# RADS version 4.0

# Data Manual

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# Contents

# Chapter *1*

# Introduction

This manual is intended to explain the details about the many variables available in the RADS data base. Many of the variables come in different "flavours", like one could choose to use the wet tropospheric correction based on radiometer measurements (wet_tropo_rad) or one of the atmospheric models (e.g., wet_tropo_ecmwf). RADS also provides the option to use more generic variable names (like wet_tropo) that will pick the best available correction depending on the satellite mission (or period).

The variables are organised various chapters. Consult the table of contents to find the variables you are looking for, or go to the index at the end of the manual, where all variables are listed.

For each variable, a list of different flavours is presented. For an example, turn to Section 3.5. This Section describes the various wet tropospheric corrections. The table in that Section lists in the first column the various variable names, followed by the field number as was used in RADS 3 (and can still be used in RADS 4), a short description, and the units of this variable. The next column lists for which altimeter missions this variable is available (see Table 1.1), where "all"

| Altimeter | Abbr. | Nr | References |
|---|---|---|---|
| GEOS 3 | g3 | 1 | (not included in RADS) |
| Seasat | ss | 2 | (not included in RADS) |
| Geosat | gs | 3 | |
| ERS-1 | e1 | 4 | [*Francis*, 1990; *Francis et al.*, 1991] |
| TOPEX | tx | 5 | [*Fu et al.*, 1994] |
| Poseidon | pn | 6 | |
| ERS-2 | e2 | 7 | [*Francis et al.*, 1995] |
| GFO | g1 | 8 | |
| Jason-1 | j1 | 9 | [*Ménard et al.*, 2003] |
| Envisat | n1 | 10 | |
| Jason-2 | j2 | 11 | [*Lambin et al.*, 2010] |
| CryoSat-2 | c2 | 12 | [*Wingham et al.*, 2006] |
| SARAL | sa | 13 | |
| HY-2A | hy | 14 | (not included in RADS) |
| Jason-3 | j3 | 15 | (to be launched summer 2015) |
| Sentinel-3A | 3a | 16 | (to be launched autumn 2015) |
| Sentinel-3B | 3b | 17 | (to be launched end 2016) |

Table 1.1   Abbreviation and numbers used for the various altimeter missions.

stands of all missions, and "other" stands for all missions not mentioned above it. The second to last column is the default range used for editing (NaN is returned when the value exceeds this range). When this column is empty, no range limits are set. Finally, the rightmost column relates to a list of notes provided in that Section.

Near the bottom of each variable table a number of "aliases" are provided. These are short-cuts to one (or more) of the flavours of variables. For example, the tables in Section 3.5 shows that for most altimeter missions the alias wet_tropo means that radiometer wet tropospheric correction is used (wet_tropo), but, when not available, for example during extended outage, the ECMWF model wet tropospheric correction (wet_tropo_ecmwf) is used instead. These "aliases" make it easier to get the preferred flavour of the variable which may differ from mission to mission (for example, some do not have a radiometer). This largely simplifies the construction of sea level anomalies, as described in Section 3.1.

# Time and location

## 2.1 Time

Time in the RADS data sets is stored as 8-byte floats in UTC seconds since a given epoch (normally 1 January 1985 or 1 January 2000). RADS will automatically convert these values into a few common time scales, depending on which time variable is selected. However, irrespective of the time scale, the clock references to UTC, rather than an atomic clock, meaning that leap seconds may result in a duplication of measurement times. No provision has been made to avoid confusion between measurements made before and after a leap second.

The time corresponds to the moment of reflection of the radar pulse on the sea surface and is corrected for biases.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| time_1985 | 101 | time since 1985-01-01 00:00:00 | s | all | | |
| time_2000 | 106 | time since 2000-01-01 00:00:00 | s | all | | |
| time_rel_eq | 102 | time relative to equator crossing | s | all | | 1 |
| time_local_solar | 103 | local solar time | s | all | | 2 |
| time_mjd | 105 | time since 1858-11-17 00:00:00 | days | all | | 3 |
| time_ymdhms | 104 | time formatted as ymdhms | | all | | 4 |
| time | 1 | *alias of* time_1985 | | all | | 5 |

Notes:

1. Time is negative prior to equator crossing, positive thereafter.
2. The local solar time is expressed as seconds since the start of the day.
3. Time in Modified Julian Days.
4. The variable time_ymdhms will produce a floating value of the type 20110908135001.536 for 8 Sep 2011 13:50:01.536 UTC.
5. No time limit is set by default. Can be controlled by the t= or ymd= flags on the command line.

## 2.2 Latitude and longitude

The position of the centre of the footprint of the measurement is given by its geographical longitude and latitude relative the TOPEX reference ellipsoid. Longitude is in degrees relative to the Greenwich meridian, positive measuring east. Latitude is in degrees relative to the equator, positive measuring north.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| lat | 2, 201 | latitude | degrees north | all | -90 90 | |
| lon | 3, 301 | longitude | degrees east | all | -180 180 | 1 |

Note:

1. RADS will automatically adjust the values to be within the range specified. So, by default, longitudes are kept within the -180 to +180 range.

## 2.3   Orbital altitude

The orbital altitude is the height of the centre-of-mass of the satellite above the TOPEX reference ellipsoid (semi-major axis = 6378136.3 m, inverse flattening = 298.257) as computed by satellite orbit determination. Numerous solutions exist, based on varying combinations of tracking data or gravity field solutions, or computed at shorter or longer latency. Some "legacy solutions" (those that were provided on the original data products) are included for reference even when they have been long replaced by more accurate solutions.

The altitude is that of the centre-of-mass of the spacecraft, so corrections from the tracking devices (DORIS, GPS, PRARE, SLR) to the centre-of-mass, as well as motion of the centre-of-mass within the spacecraft are accounted for, and should also be accounted for when later subtracting the altimeter range referenced to the same point.

If the time tags on the original GDR data include a bias, the orbit is either (re)interpolated at the *corrected* time tag, or a correction proportional to the orbital altitude rate is applied.

Notes:

1. JGM-3 [*Tapley et al.*, 1996] was the original gravity field solutions used by NASA for the orbit determination of Geosat and TOPEX/Poseidon that featured on the GDR products. Though the gravity field was tailored to the TOPEX orbit, it was generally regarded the best at the time and was hence also used more widely than just for TOPEX/Poseidon. The radial orbit accuracy of about 3 cm for TOPEX/Poseidon and 8 cm for Geosat has since been superseded by more up-to-date orbit solutions.

2. DGM-E04 was a gravity field model developed at the Delft University of Technology tailored to the ERS-1 and ERS-2 orbits and derived from the JGM-3 model. The model significantly improved the radial orbit accuracy to about 3.5 cm, better than any general purpose models available at the time [*Scharroo and Visser*, 1998].

3. CNES produces the operational and precise orbits for a number of satellites. Unfortunately, in RADS the CNES orbits are based on mix of gravity field solutions. The CNES orbits for the TOPEX/Poseidon mission feature on the GDRs and are based on the JGM-3 gravity field model [*Tapley et al.*, 1996]. The CNES orbits for CryoSat and Envisat are obtained from their respective GDR products and are based on the EIGEN-GL04c gravity field model [*Ablain et al.*, 2008].

