International Standardization for Satellite Altimetry Calibration: Lessons from the past & roadmap to the future

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Abstract

Satellite altimetry today provides exceptional means for absolute and undisputable monitoring of changes in sea level and inland waters (rivers and lakes), over regional to global scales, with accuracies of [mm/yr] and with respect to the center of mass of the Earth. Altimetry also measures wind speed on sea surface, sea state, determines ocean circulation, bathymetry, but also monitors melting rates of ice sheets in Arctic, Antarctica, and the Himalayas and observes the amounts of the sea ice and freeboard; All these with an accuracy less than 1 cm from an altitude of 800-1300 km above the Earth's surface. To continue doing that, altimetry system's responses have to be continuously monitored and controlled for their quality, biases, errors, drifts, etc. Relations among different missions have to be established on a common and reliable earth-center reference system, maintained for a long period of time (at least 20 years). At this stage, it is high time to (1) Build upon commonly adopted procedures, protocols and uncertainty for Cal/Val, (2) Provide control and checks for monitoring altimeter degradation as fast as possible, (3) Connect one altimetry mission with another, seamlessly and smoothly, (4) Adopt a stable framework for international and interdisciplinary cooperation, (5) Allow data integration between different scientific fields and disciplines, (7) Ensure Cal/Val procedures, results are well documented and traceable to SI units, (8) Provide transparent protocols and best practices for establishing new Cal/Val site and finally, dissipate responsibility to end user to decide the extent of fit for his requirements.

This presentation generates a summary roadmap to be used by all satellite altimetry Cal/Val community to (1) support accuracy in scientific and monitoring data we produce and evaluate, (2) provide accurate information presented to the public for understanding effects of sea level rise to their lives, and finally (3) to help make the right decisions, and put into action the right policies for climate change. Ways to express uncertainty are given to meet the standard of Fiducial Reference Measurements but also provide SI-traceable calibration results.

1. What is Fiducial Reference Measurements for Altimetry

Cal/Val results
traceable to SI and Metrology standards.
(light speed, time, etc.)

Measurement Uncertainty
- Critically review current Cal/Val methodology;
- Identify each component to uncertainty ;
- Documented & unbroken chain of calibrations;
- Connect uncertainty to SI-tracebale measurements.

Fiducial Reference Measurements
- Establish procedures for Cal/Val uncertainty budget,
- Results well-characterized and reliable in the long-term,
- Comparable through world's measurement system;
- Impervious to instrument, setting, location, conditions, ...
- Standards, procedures, practices for FRM4ALT.

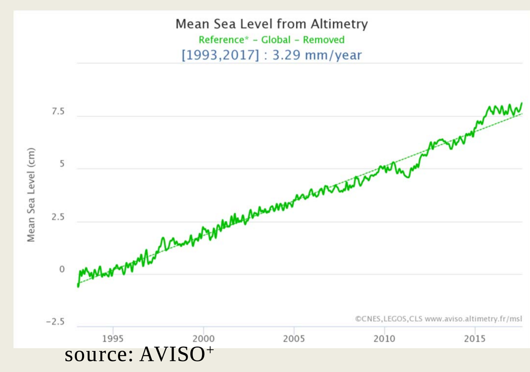
A. Site Selection,
B. Absolute Positioning,
C. Atmosphere Delays,
D. Geophysical Effects & reference surfaces,

Water Level Determination

Transponder Internal Delay

2. Why FRM for altimetry now?

- ✓ Build up **objective** and **reliable** record for Earth observation;
- ✓ **Traceable** in the long term;
- ✓ **Comparable** world-wide;
- ✓ Connected to undisputed reference and measurement systems.



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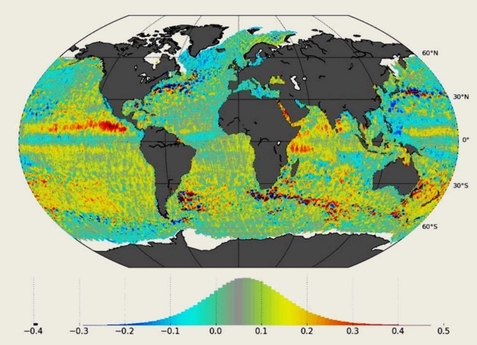

