Global altimeter SWH data set - June 2014

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INTRODUCTION

Altimeter SWH measurements are presently available almost continuously over a 23-year time period from the nine altimeter missions ERS-1&2, TOPEX-Poseidon, GEOSAT Follow-ON (GFO), Jason-1, Jason-2, ENVISAT, Cryosat and SARAL . Each altimeter data product has specific characteristics (format, flags), and in order to facilitate the access to SWH altimeter measurements and the use of this long time series, data were extracted from the original products, screened according to quality flag values, corrected and gathered into homogeneous daily data files.

RECENT CHANGES

In the present version 11:

- the data set has been updated (cf Table in section DATA)
- SARAL AltiKa GDR data have been added to the data set
- SWH rms threshold tests were updated for ENVISAT, Jason-2 and Cryosat-2
- a new routine for eliminating SWH outliers was implemented for the whole data set of Jason-1&2, ENVISAT, Cryosat-2, and SARAL

In version 10:

- Cryosat-2 IGDR global new data set downloaded from the NOAA ftp site (January 25, 2013)
- a SWH correction was estimated for Cryosat-2 IGDR
- the new version D of Jason-2 is used

In version 9.0:

- Cryosat-2 IGDR data have been added
- an error has been corrected concerning the ENVISAT SWH correction for cycles 88 to 92 (22-03-2010 to 13-09-2010), and for cycle 107: in version 8.0 an erroneous correction was applied on the SWH data for these cycles (the previous correction for ENVISAT GDR V1 was indeed applied on these data, which are in version V2.1)

In version 8.0:

- the C-band backscatter coefficient, and 1 Hz standard deviation value, have been added to the data set for Jason-1 and Jason-2.
- the S-band backscatter coefficient, and 1 Hz standard deviation value, have been added to the data set for ENVISAT. This parameter is available from cycle 10 to cycle 65 pass number 145 (17-01-2008), after this time a power drop reduced the quality of the S-band parameters, which are no longer useful.

- new SWH calibrations were estimated, and applied, for ERS-2 (end of the mission in july 2011), Jason-1 and Jason-2 – see calibration figures in Annexe I.
- the ENVISAT GDR have been reprocessed in version V2.1 (ESA 2010), from cycle number 10 to present. In the new version, SWH has a different behaviour than in the previous version. Buoy comparisons show a negative non linear bias at low sea state (SWH<3 m). New corrections were estimated, and applied in the present data base – see calibration figures in Annexe I, and Queffeulou et al 2011.
- a new data screening procedure was introduced for Jason-1, Jason-2 and ENVISAT (see DATA SCREENING section)

DATA

The altimeter data are the Geophysical Data Records (GDR), or equivalent, distributed by the space agencies, as summarized in Table 1.

Satellite	Product	Cycles	Time Period	Comments
ERS1	OPR	not defined	01-08-1991 to 30-03-1992	Phases A&B 3-days
		83 to 101	14-04-1992 to 20-12-1993	Phase C 35-days
		not defined	24-12-1993 to 10-04-1994	Phase D 3-days
		not defined	10-04-1994 to 21-03-1995	Phases E&F 168-days
		144 to 156	24-03-1995 to 02-06-1996	Phase G 35-days
ERS2	OPR	1 to 169	15-05-1995 to 04-07-2011	
ENVISAT	GDR v2.1	6 to 113	14-05-2002 to 08-04-2012	
TOPEX Poseidon	M-GDR	1 to 481	25-09-1992 to 08-10-2005	
Jason-1	GDR	1 to 537	15-01-2002 to 21-06-2013	
Jason-2	GDR	0 to 212	04-07-2008 to 14-04-2014	Mission going on
GEOSAT FO	GDR	37 to 222	07-01-2000 to 07-09-2008	
Cryosat-2	IGDR	4 to 53	14-07-2010 to 20-05-2014	Mission going on
SARAL	GDR	1 to 12	14-03-2013 to 08-05-2014	Mission going on

ERS-1 data are the ESA Radar altimeter Ocean Product (OPR) described in Cersat (1996), for phase C (April 14, 1992 - December 20, 1993) and phase G (March 24, 1995 – June 6, 1996), characterised by a 35-day repeat cycle orbit.
The ERS-1 phases A - B (August 1, 1991 to March 30, 1992), and D (December 23, 1993 to April 10, 1994), with the 3-day repeat cycle, and E - F (April 10, 1994 to March 21, 1995), with the 168-day repeat cycle, are also available in the OPR processing (same as for ERS-2), with still some data gaps, which will be filled in a near future.

