The Science Contributions of DORIS and Synergy with other Space Geodesy Techniques

Frank G. Lemoine (1), Guilhem Moreaux (2), Jérôme Saunier (3),
Pascale Ferrage (4), Nikita P. Zelensky (5), Alexandre Couhert (4), Alexandre Belli (6)

(1) NASA Goddard Space Flight Center Greenbelt, Maryland, U.S.A.
(2) Collect Localisation Satellites, Ramonville Saint-Agne, FRANCE
(3) Institut Géographique National, St-Mandé, FRANCE
(4) Centre National D'Etudes Spatiales, Toullouse, FRANCE
(5) ESSIC/University of Maryland, College Park, Maryland, U.S.A.
(6) NASA Postdoctoral Program @ NASA GSFC, Greenbelt, Maryland, U.S.A.

International Workshop for the
Implementation of the Global Geodetic Reference Frame (GGRF) in Latin America
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Global Geodetic Observing System

Outline

1. DORIS as a service for orbit determination.

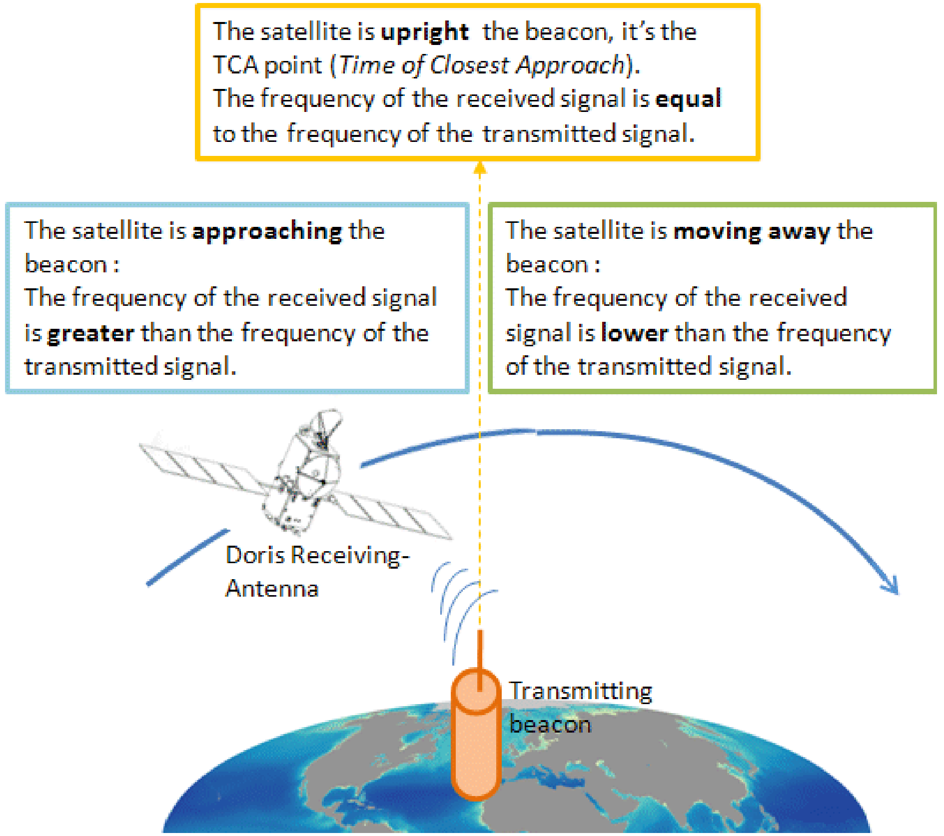
   (A) Rationale.
   (B) History and current performance.
   (C) DIODE near-real time service.

2. DORIS contribution to measurement of Sea surface height and mean sea level.

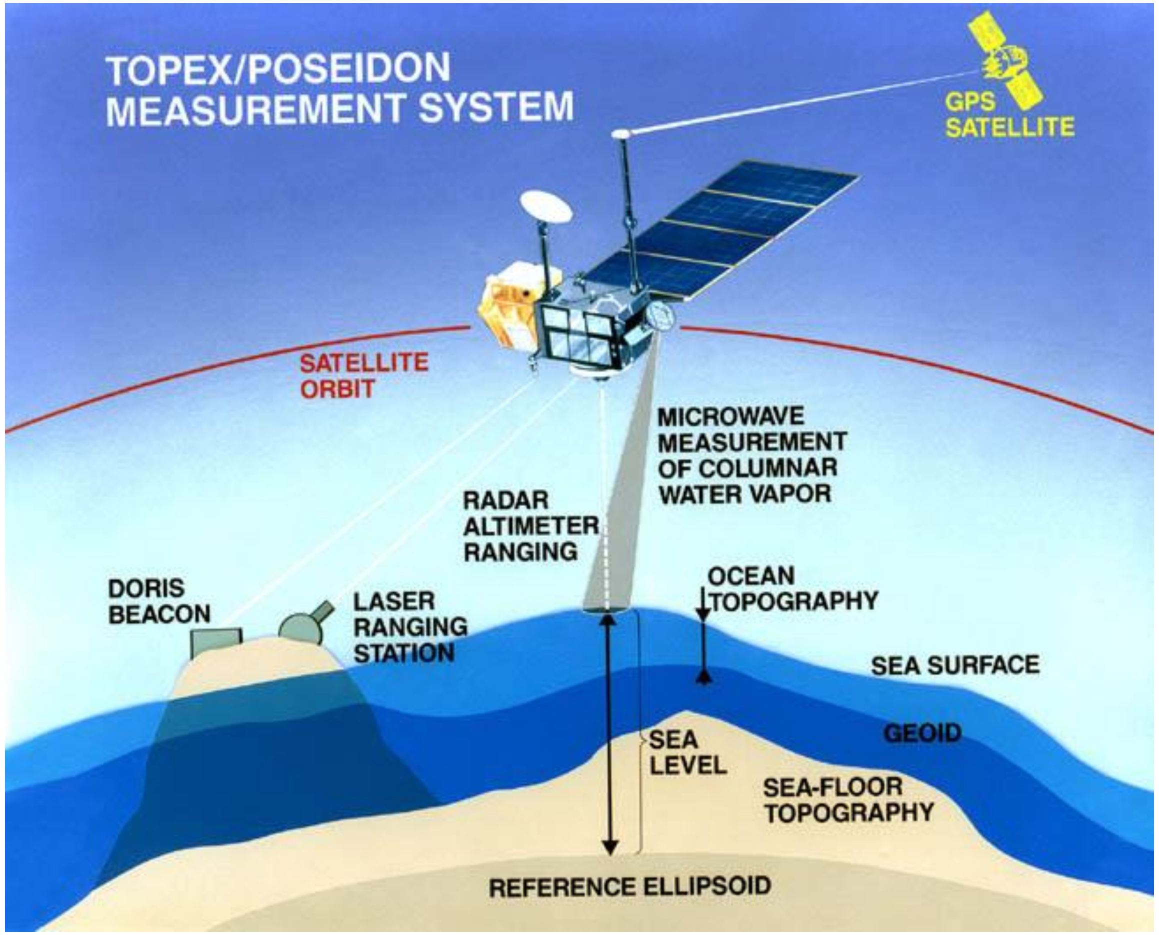
3. DORIS as a contributor to the ITRF.

4. Synergy with other techniques: (SLR, time transfer, Jason-2 T2L2 experiment).

5. Working Groups & Future products.



Rationale for precise orbit determination (POD) (1)



1. The accuracy of the orbit should ideally be equal to or better than the altimeter measurement precision.

2. The orbit has to be stable and accurate through time in order to be able to map out time-varying change in the ocean height on many time scales (weeks to years).

3. We need multiple tracking systems on one spacecraft in order to be able to intercompare the results and validate the orbit quality.

4. The measurement of Sea Surface Height (SSH) or the change in Mean Sea Level has such societal significance, that we must be able to validate the orbit accuracy with different space geodetic measurements (SLR, DORIS, GNSS).

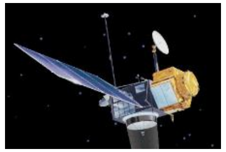
Rationale for precise orbit determination (POD) (2)

Examples of altimeter measurement precision & orbit accuracy

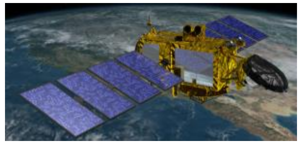
GEOS-3

Seasat

TOPEX

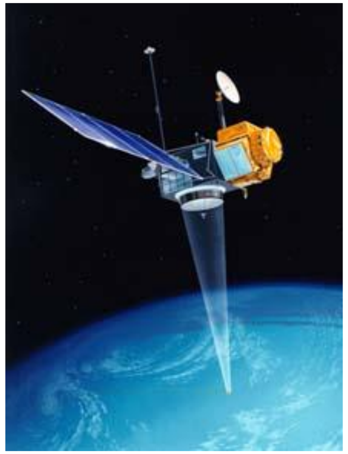


Jason-3



Satellite	Dates	Altimeter Precision (cm)	Orbit Accuracy (Initial) (cm)	Orbit Accuracy (After reprocessing) (cm)	Tracking Data
GEOS-3	4/1975 - 12/1978	25	500	--	SLR, SST
Seasat	7/1978 – 10/1978	5	100	~10-20	SLR, Doppler
Geosat	3/1985 – 12/1989	4	30-50	~2-5	Tranet Doppler
TOPEX	10/1992 – 11/2004	2	2-3	~1.5	SLR, DORIS, GNSS (1993-94 only)
Jason-1	12/2001 – 06/2013	~1	~1 - 1.5	~1	SLR, DORIS, GNSS
Jason-2 & 3	7/2008 & 1/2016 to present	~1	~1 – 1.2	6—8 mm	SLR, DORIS, GNSS