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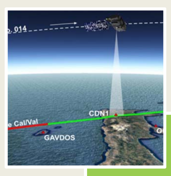
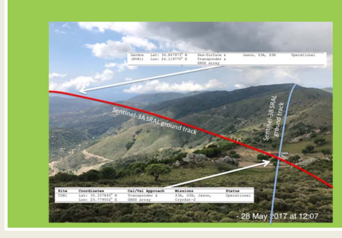
3. Constituents influencing Cal/Val uncertainties

Site Selection



- Repeat Cycle
- Across-track distance
- Land contamination
- Water Depth
- Directional errors
- Multi-mission
- Reference surfaces
- Accessibility
- Security
- Ground stability
- Geodetic ties
- GNSS visibility
- Power supply & Communications

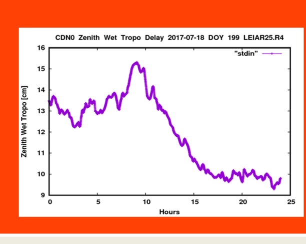


Absolute positioning

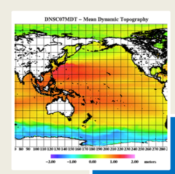
- Diverse GNSS satellites
- Diverse receivers & antennas
- Absolute GNSS antenna calibration
- 30s sampling rate
- 20 Hz high-rate ring buffer
- Reference frames
- Relative & absolute positioning
- Height diffs <2mm
- Diverse positioning systems (i.e., GNSS, DORIS, SLR, etc.)
- UTC time for time tagging
- At least 2-3 years of continuous operation.

Atmospheric Delays

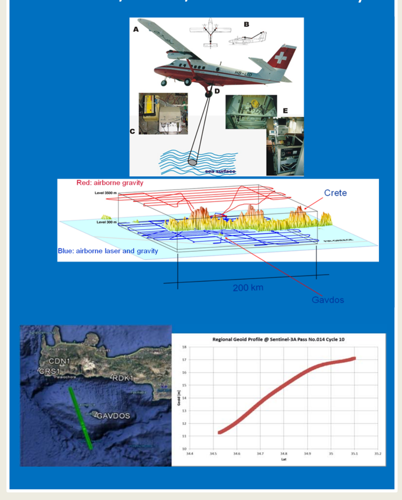
- GNSS-Derived ionospheric & zenith tropospheric delays at the time of satellite overpass
- Operation of meteo sensors
- Validation w.r.t. global/regional modeling
- Radiosondes, photometers, radiometers measurements
- OLCI observations.



Geophysical effects



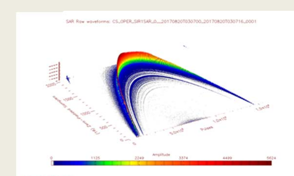
- Models for earth tides (solid earth, ocean tidal loading, pole tide) shall follow IERS conventions
- Establish reference geoid, MSS, MDT surfaces
- Validate reference surface with local/regional marine/aerial/terrestrial surveys



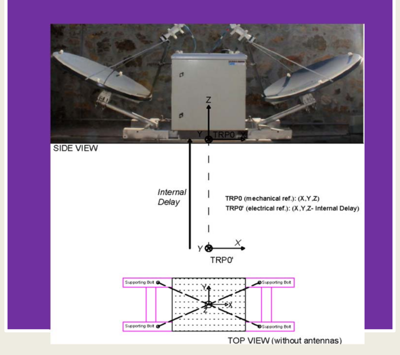
Water level determination

- Multiple (at least three) tide gauges of diverse measuring principle (radar, acoustic, pressure, floating).
- Geodetic ties between GNSS and tide gauge sensors via spirit leveling surveys with ± 1mm
- Calibration certificates from manufacturers for repeatability, reproducibility, hysteresis, drift, non-linearity, etc.
- Validation of instrument's performance, by the Cal/Val site operator, prior its permanent installation
- Field validation experiments to be conducted at least every 6 moths using a reference instrument
- Relative field calibration between operating tide gauges
- At least 1 hour of water level reading centered to the satellite overpass time of closest approach.

