Low Uncertainty Earth Observation Satellite data with the Calibration Life Cycle
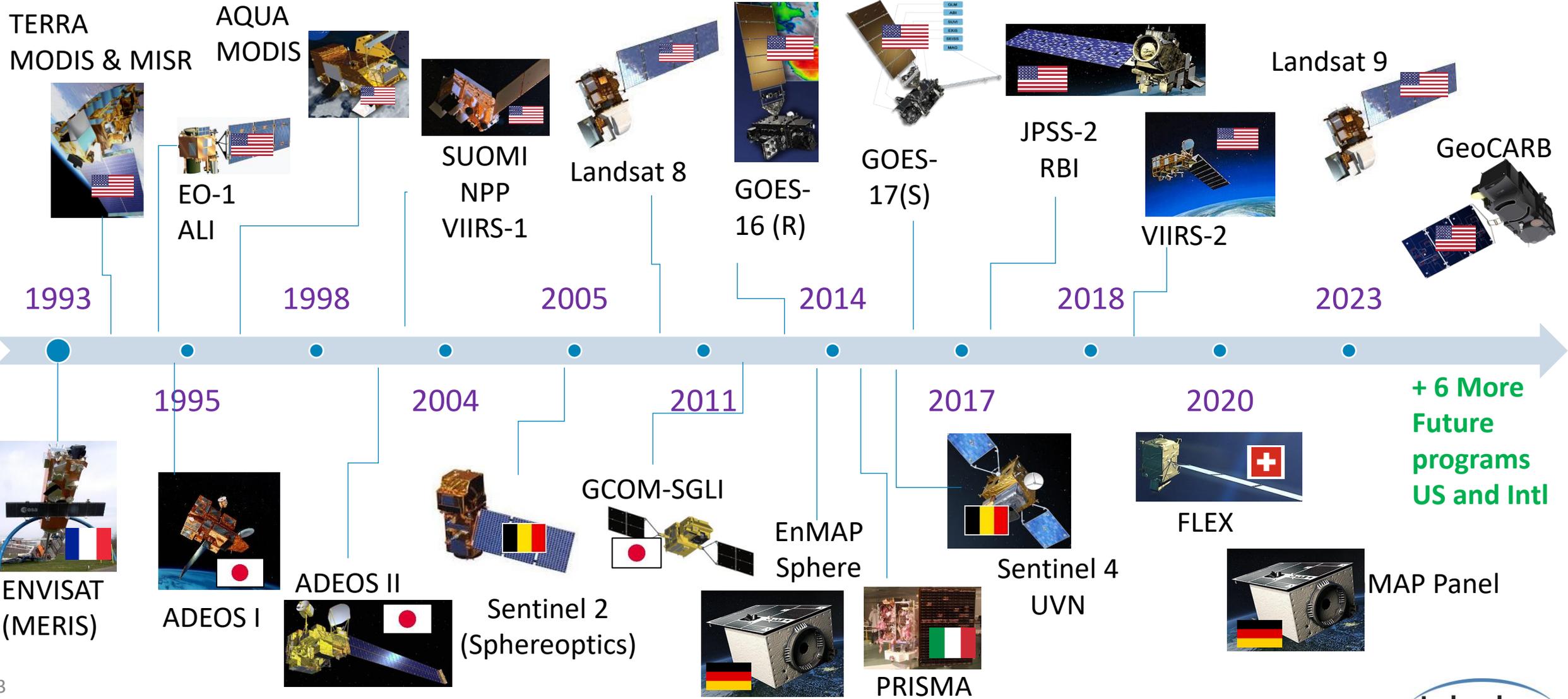## ISIEX January 28, 2026

Theodore Schwarz, Optical Applications Engineer,
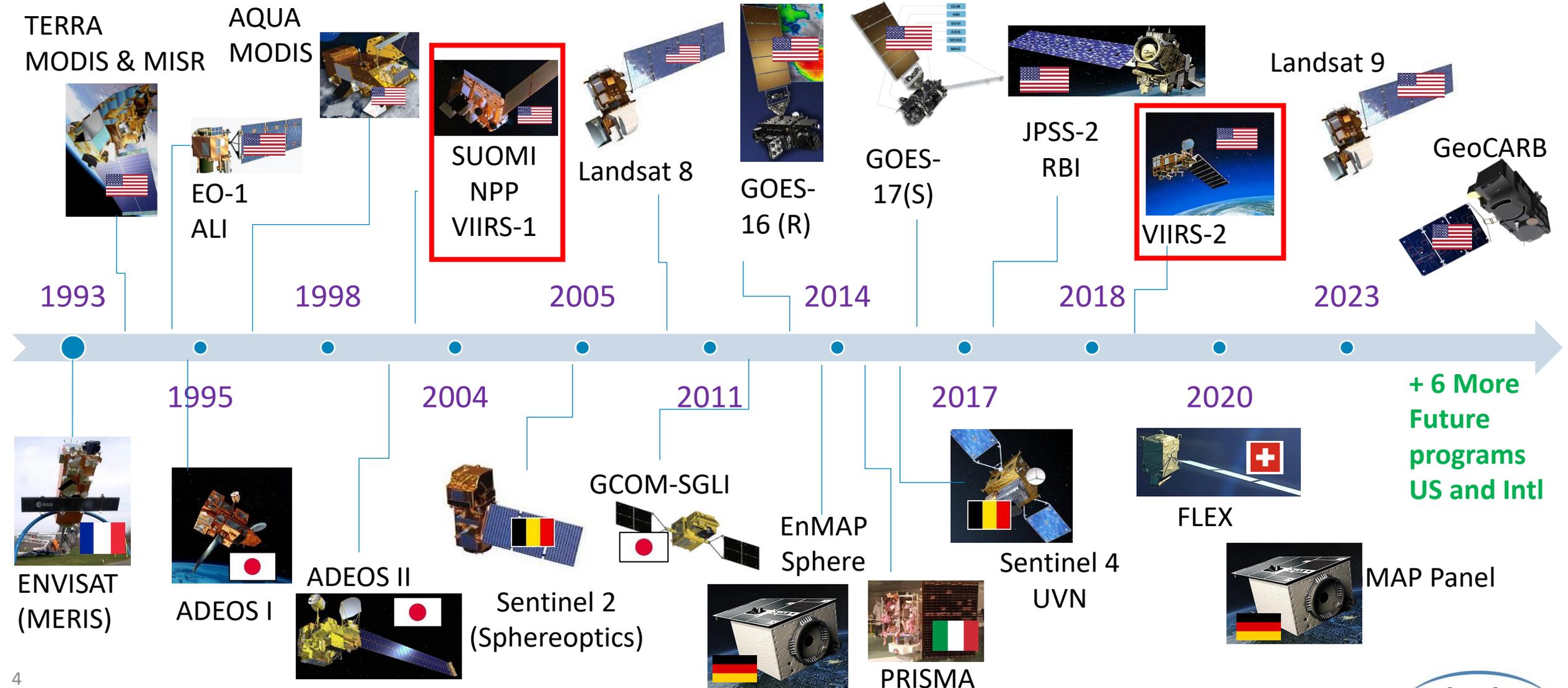Labsphere (NH USA), tschwarzlabsphere.com, C: +1 617-304-4255

1

Overview

- **Labsphere**
  - History of involvement with Earth Observation calibration
- **Why lower uncertainty is a requirement**
  - Value and Revenue…and Calibration?
- **Uncertainty Specifics**
  - End result
  - Underlying equations
- **The Calibration Life Cycle**
  - How to achieve low-uncertainty

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Labsphere history with On-Board EOS Calibration

TERRA
MODIS & MISR

AQUA
MODIS

EO-1
ALI

SUOMI
NPP
VIIRS-1

Landsat 8

GOES-
16 (R)

GOES-
17(S)

JPSS-2
RBI

Landsat 9

GeoCARB

VIIRS-2

1993

1998

2005

2014

2018

2023

1995

2004

2011

2017

2020

+ 6 More
Future
programs
US and Intl

ENVISAT
(MERIS)

ADEOS I

ADEOS II

Sentinel 2
(Sphereoptics)

GCOM-SGLI

EnMAP
Sphere

PRISMA

Sentinel 4
UVN

FLEX

MAP Panel

Timeline Dates are Labsphere Product Completion (not launch)

Labsphere

Labsphere history with On-Board EOS Calibration

TERRA MODIS & MISR

AQUA MODIS

EO-1 ALI

SUOMI NPP VIIRS-1

Landsat 8

GOES-16 (R)

GOES-17(S)

JPSS-2 RBI

VIIRS-2

Landsat 9

GeoCARB

1993 **1998** **2005** **2014** **2018** **2023**

1995 **2004** **2011** **2017** **2020** + 6 More Future programs US and Intl

ENVISAT (MERIS)

ADEOS I

ADEOS II

Sentinel 2 (Sphereoptics)

GCOM-SGLI

EnMAP Sphere

PRISMA

Sentinel 4 UVN

FLEX

MAP Panel

Timeline Dates are Labsphere Product Completion (not launch)

NOAA JPSS-VIIRS instrument

- Polar orbiting weather satellites

- VIIRS instruments on JPSS 2, 3, and 4 spacecraft

- Pre-launch calibration during ambient and TVAC campaigns

- Utilizing novel Labsphere uniform source solutions

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The Need for Low Uncertainty

- Decadal survey benchmark measurements
  - IR flux (λ) to space (0.065K)
  - Reflectance (λ) of solar radiation to space (0.3%)
  - Traceable to SI Watt

- Information on critical forcing:
  - Atmospheric temp, water
  - Radiative flux
  - Cloud/surface albedo
  - Temp/emissivity

Reflected Solar Accuracy and Climate Trends
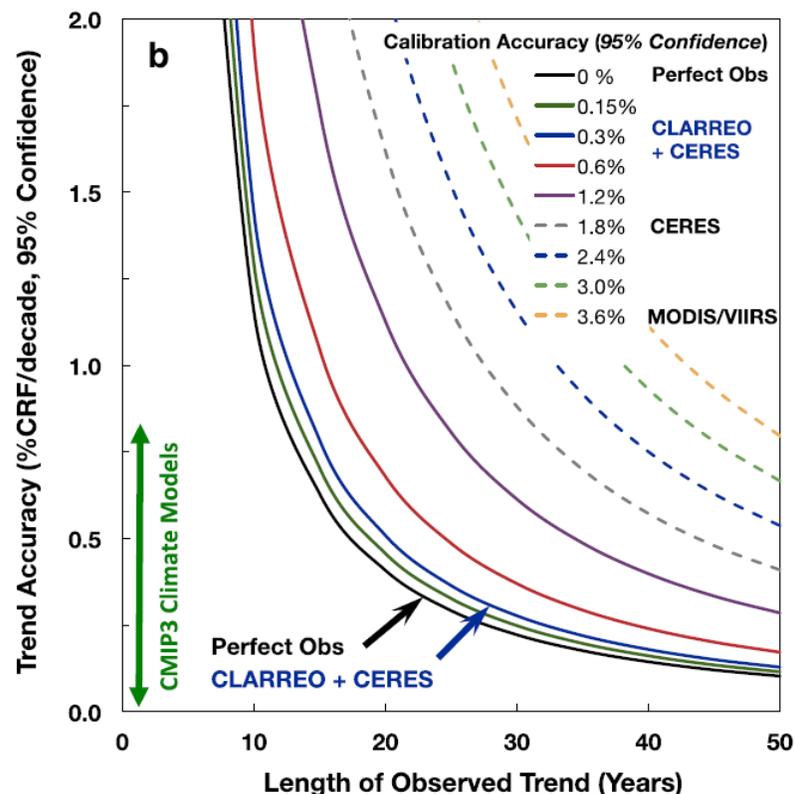
Climate Sensitivity Uncertainty is a factor of 4 (IPCC) which = *a factor of 16 uncertainty in climate change economic impacts*