ERS-2 data are the OPR (Cersat 1996), for the whole mission, from May 15, 1995 to July 7, 2011. After June 22, 2003 the ERS-2 coverage has been seriously reduced due to the failure of the on-board tape recorder.

TOPEX Poseidon are the Merged Geophysical Data Record (M-GDR) described in AVISO (1996), over the whole mission, from September 25, 1992 to October 9, 2005.

Jason-1 are the GDR (Picot et al. 2003) from cycle 1 (January 15, 2002) to cycle 537 (June 21, 2013). The Jason GDR processing is version *c* for the whole data set. A correction for SWH in version *c* has been estimated through comparisons with buoy data. Note that after cycle 374 (03-03-2012) Jason-1 was put on the geodetic orbit with a 11-day sub-cycle. The cycle numbering was restarted at 500 (07-05-2012).

Jason-2 are the GDR version "D" (OSTM/Jason-2 Product Handbook, 2008) from cycle 0 (July 4, 2008) to cycle 212 (April 4, 2014). Comparison between the version "D" and the previous version "T" (Queffeulou 2012-b) shows no significant change for SWH, and improvement of sigma0 quality (mle3 estimate) but with a bias about 0.2 dB, taken into account in the calibrated values. The SWH correction estimated for version "T", through comparisons with buoy data, is also applied for version "D".

GEOSAT Follow On are the GDR (NOO 2002), distributed by John Lillibridge (NOAA/NESDIS/ORA), from cycle 37 (January 7, 2000) to cycle 222 (September 9, 2008).

ENVISAT are the ESA RA-2 GDR V2.1 product available from cycle 6 (May 14, 2002) to cycle 110 (January 20, 2012) and described in ESA 2002 and 2010.
During cycle 94 the ENVISAT satellite orbit was lowered by ~17.4 km to ensure the continuation of the mission for an additional 3 years (manoeuvres occurred between 22nd October 2010 and 2nd November 2010). Since then, the cycle length is 30 days (instead of 35 previously) and the number of orbits per cycle is 431 (instead of 501). More details on the orbit change can be found on the web site:
http://earth.esa.int/object/index.cfm?fobjectid=7267.

Cryosat-2 data are the IGDR produced and provided by the *NOAA Laboratory for Satellite Altimetry (* http://ibis.grdl.noaa.gov/SAT/NearRealTime/). Data are available at ftp://ftp.star.nesdis.noaa.gov/pub/sod/lsa/cs2igdr/. This SWH data set was validated using comparisons with collocated altimeter measurements from Jason-1, Jason-2 and ENVISAT RA-2 (Queffeulou 2013-a). The whole data set was updated for cycle 4 (July 14, 2010) to cycle 53 (May 20, 2014).

SARAL AltiKa data are the GDR-T, available at ftp://avisoftp.cnes.fr/AVISO/pub/saral/ , and described in SARAL/AltiKa Products handbook (2013). Cycles 1 (March 14, 2013) to 12 (May 8, 2014) were processed. SARAL/AltiKa was launched in February 25, 2013. IGDR data were rapidly available after launch, and enable preliminary validation, showing the very good accuracy of SWH measurements. SARAL/AltiKa is operated at Ka-band, a higher frequency than Ku-band, and is more sensitive to rain and cloud attenuation than other altimeters. Erroneous SWH measurements in rain attenuation situations were eliminated using a (swh_rms , swh) threshold relationship developed during the preliminary validation phase (Queffeulou 2013-b), and updated over GDR-T cycle number 4 to 8 (to be published).

