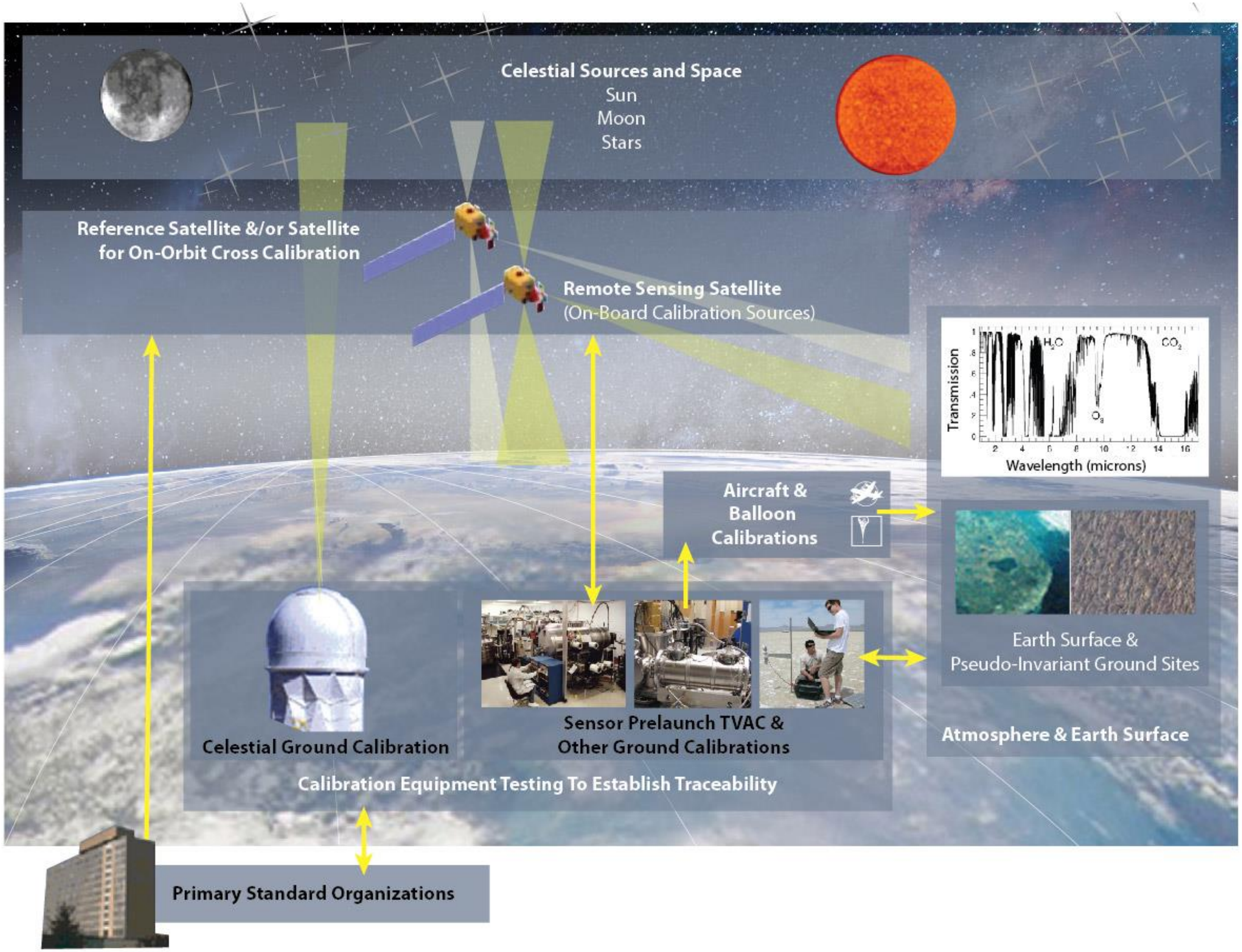

Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing

Publication Background

- Presents guidelines on conducting a radiometric calibration of an electro-optical (EO) sensor for space-based remote sensing
- Intended as a useful reference for planning and successfully carrying out a sensor calibration
    - Managers, technical oversight personnel, scientists, and engineers
- Represents lessons learned by authors from academic institutions, US government, and industry

Joe Tansock, Daniel Bancroft, Jim Butler, Changyong Cao, Raju Datla, Scott Hansen, Dennis Helder, Raghu Kacker, Harri Latvakoski, Martin Mlynczak, Tom Murdock, James Peterson, David Pollock, Ray Russell, Deron Scott, John Seamons, Tom Stone, Alan Thurgood, Richard Williams, Xiaoxiong (Jack) Xiong, Howard Yoon

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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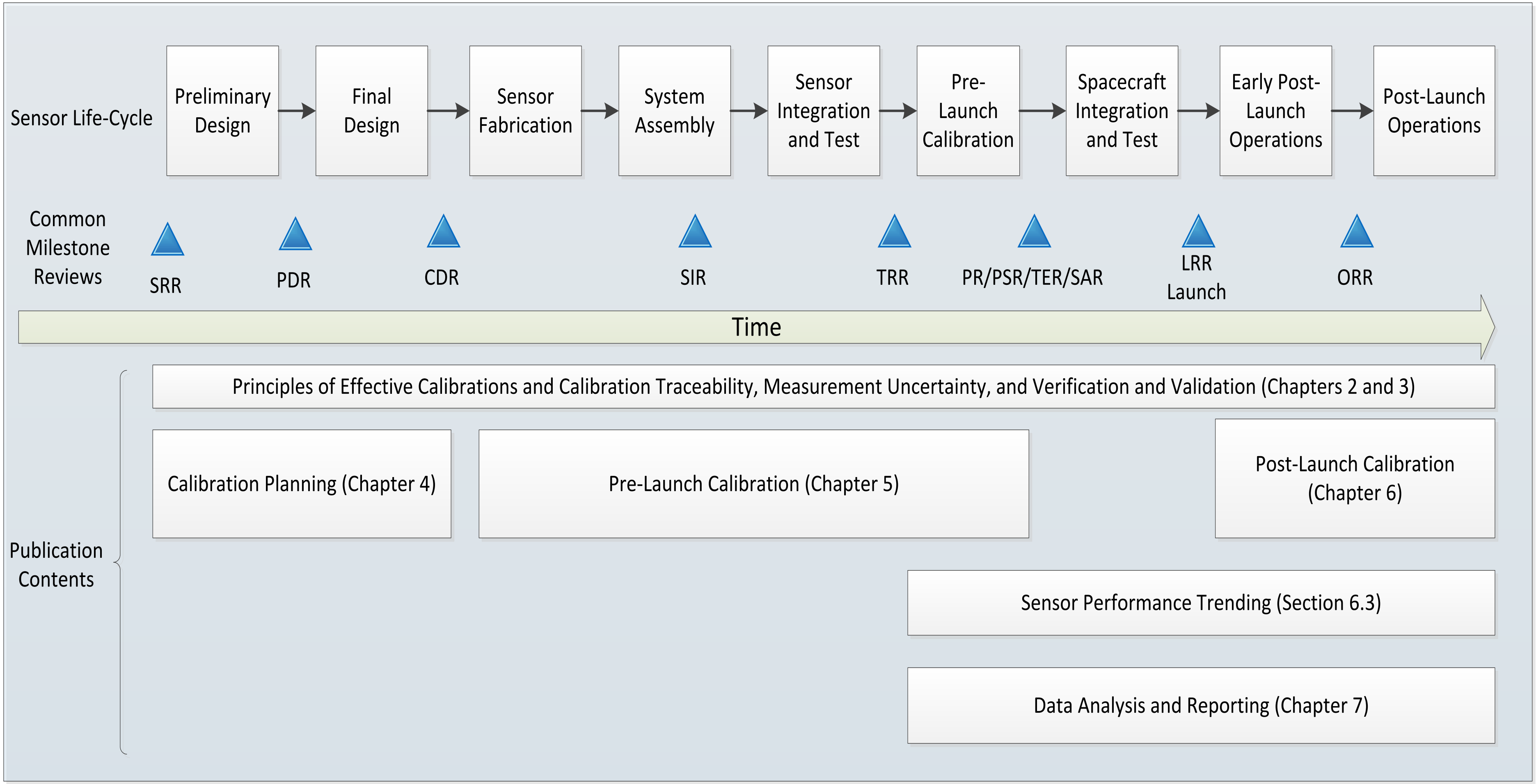
AEROSPACE

NIST National Institute of Standards and Technology U.S. Department of Commerce

SDSU

Publication Background

- Contents address calibration throughout the lifetime of the sensor



Sensor Life-Cycle

Preliminary Design → Final Design → Sensor Fabrication → System Assembly → Sensor Integration and Test → Pre-Launch Calibration → Spacecraft Integration and Test → Early Post-Launch Operations → Post-Launch Operations

Common Milestone Reviews

SRR

PDR

CDR

SIR

TRR

PR/PSR/TER/SAR

LRR
Launch

ORR

Time

Publication Contents

Principles of Effective Calibrations and Calibration Traceability, Measurement Uncertainty, and Verification and Validation (Chapters 2 and 3)

Calibration Planning (Chapter 4)

Pre-Launch Calibration (Chapter 5)

Post-Launch Calibration (Chapter 6)

Sensor Performance Trending (Section 6.3)

Data Analysis and Reporting (Chapter 7)

What is Calibration?

