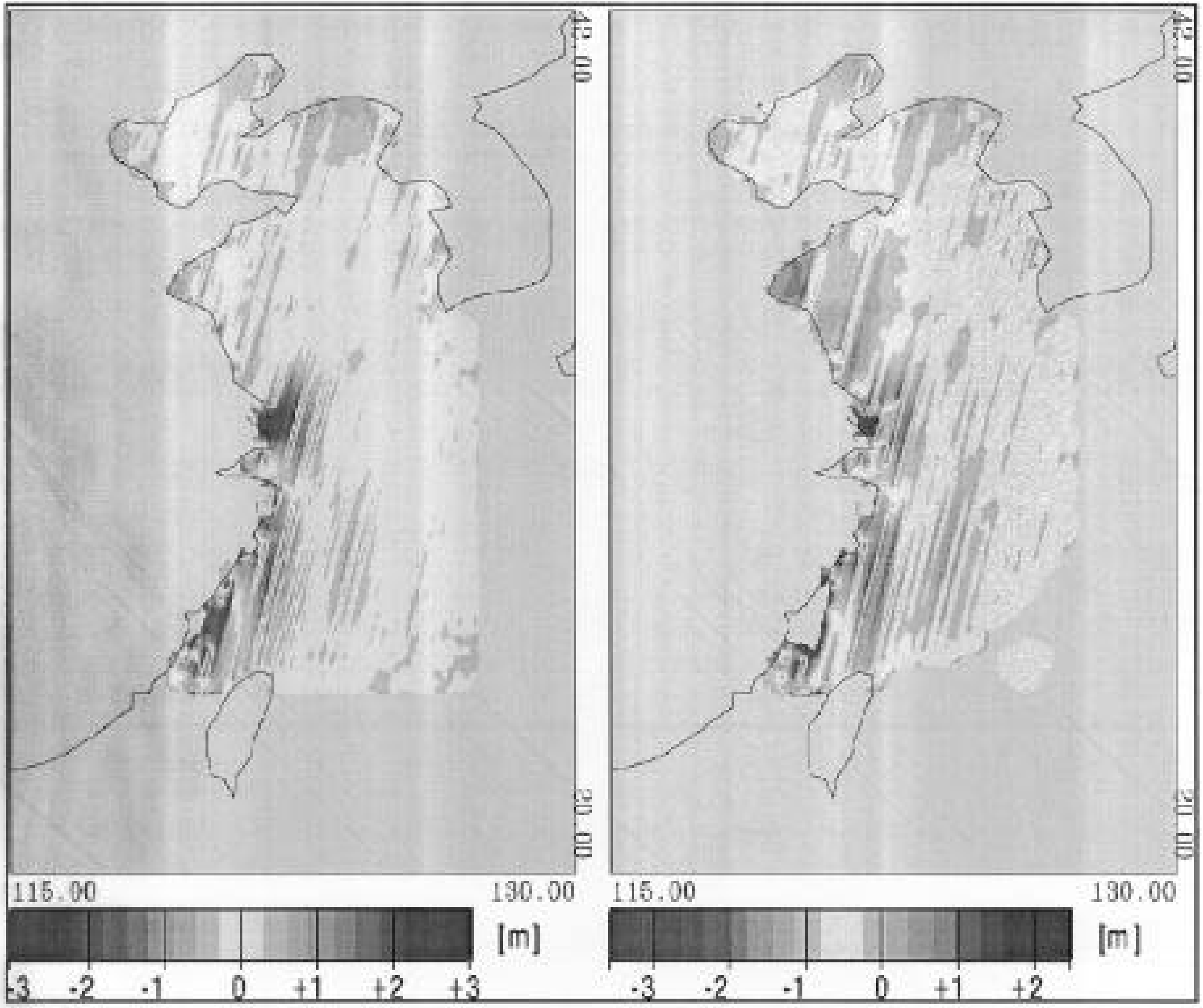

Fig. 15: Sea Surface Height Residuals From OPR2 and Retracked Altimeter Data

needed. For the investigation a standard product of GFZ/D-PAF (Gruber et al., 1993) is used, a long period sea surface height model, which is generated from all available ERS-1 OPR2. This model contains almost 5 years of data and has a spatial grid resolution of 6', which means that it can be taken as a long period mean sea surface. The results are compiled in figure 15 and 16 and in table 9.