4. PGS7777 is a NASA preliminary gravity field solution tailored to the Geosat and GFO satellite orbits. The NASA PGS7777 orbit solution for GFO [*Lemoine*

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| alt_jgm3 | 401 | JGM-3 altitude | m | gs pn tx | | 1 |
| alt_dgme04 | 402 | DGM-E04 altitude | m | e1 e2 | | 2 |
| alt_cnes | 404 | CNES altitude | m | c2 n1 pn tx | | 3 |
| alt_pgs7777 | 410 | PGS7777 altitude | m | g1 | | 4 |
| alt_ggm02c_itrf2000 | 411 | GGM02c(ITRF2000) altitude | m | gs pn tx | | 5 |
| alt_ggm02c_itrf2005 | 413 | GGM02c(ITRF2005) altitude | m | pn tx | | 5 |
| alt_eiggl04s | 414 | EIGEN-GL04c altitude | m | j1 | | 6 |
| alt_gdrcp | 415 | GDR-C' altitude | m | g1 gs j1 j2 n1 pn tx | | 7 |
| alt_gps | 416 | GPS altitude | m | j1 j2 | | 8 |
| alt_eig6c | 417 | EIGEN-6C altitude | m | c2 n1 | | 9 |
| alt_eig6s2 | 417 | EIGEN-6S2 altitude | m | j1 j2 | | 9 |
| alt_gdrd | 418 | GDR-D altitude | m | c2 j1 j2 n1 sa | | 10 |
| alt_std1204 | 419 | GSFC/Std1204 altitude | m | j1 j2 tx | | 11 |
| alt_reaper | 420 | REAPER/COMBI altitude | m | e1 e2 | | 12 |
| alt_reaper_deos | 421 | REAPER/DEOS altitude | m | e1 e2 | | 12 |
| alt_reaper_gfz | 422 | REAPER/GFZ altitude | m | e1 e2 | | 12 |
| alt_reaper_esoc | 423 | REAPER/ESOC altitude | m | e1 e2 | | 12 |
| alt_std1404 | 424 | GSFC/Std1404 altitude | m | j2 | | 13 |
| alt_gdre | 425 | GDR-E altitude | m | c2 | | 14 |
| alt | 4 | *alias of* alt_gdre alt_cnes | | c2 | | 15 |
| alt | 4 | *alias of* alt_reaper alt_gfz | | e1 e2 | | 15 |
| alt | 4 | *alias of* alt_pgs7777 | | g1 | | 15 |
| alt | 4 | *alias of* alt_gdrcp | | gs | | 15 |
| alt | 4 | *alias of* alt_gdrd alt_eiggl04s | | j1 | | 15 |
| alt | 4 | *alias of* alt_gdrd | | j2 sa | | 15 |
| alt | 4 | *alias of* alt_gdrd alt_gdrcp | | n1 | | 15 |
| alt | 4 | *alias of* alt_gdrcp alt_jgm3 | | pn tx | | 15 |

*et al.*, 2006] is based on SLR data only as the GPS tracking system on GFO failed.

5. Orbit solutions created at NASA using the GGM02c gravity field and station coordinates in the ITRF2000 or ITRF2005 reference frame.

6. Orbits produced with the EIGEN-GL04c or EIGEN-GL04s gravity fields.

7. Orbits produced under strict Jason GDR-C' standards.

8. Reduced-dynamic (fast-delivery) orbits based on GPS tracking data only.

9. Orbits provided by ESOC using the EIGEN-6C or EIGEN-6S2 gravity field.

10. Orbits produced under strict Jason GDR-D standards (current baseline). Data since April 2015 are in fact produced with GDR-E standards, but the variable name and comment have not been updated to reflect this.

11. Orbits provided by GSFC using their standards "Std1204". They are "GDR-D comparable" and use the goce2s_fit2 gravity field [*Lemoine et al.*, 2013].

12. Orbits produced by the REAPER project. A combined solution and individual solutions created by DEOS (TU Delft), GFZ and ESOC are available [*Rudenko et al.*, 2011].

13. Orbits provided by GSFC using their standards "Std1404". They are "GDR-E" comparable.

14. Orbits products under strict Jason GDR-E standards (baseline for the production of orbits since April 2015).

15. The variable alt refers to the preferred (best) orbit solution for each satellite. If two variable names are mentioned, RADS picks the first one by preference; it that is not available, the second variable is used.

## 2.4   Orbital altitude rate

The rate of change of the orbital altitude is relevant for computing the Doppler correction or a correction to the altitude as a result of a time tag bias. Furthermore, the orbital altitude rate can be used to estimate time tag biases.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| alt_rate | 5, 501 | orbital altitude rate | m/s | all | | |

# Sea level variables

## 3.1 Sea level anomaly

The sea level anomaly (SLA) or sea surface height anomaly (SSHA) is the height for the sea surface relative to a long term mean. It can be constructed by subtracting from the satellite orbital altitude the altimeter range, propagation corrections, sea state bias, tides, and a mean sea surface model.

The sea level anomaly in RADS is always computed on-the-fly. This means that the RADS software will gather the required variables and their selected flavours from the netCDF data files, edit those data based on the user-selected criteria, and then constructs the sea level anomaly based on those. If any of the variables that make up the sea level anomaly is not available, marked invalid, or is out of range, then the sea level anomaly is also marked invalid (set to the NaN value). In addition, variables that do not strictly make up the sea level anomaly (like wave height or wind speed) can be used as edit criteria, e.g. rejecting data with high sea states.

The rads.xml configuration file spells out, in reverse polish notation (RPN), how the sea level anomaly is computed. The 'sea level equation' is written as:

```
<data>
    alt range SUB dry_tropo SUB wet_tropo SUB iono SUB
    inv_bar SUB tide_solid SUB tide_ocean SUB tide_load SUB
    tide_pole SUB ssb SUB mss SUB ref_frame_offset SUB
</data>
```

where SUB stands for 'subtract' and the others are names or aliases of the various variables that make up the sea level anomaly. If any of these variables is NaN, the result is NaN as well. The use of aliases comes in handy here. We can, for example, switch out the orbit solution between one flavour and another simply by directing the alias alt from say alt_jgm3 to alt_dgme04. We would not have to change anything to the sea level equation.

The configuration file also spells out which variables are used as 'quality flag'. That is, if any of these variables is set to NaN, the sea level anomaly is also set to NaN, even though these variables strictly do not contribute to the computation of sea level. For example:

```
<quality_flag>
    swh sig0 range_rms range_numval flags
</quality_flag>
```

Note:

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| sla | 0 | sea level anomaly | m | all | -5 5 | 1 |
| ssha | | *alias of* sla | | all | | |

1. The limits on the sea level anomaly can be changed in the configuration file, of by using the h= flag on the command line.

## 3.2 Altimeter range

The range between the satellite and the sea surface is based on the total travel time of the radar pulse divided by twice the speed of light. This range is then corrected for internal paths within the instrument (internal calibration), variations in the frequency of the ultra-stable oscillator (USO correction), and the distance between the antenna and the satellite centre of mass (centre-of-mass offset). The range is further corrected for the Doppler effect. As such the range measures the distance between the satellite centre of mass and the sea surface, except for path delays in the atmosphere and sea surface interactions.

To compute the height of the sea surface, we subtract the primary range (generally Ku-band) from the satellite orbital altitude and then further correct for path delays and other corrections.

Dual-frequency altimeters measure the range also on a secondary frequency (C- and S-band) which allows for the computation of the ionospheric path delay directly for altimeter observations rather than models.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| range_ka | 601 | altimeter range (Ka) | m | sa | | |
| range_ku | 601 | altimeter range (Ku) | m | other | | |
| range_ku_mle3 | 601 | altimeter range (MLE3) | m | j2 | | 10 |
| range_c | 602 | altimeter range (C) | m | tx j1 j2 | | |
| range_s | 602 | altimeter range (S) | m | n1 | | |
| range | 6 | *alias of* range_ka | | sa | | |
| range | 6 | *alias of* range_ku | | other | | |

Notes:

1. A constant bias of -124 mm is added to the Geosat range. An additional internal calibration and USO correction comes from an external file [*Brian Beckley*, priv. comm., 2002].

2. The range of the ERS-1 and ERS-2 altimeters has been corrected for SPTR bias jumps and USO drift based on offline tables [*Martini and Féménias*, 2000].

3. A constant bias of 409.2 mm is added to the ERS-1 range [*Francis et al.*, 1993; *Stum et al.*, 1998].

4. The ERS-2 USO correction appears to be low during the periods 1997-07-26 20:24:04 to 1998-01-07 03:58:09 and 1998-03-17 11:10:48 to 2000-01-08 06:04:13. During both periods 4.77 mm is added to the USO correction (and to range).

5. The USO correction for Envisat is based on external USO correction files (1-Hz data): http://earth.esa.int/pcs/envisat/ra2/auxdata/

6. The Envisat Ku- and S-band ranges are increased by a constant of 409.2 mm (same as ERS-1). During the short operation of the Side B altimeter an addi-

tional 9 mm is added to both ranges. An additional 150 mm is added to the S-band range to account for a bias in the dual-frequency ionosphere correction [*Scharroo and Smith*, 2010].

7. S-band range for Envisat is available only until the loss of the S-band signal.

8. TOPEX Ku- and C-band ranges are corrected for internal path delays and oscillator drifts based on external correction files (one value per cycle: http: //topex.wff.nasa.gov/) [*Hayne et al.*, 1994]. An additional -15.4 mm is added to the C-band range to account for a bias in the dual-frequency ionosphere correction [*Scharroo and Smith*, 2010].

9. A constant bias of -2.3 mm is added to the Jason-1 C-band range to account for a bias in the dual-frequency ionosphere correction [*Scharroo and Smith*, 2010].