Climate Sensitivity Uncertainty = Cloud Feedback Uncertainty = Low Cloud Feedback = *Changes in SW CRF/decade (y-axis of figure)*

Higher Accuracy Observations = CLARREO reference intercal of CERES = *narrowed uncertainty 15 to 20 years earlier*

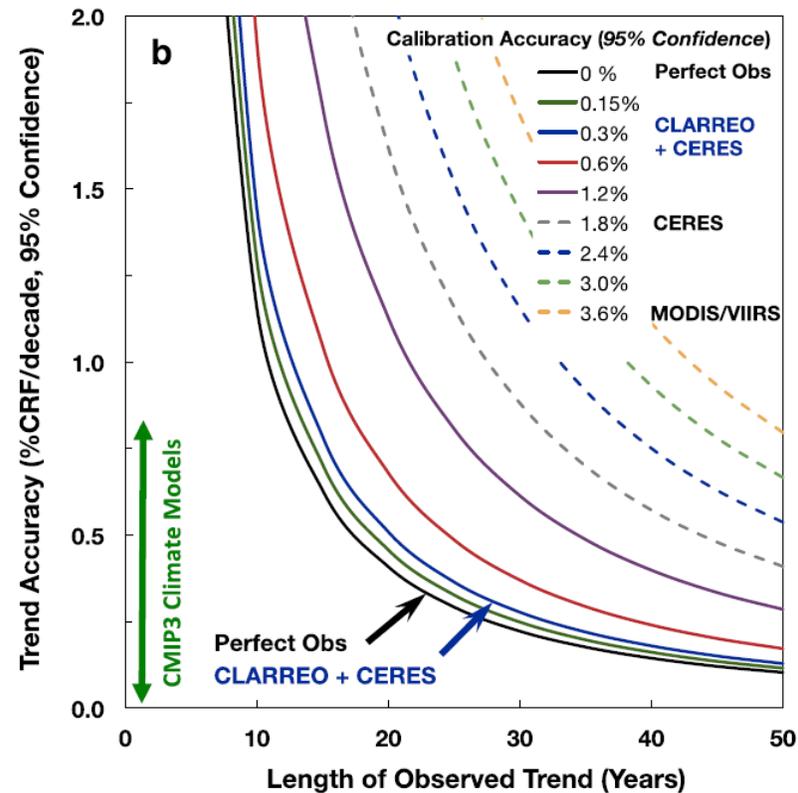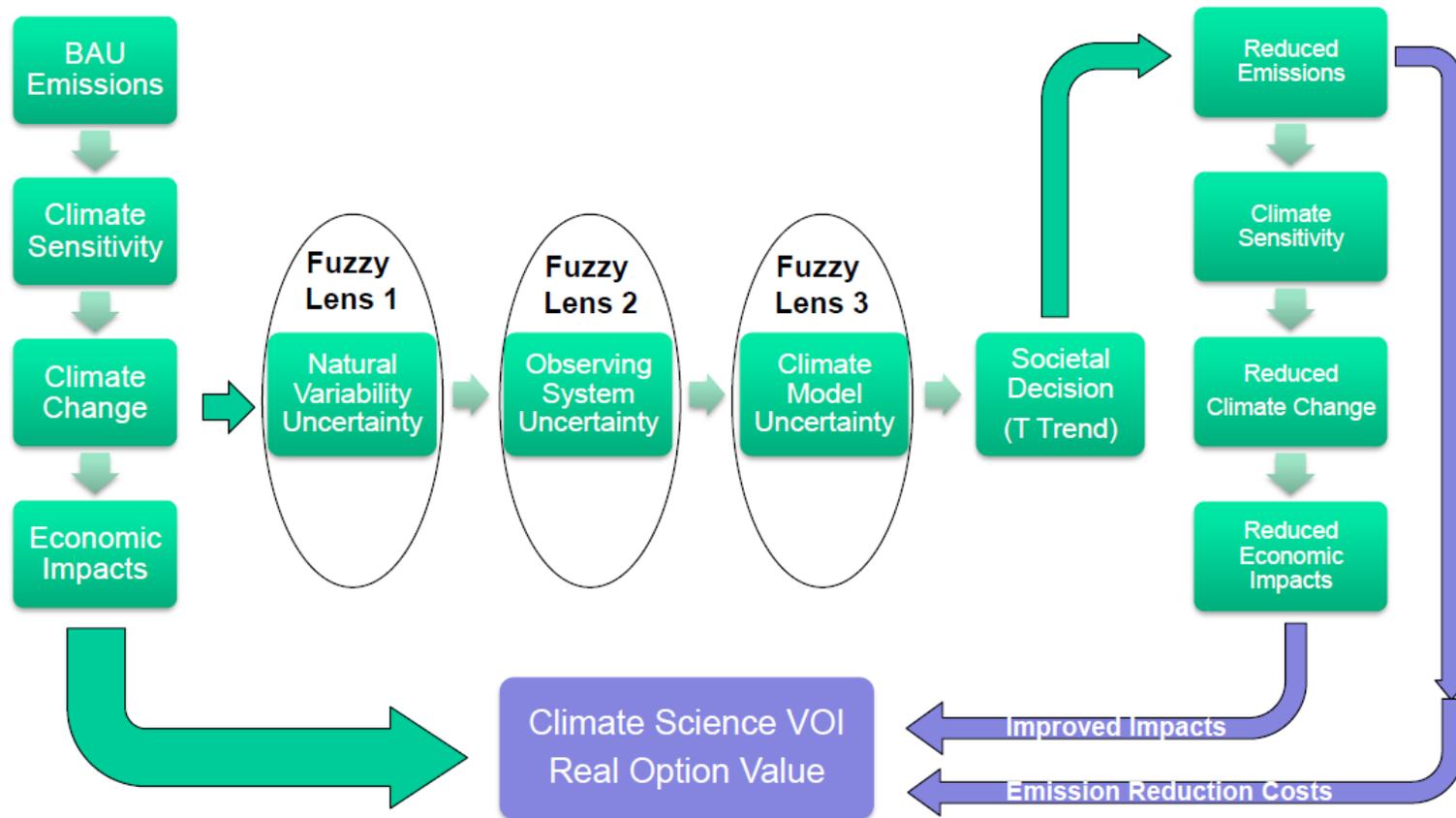*Wielicki et al. 2013, Bulletin of the American Meteorological Society*

High accuracy is critical to more rapid understanding of climate change

6

Wielicki, B.A. et al. 2013. Achieving climate change absolute accuracy in orbit. *Bull. Amer. Meteor. Soc.*, **94**, no. 10, 1519-1539

Confi

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The Need for Low Uncertainty

- Data record is limited by the noise of natural variability

- Multiple variability ranges
  - ENSO 3-5 yrs
  - Solar output 11 yrs
  - Pacific decadal 10-30 yrs

- Perfect observing system – 12 yrs
  - Uncertainty in measurements increases required record length

- Value of lowered uncertainty is estimated in the *trillions*

Reflected Solar Accuracy and Climate Trends

Calibration Accuracy (95% Confidence)
- 0 % — Perfect Obs
- 0.15%
- 0.3% — CLARREO + CERES
- 0.6%
- 1.2%
- 1.8% — CERES
- 2.4%
- 3.0%
- 3.6% — MODIS/VIIRS

Climate Sensitivity Uncertainty is a factor of 4 (IPCC) which = *a factor of 16 uncertainty in climate change economic impacts*

Climate Sensitivity Uncertainty = Cloud Feedback Uncertainty = Low Cloud Feedback = *Changes in SW CRF/decade (y-axis of figure)*

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Wielicki et al. 2013, Bulletin of the American Meteorological Society

High accuracy is critical to more rapid understanding of climate change

Wielicki, B.A. et al. 2013. Achieving climate change absolute accuracy in orbit. *Bull. Amer. Meteor. Soc.*, **94**, no. 10, 1519-1539

How does Uncertainty equal Value?

VOI Estimation Method: Cooke et al. 2016a

- Better Modeling
- Better predictive power
- Long term infrastructure planning
- Change perception and get humans to "do the right thing"

Wielicki, B.A., Cooke, et al., Economic Value of a More Accurate Climate Observing System. 2017 Calcon Proceedings

Societal Need for an Advanced Climate-Observing System

- An **advanced climate observing system** (*including SITSats*) **could reduce trend-detection uncertainties by 15 to 30 years from current approaches**

- **Cost and Economic Value**
  - Current expenditures on climate research (globally) – $4 billion U.S. per year
  - Estimated costs of an advanced climate observing system – $12 billion U.S. per year for 30 years (triple current levels)
  - Global gross domestic product (GDP) – $85 trillion U.S.
  - "Business as usual" estimated damages in second half of this century
    - 0.5% to 5% of GDP ($0.4 to $4 trillion U.S. per year)
  - Economic value of better data and decisions through 2100 – $5 to $20 trillion U.S.
  - Cost of delaying – $500 billion U.S. per year
  - Return on investment – $50 per $1 invested

  Discount rate applied: 3%/yr. Results from Cooke et al. 2014, 2016, 2020

> Cost of delay in establishing an adequate climate observing system is 50X that of the investment

Wielicki, B.A., Cooke, et al., Economic Value of a More Accurate Climate Observing System. 2017 Calcon Proceedings
SI-Traceable Space-based Climate Observing System (SITSCOS), 2019 NPL Workshop

Interoperability

- **The most valuable data is Interoperable data = where the data utility is not dependent on its source and it can be readily combined with data from other sources.**

- **BUT, even the "same" satellites are not the same**
  - It takes a lot of effort to make them match up
    - Like two watches set to different time zones without a common reference.

- **EX: Landsat 8 and 9 were identical builds and there were still differences at initial launch that had to be corrected. They are now within 1%, but after calibration.**
  - Fundamentally, if the data is not right, your ability to "fix it" with software…without breaking something else…is the limit of that data's utility.

- **EX: It has taken years and thousands of man hours to make Sentinel 2 and Landsat 8 Interoperable**
  - That is (2) satellites: How can this be done in the scale of constellations?

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One Satellite vs. A Constellation

- **We are now launching dozens of lower cost EOS satellites a year….and generations of satellites to act as homogenous imaging systems**

- **What needs to change to enable these sensors to be at "science" level?**

- **Calibration techniques need to evolve to the support the nature of the target observations.**

- **Calibration needs to become ubiquitous, automated, and independent of expert intervention….and CHEAP.**
  - How can calibration scale to meet this need?

- **EX: Spectral Band Adjustment Factors (SBAFs) lead to better consistency.**
  - BUT these techniques are just pushing the energy around and not fixing the fundamental problem?
  - Are SBAFs "calibration" or a short-cut to consistency?