Table 9 indicates a factor of 15.5 between the number of sea surface height residuals of OPR2 and retracked data. It should be kept in mind that there are a different number of arcs between both data, because of missing or undefined retracked data (see section 4.3). There is a mean of -8 cm between OPR2 data and the long term mean model. The reason is unclear, however, temporal variability is assumed. There is also a high RMS apparent, which is slightly better than from the crossover analysis. For the retracked data base a much bigger mean value of the sea surface residuals can be seen. The difference in the mean between OPR2 and retracked data of 74 cm is not equal the value from the collinear analysis (see table 5). The reason is unclear, but differences in the spatial distribution could be assumed. However, the RMS of the retracked data base is quite similar to the corresponding OPR2 result, which is very promising. But let us look at the spatial distribution of the sea surface residuals in figure 15. Both images look very similar. It is apparent where the high RMS of the sea surface height residuals is coming from; close to the Chinese coast and especially at the Jangtse estuary. This area seems to be very difficult to monitor with altimeter data.

At that moment it is not yet clear whether the RMS differences between OPR2 and retracked data are caused by data quality or missing data in the retracked data base. However, sea surface height residuals allow a one by one comparison between corresponding OPR2 and retracked arcs. Within the sea surface residuals procedure one can save the statistical information (number of measurements, minimum, maximum, mean, RMS) of each arc, which is compared with the long term sea surface height model. If one has the informations for both OPR2 and retracked data, then one can compare the statistical informations of corresponding arcs. This analysis has been performed and the results are compiled figure 16. Both images in figure 16 show scatter plots of corresponding arcs. The left image illustrates the relation between the number of measurements per arc for OPR2 and retracked data. It is 1:18.6, which means each 1 Hz OPR2 measurement is represented by almost 19 single retracked data. The right image shows the comparison of corresponding RMS of the sea surface residuals. It seems that both data types have the same quality. In the mean the RMS of the retracked data is 0.4 cm higher than for the OPR2, which shows that the quality of both data types is almost the same. For the not-retracked waveform data base the RMS is 4.5 cm higher than for the OPR2. This means, that the retracking correction leads to a 5 cm RMS improvement.