Rationale for precise orbit determination (POD) (3)



TOPEX/Poseidon
1992-2006

Jason-3
2016 –

Example Ground Track Coverage for TOPEX (& Jason-1, Jason-2, Jason-3)

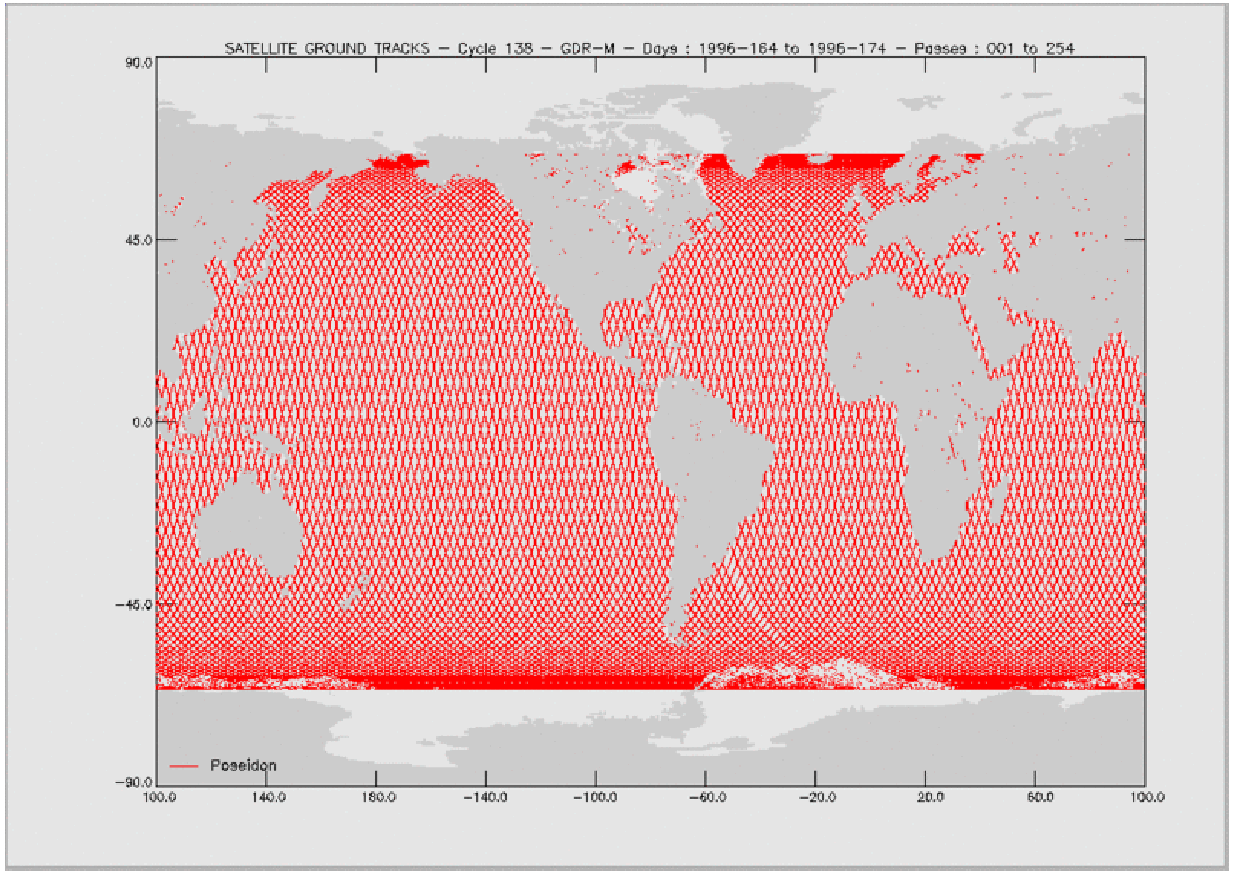


Image from AVISO (Toulouse, France)

An altimeter maps the ocean from a set of reference ground tracks and behaves like an "orbiting tide gauge".

Here the ground track repeats every 9.9156 days.

Altitude 1336 km. Inclin. = 66.039°;
Ground track repeat: 9.9156 days.
Cross-track separation (equator): 315 km

How has DORIS POD Evolved to better serve the science users ? (1)

Improvement in stability & quality of monumentation AND better operating environment.
(*Fagard, J. Geodesy, 2006; Saunier, Adv. Space Res. 2016*)

Early Rothera (Antarctica), ROTA.

Early Santiago (Chile), SANB.

Current DORIS Monument types (*Saunier, Adv. Space Res., 2016*)

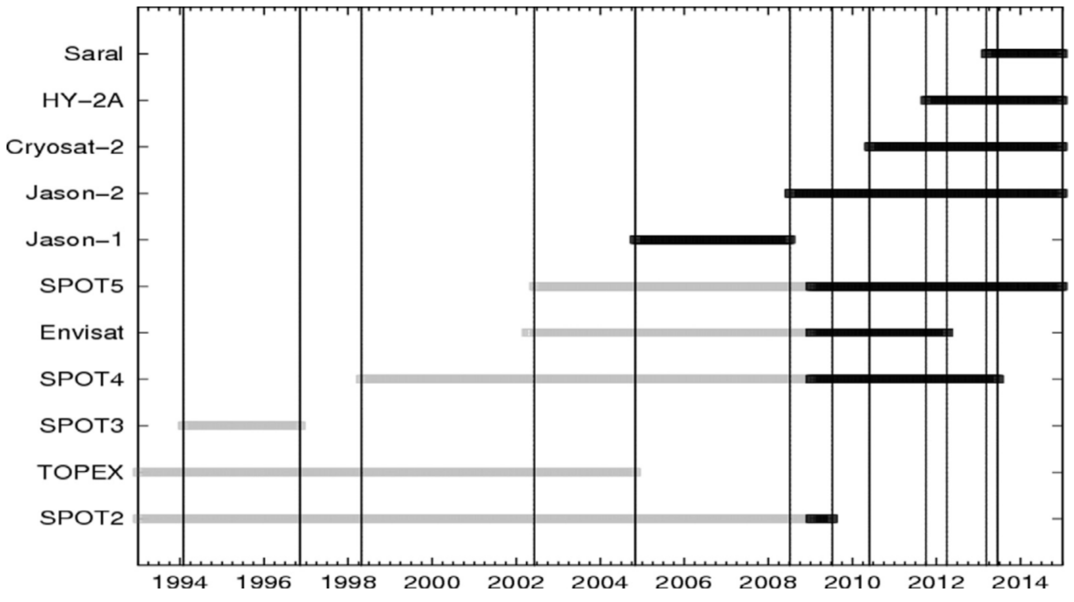
Type I.
(CADB, Cacheoira).
Metal tower on load-bearing building pillar.

Type II.
(ARFB, Arequipa)
Concrete reinforced pillar extending up to 1.5 m depth.

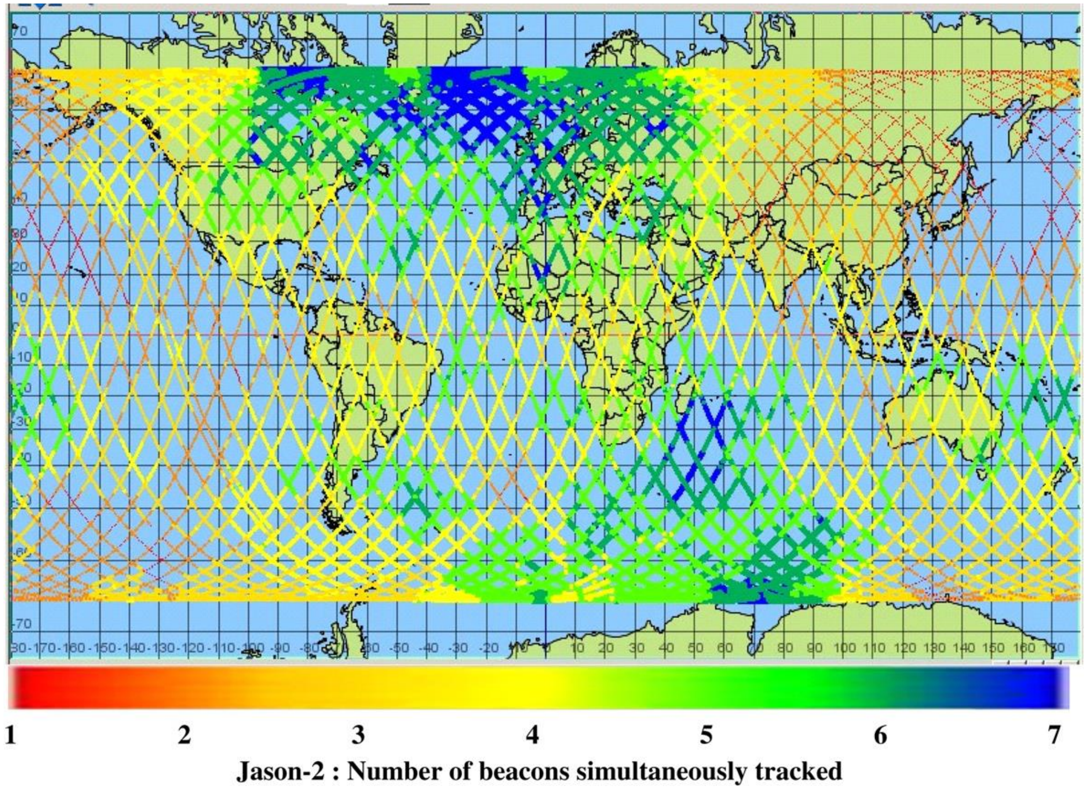
Type III.
(SJUC, San Juan)
Metal tower on anchored concrete foundation.