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Value-centric design methods were developed for fractionated spacecraft architectures

Valuation of Small Satellite Data

- Value-centric design methodology* has been used to quantify life-cycle value of fractionated spacecraft architectures
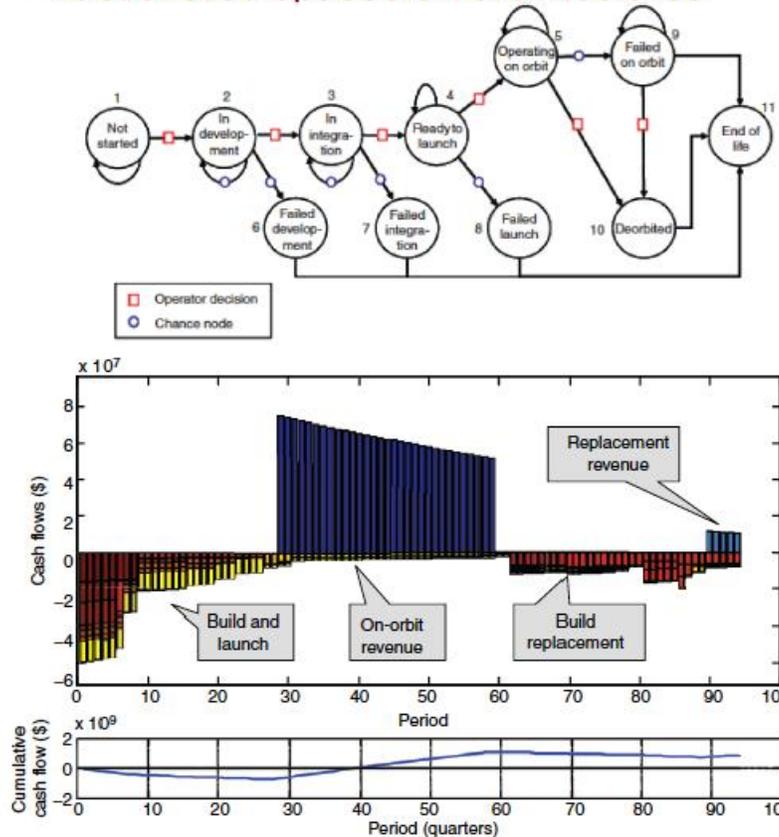
- NRC Recommendation: "NASA should establish a value-based decision approach..." [2015]

- "a value-centered framework is capable of distinguishing among competing Earth measurements" – [NRC committee, 2015]

$$V = B \times A = (I \times U \times Q \times S) \times A$$

Siddiqi, A., Magliarditi, E., and de Weck, O. L., "Valuing New Earth Observation Missions for System Architecture Trade Studies"" IEEE International Geoscience and Remote Sensing Symposium, (2019)

Labsphere
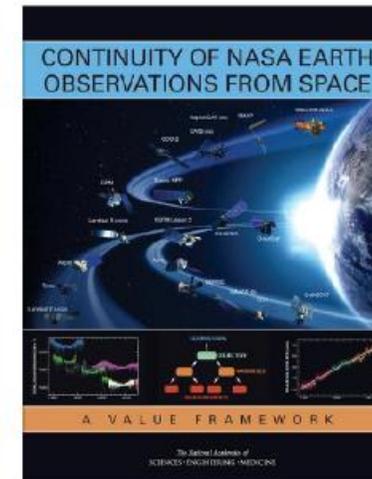
What is Analysis Ready Data?

- "In 2006, Clive Humby coined the phrase 'Data is the new oil'. Michael Palmer expanded on Humby's quote by saying, like oil, data is 'valuable, but if unrefined it cannot really be used. [Oil] has to be changed into gas, plastic, chemicals, etc. to create a valuable entity that drives profitable activity; so, data must be broken down and analyzed for it to have value.'", - Wikipedia

- **The amount of electro-optical airborne and satellite data available today is expanding exponentially, but its inherent optical performance, signal quality, efficiency and useability is not matching pace.**

- **Better data is needed, not just more data.**

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Enabling Data Extraction & Sensor Fusion

Harmonizing Data in a Sensor Fleet

• 100's in a Constellation

Harmonizing Across Platforms

• Big Sat/Small Sat/UAV

Sensor Fusion Across Technology

• Satellite / SAR / Virtual Constellations

Optimize Machine Learning (ML) / Artificial Intelligence (AI)

• Extracting more value/insight

https://www.planet.com/pulse/satellite-interoperability-workshop/

L0   L1   L2   L3   L4

Source: Zuleta, "Virtual Constellations, ARD and Sensor Fusion: the future of earth observation" JACIE 2020
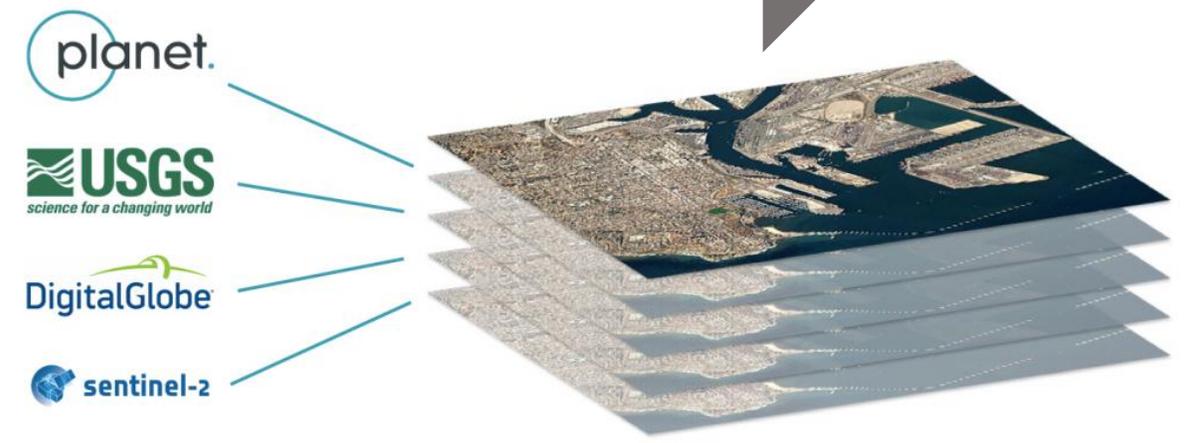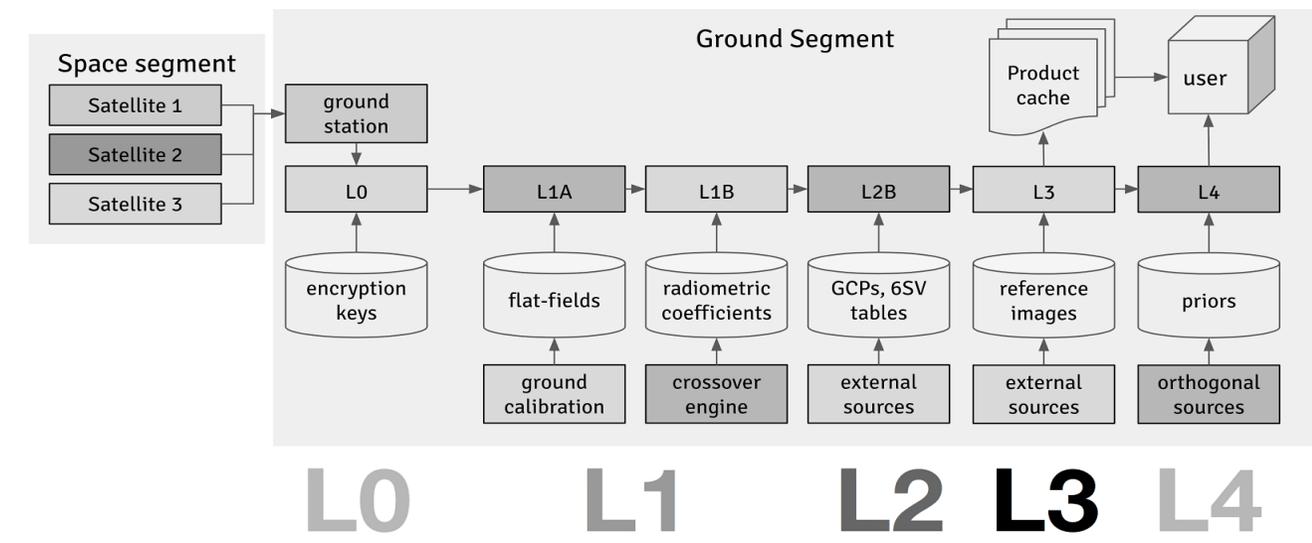
Uncertainty Evaluation – Results

Vantor WoldView-Legion

- State of the art commercial EO satellite constellation
- Launch: 2024
- Dry Mass: 630kg
- Spectral bands: 8
- GSD: 1.36m (multi-spectral)

Credit: Maxar

LandSat-8

- Flagship government EO mission
- Launch: 2013
- Dry mass: 1512kg
- Spectral bands: 9 (OLI)
- GSD 30m (multi-spectral)

Credit: NASA

Labsphere
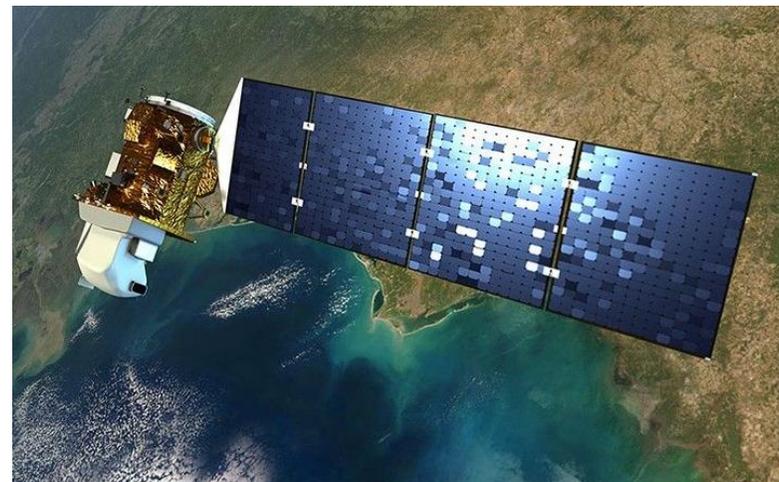
Uncertainty Evaluation – Results

Vantor WoldView-Legion

Vantor WorldView class sensors uncertainty specification for calibrated radiometric data products:

- Less than 10% of dynamic range there shall be no specification.

- Between 10% and 85% of the dynamic range the absolute radiometric response specifications shall not exceed ±5% uncertainty for VNIR sensors and ±10% for SWIR sensors.

