Metrology for accurate satellite-based observations of climate variables

15 November 2022

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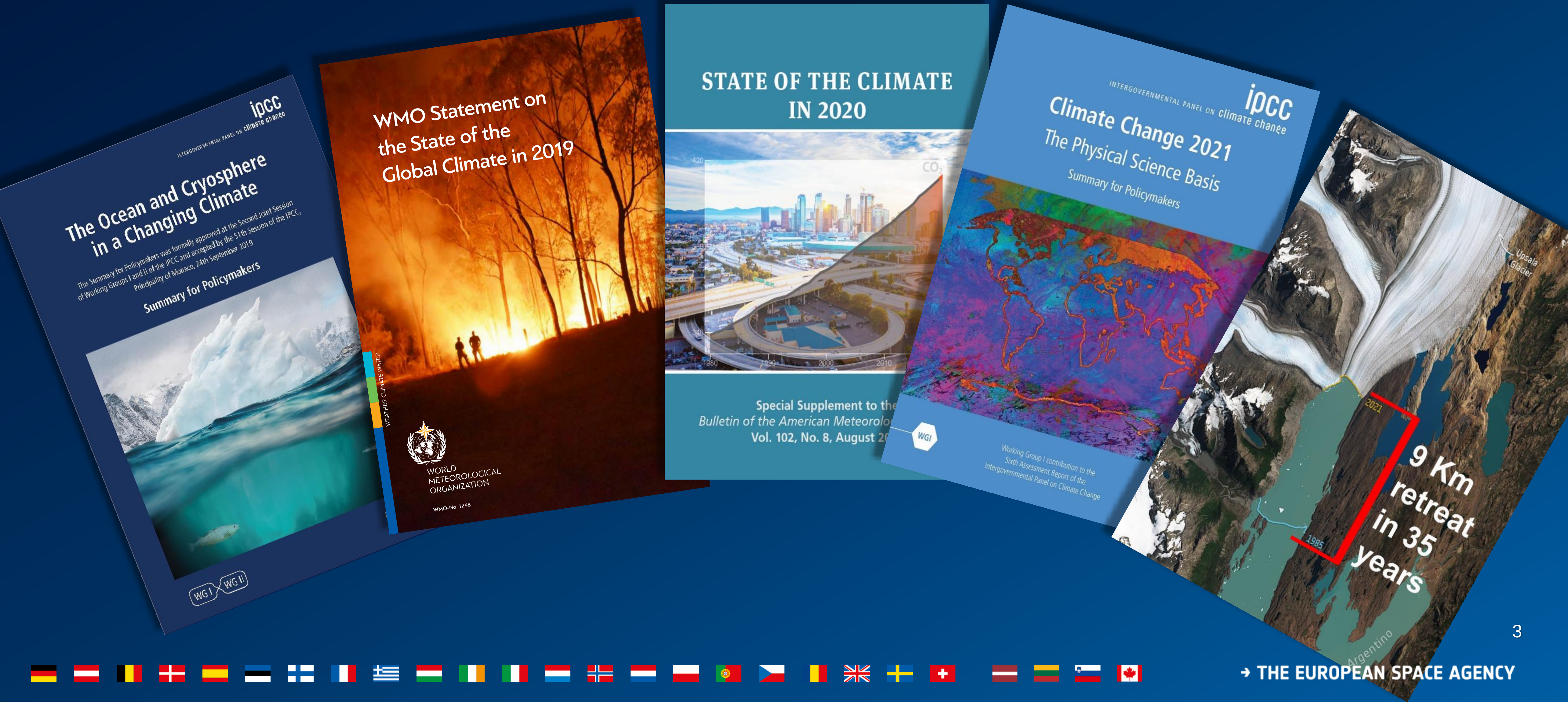
Head of Earth Surfaces & Interior Section,
Earth & Mission Sciences Division, ESTEC, ESA

27th meeting of the General Conference on Weights and Measures

CGPM

Worldwide Urgent Priorities

EO provides unequivocal evidence and facts in climate reports

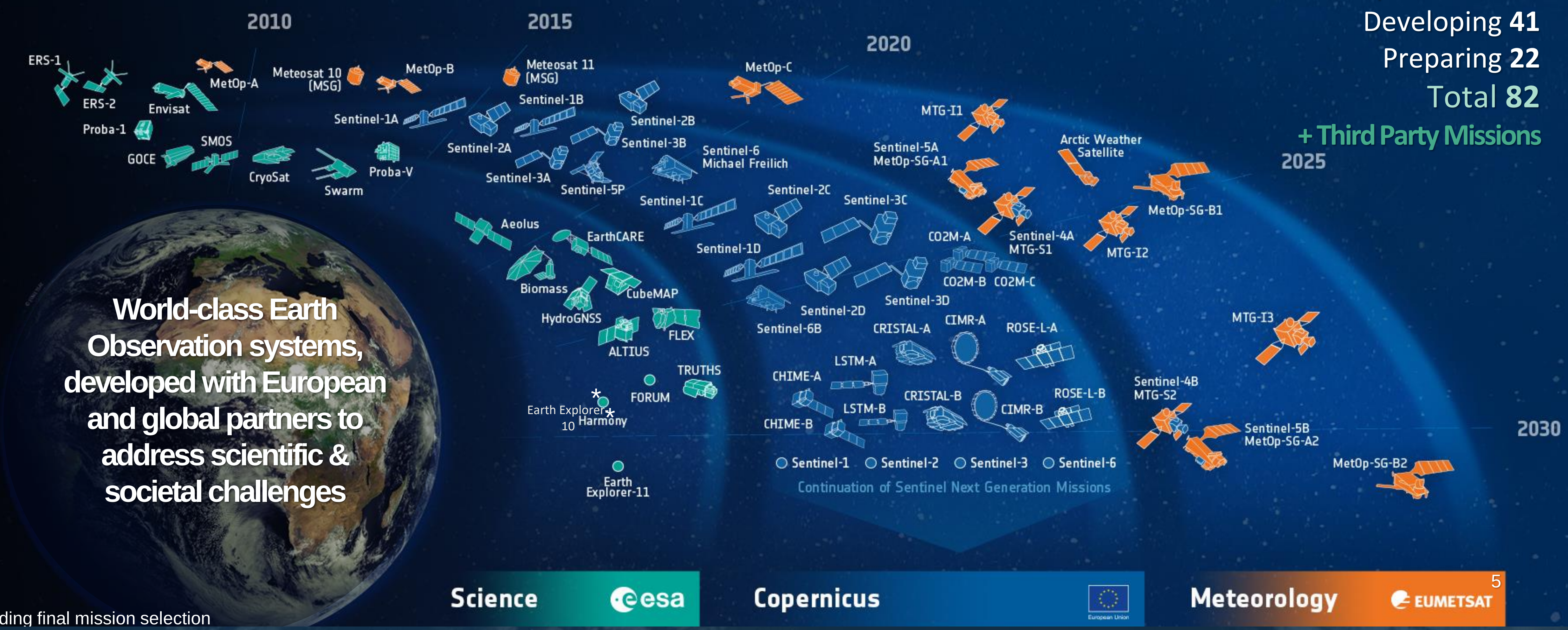



24
CTC-3

ESA's Earth Observation Misions

Satellites

Heritage **04**
Operational **15**
Developing **41**
Preparing **22**
Total **82**
+ Third Party Missions



World-class Earth Observation systems, developed with European and global partners to address scientific & societal challenges

*Pending final mission selection

Copernicus Big-Data Revolution with First Generation Sentinels

Copernicus is the largest producer of EO data in the world

All global landmass is observed every 5 days at 10m resolution

25 TB of Daily Data Production by Sentinels

250 TB of Daily Sentinel Products Disseminated for Services to Society

Examples of Evolving needs in Metrology for Environment and Climate at the European Space Agency.

Why is a Climate Observing System Important?

- Climate change has very different requirements than weather observations:
  - *10 times more accuracy: 0.03K instead of 0.3K*
  - *10 times as many key variables: 50 vs 5*
  - *Prediction time scales of decades vs days*
  - *Need for independent observations and analysis to verify surprises: cannot go back in time to verify them*
  - *Observations that must maintain consistency over many decades*
    - *Much longer than space based instrument lifetimes (5-15 years)*
    - *Longer than a scientist's career*
- Climate system physical, chemical, and biological processes occur on scales that vary from millennia down to seconds, and from global down to micrometers
- The challenge of such an observing system exceeds anything humanity has attempted to date for any scientific field.

(Bruce Wielicki)

CEOS GSICS

SI-Traceable Space-based Climate Observing System:
a CEOS and GSICS Workshop
National Physical Laboratory,
London, UK,
9-11 Sept. 2019

SITSCOS Workshop Report

Editors: Nigel Fox, Tim Hewison, Greg Kopp, Bruce Wielicki

https://doi.org/10.47120/npl.9319

TAKING THE PULSE OF THE PLANET

Essential Climate Variables are key indicators that describe Earth's changing climate. Scientists use these variables to study climate drivers, interactions and feedbacks, as well as reservoirs, tipping points, and fluxes of energy, water and carbon.