DATA SCREENING

Altimeter SWH measurements are extracted from the various products and selected according to the specific quality flags described in the dedicated user guides.
The following flags and conditions are tested, according to the altimeter.

For ERS: swh zero and default values; number of averaged 20 Hz measurements larger than 16; measurement confidence data (mcd) flag bits 0, 7 and 8.

For TOPEX: swh zero and default values; swh_Pts_Avg equal to 8; AGC_Pts_Avg equal to 16; Geo_Bad_1 bits 1 and 3; Geo_Bad_2 bit 0.

For Poseidon: above TOPEX flags and Alt_Bad_1 bits 2-5; Alt_Bad_2 bits 2-5.

For GFO: quality word I, bits 2, 3, 7, 10,11; noaa_flag<3; nval_swh=10; swh_std/swh<0.2

For Jason: qual_1Hz_alt_data flag; swh_numval_ku larger than 18; surface_type 0 or 1; swh_rms_ku>0; swh_ku>0.

For ENVISAT: quality_flag; ku_sig_wv_ht and std zero and default values; meas_conf_data_flags bit 16; alt_surface_type 0 or 1; num_18Hz_ku_ocean_swh larger than 18; ku_ocean_retracking_quality flag: ku_ocean_backscatter_coef zero and default values; abs(off_nad_ang_wvform)<1000;

Specific tests are also performed for Jason-1 , Jason-2, ENVISAT and Cryosat, based on the ratio of SWH standard deviation to SWH mean values, established during the validation (Queffeulou 2004, 2009, 2012-a).

Above quality flags and tests are not sufficient to discard all the erroneous SWH data. Spurious measurements are still observed: some are located in the vicinity of the coast where some land can be within the altimeter footprint, or in areas of high scattering resulting in so-called sigma0 blooms (e. g. Thibaut et al. 2007). Some other individual spurious measurements (corresponding mainly to high values of SWH) are not explained. Consequently the data are filtered to eliminate these measurements. The screening is based on the analysis of the differences between successive along track SWH measurements. For each pass (half orbit) mean value and standard deviation of differences of SWH measurements from pairs of consecutive points are estimated. At 1 second along track sample, two consecutive points are separated by about 6 or 7 km. A range is then defined by the mean value of the differences plus or minus 3 times the standard deviation (4 times for GFO). Individual data for which the differences with the neighbouring measurements are outside this range are then discarded. Specific thresholds are also used at the beginning or at the end of continuous along track series i.e. corresponding to over land passes or to flagged data series. The whole data set from ERS-1, ERS-2, TOPEX Poseidon and GFO were processed in this way. The number of discarded data is low. Only a few measurements per pass, when it happens. All of them appear to be erroneous measurements.

For Jason-1, Jason-2 and ENVISAT a new data screening was applied, using running along track windows, 100 km wide. For each measurement the along track data within 50 km each side are selected. This represents a maximun number of 15 (Envisat) to 19 (Jason) selected data. Then over this segment the 2 extreme SWH data are discarded, and the mean value (m) and standard deviation (s) are estimated over the residual data set. If the SWH value is outside the interval defined by $m \pm 4s$, then this data is considered as erroneous and is discarded. Up to 3 iterative passes were empirically adjusted for the processing.

For Cryosat-2 the same data screening as above was applied. Specific flags and test were also used, from comparisons with Jason-1, Jason-2 and ENVISAT (Queffeulou 2012-a).

ICE & LAND MASK

Individual altimeter data contaminated by sea ice or land were further eliminated using ice and land masks.

The ice mask is build using the Polar Sea Ice concentration product freely available at CERSAT data centre. Ftp address to get this product is
ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-concentration

The earth mask is build using the Land-Sea Mask available at USGS from the Global Land 1-KM AVHRR Project (http://edcsns17.cr.usgs.gov/1KM).