- [±10% uncertainty for VNIR sensors and ±15% for SWIR sensors for IOC]

- Greater than 85% of dynamic range there shall be no specification

Source: Kuester, "Radiometric Performance of Maxar Legion Earth-Observing Sensors" JACIE 2025

LandSat-8
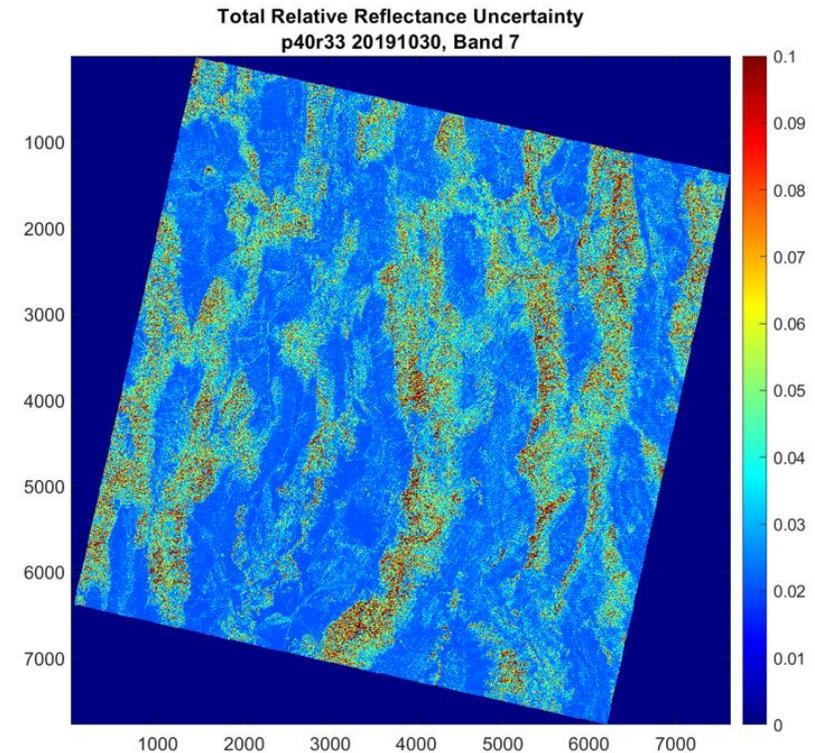
Relative reflectance total uncertainty image (left) and histogram (right) for Landsat 8, p40r33, 10/30/2019, Band 7.

Source: Ryan, "Landsat 8 L1T Product Radiometric Pixel Uncertainty" JACIE 2025

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Uncertainty Terms

- **Measurand – Quantity intended to be measured.**

- **Error – The difference between a measurand and the true value.**

$$error = Reading - True\ Value$$

- **Accuracy – Closeness of a measured value to a true value.**

$$Accuracy = \frac{Error}{True\ Value} \times 100\%$$

- **Uncertainty – A parameter, associated with the result of a measurement, that characterizes the dispersion of values that could reasonably be attributed to the thing being measured[1].**
  - Establishing a rigorous and detailed budget of sources contributing to the nature (random/systematic) of uncertainties of any measurement in relation to a defined reference.[2]
  - Refers to the measurement at a given instance in time, NOT the instrument.

1. NPL, https://www.npl.co.uk/resources/q-a/difference-accuracy-uncertainty
2. SI-Traceable Space-based Climate Observing System a CEOS and GSICS Workshop NPL, Sept 9-11, 2019.

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Uncertainty Terms

- **Coverage Factor – k, value that defines an interval with an approximate confidence level.**

- **Standard Uncertainty, u, Uncertainty expressed as a standard deviation.**

- **Combined Standard Uncertainty – u_c, combination of uncertainty in RSS where each term represents 1σ**

$$u_c(y) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}$$

- **Expanded Uncertainty – U_c, uncertainty after applying the coverage factor**

$$U_c(y) = u_c(y) \cdot k$$

- **Traceability – Documenting and evidencing the link of any measurement to its primary reference.[1]**

1. SI-Traceable Space-based Climate Observing System a CEOS and GSICS Workshop NPL, Sept 9-11, 2019.

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Example: Downwelling Irradiance

- All variables and uncertainties feed into the measurement equation, $E_d(\theta_s)$

- This feeds into the calculation for water-leaving radiance.

- Each variable has a prob. Dist. Fct. and an uncertainty.
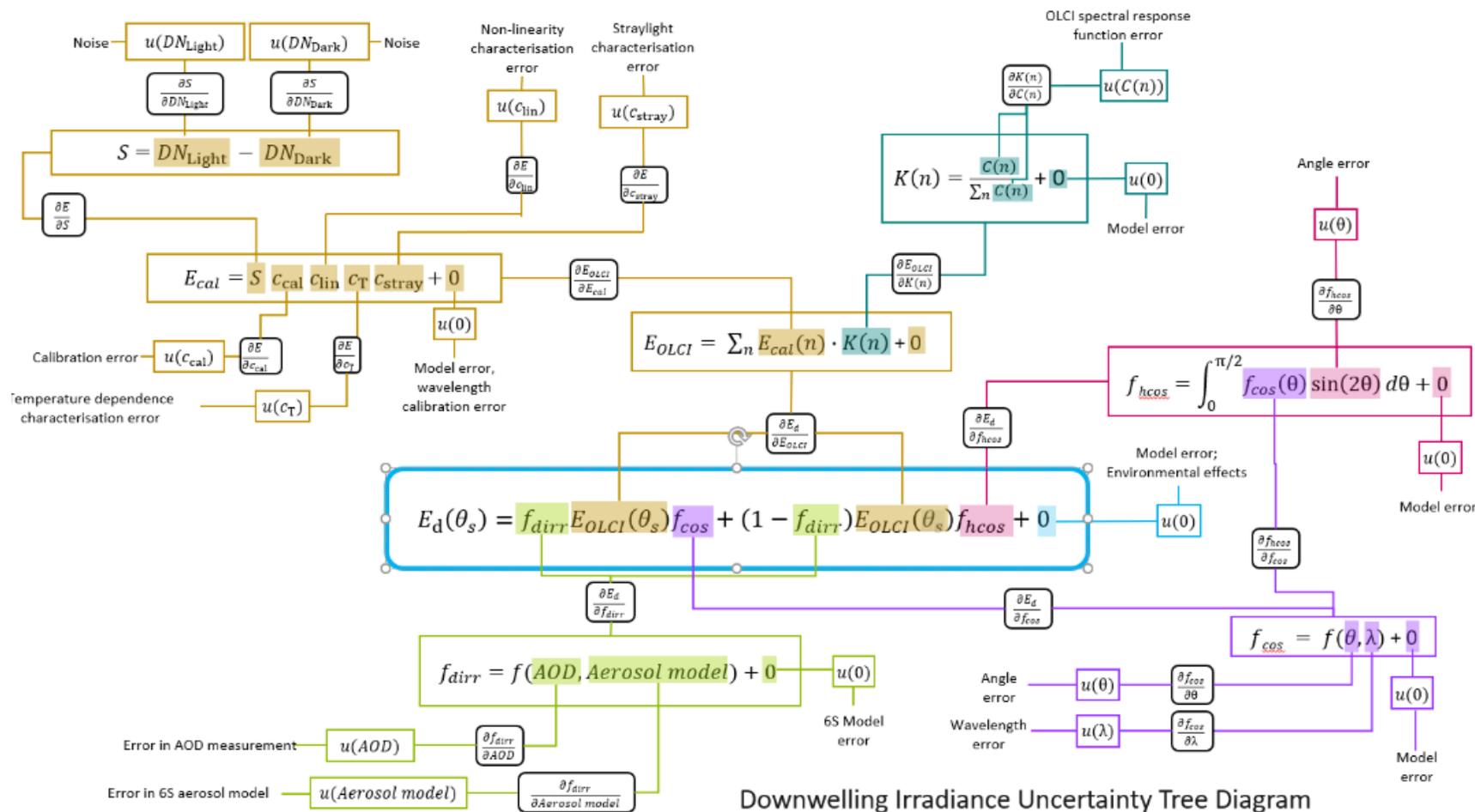
Downwelling Irradiance Uncertainty Tree Diagram

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What is the EO Calibration Lifecycle?

- **Key to low-uncertainty and analysis-ready data**
- **Mission Planning**
  - Instrumentation
  - Calibration
- **Instrument Design & Laboratory Verification**
  - Ground Support Equipment (GSE)
  - On-Board Calibration
  - Vicarious Calibration Planning
- **Field & Operational Validation**
  - Vicarious Cal
- **Next Generation Feedback**
  - Design

The EO Calibration Lifecycle:

- **Performance vs. Objectives**
- **Calibration/Validation Concept**
  - On-board, vicarious, lab service
- **Prototype Test**
- **Sensor level Calibration**

- NMI Standards
- Performance Baseline Generation
- Best Testing Practices
- System Level Calibration

Instrument Design

Feedback to Next Generation

Traceable Chain (NMIs)

Laboratory Verification

In-Flight Operation & Validation

Field Test Verification

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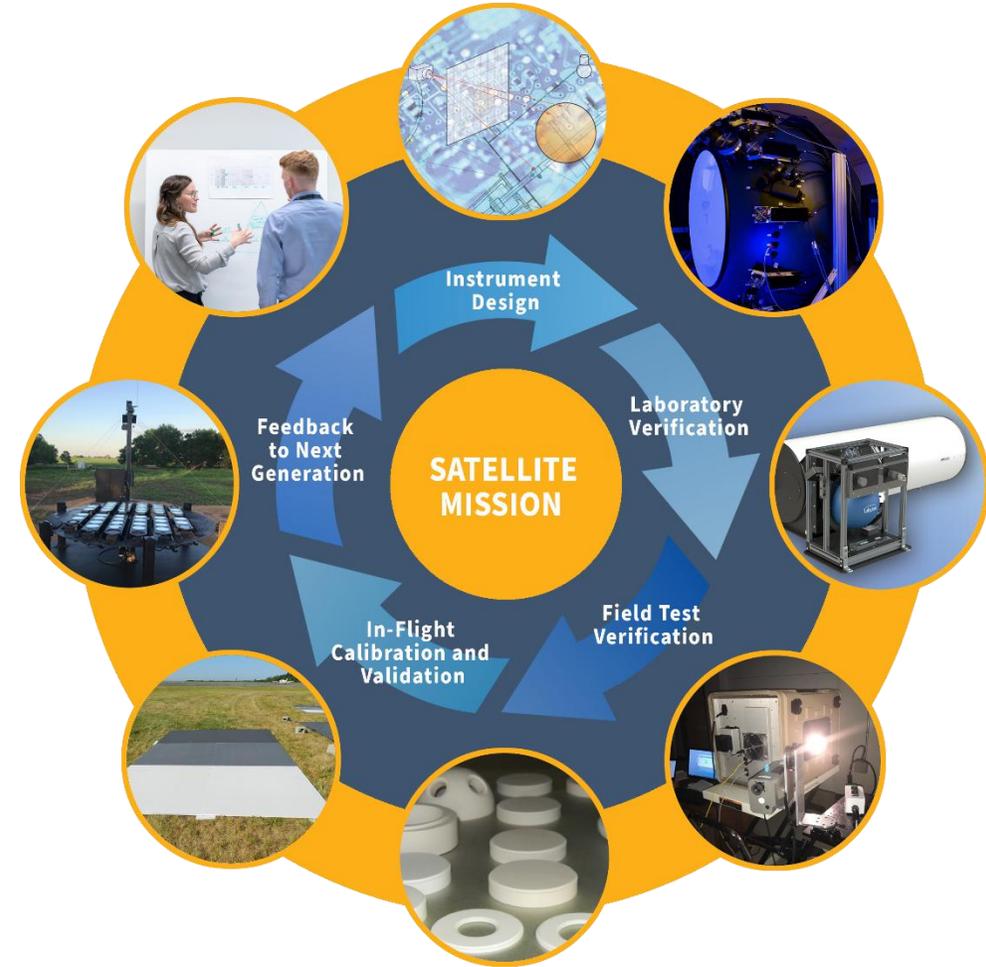
Absolute Calibration in the Laboratory