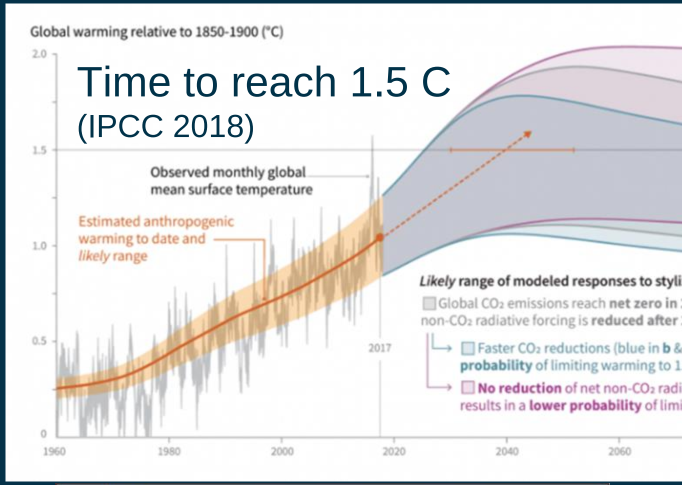
The climate-quality datasets produced by the Climate Change Initiative are a major contribution to the evidence base used to understand climate change.

> "Satellite products provide a valuable complement to in-situ measurements. These observations are valuable (high confidence) for regional applications since they provide multi-channel images at very high spatiotemporal resolutions"
>
> IPCC AR6 2021

The critical role of metrology and SI in addressing global Climate challenges

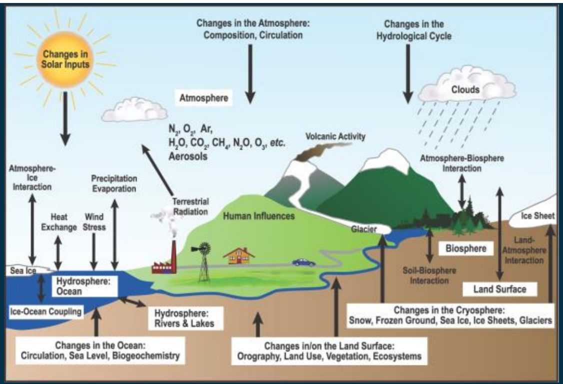
NEED:- Trustworthy observations from space to:

- Monitor and assess progress resulting from mitigation
- Improve understanding of climate sensitivities, dependencies & forecasts
- Support adaptation, Food security emergency response, de-risk investments



REQUIRES

- Quantitative, comprehensive, accessible, useable data
- Integrated, interoperable global observing system (space and in-situ)
- Robust reference(s) (benchmarks) against which to reliably measure change in as short a timescale as possible
- International acceptance



Confidence from metrological traceability to international standards (SI) at location of measurement

When & how big do we build the next Thames barrier?

Climate-Space – ESA's role…

International Climate Network
UNFCCC | IPCC | GCOS | WCRP | Future Earth | CEOS | CGMS | GEO | EUMETSAT | ECMWF | C3S | SCO | CMIP …

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INPUT
Addressing requirements from international climate network and drivers, such as GCOS, WCRP, UNFCCC, IPCC, climate services/C3S, State of the Climate reports.

ECV… …Rs: OCEAN & CRYOSP… (SST, SSS, OC, Sea… …, Sea Level, Sea Ic… …cier, Ice Sheet)

EC… …DRs: ATMOSPHERE (… …LL GHG, Ozone, Aer… …pre-cursor Aeroso… …ne, Water Vapour)

… CDRs: TERRESTRIAL … MR & HR Land Cov… …es, Soil Moisture, …ass, Permafrost, Fire…

UNFCCC Paris Agreement

Support to climate modelling

R&D and Services

Scientific evidence base

High-quality CDRs

OUTPUT
R&D, pre-operational development

Delivering Climate Observations to Society
Climate Ambassador

Using the excellence base to expand on cross-cutting activities

Support Member States in responding to the requirements of the UNFCCC Paris Agreement	Linking observation and modelling community: CMIP IPO, CMUG, CMIP7+	R&D: cycles, tipping points, trends, cross ECV, R&D and pre-operational development for climate services	State of the Climate, IPCC, WMO etc

OUTPUT

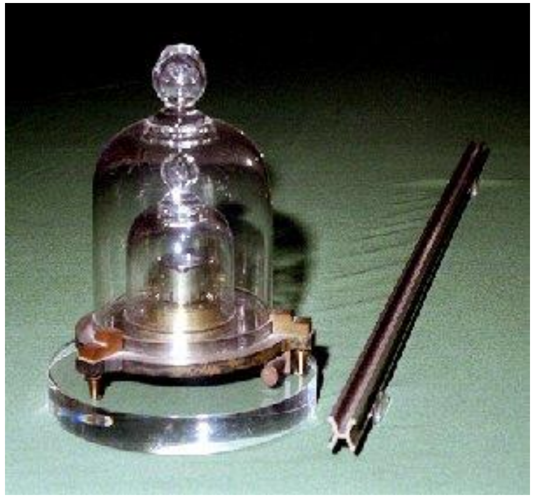
ESA recognises **the essential role of the International System of Units (SI) in providing confidence in the accuracy and global comparability of measurements** needed for protection of the environment, global climate studies and scientific research

Core principles of metrology

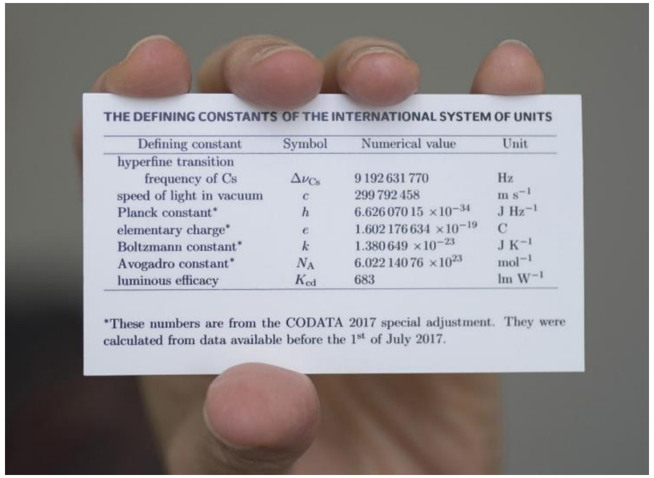
STABILITY
Century scale

INTEROPERABILITY
equivalence world wide

COHERENCE
Combining different measurements



20 May 1875



THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

20 May 2019

TRACEABILITY

UNCERTAINTY

COMPARISON

QA4EO

Steps to an FDR / TDP or FRM Uncertainty budget

MEASURAND 01

Define the measurand and measurement function

TRACEABILITY 02

Establish the traceability with a diagram

UNCERTAINTY 03

Evaluate each source of uncertainty and fill out an effects table

CALCULATE 04

Calculate the product and its uncertainty

STORE 05

Store relevant information for future users

Guidance documentation and training materials available at www.qa4eo.org

Fiducial Reference Measurements (FRM)

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Fiducial Reference Measurements (FRM) are a suite of **independent, fully characterized, and traceable ground measurements** that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO).

