|  |  | Doc. No.: <br> Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 1 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

## CryoSat

## In-Flight Calibration Approach

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|  |  | Doc. No.: <br> Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 2 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

## Change Record

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|  |  | Doc. No.: Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 4 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

7.3.6 Transponder Deployment and Visibility ..... 36
7.3.7 Practical Arrangements ..... 38
7.4 Data Processing ..... 38
8 Summary ..... 44
Annex A

| cesa |  | Doc. No.: Issue: Date: Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 5 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

## 1 Scope

This document determines the in-flight calibration activities for CryoSat. These activities will (largely) be performed within the Commissioning Phase ${ }^{1}$ and this document is an input to the overall Commissioning Phase Plan, AD 1.
The scope of the calibration activities, for the purpose of this document, is restricted to the payload ${ }^{2}$. Furthermore, calibration of the Star Trackers (mainly the focal length) is a task for the industrial contractor, using existing tools. Therefore the Star Tracker calibration is addressed in AD 1. This present document addresses SIRAL and DORIS, although the latter is partially under the responsibility of CNES under the terms of the CryoSat DORIS Mission Implementation Agreement.

### 1.1 SIRAL

SIRAL makes measurements of radar echo signals as a function of delay time, in three different measurement modes: LRM (Low Resolution Mode), SAR mode and SARIn mode. The calibration of these measurements is largely controlled by pre-launch characterisation measurements and internal calibration means. However some external measurements are needed in-flight, typically to determine biases in the system.

The techniques, performance and associated processing of the internal calibration data is covered by numerous other project documents. This present document addresses the external calibration.

The objectives of external calibration are:

- range calibration of the SIRAL;
- sigma-0 calibration of the SIRAL;
- calibration of the angle of arrival of the SIRAL interferometer.


### 1.2 DORIS

Calibration of the DORIS on CryoSat has two parts:

- "traditional" DORIS calibration and validation, similarly to other DORIS missions;
- calibration of any long-term secular drift in the DORIS-derived orbits.

This document provides the outline of activities which will be performed by a specialised group.

[^0]|  |  | Doc. No. Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 6 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

## 2 Documents

### 2.1 Applicable Documents

AD 1

The following documents provide additional information and may be referred to herein.
Draft 7 DORIS-CryoSat Mission Implementation Agreement
RD 1
CS-PL-ESA-SY-0xxx
Commissioning Phase Plan

### 2.2 Reference Documents

RD 2
CS-TN-DOR-SY-0005 Draft
CryoSat External Calibration
RD 3
CS-PL-DOR-SY-0014 Issue 1 S
SIRAL Calibration and Characterisation Plan: External Calibration
RD 4
CS-TN-DOR-SY-0039 Issue 1 Interferometric Baseline Attitude Knowledge
RD 5

RD 7

HE-5AS Star Tracker - CryoSat Performance Report Transponder Altimetry: An Investigation of a Precise Height Measurement System, Paul Denys, PhD Thesis, University of Newcastle upon Tyne, May 1995
The EnviSat RA-2 Sigma-0 Absolute Calibration, M. Roca, H. Jackson and C. Celani, submited to IEEE Trans Ant. Prop. 2003

## 3 DORIS

### 3.1 Basic Calibration and Validation

The basic activities required to calibrate and validate DORIS are covered by the DORISCryoSat Mission Implementation Agreement, RD 1, which identifies, amongst the undertakings of CNES:
"Analyse the performance of DORIS/CryoSat, validate this performance during system test and commissioning and perform quality control for the precise orbit determination throughout the mission;"

In addition to this, following the EnviSat approach, a group of orbit-determination experts has been established to independently compute precise orbits and perform calibration and validation of DORIS. Members of this group have been selected via the CryoSat Cal/ Val AO and are already members of the CryoSat Calibration, Validation and Retrieval Team (CVRT). The group will also be responsible for long-term orbit validation and indirect calibration of the SIRAL range measurement (see Section 4, "SIRAL Range Calibration") and is called the CryoSat Orbit and Altimeter Validation Group.
The data required by this group, and the sources of these data, are shown in Table 3.1-1.

Table 3.1-1 Data types and source for independent orbit determination.

| Type | Parameters | Source |
| :---: | :---: | :---: |
| Static Flight Dynamics Properties | - geometry <br> - reference points <br> - surface areas <br> - surface properties <br> - attitude control laws <br> - magnetic moment <br> - thermal dissipation with respect to geometry | ESA CryoSat Project ${ }^{1}$ |
| Dynamic Flight Dynamics Properties | - mass <br> - centre of gravity | ESOC Flight Dynamics website ${ }^{2}$ |
| DORIS station characteristics | - location <br> - ... | PDS or IDS ${ }^{3}$ |
| CryoSat Manoeuvres | - time <br> - delta-v | ESOC Flight Dynamics website |
| CryoSat attitude thruster activation | - time <br> - thruster pair <br> - impulse | PDS |
| CryoSat attititude | - Level 0 quarternions | PDS |
| CryoSat DORIS receiver characteristics | - TBD | PDS or IDS |
| DORIS level lb data | - corrected doppler data | PDS or IDS |
| CryoSat Laser Tracking data | - laser range normal points | ILRS ${ }^{4}$ |

1. CryoSat Static Flight Dynamics Properties, CS-TN-ESA-SY-00xx
2. http://nng.esoc.esa.de/envisat/ENVmano.html (the equivalent page for EnviSat)
3. International DORIS Service, at CNES (SSALTO), see http://ids.cls.fr/html/data centers.html
4. International Laser Ranging Service, see
http://ilrs.gsfc.nasa.gov/products_formats_procedures/index.html

The activities which will be performed are closely based on the approach which was used for EnviSat. The key features are:
1 establish common data-sets (i.e. DORIS doppler data), standards and models between the groups;
2 definition of tools and external data needed to determine the quality of the orbit;
3 definition of tests able to qualify the orbit;
4 each team in the group computes the orbit with its own processor and compares with the SSALTO orbit, computed with the baseline configuration;
5 orbit comparisons to establish which parameter or model needs to be updated.

### 3.2 Long-term Validation and Characterisation of Orbit Errors

CryoSat is intended to measure small secular changes in the elevation of the ice-caps. It is thus susceptible to (hypothetical) small secular changes in the precise orbits in such regions (which are not covered by ocean cross-overs). Such effects could be caused, for example, by evolution of coordinate systems, long period tidal aliasing, etc. A long-term activity (which could be regarded as calibration or validation) is required to monitor this.
A detailed plan for the long term validation and characterisation of the CryoSat orbits will be defined by the CryoSat Orbit and Altimeter Validation Group. Some elements of this are:

- the reference frame will be fixed;
- new ITRF solutions will be examined but not used to update the models;
- orbits could be based on DORIS only, using SLR measurements as an independent test;
- altimeter cross-over analysis over the ocean will monitor overall trend and covariance of errors in elevation and backscatter coefficient;
The commissioning phase will be used to perform basic validation checks, rather than to try to fully validate the orbit. During the following 2 years the full validation will be performed, using a long data-set. The models and processors will then be refined and reprocess of the orbit data will be performed ${ }^{3}$, in parallel to the foreseen reprocessing of SIRAL data.

[^1]
## 4 SIRAL Range Calibration

### 4.1 Background

Calibration of the range measurement of previous altimeters has been performed by the following methods:

- absolute calibration, in which the altimeter range measurement is compared to an independent determination of the range (see Table 4.1-1);
- indirect calibration, in which the altimeter range measurement is compared to other altimeters or geophysical "constants" derived from other altimeters (see Table 4.1-2).

Table 4.1-1 Summary of absolute range calibration activities for satellite altimeter missions. All of these activities used the ocean surface as the target for the altimeter. The column titled "Result" gives the estimated uncertainty in the final bias value rather than the bias itself.

| Mission | Method and Resources | No. of passes | Duration | Result (cm) |
| :---: | :---: | :---: | :---: | :---: |
| SeaSat (1978) | - transportable laser deployed to Bermuda; <br> - single, existing tide gauge; <br> - "overhead" geometry with interpolation of altimeter data over island. | 4 |  | $\pm 10$ |
| ERS-1 (1991) | - transportable laser deployed to Monte Venda; <br> - support from 5 fixed laser stations; <br> - instrumentation installed on "Venice Tower" (radiometer, GPS, existing tide gauges); <br> - pre-launch GPS campaigns. | 11 | 6 weeks | $\pm 5$ |
| TOPEX/Poseidon (1992) | - support from 2 existing, fixed laser stations; <br> - extensive instrumentation (tide gauges, GPS, radiometer) installed on "Harvest" oil platform. | 146 | 4 years | $\pm 0.3^{1}$ |
| TOPEX/Poseidon (1992) | - transportable laser deployed to Lampedusa: <br> - instrumentation (tide gauges, radiometer, GPS) installed at Lampedusa and Lampione; <br> - deployment of large GPS buoys. |  |  |  |
| Jason (2001) | - transportable laser deployed to Ajaccio; <br> - extensive instrumentation (tide gauges, radiometer, GPS) installed at Ajaccio and Senetosa; <br> - pre-launch GPS mapping of sea-surface. | 56 | 10 months | $\pm 0.6^{1}$ |
| EnviSat (2002) | - support from 6 existing, fixed laser stations; <br> - extensive instrumentation (tide gauges, radiometers, GPS) installed at 3 locations in NW Mediterranean; <br> - deployment of 4 large GPS buoys; <br> - pass-by-pass deployment of small GPS buoys; <br> - extensive sea-surface modelling. |  | 8 months | $\pm 6^{2}$ |

1. not an uncertainty; this is simply the observed $\sigma$ of the measurements divided by $\sqrt{n}$
2. preliminary result: this is likely to improve to $\pm 2 \mathrm{~cm}$.