- **Sphere Material**

- **Sphere Size**

- **Dynamic Range**

- **Source Types**
  - Plasma, Xe, LED, Lasers, QTH, UV/IR

- **Spectral Requirements**

- **Monitoring Spectral Range**

- **Mechanical features**

- **Environmental**
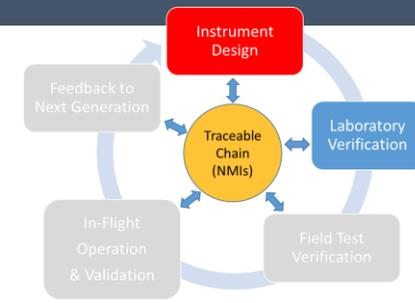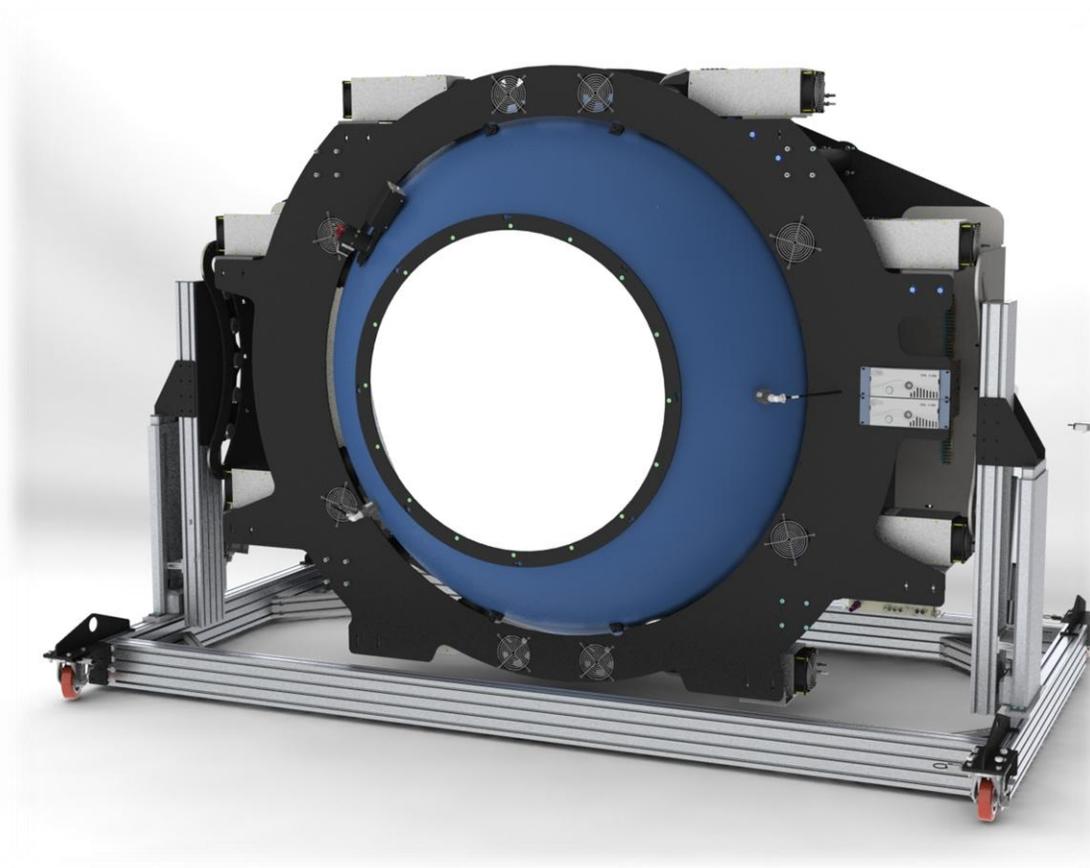
OTHERS:
- Stability and Control
- Software Modifications
- Thermal Control
- Lead Time

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Absolute Calibration in TVAC

LVIS Vacuum-Compatible Light Head

Vacuum Bulkhead

External Support Hardware

Software Integration

LED Power, TEC, Thermal Feedback

E-Box

Optical Feedback
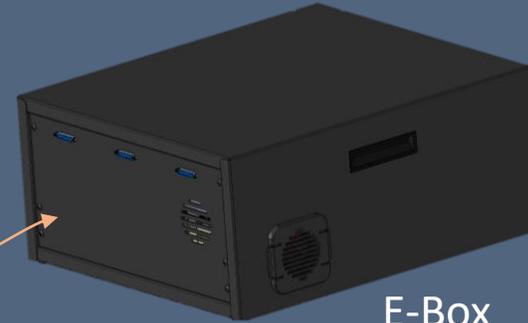
Spectro-radiometer

Coolant Loop

Chiller

Labsphere
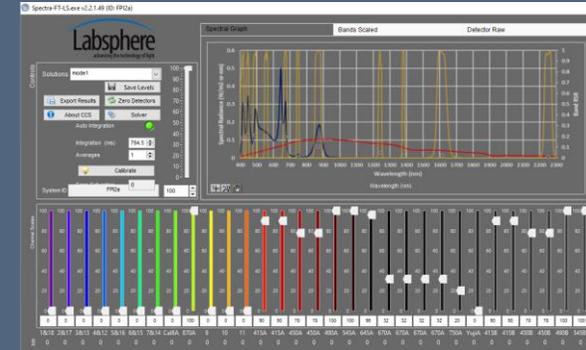
Spectral Requirements

- **Spectral Matching**
    - Requires multiple lamp types
    - Tight specifications may require filters on source
- **High Blue Content**
    - Multiple plasma
    - LEDs
- **High NIR (>1200nm)**
- **Simultaneously meeting levels in multiple bands**

Legend:
- Direct Starlight
- Direct Sunlight
- Overcast Sunlight
- Full Moon
- Quarter Moon
- 1300K Blackbody Photopic Source
- 2856K Blackbody Photopic Source
- 5800K Blackbody Photopic Source
- Blue Sky
- Eye CIE
- Rod CIE
- Joe Cloudy No Moon Night
- SWUX

x-axis: Normalized Spectral Irradiance
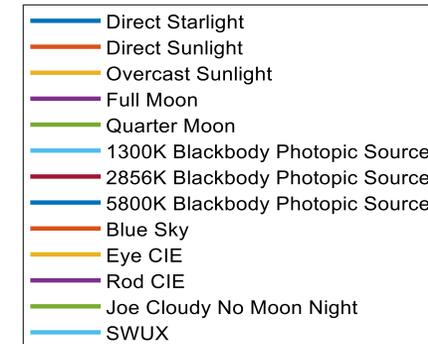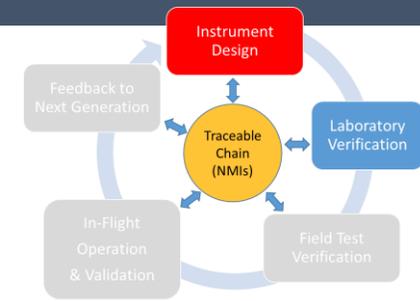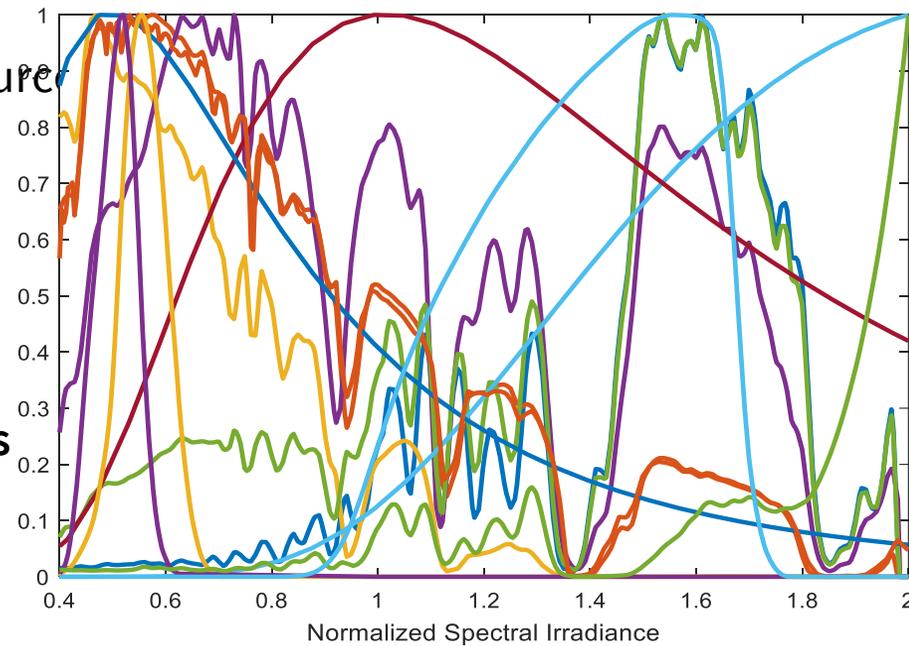
Goddard Laser for Absolute Measurement of Radiance (GLAMR)
Joel McCorkel[1], Brendan McAndrew[2], Kurt Thome[1], Jim Butler[1]
[1]Code 618, [2]Code 551 – NASA/GSFC
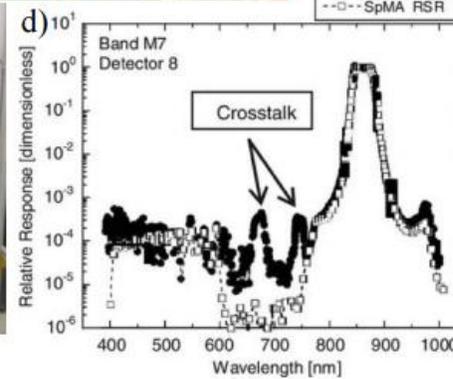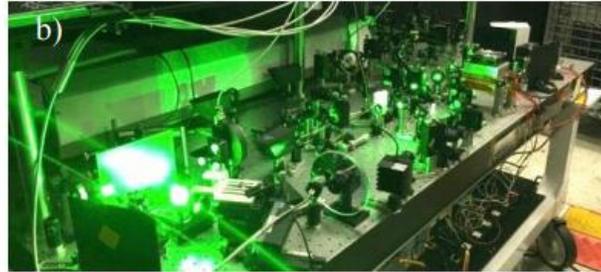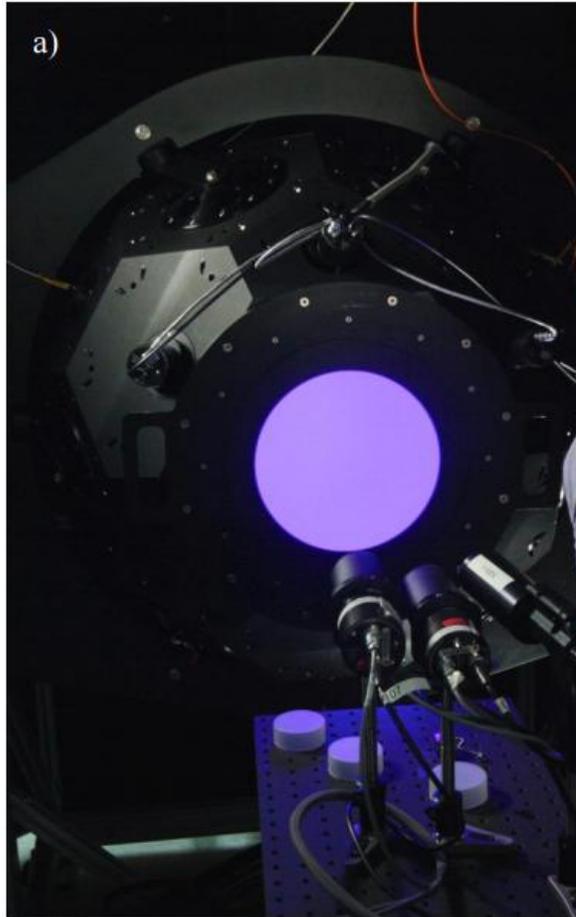
GLAMR is a tunable and high-powered laser system that provides an ideal light source for characterizing the spectral and radiometric response of an instrument. This pure signal is allows decoupling of sensor features (e.g. linearity, crosstalk, scattered light) and orders of magnitude better absolute radiometric accuracies.