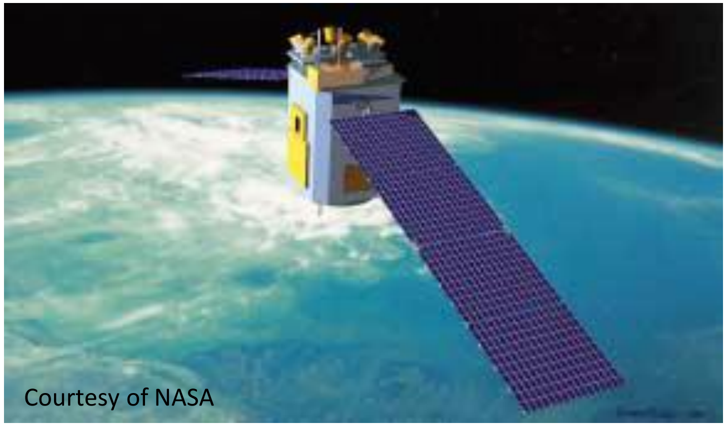
- Calibration is the process of characterizing the parameters required to understand, describe, and quantify the performance of a sensor
- Converts a sensor’s output to engineering units with traceability to a known standard and within a specified uncertainty
- Identifies and characterizes unique sensor performance characteristics
    - Allows for approaches to mitigate sensor problems through informed strategies for calibration and mission operations

Why is Calibration Necessary?

- EO sensors require calibration to:
  - Identify and quantify sensor’s response to known radiometric input
  - Characterize the interactions and dependencies between the optical and electronic components
  - Discover sensor specific performance dependencies
  - Evaluate systematic errors

Calibration Success Example

- SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)
  - 10-channel radiometer - spans range of wavelengths from 1.27 to 17 µm
  - Launched December 7, 2001
  - Still on-orbit collecting data



Courtesy of NASA

- Calibration planning began early in the sensor design[1]
  - Coordinated with science, instrument, and calibration teams
  - Iterated on calibration approach (strawman plan formulated)
  - Updated sensor design capability to support calibration
  - Drafted uncertainty budget and tracked throughout development process
  - Performed comprehensive ground calibration before launch
- Both pre- and post-launch calibrations were used to minimize uncertainty[2]

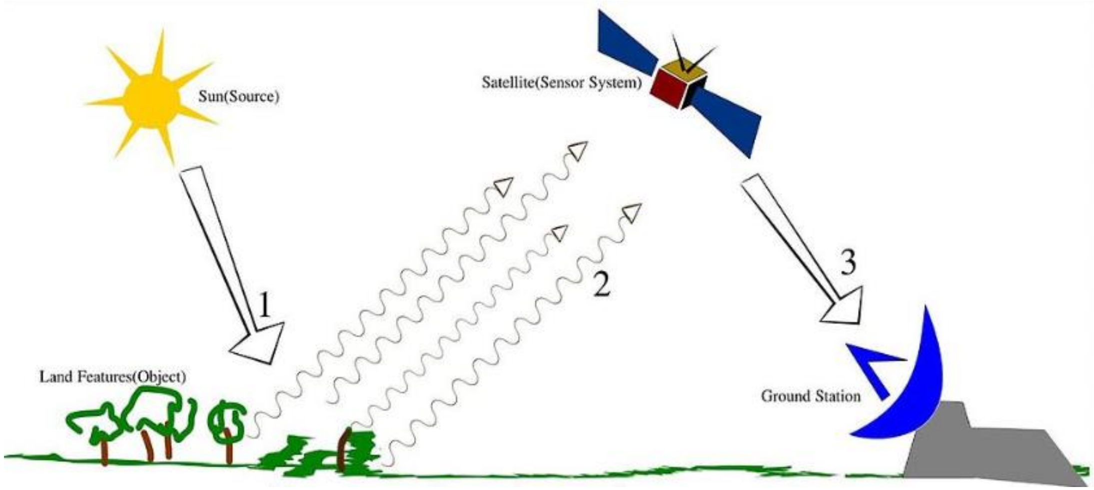
[1] Tansock et al., SABER Ground Calibration, IJRS, 2003; [2] Tansock et al., "An Update of the SABER Calibration", 2006

Calibration Requirements Across Disciplines

- Sensor calibration requirements vary with the application of the sensor
  - Parameters required are dependent on the instrument and the mission
    - Parameters that are important for one instrument may be irrelevant for another
- This document focuses on the calibration requirements of three disciplines:
  - Earth Sciences
  - Atmospheric Sciences
  - Department of Defense (DoD) Applications

Calibration Requirements for Earth Sciences

- Earth sensors are designed for a broad range of studies of the Earth's land, ocean, and atmosphere
- Examples:
  - Moderate Resolution Imaging Spectroradiometer (MODIS)
  - Visible Infrared Imager Radiometer Suite (VIIRS)
  - Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

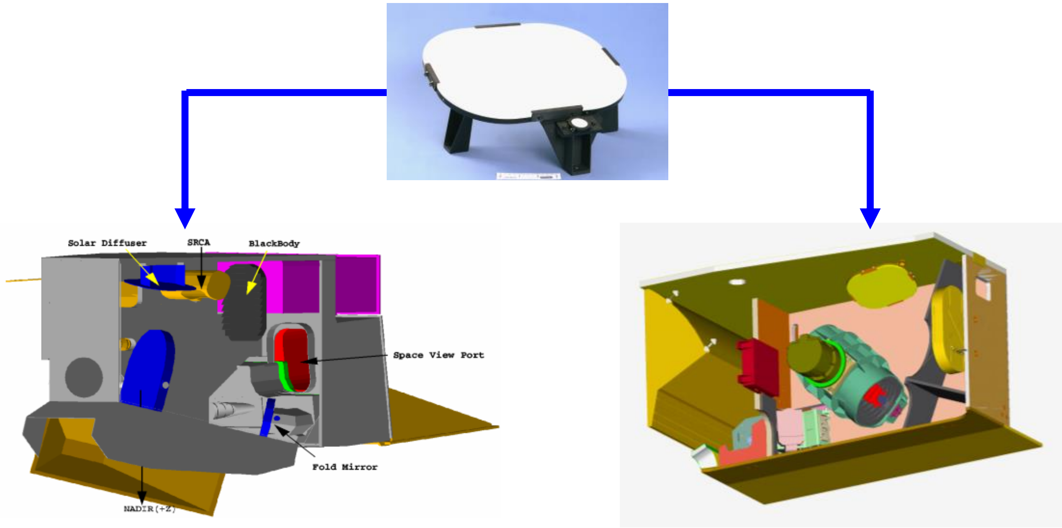


Remote sensing using passive sensor system

"Remote Sensing Illustration" by Arkarjun - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons -http://commons.wikimedia.org/wiki/File:Remote_Sensing_Illustration.jpg#mediaviewer/File:Remote_Sensing_Illustration.jpg

Calibration Requirements for Earth Sciences

- Data from multiple sensors are often used together to study changes in the earth surface properties
  - These sensors must be calibrated with the same traceability
  - Sensor spatial/spectral performance is also a key element
  - Many science products are spatially geolocated but are generated using more than one spectral band



Courtesy of NASA

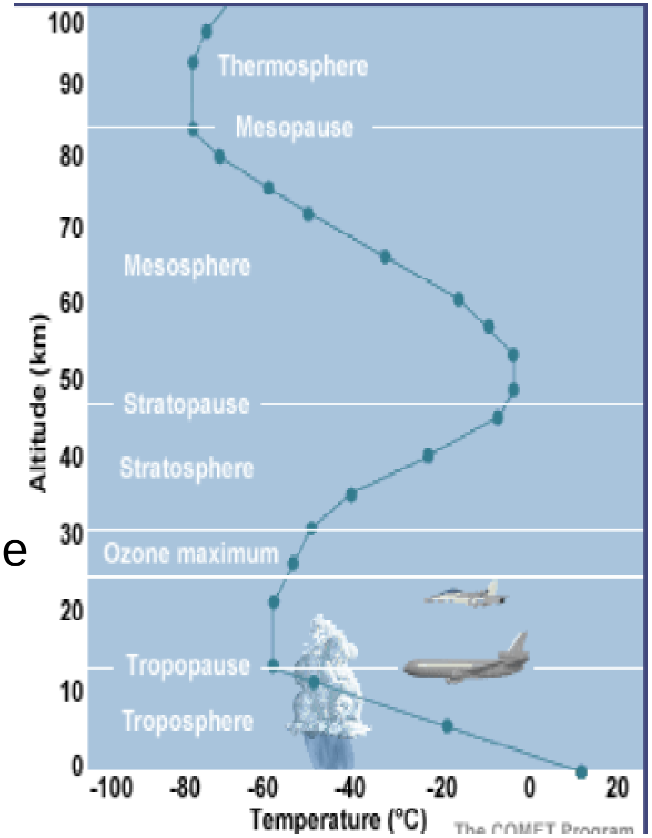
Same calibration traceability for Terra/Aqua MODIS and S-NPP/JPSS VIIRS reflective solar bands

Calibration Requirements for Earth Sciences

- Land remote sensing often requires atmospheric corrections
  - Requires sensor properties such as polarization and spectral responses
- Measurements of changes in the Earth’s surface properties are sensitive to changes in the sensor’s calibration
  - For example, drought monitoring relies on evaluating yearly changes in vegetation using a baseline that typically contains over 10 years of data (e.g., the Normalized Difference Vegetation Index (NDVI))
    - Undetected changes in the sensor’s calibration could be incorrectly interpreted as vegetation stress or drought (Wang et al., 2012)
- For ocean color, an accuracy of $\approx$ 0.5% is needed for TOA radiance retrieval
  - Contributions of artifacts such as polarization, straylight, and non-linearity need to be calibrated on the order of 0.1%
  - Many of these effects can only be characterized pre-launch but post-launch calibration if often required for gain calibration
- Both pre-launch characterization and on-orbit calibration are critically important