How has DORIS POD Evolved to better serve the science users ? (2)

More satellites, and increase in number of tracking channels for the DORIS receivers.
Improved observation geometry for positioning of beacons, and more data for satellite tracking.



DORIS data used in ITRF2014
(*Moreaux et al., Adv. Space Res. 2016*)

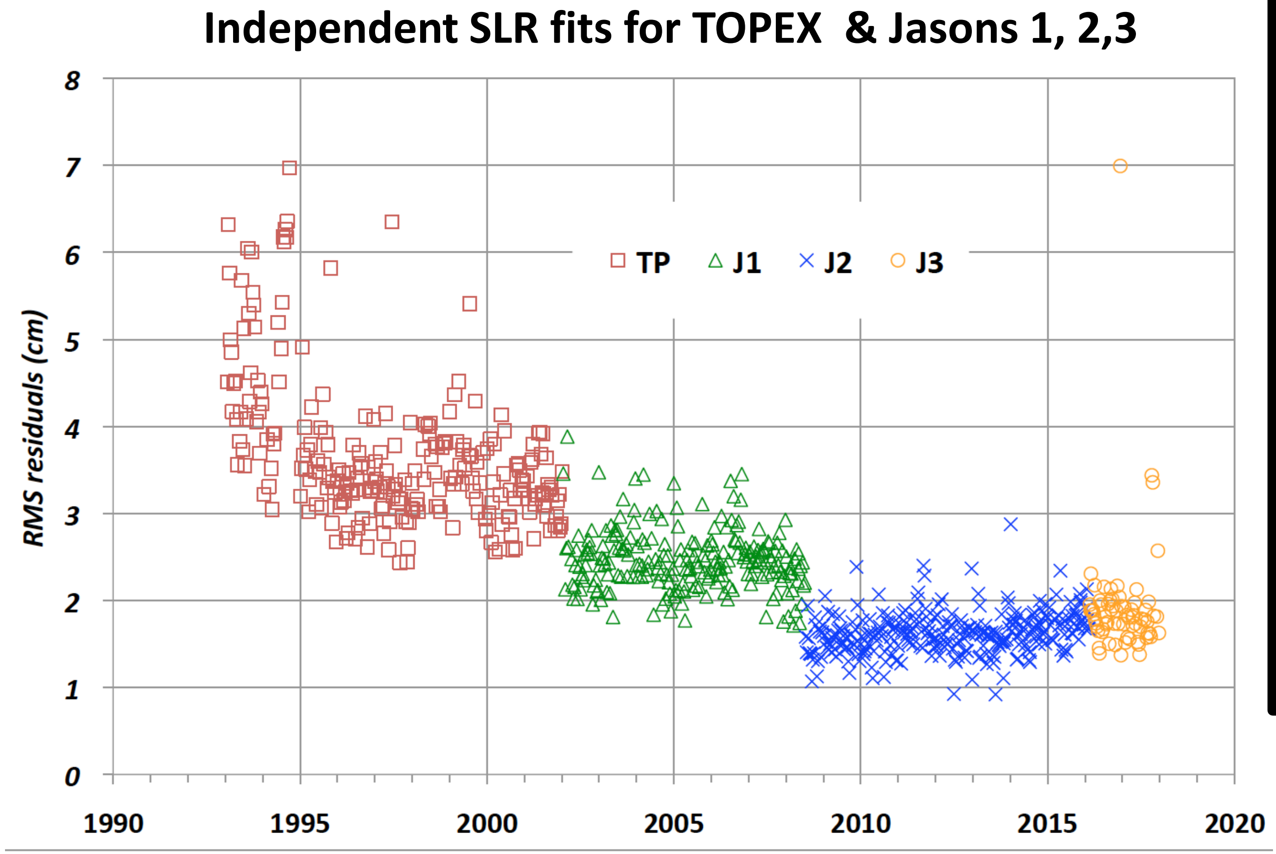


Geographical Distribution vs. number of beacons observed for Jason-2 (2008)
(*Auriol and Tourain., Adv. Space Res. 2010*)

The years 2002 & 2008 are inflection points in the quality of DORIS POD and quality of geodetic products.

What is the quality of POD and how has it evolved since 1993?

Independent SLR fits for DORIS-only orbits.



(from Nikita Zelensky, ESSIC/Univ. of Maryland, 2018)

- We use satellite laser ranging (SLR) to evaluate the quality of the DORIS-only orbits for the different satellites.
- For simplicity, we don't consider the DORIS time-bias w.r.t to SLR that is otherwise commonly estimated when the SLR and DORIS data are analyzed together.
- We see clear "break points" where the DORIS system (coordinates and ability to do POD) improved:
- The first occurs in 2002, with the introduction of SPOT-5 & ENVISAT, equipped with 2-channel DORIS receivers.
- The second occurs in 2008, with the introduction of Jason-2 in 2008, equipped with an 8-channel DORIS receiver.

SPOT-5

ENVISAT

Jason-2

What is the DORIS "DIODE" real-time service?

How does it serve science users?

DORIS Satellite Antenna

DORIS data From beacons

DIODE = On Board Kalman Filter:
- Satellite state vector,
- Frequency of satellite Ultra Stable Oscillator,
- Beacon parameters, etc.

Satellite orbit in real-time

- Steers satellite instruments (e.g. mode of altimeter, land vs ocean.).
- Real-time orbit distributed with fast-delivery altimetry data (latency of 1-3 hrs, e.g. from AVISO, EUMETSAT, NOAA, EU/Copernicus).

DIODE: A Short History	
• 1998: First used on SPOT-4.	• 2008. Jason-2. DIODE orbit helps to control the altimeter.
• 2002: Used with ENVISAT, SPOT-5	• 2010. Provides time reference (TAI)
• 2005: Provides input to Attitude Control system (Cryosat-1)	• > 2016. Improved Kalman filter updates beacon frequencies and Earth polar motion. 2.5 – 3.5 cm RMS radial agreement with CNES a posteriori orbit (GDRE).

DIODE = "Détermination Immédiate d'Orbite par DORIS Embarqué"

Jayles et al., ***Marine Geodesy***, 2015, doi:10.1080/01490419.2015.1015695.

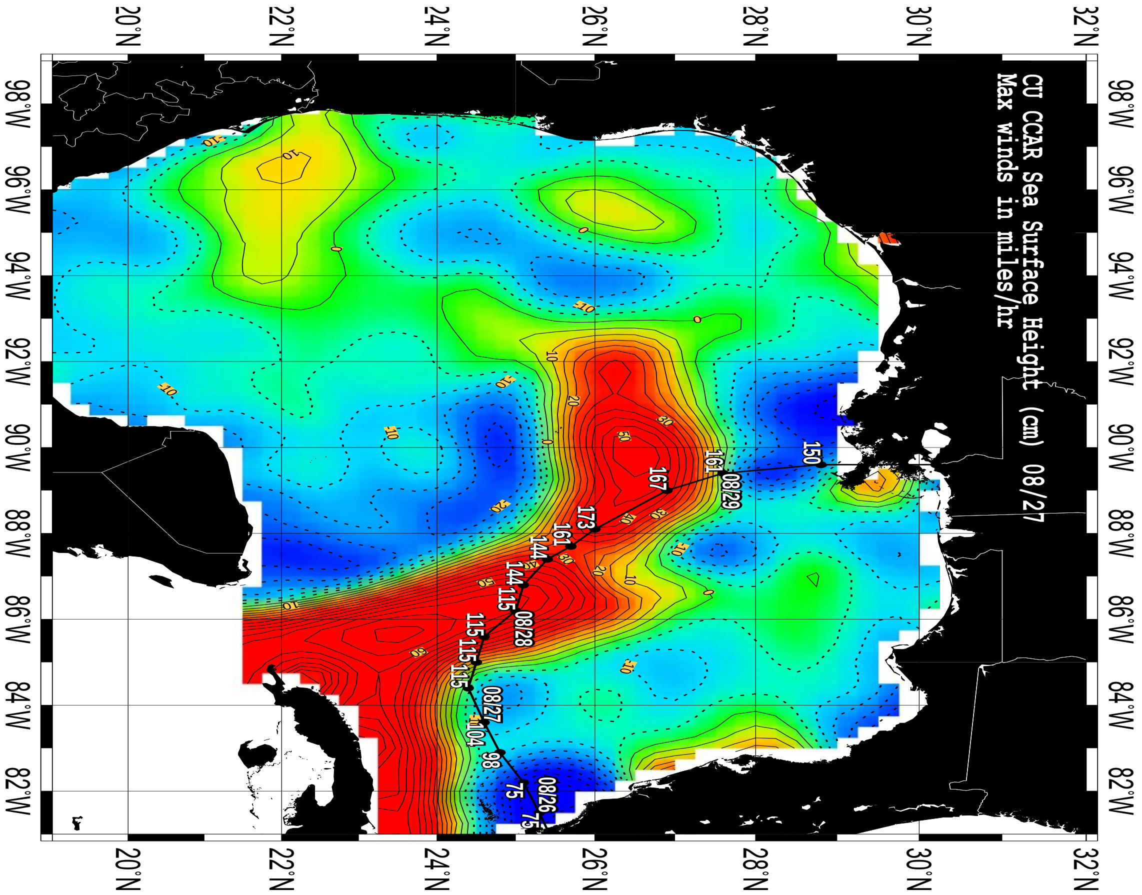
Jayles et al., ***Adv. Space Res***., 2016, doi:10.1016/j.asr.2016.05.032.