McCorkel, NASA/GSFC

Earth Sciences Division – Hydrospheric and Biospheric Sciences
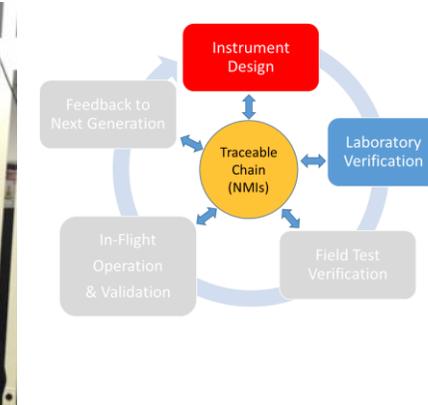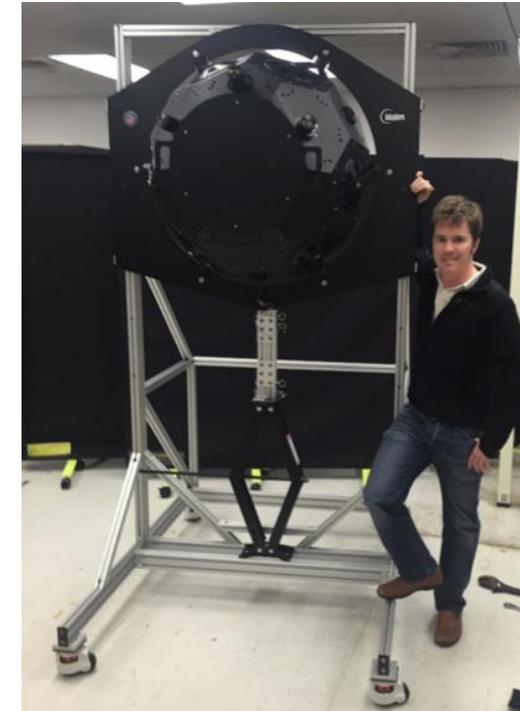
Geodesic Design with seams <0.5mm

25

The EO Calibration Lifecycle:

- **Performance vs. Objectives**
- **Calibration/Validation Concept**
  - On-board, vicarious, lab service
- **Prototype Test**

Instrument Design

- NMI Standards
- Performance Baseline Generation
- Best Testing Practices

Laboratory Verification

Traceable Chain (NMIs)

- Cal/Val Plan of Record
- Commissioning
- Calibration on-board
- Vicarious Calibration
- Data Quality Assessment

Feedback to Next Generation

In-Flight Operation & Validation

Field Test Verification

- At-Site Testing
- Vicarious Calibration
- Commissioning

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Onboard Calibration: Sources and sphere for ENMAP

- **Active calibration from QTH lamps and LEDs**
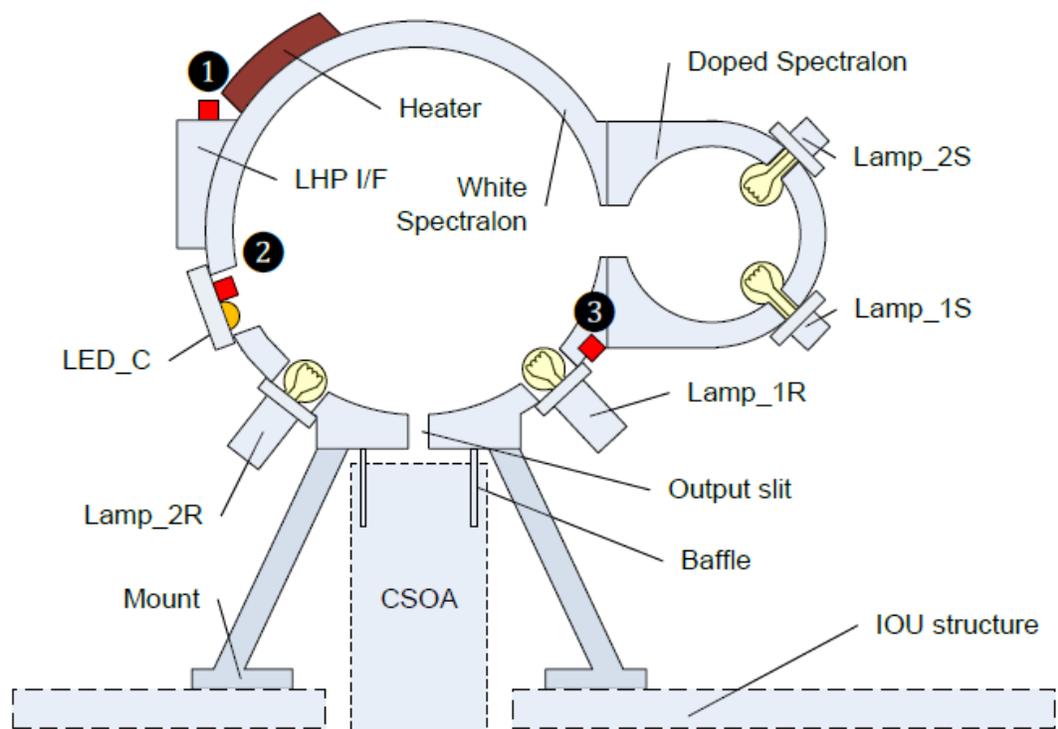
Fig. 4. General design of the OBCA

An on-board calibration assembly(OBCA) on the ENMAP satellite, Wilkens, Sang, Erhard, Bittner, et. Al., International Conference on Space Optics, 2016.

# Onboard Calibration: Jones' Source FPA Illuminator

Dichroic beamsplitter location

Entrance Pupil

ATLIS-P telescope
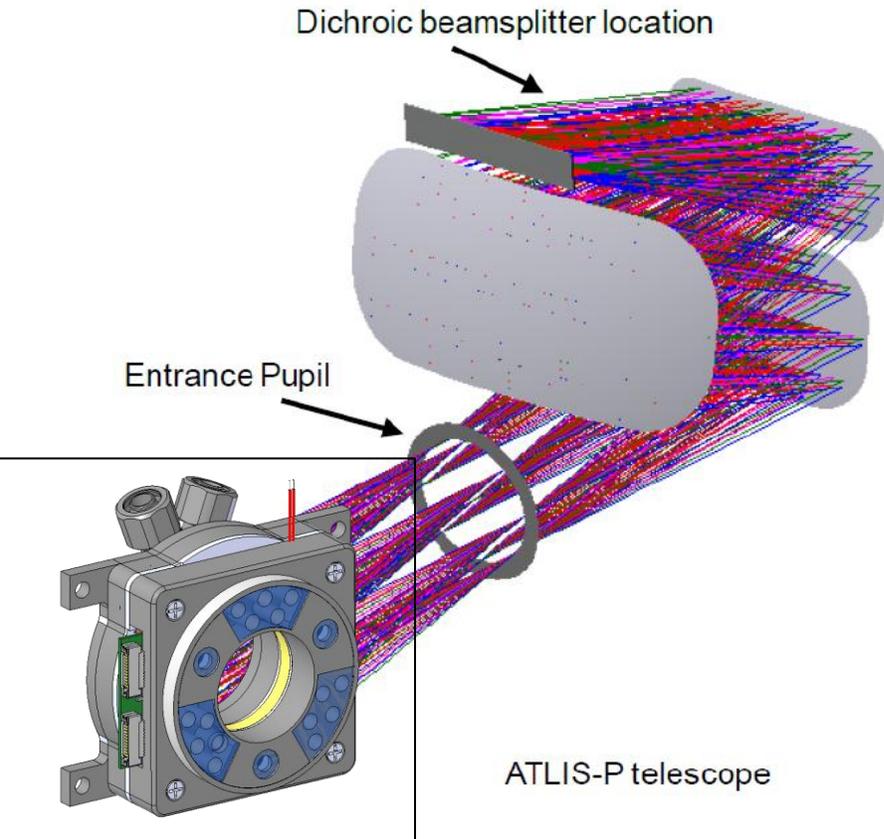
Spiral calibration source development yields more mature product for future technology insertion

Blackbody Design & Demonstration	Breadboard Design & Procurement	Breadboard Characterization & Brassboard Design	Brassboard MAI&T	Flight Design & Qualification
Phase 0	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
• Demonstrate thermal uniformity and responsivity • Demonstrate active temperature control • Demonstrate high (>0.995) emittance	✓ Generate supplier statement of work and specification ✓ Procure VSWIR sources ✓ Define test setup and equipment	✓ Receive and test breadboard VSWIR sources • Design, analyze, and procure brassboard and thermal infrared sources	• Demonstrate and characterize the brassboard design with ATLIS-P telescope • Demonstrate and characterize mechanical functionality	• Finalize Flight design and qualify thru full environmental testing including radiation
Metrics	*Metrics*	*Metrics*	*Metrics*	*Metrics*
• Design for thermal infrared blackbody emitter • Measurements that anchor thermal model and optical parameters	✓ Generate SSOW and Spec for calibrator procurement ✓ Procure FPA, Dewar, and Electronics ✓ Finalize test equipment list and procure	• Integrate VSWIR calibrator with ATLIS-P telescope • Characterize breadboard VSWIR calibrator • Identify space qualified sources	• Stable, uniform illumination of FPAs across FOV • Demonstrated compliance with 2019 RMA • Exit TRL 5+	• Calibrator passes environmental qualification • Calibrator successfully tested on Engineering Development Unit

Raytheon
Intelligence & Space

Puschell, J., Schiller, S., "Improved Radiometric calibration of Imaging Systems (IRIS) for next generation small satellite imagers" SPIE O&P 2022