Calibration Requirements for Atmospheric Sciences

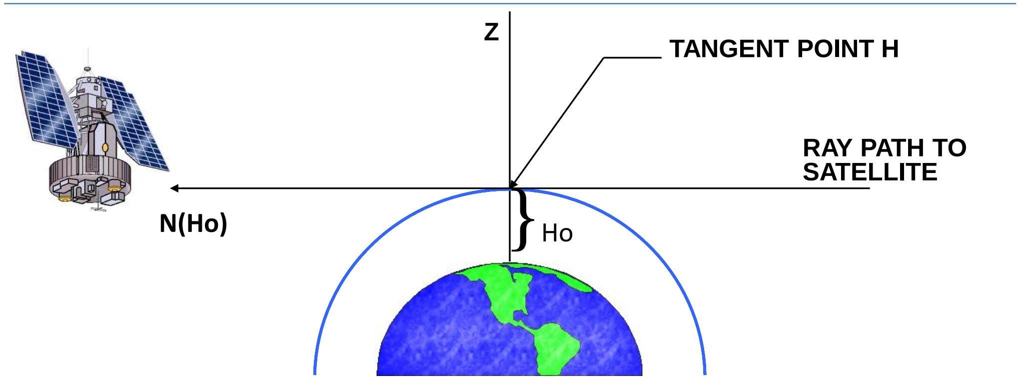
- Atmospheric science EO sensors use passive remote sensing techniques to measure radiance emitted by the Earth and atmosphere, or radiance from the Sun that is reflected by the Earth and the atmosphere
- Spectrally integrated radiance ($Wm^{-2}sr^{-1}$) is measured by narrow-band and broad-band radiometers
    - Some instruments use nadir viewing for the purpose of deriving properties at the Earth's surface, in the troposphere, and in the lower stratosphere
    - Other instruments observe the Earth's limb for deriving the composition and structure of the stratosphere, mesosphere, and thermosphere



http://saberoutreach.hamptonu.edu/saber-intro.pdf
(Chart by R. Bradley Pierce, NASA LaRC)

Calibration Requirements for Atmospheric Sciences

- Radiance measurement analyses generally fall into two categories:
  1. Deriving properties related to the energy balance of the Earth system
     - Applications of measured radiance to Earth’s energy balance depend critically on knowing absolute calibration and its time variation
  2. Deriving atmospheric state profiles (atmospheric sounding)
     - Atmospheric state profiles are often determined by “inverting” the radiative transfer equation, where small errors in absolute radiance turn into large retrieval errors



$$N(H_o) \cong \int_{\Delta\nu} \int_{\Delta X} J_\nu(x)\, \frac{d\tau\,(\nu,q,T,P)}{dx}\, dx\, d\nu$$

q (e.g., CO_2 known) $J_\nu(x) \rightarrow T$ **T known, retrieve H_2O, O_3, etc.**

Courtesy of NASA

Calibration Requirements for Atmospheric Sciences

- Absolute calibration accuracy to better than 1% of the measured radiance is essential for the accurate retrieval of atmospheric temperature
    - Infrared radiometers and spectrometers determine temperature by measuring radiance in the carbon dioxide (CO_2) bands near 15 µm (667 cm^{-1})
    - Sensitivity of the Planck function to temperature shows that a 1 K uncertainty in temperature leads to uncertainty in the radiance ranging from 1.36% (270 K) to 2.2% (210 K)
    - Given that the sum of all error sources must be less than 1 K, the absolute radiometric calibration must be better than 1% over the range of observed radiances
- Accurate radiometric calibration and instrument characterization are essential for generating high quality data products
    - Properties such as water vapor content, cloud coverage, cloud and aerosol optical depth, cloud height, and cloud particle size and phase impact the earth's radiation budget

Calibration Requirements for DoD Applications

- The DoD uses many types of sensors in multiple constellations of satellites, on drones and aircraft, and on the ground for a variety of applications:
  - Weather and battle-space characterizations in support of the warfighter
  - Theater missile warning in support of the warfighter
  - Monitoring of missile launches (missile warning) world-wide
  - Technical intelligence (TI)
    - TI can span a large range of applications:
      - Assessing the movement of resources for political situations
      - Ascertaining the capabilities of an industrial area, such as how many missiles or vehicles are being *produced in a given plant*

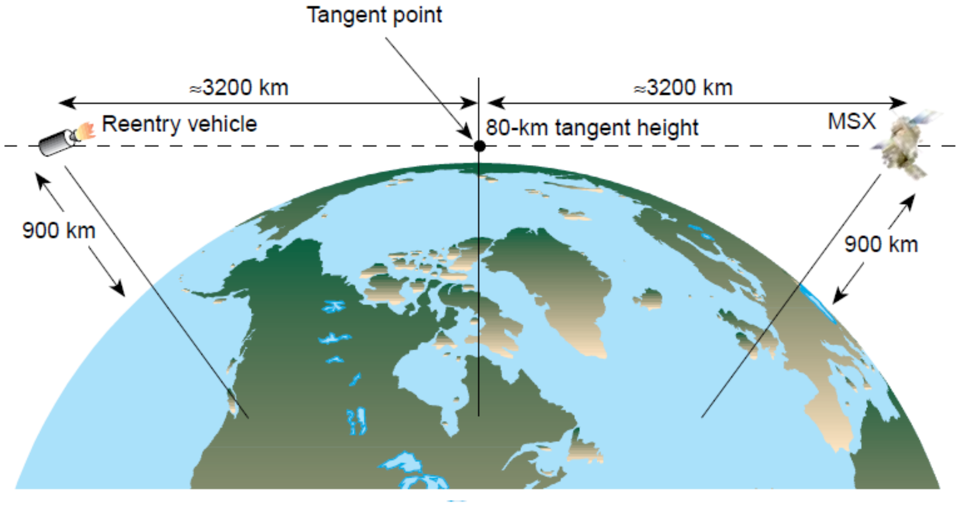


Figure 2. Geometry of MSX viewing a reentry vehicle through the Earth-limb. The target is equidistant from the tangent point at 80 km. (A.T. Stair, 1996)

Calibration Requirements for DoD Applications

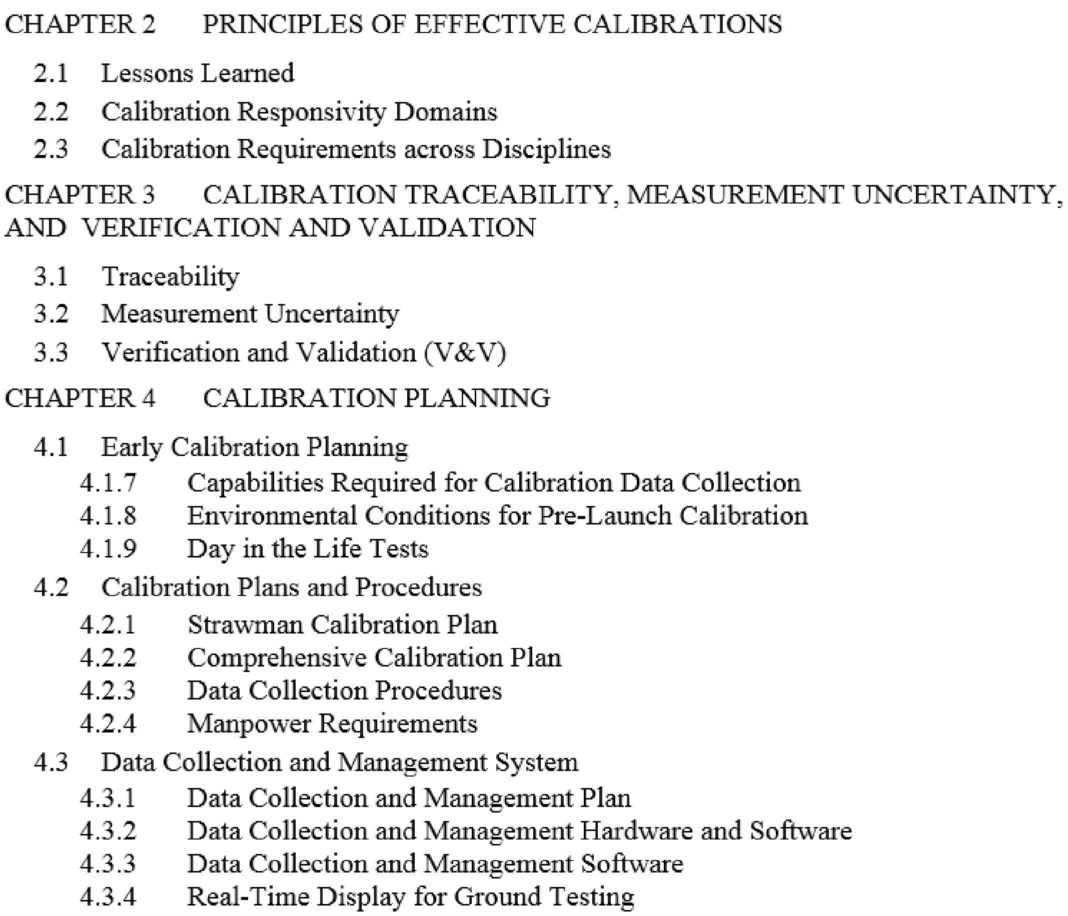
- Data from existing DoD systems are used in architecture studies for future systems
  - Helps establishes the requirements for:
    - Sensitivity
    - Spatial resolution
    - Goniometrics (line of sight (LOS) and FPVT)
    - Timeliness
    - Spectral capability (filter bandpass locations and widths)
    - Absolute accuracy
    - Repeatability (precision)
- Quality of the data plays a key role in establishing the design, complexity, and number of sensors required
  - Fundamental properties of a system that will be a major acquisition cost and schedule drivers