ships4sst

https://ships4sst.org/

fiducial reference measurements for satellite ocean colour

https://frm4soc.org/

fiducial reference temperature measurements

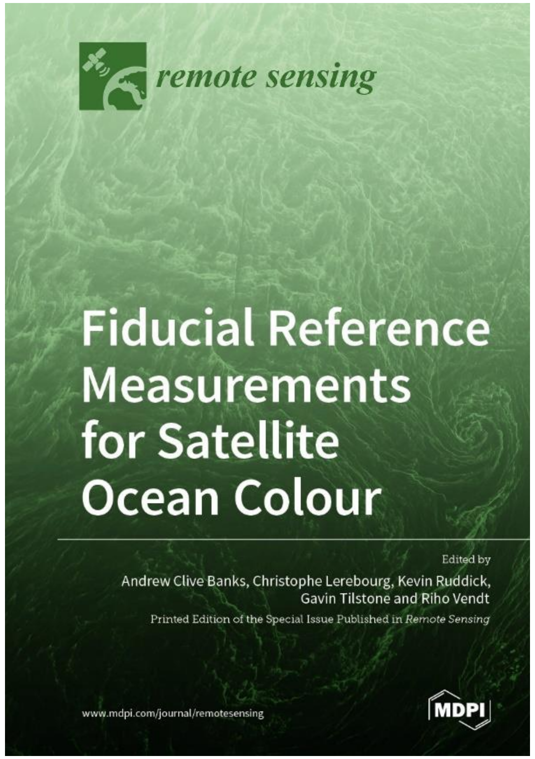
http://www.frm4sts.org/

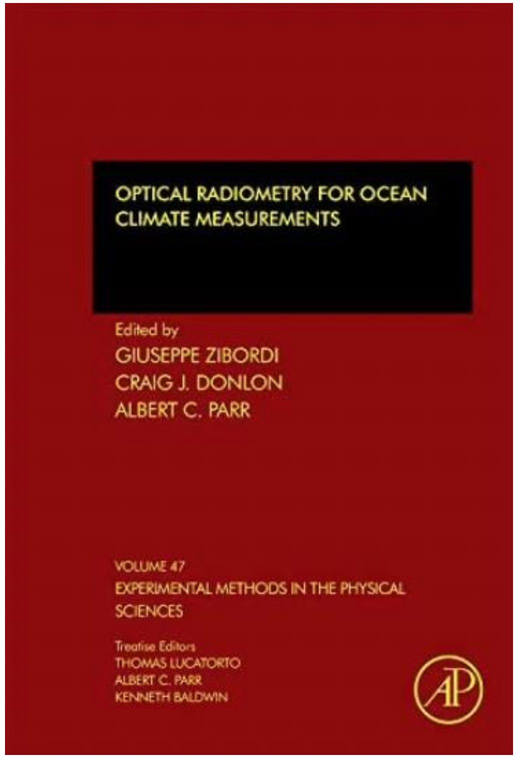
FRM4ALT Fiducial Reference Measurements for Altimetry

https://www.frm4alt.eu

fiducial reference measurements for vegetation

https://frm4veg.org/





FRM-BOUSSOLE: Buoy for the acquisition of long-term optical time series

http://www.obs-vlfr.fr/Boussole

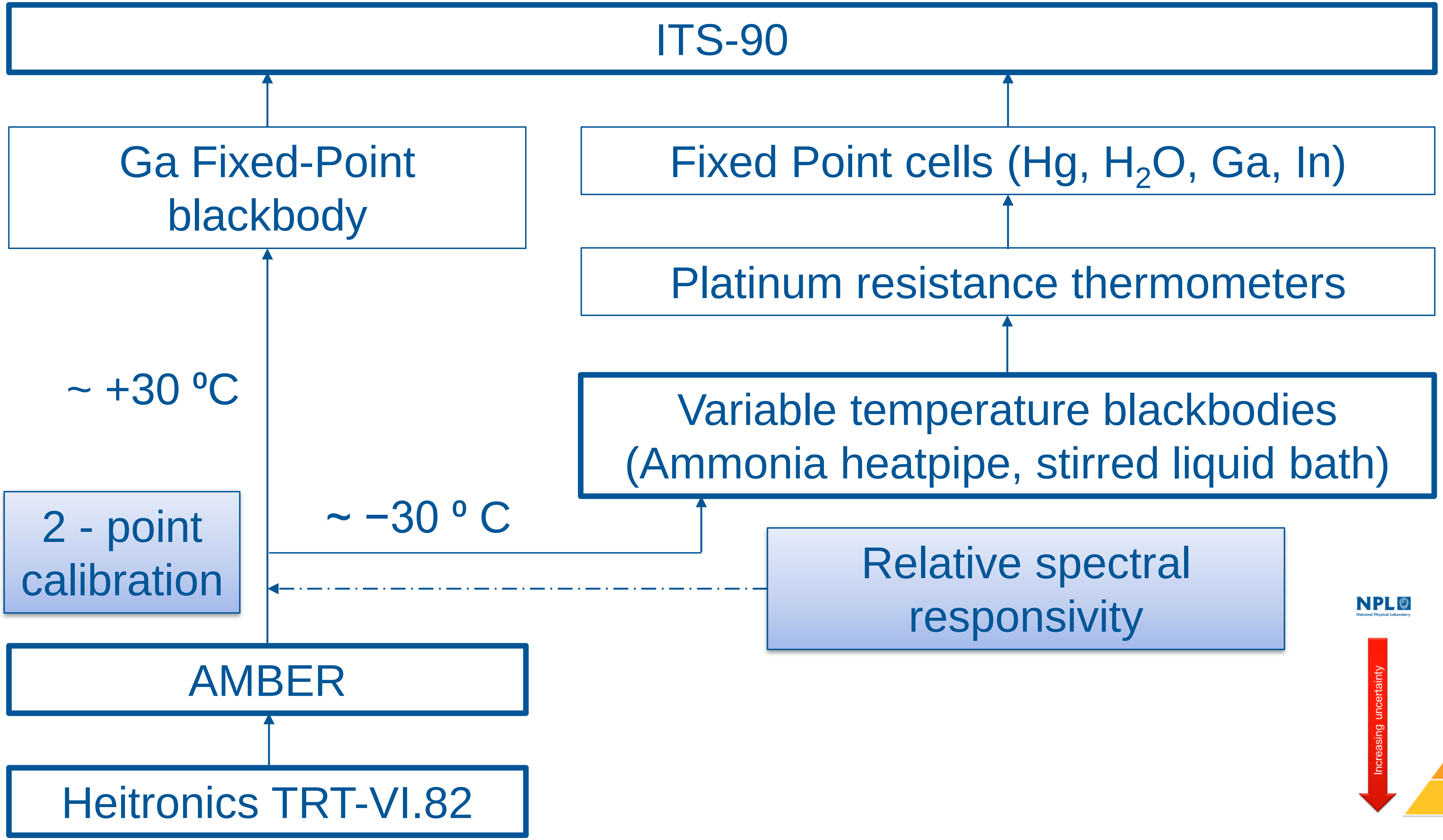
Pandonia FRM: Fiducial Reference Measurements for Ground-Based Direct-Sun Air-Qu

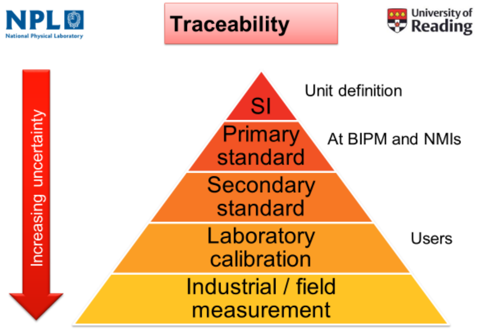
https://www.pandonia-global-network.org/

Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations FRM4DOAS

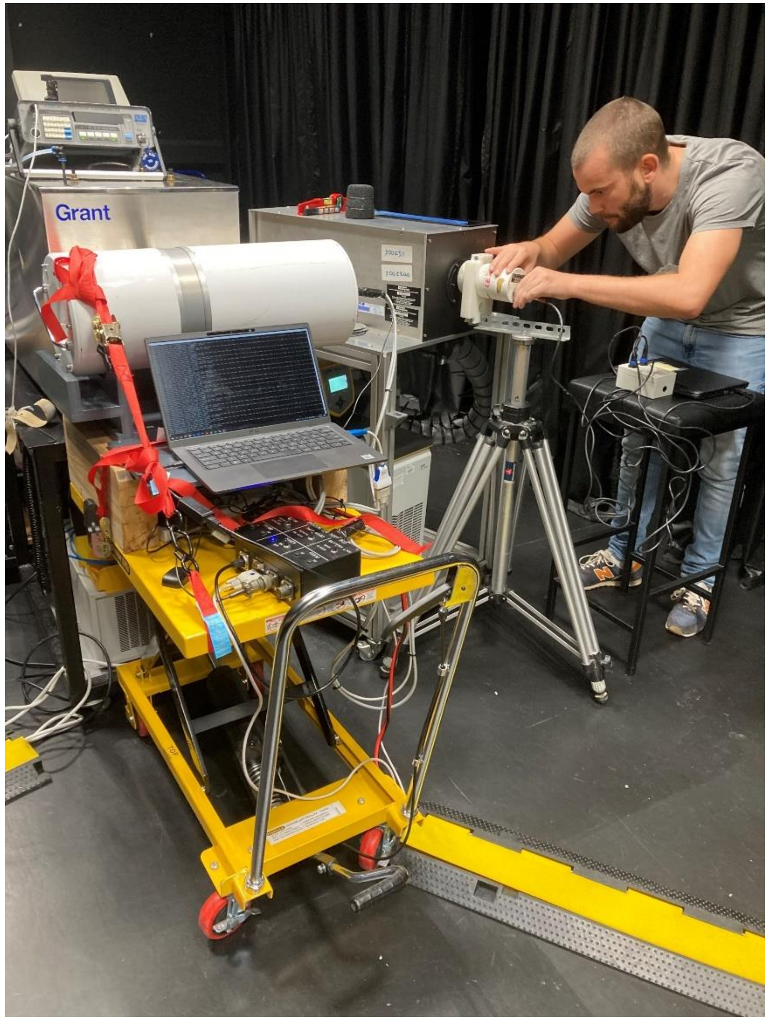
https://frm4doas.aeronomie.be/

Traceability of Fiducial Reference instruments





Lab comparison
13th -17th June, 2022, @ NPL, Teddington, UK

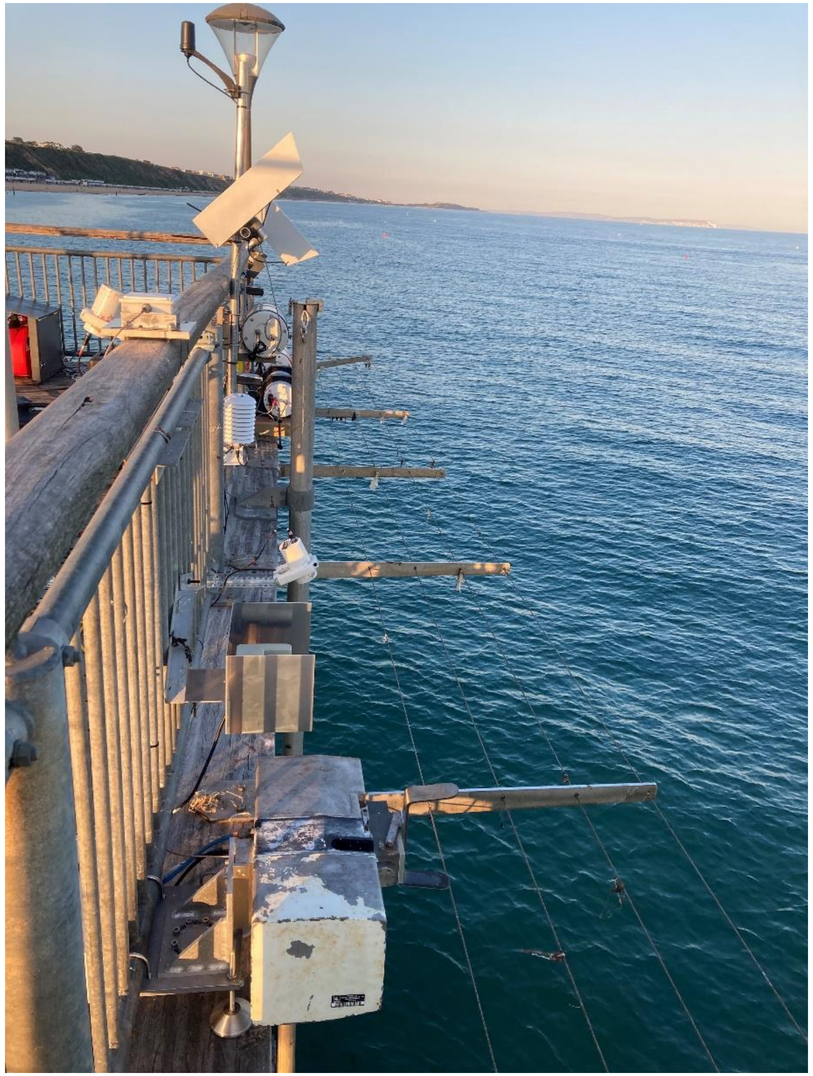


Radiometer comparison

Blackbody comparison

Field comparison

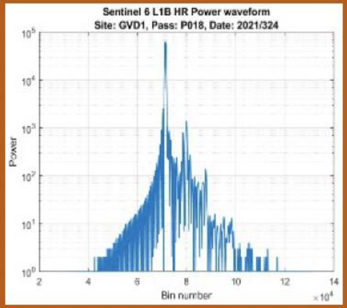
Preparation

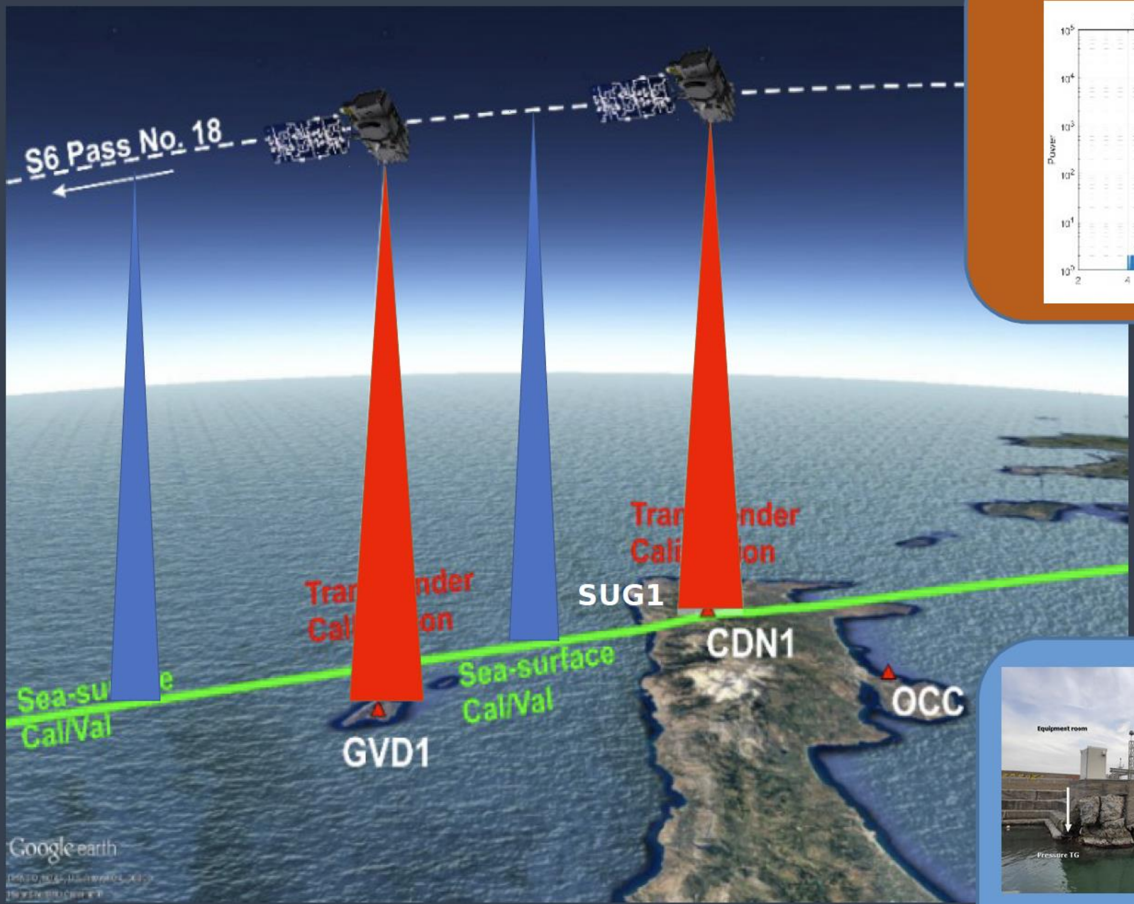


After set-up

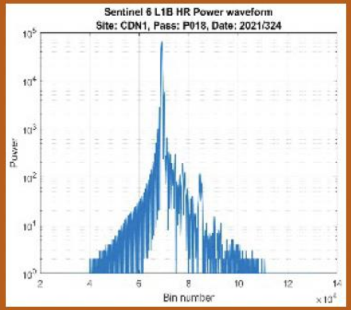
Simultaneous Transponder & Sea-Surface Cal/Val