An Application of Near-Real time Altimetry

Monitor Hurricane Intensification over Warm Core Ocean Eddies

Sea Surface Height variations show the location of warm water eddies – which appear higher in absolute height. Their latent height can contribute to hurricane intensification.

Mapping of Gulf of Mexico Sea Surface Height Variations by Dr. Robert R. Leben, University of Colorado, Boulder.

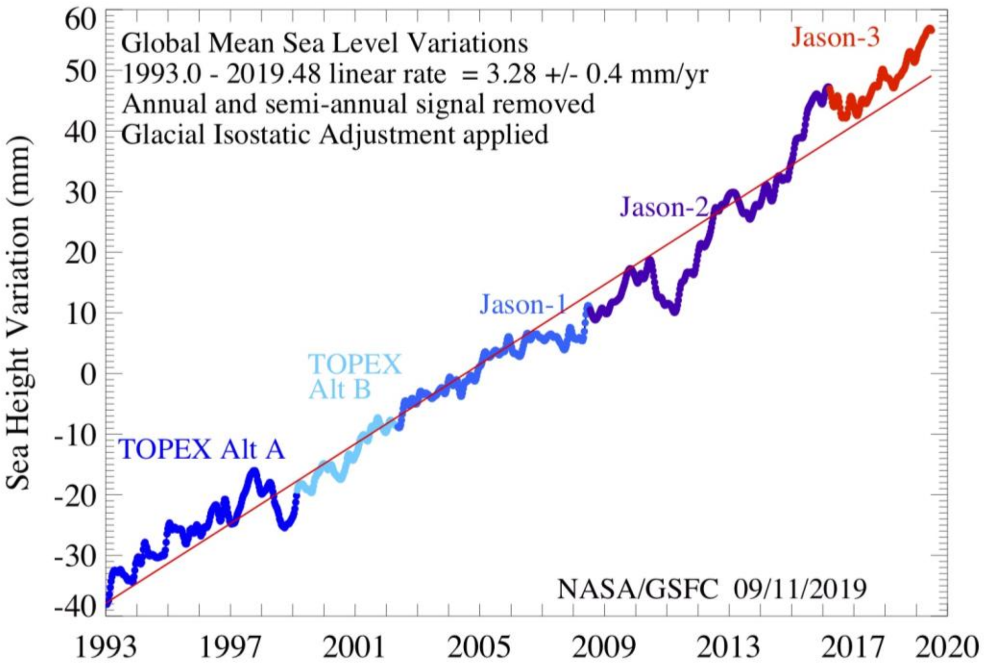


- This example from Hurricane Katrina (2005).
- Contours are 5 cm of sea surface height.
- Peak height of eddy is ~50 cm above reference surface.
- Sea surface Temperature only measures the ocean skin temperature. Altimeter height can be used to derive the heat content of the water column.

http://oceanmotion.org/html/impact/natural-hazards.htm
http://www.nasa.gov/centers/jpl/news/ostm-20080701.html

Measurement of Regional and Global Mean Sea Level Change

Global mean sea level variations from TOPEX, Jason-1, Jason-2 & Jason-3;
http://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData



- For these GMSL measurements, all orbits are computed from available SLR & DORIS data.
- All orbits must be in a consistent reference frame (e.g. ITRF2014), using the most-up-to-date standards and geophysical models.
- GNSS data is used to compute independent orbits, and these different orbits are constantly intercompared with those produced from SLR & DORIS data.
- GNSS data is available from satellite receivers only starting with Jason-1 (~2002).
- The GMSL data now allows use to compute an acceleration that is robust, i.e. $0.084 \pm 0.025\, mm/yr^2$.

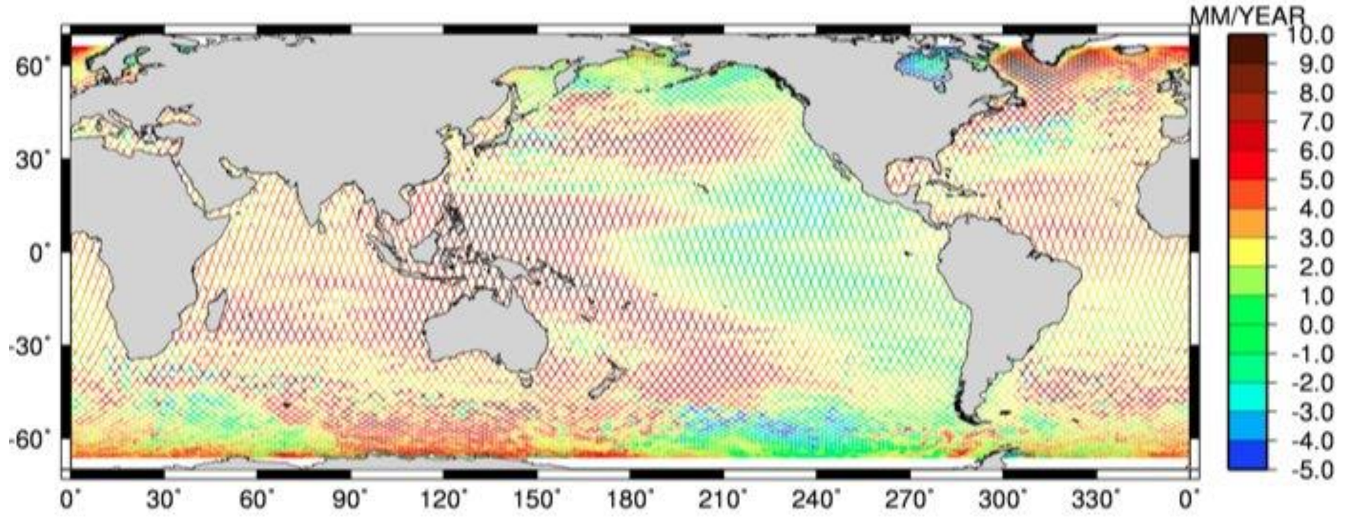
Nerem R.S. et al., "Climate-change–driven accelerated sea-level rise detected in the altimeter era" P.N.A.S., 2018, doi:10.1073/pnas.1717312115.

TOPEX/Poseidon
1992 - 2002

Jason-1, 2001- 2009
Jason-2, 2008-
Jason-3, 2016-

Measurement of Regional and Global Mean Sea Level Change

Regional mean sea level variations from TOPEX, Jason-1, Jason-2 & Jason-3 with respect to 1993-2002 mean; http://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData



TOPEX/Poseidon
1992 - 2002

Jason-1, 2001- 2009
Jason-2, 2008-
Jason-3, 2016-

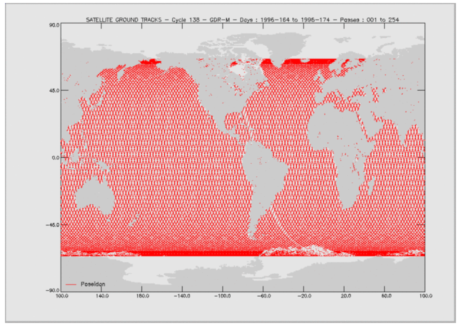
Global mean sea level change is driven by (1) addition of mass (e.g. ice melt from glaciers and ice sheets), (2) thermal expansion due to ocean heating; (3) global, ongoing deformation of the ocean basins from the last Ice Age (Global Isostatic Adjustment).

On a local scale close to the coasts, more effects appear, subsidence or rebound from natural or anthropogenic effects.

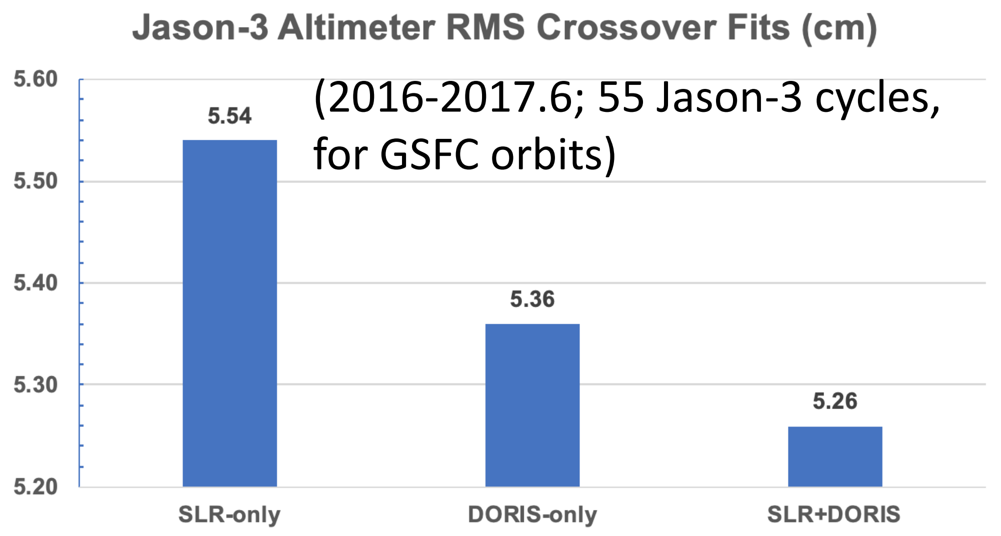
The altimeter data have been interpolated to a fixed geodetic grid represented by the mean repeat ground tracks. The grid shows the power of the altimeter data to monitor the ocean surface topography over time, and the importance of providing accurate and precise orbits in a long-term and stable reference frame.