Table 4.1-2 Summary of indirect range calibration activities for satellite altimeter missions. The column titled "Result" gives the estimated uncertainty in the final bias value rather than the bias itself.

| Mission | Method | No. of <br> passes | Duration | Result <br> (cm) |
| :---: | :--- | :--- | :--- | :--- |
| ERS-2 | Collinear tracks with ERS-1 |  |  |  |
| ERS-2 | Cross-overs with ERS-1 and Topex/Poseidon |  |  |  |
| ERS-2 | Comparison of Mean Sea Surfaces |  |  |  |
| ERS-2 | Orbit determination |  |  |  |
| Jason |  |  |  |  |
| Jason |  |  |  |  |
| EnviSat | Collinear tracks with ERS-2 |  |  |  |
| EnviSat | Cross-overs with ERS-2, Topex/Poseidon and <br> Jason |  |  |  |
| EnviSat | Comparison of Mean Sea Surfaces |  |  |  |
| EnviSat | Sea level anomaly and orbit determination | 14 | 1 day | $\pm 5 \mathrm{~cm}$ |

It is clear from the Tables that the absolute calibration methods require the commitment of significant resources over a period of time. If small eventual errors are to be obtained this time is of considerable duration. In contrast the indirect methods only require analysis of satellite data collected over a relatively short period.
Absolute calibration was necessary for the early missions because indirect calibration was not a realistic option: there were neither simultaneous missions for cross-calibration nor sufficiently accurate knowledge of geophysical parameters such as the ellipsoid semimajor axis or the mean sea surface. For example the absolute range calibration of ERS-1 identified a 30 cm error in the semi-major axis of the WGS84 ellipsoid.
By the launch of ERS-2 (1995) cross-calibration (against ERS-1 and TOPEX/Poseidon) was sufficiently mature that it was the only calibration method planned for this mission. More recently, the indirect calibration of EnviSat has included techniques in which precise orbit determination and the knowledge of the mean sea surface are so well established that range (and datation) calibration may be achieved by analysis of EnviSat data alone, using as little as one day of data.
In order for these indirect techniques to provide accurate and precise results they are restricted to ocean surfaces. Over oceans the altimeter range measurement has low noise and the reflecting surface is well understood; the mean sea surface is also a very well known quantity. Over ice surfaces, in contrast, the effective reflecting surface is still an area of research and the surface is less well known. Nevertheless cross-calibration over ice sheets has been performed, as shown in Table 4.1-2.

### 4.2 CryoSat Approach

For CryoSat the range calibration will be indirect. Ocean data in LRM are equivalent to "traditional" altimeter data and standard techniques (cross-overs, collinear tracks) will be employed by the Orbit and Altimeter Validation Group to provide a relative bias offset with respect to EnviSat/RA-2 and Jason-1. Both of these are already operational and are expected to continue to be operational during the CryoSat lifetime.

|  |  | Doc. No.: <br> Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 11 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

For the SAR and SARIn modes this approach cannot be directly used - operational and data-flow requirements over oceans would prevent the collection of a suitably large dataset.

The approach for these modes will be to use a feature of the data processor specifically introduced to enable validation of the range measurement in these modes. The Instrument Processing Facility (IPF) produces, as part of the Level 1 b product in SAR and SARIn modes, an output at 1 Hz which by-passes the SAR processing to produce pulse-width limited echoes. These are directly comparable to LRM echoes, although LRM mode does not operate simultaneously with SAR or SARIn. In order to determine any range bias in the 1 Hz SAR / SARIn data the following options exist:

- for normal operational transitions over ocean between SAR/LRM and SARIn/LRM, comparison with LRM range measurements immediately before or after;
- vicarious comparison with colocated EnviSat or Jason data over ocean (or cross-overs with these data) using normal operational mode transitions;
- specific campaigns to perform cross-calibration with EnviSat and/or Jason (note that for SARIn mode the ocean data collected for angle of arrival calibration, described in Section 7.2.1, "Ocean Surfaces" may be used).
In practice each will be possible using dedicated functions of the Monitoring Facility, but it is likely that the first option will need additional manual intervention.
After the indirect range calibration of these SAR/SARIn 1 Hz reconstituted pulse-width limited data, they may then be compared to the range measurements in SAR and SARIn mode. In this way the 1 Hz dat act as a "transfer standard".


## 5 SIRAL Sigma-0 Calibration

### 5.1 Background

Sea-surface windspeed and $\sigma^{\circ}$ are related, and so some previous efforts to calibrate $\sigma^{\circ}$ have been performed directly, while others have been performed via the windspeed. Due to the slope of the empirically derived relationships, except at the lowest windspeeds, small errors in $\sigma^{\circ}$ have a strong effect on derived windspeed.
Prior to EnviSat (2002) an absolute calibration of $\sigma^{\circ}$ had never been performed, and insufficient EnviSat absolute calibration data are available at present. Until EnviSat the existing status was a mixture of theory, empirical relationships and relative calibration, often between diverse systems.
Cox and Munk (1954) established an empirical relationship between surface mean-squareslope of ocean surfaces and windspeed, using an optical sun-glint technique. In 1978 Brown showed that $\sigma^{\circ}$ at normal incidence is inversely proportional to surface mean-square-slope. Then in 1979 Brown developed the first wind algorithm (with 2 branches) based on the Cox and Munk results, normalised by 39 ship and 19 buoy colocations with GEOS-3. This was followed by an extension (Brown et al, 1981) with 184 buoy colocations with GEOS-3 to provide a 3-branch wind algorithm.
However the calibration status of GEOS-3 is unknown, despite enquiries among many of the original scientists and engineers involved.
Fedor and Brown (1982) applied the Brown et al 3-branch algorithm to SeaSat. This required cross-calibration of the $\sigma^{\circ}$ values. They found 19 cross-overs (within 1 hour) with the following result:

- SeaSat = GEOS-3 + 1.6 dB
- standard deviation 0.37 dB

Based on this processing Chelton and McCabe (1985) found significant distortions in SeaSat windspeed histograms. This was due to discontinuities in the algorithm used to convert telemetry to $\sigma^{\circ}$, and to cusps in Brown et al wind algorithm. Consequently they derived a new telemetry to $\sigma^{\circ}$ algorithm (after Hancock) with 0.15 dB bias uncertainty and a new wind algorithm. This was derived empirically from scatterometer colocations. The algorithm was later improved by Chelton and Wentz (1986).
Witter and Chelton (1991) applied the Chelton and Wentz algorithm to Geosat data. They identified non-linear $\sigma^{\circ}$ errors in the SeaSat algorithm (below $\sigma^{\circ}=11 \mathrm{~dB}$ ) which had been incorporated into the Chelton and Wentz algorithm. According to Callahan et al (1994) there were further (unspecified) offsets between Geosat and SeaSat, however he is now unable to provide further information. The Witter and Chelton algorithm (also known as the Modified Chelton and Wentz algorithm) has become quasi-standard.
Subsequent altimeters have effectively or explicitly introduced the concept of a relative bias calibration of their $\sigma^{\circ}$ values in order to use the Witter and Chelton wind algorithm.

With EnviSat there has been, for the first time, an effort to perform an absolute calibration of $\sigma^{\circ}$ using a dedicated transponder (Roca et al, RD 7). This excercise (which still needs more data to derive a definitive result) provides an absolute offset from the current relative scale of slightly more than 1 dB . Since a relative calibration of EnviSat data to other altimeters has also been produced this value is applicable to all other altimeter data as well.

|  |  | Doc. No.: Issue: Date: Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 13 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

### 5.2 CryoSat Approach

For CryoSat the approach will be indirect, or relative calibration, making use of the EnviSat absolute calibration results. The principal method is the comparison of histograms of $\sigma^{\circ}$ over oceans. An example of such a histogram from several altimeters is shown in
Figure 5.2-1. This shows the characteristic normal distribution with a mean at about 11 dB (note that these data have not been adjusted for the absolute calibration result described in the previous section, nor have the Jason-1 data been relatively calibrated).
The method to be applied to CryoSat data is the following:
1 CryoSat LRM data over ocean areas will be processed in the Monitoring Facility to generate histograms for each EnviSat 35-day cycle;
2 comparison with the equivalent EnviSat histogram will provide the $\sigma^{\circ}$ bias value;
3 CryoSat SAR and SARIn data are processed in pulse-width limited mode with a 1 Hz sampling in the PDS in order to support validation activities; the $\sigma^{\circ}$ values from these will be compared with the direct SAR and SARIn values to provide the inter-mode calibration.

Figure 5.2-1 Histogram of $\sigma^{\circ}$ over ocean, measured by the altimeters on ERS-2, EnviSat and Jason-1.