10. A separate range based on an MLE3 retracker is available for Jason-2.

## 3.3 Altimeter range statistics

The altimeter ranges are provided in RADS as (approximately) 1-second averages based on 10, 20, or 40 'elementary' measurements during that second. The altimeter range reported is, in fact, not the statistical mean, but is generally determined as follows:

- Interpolate the orbital altitude at the same time tags as the elementary measurements;

- Subtract the orbital altitude from the range;

- Fit a linear trend true 'range minus orbit';

- Remove the linear trend;

- Compute the standard deviation of the residuals (using $n - 2$ in the denominator) where $n$ is the number of elementary measurements during a 1-Hz period;

- Evaluate the linear trend at the mid point and add the local orbital altitude back at this point to obtain the average range.

Hence, technically, range_rms is not the standard deviation of the altimeter range, but the standard deviation of the elementary 'orbit minus range' values with a trend fitted and removed as well, and taking into account the extra degree of freedom. It should also not be confused with an error estimate for the range measurement.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| range_rms_ka | 2002 | std dev of Ka-band range | m | sa | 0.0 0.17 | |
| range_rms_ku | 2002 | std dev of Ku-band range | m | g1 gs | 0.0 0.25 | |
| | | | | j1 | 0.0 0.2 | |
| | | | | j2 | 0.0 0.17 | |
| | | | | tx | 0.0 0.15 | |
| | | | | other | 0.0 0.4 | |
| range_rms_c | 2004 | std dev of C-band range | m | j1 j2 | 0.0 0.4 | |
| range_rms_s | 2004 | std dev of S-band range | m | n1 | 0.0 0.4 | 1 |
| range_rms | 20 | *alias of* range_rms_ka | | sa | | |
| range_rms | 20 | *alias of* range_rms_ku | | other | | |

Note:

1. Standard deviation of S-band range for Envisat is available only until the loss of the S-band signal.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| range_numval_ku | 2101 | nr of valid Ka-band measurements | | sa | 33 40 | |
| range_numval_ku | 2101 | nr of valid Ku-band measurements | | g1 gs tx | 9 10 | |
| | | | | j1 j2 | 16 20 | |
| | | | | other | 17 20 | |
| range_numval_c | 2102 | nr of valid C-band measurements | | j1 j2 | 17 20 | |
| range_numval | 21 | *alias of* range_numval_ka | | sa | | |
| range_numval | 21 | *alias of* range_numval_ku | | other | | |

## 3.4  Dry tropospheric correction and air tide

The dry tropospheric correction (the negative of the zenith hydrostatic delay, ZHD) accounts for the delay of the radar signal in the atmosphere, not counting the effect of water vapour. This effect is non-dispersive, i.e., it is the same on all frequencies, and is proportional to the surface pressure [*Saastamoinen*, 1972]. The surface pressure, in turn, is determined by interpolation (in space and time) of model grids of surface (or sea level) pressure (see Notes). Most altimeter missions provide the ECMWF operational analysis models as baseline.

Generally, the temporal spacing of the model grids is 6 hours, while the spatial resolution varies. The 6-hourly interval between successive model grids hampers the capturing of 12-hourly and 24-hourly phenomena. Common 24-hourly traveling waves turn into standing waves, while 12-hourly variations are insufficiently described. These phenomena are considered S1 and S2 *air tides* [*Ponte and Ray*, 2002].

To remedy this problem an air tide correction is applied to the sea level pressure, by removing the air tide from the 6-hourly grids before spatio-temporal interpolation and then adding the air tide back for the time and location of the measurement. This correction is already applied to the ECMWF dry tropospheric correction on the Jason-2 GDRs; for all others it is corrected in the RADS processing.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| dry_tropo_ecmwf | 701 | ECWMF dry tropo corr | m | all, but g1 gs | -2.4 -2.1 | 1 |
| dry_tropo_ncep | 702 | NCEP dry tropo corr | m | all | -2.4 -2.1 | 2, 4 |
| dry_tropo_era | 709 | ERA Interim dry tropo corr | m | all | -2.4 -2.1 | 3, 4 |
| dry_tropo_airtide | 4901 | air tide corr | m | c2 e1 j1 pn tx | | 5 |
| dry_tropo | 7 | *alias of* dry_tropo_era | | g1 gs | | |
| dry_tropo | 7 | *alias of* dry_tropo_ecmwf | | other | | |

Notes:

1. The pressure fields on which this correction is based are from the ECMWF operational analysis runs. That means that numerous changes to the models and their resolution create an unstable reference for long-term studies. Please verify any of the ECMWF model results against the other models. Because of an unfortunate choice to use surface pressure fields, instead of sea level pressure fields, for this correction, coastal areas may be affected by "leaking"

of the effect of higher terrain over land (thus lower pressure) into the sea and ocean (where there should be no terrain effect).

2. The NCEP reanalysis model used for this correction has *not* gone through any updates, so from that point of view the correction should be consistent over time. However, this older model also is less accurate and has a lower resolution (2.5°×2.5°) than the ECMWF analysis fields.

3. The ERA (ECMWF ReAnalysis) Interim model provides an excellent long-term consistency. The data is distributed by ECMWF as Gaussian grids with an approximately uniform spacing of 79 km [*Berrisford et al.*, 2011].

4. NCEP and ERA sea level pressure grids are interpolated and, over land and lakes, the pressure is then corrected for altitude based on a high-resolution terrain model, thus avoiding the coastal contamination seen in the ECMWF dry tropospheric correction.

5. The air tide correction to the dry tropospheric correction is provided for reference only. It is already applied to all variations of the dry tropospheric correction (ECMWF, NCEP, ERA interim).

## 3.5 Wet tropospheric correction

The wet tropospheric correction (the negative of zenith wet delay, ZWD) accounts for the delay of the radar signal in the atmosphere due to the presence of water vapour. This effect is non-dispersive, i.e., it is the same on Ku-, S- and C-band frequencies, and it can be determined by integrating a function of water vapour density and temperature [e.g., *Askne and Nordius*, 1987], which to good approximation simplifies to

$$\mathrm{ZWD} = \mathrm{IWV} R_w (k_3/T_m + k_2')$$

where IWV is integrated water vapour, $T_m$ is the mean temperature in the atmospheric column, and $R_w$, $k_2'$ and $k_3$ are constants [*Bevis et al.*, 1994]. The mean temperature can further be approximated from model data of near-surface air temperature, $T_s$, by

$$T_m = 50.4 + 0.789 T_s$$

[*Mendes et al.*, 2000]. In this way, the 6-hourly models of integrated water vapour and near-surface temperature are interpolated in space and time and then converted to a wet tropospheric correction. Generally, the temporal spacing of the model grids is 6 hours, but since the power of the water vapour content at 12 and 24 hours is low, an air tide correction like in case of the pressure is not needed.

Because of the large spatial and temporal variability (much more so than pressure), most altimeter missions are equipped with passive microwave radiometers, collecting brightness temperatures of the ocean surface at two or three frequencies. Using the three frequencies, or two frequencies plus the radar altimeter backscatter measurement, a wet tropospheric correction (and some related variables) can be derived. However, the radiometer measurements are strongly affected by land in the measurement footprint (extending to a radius of 40 km in some cases), limiting its use in coastal regions, hence the existence of a radiometer land flag.