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PICS Calibration

- **PICS: Pseudo-Invariant Calibration Sites.**
  - Using objects on the earth or in space that exhibit reflectance profiles that are constant
  - Measured frequently, verified infrequently
    - Mostly a relative reference
  - Deserts – Libya 4
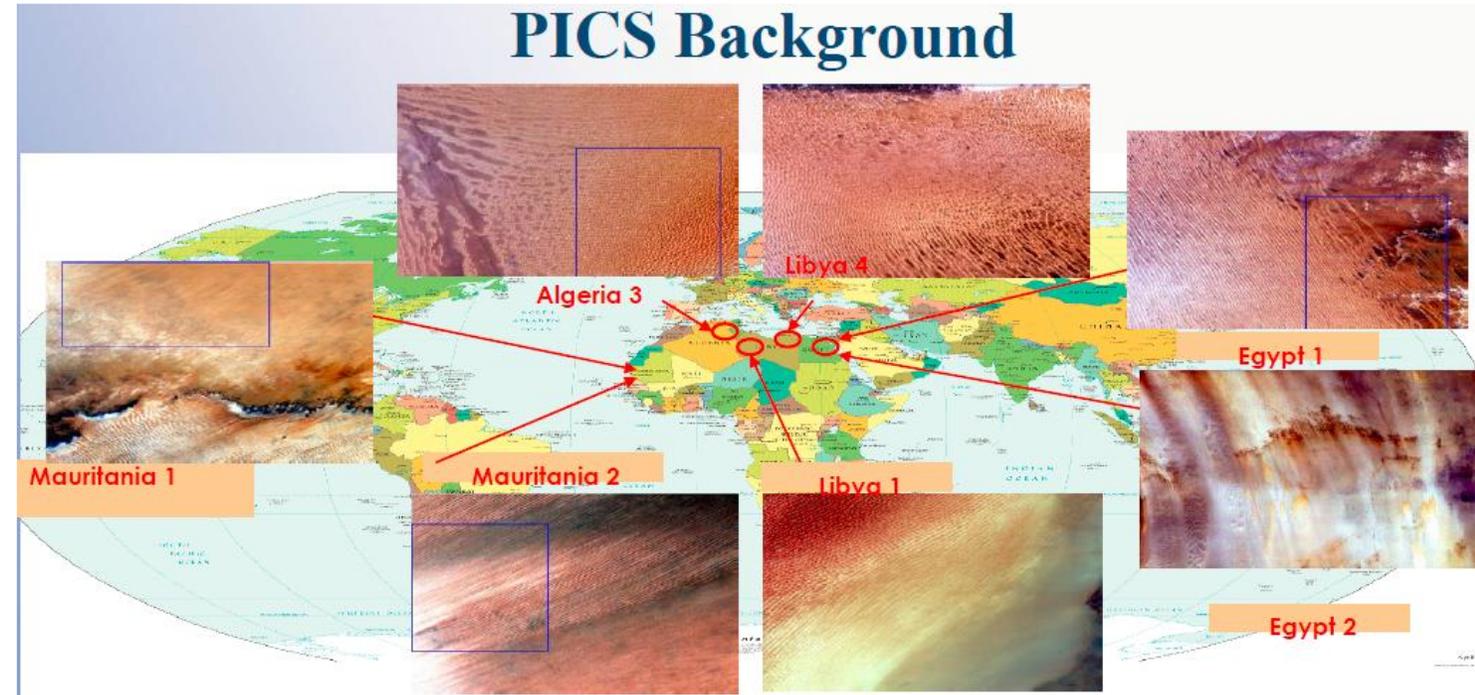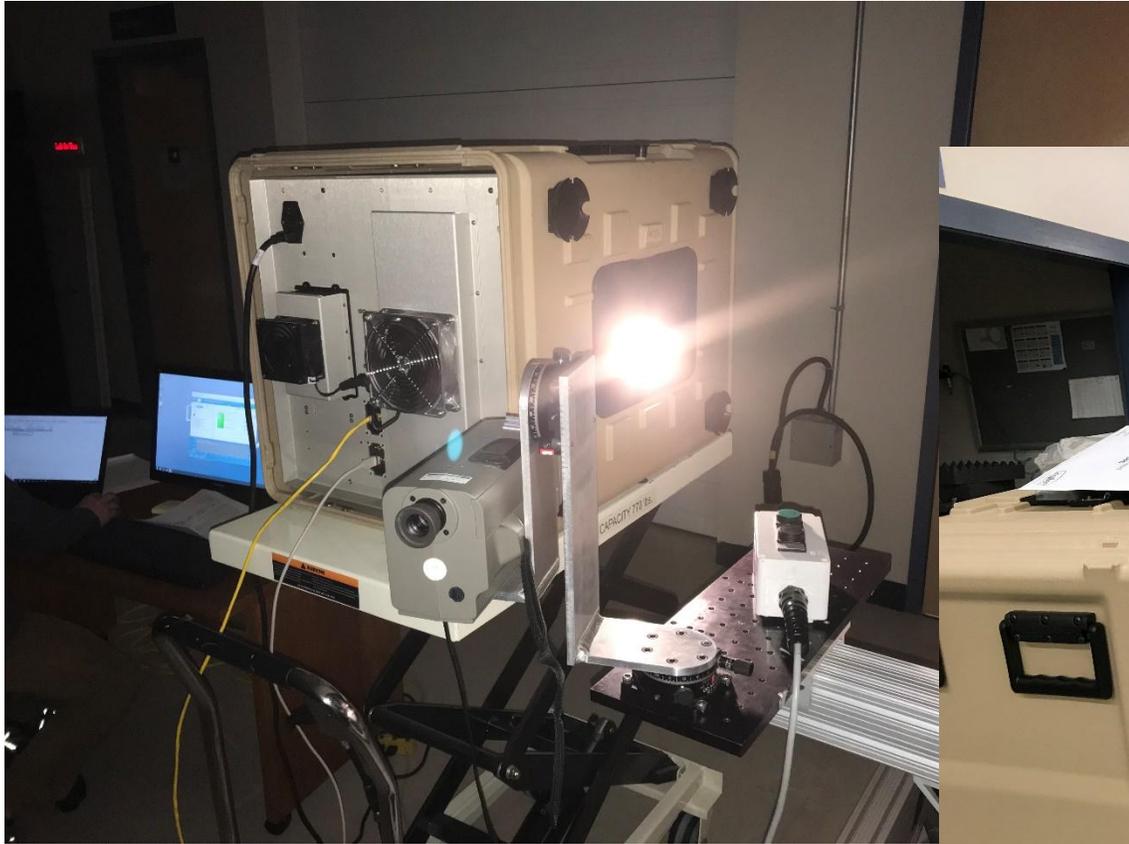

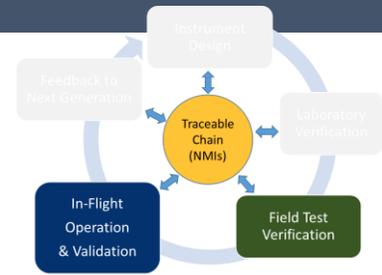http://calval.cr.usgs.gov/sites_catalog_ceos_sites.php

Source: SDSU IP Lab

Practical Reflectance with Diffuse Target
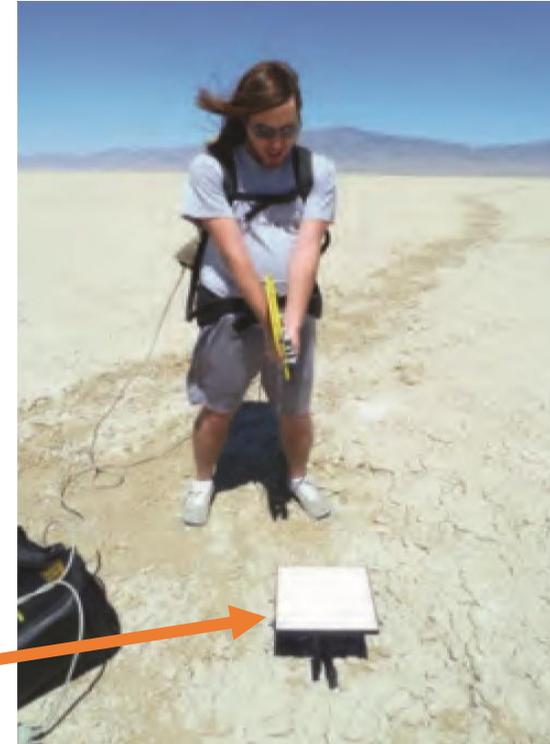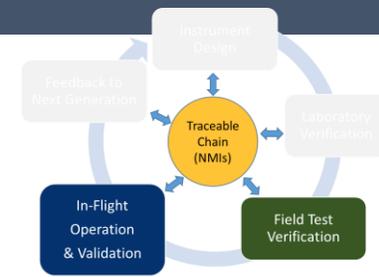
Spectral Photometer or
Radiometer Pointed at target
at "Similar" angle
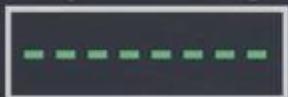
Ruggedized Uniform Sources for Field Calibrations

FLARE SYSTEM OPERATIONS
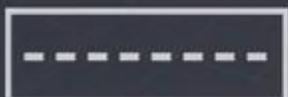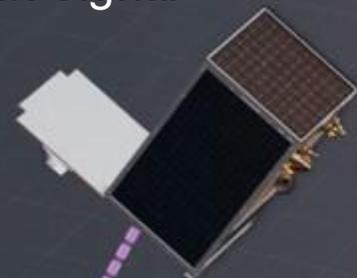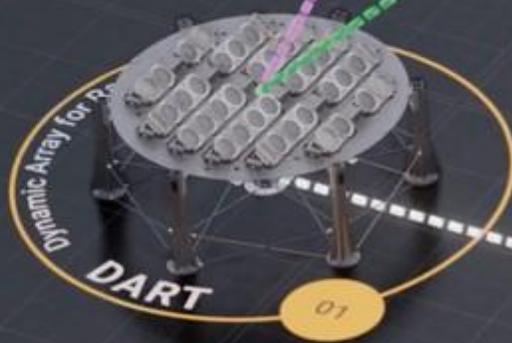
At Craft Signal

Mirror Reflectance

Downwelling Atmospheric Transmission,

Solar Radiometer Calibration

Top of Atmosphere Solar Irradiance

User Computer/FLARE Portal

Relayed Solar Signal

Direct Solar Signal

Measured Radiometric Propagation

Data and Telemetry

Mirror Array Turret

Radiometric Instrument Tower

DART 01

TRUST 02

PORTAL 03

FLARE Automated Mobile Turret (Example)

Protected System

- Faces close/seal when not in use
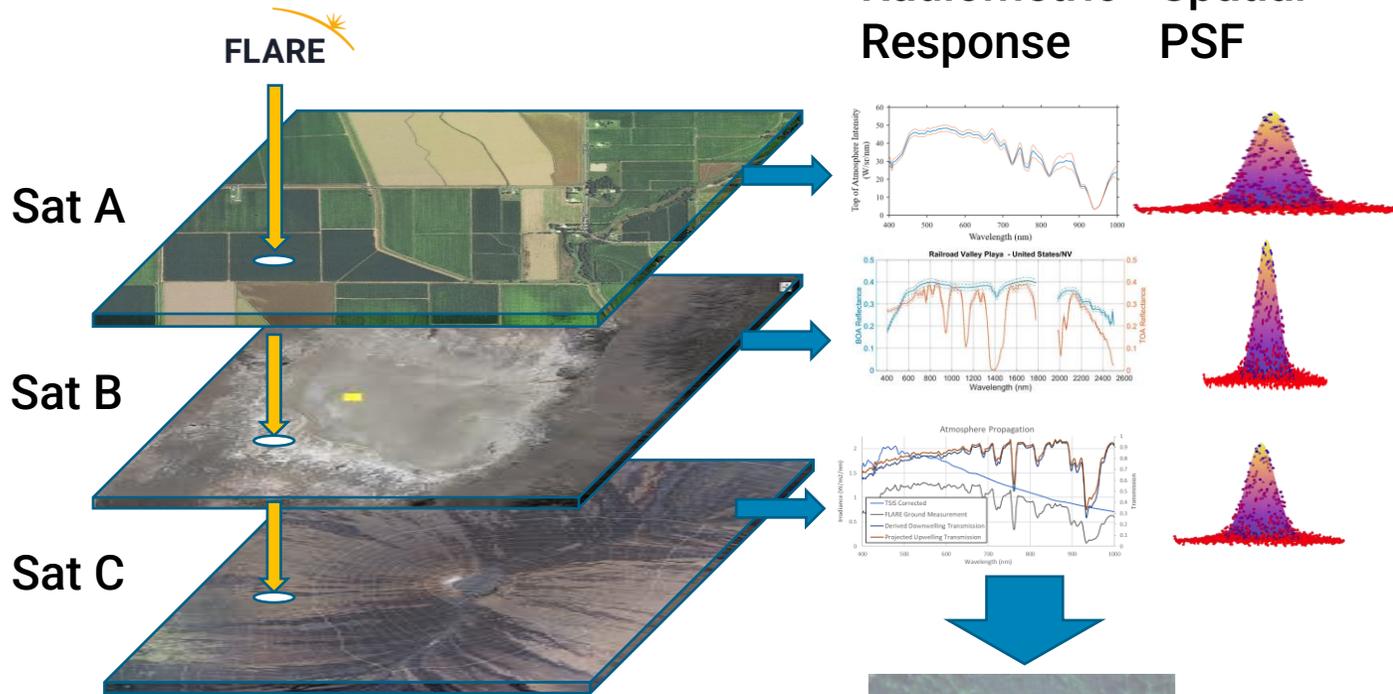- Faces can be fully open (in-use) or only partial open (off)

