Establishing the SI in space for climate action

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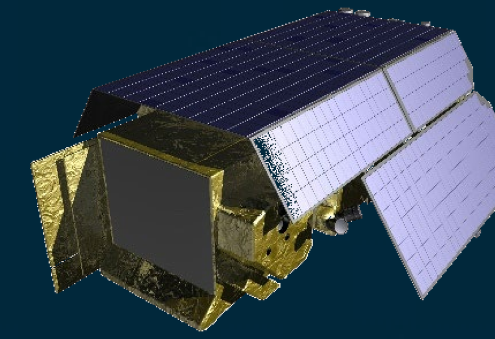
SI ~1875



SI in space, ~2030+ (TRUTHS)

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1. Introduction : The Earth is warming with consensus that mankind is the major cause. The potential for societal catastrophe is second to none!. The 'Paris Agreement' (2015) sought to contain the rise in mean Earth temperature to <2°C above pre-industrial levels with a target of <1.5°C, leading to the establishment of 'NetZero' emissions targets for the 2050s. Realistically we are now targeting <2.5-3°C

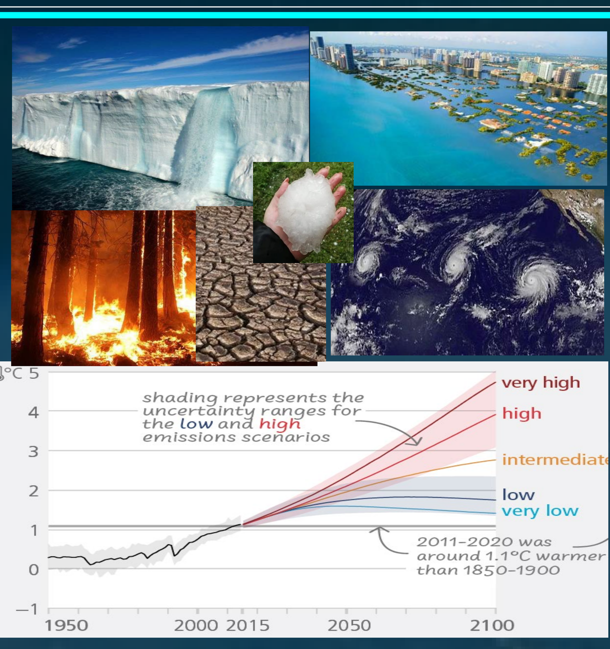


Fig 1: potential impacts of climate change, 202

2. Grand Metrology Challenge: To detect 'change', including results of mitigation, requires benchmark references of the state-of-the-planet. The 55 Essential Climate Variables (ECV), Fig.2, of GCOS [1] represent planetary indicators responding to or impacting radiation imbalance, Fig 3, and consequential Earth temperature.

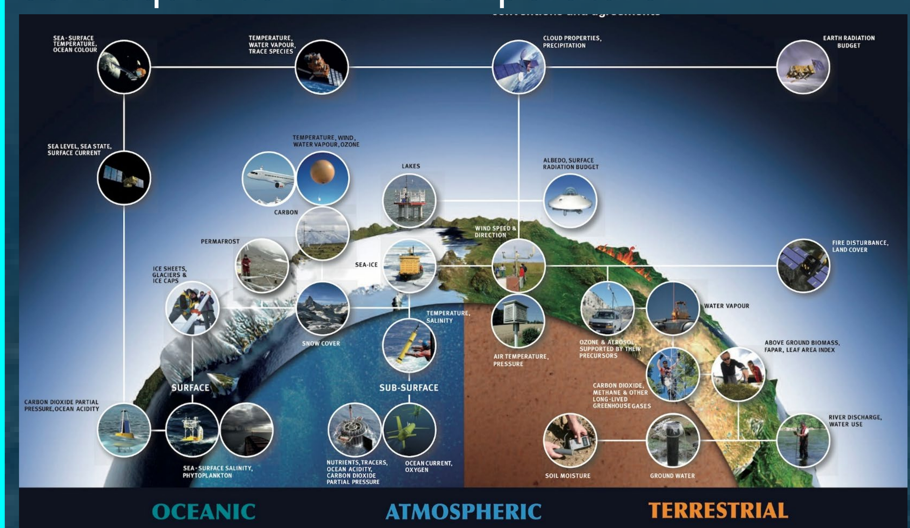


Fig 2: ECVs of WMO Global Climate Observing System (GCOS)