The radiometer wet tropospheric correction for ERS-1, ERS-2, and Envisat is based on the altimeter backscatter coefficient (before correction for atmospheric attenuation) and the radiometer brightness temperatures at 23.8 GHz and 36.5

GHz, using all the same neural network algorithm as was developed for Envisat [*Labroue and Obligis*, 2003]. For TOPEX/Poseidon, Jason-1 and -2, the radiometer wet tropospheric correction is derived from their respective 3-channel brightness temperatures using multi-layer parametric algorithms [*Keihm et al.*, 1995; *Dumont et al.*, 2001]. For GFO, the the 2-channel brightness temperatures are combined with the altimeter wind speed using a log-linear model [*Ruf et al.*, 1996]. See Sections 4.2 and 5.2 for information about corrections applied to the backscatter and brightness temperatures prior to evaluating the models.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| wet_tropo_rad | 801 | radiometer wet tropo corr | m | n1 | -0.6 0.05 | 1 |
| | | | | pn tx | -0.6 -0.001 | 2 |
| | | | | e2 | -0.6 0.0 | 3 |
| | | | | e1 g1 j1 j2 | -0.6 0.0 | |
| wet_tropo_ecmwf | 802 | ECMWF wet tropo corr | m | all, but g1 gs | -0.6 0.0 | 4 |
| wet_tropo_ncep | 803 | NCEP wet tropo corr | m | all | -0.6 0.0 | 5 |
| wet_tropo_nvap | 804 | NASA NVAP wet tropo corr | m | gs | -0.6 0.0 | 6 |
| wet_tropo_tovs_ssmi | 805 | TOVS/SSMI wet tropo corr | m | gs | -0.6 0.0 | 7 |
| wet_tropo_tovs_ncep | 807 | TOVS/NCEP wet tropo corr | m | gs | -0.6 0.0 | 8 |
| wet_tropo_era | 809 | ERA interim wet tropo corr | m | all | -0.6 0.0 | 9 |
| wet_tropo | 8 | *alias of* wet_tropo_ecmwf | | c2 | | 10 |
| wet_tropo | 8 | *alias of* wet_tropo_era | | gs | | 10 |
| wet_tropo | 8 | *alias of* wet_tropo_rad wet_tropo_era | | g1 | | 10 |
| wet_tropo | 8 | *alias of* wet_tropo_rad wet_tropo_ecmwf | | other | | 10 |

Notes:

1. Because of model bias and noise, allow positive values.

2. Need to exclude bogus zero values from TMR measurements.

3. ERS-2 MWR is not available from 2009-05-04 to 2010-01-15.

4. The ECMWF correction is actually computed by integrating several layers of the atmosphere, rather than using the simplified form discussed above. The meteorological fields on which this correction is based are from the ECMWF operational analysis runs. That means that numerous changes to the models and their resolution create an unstable reference for long-term studies. Please verify any of the ECMWF model results against the other models.

5. NCEP reanalysis model used for this correction has *not* gone through any updates, so from that point of view the correction should be consistent over time. However, this older model also is less accurate and has a lower resolution ($2.5° \times 2.5°$) than the ECMWF analysis fields.

6. The NASA NVAP model is an old water vapour model used in the Geosat era.

7. TOVS and SSMI are separate radiometer constellations whose data were used to model the water vapour content globally.

8. This the result of a merger of the TOVS radiometer data with the NCEP water vapour and near-surface temperature models.

9. The ERA (ECMWF ReAnalysis) Interim model provides an excellent long-term consistency. The data is distributed by ECMWF as Gaussian grids with an approximately uniform spacing of 79 km [*Berrisford et al.*, 2011].

10. CryoSat-2 and Geosat have no radiometer, so the wet tropospheric correction is always based on models. For the other missions we may default to the

model if the radiometer correction is not *at all* available on the product. This would be the case when the radiometer is *permanently* switched off, or off for a long time. The model will not be used during short outages.

## 3.6 Ionospheric correction

The radar signal is also delayed by ions and electrons in the upper layers of the atmosphere (the ionosphere). The delay is inversely proportional to the altimeter radar frequency, and otherwise proportional to the vertically integrated electron density, known as total electron content or TEC. This dispersive nature allows dual-frequency altimeters (TOPEX, Envisat, Jason-1 and -2) to directly determine the ionospheric path delay on either frequency. For single frequency altimeters we rely on TEC estimates from models based on other dual-frequency equipment (GPS, DORIS) or climatologies.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| iono_alt | 901 | dual-frequency iono corr | m | n1 j1 j2 tx | -0.4 0.04 | 1 |
| iono_alt_smooth | 903 | smoothed dual-freq iono corr | m | n1 j1 j2 tx | -0.4 0.04 | 2 |
| iono_bent | 902 | Bent iono corr | m | c2 e1 e2 n1 pn tx | -0.4 0.04 | 4 |
| iono_doris | 904 | DORIS iono corr | m | n1 pn tx | -0.4 0.04 | 5 |
| iono_gim | 906 | JPL GIM iono corr | m | all but gs e1 pn | -0.4 0.04 | 6 |
| iono_iri2007 | 907 | IRI2007 iono corr | m | all | -0.4 0.04 | 7 |
| iono_nic09 | 908 | NIC09 iono corr | m | all | -0.4 0.04 | 8 |
| iono_alt_mle3 | 911 | dual-freq iono corr (MLE3) | m | j2 | -0.4 0.04 | 3 |
| iono_alt_smooth_mle3 | 913 | smoothed d-f iono corr (MLE3) | m | j2 | -0.4 0.04 | 3 |
| iono | 9 | *alias of* iono_alt_smooth iono_gim iono_nic09 | | j1 j2 n1 tx | | 9 |
| iono | 9 | *alias of* iono_gim iono_nic09 | | c2 e2 g1 sa | | 9 |
| iono | 9 | *alias of* iono_nic09 | | e1 gs pn | | 9 |

Notes:

1. Positive correction values are allowed to account for noise in the altimeter dual-frequency ionospheric correction. The values for this correction have been adjusted from the original GDR products to account for relative C-band and S-band biases (Section 3.2).

2. Because of the relatively large noise in the dual-frequency ionospheric correction, iono_alt is smoothed over 35 seconds along the altimeter track (appoximately 250 km), in contrast to the 21 seconds suggested by *Imel* [1994].

3. For Jason-2, a separate dual-frequency correction based on the MLE3 retracker is available.

4. The "ancient" Bent TEC climatology [*Llewellyn and Bent*, 1973] should no longer be used.

5. The TEC model based on DORIS featured for a while on TOPEX/Poseidon and Envisat altimeter products but was far behind the accuracy of the (similar in construct) GPS-derived GIM models.

6. JPL produces, based on the global constellation of GPS satellites and IGS GPS receivers, 2-hourly maps of TEC, known as the JPL GIM model [*Komjathy et al.*, 2000]. The models have a spatial resolution of $5° \times 2.5°$ and start in August 1998.

7. The International Reference Ionosphere went through several versions, the latest of which is IRI2007 [*Bilitza and Reinisch*, 2008]. Because of its rather coarse spatial and temporal resolution, it cannot compete with the JPL GIM model, or even the NIC09 climatology.

8. The NIC09 climatology is based on 12 years of JPL GIM maps and can be extended as far back as the 1950s or extrapolated using predicted solar flux values [*Scharroo and Smith*, 2010]. This model is particularly useful for the period prior to August 1998 (before the availability of iono_gim).

9. The alias iono with use either the smoothed dual-frequency ionospheric correction or one of the models in the order as given.

## 3.7 Atmospheric (inverse barometer) correction

The inverse barometer (IB) correction accounts for the suppression of sea level due to higher sea level pressure, and its rise during lower sea level pressure. When we assume a linear relation between pressure and suppression we talk about a "static" IB correction, and because the sea level goes down with increasing pressure, opposite to the way we think of a mercury barometer, we use the term "inverse". The simplest form of this correction is:

$$\mathrm{IB} = C(p - p_0)$$

where $C$ is -9.948 mm/mbar, $p$ is the sea level pressure and $p_0$ is a reference pressure. Since the global ocean as a whole is incompressible, $p_0$ here stands for the global mean sea level pressure over oceans.

However, there are also dynamics involved in this. For example, an ocean basin cannot instantly be suppressed as a whole because of rapidly increasing regional pressure. Also wind can play a role as well. Hence, the static correction is too simplistic. A more accurate model includes wind and ocean dynamics and is hence called a dynamic atmospheric correction (DAC). RADS, AVISO, and other altimeter datasets include the dynamic atmospheric correction produced by CLS Space Oceanography Division using the MOG2D model from Legos [*Carrère and Lyard*, 2003; *Roblou et al.*, 2008] and distributed by AVISO, with support from CNES.

Over inland waters, this correction should not be applied [*Crétaux and Birkett*, 2006].

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| inv_bar_static | 1001 | static inverse baro corr | m | all | -1 1 | 1 |
| inv_bar_global | 1002 | global mean inv baro corr | m | all | -1 1 | 2 |
| inv_bar_mog2d | 1003 | MOG2D dynamic atmospheric corr | m | all | -1 1 | 3 |
| inv_bar_mok2d | 1004 | MOK2D dynamic atmospheric corr | m | all | -1 1 | 4 |
| inv_bar_mog2d_mean | 1005 | local mean of MOG2D | m | all | -1 1 | 5 |
| inv_bar | 10 | *alias of* inv_bar_mog2d inv_bar_mok2d | | all | | 6 |

Notes:

1. This correction is the simplification explained above.

2. For reference the global mean pressure, converted to an IB correction, $Cp_0$, is provided.

3. The dynamic atmospheric correction model MOG2D includes the ocean dynamic response to wind and pressure forcing. It also accounts for the aliasing of the air tides as discussed in Section 3.4. MOG2D also comes with two latencies: (a) a few days, and thus features on the IGDR-derived products, and (b) a few weeks, and thus features on the GDR-derived products. For fast-delivery products there is generally no MOG2D correction (so MOK2D will be used), but the MOG2D field will be filled in as soon as the MOG2D maps have been distributed.