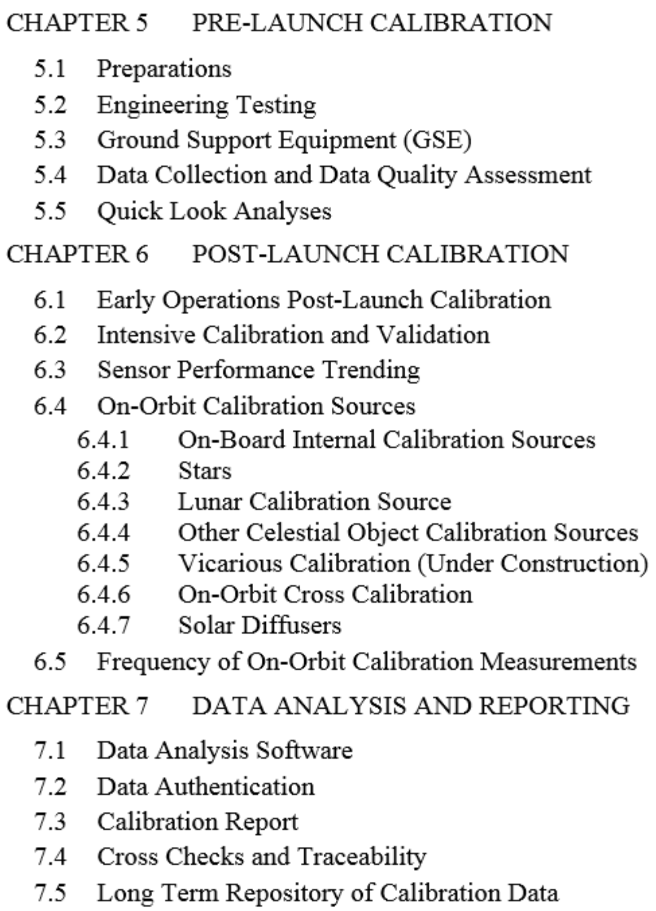
Calibration Requirements for DoD Applications

- Multiple DoD sensors are often used for the same purpose, such as using different constellations of sensors to perform missile warning
- Issue arises when multiple sensors, sensor types, and constellations are used for a common application but the individual calibrations are based on a different set of standards
    - Calibrations must be traceable to a common standard established by NIST for signatures to be derived on a common scale
    - The “test as you fly” axiom (Datla et al., 2011; Russell 2008) implies that instruments should be calibrated under the same environmental conditions as expected during operation and with the same source extraction algorithm
        - Includes environmental operational and measurement conditions such as atmospheric transmission
- For these applications
    - Calibration of the sensors will affect the quality of the interpretation of the data, and thus the success or failure of the performance of the critical task, not just the success or failure of a particular sensor or program

Calibration Publication Content

Table of Contents





Workshop Agenda

Workshop, Monday, August 11, 8:30 am to 12 noon

Topic	Name	Duration	Time (start)
Introduction	Joe Tansock	0:20	8:30 AM
Calibration Planning	Joe Tansock	1:00	8:50 AM
Break		0:15	9:50 AM
Pre-Launch Calibration	Alan Thurgood	0:30	10:05 AM
Post-Launch Calibration	Ray Russell	1:00	10:35 AM
Data Analysis and Reporting	Scott Hansen	0:15	11:35 AM
Discussion	All	0:10	11:50 AM
Adjourn			12:00 Noon

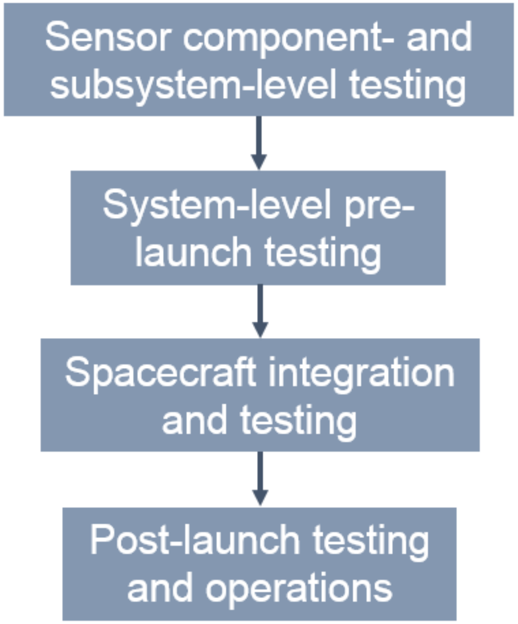
Calibration Planning

Planning Calibration

- Calibration is critical to the success of a mission
- Unfortunately, it is often an afterthought in the development of a sensor
  - Lack of planning can lead to increased cost and schedule, and inaccurate results
- Lessons learned from calibration experts show that successful and effective calibrations have various elements in common
  - These elements should always be considered for a calibration effort

Lesson Learned - Calibration Planning Should Begin During Sensor Design Phase

- Beginning calibration planning in the early stages of sensor design:
  - Promotes an optimum sensor calibration approach
  - Reduces costs and expenditures
  - Minimizing uncertainty for the intended application
- Experienced calibration personnel must be involved throughout the sensor's development phase to optimize calibration efforts
- Planning should address calibration throughout the lifetime of the sensor
  - Data management and analysis should be considered in the planning process
    - Today's sensors produce large amounts of data



Sensor component- and subsystem-level testing

System-level pre-launch testing

Spacecraft integration and testing

Post-launch testing and operations

Lesson Learned - Tradeoffs Must be Made when Planning and Implementing a Calibration

- There is always a tradeoff between what is ideal, what is desired, and what is strictly required when performing sensor calibration
    - Sensor programs have limited funding, which can affect the scope of the calibration effort
        - Reducing the scope of pre-launch calibration efforts may impart additional requirements for post-launch calibration, where options for collecting particular data sets are either limited or unavailable
    - Knowledgeable experts should be involved to identify trades among available budget, schedule, and impact to sensor performance/mission objectives

Lesson Learned - Tradeoffs Must be Made when Planning and Implementing a Calibration

- Attention and priority should be given to obtaining quality calibration measurements
    - Sufficient calibration data must be collected to span the operational envelope of the sensor
        - Scope should not extend to the point where extrapolation beyond the bounds of the calibration data set is required
    - The focus of any optimization effort should be on addressing how to perform the overall sensor calibration more efficiently, and not on reducing the scope of the calibration effort
        - Time can be saved by appropriate sequencing of the various tests to make the best use of analysts and resources
    - The quality of the test setup needs to be at least as good as the sensor under test; otherwise the sensor could end up being used to calibrate the special test equipment

Lesson Learned - Calibration Measurements Should be Traceable to Standards

- Calibration measurements should be traceable to a specific standard with a specified uncertainty
  - The sensor must provide measurements that can be trusted
  - Three properties work together to provide confidence in sensor data
    - Traceability
    - Measurement uncertainty
    - Verification and validation (V&V)
- Verified and validated calibration measurements that are traceable within the reported uncertainty provide assurance that the data can be used:
  - For multiple measurement types within a specified discipline
  - Across disciplines such as Earth sciences, atmospheric sciences, and Department of Defense (DoD) applications

Lesson Learned - Calibration Measurements Should be Traceable to Standards

- Traceability is the ability to track a measurement to a known standard unit within a given uncertainty
  - Can be achieved by using the SI-based standards of a national measurement institute, such as the U.S. National Institute of Standards and Technology (NIST)
  - Calibration should include a traceability chain to a primary standard and a quoted overall uncertainty
  - Measurements should be compared to known reference standards, and discrepancies recorded
- V&V ensures that the instrument operates as designed and produces relevant data by proven processes and standards
  - Data products and sensor performance knowledge obtained during calibration play a critical role in V&V at both the sensor and the mission level, creating a critical link between sensor calibration and overall mission-level success

Lesson Learned - System-Level Testing Provides the Best Representation of Sensor Performance

- Component-level testing may not be adequate to represent a full system-level calibration
  - Components may behave differently than expected once assembled into an EO sensor
  - Characterizing the interactions and dependencies between the optical and electronic components:
    - Provides information on how the integrated system operates
    - Allows systematic errors to be discovered, evaluated, and resolved before flight
  - System-level calibration can be visualized as the quality control aspect of system design and testing (Wyatt 1991)

Courtesy of SDL

Lesson Learned - System-Level Testing Provides the Best Representation of Sensor Performance

- SABER (Hansen et al., 2003)
  - Component-level and system-level RSR bandwidth measurements were compared
    - Eight of the SABER bands were consistent within 3.3%
    - One showed a difference of 4.5%
    - One showed a difference of 23.5%
  - For the bands showing large differences, accurate end-to-end spectral measurements were essential to achieve correct understanding of instrument science data
- SPIRIT III (Fuqua et al., 2003)
  - During engineering testing, increased out-of-band spectral leakage caused by the Stierwalt effect was discovered
    - Resolved by adding a sapphire blocking filter into the sensor configuration (SDL/98-033)
    - Had this problem not been resolved, the measurement uncertainty would have been unacceptably large, limiting the value of the data produced by the sensor

Lesson Learned - Both Pre- and Post-Launch Calibrations are Critical to Mission Success

- Pre-launch calibration, or ground calibration, provides the capability to perform tests in a controlled environment with known sources that cannot be duplicated on-orbit
  - Can discover and resolve anomalies prior to launch
- Post-launch testing, or on-orbit calibration, has the advantage of being performed under true flight conditions rather than simulated flight-like conditions
- Hubble Space Telescope (Example)
  - Component-level testing was performed
    - Reflective null corrector test (no concerns) was thought to be a better component test than tests of the primary mirror (showed potential concerns)
    - Decision was to proceed, and no sensor-level validation occurred on the ground prior to launch
  - A serious sensor focus problem was identified on orbit
    - “The Hubble Space Telescope Optical Systems Failure Report” (NASA-TM-103443, November 1990)
  - This anomaly could have been identified during pre-launch system level calibration, potentially saving millions of program dollars

Lesson Learned - Both Pre- and Post-Launch Calibrations are Critical to Mission Success

- Pre-launch calibration is essential in understanding sensor performance nuances so that they can be addressed and understood before launch
- Measurements made during pre-launch calibration are used to:
  - Verify proper instrument operation
  - Quantify calibration equation and radiometric model parameters
  - Estimate measurement uncertainties
  - Options to correct sensor performance on orbit are limited and expensive
- Measurements made during post-launch calibration are used to:
  - Measure parameters that cannot be measured on the ground
  - Maintain calibration throughout a sensor’s operational lifetime
  - Update measurement uncertainty
  - Update calibration coefficients if necessary to meet requirements