Transponder Calibration

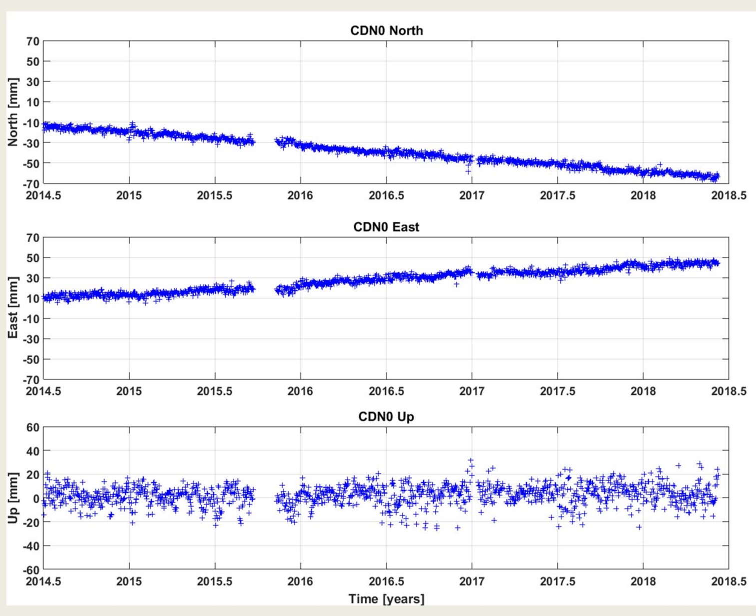


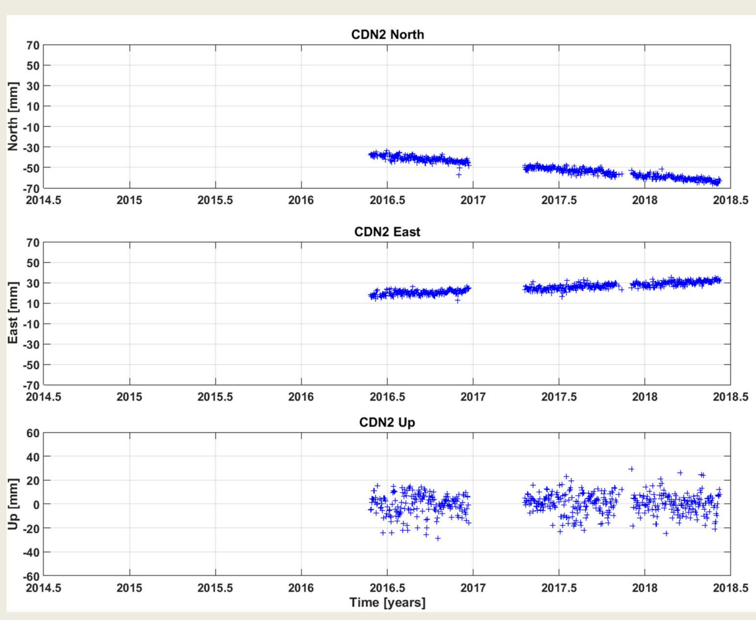
- Characterization at specialized facilities (i.e., Compact Payload Test Range @ESTEC/ESA)
- Mechanical vs electrical reference system (transponder's internal delay)
- Geodetic ties between GNSS and transponder mechanical reference
- Monitor transponder's performance w.r.t. environmental conditions (humidity, temperature, etc.)



4. FRM4ALT Activities

✓ **Absolute positioning results validation: (a) collocated GNSS receivers, (b) diverse processing strategies, and (c) atmospheric delays monitoring.**





Time series of the CDN0 & CDN2 GNSS stations in ITRF2008. Both stations are continuously operating at the CDN1 transponder Cal/Val site, Crete, Greece.

✓ Example of Uncertainty Budget Estimation

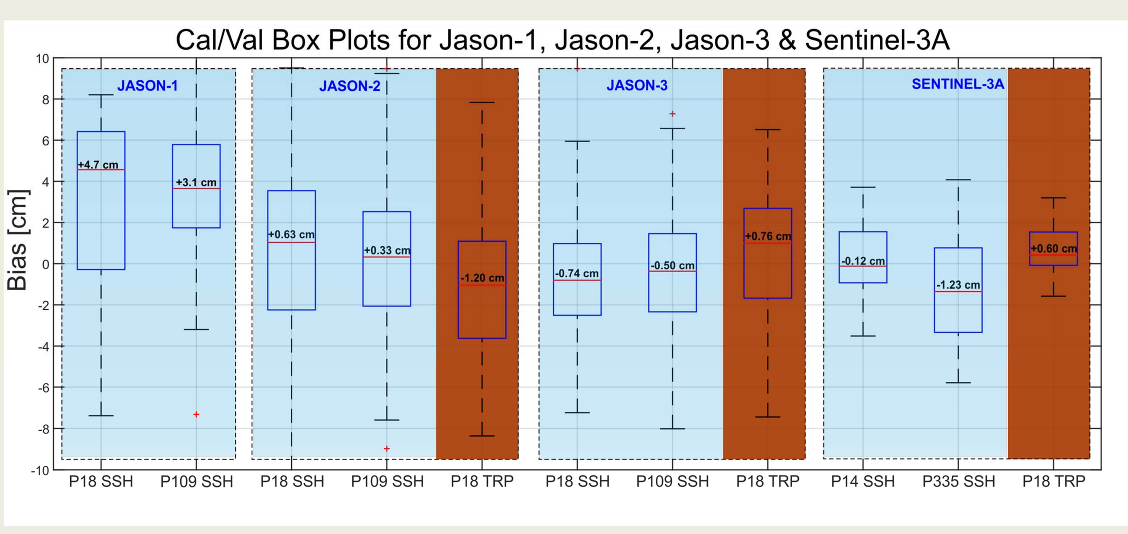
✓ **[International Standards Organization "Guide to the Expression of Uncertainty in Measurement]**