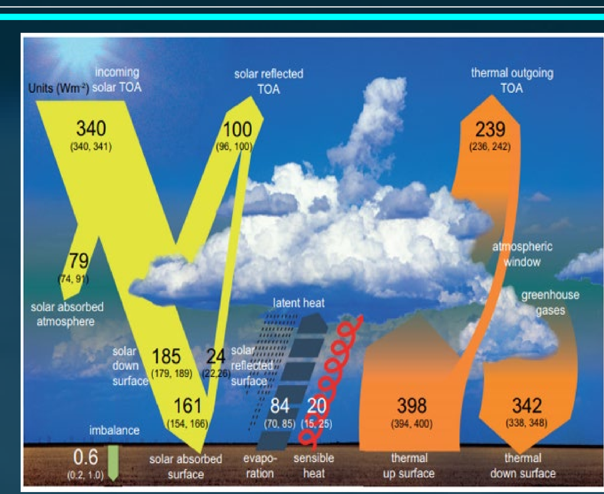
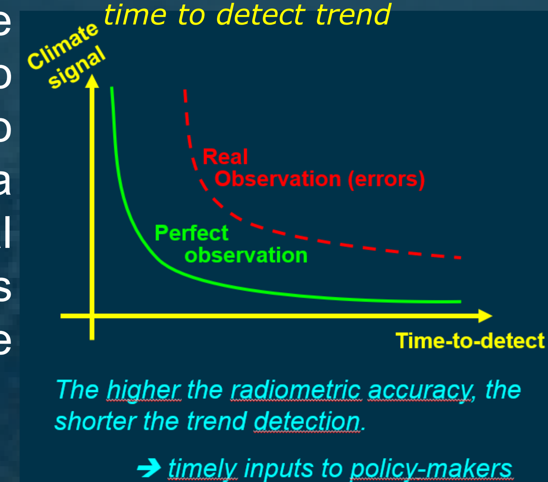


Fig 3: Illustration of Energy cycle and imbalance [2]

Benchmarks need to have sufficient accuracy & trust to allow small signals/trends to be detected from a background of natural variability (noise). This requires decades to become large enough to detect, Fig 4.

2/3rds of ECVs require observations from space. But our satellites degrade and we cannot achieve SI traceable uncertainties at the levels needed (close to the best achievable in NMI laboratories) in the harsh environment of space. Can Metrology help?

Fig 4: How uncertainty improves time to detect trend



3. Observing Earth from space

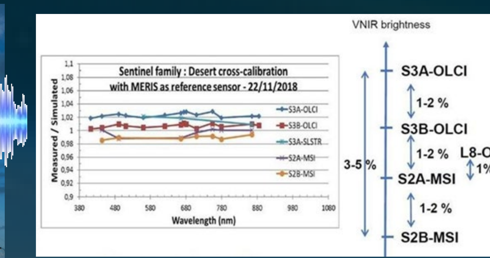


Fig 5: Radiation damage to glass

Fig 6: Biases of various optical sensors viewing same target. Broadly self-consistent but differ between themselves so where is the true value?

Although satellite sensors can be well-calibrated to SI pre-launch, they are invariably stored for months/years, then the violence of launch before exposure to radiation & vacuum (see discoloration of glass, Fig 5.). On-board 'calibration' systems suffer the same leaving in-flight uncertainties relatively large and biases between sensors, Fig 6.

Post-launch validation - comparing to 'stable' natural targets e.g. deserts & moon - can help assess stability.