4. Since the MOG2D only start in 1992, we have created a "mock-up" version of MOG2D (a simple linear variant of inv_bar_static) to match the mean of MOG2D as to not disturb continuity of the DAC prior to 1992..

5. For reference, the local long-term mean of the MOG2D correction is provided. This is the interpolation of a static grid computed as the average of all MOG2D maps over the period 1993-2009.

6. When using the inv_bar alias, inv_bar_mog2d is used while automatically defaulting to inv_bar_mok2d.

## 3.8   Solid earth and pole tide

The solid earth tide is the variation of the elevation of the crust of the earth surface as a result of the attraction by the sun and moon (other planets are generally ignored as their influence is at least an order of magnitude smaller). As per geodetic convention the "permanent tide" (the mean tide resulting from the mere presence of the sun and moon) is excluded from the solid earth tide but is included in the geoid.

The RADS implementation of the Cartwright-Taylor-Edden solid earth tide model includes 386 second order waves and 99 third order waves [*Cartwright and Taylor*, 1971; *Cartwright and Edden*, 1973].

The pole tide is the vertical deformation of the earth crust as a result of polar motion. We can visualise this as the ellipsoidal shape of the earth being moved as the rotation axis of the earth moves away or closer to the mean pole [*Munk and MacDonald*, 1960]. We use the IERS(EOP)05C04 earth orientation parameters and their predictions relative to the mean pole (0.042″ along the Greenwich meridian, 0.293″ towards 90°W).

Two Love numbers multiply the results of this simple equilibrium model: $(1 + k_2) = 1.302$ for the combination of solid earth and oceans, and $h_2 = 0.609$ for the solid earth only (over land and lakes) [*Wahr*, 1985].

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| tide_solid | 1101 | solid earth tide | m | all | -1 1 | |
| tide_pole | 1401 | pole tide | m | all | -0.1 0.1 | |
| | 11 | *alias of* tide_solid | | all | | |
| | 14 | *alias of* tide_pole | | all | | |

## 3.9   Ocean and load tide

The (pure) ocean tide is the variation of the height of the water column as a result of luni-solar attraction. Since this is measured relative to a fixed point on the

solid earth (like the sea floor), the ocean tide compares directly to tide gauge measurements. The load tide is the effect of the tides weighing on the elastic earth. In general, when the ocean tide goes up, the sea floor is going down, hence reducing the sum of the two, the geocentric ocean tide. Consequently, in order to detide the measurement of the water surface from altimetry, both the ocean tide (tide_ocean) and the load tide (tide_load) need to be subtracted over ocean surfaces, while over lakes only the load tide is subtracted.

Although some altimeter products provide the geocentric ocean tide, we have chosen to keep ocean and load tide separate, for two reasons: (1) it makes it easier to differentiate tides over land/lakes and ocean, and (2) it makes it easier to add regional tides which are generally expressed as pure ocean tides.

Tides are expressed as the sum of a (large) number of *waves* with different frequencies, each combinations of the frequencies associated with the rotation and progression of the earth, sun and moon. A select portion of those waves are expressed as grids of amplitude and phase, which can be interpolated in space and evaluated at the time of the altimeter measurement. Then, by a process called *admittance*, the amplitude and phase of a number of minor tides are inferred.

Tide models generally only include the diurnal and semi-diurnal waves (those around a period of 12 and 24 hours). On top of that there are secondary and tertiary waves with periods of a week or longer. Most of these waves can be expressed by a simple latitude and time dependent equilibrium model (the long-period equilibrium tide). The FES2004 ocean tide model also includes the non-equilibrium component of the monthly, fortnightly, tri-monthly, and weekly tides.

Although the FES and GOT models are global, they are limited in scope. Over land, the ocean tide is not defined and will be set to the NaN value. In some coastal regions, where the models may likely not be defined, the ocean tide value is set to NaN as well.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| tide_ocean_fes04 | 1213 | FES2004 ocean tide | m | all | -5 5 | 1 |
| tide_load_fes04 | 1313 | FES2004 load tide | m | all | -0.5 0.5 | 1 |
| tide_ocean_webtide | 1215 | WebTide ocean tide | m | all | -5 5 | 2 |
| tide_ocean_got47 | 1217 | GOT4.7 ocean tide | m | e1 e2 g1 gs pn tx | -5 5 | 3 |
| tide_load_got47 | 1317 | GOT4.7 load tide | m | e1 e2 g1 gs pn tx | -0.5 0.5 | 3 |
| tide_ocean_got48 | 1219 | GOT4.8 ocean tide | m | all | -5 5 | 4 |
| tide_load_got48 | 1319 | GOT4.8 load tide | m | all | -0.5 0.5 | 4 |
| tide_ocean_got49 | 1221 | GOT4.9 ocean tide | m | e1 j1 n1 pn tx | -5 5 | 5 |
| tide_load_got49 | 1321 | GOT4.9 load tide | m | e1 j1 n1 pn tx | -0.5 0.5 | 5 |
| tide_ocean_got410 | 1222 | GOT4.10 ocean tide | m | c2 j1 j2 pn sa tx | -5 5 | 6 |
| tide_load_got410 | 1322 | GOT4.10 load tide | m | c2 j1 j2 pn sa tx | -0.5 0.5 | 6 |
| tide_ocean_fes12 | 1223 | FES2012 ocean tide | m | c2 j1 j2 pn sa tx | -5 5 | 7 |
| tide_equil | 3901 | long-period equilib. tide | m | all | -1 1 | 8 |
| tide_non_equil | 3902 | long-period non-equil. tide | m | all | -1 1 | 9 |
| tide_ocean | 12 | *alias of* tide_ocean_got48 | | all | | |
| tide_load | 13 | *alias of* tide_load_got48 | | all | | |
| | 39 | *alias of* tide_equil | | all | | |

Notes:

1. The Finite Element Solution (FES2004) includes 9 short-period waves (Q1, O1, K1, P1, 2N2, N2, M2, K2, and S2) plus 24 additional short-period waves determined by admittance, and 4 long-period waves (Mf, Mm, Mtm and

MSqm) [*Lyard et al.*, 2006]. Long-period equilibrium tides (not yet included in FES2004) are added to these.

2.  WebTide is a collection of regional tide models along the Canadian coast, made available on the web by the Bedford Institute of Oceanography http:// www.bio.gc.ca/research-recherche/WebTide-MareeWeb/webtide-eng.htm. In RADS, a single value is presented in tide_ocean_webtide, determined from (in order of decreasing preference) the regional models for: Scotia/Fundy/Maine, Northeast Pacific, Arctic, Hudson Bay. Each of these models has a very limited amount of constituents, does not include admittance to infer others, and also does not include any long-period tides (equilibrium or non-equilibrium).

3.  The Goddard Ocean Tide model GOT 4.7 includes 10 short-period waves (K1, O1, P1, Q1, S1, K2, M2, N2, S2, and M4) plus 17 additional short-period waves determined by admittance [*Ray et al.*, 2011]. The 4 long-period waves from FES2004 and additional long-period equilibrium tides are added to these. **This field is slated to be removed.**

4.  The Goddard Ocean Tide model GOT 4.8 differs from GOT 4.7 only in its S2 component.

5.  The Goddard Ocean Tide model GOT 4.9 differs from GOT 4.7 only in its S2 component. **This field is slated to be removed.**

6.  The Goddard Ocean Tide model GOT4.10c differs from the current default in RADS, GOT4.8, in two ways. First, GOT4.10c is based only on Jason data, whereas 4.8 was from only TOPEX data. Second, it includes an adjustment for the geocenter. (Hence the 'c' in the name.) The processing for 4.8 and 4.10 was largely identical; one exception involved an improvement to P1 alone. GOT4.10c is an update of *Ray* [2013]. **This model will soon become the default ocean and load tide model.**

7.  FES2012 (Finite Element Solution 2012) takes advantage of longer altimeter time series, improved modelling, and data assimilation techniques, and more accurate and higher resolution ocean bathymetry. A new global finite element grid (with approx. 1.5 million nodes) was used to create a 'free' solution (independent of in situ and remote-sensing data) that has twice accuracy of the FES2004 version. The 'free' solution was assimilated with long-term altimetry data from TOPEX/POSEIDON, Jason-1, Jason-2, ERS-1, ERS-2, and ENVISAT. The FES2012 solution shows particular improvement in coastal and shelf regions.