SWH DATA CORRECTION

Comparisons with buoy data (Queffeulou 2003,2004) show that the altimeter SWH estimate is in general in agreement with the in-situ data, with standard deviations of differences of the order of 0.30 m, but tends to slightly overestimate low SWH and to underestimate high SWH. Correction to SWH were then established. These corrections, in general linear (with the exception of ENVISAT at low SWH), correspond to a few percent of SWH.
A correction was also estimated for the TOPEX SWH drift between 1996 and 1999. For GFO the correction was established for the global oceans through TOPEX and ERS-2 comparisons. For ERS-2, ENVISAT, Jason-1 and Jason-2, SWH corrections were updated regularly (last update in Queffeulou et al. 2011) using buoy comparison method of Queffeulou (2004).

Updated validation results are given in Annexe I. Details of corrections are given hereunder.

ERS-1
swh_cor = 1.1259 x swh + 0.1854 (Queffeulou and Croizé-Fillon 2009)

ERS-2
swh_cor = 1.0541 x swh + 0.0391

TOPEX (Queffeulou 2004)
Side-A(up to cycle 235):
swh_cor = 1.0539 x swh - 0.0766 + dh
with:
dh = 0 for cycle < 98
dh = poly3(98) - poly3(cycle) for 98 <= cycle <= 235
with a0 = 0.0864 ; a1= -6.0426×10^{-4} ; a2 = -7.7894×10^{-6} ; a3 = 6.9624×10^{-8}

Side-B (after cycle 235):
swh_cor = 1.0237 x swh - 0.0476

GEOSAT FO
swh_cor = 1.0625 x swh + 0.0754 ; (Queffeulou 2004)

POSEIDON
swh_cor = 0.9914 x swh – 0.0103 ; (Queffeulou 2004)

JASON-1
swh_cor = 1.0429 x swh + 0.0266 ; version *a*

swh_cor = 1.0250 x swh + 0.0588 ; version *b*

swh_cor = 1.0211 x swh + 0.0139 ; version *c* (used here)

JASON-2
swh_cor = 1.0149 x swh + 0.0277; version *'T'* and *'D'*

ENVISAT

swh_cor = 1.0095 x swh + 0.0192 ; for swh > 3.41 m
swh_cor = 0.4358 + 0.5693 x swh + 0.1650 x swh^2 – 0.0210 x swh^3 ; for swh ≤ 3.41 m

Cryosat-2

A SWH correction was estimated from comparisons with ENVISAT, Jason-1 and Jason-2 (Queffeulou 2013):
swh_cor= 0.4889+ 0.4712 x swh + 0.1546 x swh^2 - 0.0145 x swh^3 ; for swh ≤ 2.45 m
swh_cor= - 0.1057 + 1.0058 x swh ; for swh>2.45

SARAL

No correction needed (Queffeulou 2013-b): swh_cor = swh

SIGMA0 and WIND SPEED CORRECTIONS

In a first step the GDR Ku-band sigma0 measurements were calibrated: - firstly taking into account informations published by the agencies or by people involved in the monitoring of these measurements -secondly by comparison with the ENVISAT sigma0, which seems to be stable with time: for each altimeter a bias was estimated relative to ENVISAT, comparing mean values of sigma0, over the global oceans, between 66.15° S and 66.15° N, and over the common time period with ENVISAT, for TOPEX, ERS-2, Jason-1 & 2 and GFO. ERS-1 was calibrated indirectly by a first comparison with ERS-2, itself calibrated relatively to ENVISAT.

In a second step, a correction to the calibrated value of sigma0 was estimated to get a best fit when comparing wind buoy data with altimeter wind speed inferred from a unique algorithm. Presently the Abdalla (2007) algorithm is used. In the future a better algorithm will have to be defined or selected.

Details of the calibrations and corrections to sigma0 are given in Annexe II.

Jason-2 version *'D'*: for the calibrated value, a bias of 0.2024 dB was added to the Jason-2 Ku-band sigma0 in version *'D'* (Queffeulou 2012-b)

Cryosat-2: at present, Cryosat-2 sigma0 and wind speed are not calibrated. The use of these parameters is not recommended, because of the observed drift with time (Queffeulou 2013-a).