GVD1 Transponder

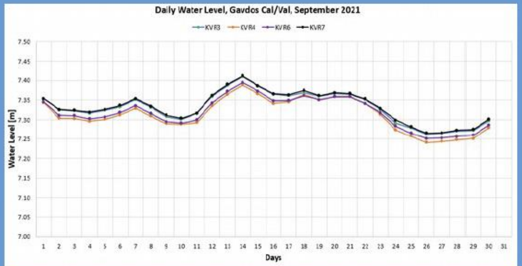




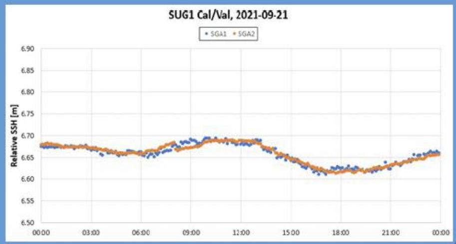
CDN1 Transponder



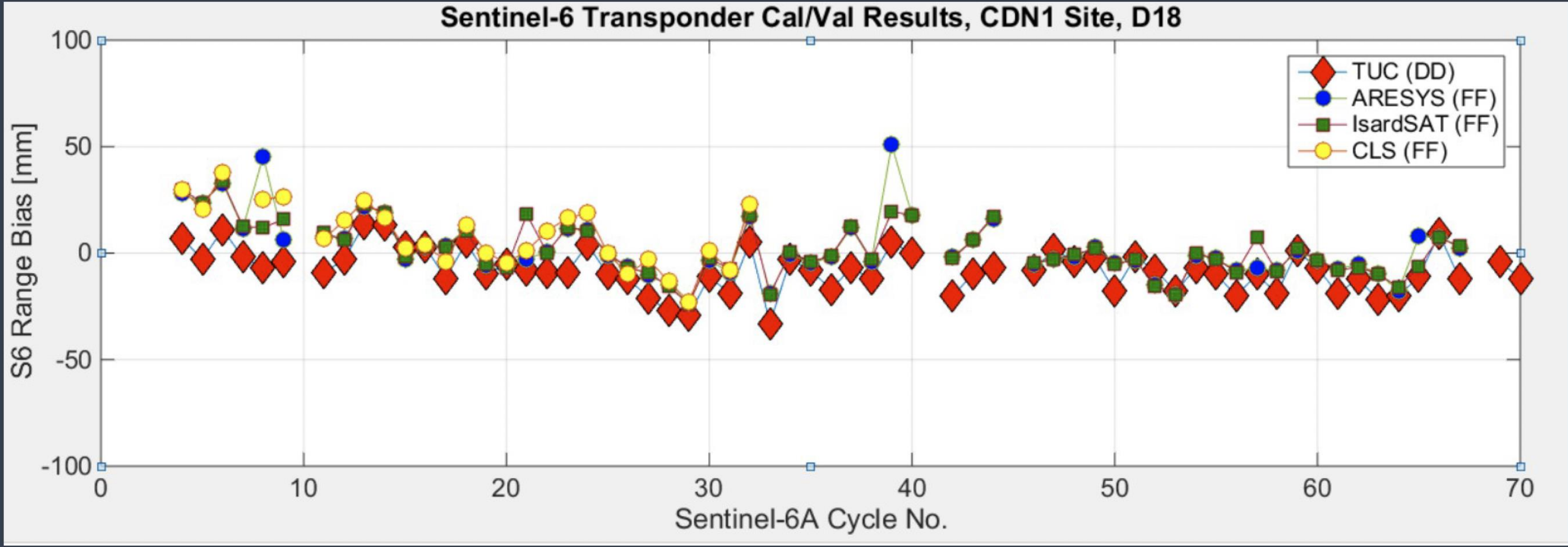
Gavdos sea-surface



SUG1 sea-surface



TPX- Range Bias @ CDN1 Transponder



Uncertainty and SI traceability in Satellite Mission Requirements

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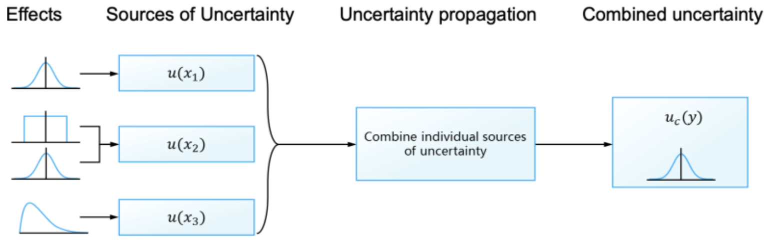
Copernicus Imaging Microwave Radiometer (CIMR) Mission Requirements Document

Prepared by	Earth and Mission Science Division
Reference	ESA-EOPSM-CIMR-MRD-3236
Issue/Revision	5.0
Date of Issue	8 November 2022
Status	DRAFT for review
Document type	Mission Requirements Document (MRD)
Distribution	ESA Unclassified – For Official Use

→ THE EUROPEAN SPACE AGENCY

$$u_{total}^2 \cong u_{NE\Delta T}^2 + u_{orbit-stability}^2 + u_{lifetime-stability}^2 + u_{pl-cal}^2 + 0$$

No more ARA! Follow the BIPM GUM approach



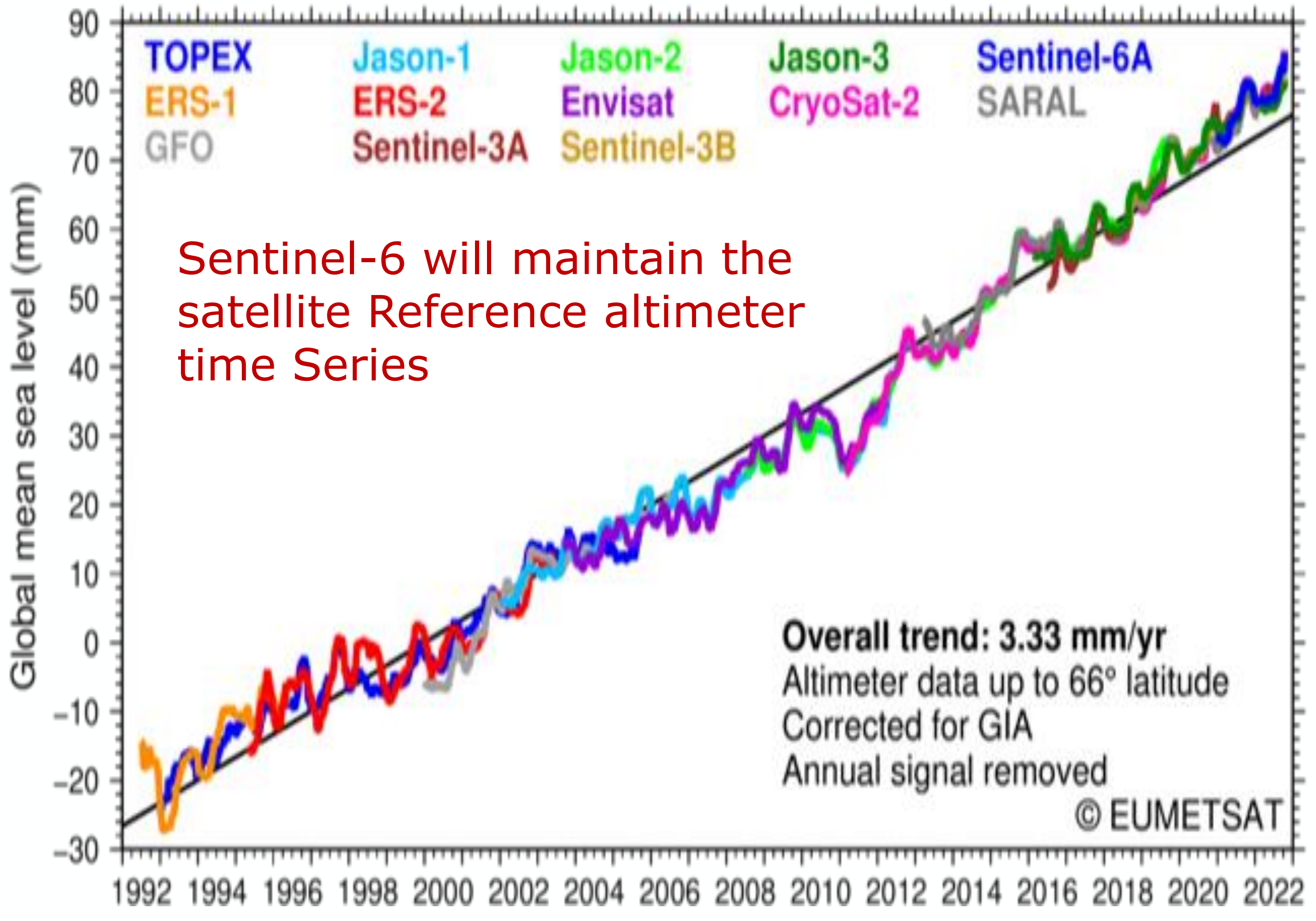
MRD-500 The calibration of L1b brightness temperature in all channels shall be maintained during science measurement acquisition using an on-board calibration system with at least two reference values that are traceable to SI.

MRD-770 A CIMR L1b data product shall contain the information necessary to generate all L2 products and populate the CIMR L1b uncertainty model.

MRD-780 Standard total uncertainties and quality indicators shall be delivered for all CIMR measurements in a L1b data product.