Issue:
Date: 17 Jan 2005
Page: 14

## 6 SIRAL Interferometric Baseline

The interferometer function is used in SARIn mode to determine the arrival angle of the first return in the echo. Combined with the range measurement this enables the determination of the elevation and location of the ground echo point. In this Chapter we shall discuss the contributing errors in the on-board system, as well as means to calibrate them. The assessment of external means of measuring the angle of arrival is deferred to the next Chapter.
A comprehensive evaluation of the errors in this process is given in RD 4, which is appended in Annex to this document.
As explained in RD 4, the arrival angle is derived from the phase difference of the return echo at the two antennas. Given the CryoSat characteristics the relationship is linear with one arcsecond of angular displacement corresponding to 0.093 degrees of phase difference.
The required overall error in the measurement of the angle of arrival, derived from the mission requirements, is 30 arc-sec.
This places stringent requirements $\left(3^{\circ}\right)$ on the errors in the relative phase difference between the two receive branches of the SIRAL.
In addition to the random errors inherent in the measurement of phase difference between the two received echoes, there are factors which can introduce systematic errors into the measurement of arrival angle. These are:

- phase differences inside the SIRAL electronics;
- phase differences between the SIRAL electronics and the antennas' phase centres (which forms the interferometric baseline);
- errors in knowledge of the orientation of the interferometric baseline.

These errors are calibrated or controlled by the use of specific features of the CryoSat system, as described in RD 4 and the following Sections. The problem of measuring a known angle of arrival is dealt with in the following Chapter.

### 6.1 Phase Differences Inside the SIRAL Electronics

The phase difference inside the instrument is determined during operation in SARIn mode by a specific calibration path (called CAL4), covering the electronics of both receive channels, including the duplexer. This needs to be combined with the output from an infrequent calibration mode, CAL1, as described in RD 4.
Changes of path length difference can result from the following effects:
1 Temperature variations of the instrument over the orbit or during the measurement. Indeed, the propagation delay through amplifiers and filters is a function of temperature. Therefore temperature differences between channels result into phase differences. The propagation delay through passive elements such as waveguides or circulators (i.e. duplexer elements) is also affected by temperature, due to thermal expansion.
2 Changes of gain setting in the IF chain. The insertion phase of such amplifiers (or the propagation delay) is a function of gain. In spite the fact that the gain setting of both receive chains is identical at a given moment, the behaviour of the amplifiers is not exactly the same due to dispersion of components. Therefore, different gain settings controlled by the gain tracker- may result in different phase difference between channels.


3 Varying position of the echoes inside the tracking window. After deramp, the delay of the echoes is converted to frequency. As the dispersion of the IF filters is not perfect, the propagation delay (and consequently the insertion phase) of these filters is a function of frequency. Furthermore, the filters of both chains not being identical (due to dispersion of components) there results a variable phase difference across the range window.
The first point is believed to have the highest magnitude and variability. CAL4 is designed to monitor in real time and during the measurements such phase drifts due to temperature gradients. The processing of the calibration pulses gives directly the phase difference between channels (for a fixed delay and gain), which is then used to compensate the data. It must be pointed out that in general, the data are acquired with a different gain and delay. The accuracy of the determination of the phase using CAL4 is affected by noise (thermal, quantisation) and by drift of the calibration coupler itself. The current prediction is $0.12^{\circ}$ for the noise and $0.1^{\circ}$ for the drift of the coupler.
The second and third points are calibrated only occasionally using the so-called CAL1 mode. Correction tables are generated off-line, giving phase difference corrections as a function of gain (point 2 above) and as a function of delay (point 3 above). The signal properties (signal strength, signal delay) and the environmental conditions (temperature) applied during the generation of these tables are not identical to those during the actual measurements. The residual error between the values of the calibration tables and the actual phase difference due to gain and delay is estimated to be less than $0.4^{\circ}$.

There results an overall accuracy for the estimation of the phase difference between channels using CAL1 and CAL4 of $0.42^{\circ}$.
It must be pointed out that, unlike CAL4, in CAL1 mode the duplexer is excluded from the calibration path but the pulse used for the calibration is the actual pulse transmitted to the ground, taken at the output of the high power amplifier. Therefore, CAL1 gives a more accurate measurement of the instrument impulse response function than CAL4, but part of the receiver is not covered (duplexer).

### 6.2 Phase differences Between the SIRAL Electronics and the Antennas' Phase Centres

There are a few elements of the instrument that are not covered by the internal path (CAL1 or CAL4). These are the waveguide harness between the duplexer and the antenna, the antenna feed and the reflectors.
The instrument has been designed to minimise phase differences in this section, by using extremely stable materials:

- the waveguides and the feed horn are made out of INVAR;
- the reflectors (including subreflectors and struts) are completely made out of CFRP (carbon fibre honeycomb and carbon fibre skins).
Considering the worst case thermal gradients on this section as well as manufacturing uncertainties, the estimated maximum phase difference is $0.4^{\circ}$, equivalent to 4 arcseconds. This includes waveguide expansion (longitudinal and transversal), thermoelastic deformations of main and sub-reflectors, translation and rotation of the feed horns.
More details of this analysis are presented in RD 4, where the resulting error term is called RF error.
As no on-board calibration of this error is foreseen the instrument has been designed for maximum intrinsic stability. In practical terms, errors in the angle of arrival (or phase dif-
ference) are indistinguishable from, and treated together with, variations in the orientation of the interferometric baseline. This is considered in the next Section.


### 6.3 Orientation of Interferometric Baseline

The orientation of the interferometric baseline in the earth-fixed reference frame is the combination of the following elements:
1 actual orientation in inertial reference frame (as determined by star trackers);
2 location of the satellite in the earth-fixed frame (as determined by precise orbit determination);
3 conversion of the inertial to earth-fixed reference frame (requiring knowledge of pole position etc.);
4 static and thermo-elastic deformation of the antenna bench, between the star trackers and the baseline (practically this includes the RF error term).
Items 1, 2 and 3 are effectively random error contributions to the determination of the baseline. Within RD 3 these are accounted for simply as the "star tracker measurement accuracy" (see Section 6.3.2). As random errors they are not amenable to calibration.
Item 4, in contrast, does not contain random components and has to be accounted for in the Level 1 b processing. It is a calibration correction and the detailed correction function, refining the pre-launch estimate, must be determined during the Commissioning Phase.
The level 1 b processor (in the star tracker CFI routine) will have a function which takes orbital position, solar direction and on-board temperature measurements and addresses a look-up table or function to provide the expected correction angle from star tracker to baseline vector ${ }^{4}$. The initial version of this can be based on pre-launch modelling.
Routine processing will be based on measurements from a single star tracker; although there are three on-board, one may be failed and one sun-blinded. In fact the normal satellite configuration will have two star trackers active, from which one, autonomously selected on-board, is used to pilot the AOCS. Data from both will be in the science telemetry stream. The selection of the two active star trackers is performed by ground command. The interferometer baseline calibration function will be different for each star tracker.
The calibration activities may be conveniently split into two parts:
1 relative star tracker alignment - star tracker measurements will be continuously available and their relative misalignment will be used to improve the modelling of the thermo-elastic distortion of the antenna bench;
2 interferometer baseline alignment - comparison of interferometric angle measurements with "truth" measurements will be more sparse and will be used to fine-tune the modelling.

### 6.3.1 Thermo-Elastic Deformation

### 6.3.1.1 Modelling

Modelling of the thermo-elastic deformation of the antenna bench has been performed by Astrium GmbH. This is described in detail in RD 4. Several thermal conditions were con-

[^2]sidered, at the extremes of the thermal range $\left(-10^{\circ} \mathrm{C}\right.$ to $\left.+40^{\circ} \mathrm{C}\right)$, including both beginning and end of life and over a range of local times. The resulting temperature maps were then used in a finite element mechanical model of the antenna bench in order to determine the resulting distortions. As well as the bench, the distortion at the star tracker mounting brackets and the displacement of the RF antenna feeds were examined, over a range of local solar times.

The results, given in RD 4, demonstrate that each star tracker shows distortion which is broadly consistent as a function of local solar time, although there is a strong dependence on interface temperature. The RF components, in contrast, are largely insensitive to interface temperature but are slightly sensitive to local solar time.
This behaviour is driven by thermo-elastic bending of the antenna bench as illustrated by Figure 6.3-1. The interface is isostatic, consisting of three blades. However the design is not perfect and the changes on the satellite side appear to drive a flexure of the bench, as shown. However it has to be pointed out that the analysis has considered the extreme thermal conditions specified for the satellite design. Subsequent thermal analysis, also provided in RD 4, has shown that the thermal conditions at the interface will vary by $\pm 2.5^{\circ} \mathrm{C}$ around one orbit and with a full temperature range of $22^{\circ} \mathrm{C}$ over all thermal conditions (compared to the specification of $50^{\circ} \mathrm{C}$ ).
Nevertheless the effects appear to be amenable to representation by relatively simple linear functions of temperature and local solar time. This is the basic assumption described above.

Figure 6.3-1 Sketch showing the bending of the antenna bench as a function of temperature of the interface to the satellite (marked i/f).


### 6.3.1.2 Measurements

The angular distortions described in the previous section were a function of interface temperature and local solar time (which determines the gradient across the antenna bench). The model function will be driven by temperature measurements from the satellite as well as geometrical parameters (e.g. local solar time).
In this Section we identify the available temperature measurements which may be used in this model.

Temperatures at various points on the antenna bench, the interface plates and on the RF hardware itself are measured by thermistors, whose readings are returned in the satellite telemetry. The locations of these thermistors are shown schematically in Figure 6.3-2.
Clearly there are ample thermistors available for determining gradients across and through the antenna bench, as well as for the determination of the distortions arising from thermal variations at the interface to the satellite.