Contributing Error Constituent	Variance Estimate	Standard Uncertainty
Measured range	3.00 mm	± 1.73 mm
Transponder Internal Delay	30.00 mm	± 15.00 mm
Dry Tropospheric Delay	2.00 mm	± 1.16 mm
Wet Tropospheric Delay	14.00 mm	± 8.10 mm
Ionospheric Delay	4.00 mm	± 2.31 mm
Geophysical corrections	20.00 mm	± 11.60 mm
Satellite orbital height	50.00 mm	± 29.00 mm
Pseudo-Doppler correction	2.00 µm	± 1.16 µm
GNSS instrument	6.00 mm	± 3.50 mm
GNSS antenna reference point	4.00 mm	± 2.00 mm
GNSS repeatability	6.00 mm	± 0.17 mm
GNSS-Transponder Leveling	0.50 mm	± 0.18 mm
Levelling instrument/method	1.00 mm	± 0.60 mm
Processing & Approximations	30.00 mm	± 17.34 mm
Orbit Interpolations		
Unaccounted effects	20.00 mm	± 11.60 mm
Root-sum-Squared Uncertainty		**± 41.50 mm**

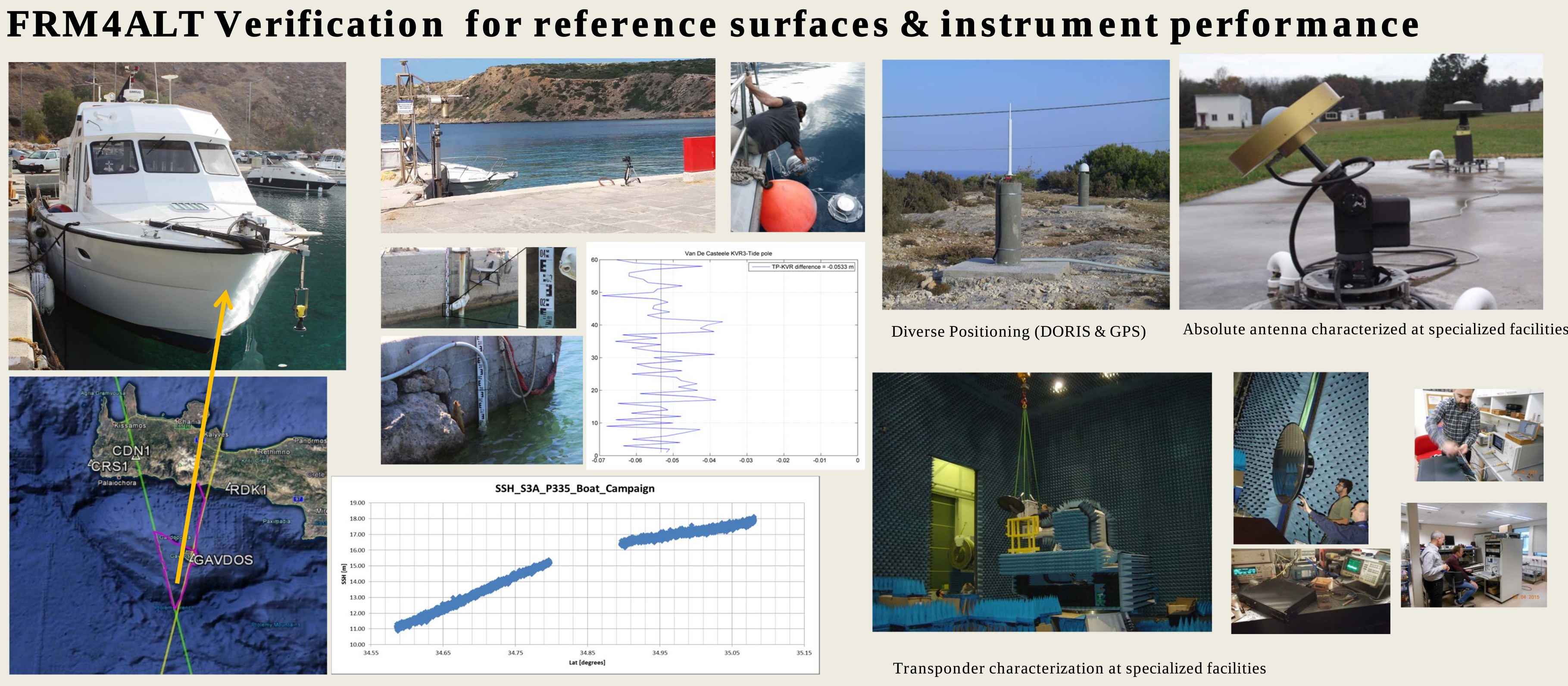
Transponder Cal/Val Uncertainty Analysis