SARAL: the AltiKa altimeter is operated at Ka-band (35 GHz), a higher frequency than the usual Ku-band (14 GHz) one. Consequently the dependence of the backscatter coefficient on wind speed and wave height is different from what is observed at Ku-band. A new a wind speed algorithm was developed (Lillibridge et al. 2014) and applied to the SARAL Ka band sigma0 measurements. Ka-band is much more sensitive to vapour and liquid water content (rain and clouds) than Ku-band. Accurate correction for that is needed before wind computation. Validation of SARAL wind speed is presently not achieved, and further studies are going on (Abdalla 2014). At present no corrections are proposed.

DATA FILE NAME, STRUCTURE, FORMAT…

One data file per day, in netcdf format.

Parameters:
1: time in day since 1 january 1900 (ex: 32872.5 for January 1, 1990, 12h; or 33706.9921875 for April 14,1992, 23h48mn45s)
2: latitude
3: longitude
4: 10 m wind speed (non calibrated)
5: 10 m wind speed corrected
6: Ku-band backscatter coefficient
7: Ku-band backscatter coefficient calibrated
8: Ku-band backscatter coefficient standard deviation
9: C- or S-band backscatter coefficient
10: C- or S-band backscatter coefficient standard deviation
11: Ku-band Significant Wave Height (1 second average)
12: Ku-band Significant Wave Height standard deviation or rms (does not exist for Poseidon)
13: Ku-band Significant Wave Height corrected
14: satellite altimeter index:
  1: ERS-1
  2: ERS-2
  3 :ENVISAT
  4 :TOPEX
  5 :Poseidon
  6 :Jason-1
  7 :GEOSAT Follow-On
  8: Jason-2
  9: Cryosat-2
  10: SARAL/AltiKa
15: cycle number
16: pass number (relative orbit number within a cycle): half revolution for TOPEX, Poseidon, Jason and GFO ; revolution for ERS and ENVISAT
17: absolute revolution number

Notes:

-The absolute revolution number parameter is not defined (NaN) in the GFO and Cryosat-2 products.

REFERENCES

Abdalla, S., 2007, Ku-band radar altimeter surface wind speed algorithm. *Proc. ENVISAT Symp. 2007*, 23-27 April, Montreux, Switzerland, ESA SP-636.

Abdalla, S., 2014, Calibration of SARAL/AltiKa wind speed, Geoscience and Remote Sensing Letters, (11), 1121-1123.

AVISO/Altimetry, 1996 : AVISO User Handbook for Merged TOPEX/POSEIDON Products, AVI-NT-02-101, Edition 3.0. CLS-CNES, 18 av. Edouard Belin, 31401 Toulouse Cedex 4, France.

CERSAT,1996 : Altimeter & Microwave Radiometer ERS Products User Manual, C2-MUT-A-01-IF, version 2.2, CERSAT, IFREMER, BP 70, 29280 Plouzané, France.

ESA, ENVISAT RA-2/MWR Product Handbook, PO-TN-ESR-RA-0050, version 1.2, J. Benveniste Editor, ESA, March 22, 2002.

ESA, 2010
ENVISAT-1 Products Specifications, Volume 14: RA-2 Products Specifications
http://earth.esa.int/pub/ESA_DOC/ENVISAT/RA2/ENVI22D_Vol14_Ra2mwr_4C.pdf

ENVISAT RA-2/MWR Level 2 User Manual
http://earth.esa.int/pub/ESA_DOC/ENVISAT/RA2-MWR/PH_light_1rev3_ESA.pdf

ENVISAT Altimetry Data Set Version 2.0 - Level 1B and Level 2 processing upgrades
http://earth.esa.int/pub/ESA_DOC/ENVISAT/RA2/Envisat_Altimetry_Data_Set_Lev1_&_Lev2_processing_upgrades1_1.pdf

Lillibridge J., Scharroo R., Abdalla S. and D. Vandemark, 2014, One- and Two-Dimensional ,Wind Speed Models for Ka-Band Altimetry, Journal of Atmospheric and Oceanic Technology ,Volume 31, Issue 3 (March 2014) pp. 630-638.