### 6.3.1.3 Summary

A great deal of information is provided in RD 4; this Section summarises the results for the thermo-elastic deformation of the antenna bench, including both RF error and star tracker brackets.

Figure 6.3-2 Left: location of thermistors (shown as red squares) on the antenna bench. There are 4 on each side of the bench and 2 on the antenna dishes. Right: location of thermistors on the instrument mounting plate. There are 3 in line between the heat pipes to measure the gradient between the isostatic mounting points for the antenna bench, and one close to the transmitter power supply.


- antenna-bench "curvature" measured at the star tracker interfaces (due to interface temperature variations) considering the extreme temperature variations over the satellite lifetime: 4.4 arc-sec.
- the same parameter, considering one orbit: 0.42 arc-sec around a mean value.
- antenna bench distortion (mainly due to variations in mean local solar time, which varies with an 8 -month period in the CryoSat orbit): $\pm 1.5$ arc-sec.
- Total variation in RF error (mostly dependent on mean local solar time) is less than $\pm 1.5$ arc-sec.
- distortion of the star tracker bracket: 3.2 arc-sec (maximum).
- RF harness (a short waveguide section): 0.05 arc-sec.


### 6.3.2 Star Tracker Measurements

There are three star trackers mounted on the antenna bench, looking in different directions. Three is the minimum number required to ensure resistance to simultaneous sun and moon blinding, in two different directions. Two star trackers are active at all times (in the absence of failures) and the measurements available in the science telemetry. Due to their differing locations on the antenna bench the angular deviation due to thermo-elastic deformation is different for each unit, as described in RD 4.
The relative star tracker alignment requires simultaneous operation of all three star trackers. The deviations in their inertial pointing will provide the first stage in refinement of the modelling of the antenna bench.
The error budget for the knowledge of star tracker attitude in the earth-fixed frame is given in Table 6.3-1.
The star trackers measurements around their roll axis is significantly more noisy (but still within the requirements) than around pitch and yaw. The relationship of the star tracker


Table 6.3-1 Error budget for the star tracker measurements. The pitch, roll and yaw axes refer to the star tracker camera head from of reference, in which the boresight lies along the roll axis. These random errors are $1 \sigma$. Harmonic errors are errors at the orbital period driven by thermal stability of the boresight.

| Element | Assumption | Source Error | Random Error <br> (arcsec) | Harmonic <br> Error (arcsec) |
| :---: | :---: | :---: | :---: | :---: |
| Star Tracker | Inertial frame <br> performance | RD 5 | 1.3 (pitch/yaw) <br> 11.3 (roll) | 2 |
| Location of satel- <br> lite in earth-fixed <br> frame | DORIS precise <br> orbit | 1 m along track | 0.03 | - |
| Transformation <br> from inertial <br> (J2000) from to <br> earth-fixed (ITRF) | Earth orientation <br> parameters | uncertainty in <br> UT1 $1 \mu \mathrm{~ms}$ (IERS <br> Bulletin B) | $1.5 \times 10^{-5}$ | - |
| Total |  |  | $\mathbf{1 . 3}$ (pitch/yaw) <br> $\mathbf{1 1 . 3}$ (roll) | $\mathbf{2}$ |

axes to the antenna plate is shown in Figure 6.3-3. The interferometer makes measurements of the cross-track angle of the point from which the first return in the echo comes. This angle is dominated by the pitch axis of the star tracker. The performance in roll has no impact on the calibration of the interferometric baseline (nor on routine operations).

Figure 6.3-3 Directions of the star tracker axes are indicated: red is pitch, green is yaw and blue is roll. The variation in the cross-track angular measurement of the interferometer is almost entirely determined by the performance in pitch.


Issue:
Date: 17 Jan 2005
Page: 20

## 7 Measurement of Angle of Arrival

Measurement of the orientation of the interferometric baseline is performed by operating the SIRAL in interferometric mode over a surface or target whose physical properties are such that the direction between the SIRAL and the first echo arrival are independently (geometrically) known. There are two such targets possible:

- a natural plane surface;
- an artificial point target (a transponder).

The echo properties of these targets are different, since natural surfaces exhibit speckle while the transponder produces a coherent echo and is thus speckle-free. Transponders enable the baseline orientation to be determined using a substantially shorter length of ground track, as shown below.
However there are insufficient transponders available to provide orientation measurements all around the orbit. A combination of natural plane surfaces and transponders will therefore be used.

### 7.1 Calibration Modes

According to the original calibration concept, for calibration of the angle of arrival over natural plane surfaces the SIRAL would be used in either of two modes:

- SARIn mode, in which the instrument is in its normal measurement configuration;
- CAL3 (or external calibration) mode, in which the instrument operates in a configuration equivalent to LRM but with both channels operating and complex data being delivered.
The rationale of these modes is described in RD 2, and CAL3 is mentioned in various other calibration documents (including RD 4).
However, more recent work, summarised in Annex A, "Calculations for SARIn Calibration", has shown that the SARIn mode is able to provide suitable calibration results over short track lengths (in contrast to previous calculations). As the design progressed it became apparent that the CAL3 mode had several important differences from the normal SARIn mode, mostly related to thermal power dissipation, which would influenced the eventual results. Consequently the CAL3 mode has been removed from the design and the calibration planning.
In summary, references to CAL3 in the reference documents should be ignored - external calibration of the interferometric baseline will be performed in SARIn mode.


### 7.2 Natural Plane Surfaces

In Annex A the case of SARIn mode over a natural plane surface is considered. Using CryoSat parameters Wingham shows that in order to achieve a standard deviation of $10^{-3} \circ$ in the measured angle of arrival it is necessary to use measurements over a track length of 13.3 km , corresponding to about 2 seconds of operation.

To be useful for calibration a natural plane surface should have the following properties:

- be plane with respect to the ellipsoid (the theory has been developed using spherical surfaces, but the difference between the ellipsoid and the sphere is negligible - hereinafter this is referred to as "plane";
- be plane over a scale in excess of 13.3 km along-track;
- be plane over an across-track scale sufficient to fill the beam: 20 km ;
- be plane, to better than the required sensitivity (nominally $10^{-3 \circ}$, or 3.6 arcsec );
- be aligned such that the line of sight from the satellite is normal to the surface - this is most easily achieved with horizontal surfaces but this is not a unique solution;
- be known - the orientation of the normal to the surface, with respect to the ellipsoid, has to be known to better than the required accuracy (nominally 3.6 arcsec).
Natural surfaces which may include suitable plane areas are of the following types:
- ocean surfaces;
- large lakes;
- dry lakebeds and salt lakes;
- ice surfaces.

These are discussed in the following sections.

### 7.2.1 Ocean Surfaces

In order to investigate the slope characteristics of the ocean surface, a Mean Sea Surface (MSS) has been used; in this case the CLS01 MSS, provided by CLS, Toulouse, described in Annex B, "CLS01 Mean Sea Surface". The MSS is the mean over a long period, as measured by satellite altimetry. The actual surface during any given overpass may vary from this mean due to a range of effects, including mesoscale ocean circulation, atmospheric forcing, tides etc. Such dynamic variation is expressed in measures of variability.

The CLS01 MSS is derived from 7 years of TOPEX/Poseidon data, 5 years of ERS-1/2, the ERS-1 geodetic data and 2 years of GEOSAT data. The CLS01 MSS has a $1 / 30^{\circ} \times 1 / 30^{\circ}$ grid providing a (latitudinal) resolution of 2 nm or 3.7 km . The mean ocean topography corresponds to the 1993-1999 period. The surface covers all the global oceans from $80^{\circ} \mathrm{S}$ to $82^{\circ} \mathrm{N}$ where altimetric data are available. The MSS is shown in Figure 7.2-1.
The MSS combines the effect of geoid undulation and mean ocean circulation, the largest signal being due to geoid undulations. The height range is from -105 m to +86 m . Most areas of the globe thus have some large-scale slope due to the geoid undulation. The few maxima and minima of this large-scale undulation (where the large scale slope is zero) are located in places where the small-scale structure in the marine geoid, principally due to bathymetry, tends to be relatively strong. A view of the least disturbed such region, the local minimum off the west coast of Mexico, is shown in Figure 7.2-2. This surface appears to offer too much variation to be useful for calibration.
In order to extend the range of surfaces which can be used we shall have to accept surfaces which are not truly plane ${ }^{5}$ and horizontal, so long as their mean surface slope is less than a tolerable level. A zoom of a small part of such a region is shown in Figure 7.2-3.
This clearly shows that surface curvature exists on scales of less than 20 km . In order to identify suitable surfaces in the ocean we shall define slope as the maximum surface deviation, defined below, over a 10 km distance. On this scale a surface slope of $10^{-30}$ corresponds to a maximum surface deviation of 1.8 cm .

The maximum surface deviation has been computed in the following way: for each $1 / 30^{\circ}$ data point in the CLS01 MSS the maximum surface height difference from the height at that point, in a 20 km cell centred on that point, is found. To this is added the temporal variability signal applicable at that point from a lower resolution ( $1 / 4^{\circ}$ ) Temporal Varia-

[^3]Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 22

Figure 7.2-1 CLSO1 Mean Sea Surface


Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 23

Figure 7.2-2 The Mean Sea Surface in the Northern Pacific, west of Mexico. This region is a local minimum of the large-scale geoid undulation, but has small-scale structure. Each of the large grid squares contains a $5 \times 5$ set of the elementary $1 / 30^{\circ}$ nodes of the MSS, and thus represents an area about 20 km on each side. The range of surface heights in the image is 125 mm .