    Please note that tide loading effects have not yet been computed for FES2012, and therefore you should use the load tide from one the GOT load tide models with the ocean tide from FES2012. Since the load tide models are global, this would not limit the area for which you can determine geocentric tides (ocean plus load tides). http://www.aviso.oceanobs.com/en/data/products/ auxiliary-products/global-tide-fes2004-fes99/description-fes2012.html

8.  The equilibrium ocean tide includes 15 tidal spectrum lines from the Cartwright-Tayler-Edden tables [*Cartwright and Taylor*, 1971; *Cartwright and Edden*, 1973] plus an additional 123 second and third order waves [*Tamura*, 1987].

9. The four long-period non-equlibrium ocean tidal components (Mm, Mf, Mtm, and MSqm) from the FES2004 model are represented in tide_non_equil. The equilibrium parts of those have been removed to avoid double accounting.

## 3.10   Sea state bias

Sea state bias (SSB) is the term used for any altimetric range offset as a function of the sea state (wave height, wind speed, wave age, swell). In fact, there are three components to the sea state bias:

**Electromagnetic (EM) bias** is the tendency of a radar to measure towards the wave troughs since they are better reflectors than the wave peaks.

**Skewness bias** comes from the fact that the sea surface has a skewed height distribution. While the altimeter measures the median height of the surface in the footprint, what we want to measure is the mean height, which is lower.

**Tracker bias** is the any error in the waveform tracker that is a function of the sea state, which may be either instrumental or algorithmic.

Because of the instrumental part of sea state bias, every altimeter, in principle, requires a different sea state bias correction model. But also when a new tracker algorithm is implemented, the sea state bias changes. This is one of the reasons for the wide proliferation of SSB models.

In the earlier days of altimetry the sea state bias was generally considered as a simple fraction, around –3.5%, of significant wave height [*Chelton*, 1994]. Then *Gaspar et al.* [1994] brought a major improvement in SSB modelling by expressing SSB as a polynomial function of SWH and wind speed, recognising that not only the wave height, but also the shape of the waves (altered by wind) has influence on the altimeter range bias. But this approach still exhibits some limitations, in that it imposes the type of variations that are allowed as a result of changes in SWH or wind speed. Currently, SSB models tend to be non-parametric, generally expressed in the form of a grid with SWH and wind speed as coordinates [e.g., *Gaspar and Florens*, 1998]. But several more complex multi-dimensional models are currently under development [e.g., *Feng et al.*, 2010; *Tran et al.*, 2010].

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| ssb_bm3 | 1501 | parametric sea state bias | m | e1 e2 g1 gs pn tx | -1 1 | 1 |
| ssb_cls | 1502 | CLS non-parametric SSB | m | j1 j2 n1 tx | -1 1 | 2 |
| ssb_csr | 1503 | CSR BM4 sea state bias | m | tx | -1 1 | 3 |
| ssb_hyb | 1504 | NOAA hybrid sea state bias | m | g1 gs n1 pn sa | -1 1 | 4 |
| ssb_cls_c | 1505 | CLS non-parametric SSB (C-band) | m | j1 j2 | -1 1 | 2 |
| ssb_cls_mle3 | 1512 | CLS non-parametric SSB (MLE3) | m | j2 | -1 1 | 5 |
| ssb_tran2012 | 1513 | Tran et al. 2012 non-parametric sea state bias | m | j2 | -1 1 | 6 |
| ssb | 15 | *alias of* ssb_bm3 | | e1 e2 pn | | |
| ssb | 15 | *alias of* ssb_cls | | j1 j2 n1 tx | | |
| ssb | 15 | *alias of* ssb_hyb | | c2 g1 gs sa | | |

Notes:

1. One-, three- or four-term polynomials of SWH and wind speed [*Gaspar et al.*, 1994].

2. Non-parametric sea state bias models for Ku-band and C-band by CLS [*Gaspar et al.*, 2002; *Labroue et al.*, 2004].

3. Four-term sea state bias model for TOPEX (different model for side A and side B altimeters) [*Chambers et al.*, 2003].

4. Hybrid (mix between parametric and non-parametric techniques) sea state bias models produced at NOAA [*Scharroo and Lillibridge*, 2005].

5. For Jason-2 data retracked by MLE3, a separate non-parametric model is available.

6. The non-parametric SSB model developed by *Tran et al.* [2012] will be part of the upcoming GDR-D standards.

## 3.11 Mean sea surface and geoid

The sea level anomaly (SLA) is expressed as the difference of the instantaneous tide-corrected sea surface with respect to a well-established mean. Over the years several (more or less) global mean sea surface models have been developed from the compilation of satellite altimeter (and sometimes gravity) data. Generally, the more altimeter data collected, the more precise the model. But also the resolution of the model counts. Each model has been referenced to the TOPEX reference ellipsoid, just as the satellite orbits (Section 2.3).

Another reference surface is the geoid (the theoretical mean sea surface in absence of ocean currents, wind, etc.). Geoid models are generally made from satellite tracking data (for the longer wave lengths), and altimetry and in-situ gravimetry (for the shorter wave lengths).

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| mss_cls01 | 1605 | CLS01 mean sea surface | m | all | -200 200 | 1 |
| mss_egm2008 | 1610 | EGM2008 mean sea surface | m | all | -200 200 | 2 |
| mss_dncs2008 | 1612 | DNSC08 mean sea surface | m | all | -200 200 | 3 |
| mss_dtu10 | 1613 | DTU10 mean sea surface | m | all | -200 200 | 4 |
| mss_cls11 | 1614 | CNES-CLS11 mean sea surface | m | | -200 200 | 5 |
| mss_dtu13 | 1616 | DTU13 mean sea surface | m | c2 j1 j2 pn sa tx | -200 200 | 6 |
| geoid_egm2008 | 1611 | EGM2008 geoid | m | all | -200 200 | 2 |
| geoid_eigen6 | 1617 | EIGEN6c3stat geoid | m | c2 j1 j2 pn sa tx | -200 200 | 7 |
| mss | 16 | *alias of* mss_dtu10 | | all | | |
| geoid | | *alias of* geoid_egm2008 | | all | | |

Notes:

1. Widely used, but outdated, mean sea surface model based on ERS-1/2 and TOPEX data created at CLS [*Hernandez and Schaeffer*, 2001].

2. Combined geoid and mean sea surface solution [*Pavlis et al.*, 2008].

3. Older version a mean sea surface model based on RADS data created at DNSC (now DTU) [*Andersen and Knudsen*, 2009].

4. The DTU10 mean sea surface model created at DTU based on RADS data [*Andersen and Knudsen*, 2010].

5. Newest iteration of mean sea surface models at CNES/CLS [*Schaeffer et al.*, 2012].

6. The DTU13MSS is the latest release of the global high-resolution mean sea surface from DTU Space, which includes two major advances over DTU10MSS. First, the time series have been extended to 20 years from 17 years. Second,

the DTU13MSS ingests Cryosat-2 SAR lead data in order to map the high latitude parts of the Arctic Ocean. In high-latitude regions a combination of joint ERS-1/ERS-2/ENVISAT and Cryosat-2 altimetry have been used. Also, the Jason-1 geodetic mission has been used for the DTU13MSS. [*Andersen et al.*, 2013]. **This will soon become the default MSS model, replacing DTU10.**

7. The EIGEN?6C3stat geoid model has been generated in preparation for the final release of EIGEN?6C4. It was computed from a combination of LAGEOS, GRACE, and GOCE data, augmented with DTU13 surface gravity data to degree and order 1949 (corresponding to approximately 10 km spatial resolution). [*Förste et al.*, 2013; *Shako et al.*, 2014]. **This will soon become the default geoid model, replacing EGM2008.**

# Chapter 4

# Wind speed and wave height variables

## 4.1 Significant wave height

The significant wave height (SWH) is generally defined as the mean wave height (peak to trough) of the highest one-third of the ocean waves. Another commonly used definition is four times the standard deviation of the elevation of the sea surface in the radar footprint.