Sensor Performance Model and Calibration Equations

- A unique sensor model based on mission requirements should be compiled during calibration planning to better understand sensor performance
  - Enables the sensor designers to tailor the instrument design to meet mission requirements
- A sensor-specific calibration (derived from measurement equation) equation should then be created to convert sensor output (in units of counts, volts, etc.) to desired engineering units
- Calibration parameters that are required to fully calibrate or characterize the instrument, but are not needed in the calibration equations become part of the sensor’s radiometric model or sensor performance metrics

Typical Calibration Equations and Parameters for Imaging Radiometers

- Irradiance Calibration Equation
  - The irradiance calibration equation converts sensor response in digital counts into physical units for a point source

$$E_{M,k,t} = \frac{1}{\Re_E UNF_{irrad}} P\left[r_{k,t}, PRF\right] = \frac{1}{\Re_E UNF_{irrad}} P\left[\frac{B_k G_I}{F_{NUC,k}}\left[F_{Lin,k}\left(r_{T,k,t}\right) - F_{Lin,k}\left(r_{O,k,t}\right), PRF\right]\right]$$

$E_{M,k,t}$	Measured irradiance (W/cm^2)	G_I	Integration time normalization (unitless)
$\Re_E$	Peak irradiance responsivity (counts/Wcm^2)	$F_{NUC,k}$	Nonuniformity correction function (unitless)
UNF_{irrad}	Irradiance uniformity correction (unitless)	$F_{Lin,k}\left(r_{T,k,t}\right)$	Nonlinearity correction function (unitless)
$P\left[r_{k,t}, PRF\right]$	Point source extraction operation	$r_{T,k,t}$	Raw pixel response (counts)
$r_{k,t}$	Corrected pixel response (counts)	$r_{O,k,t}$	Raw pixel background response (counts)
PRF	Point response function (unitless)	t	Time – parameters vary as function of time
B_k	Bad pixel mask function (unitless)	k	Pixel index – unique to each pixel

Typical Calibration Equations and Parameters for Imaging Radiometer

- Radiance Calibration Equation
  - The radiance calibration equation converts sensor response in digital counts into physical units for an extended source

$$L_{M,k,t} = \frac{1}{\Re_L} r_{k,t} = \frac{1}{\Re_L}\left[\frac{B_k G_I}{F_{NUC,k}}\left[F_{Lin,k}\left(r_{T,k,t}\right) - F_{Lin,k}\left(r_{O,k,t}\right)\right]\right]$$

$L_{M,k,t}$	Measured radiance (W/cm^{2}sr)	$F_{Lin,k}(r_{T,k,t})$	Nonlinearity correction function (unitless)
$\Re_L$	Peak radiance responsivity (counts/Wcm^{2}sr)	$r_{T,k,t}$	Raw pixel response (counts
$r_{k,t}$	Corrected pixel response (counts)	$r_{O,k,t}$	Raw pixel background response (counts)
B_k	Bad pixel mask function (unitless)	t	Time – parameters vary as function of time
G_I	Integration time normalization (unitless)	k	Pixel index – unique to each pixel
$F_{NUC,k}$	Non-uniformity correction function (unitless)		

- Characterization of parameters requires separation of responsivity domains
  - Radiometric, spatial, spectral, temporal, polarization

Typical Radiometric Model Parameters for an Imaging Radiometer

- The radiometric model consists of additional parameters needed to understand and model instrument performance

- Source characterization parameters

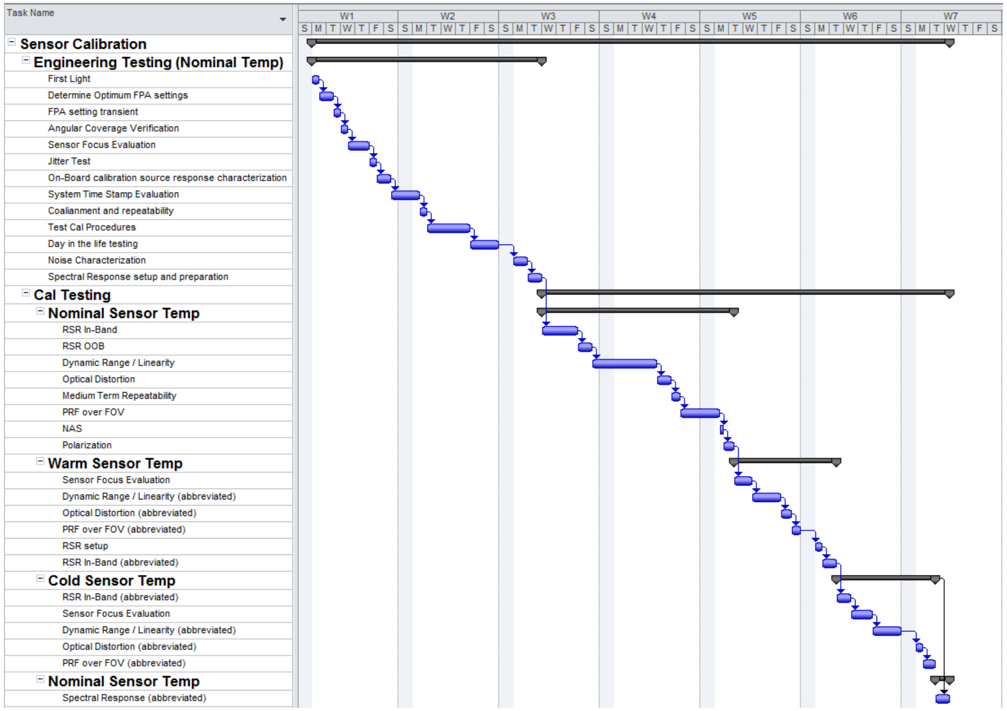
Relative Spectral Response	Effective Field of View	Polarization Sensitivity
Near Angle Scatter	Focus	Point Response Function
IFOV Line-of-Sight Map	Waveband Crosstalk	Focal Plane Image Latency

- Sensor performance metrics

Noise-Equivalent Irradiance (NEI)	Noise-Equivalent Radiance (NER)
Saturation-Equivalent Irradiance (SEI)	Saturation-Equivalent Radiance (SER)
Noise-Equivalent Flux Density (NEFD)	NUC and Stability (Fixed Pattern noise)
Response Repeatability & Response Noise	Dark Offset/Background Repeatability (Dark Noise)
Angle Repeatability & Jitter	1/f Noise
Sensor Time-Stamp Characterization	Sensor Frequency Response
Dynamic Range	Saturation Behavior
On-Board Calibration Source Characterization	Any other unique sensor performance parameters

Test Schedules (Calibration Planning)

- Calibration is performed at the end of sensor development
    - Generally on the critical path with lots of schedule pressure
- A detailed and accurate test schedule provides credible documentation
    - Justifies the calibration schedule
    - Allows for making accurate impact assessment



Task Name

- Sensor Calibration
    - Engineering Testing (Nominal Temp)
        - First Light
        - Determine Optimum FPA settings
        - FPA setting transient
        - Angular Coverage Verification
        - Sensor Focus Evaluation
        - Jitter Test
        - On-Board calibration source response characterization
        - System Time Stamp Evaluation
        - Coalianment and repeatability
        - Test Cal Procedures
        - Day in the life testing
        - Noise Characterization
        - Spectral Response setup and preparation
    - Cal Testing
        - Nominal Sensor Temp
            - RSR In-Band
            - RSR OOB
            - Dynamic Range / Linearity
            - Optical Distortion
            - Medium Term Repeatability
            - PRF over FOV
            - NAS
            - Polarization
        - Warm Sensor Temp
            - Sensor Focus Evaluation
            - Dynamic Range / Linearity (abbreviated)
            - Optical Distortion (abbreviated)
            - PRF over FOV (abbreviated)
            - RSR setup
            - RSR In-Band (abbreviated)
        - Cold Sensor Temp
            - RSR In-Band (abbreviated)
            - Sensor Focus Evaluation
            - Dynamic Range / Linearity (abbreviated)
            - Optical Distortion (abbreviated)
            - PRF over FOV (abbreviated)
        - Nominal Sensor Temp
            - Spectral Response (abbreviated)

- Short-term savings gained by reducing or eliminating ground calibration testing can lead to
    - Increased costs for additional on-orbit calibration time
    - Compromised on-orbit performance when parameters that can only be measured on the ground are unavailable

Environmental Conditions for Pre-Launch Calibration

- When conducting pre-launch calibration, it is best to follow the axiom “test as you fly” or “test like you fly” (Datla et al., 2011; Russell 2008)
  - Instruments should be calibrated under the same environmental conditions as expected during operation

Space Flight Sensor

TVAC chamber to simulate the space environment
Croygenic operating pressure ~10-7 Torr
LN_2 shroud provides low background

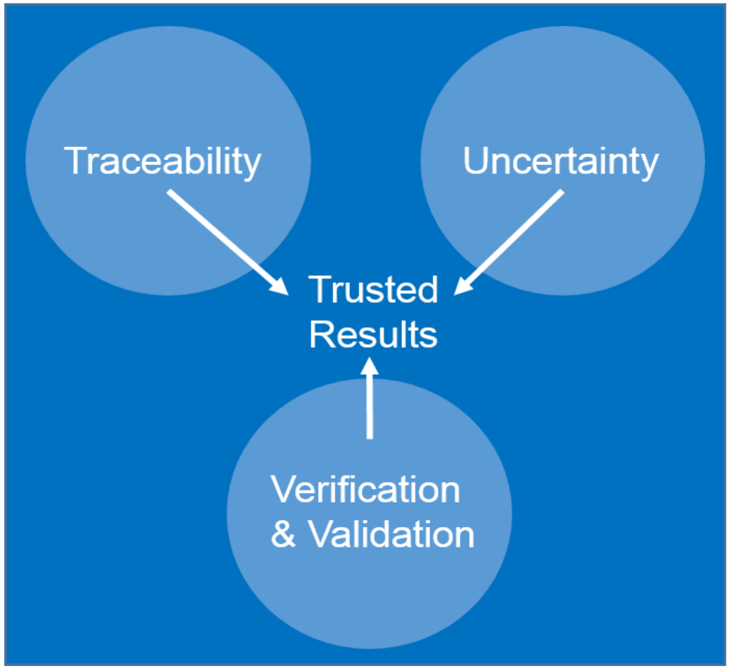
Airborne or Aircraft Sensor

Altitude simulation (0 to 100,000 ft)
Temperatures: -60°C to 125°C
Pressure: Ambient to ~10 Torr