Mirror Selections

- Tuned to application
- Modular plates
- Selectability
  - "Faces" can be "on" or "off"
 - Mirror groups can be angle offset to be exclusive of other mirror FoVs

Calibration for ALL Assets – Unlock the Value of ARD

FLARE

Sat A

Sat B

Sat C

Radiometric Response

Spatial PSF

FUSED DATA PRODUCT

- **Go right to surface reflectance**
  - Atmospheric characterization and removal
  - Sensor response to known signals
  - BRDF

- **Provide a stable, traceable reference for any GSD/FOV**
  - Understand Geometry – PSF, MTF
  - Understand Radiometry – 0.35-2.5um
  - Precise Geo-location (GCP)

- **Harmonize different EO constellations & architectures**

- **Time Series / Change Detection**
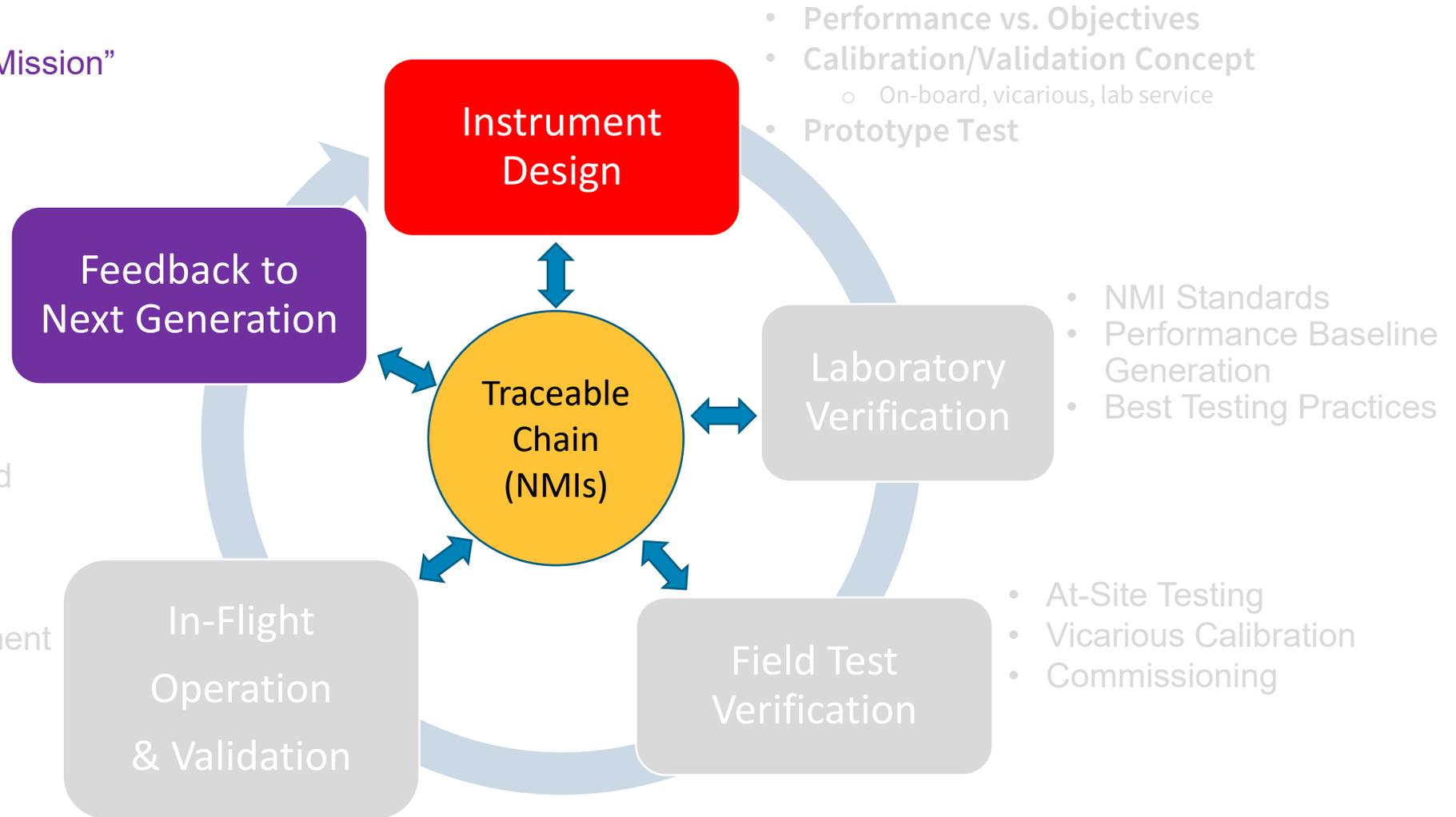- **Monitoring / Diagnostic Efforts**
- **Optimize ML/AI results**

Labsphere
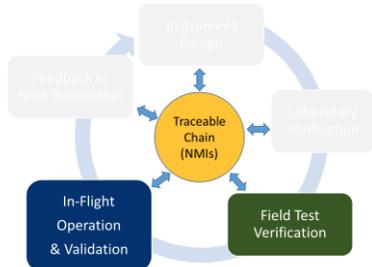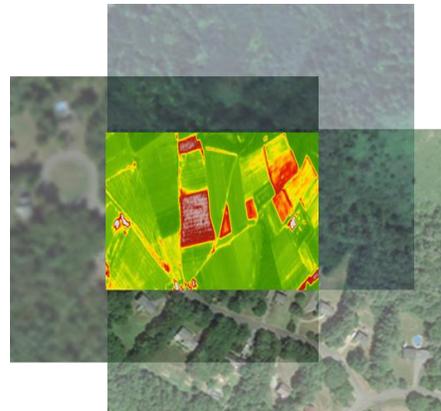
The EO Calibration Lifecycle:

- Support the "Forever Mission"
- What works…
- New technology
- New methods
- Legacy compatibility

- Performance vs. Objectives
- Calibration/Validation Concept
  - On-board, vicarious, lab service
- Prototype Test

- NMI Standards
- Performance Baseline Generation
- Best Testing Practices

- Cal/Val Plan of Record
- Commissioning
- Calibration on-board
- Vicarious Calibration
- Data Quality Assessment

- At-Site Testing
- Vicarious Calibration
- Commissioning

Instrument Design

Feedback to Next Generation

Traceable Chain (NMIs)

Laboratory Verification

In-Flight Operation & Validation

Field Test Verification

Labsphere

Feedback to Next Generation

- **Support the "Forever Mission"**
  - Each generation feeds the next
  - The mission is the imagery…not the instrument.

- **What worked…what did not…**
  - Learning from operational life of prior generation(s)

- **Add new technology**
  - Improve architectures, sensors, electronics and optics

- **Incorporate new methods**
  - Calibration, processing and software

- **Enable legacy compatibility**
  - Ensure the imagery has continuity with the mission.

Development & SLA Inclusion

Pre-Launch

Launch

Commissioning

Operations

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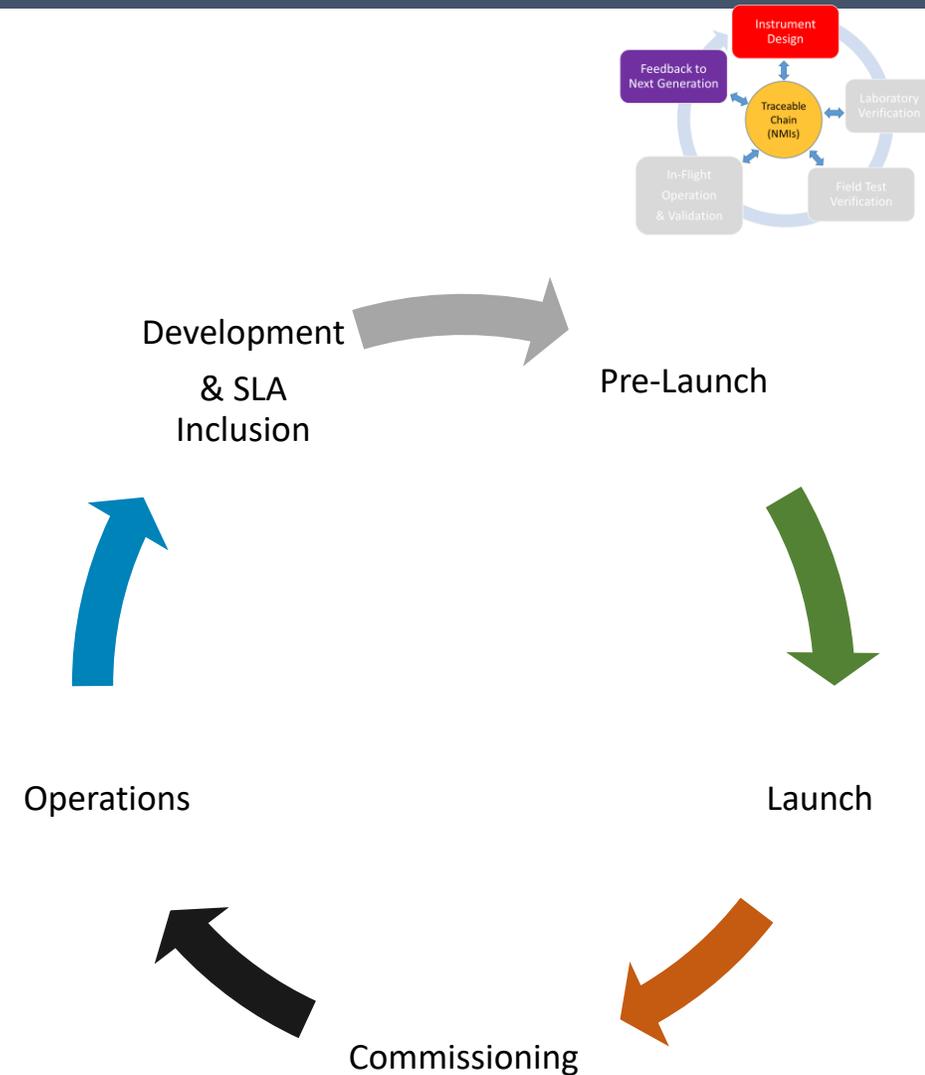
Summary

- **Low-uncertainty data provides value**
  - Enables data analysis
  - Enables sensor fusion
- **Uncertainty reporting is a key component of data publishing**
  - Can be a competitive advantage
- **The Calibration life-cycle**
  - Plan for calibration in instrument design
  - Understand instrument performance pre-launch
  - Build means and methods to validate the instruments
    - On-Board
    - Vicarious
    - Cross-Calibration
  - Build continuity of product/data between your generations of satellites

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