Figure 7.2-3 A small region of the MSS showing $10 \times 10$ of the nodes (intersections of the grid lines)

bility dataset also provided by CLS. This temporal variability dataset is shown in Figure 7.2-4.
The distribution of the maximum surface deviation, over the surface of the oceans, is shown in Figure 7.2-5. This figure also includes a delineation of a set of zones which may be used for a suitable natural plane surface, as well as representative CryoSat ground tracks over a one day period. The zones provide almost complete latitude coverage between $-60^{\circ}$ and $60^{\circ}$ latitude, but in order to provide such coverage it has been necessary to extend the range of surface slopes (or equivalently, the maximum surface deviation) beyond $10^{-3 \circ}$, or 1.8 cm . In fact a cutoff at $4-5 \mathrm{~cm}$, corresponding to about $2.5 \times 10^{-3 \circ}$ has been taken in defining the zones, although it is clear from Figure $7.2-5$ that many zones do meet the more stringent requirement of $10^{-3} \circ$.
One such zone which meets the requirement (it is the "flattest" large area, i.e. region of low maximum surface deviation, found in Figure 7.2-5) is in the south-eastern part of the Pacific Ocean, and is shown as a surface plot in Figure 7.2-6. Although this surface has a clear large-scale slope, it is exaggerated in this illustration as the height range of the figure is less than a metre, and is less than $2 \times 10^{-5}$ 。
A further factor, which may degrade the results, is the prevalence of ocean waves in the selected zones. Generally altimeters are immune to the effects of ocean waves as the footprint covers a sufficiently large area that they fully sample the range of heights of surface scatterers and, furthermore, they are not directionally sensitive. In contrast, SIRAL is directionally sensitive and has a higher spatial resolution ( 250 m along-track) so that it may not adequately smooth out wave effects. In Figure $7.2-7$ we show the average significant waveheight ${ }^{6}$ for each of 4 months; there is a clear seasonal difference between northern and southern hemispheres.
The wavelength of ocean waves, $L$, depends on the period, $T$, is given by:

$$
L=\frac{g T^{2}}{2 \pi}
$$

where $g$ is the acceleration due to gravity.
A wavelength of 250 m corresponds to a period of about 13 s , which is in the range of swell waves. Swell is characteristic of the large ocean basins and tends to be aligned with the prevailing wind direction, which is latitudinal, and therefore tends not to be aligned with the CryoSat flight direction. The asymmetry in the effect of a uniform wave-field on the SIRAL footprint is illustrated in Figure 7.2-8, for the case of a uniform wave of wave length 300 m , aligned at $1.5^{\circ}$ to the along-track and across-track directions, respectively.
Qualitatively it appears that the wave direction would have to be closely aligned to the flight direction in order to significantly disturb the slope measurement. This will be studied further.

### 7.2.2 Large Lakes

Large lakes offer surfaces which are free of most of the sources of variability in the ocean, although atmospheric effects can be more important than in the open ocean. Lakes, particularly deep lakes, do exhibit surface curvature.

[^4]Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 25

Figure 7.2-4 Temporal variability of the oceans, derived from altimeter data, by CLS


## Nu (unc)

Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 26

Figure 7.2-5 Distribution of sea-surface slopes, with one day of CryoSat orbits and the derived zones.


Figure 7.2-6 The Mean Sea Surface in the south-eastern part of the Pacific Ocean. The area shown covers $3.3^{\circ}$ square and the full range of surface elevation is 104 mm , corresponding to a slope of $<2 \times 10^{-5}$.


Large lakes are relatively sparse; the distribution of lakes with surface area over $100 \mathrm{~km}^{2}$ is shown in Figure 7.2-9. This lower cut-off area only represents a linear dimension of 10 km , which is inadequate. In order to meet the track length required the lake surface area should be at least $400 \mathrm{~km}^{2}$. These values are shown as dashed lines in Figure 7.2-9. We can conclude that, at most, 300 lakes would be of a size suitable for calibration.

Consideration of surface curvature will eliminate some of these lakes.
We will not pursue the use of lakes as a natural plane surface while other options (specifically the use of ocean areas) remain open.

### 7.2.3 Dry Lakebeds and Salt Lakes

Dry lakes, particularly those in the form of salt flats, have flat surfaces - they formed by the evaporation of shallow lakes and are therefore not associated with the gravity anomalies found in deep lakes. The surface of such dry lakes is stable, except for occasional flooding events. Some, such as Uyuni in Bolivia, are large enough to provide suitable calibration targets.

The AO Proposal 1264 (Schutz) identifies some sites in the USA, and they exist in other places, notably in the Andes.
Again, however, we will not persue this approach now.

### 7.2.4 Ice Surfaces

The surfaces of the major ice sheets and shelves appear to have many plane areas. However these are not particularly well determined or mapped. Again, we will not pursue further study of ice surfaces while other options remain.


|  |  | Doc. No.: <br> Issue: <br> Date: <br> Page: | ```CS-TN-ESA-SY-0354 l 17 Jan 2005 29``` |
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Figure 7.2-8 The upper figure illustrates the effect on a SIRAL doppler cell of an ocean wave, with wavelength 300 m , aligned at $1.5^{\circ}$ to the satellite ground track. Note that the aspect ratio of the figure is compressed 10:1. The lower figure shows the same situation but with the wave aligned $1.5^{\circ}$ to the cross-track direction.


Figure 7.2-9 Distribution of lake sizes, as the number of lakes exceeding a given surface area. Closed lakes refer to lakes without an outlet, such that the lake level represents the local balance between precipitation and evaporation.


### 7.3 Transponders

Transponders have been previously used with conventional pulse-width limited altimeters (including GeoSat, ERS-1, ERS-2 and EnviSat), as described in RD 6 and RD 7 for example. They have normally been used for range measurements (establishing the minimum range to the transponder during the pass) and, in RD 7, also for measurements of echo power.

We will first consider the characteristics of the transponder echo for calibration of the angle of arrival, and estimate the accuracy. In the next section we will discuss transponder characteristics and review the existing and potential new equipment. Finally we present plans for deployment of transponders.

### 7.3.1 Echo Characteristics and Geometry

Transponders offer a highly accurate measurement of the baseline orientation, due to two factors:

- they have a coherent echo (no speckle);
- they can be precisely located.

The absence of speckle means that decorrelation of the echoes is not required. The number of pulses required to achieve a sensitivity of $10^{-3 \circ}$ in the measured angle is then determined by the signal to noise ratio (i.e. link budget). Using pessimistic values (as given in RD 2) the result is about 160, which, in SARIn mode, can be achieved in 3 bursts, or 126 ms , which comfortably exceeds the time the transponder will be in the field of view of the antenna (about 2 s ).
We now extend the analysis of RD 2 to establish the performance (in terms of angular sensitivity) which can be achieved by exploiting all the echoes available during a transponder pass, and with current estimates of SIRAL and transponder parameters.
According to RD 2 the angular sensitivity, $\sigma_{\alpha}$ is expressed as:

$$
\sigma_{\alpha} \approx \sqrt{\frac{\sqrt{3} \cdot\left(1 / \eta^{2}-1\right)}{2 \cdot(k D)^{2} N}}
$$

where
$k$ is a constant representing the ambiguity rank
$D$ is the baseline length ( 1.2 m )
$N$ is the number of averaged waveforms
$\eta$ is the total signal coherence - in the transponder case this is simply the thermal noise coherence $\eta_{N}$ where

$$
\eta_{N}=\frac{1}{1+1 / \mathrm{SNR}}
$$

where SNR is the signal to noise ratio in the relevant range bin. The value derived in RD 2 made an assumption of $75 \mathrm{dBm}^{2}$ for the RCS of the transponder, and worst-case assumptions for the SIRAL link budget. In fact the design value of the "EnviSat sigma-0" transponder (see Section 7.3.4) is $75.7 \mathrm{dBm}^{2}$, while the "ERS" transponders (see Section 7.3.3) have variable cross-section (controlled by an internal attenuator) of 26-111 dB. Therefore the assumptions of RD 2 are valid and the SNR value of 40 dB derived in RD 2 will be used here.

The SIRAL antenna beamwidth is $1.1^{\circ}$ along-track (and $1.2^{\circ}$ across-track) so for a pass within 5 km of the transponder the transponder echoes will be received for a period of 1.6 s (or more). This is illustrated in Figure 7.3-1.

In SARIn mode there are 64 pulses per burst and a Burst Repetition Frequency of 21.4 Hz , so the number of pulses to be assumed in 1.6 s is 2190.
The resulting angular sensitivity is 0.97 arcsec.

|  |  | Doc. No.: Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 31 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

Figure 7.3-1 The 3 dB footprint of CryoSat is slightly asymmetrical, corresponding to the beamwidth of $1.2^{\circ}$ across-track and $1.1^{\circ}$ along-track. The diagram shows the footprint with a scale marked in kilometres. For a transponder placed within 2.5 km of the ground-track the transponder remains within the footprint for at least 2 s (corresponding to $\pm 6.5 \mathrm{~km}$ along-track at the satellite ground speed of $6.5 \mathrm{~km} / \mathrm{s}$ ). At $\pm 5 \mathrm{~km}$ from the ground track the transponder remains within the 3 dB footprint for 1.6 s .