Naval Oceanographic Office, NOAA Laboratory for Satellite Altimetry, GEOSAT Follow-On GDR User's Handbook, ,NOAA/NESDIS/ORA :E/RA31, 1315 East-West Highway #3620, Silver Spring, MD 20910-328, USA, 2002.

OSTM/Jason-2 Product Handbook, *SALP-MU-M-OP-15815-CN*, Ed 1.2, November 2008
http://www.aviso.oceanobs.com/no_cache/fr/donnees/boite-a-outils/manuels-d-utilisation-des-donnees-aviso/

Picot N., K. Case, S. Desai and P. Vincent, 2003 : AVISO and PODAAC User Handbook. IGDR and GDR Jason Products, SMM-MU-M5-OP-13184-CN (AVISO), JPL D-21352 (PODAAC).

Queffeulou P., 2003, Long term quality status of wave height and wind speed measurements from satellite altimeters. Proceedings of the ISOPE conference, Honolulu, Hawaii, USA, May 25-30.

Queffeulou P., 2004, Long term validation of wave height measurements from altimeters, Marine Geodesy, 27, 495-510.

Queffeulou P., 2006, Altimeter wave height validation – an update, OSTST meeting, Venice, Italy, March 16-18, 2006 (http://www.aviso.oceanobs.com/en/courses/ostst/ostst-2006/index.html).

Queffeulou, P., 2009, Altimeter wave height measurements - validation of long time series. Poster, OSTST meeting, Seattle, June 2009 (http://www.aviso.oceanobs.com/en/courses/ostst/ostst-2009-seattle/posters/).

Queffeulou P. and D. Croizé-Fillon, 2009, La mesure satellite de hauteur de vague par altimètre. État des lieux, application à la climatologie et à la modélisation des états de mer. AMA 2009, Les ateliers de modélisation de l'atmosphère, Toulouse, 27-29 janvier 2009. (http://www.cnrm.meteo.fr/ama2009/ama_consultation_resumes_longs.php).

Queffeulou P., F. Ardhuin and J.-M. Lefèvre, 2011, Wave height measurements from altimeters: validation status and applications, OSTST meeting, San Diego, 19-21 october, 2011. Poster available at http://www.aviso.oceanobs.com/en/courses/sci-teams/ostst-2011/ostst-2011-posters/index.html

Queffeulou P., 2012-a, Cryosat-2 IGDR SWH assessment – January 17, 2012. Report available at ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/Cryosat2_igdr_swh_assessment.pdf

Queffeulou, P., 2012-b, Preliminary assessment of Jason-2 GDR version D for SWH and sigma0 data, September 2012. Report available at ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/J2_versions_D_T.pdf

Queffeulou P., 2013-a, Cryosat-2 IGDR SWH assessment update – May, 2013. Report available at ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/Cryosat2_igdr_swh_assessment_update.pdf

Queffeulou P., 2013-b, Merged altimeter wave height data base. An update. Proceedings of ESA Living Planet Symposium, 9-13 September 2013, Edinburgh, UK, ESA SP-722 December 2013, ESA Communications, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands. Available at ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/publications/ESA_Living_Planet_Symposium_2013.pdf

SARAL/AltiKa Products handbook, CNES : SALP-MU-M-OP-15984-CN , Issue 2, rev 3 , July 19, 2013 . ftp://avisoftp.cnes.fr/AVISO/pub/saral/documentation/SARAL_Altika_products_handbook_v2.3_July2013.pdf .

Thibaut P., F. Ferreira and P. Femenias, 2007, Sigma0 blooms in the ENVISAT radar altimeter data, Proc. ENVISAT Symposium 2007, Montreux, Switzerland 23-27 April 2007, ESA SP-636, July 2007.