How do we know the satellite orbits for GMSL are accurate?

Use Independent Data,
e.g. Altimeter Crossovers within a data arc (~9.91 days)

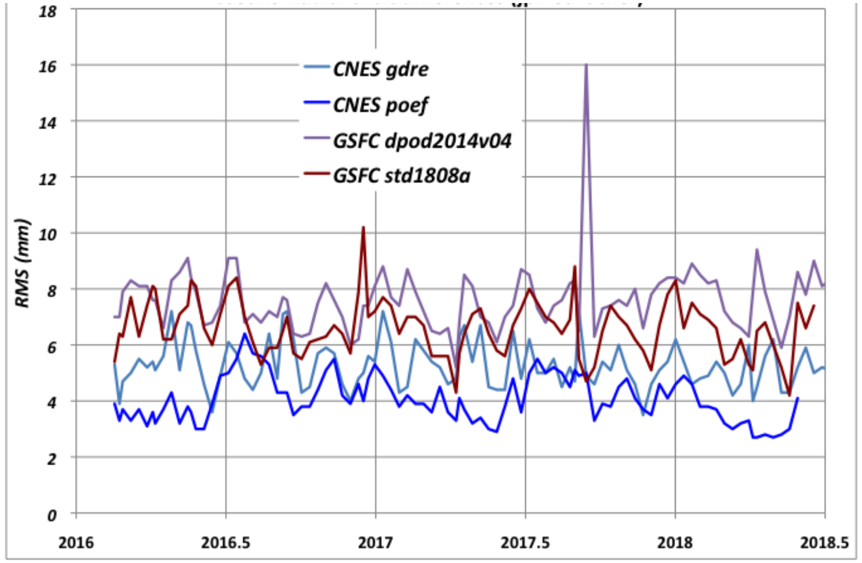


Crossovers are edited (removed) by 1. In areas of boundary currents (Gulf stream) and the ACC, (2) close to coasts, (3) large outliers.



Intercompare orbits computed from different sources using different data.

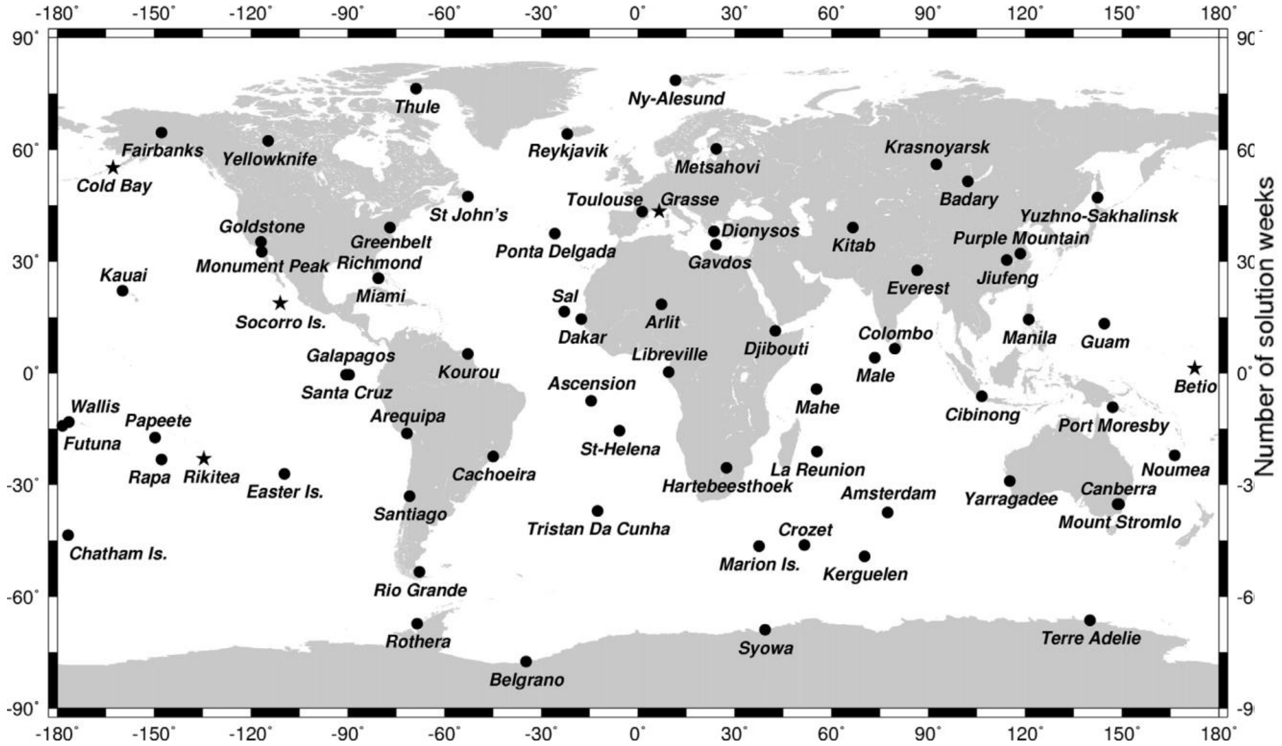
Jason-3 RMS Radial Orbit Differences (mm) vs. JPL18a/GPS orbits by Analysis Center source

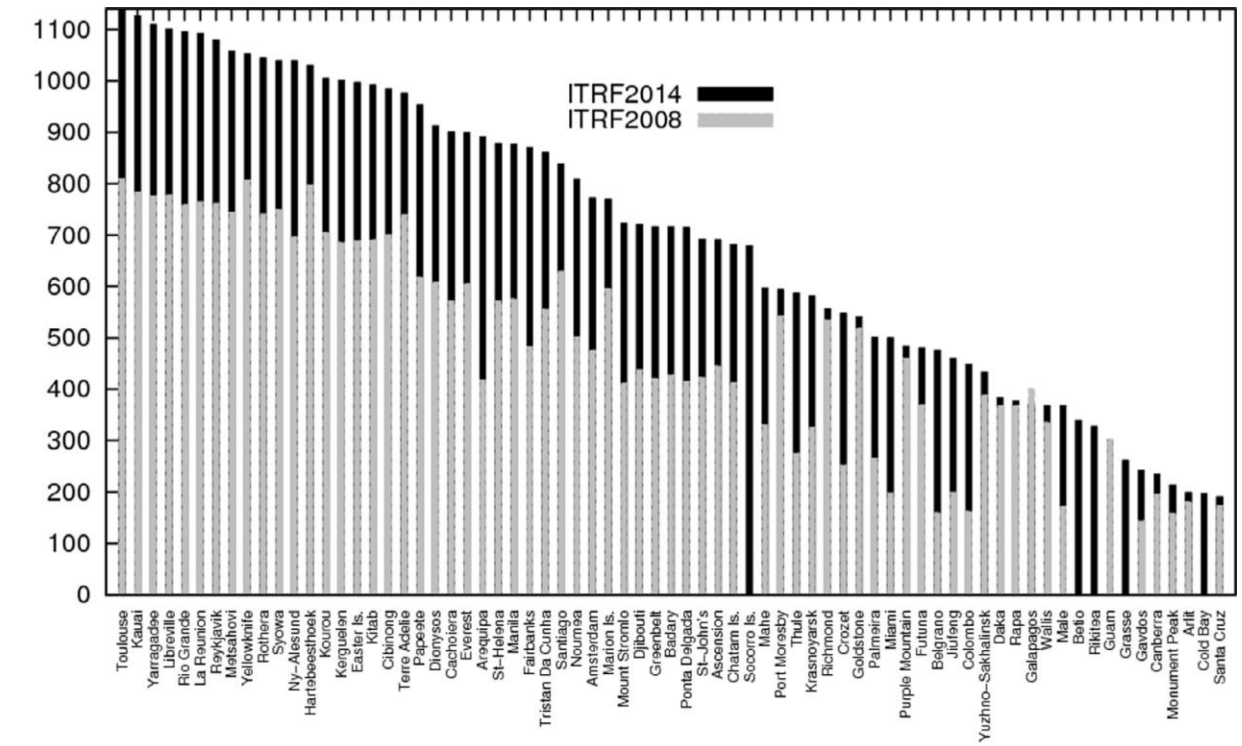


CNES gdre = 2016 version (DORIS + GNSS)
CNES poef = 2018 version (DORIS + GNSS)
GSFC dpod2014 = 2016 version (SLR+DORIS)
GSFC std1808a = 2018 version (SLR+DORIS)