Now we address the accuracy of location, and ultimately the knowledge of the true baseline orientation. The transponder will be located by GPS. Differential GPS can achieve positional errors of order 1 cm when full geodetic processing is applied. Additionally there will be an eccentricity error due to knowledge and measurement of the position of the transponder echo reference point compared to the GPS-measured reference point. This reference point will nominally be the mid-point between the two antennas, offset towards the nadir by the internal path-length.
For the purpose of this analysis we shall assume an error in the transponder location of 25 cm with respect to the ellipsoid.
The satellite location will be determined from precise orbit determination using the DORIS data. The expected errors in this location are:

- along-track: $<20 \mathrm{~cm}$
- across-track: $<20 \mathrm{~cm}$
- radial: $<10 \mathrm{~cm}$

We shall assume an error of 1 m .
The linear combination (in the worst direction) of these assumed errors ( 1.25 m ), at a satellite range of 720 km , results in an error in the direction from the satellite to the transponder of 0.36 arcsec .

## Summary:

- Angular error in direction measurement: 0.97 arcsec
- Angular error in direction knowledge: 0.36 arcsec.


### 7.3.2 Transponders and SIRAL

An ideal transponder would produce an echo as if from a point target - a corner reflector would have this behaviour. However a corner reflector would have to be very large in order to provide a sufficiently strong signal to distinguish it from background clutter; the EnviSat sigma-0 transponder has a radar cross-section of $75 \mathrm{dBm}^{2}$. Real transponders combine recieve and transmit antennas with active amplification to acheive the required return signal level. As a result the transponder has physical characteristics which could, theoretically, cause the echo to deviate from a point target response. These characteristics, and some relevant comments, are:

- finite bandwidth - no problem with existing designs;
- finite beamwidth - taken into account in planning and data analysis;
- gain variation over bandwidth - see below;
- gain variation pulse-to-pulse - see below;
- phase variation over bandwidth - see below;
- phase variation pulse-to-pulse - see below;
- electrical path length - equivalent to increased range;
- coupling from received to transmitted signals - no problem with existing designs.

For the purpose of calibrating the angle of arrival the principle concern is that the transponder should enable the doppler beams to be properly formed. The physical characterisitics above which have the comment "see below"are shared by the amplifiers which are in the SIRAL itself and are not a cause of particular concern. As for interferometery, atransponder is a single target, returning a single echo, so the interferomeric performance (i.e. differential echo in the two SIRAL receiver channels) is not directly dependent on characteristics of the transponder.
The following existing transponders are (potentially) available:

- "ERS" transponders:
- ESA "ERS" transponder (currently in the custody of RAL);
- Danish "ERS" transponder;
- Austrian "ERS" transponder;
- ESA "EnviSat sigma-0" transponder (currently in ESRIN);
- newly developed CryoSat transponders.

We address these in subsequent paragraphs.
In addition to these some others have been developed (e.g. an "ERS" transponder procured by the US Navy) but their status is unknown and they are not considered further.

### 7.3.3 ERS Transponders

The "ERS" transponders are simple designs in which the receive antenna is directly coupled to the transmit antenna, through a pair of linear amplifiers and a variable (rotary vane) attenuator. Low cross-coupling between receive and transmit antennas prevents signal regeneration. The block-diagram of one of these is shown in Figure 7.3-2. The amplifiers have a minimum fixed gain of 42 dB , and the variable attenuator has a range of 60 dB . Additionally a fixed attenuator of 10 dB is installed in the signal path. There are also waveguide isolators between the antennas and the amplifiers and several coaxial isolators. The total gain of the amplifier chain, $G$, as a function of the attenuator setting, $A$, is given by:

$$
G=77-A \mathrm{~dB}
$$

Figure 7.3-2 Block diagram of an "ESA" Transponder. A number of isolators are omitted from the diagram. The Calibration Network is present in the ESA prototype, but not in others - it is not necessary for the CryoSat application. Amplifiers A1 and A2 are amplifiers wit a fixed gain of 42 dB . The rotary vane attenuator A3 provides up to 60 dB of attenuation under manual control and a further 10 dB attenuator is installed in the path.


Two types of transponder were developed. The original, Type I, had the front-fed parabolic antennas mounted horizontally, side by side. The Type II was developed later in an attempt to make a more portable system. This had parabolic antennas mounted vertically, back-to-back, on each side of the electronics box with deployable plane metal reflectors to provide the zenith view. The specifications of both types are given in Table 7.3-1 ${ }^{7}$.
These devices were designed for range measurements, or calibration, and have negligible internal delay and a sufficiently wide bandwidth. ERS had a slightly different transmit frequency from CryoSat but the available bandwidth is adequate for both types. These transponders will provide an effective point target for CryoSat in the SARIn mode.
The status and availability of the ERS Transponders is summarised below.

### 7.3.3.1 ESA "ERS" Transponder

This transponder, the prototype of the Type I transponders, was developed by RAL (UK)in 1987. After completion of the contract it was loaned to RAL and has been used with GeoSat, ERS-1 and ERS-2 and TOPEX/Poseidon. The transponder is currently in storage at RAL (UK); it has not been used for several years.
This transponder will be deployed for CryoSat calibration, but before this it needs inspection, possibly refurbishment and maintenance, and one or more trial deployments with EnviSat to confirm the operational procedures for the transponder.
A set of spares is available, but during the CryoSat Commissioning Phase the transponder will be 18 years old, and failures cannot be excluded. For this reason a second transponder will be deployed (TBC).

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Issue: 1
Date: 17 Jan 2005
Page: 34

Table 7.3-1 Specifications of the two types of ERS transponder. Note that the SIRAL centre frequency and bandwidth are 13.575 GHz and 350 MHz respectively. The occupied bandwidth is thus $13.400-13.750 \mathrm{GHz}$.

| Parameter | Type I | Type II |
| :--- | :--- | :--- |
| Antenna diameter | 0.61 m | 0.45 m |
| Radar cross section ${ }^{1}$ | $44-5-104.5 \mathrm{~dB}$ | $44-5-104.5 \mathrm{~dB}$ |
| Beam width | $2.5^{\circ}$ | $1.7^{\circ}$ |
| Beam co-linearlity | $\pm 0.1^{\circ}$ |  |
| Beam pointing | $\pm 0.1^{\circ}$ |  |
| Antenna gain | 35.8 dB | 35.8 dB |
| Inter-antenna isolation | 105 dB | 105 dB |
| Amplifier frequency range | $13.2-14.1 \mathrm{GHz}$ | $13.4-14.0 \mathrm{GHz}$ |
| Amplifier gain | $17-77 \mathrm{~dB}$ | $17-77 \mathrm{~dB}$ |
| Amplifier gain variation across band | $< \pm 0.5 \mathrm{~dB}$ |  |
| Amplifier 1 dB suppression point | 20 or 23 dBm |  |
| Amplifier phase Inearity across band | $\pm 7^{\circ}$ |  |
| Internal gain monitoring precision | $\pm 0.05 \mathrm{~dB}$ |  |
| Gain stability over temperature |  | $0.2 \mathrm{~dB} /{ }^{\circ}$ |
| Internal path-length monitoring precision | $\pm 0.5 \mathrm{~mm}$ | $\pm 0.5 \mathrm{~mm}$ |
| Path-length stability over temperature | $0.1 \mathrm{~mm} /{ }^{\circ}$ | $<0.5 \mathrm{~mm} /{ }^{\circ}$ |
| Dimensions (I $\mathrm{h} \times \mathrm{w}$ ) | $1.32 \times 0.76 \times 0.61 \mathrm{~m}$ | $0.72 \times 0.53 \times 0.69 \mathrm{~m}{ }^{\circ}$ |
| Weight | $\sim 80 \mathrm{~kg}$ | $\sim 40 \mathrm{~kg}$ |

1. given by $\sigma=G_{a n t 1} \times G_{a n t 2} \times G_{s y s} \times \frac{\lambda^{2}}{4 \pi}$
2. folded for transport; when deployed the width increases to 1.76 m

### 7.3.3.2 Danish "ERS" transponder

This Type II transponder has been deployed on the Greenland ice cap with ERS-1 and ERS-2. It belongs to the University of Copenhagen and is currently located there. Its availability to support the CryoSat calibration is confirmed.
It has been recently tested with EnviSat and is in operational condition.

### 7.3.3.3 Austrian "ERS" transponder

This Type II transponder is the property of the Space Research Institute of the Austrian Academy of Sciences at Graz. It has been deployed in support of scientific studies with ERS-1, ERS-2, TOPEX/Poseidon, EnviSat and Jason. It is currently deployed and operational on the island of Gavdos, south of Crete (see http: / / www.gavdos.tuc.gr).
As it is used in a on-going scientific project we assume that this transponder will not be available for dedicated deployment in support of CryoSat.