SWH is determined from the rate of increase of returned power of the radar altimeter pulse (the waveform slope) and requires no further correction other than some instrument parameters. There is one complexity in this, and that is that SWH is defined as follows:

$$\text{SWH}^2 = \alpha^2(\sigma_c^2 - \sigma_p^2)$$

where $\sigma_c$ is a measure of the waveform slope and $\sigma_p$ is an instrument parameter, and $\alpha$ is a constant. Because of noise in the measurement of $\sigma_c$ and a possible bias in $\sigma_p$, $\text{SWH}^2$ could become negative. In most GDR products, SWH is then set to zero, which creates a wrongly truncated measurement, and makes it difficult to correct for any biases in SWH the measurement (which would raise the zero SWH above zero). Where we can, however, in RADS, this case is tackled by writing out the negative of the square root of the absolute value of the argument instead. Hence:

$$\text{SWH} = -\alpha\sqrt{\sigma_p^2 - \sigma_c^2} \ \text{ when } \ \sigma_c < \sigma_p$$

$$\text{SWH} = \alpha\sqrt{\sigma_c^2 - \sigma_p^2} \ \text{ when } \ \sigma_c \geq \sigma_p$$

(See Note 1 below).

The 1-Hz standard deviation of SWH is determined from the individual 10-, 20-, or 40-Hz elementary measurements. Note that this is the standard deviation of the elementary measurements (denominator is $(n-1)$), not an estimate of the error of SWH.

Notes:

1. The SWH of Envisat and CryoSat will be set to a negative value when $\sigma_c < \sigma_p$. For other missions, the value is set to 0.

2. During the degradation of the TOPEX SWH measurements (cycles 98-235) the SWH values are corrected according to *Queffeulou* [2004]. Thereafter 32 mm was added.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| swh_ka | 1701 | Ka-band significant wave height | m | sa | 0 8 | |
| swh_ku | 1701 | Ku-band significant wave height | m | c2 n1 | -0.5 8 | 1,2 |
| | | | | other | 0 8 | |
| swh_c | 1702 | C-band significant wave height | m | j1 j2 tx | 0 8 | |
| swh_s | 1702 | S-band significant wave height | m | n1 | -0.5 8 | 1,3 |
| swh_ku_mle3 | 1711 | Ku-band significant wave height (MLE3) | m | j2 | 0 8 | 4 |
| swh_ww3 | 1712 | WaveWatch3 significant wave height | m | c2 j2 sa | | 5 |
| swh_rms_ka | 2802 | std dev of Ku-band SWH | m | sa | 0 2.1 | |
| swh_rms_ku | 2802 | std dev of Ku-band SWH | m | g1 | 0 0.5 | |
| | | | | j1 j2 | 0 1.5 | |
| | | | | tx | 0 0.9 | |
| | | | | other | 0 2.1 | |
| swh_rms_c | 2804 | std dev of C-band SWH | m | j1 j2 tx | 0 2.1 | |
| swh_rms_s | 2804 | std dev of S-band SWH | m | n1 | 0 2.1 | 3 |
| swh | 17 | *alias of* swh_ka | | sa | | |
| swh | 17 | *alias of* swh_ku | | other | | |
| swh_rms | 28 | *alias of* swh_rms_ka | | sa | | |
| swh_rms | 28 | *alias of* swh_rms_ku | | other | | |

3. S-band SWH for Envisat is only until the loss of the S-band signal.

4. For Jason-2, significant wave heights from the MLE3 retracker are available as well.

5. The SWH in this field is based on wave hindcasts done by NOAA using the WaveWatch III model and GFS analysis winds [*Chawla et al.*, 2011]. The hindcasts cover the entire globe and are carried out in monthly installments, so they are only available on delay-time data in RADS. The original resolution of these model grids is 1° by 1° by 6 hours. For other WaveWatch 3 fields see Section 4.4.

## 4.2 Altimeter backscatter coefficient

The backscatter coefficient is derived from the total returned power of the radar altimeter pulse. After correction for losses due to water vapour in the atmosphere, it identifies the small scale ripples on the sea surfaces, and hence becomes a measure for wind speed (Section 4.3).

The correction for atmospheric losses is generally determined from the radiometer measurements. In case the brightness temperatures were corrected with respect to the GDR values (Section 5.2), so is the wet tropospheric correction, the atmospheric correction to the backscatter and the backscatter coefficient itself.

The 1-Hz standard deviation of backscatter coefficient is determined from the individual 10-, 20- or 40-Hz elementary measurements. Note that this is the standard deviation of the elementary measurements (denominator is $(n-1)$), not an estimate of the error of the backscatter coefficient.

Notes:

1. The ERS-1 backscatter coefficient is corrected for varying biases due to the attitude control. Between 0 and 0.35 dB was added.

2. The GFO backscatter is corrected for a few deficiencies in lookup tables, adding 0.37 dB before 6 Dec 2000 and between 7 and 9 March 2001.

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| sig0_ka | 1801 | Ka-band backscatter coefficient | dB | sa | 6 27 | |
| sig0_ku | 1801 | Ku-band backscatter coefficient | dB | other | 6 27 | 1-5 |
| sig0_c | 1802 | C-band backscatter coefficient | dB | j1 j2 tx | 6 27 | 3-5 |
| sig0_s | 1802 | S-band backscatter coefficient | dB | n1 | 6 27 | 6 |
| sig0_ku_mle3 | 1811 | Ku-band backscatter coefficient (MLE3) | dB | j2 | 6 27 | 7 |
| sig0_rms_ka | 2902 | std dev of Ka-band SWH | dB | sa | 0 1 | |
| sig0_rms_ku | 2902 | std dev of Ku-band SWH | dB | all | 0 1 | |
| sig0_rms_c | 2904 | std dev of C-band SWH | dB | j1 j2 tx | | 8 |
| sig0_rms_s | 2904 | std dev of S-band SWH | dB | n1 | | 6 |
| sig0 | 18 | *alias of* sig0_ka | | sa | | |
| sig0 | 18 | *alias of* sig0_ku | | other | | |
| sig0_rms | 29 | *alias of* sig0_rms_ka | | sa | | |
| sig0_rms | 29 | *alias of* sig0_rms_ku | | other | | |

3. The Jason-1 Ku- and C-band backscatter are aligned with TOPEX values by subtracting 2.40 and 0.725 dB, respectively. For the time being, the same biases are applied to Jason-2. However, wind speed values are not adjusted.

4. The Jason-2 Ku- and C-band backscatter are reduced in noise based on a correlation with off-nadir angle [*Quartly*, 2009]. In addition, biases of 2.40 and 0.725 dB have been removed from the Ku- and C-band backscatter, respectively.

5. TOPEX backscatter is corrected following the off-line Wallops correction tables.

6. S-band backscatter for Envisat is only until the loss of the S-band signal.

7. For Jason-2, the backscatter coefficient from the MLE3 retracker is available as well.

8. For TOPEX, the standard deviation is that of the automatic gain control, not of the backscatter coefficient. That means that the variation of the total volume of the waveform in not included, only the variation of the gain setting of the instrument.

## 4.3  Wind speed

Wind speed can be derived from the altimeter backscatter coefficient (Section 4.2). The larger the backscatter, the lower the wind speed. Several models have been developed to map this relationship, some depending merely on backscatter, some also taking into account significant wave height. Which models are applied to which satellites is shown in the notes below.

Three-channel radiometers provide the opportunity to estimate wind speed. In essences this is the reverse side of the fact that one of those channels can be replaced with the altimeter wind speed to obtain the wet tropospheric correction. This variable is available for all missions with 3-channel radiometers.

Atmospheric models, like those at ECMWF also provide wind speed and wind directions, or their vectorial components pointing north and east. Those model values are provided for some missions as well.

Notes:

1. For Geosat, GFO, ERS-1 and ERS-2, the wind speed is based on the Modified Chelton-Wentz (MCW) algorithm [*Witter and Chelton*, 1991]. In case of GFO

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| wind_speed_alt | 1901 | altimeter wind speed | m/s | all | -1 30 | 1-5 |
| wind_speed_rad | 1902 | radiometer wind speed | m/s | j1 j2 pn tx | 0 30 | |
| wind_speed_ecmwf_u | 1903 | ECMWF model wind speed (U) | m/s | e2 j1 j2 n1 sa | | 6 |
| wind_speed_ecmwf_v | 1904 | ECMWF model wind speed (V) | m/s | e2 j1 j2 n1 sa | | 6 |
| wind_speed_ecmwf | | ECMWF model wind speed | m/s | e2 j1 j2 n1 sa | | 6 |
| wind_speed_gfs_u | 1903 | NOAA/GFS model wind speed (U) | m/s | sa | | 7 |
| wind_speed_gfs_v | 1904 | NOAA/GFS model wind speed (V) | m/s | sa | | 7 |
| wind_speed_gfs | | NOAA/GFS model wind speed | m/s | sa | | 7 |
| wind_speed | 19 | *alias of* wind_speed_alt | | all | | |

    0.63 dB was subtracted from the backscatter coefficient before feeding it into the MCW algorithm.