DORIS Contribution to the ITRF

e.g. ITRF2005, ITRF2008, ITRF2014 and now ITRF2020

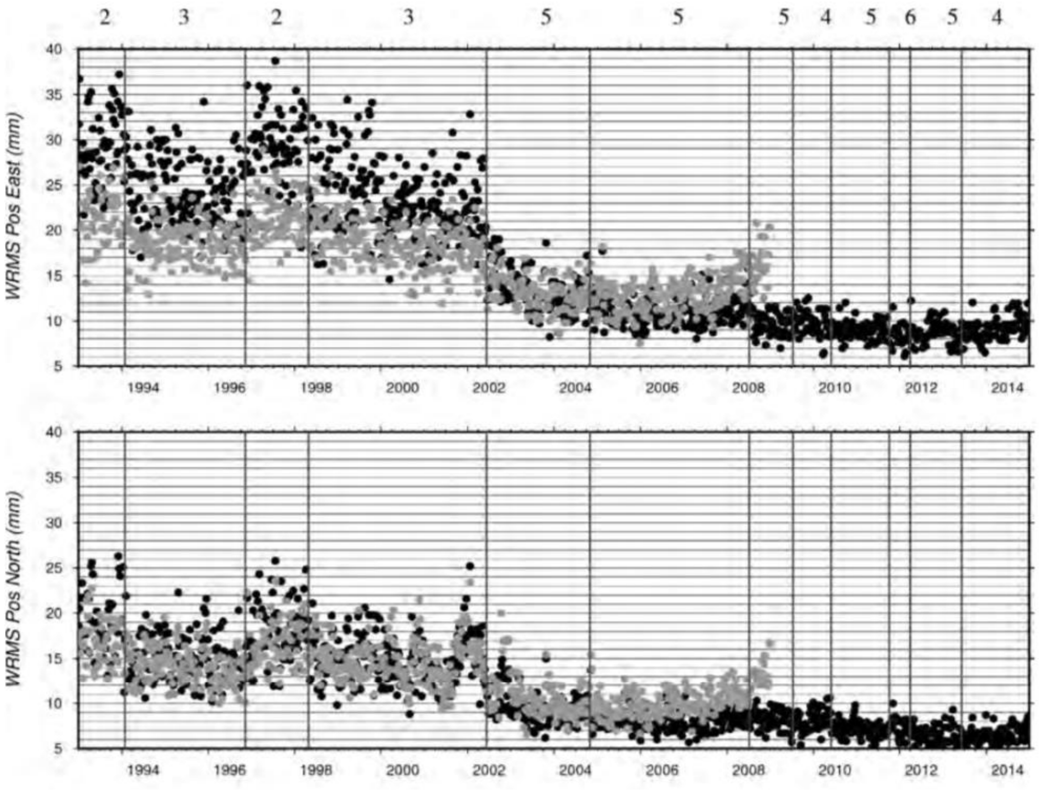


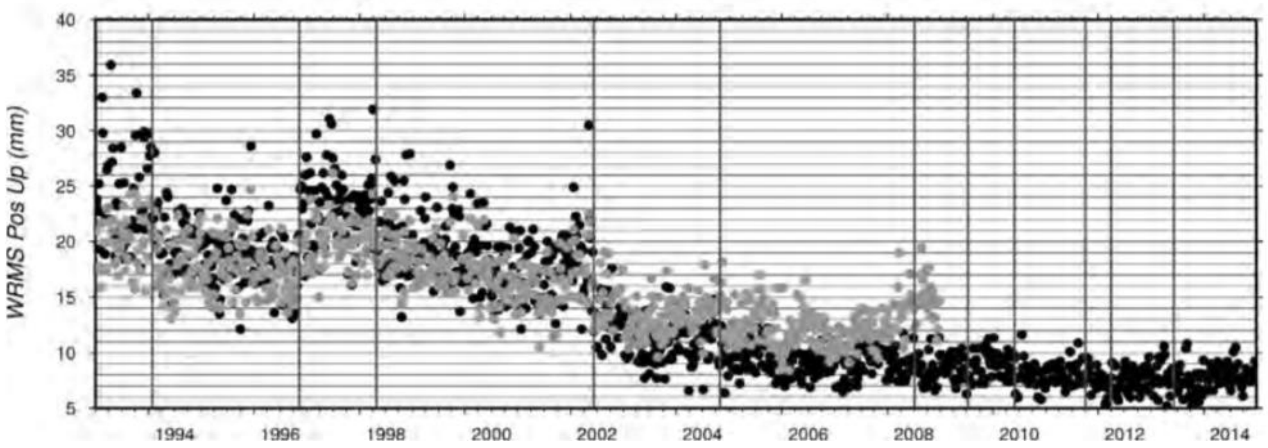


(Left) Geographical distribution of DORIS stations included in the IDS Contribution to ITRF2014, and (**Right**) No of weeks of site positions in ITRF2008 & ITRF2014. (*Moreaux et al., Adv. Space Res., 2016, doi:10.1016/j.asr.2015.12.021*).

DORIS Contribution to the ITRF

e.g. ITRF2005, ITRF2008, ITRF2014 and now ITRF2020



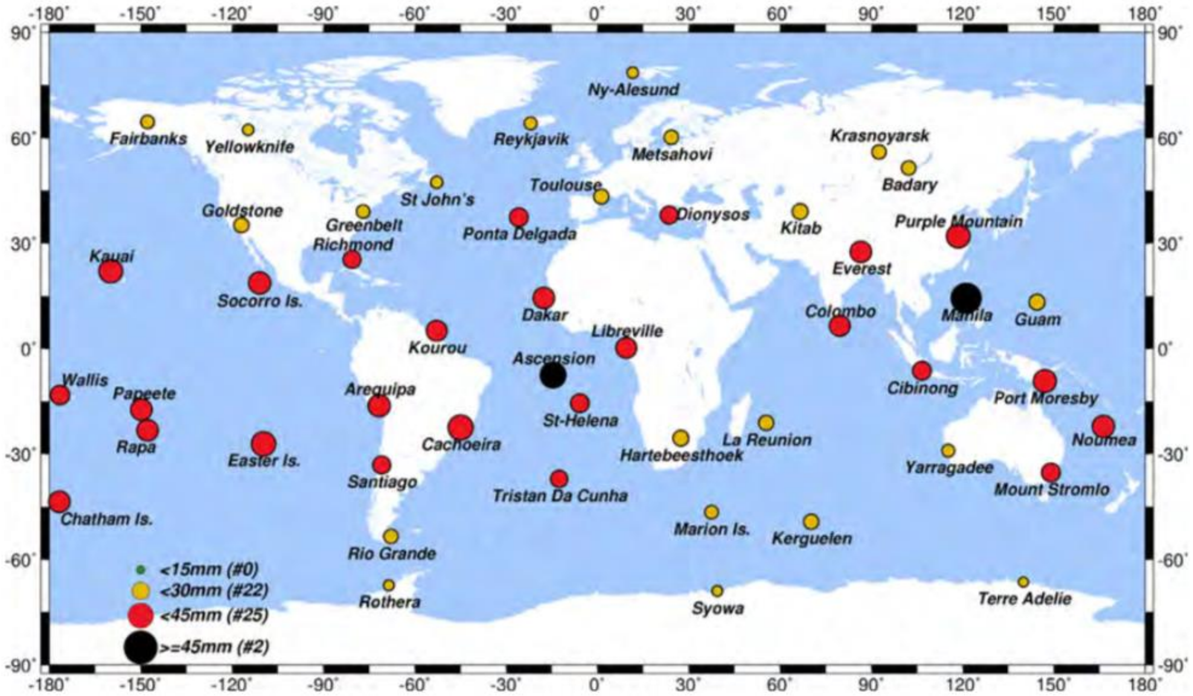


ITRF2008-like (**grey**) and ITRF2014 (**black**) weekly solutions WRMS of the station residuals wrt IDS-TRF2014. Vertical lines correspond to DORIS satellite constellation changes.
(***Moreaux et al., Adv. Space Res., 2016, doi:10.1016/j.asr.2015.12.021***).