Courtesy of SDL

Producing Trusted Data

- The sensor must provide measurements that can be trusted
  - Three properties work together to provide confidence in sensor data
    - Traceability
    - Measurement uncertainty
    - Verification and validation (V&V)



Traceability

- Traceability can be defined as an unbroken record of documentation or an unbroken chain of measurements, and their associated uncertainties (www.nist.gov)
- In 2008, the *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms* (VIM) reworded the term 'traceability' to 'metrological traceability'
    - Defined it explicitly for metrology as the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (JCGM 200:2008)

The principle benefit of traceability is to improve the likelihood that data products:

- provide a quantitative description of the measured parameter
- are invariant with time
- are sufficiently robust for regulator, policy, or commercial decisions (Fox, 2004)

In addition to the VIM, this committee also developed the *Guide to the Expression of Uncertainty in Measurement* (GUM) (JCGM 100:2008) to address metrological traceability

Metrological Traceability

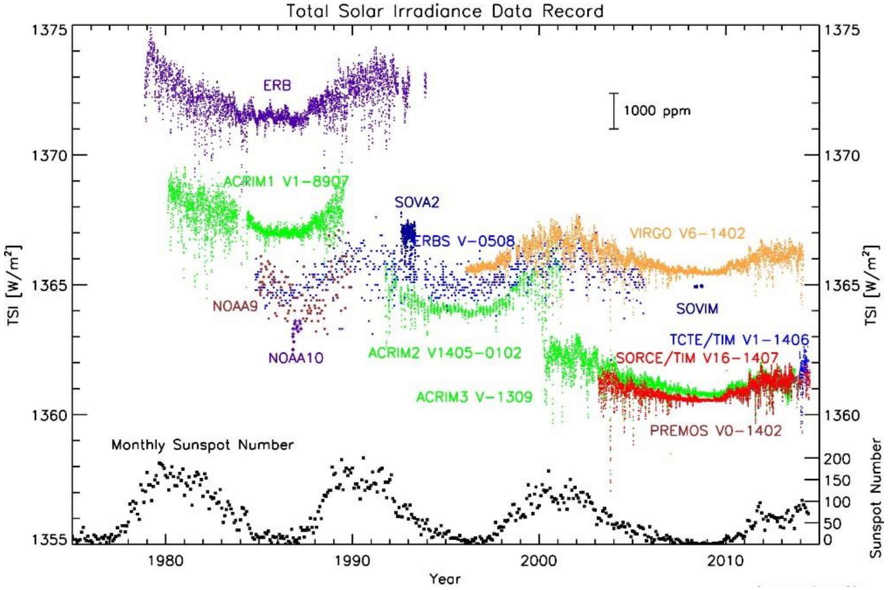
- Metrological traceability is the property of a measurement, and not attributed to an instrument, the calibration report, or a laboratory
- To substantiate a claim of metrological traceability, the provider must:
  - Document the measurement process or system used to establish the claim
  - Provide a description of the chain of calibrations that were used to establish a connection to a particular specified reference

A full description of NIST's policy on the subject can be found at www.nist.gov/traceability/

- The following elements are common to all valid statements or claims of metrological traceability (http://www.nist.gov/traceability/traceability_toc.cfm):
  - A clearly defined particular quantity that has been measured
  - A complete description of the measurement system or working standard used to perform the measurement
  - A stated measurement result, which includes a documented uncertainty
  - A complete specification of the reference at the time the measurement system or working standard was compared to it
  - An internal measurement assurance program for establishing the status of the measurement system, specified reference, or working standard at all times pertinent to the claim of metrological traceability

Metrological Traceability (Example)

- Data sets must be calibrated with the same traceability, and differences between instruments must be clearly understood
    - Includes the earth’s atmospheric and surface properties, and DoD applications
- The experience at NASA in the measurement of top of atmosphere (TOA) total solar irradiance (TSI) is an example of how the remote sensing community has been working toward this goal for the past 20 years



- Various instruments throughout the years gave slightly different results
- Calibration facility improvements employed using absolute cryogenic radiometer
- Results showed various systematic effects, and there is now consistency reported in the TSI measurements from space (Kopp et al., 2012)

(http://spot.colorado.edu/~koppg/TSI/, Image G. Kopp, 10 Jul 2014)

Système International (SI) Traceability

- The need for pre-launch SI traceability of space-bound sensors to establish metrological traceability for space-based measurements has been discussed at various workshops
    - NPOESS, NOAA, NASA, and NIST (Ohring et al., 2004; Ohring 2007; Cooksey and Datla 2011)
- Workshops also emphasized the need for on orbit SI traceability and recommended benchmark satellite missions with SI traceable standards
    - CLARREO mission is being planned to carry SI traceable standards for calibration of its sensors, and to provide benchmark measurements
        - Benchmark measurements can provide calibrations to other satellite sensors through measurement inter-comparisons using techniques such as simultaneous nadir observations (SNO)

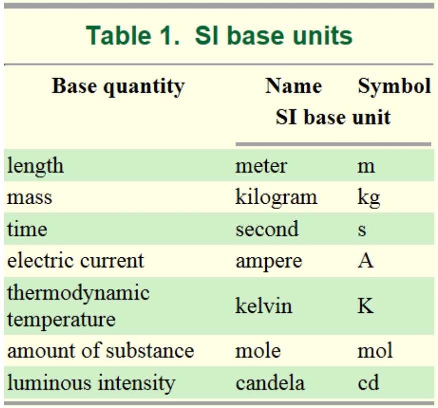


Table 1. SI base units

Base quantity	Name	Symbol
	SI base unit	
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

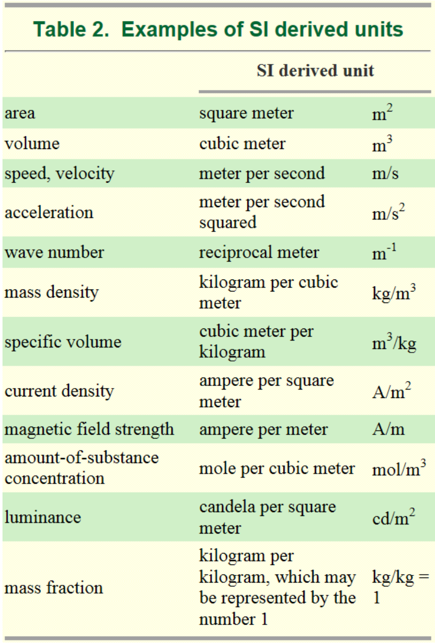


Table 2. Examples of SI derived units

	SI derived unit	
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
wave number	reciprocal meter	m^{-1}
mass density	kilogram per cubic meter	kg/m^3
specific volume	cubic meter per kilogram	m^3/kg
current density	ampere per square meter	A/m^2
magnetic field strength	ampere per meter	A/m
amount-of-substance concentration	mole per cubic meter	mol/m^3
luminance	candela per square meter	cd/m^2
mass fraction	kilogram per kilogram, which may be represented by the number 1	kg/kg = 1

http://physics.nist.gov/cuu/Units/units.html

Measurement Uncertainty

- Uncertainties associated with radiometric measurements result from many factors
  - Noise, nonlinearity, non-uniform detector array response, nonideal spectral and spatial responsivity, and standard calibration source uncertainty. (Wyatt et al., 1998)
- A comprehensive uncertainty budget should be established early in the calibration planning process
  - Keep the uncertainty budget up-to-date with the most recent sensor performance and calibration source uncertainty estimates

- Identify and reduce the largest uncertainties to give the smallest overall uncertainty
- Report results in standard units and use established guidelines for estimating uncertainty
- Recognize the need for other programs to use your results

- For all uncertainty estimates, report detailed logic and supporting background so that reassessment at a later date is possible
- Be realistic when estimating uncertainty; no one ultimately benefits by providing an overly optimistic level of uncertainty
- Establish multiple traceability paths to physical standards to verify or help quantify uncertainty estimates

Calibration Plan

- Calibration plan should be prepared before the start of any testing
  - Addresses the entire sensor life cycle from design, fabrication, assembly integration and test, pre-flight calibration, spacecraft integration and test, and all on-orbit operations
  - Specifies the test setup and calibration measurement configurations
  - Defines each test, source, magnitude, and number of settings, etc.
  - Provides schedule
- Calibration plan example statement:

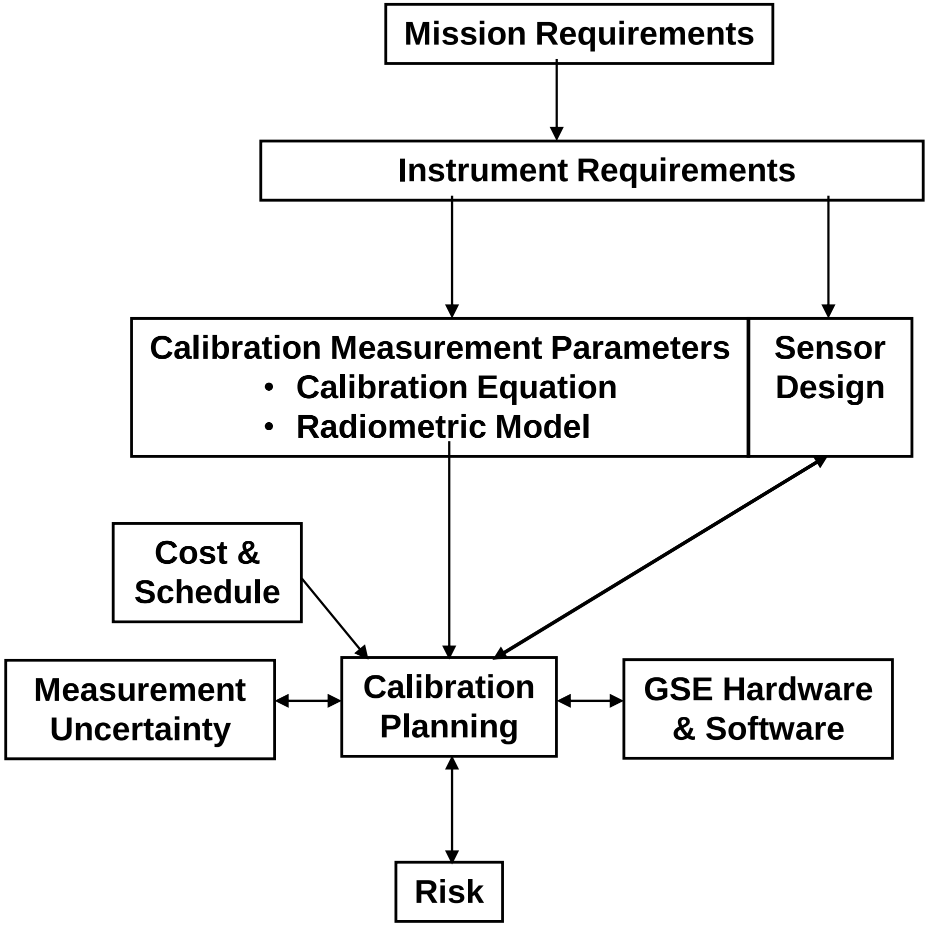
Ten extended source temperatures are baselined. These settings are estimated to provide about two measurements per decade of response in the flux range given by the extended source temperature range.

Strawman Calibration Plan

- A strawman calibration plan is developed early in calibration planning ideally during program design phase
- Potential Strawman Calibration Plan contents (depends on project)
  - Sensor and mission requirements that determine calibration requirements
  - Assumptions
  - Calibration equations and supporting radiometric model
  - Component-level calibrations required
  - Tests to be performed and phase during which the test will be performed
  - Tests used to quantify sensor performance and verify calibration requirements
  - Calibration monitoring requirements and concept for trending measurements
  - Measurement combinations for each calibration measurement
  - Baseline calibration schedule and manpower needs
  - Initial budget for calibration uncertainties
  - Calibration facility, sources and other hardware, and software requirements
  - On-orbit sources required and measurement feasibility
  - Concept of operations for on-orbit measurements
  - Availability and validity of calibration sources
  - Concept for data quality assessment
  - Concept data management approach for each phase of calibration
  - Projected risks of not meeting req.
  - ROM cost estimate

Strawman Calibration Development

- "SABER Ground Calibration" (Tansock et al., 2003) provides an example of the strawman planning process
- If measurement parameters did not meet specifications given by the uncertainty budget
  - Calibration planning process was repeated until a solution met instrument calibration requirements, budget and schedule at a minimum risk



Comprehensive Calibration Plan

- After a strawman calibration plan has been finalized, the comprehensive calibration plan is then prepared
- More mature and detailed plan
  - Revises the elements of the strawman calibration plan based on updated sensor design and performance information, and verifies the elements of the calibration approach
- Major changes or updates from the strawman plan should be reviewed and approved by stakeholders
- The output of the comprehensive calibration planning process is a formal, detailed, and well organized document
  - Mature and detailed plan with concurrence from all stakeholders

Calibration Data Collection Procedures

- Calibration data collection procedures should be prepared before the start of any testing
  - Data collection procedures identify each step of the data collection process to ensure that the resulting data are accurate, repeatable, adequate for subsequent data analyses
  - One for each measurement
  - Step-by-step procedure
    - Implementation details of each test (nuts and bolts of data collection)
    - Example step:

3.2.5	Verify the extended source blackbody is set temperature for upcoming test combination and is stable

Data Collection Procedures

- Calibration plan provides a top-level overview of calibration data collection, but does not provide the necessary detail to actually collect data
- Data collection procedures identify each step of the data collection process
  - Ensure the resulting data are accurate, repeatable, and adequate for subsequent data analyses

- Test description
- Preparation steps (needed hardware, configuration, etc.)
- Data collection steps
- Data collection time requirement estimates
- Data storage and download time requirements
- Reference to test plan and data products
- Documentation of related command files
- Data collection notes
- Data collection log sheets
- Quick-look analyses to be performed shortly after data collection before breaking the hardware configuration
- Data collection success criteria

Manpower Resource Planning

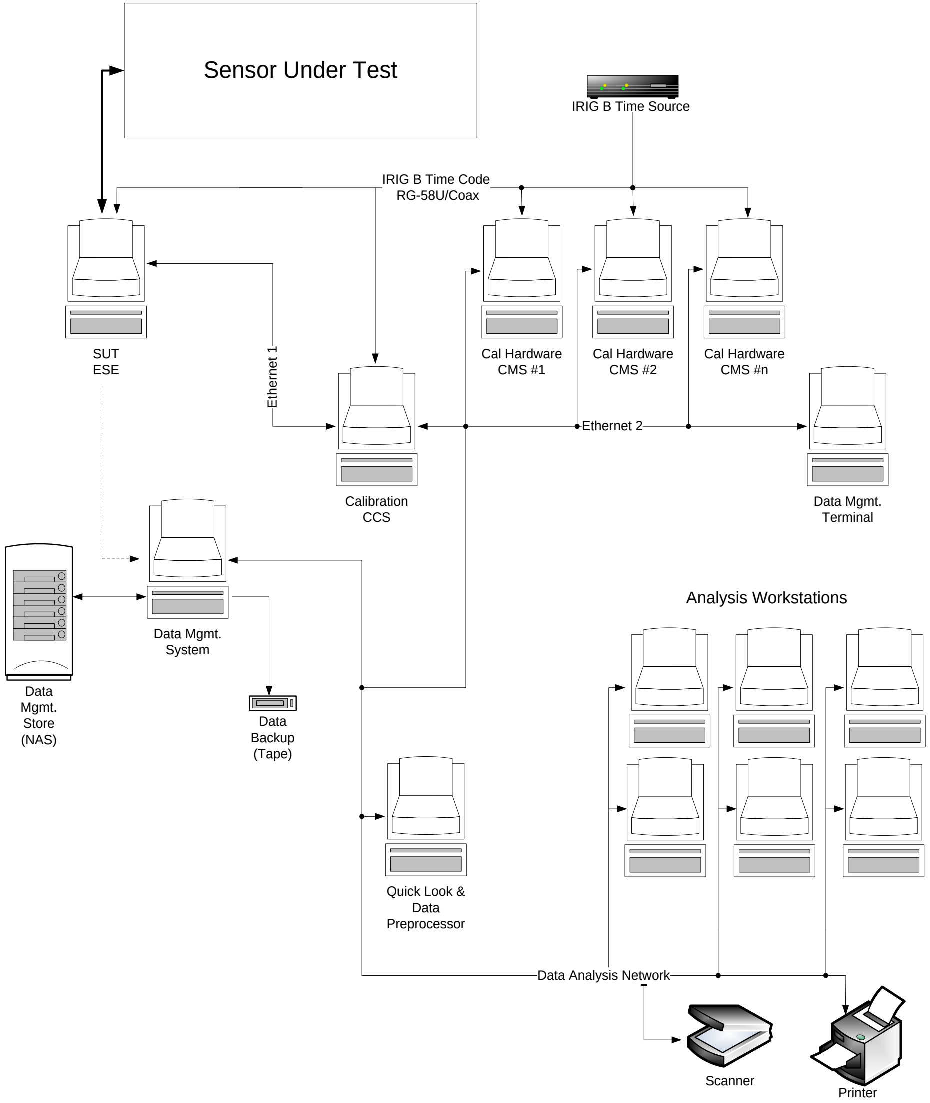
- Detailed data collection procedures along with schedules help finalize manpower resource requirements
  - Data collection tasks (data collection engineers)
  - Test hardware monitoring and support (operational support)
  - Data management (computer engineers)
    - Preprocessing, data QA, managing the data (e.g., moving data between data collection and data analysis systems, data storage, data archive)
  - Quick-look data analyses (data analysts)
  - Test status briefings (all the above)
  - Post test data analyses and reporting (data analysts)
- Adequate manpower must be available to perform these tasks within the allocated schedule

Data Collection and Management System

- Data collection and data management systems are program dependent, but in general should provide:
  - Hardware and software tools to efficiently and accurately configure the sensor, test hardware, and collect calibration data
    - Modern sensor calibration should include automated data collection
    - Real time displays are critical to successful ground testing and calibration
  - Tools and data structures (files) needed to perform data analyses
- Data Collection and Management System Plan should address
  - Data collection (hardware and software)
  - Data flow
  - Estimated data volume
  - Data management hardware
  - Data handling
  - Data processing software
  - Data quality assurance
  - Data archiving

Data Collection and Management System

- Generic system example for prelaunch calibration =>
- Ensure proper functionality and smooth operation
  - Assemble, integrate, and test before operation
  - Data collection and data management hardware readiness status must be part of the test readiness review (TRR)