### 7.3.4 EnviSat Sigma-O Transponder

The ESA "EnviSat sigma-0" transponder was designed to calibrate the sigma-0 measurement of the EnviSat RA-2 instrument. Therefore cross-coupling and suppression of local "clutter" were important factors in the design, and to overcome these effects it incorporates a long internal delay. Its key specifications are listed in Table 7.3-1 and it is described

Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 35

Table 7.3-1 Specifications of the EnviSat RA-2 sigma-0 transponder. The need for requirements on phase variation was identified but such requirements were never specified (TBD: "to be determined").

| Parameter |  |
| :--- | :--- |
| Beam width | $>2.6^{\circ}$ |
| Radar Cross-Section (RCS) | $75.7 \mathrm{dBm}{ }^{2}$ |
| RCS stability | 0.1 dB |
| Absolute gain calibration accuracy | 0.2 dB |
| Trigger dynamic range | 15 dB |
| Centre frequency | 13.575 GHz |
| Bandwidth | 320 MHz |
| Gain slope over bandwidth | 0.5 dB |
| Gain slope rate | $0.05 \mathrm{~dB} / \mathrm{MHz}$ |
| Phase variation over bandwidth | TBD |
| Phase variation rate | TBD |
| Time delay | $55 \mu \mathrm{Ls}$ |

in RD 7. In addition to the sigma-0 usage it has been designed to have a "range mode" in which the digital delay section may be by-passed by software commanded switches as shown in Figure 7.3-3, rendering it equivalent to the "ERS" transponders.
The EnviSat project intends to operate this transponder until the end of the EnviSat mission. It is stationed at Frascati in Italy and is initially operated in "mobile" mode, in which it is transported to a small number of known sites, in order to increase the number of

Figure 7.3-3 Block diagram of the EnviSat sigma-0 transponder. The switch A enables the optical delay line to be by-passed, and the switch B connects the output signal to a second antenna, which is then necessary as there is no internal delay.


Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 36
passes. Later it will be operated from a single fixed site. An agreement is being made with the EnviSat project to switch the transponder to range mode for CryoSat passes, but the available passes will be very limited due to the geographical constraints imposed by EnviSat operations. Figure 7.3-4 shows the CryoSat passes over the selected transponder sites during the 6-month Commissioning Phase. Only one usable pass per transponder occurs and the additional surveyed sites do not improve matters.

Figure 7.3-4 CryoSat passes over the selected EnviSat transponder sites near Rome. Black ellipses indicate the SIRAL 3dB bemwidth at each of the surveyed sites while the red ellipses idicate the selected sites (marked by a cross). CryoSat orbits during the first 6 months of the mission are shown. There is one usable pass for each transponder site during this period; a total of 4 .


### 7.3.5 New CryoSat Transponders

A transponder design similar to the original ERS design (i.e. two antennas with an amplifier path between them) is under investigation for production as several units (order of magnitude 10). At present the procurement of these is not secured however.

### 7.3.6 Transponder Deployment and Visibility

The number of times a transponder will be in the SIRAL footprint during any period of time is latitude dependent, becoming smaller at low latitude. The orbital plane precesses at $0.2387^{\circ}$ / day, compared to the rotation of the earth-sun line of $0.9856^{\circ} /$ day. The result is that the local solar time of the orbit changes at $0.7469^{\circ} /$ day, passing through 12 hours in 241 days ( 8 months). This is a change of 1 hour of local solar time in 20 days. During a Commissioning Phase of 6 months the local solar time will change by $136^{\circ}$ (i.e. 9 hours), starting with the launch orbit, which is in the dawn-dusk plane.

The average spacing between tracks, as a function of latitude, is shown in Figure 7.3-5.
This plot shows the spacing corresponding to the full 369 orbit repeat cycle as well as the

Doc. No.: CS-TN-ESA-SY-0354
Issue: 1
Date: 17 Jan 2005
Page: 37

Figure 7.3-5 Orbital spacing as a function of latitude, for the full 369 day repeat cycle, and a number of shorter periods: in 244 days is the orbit plane rotates $180^{\circ}, 122$ days corresponds to a rotation of $90^{\circ}$, and 60 and 30 days are two and one subcycles respectively.

average spacing ${ }^{8}$ for some shorter cases. These are the 244 day period required for the $180^{\circ}(12 \mathrm{~h})$ plane rotation, 122 days for $90^{\circ}(6 \mathrm{~h})$ and periods of 30 and 60 days.
In Section 7.3.1, "Echo Characteristics and Geometry" we showed that a cross-track distance of up to about 5 km could be used as a guide for deployment planning. We also showed that near Rome (at a latitude of $41^{\circ}$ ) the frequency of passes is not high enough to provide adequate sampling during the Commissioning Phase. Figure 7.3-5 shows that the average inter-track spacing can be halved by increasing the latitude to about $67^{\circ}$, and it improves more rapidly at higher latitudes. At the highest latitudes a single transponder can be used for many passes.
Potential sites, therefore, need to have the following atributes:

- high latitude;
- accessibility from Europe;

[^6]- year-round operations;
- security;
- low-volume communications;
- local power;
- availability of local support staff for general operationns and in case of contingencies (the transponders are intended to be low maintenance).
The second criterion (accessibility) effectively eliminates high-latitude southern hemisphere locations. There are, anyway, very few sites in Antarctica which are at as high latitude as the possible Arctic sites. The types of site, in the Arctic which could satisfy these conditions are also few: satellite ground stations (SvalSat at Svalbard is the highest latitude available) and permanently manned Arctic bases. Two which are used in connection with CryoSat are Station Nord (Greenland) operated by the Danish miliatary and Alert (Canada) operated by the Canadian Armed Forces. Svalbard is the best choice as, in addition to regular scheduled transport services to the rest of Europe, it has excellent infrastructure to support the transponder operations and already has organisational connections to ESA.

We now address the visibility of the transponder from the CryoSat orbit. We have investigated the available passes over the transponder for each hour of local time of the orbital plane, assuming that the injection is exactly into the nominal (target) orbit for the injection by the launcher, knowing that this injection is into the dawn-dusk orbital plane. Of course the actual injection will not correspond exactly to this due to launcher dispersion, and corrections will be made after launch to acheive the reference orbit. The detailed orbital parameters of this will be computed at the time. This uncertainty will modify the overall timing of the transponder passes but the relative timing which we present here, should remain valid.

We present in Figure 7.3-6 to Figure 7.3-8 a series of plots of the passes over Svalbard for each local hour of the orbital plane as it drifts. In these plots the transponder has been placed at the exact location of the SvalSat X-band antenna - in practice it will be in a slightly different location but this does not change the general conclusions of this analysis. The number of opportunities are rather low, averaging less than 2 usable passes in each hour, but sufficient.

A summary plot of the available passes is shown in Figure 7.3-9, which identifies the usable passes, characterised by day of occurence, off-nadir angle, peak power etc. In the nominal orbit the first pass occurs on day 19 and the small number of passes means that none can be missed. Procedures will be introduced to maximise the probability of success.

### 7.3.7 Practical Arrangements

The exisiting transponders are proposed to be deployed in accordance with Table 7.3-1. Since only 4 transponders are available the distribution in latitude will be limited, and, in the case of the University of Copenhagen transponder the deployment will also be timelimited, during the northern summer.

### 7.4 Data Processing

Data processing for the transponder echoes will be performed using a dedicated transponder processor to be developed at ESTEC.

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 Doc. No.: CS-TN-ESA-SY-0354 Issue: 1Date: 17 Jan 2005
Page: 39

Figure 7.3-6 CryoSat tracks over Svalbard for each hour from 1800 to 0200 . The 3 dB footprint of the SIRAL is shown (as a thick line) at the transponder. Other circles are at range increments of 2 km .


## 上ese

 Doc. No.: CS-TN-ESA-SY-0354Issue: 1

Date: 17 Jan 2005
Page: 40

Figure 7.3-7 CryoSat tracks over Svalbard for each hour from 0200 to 1000. The 3dB footprint of the SIRAL is shown (as a thick line) at the transponder. Other circles are at range increments of 2 km .


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 Doc. No.: CS-TN-ESA-SY-0354Issue: 1

Date: 17 Jan 2005
Page: 41

Figure 7.3-8 CryoSat tracks over Svalbard for each hour from 1000 to 1800. The 3dB footprint of the SIRAL is shown (as a thick line) at the transponder. Other circles are at range increments of 2 km .



|  |  | Doc. No. Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 43 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

Table 7.3-1 Proposed deployment of the four exisiting transponders

| Transponder | Ownership | Deployment | Latitude <br> (deg) | Comment |
| :---: | :---: | :---: | :---: | :---: |
| ERS Type 1 | ESA | ESTEC | 52 | This transponder needs intensive <br> support operations |
| ERS Type 2 | University of <br> Copenhagen | Greenland | $70-73$ | This is identified in AO proposal <br> 1270 (Forsberg). It is likely to be a <br> time-linited deployment |
| ERS Type 2 | University of <br> Graz | Neumayer | -70 | Assuming this is the transponder <br> identified in the AO proposal <br>  <br> (274 (Miller). Deployment is <br> stated to be year-round. |
| EnviSat Sigma-0 | ESA | ESRIN | 42 | This location is fixed by EnviSat <br> needs |


|  |  | Doc. No.: Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 44 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

## 8 Summary

A summary of the approaches described in Section 3 to Section 6 is given in Table 8.0-1. This identifies the key issues and the party responsible for the implementation of the activities.