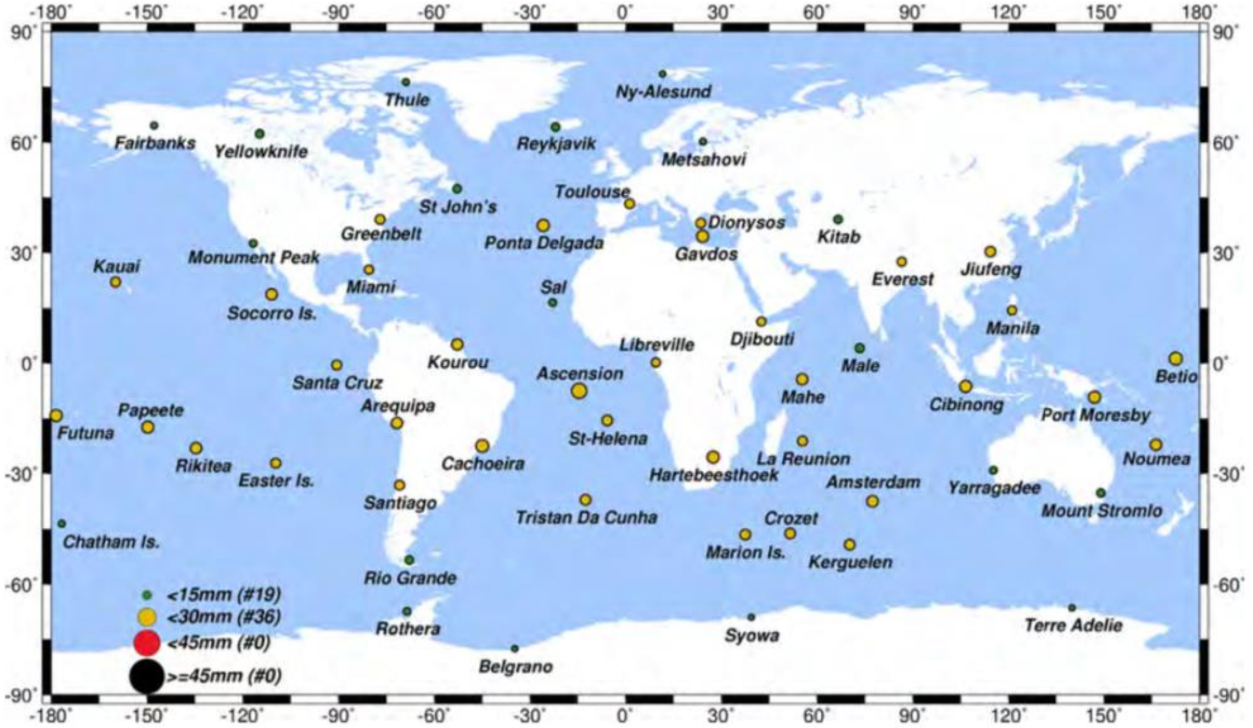
DORIS Contribution to the ITRF

e.g. ITRF2005, ITRF2008, ITRF2014 and now ITRF2020

3D RMS of station residuals (year 2000) from ITRF2014



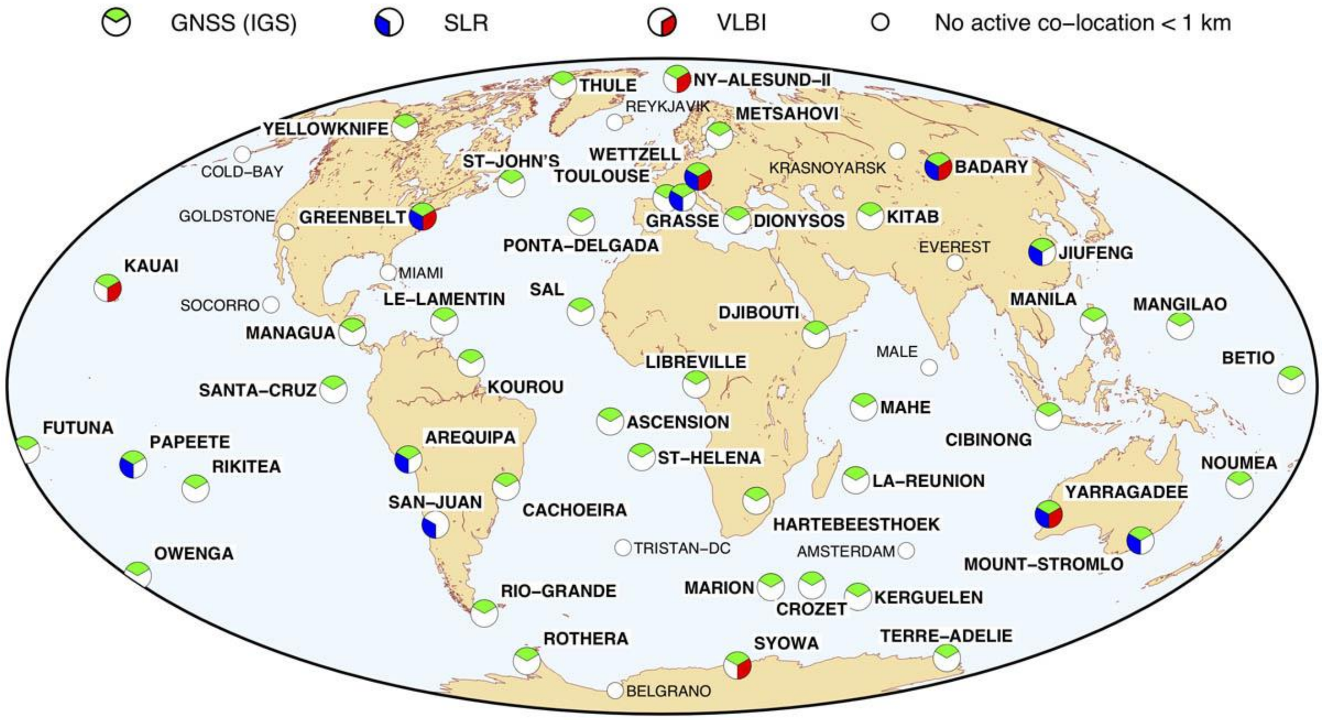
3D RMS of station residuals (year 2007) from ITRF2014



Geographical distribution of 3D RMS of station residuals in 2000 (Left) and 2007 (Right). (*Moreaux et al., Adv. Space Res., 2016, doi:10.1016/j.asr.2015.12.021*).

DORIS Contribution to the ITRF

Colocations with SLR & VLBI



DORIS/VLBI colocations	
Kauai	09/1990
Badary	11/1991
Syowa	10/1993
Greenbelt	06/2000
Yarragadee	~06/2011
Wettzell	09/2016
Ny Alesund II	10/2018

DORIS/SLR colocations	
Arequipa	12/1988
Badary	11/1991
Yarragadee	09/1992
Papeete	07/1995
Mt. Stromlo	10/1998
Greenbelt	06/2000
Jiufeng	12/2003
Grasse	08/2008
Wettzell	09/2016
San Juan	10/2018

Today:
48 colocations out of 59 DORIS sites.

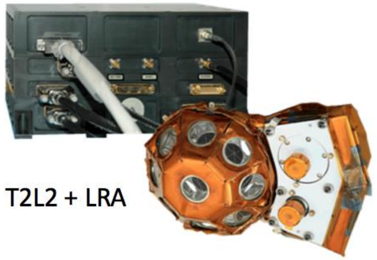
Colocations w. SLR: 10 sites.
Colocations w. VLBI: 7 sites.

- DORIS @ Hartebeesthoek since 03/1988.
  SLR & VLBI are ~2.1 km from the DORIS antenna.
- DORIS @ Metsahovi since 06/1988.
  (New) SLR & VLBI will be ~2.7 km from the DORIS antenna.

Future SLR/DORIS Colocations:
Changchun (China): awaiting approval.
Ny Alesund (Svalbard): ~2022.
Papenoo (Tahiti): Planning underway.

Synergy of SLR & DORIS: Time Transfer by Laser Link – T2L2 (1)

T2L2 on-board Jason-2



T2L2 :
- Designed for remote clocks synchronization, on-ground and on-board

Time Transfer :
- Determine Time Bias in laser stations (ILRS)
- Read the frequency bias of the USO (Ultra Stable Oscillator)

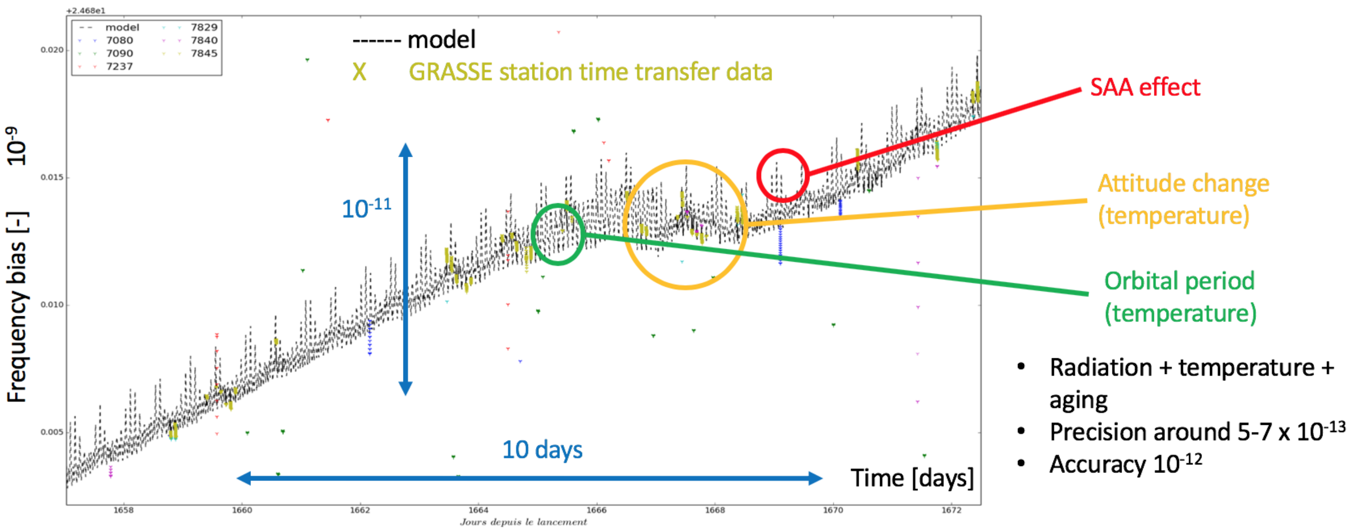
(July 2008- early 2018)

1. A Laser pulse is transmitted from the SLR station and its time-tagged on the ground (transmission & reception, 2way)
2. The laser pulse is recorded at the satellite, by the clock onboard Jason2, which is the DORIS Ultrastable Oscillator.
3. This allows time transfer to Jason-2, alignment of time systems to SLR stations in common view.
4. Once a detailed clock mode is developed for the DORIS USO, time can be propagated to the other SLR stations using a reference clock (e.g. Grasse).