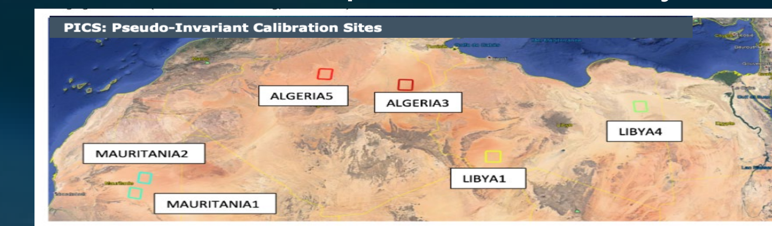


Fig 7: CEOS reference desert sites, so called Pseudo Invariant Calibration sites (PICS).

'Field-campaigns' with SI-traceable instruments measuring the same earth scene/parameter can establish performance boundaries, but uncertainties are inadequate.

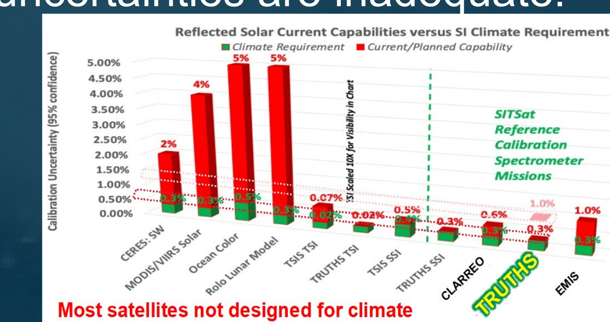


Fig 8: Uncertainties of current observing system (red) and climate need (green) [3].

4. Fiducial Reference Measurements (FRMs) Policy makers & other risk/financial sensitive organisations need for robust evidence to take reliable action led the worlds space agencies to embrace the concepts of metrology, with the aim to provide quantitative indicators of quality, (although QA4EO was only formalised by Committee on Earth Observation Satellites (CEOS) in 2010 [4]).

Fig 9: Break in traceability chain leads to data unreliability.

Since then, efforts to engage with NMIs and evidence SI-traceability has increased dramatically.

To distinguish 'field' measurements undertaken following metrological best practise, CEOS has created criteria and associated assessment process to certify satellite validation activities into classes of FRM quality [5].

5. SI-Traceable Satellites, (SITSats) In 2001, NPL led an international team to propose a novel satellite mission called Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) to an ESA call for ideas [6]. TRUTHS sought to establish a metrology capability in space providing SI-traceable calibrations to tother satellites in addition to its own observations of the Earth and Sun at unprecedented uncertainties of <0.5% for the Earth. *Such satellites have now been designated as a new class, called SITSats.*

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The uncertainty was to be achieved on-board through the flight of a primary SI optical radiometric standard, a cryogenic radiometer and associated equipment to mimic a pre-flight ground calibration. Feedback indicated the concept was a good solution but at the time 'no one needed better uncertainties than currently achieved (~5%!)'.

6. TRUTHS was incorporated into the ESA Earthwatch program in 2019, funded by a a partnership of nations led by the UK together with Switzerland, Czech Republic, Greece and Romania and more recently Spain. This success was greatly enhanced through a robust science case helped by efforts from a NASA project called CLARREO [7] which, in 2013 responded to a climate need of the US decadal survey [8].

Measures incoming & Earth/Moon reflected radiation from the Sun

- **320 to 2400 nm @ ~4-6 nm BW (1 nm for solar UV)**
- **Global nadir @ 50 m ground resolution (capability) with 100 km swath**
- **Target uncertainty of 0.3% (k=2) (spectral**

Fig 10: What TRUTHS does! – performance & applications.

The mission comprises a hyperspectral imager (HIS) providing spectrally continuous observations of the sun & Earth [9].

The spectral range and bandwidth allow it to address nearly 20 ECVs and convolve with the observational characteristics of other sensors so that TRUTHS can provide a calibration. The uniqueness is of course the SI-traceability and uncertainty achieved from the on-board calibration system which has not changed in substance to that proposed in 2001.