Contributing Error Constituent	Variance Estimate	Standard Uncertainty
GNSS height	0.10 mm	± 0.10 mm
GNSS receiver	6.00 mm	± 3.50 mm
Antenna reference point	2.00 mm	± 2.00 mm
Water level	1.30 mm	± 1.30 mm
Tide gauge zero point	0.15 mm	±1.00 mm
Tide gauge vertical alignment	2.40 mm	± 1.40 mm
Tide gauge certificate	5.50 mm	± 5.50 mm
Leveling repeatability	0.13 mm	± 0.12 mm
Monumentation	1.10 mm	± 0.64 mm
Vertical misalignment	1.00 mm	± 0.60 mm
Leveling observer	1.00 mm	± 0.60 mm
Leveling instrument/method	1.00 mm	± 0.60 mm
Tide pole reading	1.00 mm	± 0.60 mm
MSS	33.00 mm	± 33.00 mm
MDT	85.00 mm	± 85.00 mm
Geoid	80.00 mm	± 46.20 mm
Processing	0.50 mm	± 0.30 mm
Geoid slope/offshore transfer	10.00 mm	± 5.80 mm
Unaccounted		
Unaccounted effects	20.00 mm	± 11.00 mm
Root-sum-Squared Uncertainty		**± 36.16 mm**

Sea-Surface Cal/Val Uncertainty Analysis



✓ FRM4ALT Verification for reference surfaces & instrument performance



Diverse Positioning (DORIS & GPS)

Absolute antenna characterized at specialized facilities

Transponder characterization at specialized facilities

Roadmap to FRM Standardization for Altimetry

- o Select a standard atomic **time** & coordinate **reference system** for all measurements in Cal/Val altimetry;
- o Define a minimum set of **essential observations** & ground-based instruments to support the Cal/Val;
- o Standardize how measurements (GNSS, tide gauges, transponders, sensors, radiometers, etc.) are set up to define "benchmark calibrating parameters",
- o **Characterize** and **calibrate instruments** before putting into use in the field;
- o Institute the fundamental & undisputable **metrology standards** (e.g., light speed, atomic time, etc.) to build and place trust upon all measurements and results in altimetry calibration;
- o Define error constituents, document all procedures and practical steps **to be followed for all FRM Cal/Val sites** for describing and reporting uncertainty budgets for Cal/Val;
- o Put into operation procedures & techniques for evaluating differences in instrumentation measurements and for arriving at the "true" value of the parameter under investigation;
- o Describe regular **maintenance standards**, following agreed **protocols** and characterization **procedures** (i.e., 6 months tide gauges have to be sent to Lab for characterization, etc.);
- o Regulate the way of **global distribution of Cal/Val sites** on the globe;
- o Establish a procedure for consolidated approach to **data formatting**, **archiving** and **distribution**, and
- o Be prepared for **future satellite altimetry Cal/Val**, New sites are to be ready to accommodate new measuring techniques (Ka-band, Ku-band, two-dimensional, wide-swath altimetry, etc.).

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