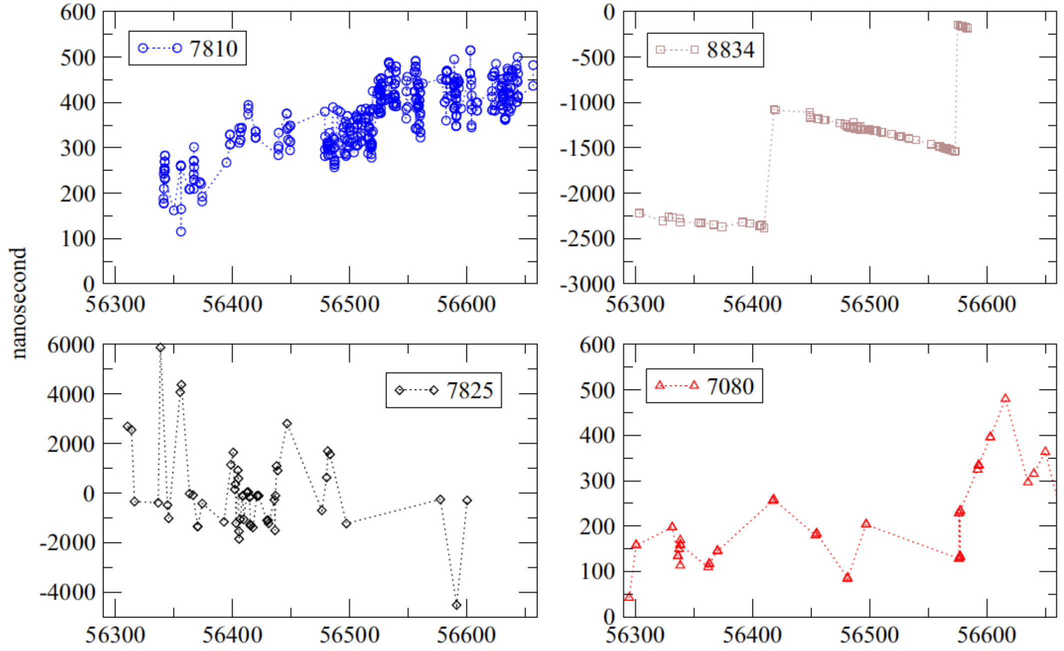
Grasse (France) Laser Station. Time standard is H_2 maser.

Samain, E. et al., 2008. "Time Transfer by Laser Link – the T2L2 Experiment on Jason-2 and further experiments***". Int. J. Mod. Phys. D 17,*** 1043–1054.

Synergy of SLR & DORIS: Time Transfer by Laser Link – T2L2 (2)



- Radiation + temperature + aging
- Precision around 5-7 x 10^{-13}
- Accuracy 10^{-12}



Data from Jason-2/T2L2 reveal the behavior of the DORIS USO, and unmodeled effects on the DORIS/USO frequency, e.g. due to passage through the South Atlantic Anomaly (SAA), attitude changes, and USO temperature changes.
Belli, A. et al., Adv. Space Res., 58, 2589-2600, 2016, doi: 10.1016/j.asr.2015.11.025.

Clockwise from Upper Left.
Time biases for SLR stations relative to Grasse, for Zimmerwald (7810), Wettzell (8834), Yarragadee (7090), and Mt Stromlo (7825) from Exertier et al. (2017). Units are ns.
***Exertier et al.*, "Time biases in laser ranging observations: A concerning issue of Space Geodesy", Adv. Space Res., 60, 948-968, 2017, *doi:* 10.1016/j.asr.2017.05.016.**

Possible future product: A DORIS contribution to geocenter

Geocenter from Jason-2 (DORIS) & Jason-2 (SLR) (Couhert et al., 2018),
LAGEOS1+2 (Ries, 2016), and GPS+GRACE (Haines et al., 2015)

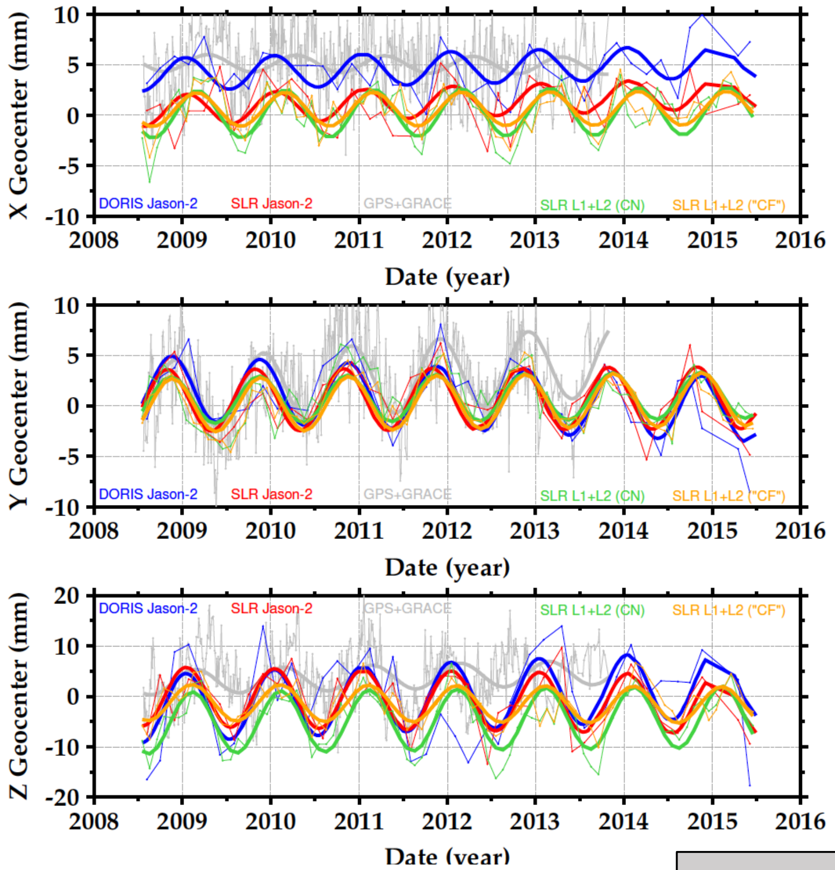


Table 9
Estimates of Geocenter Annual Variations From This Study and Independent Results

	X		*Y*		*Z*	
Solution	*A* (mm)	ϕ (day)	*A* (mm)	ϕ (day)	*A* (mm)	ϕ (day)
GPS+GRACE	0.9	105	3.5	334	—	—
SLR L1+L2 (CN)	2.3	61	2.3	317	6.1	41
SLR L1+L2 (CF)	1.7	59	2.7	322	3.6	39
DORIS Jason-2	1.6	13	3.2	322	6.4	18
SLR Jason-2	1.5	21	3.1	302	5.9	21

Note. *A* ratio = Amplitude ratio; $\delta\phi$ = Phase shift; GPS = Global Positioning System; DORIS = Doppler Orbitography and Radiopositioning Integrated by Satellite; SLR = Satellite Laser Ranging; CN = center-of-network; CF = center-of-figure.

The paper explains how the DORIS data can be processed to produce a geocenter time series. This points to the possibility to derive a new IDS product for users using the non-polar orbiting satellites (e.g. Jason-2, Jason-3, HY-2C, SWOT).
The IDS GB is considering to establish a Pilot Project and Working Group to further explore the development of this potential new product.

Figure 3 & Table 9 from **Couhert et al. (2018, "Systematic error mitigation in DORIS-derived geocenter motion", JGR-Solid-Earth, doi:10.1029/2018JB015453.**

Ways to get involved in the IDS

1. Join an existing or a proposed working group
A) Working Group on “Near-Real Time” data.
B) Proposed working on the geocenter (Still to be formally approved by the IDS Governing Board).

2. Explore DORIS products: https://ids-doris.org/

3. Look at station coordinate time series viewer: https://apps.ids-doris.org/apps/stcdtool.html

4. Partner with an existing. Associate Analysis Center (AAC), or Analysis Center (AC) in analysis of DORIS data.
5. Help elucidate key modelling problems (improve non-conservative modeling for DORIS satellites; better ways to process DORIS data).
6. Propose a new DORIS site (a modest expansion in the network is under consideration) that would support the network and satisfy clear scientific objectives.

Working Group on NRT Data

The general objective of this working group is a thorough assessment on applications, benefits, requirements and prospects of DORIS data with improved data latency. Currently, data is available as daily RINEX files with a latency of about one day. Thus, DORIS real-time and near real-time (NRT) applications of any kind are currently only possible on board of the satellite..

DORIS NRT data sets would be useful for different applications, one of them is the modelling of the Earth's ionosphere. Using DORIS in combination with GNSS (and additional techniques) helps to improve the accuracy and reliability of ionospheric maps, especially in ocean regions with poor GNSS coverage. This has been proved for post-processing applications but will probably also hold for NRT.
For more information contact the NRT Working Group Chair:
Denise.Dettmering@tum.de

Backup

Another application for satellite altimetry, enabled by Precise Orbit Determination (POD):

Monitor Global Lakes and Reservoirs with Satellite Altimetry

1. **The satellite altimeter tracking mode can be altered over land to obtain returns over water bodies (reservoirs and lakes).**
2. **Groups in the U.S., & France have extracted this information for a global set of reservoirs and lakes that coincide with the TOPEX/Jasons1-3 ground tracks.**
3. **The information is useful for resource managers and hydrologists.**

CNES data for lakes and river "Crossings" information is at URL: **http://hydroweb.theia-land.fr/**

Lakes and Reservoirs are Monitored in the "**Global Reservoirs and Lakes Monitor (G-REALM)",** maintained by Dr. Charon Birkett (now at NASA GSFC): URL: **https://ipad.fas.usda.gov/cropexplorer/global_reservoir/**