Table 8.0-1
Summary of the approaches to calibration described in this document

| Parameter | Term | Approach | Issues | Responsibility |
| :---: | :---: | :---: | :---: | :---: |
| DORIS | "traditional" orbit validation long-term drift | EnviSat techniques comparison with laser orbits | development of techniques | CVRT Orbit and Altimetry SubGroup |
| SIRAL Range | bias <br> long-term drift | indirect calibration indirect calibration |  |  |
| SIRAL Sigma- $0$ | bias <br> long-term drift | indirect calibration indirect calibration |  | CryoSat Monitoring Facility |
| SIRAL Angle of Arrival | internal SIRAL terms | internal calibration (CAL1, CAL2 and CAL\$) |  | CryoSat Project and Level 1b Processor |
|  | external SIRAL path + antenna bench | finite element modelling and onboard temperature measurement | new software development | CryoSat Project and Level 1 b Processor (CFI libraries) |
|  | external calibration of antenna bench modelling | transponders | ERS transponders: ownership, refurbishment | CryoSat Project + transponder owners |
|  |  |  | EnviSat transponder: feasibility in SARIn mode, dual-use | CryoSat + EnviSat Projects |
|  |  |  | Dedicated CryoSat transponders | CryoSat Project |
|  |  |  | Software development | Software extension to Level 1b Processor |
|  |  | oceans | feasibility | study and development by CryoSat Project; potential extension to Level 1b Processor |
|  |  | lakes | not yet |  |
|  |  | salt lakes | distribution, size, volume scattering | UCL, CryoSat Project |
|  |  | ice caps | too many unknowns, not yet |  |


|  |  | Doc. No. Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 45 \end{aligned}$ |
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## ANNEX A Calculations for SARIn Calibration

prepared by D.J.Wingham, UCL

## Use of SARIN mode for external interferometer calibration.

This note is concerned with estimating the length of satellite track needed to perform an external calibration of the interferometer with the instrument in SARIn mode.

For small phase errors $\varepsilon_{\phi}$, the corresponding error in direction is

$$
\begin{equation*}
\varepsilon_{\theta}=\varepsilon_{\phi} / k B \tag{1}
\end{equation*}
$$

where $k$ is the carrier wavenumber and $B$ the interferometer baseline length. The standard deviation of the phase measurement in SARIn mode is given by

$$
\begin{equation*}
\sigma=\sqrt{\frac{\left(1-C^{2}(0)\right)}{2 \mu(0) N C^{2}(0)}} \tag{2}
\end{equation*}
$$

where $N$ is the total number of looks, $\mu N$ is the 'effective' number of looks, accounting for the variation in power of the echo over the Doppler beam stack, and $C$ is the coherence, also defined so as to take account of the variation from look-to-look. The parameters $\mu(\tau)$ and $C(\tau)$ are functions of the multi-looked echo delay time $\tau$; the behaviour of these functions is plotted in figs. 1 and 2 below. For our purposes it is the value of these functions at $\tau=0$ that is relevant.


Fig. 1. The variation in the effective number of looks $\mu(\tau)$ as a function of delay time. The distinct drop in the vicinity of $\tau=0$ reflects that the most rapid variation in echo power from look to look occurs at this delay time.

|  |  | Doc. No.: Issue: Date: Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 46 \end{aligned}$ |
| :---: | :---: | :---: | :---: |



Fig. 2. The variation in the echo coherence $C(\tau)$ as a function of delay time. The definition of the function used here takes account of the variation in coherence of individual echoes from look to look. The plot shown corresponds to the high SNR limit, and to low surface waveheight.

To determine the number of looks $N$ we determine first the number of looks per sample along the ground track, and then the number of (independent) samples per unit length of ground track. In SARIn mode, the satellite travels a distance $\sim \kappa h \delta$ in illuminating a given point on Earth over an angular range $\pm \delta$ about the nadir direction. Here, $\kappa=1+h / R$, where $h$ is the altitude and $R$ the Earth radius. The satellite is traveling at a velocity $v \kappa$, where $v$ is the velocity of the nadir point along the ground track. If $T_{B}$ is the burst repetition frequency, the number of looks $N_{s}$ at each location on the surface is:

$$
\begin{equation*}
N_{s} \sim \frac{2 \kappa h \delta}{v \kappa T_{B}}=\frac{2 h \delta}{v T_{B}} \tag{3}
\end{equation*}
$$

and these will be independent if $T_{B}$ is large enough, which it is in our case. Echoes from each successive location on the ground track on Earth will be independent if when viewed from the satellite they are spaced by at least the Doppler beam angular sampling interval, $\zeta_{b}$, that is, at intervals of approximately $h \zeta_{b}$ along the ground track. The number of independent looks per unit length of ground track is therefore:

$$
\begin{equation*}
n=\frac{2 \delta}{v T_{B} \zeta_{b}} \tag{4}
\end{equation*}
$$

The objective is to determine the interferometer direction with a standard deviation equal to $\sigma_{c}$. Combining eqns. (1), (2) and (4), the length of track $L_{c}$ needed to achieve this is:

$$
\begin{equation*}
L_{c}=\frac{\left(1-C^{2}(0)\right) v T_{B} \xi_{b}}{\mu(0) C^{2}(0) k^{2} B^{2} \delta \sigma_{c}^{2}} \tag{5}
\end{equation*}
$$

|  |  | Doc. No.: Issue: <br> Date: <br> Page: | $\begin{aligned} & \text { CS-TN-ESA-SY-0354 } \\ & 1 \\ & 17 \text { Jan } 2005 \\ & 47 \end{aligned}$ |
| :---: | :---: | :---: | :---: |

For CryoSat SARIn mode, $\delta$, the Nyquist angle of the Doppler beams, is $0.82^{\circ}, v$ is $6.8 \times 10^{3} \mathrm{~ms}^{-1}, T_{B}$ is $4.68 \times 10^{-2} \mathrm{~s} \zeta_{b}$ is $0.025^{\circ}, B$ is 1.2 m and $k$ is $285 \mathrm{~m}^{-1}$. From figs. (1) and (2), one also has that $\mu(0)=0.53$ and $C(0)=0.975$. With these values, the length of track required to obtain a standard deviation in direction of $10^{-3} \circ$ is 13.32 km .

# Annex B CLSO1 Mean Sea Surface 

prepared by F. Hernandez, CLS

The mean sea surface has been computed using a 7-year TOPEX/Poseidon mean profile, a 5-year ERS-1/2 mean profile, a 2-year GEOSAT mean profile and the 2 168-day non repeat cycle data of the ERS-1 geodetic phase. All these data have been preprocessed in order to be a) more homogeneous, and referenced to the 7 -year TOPEX/Poseidon mean profile, b) less contaminated by the ocean topography variable signal (the mean ocean topography signal contained in the surface therefore corresponds to the mean sea level during the period 1993-1999). The surface has been estimated on a grid of 2 arcminutes ( $1 / 30$ degree) using a local inverse method. This also provides an estimation error field.
This mean sea surface contains:

- over ocean, the mean geoid ${ }^{1}$ plus the mean ocean dynamic topography (1993-1999);
- over land, the EGS96 ${ }^{2}$ mean geoid;
- in coastal areas (between ocean and land) a smooth extrapolation/relaxation of the ocean values (geoid+mean dynamic topography) toward the EGM96 geoid.

The corresponding values (ocean, continent or coastal) can be identified with the MSS error values.
This mean sea surface is reference to the TOPEX/Poseidon Earth ellipsoid, whose characteristics are:

$$
\begin{array}{ll}
a & =6378136.3 \mathrm{~m} \\
1 / f & =298.257 \\
\mathrm{GM} & =398600.4415 \mathrm{~km}^{3} \mathrm{~s}^{-2}
\end{array}
$$

Since the TOPEX/Poseidon sea surface heights were calculated using the NASA Precise Orbit Determination (which is based on the JGM-3 model), the Mean Sea Surface is based on the same standards ${ }^{3}$.

[^7]
[^0]:    1. Calibration will mainly be performed during the Commissioning Phase but some activities will be needed throughout the routine operations
    2. The CryoSat payload comprises the SIRAL, DORIS and a set of Star Trackers.
[^1]:    3. This document shall be taken as an technical objective: the programmatic arrangements to fulfil this plan are not currently in place.
[^2]:    4. In contrast, the analysis provided in RD 3 assumes a strategy in which the baseline orientation is determined at discrete intervals and the derived mispointing angle is applied during the intervening times.
[^3]:    5. with respect to the ellipsoid
[^4]:    6. Significant waveheight is the mean of the highest one-third of all waveheights; it is empirically equal to 4 times the standard deviation of the distribution of the heights of surface facets.
[^5]:    7. The Type I transponder was developed under ESA contract; details of Type II are extracted from Transponder Altimetry: An Investigation of a Precise Height Measurement System, Paul Denys, PhD Thesis, University of Newcastle upon Tyne, May 1995
[^6]:    8. for periods less than the full repeat the grid is not completed and not all spacing is uniform.
[^7]:    1. the mean geoid is the geoid that would exist in the presence of the Sun and the Moon (or, equivalently, if no permanent tidal effects are removed)
    2. Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp, and T.R. Olson, 1998: The Development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. Report NASA/TP-1998-206861, edited by Goddard Space Flight Center, NASA, Greenbelt, Maryland 20771, USA. pp. 575
    See http: //cddisa.gsfc.nasa.gov/926/egm96/egm96.html
    3. See Tapley et al., 1994: Precision orbit determination J. Geophys Res., 99, 24383-24404