Sentinel-6 - dedicated to Sea Level Rise
esa
Sentinel-6B 2025-
Sentinel-6A 2019-
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES
NOAA
EUMETSAT
esa
NASA
European Commission

Sea-Level rise is a societal threat

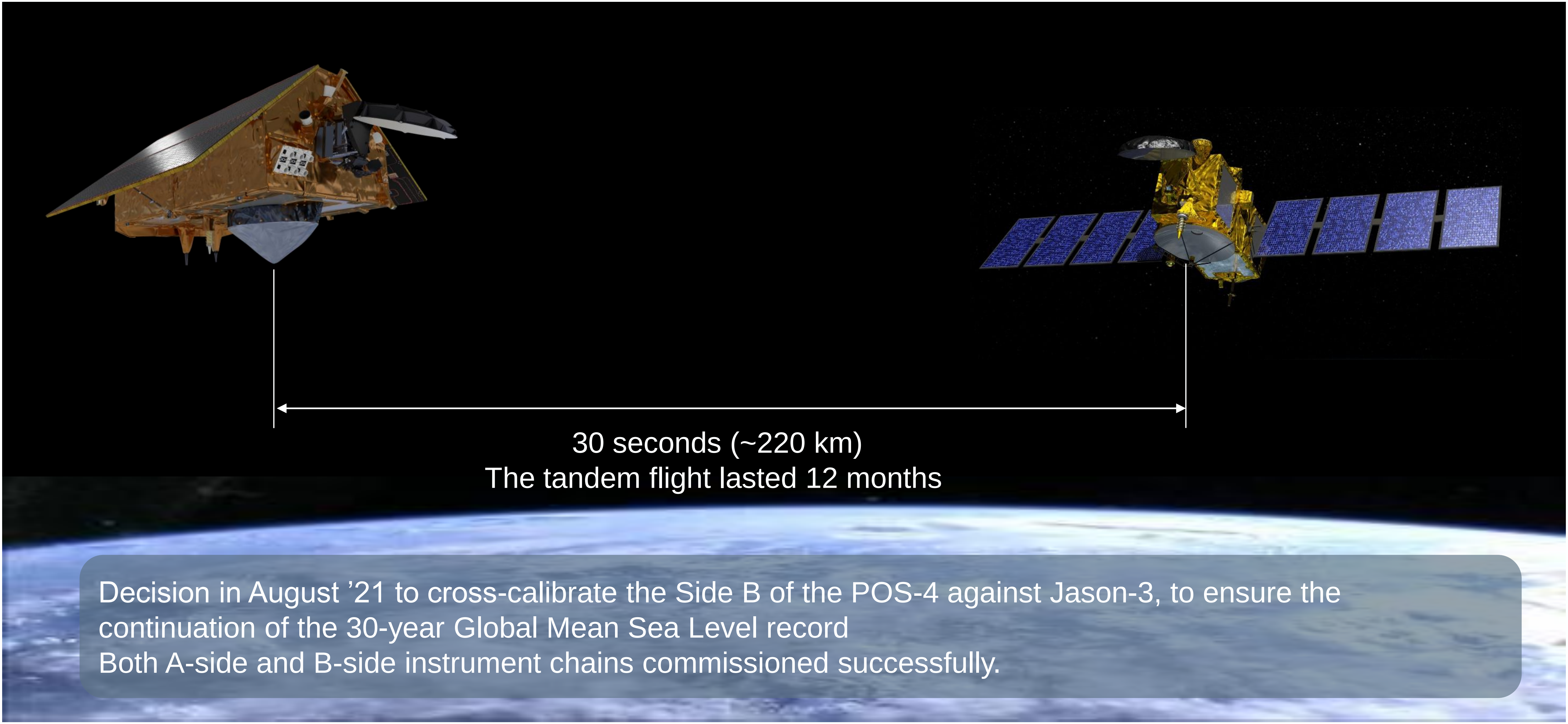


Low-lying coastal zone is home to 680 million people

3 million extra people at flooding risk for every cm of sea level rise

IPCC predictions for 2100 show 0.43 - 0.84 meter increase of average sea levels

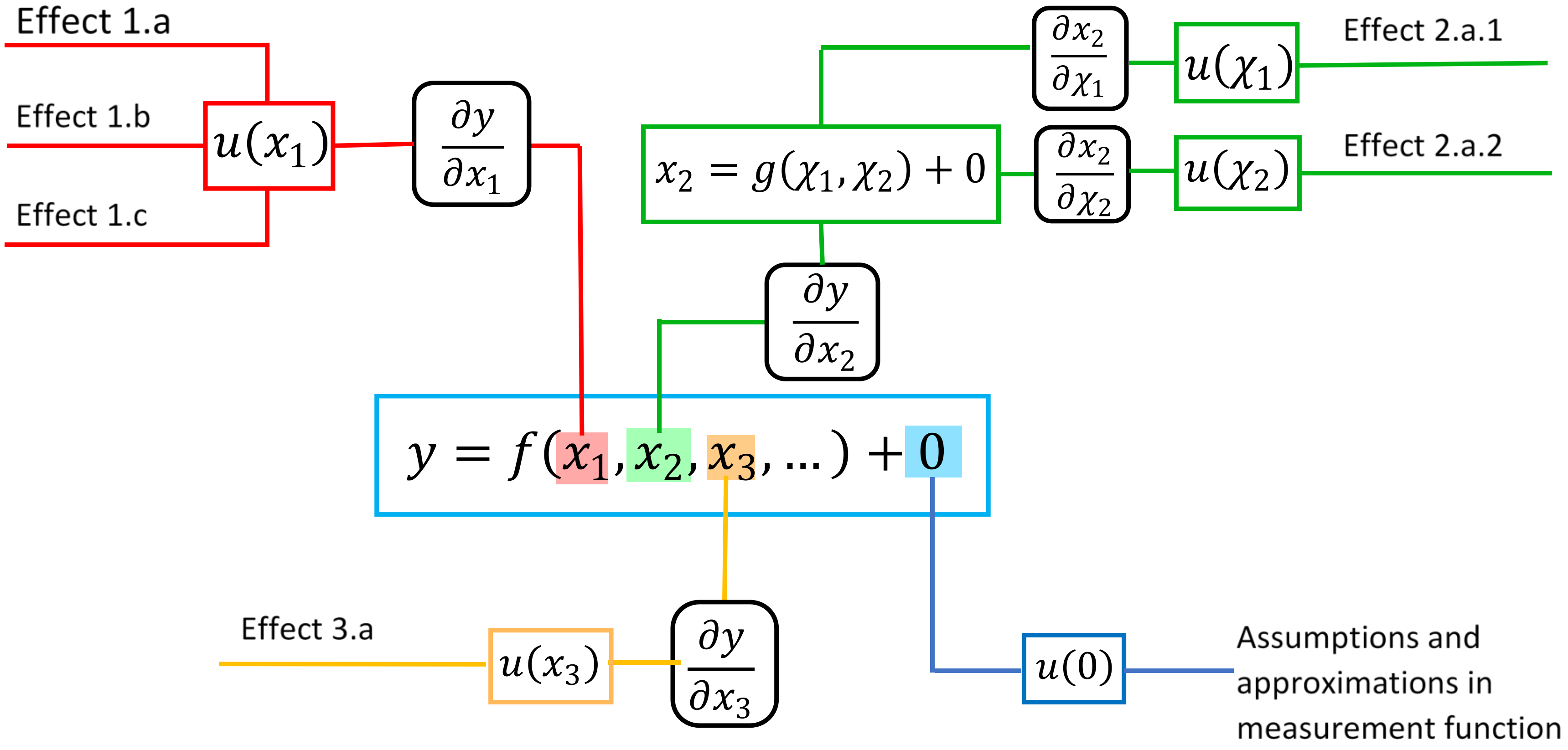
FRM: Sentinel-6 and Jason-3 Tandem flight



Decision in August ’21 to cross-calibrate the Side B of the POS-4 against Jason-3, to ensure the continuation of the 30-year Global Mean Sea Level record

Both A-side and B-side instrument chains commissioned successfully.