7. A metrology laboratory in space The highest accuracy pre-flight radiometric calibration of an imaging optical sensor now uses tuneable laser radiation as a source. This monochromatic radiation is typically converted to radiance by reflection from a diffusely reflecting panel or integrating sphere. The radiance is then tied to SI-units through a solid-state detector traceable to a cryogenic radiometer (compares the heating effect of optical and electrical power) [10,11]. For TRUTHS, this chain is replicated - although sunlight dispersed by a prism monochromator replaces the laser as the radiation source. The only aspect that is not recalibrated in orbit is the absorptance of the cavity absorber of the Cryogenic Solar Absolute Radiometer (CSAR) (~0.99995) and the voltage/resistor references determining power,

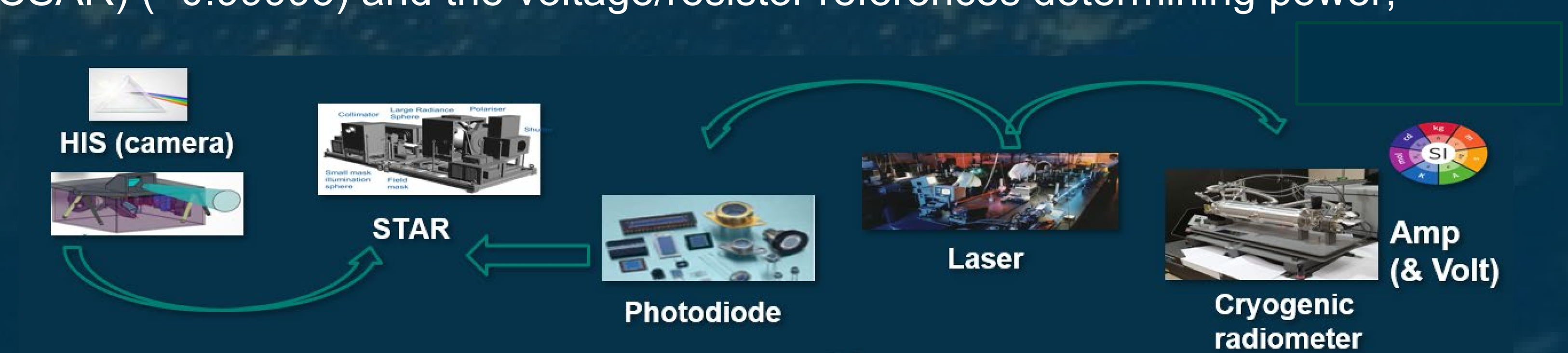

Fig 11a: Terrestrial pre-flight calibration traceability chain from cryogenic radiometer to instrument (HIS) using a tuneable laser. The STAR is an NPL facility incorporating a tuneable laser and integrating sphere for deployment in a clean room to calibrate sensors under vacuum.