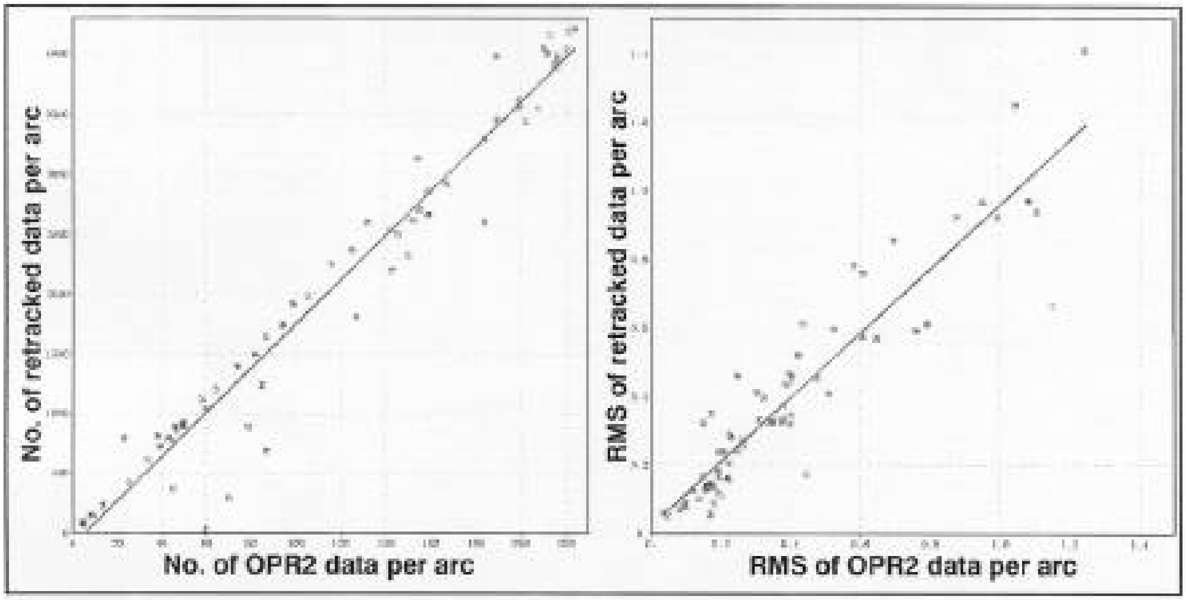

Fig. 16: SSH Residual Arc Comparison

5. Future Improvements and Conclusions

The work, the processing, and coastal applications of altimeter waveform data have clearly demonstrated that a huge effort is needed to achieve reasonable data quality and, thus, the possibility to perform altimeter applications. The results, however, have shown, that the work is not in vain, i.e. it is useful to work with this data. One thing became apparent, there is not only the issue to retrack the waveforms. In order to get high quality altimeter data, several data upgrades from filtering, editing, merging new orbits, tides, and atmospheric corrections have to be performed. Furthermore, a sophisticated data base, format, and data handling are necessary to handle 20Hz data instead of the usual ocean 1 Hz data.

In general, the coastal investigations have demonstrated that almost the same quality of ERS OPR2 could be achieved with waveform data, however, with much more data and much closer to the coast line.

The investigations made apparent that there are several points where waveform data could be improved. For coastal altimetry the ocean tides are the most challenging issue. Global model, such as FES95, are very accurate in open ocean areas, on shallow water regions, however, errors in the meter level could occur. Other critical areas near coasts are the estuaries of big rivers, like the Jangtse in the investigation region. It seems that there could be huge oceanic amplitudes which have other reasons and periods than tides. It must be concluded that these local phenomena require a careful use of altimeter waveforms.

The tropospheric media corrections are another critical point for waveform processing. Radiometers, which measure the wet component, produce no or useless data close to the coast. Thus, accurate meteorological fields are needed. This requires local measurements and local modeling of the atmospheric conditions. For many regions of the Earth both requirements will remain open issues in the near and far future. Therefore, one has to merge the meteorological fields from global models runs. These data, however, are delivered with a spatial resolution of 2 degree boxes and do not provide accurate local informations, which are needed for local investigations.

Recent investigations (Scharroo and Visser, 1998) have demonstrated that the satellite heights can be calculated with centimeter accuracy. For the orbital heights two requirements must be stated:

- empirical orbit adjustment procedures, such as "tilt and bias", are not allowed in coastal areas, because their requirement of a stationary sea surface is not more true
- empirically adjusted gravity models with altimeter data may not be used for orbit computations, because the least squares procedures result in improved "ocean orbital heights" and worse "land orbital heights"; coastal altimetry and land altimetry analysis need accurate orbital heights everywhere, thus, empirically adjusted gravity models are excluded from use

The solution will be reprocessed orbits from the CHAMP and GRACE missions in the new millennium.

Local investigations at the Jangtse estuary have demonstrated that a more careful waveform retracking is required, because small islands or tides induced changes of wet and dry surfaces result in different waveform shapes. A partly solution could be the use of other weighting parameters for the least squares approach (see section 2.3.4). Also, a careful editing of outliers must be performed to improve the retracked data base quality.

In general, the coastal altimetry work has shown that it is possible to generate OPR2 like retracked data, which are much higher rated and closer to the coast. With this data, altimeter related applications, such as gravity anomalies, can be further improved, especially in coastal regions.

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