Methodologies – Uncertainty Tree Diagram



$$V(t_p, s) = \frac{\lambda_0}{(4\cdot\pi)^{\frac{3}{2}} L_{\mathrm{atm}}(s)} \cdot \int_{\mathrm{Vol}} \frac{\chi[t_{\mathrm{p}} - t_{\mathrm{r}}(\zeta, s)]G(x,y,s)R(x,y,\zeta)}{r^2(\zeta)} \exp[-i2\pi(f_0 + f_d)\cdot t_0 + \phi_0] \mathrm{d}x\cdot\mathrm{d}y\cdot\mathrm{d}z + n(t_{\mathrm{p}})$$

$|V(t_{\mathrm{p}}, s)|^2$ — Squared

$< |V(t_{\mathrm{p}}, s)|^2 >$ — Multilook

$$P_{\mathrm{ML}}(t_{\mathrm{p}}) = \frac{\lambda_0^2}{(4\pi)^3 L_{\mathrm{atm}}^2} \cdot \int_{\mathrm{Vol}} \frac{|\chi[t_{\mathrm{p}} - t_{\mathrm{r}}(z)]|^2 G^2(x,y)\sigma_0(x,y,z)}{r^4(z)} \mathrm{d}x\cdot\mathrm{d}y\cdot\mathrm{d}z + N(t_{\mathrm{p}})$$

Assumption 1: Far Zone

approximation due to far-zone =>

$$\frac{1}{r^4(z)} \approx \frac{1}{H^4}$$

Assumption 2: Antenna Pattern

$\theta_{3\mathrm{dB}}$ is 3dB antenna pattern aperture (characterised on ground)

ξ^2 is the squared antenna mispointing

G_0 is the antenna Gain at boresight (characterised on ground)

$$G_0^2 \exp\left\{-\frac{8\ln(2)}{\theta_{3\mathrm{dB}}^2}(\theta^2 - \xi^2)\right\}$$

$G^2(x, y)$ assumed to be **gaussian and isotropic** $(\theta_{x3\mathrm{dB}} = \theta_{y3\mathrm{dB}} = \theta_{3\mathrm{dB}})$:

Assumption 3: Gaussian Ocean

$\sigma_0(x, y, z)$ assumed to be gaussian with skewness of 0.1

$$\sigma_0(x,y,z) = Pu\left\{\frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)\left[1 + \frac{\lambda_s}{6}\left(\frac{z^3}{\sigma_z^3} - \frac{3z}{\sigma_z}\right)\right]\right\}$$

$\gamma_s = 0$ assumed E.M skewness — Assumption 3b

$$\sigma_0(x,y,z) = Pu\left\{\frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)\left[1 + \frac{\lambda_s}{6}\left(\frac{z^3}{\sigma_z^3} - \frac{3z}{\sigma_z}\right) - \frac{\gamma_s}{3}\left(\frac{z}{\sigma_z}\right)\right]\right\}$$

σ_z is sea surface height and $SWH = 4\sigma_z$ Gaussian distribution of ocean heights

Pu is amplitude of waveform and used to derive backscatter coefficent $\sigma_0(x, y, z)$

λ_s (ocean topography skewness) is given in input as 0.1

Assumption 4: Point Target Response

$|\sin c|^2$ approximated as gaussian with std σ_t

$$|\chi[t_p - t_r]|^2 = |\sin c[B_r(t_p - t_r)]|^2 \approx \exp\left[-\frac{1}{2\sigma_t^2}(t_p - t_r)^2\right]$$

$$P_{\mathrm{ML}}(t_p) = \frac{\lambda_0^2}{(4\pi)^3 L_{\mathrm{atm}}^2 \cdot H^4} \cdot \left(\int_{\mathrm{Vol}} |\chi[t_{\mathrm{p}} - t_r(z)]|^2 G^2(x,y)\sigma_0(x,y,z)\mathrm{d}x\cdot\mathrm{d}y\cdot\mathrm{d}z\right)\cdot \mathrm{gamrnd}\left(L, \frac{1}{L}\right) + N(t_{\mathrm{p}})$$

$$P_{\mathrm{ML}}(t) = A\exp(-v_1)\cdot[1 + \mathrm{erf}(u_1)] - \frac{A}{2}\cdot\exp(-v_2)[1 + \mathrm{erf}(u_2)]$$

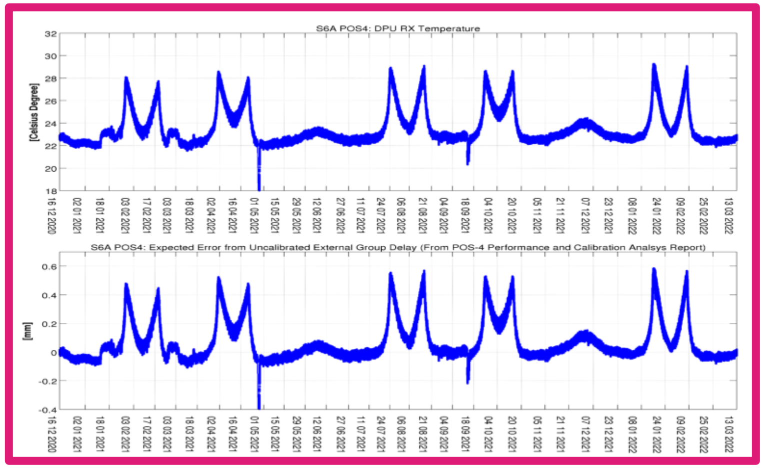
(E. Wooliams)

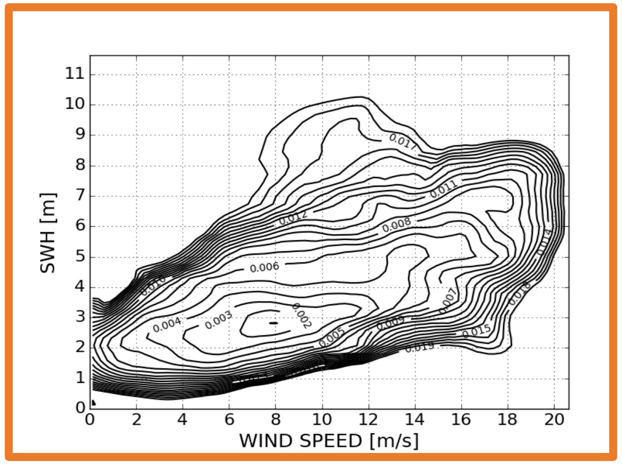
Propagating Uncertainties and Error Correlation Structures through Retracking and Sea State Bias Correction

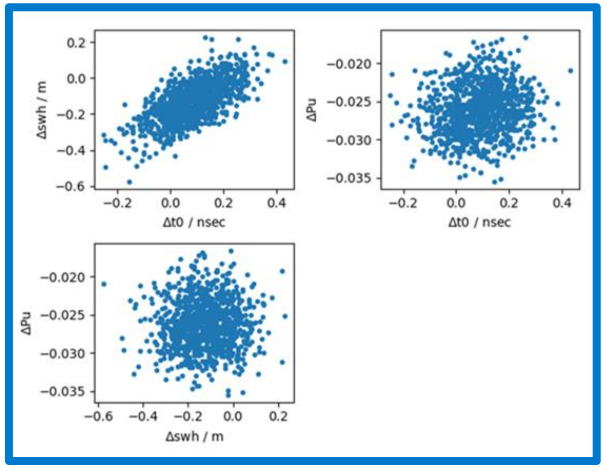
Sajedeh Behnia[a], Jonathan Mittaz[a,b], Hannah Cheales[a], and Emma Woolliams[a]
[a]National Physical Laboratory and [b]Reading University

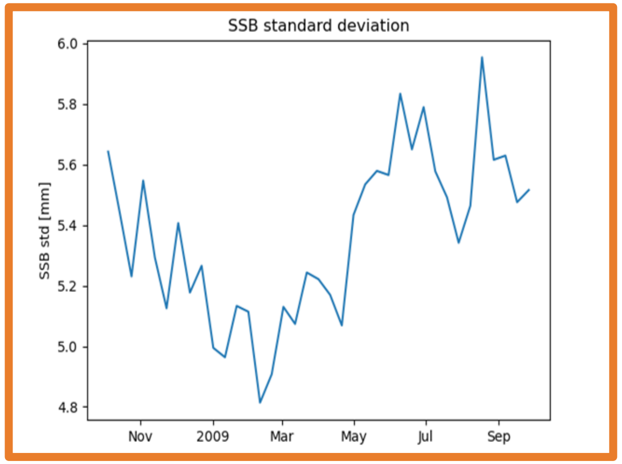
National Physical Laboratory
2022 Ocean Surface Topography Science Team (OSTST) meeting