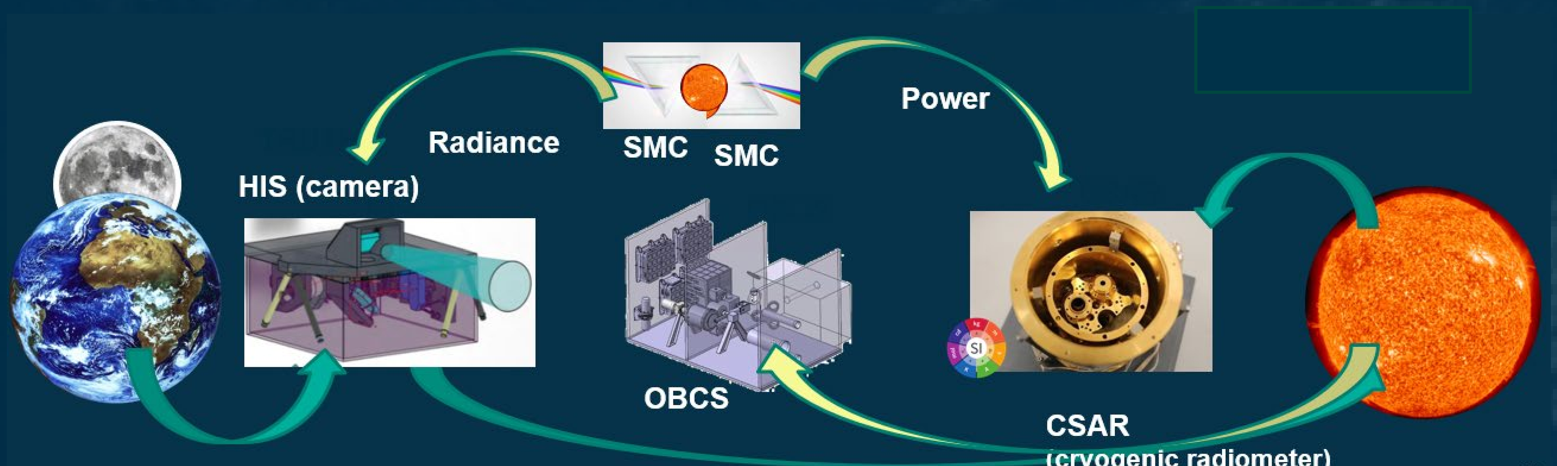

Fig 11b: The on-board calibration facility of TRUTHS with the OBCS comprising an integrating sphere and monochromator (SMC) to disperse solar radiation in place of laser radiation.

8. Delivering SI from space Following calibration (~fortnightly) the CSAR observes changes in total energy arriving at the Earth from the Sun at <0.02% uncertainty and the HIS measures either the sun or moon as the satellite moves into Earth eclipse or reflectance from the Earth during sun-lit part of the orbit. TRUTHS thus establishes benchmarks to assess attribution to changes in energy imbalance and various cycles (carbon/water) of the Earth system.

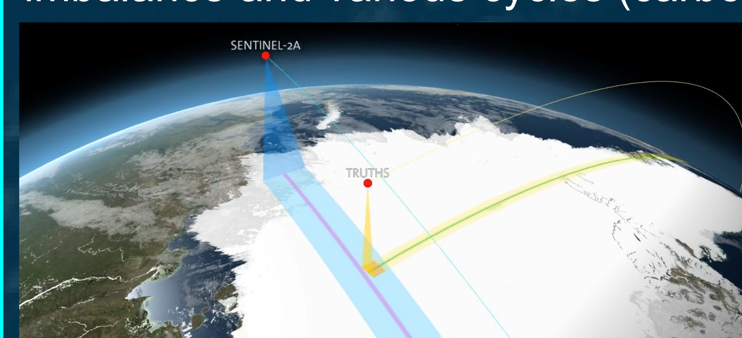

Fig 12: The observation track of TRUTHS (green/yellow) overlapping with the track of a sun-synchronous satellite such as Sentinel 2 over the polar region (left). The right-hand picture shows the simultaneous (within 15 min) overlaps of TRUTHS and Sentinel 2 over a 6 month period.

The orbit of TRUTHS (90° polar) is selected to allow the diurnal cycle to be evaluated. It also allows simultaneous nadir observations with other satellites on a regular basis. This enables TRUTHS to provide in-flight calibrations to upgrade and certify the performance of the global space-based observing system. Removing biases in data from agencies and commercial satellites to allow harmonisation and embed trust through SI-traceability leading to unequivocal evidence to underpin 'fit for purpose' climate action.

9. Summary The SI has served terrestrial science and commerce for 150 years through provision of invariant references and principles to anchor and harmonise measurements across the world and time. We are now in an era where the SI needs to extend its reach to ensure it can meet the challenges of primary standard level uncertainties in harsh environments of deserts, oceans, cryosphere and in particular space. FRMs and their space version, SITSats, illustrate the journey and progress that SI is making in partnership with the climate observation community. fit for purpose climate action.

10. References

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