2. The CryoSat and Envisat wind speed is based on the ECMWF 1-parameter algorithm tailored to Envisat [*Abdalla*, 2007].

3. The Ka-band altimeter of SARAL required a new 1-parameter algorithm, similar to Envisat's, again matching ECWMF wind fields [*Lillibridge et al.*, 2014].

4. The TOPEX/Poseidon wind speed is based on the 2-parameter model by *Gourrion et al.* [2002].

5. For Jason-1 and Jason-2, a variant of the 2-parameter model by *Gourrion et al.* [2002] tailored to Jason-1 is used to derive wind speed [*Collard*, 2005].

6. The U (towards east) and V (towards north) components of the wind speed according to ECMWF model data. The absolute magnitude can be computed on-the-fly.

7. The U (towards east) and V (towards north) components of the wind speed according to $0.5° \times 0.5° \times 6h$ model grids from NOAA's Global Forecast System. The absolute magnitude can be computed on-the-fly. *The inclusion of these fields is experimental, and may be removed in the future.*

## 4.4   Other wave model data

    For calibration and validation purposes, and to support further studies that include wind and wave processes (like swell and their effect on sea state bias) a number of variables from the WaveWatch 3 models. These variables are currently only available during the year 2000 to 2012 (inclusive). The original resolution of the model grids is 1° by 1° by 6 hours.

    In addition, SWH from the WaveWatch 3 model is made available as swh_ww3 (see Section 4.1).

| Variable | field | name | units | sat | range | note |
|---|---|---|---|---|---|---|
| wave_m0 | 4001 | WaveWatch3 wave height variance | $m^2$ | all | | |
| wave_m1 | 4002 | WaveWatch3 first moment of wave height | $m^2/s$ | all | | |
| wave_m2 | 4003 | WaveWatch3 wave velocity variance | $m^2/s^2$ | all | | |
| wave_m4 | 4004 | WaveWatch3 wave slope variance | $rad^2$ | all | | |
| wave_shs | 4005 | WaveWatch3 wave swell | m | all | | |

# Chapter 5

# Additional variables

## 5.1 Engineering and geophysical flags

The engineering and geophysical flags are historically a number of bits in a 2-byte integer number that describe either instrument settings, type of surface overflow, or warnings about the quality of the data. In RADS4 there are a number of *aliases* to help pick out single bits from this word. The editing, however, is currently still determined by the limits set on the flag word, where the lower limits indicates which bits of the flag word *should not* be set, and the upper limits indicates the bits of the flag word that *should* be set. In other words, a record will be rejected if either:

- flags AND flags_low is not equal to 0.
- flags AND flags_high is not equal to flags_high.

where flags_low and flags_high are the lower and higher limit of flags specified, and AND is the logical bitwise AND operator.

In future version of the data base the flag word flags will be phased out and only the more elementary flag variables that are now defined as aliases will be available.

| Variable | field | name | units | sat | range | note |
|----------|-------|------|-------|-----|-------|------|
| flags | 2601 | flag word | | c2 | 48 0 | |
| | | | | e1 e2 j1 j2 | 65512 0 | |
| | | | | g1 | 65384 0 | |
| | | | | gs | 51176 0 | |
| | | | | n1 | 36712 0 | |
| | | | | pn | 448 0 | |
| | | | | tx | 49640 0 | |
| | 26 | *alias of* flags | | | | |

The individual bits of the flag word flags are described in the following table. Note that the limits on these alias are not actually set at this time, but they are a transposition of the editing ranges for each individual altimeter as indicated in the table above. In general, 0 means no or OK, 1 means yes or bad.

| Variable | field | name | values | sat |
|---|---|---|---|---|
| flag_alt_oper_mode | 2516 | bit 0: hardware/software status | 0 = nominal, 1 = bad | pn tx |
| | 2516 | bit 0: altimeter status | 0 = Side A, 1 = Side B | j1 j2 n1 |
| | 2516 | bit 0: altimeter status | 0 = LRM, 1 = PLRM | c2 |
| qual_sptr | 2516 | bit 0: SPTR availability | | e1 |
| qual_attitude | 2501 | bit 1: quality of attitude | 0 = ok, 1 = bad | e2 j1 j2 n1 tx sa |
| | | bit 1: quality of attitude | 0 = ok, 1 = suspect | g1 gs pn |
| qual_dh | 2502 | bit 2: dH status | 1 = suspect | gs |
| flag_rad_oper_mode | 2502 | bit 2: TMP 21 GHz Channel status | 0 = A, 1 = B | pn tx |
| qual_iono_alt | 2503 | bit 3: quality of dual-frequency iono corr | 0 = ok, 1 = bad | j1 j2 n1 tx |
| surface_type | 2504 | surface type | 0 = open ocean, 2 = enclosed sea or lake, 3 = land, 4 = continental ice | all |
| surface_type_rad | 2506 | bit 6: radiometer land flag | 0 = water, 1 = land | all but c2 gs |
| qual_alt_rain_ice | 2507 | bit 7: altimeter rain/ice flag | 0 = no rain/ice, 1 = rain/ice | all but c2 gs |
| qual_rad_rain_ice | 2508 | bit 8: radiometer rain/ice flag | 0 = no rain/ice, 1 = rain/ice | e1 e2 j1 j2 n1 pn tx |
| qual_rad_tb | 2509 | bit 9/10: radiometer quality flag | 0 = ok, 1 = interp. near land, 2 = extrap., 3 = interp. failed | pn tx |
| | | | 0 = ok, 1 = bad tb238, 2 = bad tb365, 3 = both bad | e1 e2 n1 |
| | | | 0 = ok, 1 = bad tb220, 2 = bad tb370, 3 = both bad | g1 |
| | | | 0 = ok, 1 = bad tb187/tb238, 2 = bad tb340, 3 = both bad | j1 j2 |
| | | | 0 = ok, 1 = bad tb238, 2 = bad tb370, 3 = both bad | sa |
| qual_range | 2511 | bit 11: quality of range | 0 = ok, 1 = some 10Hz invalid | gs |
| | | | 0 = ok, 1 = suspect | other |
| qual_swh | 2512 | bit 12: quality of SSB | 0 = ok, 1 = suspect | gs |
| | 2512 | bit 12: quality of SWH | 0 = ok, 1 = suspect | other |
| flag_alt_track_mode | 2514 | bit 14: altimeter tracking mode | 0 = nominal, 1 = preset | e1 e2 |
| | | | 0 = nominal, 1 = coarse or acquisition | gs tx |
| | | | 0 = nominal, 1 = C-band coarse | j1 |
| | | | 0 = nominal, 1 = acquisition | pn |
| qual_orbit | 2515 | bit 15: orbital quality flag | 0 = ok, 1 = suspect | all |
| flag_land | 2504 | bit 4: water/land flag | 0 = water, 1 = land | all |
| flag_ocean | 2505 | bit 5: ocean/non-ocean flag | 0 = ocean, 1 = non-ocean | all |

## 5.2   Radiometer brightness temperatures

## 5.3   Bathymetry and topography

SRTM30PLUS topography/bathymetry topo_srtm30plus

V10 of SRTM30_PLUS was released in May 2014. Ocean data are based on the Smith and Sandwell global 1-minute grid between latitudes +/- 81 degrees. Higher resolution grids have been added from the LDEO Ridge Multibeam Synthesis Project, the JAMSTEC Data Site for Research Cruises, and the NGDC Coastal Relief Model. Arctic bathymetry is from the International Bathymetric Chart of the Oceans (IBCAO) [Jakobsson et al., 2003].

Land data are based on the 1-km averages of topography derived from the USGS SRTM30 grided DEM data product created with data from the NASA Shuttle Radar Topography Mission. GTOPO30 data are used for high latitudes where SRTM data are not available.

For more information about SRTM30_PLUS, please see: http://topex.ucsd.edu/ WWW_html/srtm30_plus.html

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