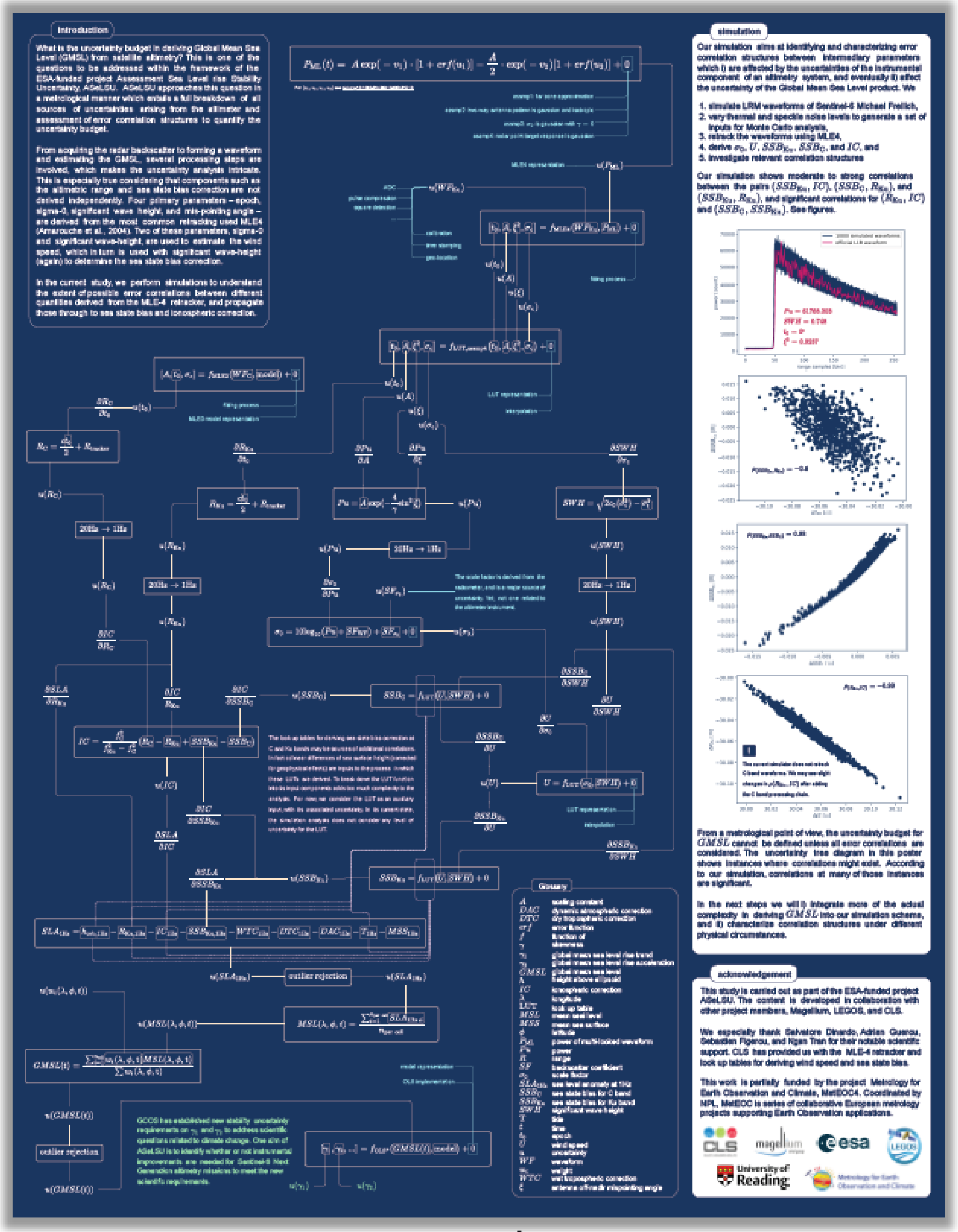
ESA ASELSU Study



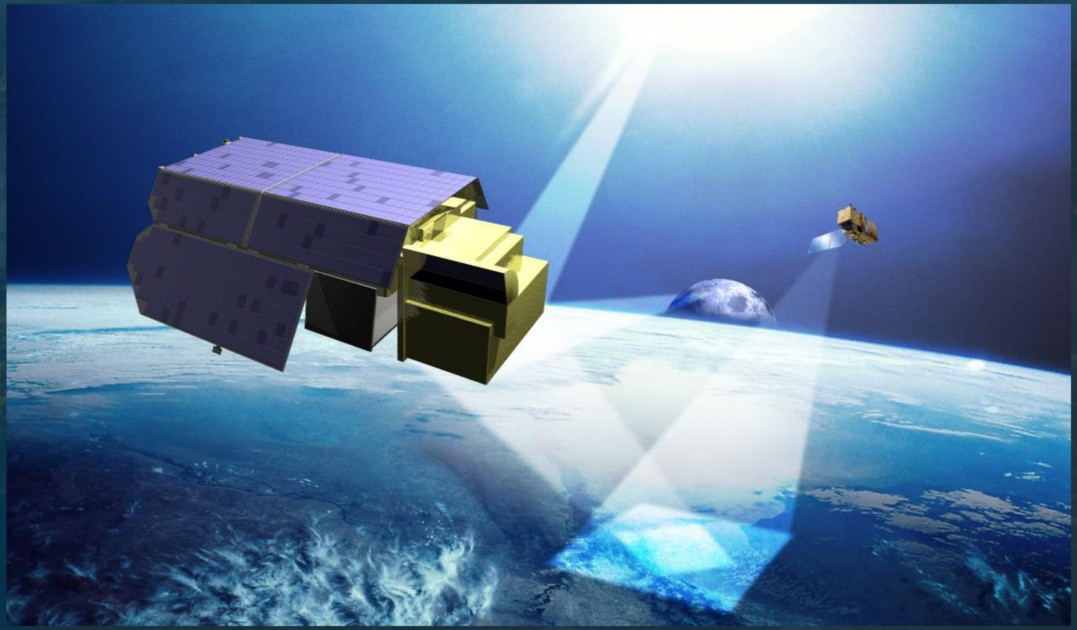








T raceable
R adiometry
U nderpinning
T errestrial- &
H elio-
S tudies



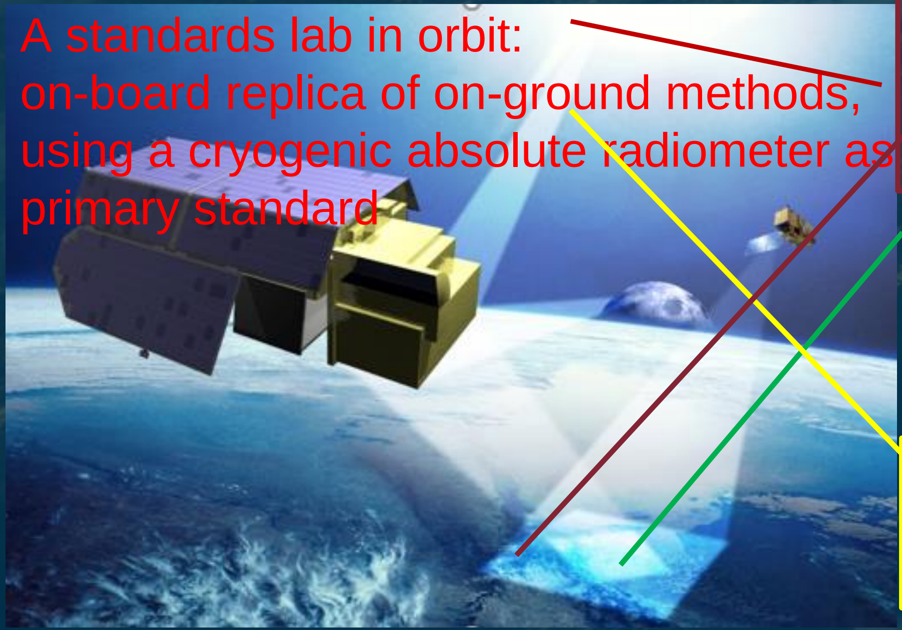
A 'gold standard' reference in space to support the climate emergency

An ESA EarthWatch mission

SITSats and TRUTHS Mission Objectives

*What is a SITSat?: 'Space borne missions specifically designed, characterised and documented to provide **high accuracy SI-Traceable** 'reference' measurements.' (Evidencing comprehensive uncertainty to SI, 'in-space', of all contributors to observations made from the satellite)*

TRUTHS is an **operational climate mission**, that will enable:



1. **Climate benchmarking:** enhance our ability to estimate the **Earth Radiation Budget** (and attributions) through direct measurements of incoming & outgoing energy and reference calibration of other ERB & similar missions.
2. **Satellite cross-calibration:** establish a 'standards laboratory in space' to create a '**gold standard**' reference data set to cross-calibrate other sensors and improve the quality and interoperability of their data throught: simultaneous observations, surface reference sites and the moon
3. provide SI-traceable measurements of the **solar spectrum (incoming & reflected)** to address its impact on climate and interactions with the atmosphere and surface

*A **benchmark measurement** is one with characteristics (documentation, SI-Traceable uncertainty, representative sampling) that allows it to be unequivocally considered a 'reference' of the specified measurand against which future measurements of the same measurand, can be compared.*

Conclusion

- **Climate data records from satellites** are a fundamental at ESA – **we are committed** to deliver *Climate Space*
- **Metrology is essential** due to the overwhelming volume of data from space: small errors have major impacts on climate time series
- We are **embedding Metrology** (uncertainty and traceability) into all of our satellite engineering and scientific processes:
  - In our satellite designs and data processing
  - Via Fiducial Reference Measurements (FRM) for validation
  - For our flying constellations using tandem flights
  - In new SITSat missions dedicated to SI traceability (e.g. TRUTHS)
  - By implementing QA4EO uncertainty modelling techniques

ESA recognises **the essential role of the International System of Units (SI) in providing confidence in the accuracy and global comparability of measurements** needed for protection of the environment, global climate studies and scientific research

Thank you Any Questions?

Contact:
Craig.Donlon@esa.int

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