Data Collection and Management System

- Potential data collection and data management software

Need or Requirement	Description and Details
Facility data logging	Environmental conditions logging
Individual systems	Command, control and monitoring of test chambers, test hardware and subsystems
Sensor command and data system	1. Configure sensor under test 2. Real-time monitoring of sensor response 3. Sensor data collection
Master controller	Manual and/or scripted communication and commanding 1. Control and monitoring of subsystem configurations 2. Control sensor under test configuration 3. Initiate sensor data collections 4. Log all measurement configuration information
Quality assurance	Check for data anomalies, operational bounds, etc.
Data base	Gather all information and populate the database for each test point or data collection
Data archival	Structuring and copying all data to processing storage and long-term archive
Preprocessing	Number crunching to extract statistics and informational quantities from the raw data
Test point construct	Gather sensor data and all information associated with a test point for analysis
Processing and analysis	The specialized software tools that turn test-point constructs into calibration parameters, uncertainties and data products

Pre-Launch Calibration

Pre-Launch Calibration

- Pre-launch calibration (ground calibration)
  - Provides capability to perform tests in a controlled environment with known sources that cannot be duplicated on-orbit
  - Allows anomalies to be discovered prior to launch
  - Verifies proper instrument operation
  - Quantifies calibration equation and radiometric model parameters
  - Estimates measurement uncertainties
  - Essential to understanding sensor performance nuances so that they can be addressed and understood before launch
    - Options to correct sensor performance on orbit are limited and expensive

Pre-Launch Calibration

- Typical phases of pre-launch calibration
  - Preparing ground support equipment (GSE)
  - Engineering testing
  - Calibration testing
  - Quick look analyses

Ground Support Equipment (GSE)

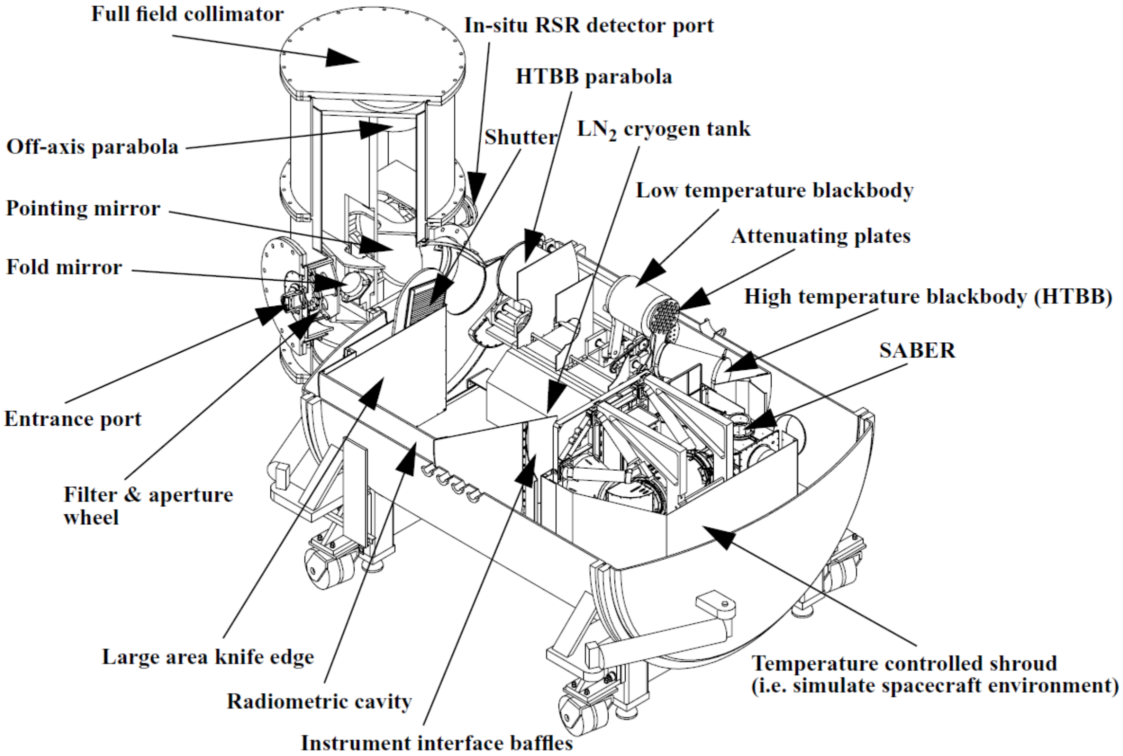
- Includes test chambers, calibration sources, electrical support equipment (ESE), data collection and management system, and sensor GSE
- Sufficient time and resources must be allocated In the planning phase to prepare for pre-launch calibration measurements
    - Prepare existing equipment
    - Develop and acquire the unique equipment
- Test chambers
    - Thermal-vacuum (TVAC) chambers are used to simulate the operational environment of space satellite sensors
        - Must provide the mechanical, electrical, and thermal configurations
    - Airborne or aircraft sensors require a flight simulation chamber

Test Chambers (Examples)

SDL THOR Chamber

- Cryogenically cooled with LN_2
- 6’ 10” inside diameter x 12’ long cold shroud
- Typical cryogenic operating pressures of 10^{-7} Torr
- LN2 cooled shroud space environment simulation
- 4’ wide x 10’ long cold bench

SABER Calibration Test Facility (Tansock et al., 2003)



- Cryogenically cooled with LN_2
- Linearity attenuator plate
- Sources located in single facility
- Test chamber
- Collimator
- Low and high temperature BBs Cold shutter
- Cold baffles
- Instrument rotation stage

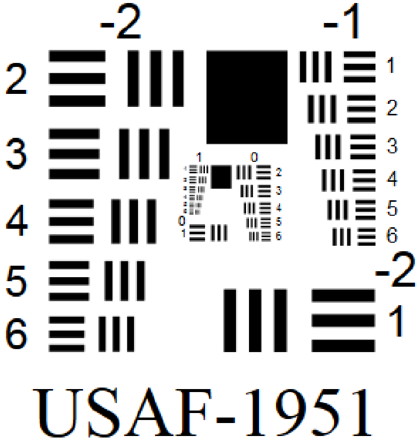
Ground Calibration Sources

- Spectral sources used for:
  - Spectral wavelength calibration
    - Emission sources such as gas lamps with well known peak emission wavelengths
    - Absorption sources such as gas cells or NIST SRM 1921b (Polystyrene film) with well known peak absorption wavelengths
  - Sensor or component spectral response / spectral transmittance or reflectance
    - Tunable lasers / integrating sphere (e.g., NIST SIRCUS)
    - Monochromator with QTH lamps, arc sources, and blackbodies
    - Fourier transform spectrometer with QTH lamps, glowbars, and blackbodies

Courtesy of SDL

Ground Calibration Sources

- Spatial sources used for:
  - Spatial frequency response
    - Bar patterns
  - Modulation transfer function (MTF)
    - Knife edge sources
    - Line source from a narrow slit
    - Point sources from pinhole apertures
  - PRF, distortion
    - Point source (or grid of point sources)



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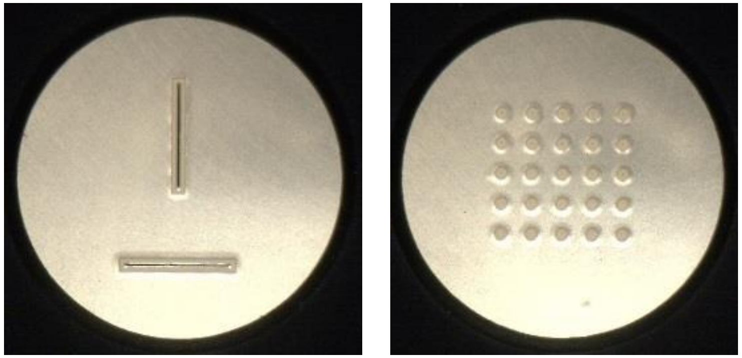


Courtesy of SDL

Ground Calibration Sources

- Linearity sources
  - Absolute radiance source at multiple levels throughout dynamic range
    - Difficult to get source with low enough uncertainty over full range
    - Residual RSR uncertainties are coupled into results
  - Small signal source modulated at a constant amplitude coupled with a large signal source for full sensor dynamic range (occasionally referred to as AC/DC method)
    - Does not require any radiometric knowledge about either source
    - Only source requirement is that small signal source amplitude is repeatable
  - Set of precision pinholes to cover part of the sensor dynamic range coupled with a radiance source that can cover the full sensor dynamic range
    - Multiple overlapping sets of data are taken using the set of apertures with different source temperatures to cover the full dynamic range
    - Overlapping sets of data allow the separation of sensor linearity from knowledge of aperture areas
    - Does not require any radiometric knowledge about the radiance source


Courtesy of SDL

Ground Calibration Sources

- Radiance sources
  - Sources approaching ideal behavior
    - Cavity blackbody with low thermal gradients and low temperature uncertainty
    - Output radiance should still be tested to verify performance
  - Repeatable sources calibrated against another standard
    - Standard lamp coupled with a diffuse surface such as Spectralon® panel
    - Integrating sphere coupled with lamp(s) or blackbody(s)
    - Recommend some kind of monitoring system be used to alert user to any changes in performance such as contaminated integrating sphere surface

Ground Calibration Sources

- Temporal sources
  - Optical chopper coupled with a blackbody or lamp
  - Pulsed or modulated sources such as LEDs, laser diodes, etc.
- Irradiance sources
  - Any of the radiance sources coupled with a collimator and precision pinhole aperture
    - Aperture area and collimator focal length must be known
    - Spectral reflectance or transmittance of collimator must be known
    - May require a diffraction correction (depending on wavelength and geometry)
  - Spectral irradiance standard lamps
  - Output irradiance should still be tested to verify performance (NIST BXR & MDXR)

GSE Preparation

- Quality of a calibration is only as good as the tools and references used to perform the calibration
  - GSE used in the calibration must be well-characterized, stable, and accurate
- Calibration hardware and software should be tested and characterized prior to the actual calibration
  - Minimizes schedule delays
  - Prevents possible calibration degradation due to equipment issues
- Time should be budgeted for testing calibration equipment against available NIST standards
- Anticipate the unexpected
  - Address unwanted stray light paths, unwanted optical vignetting, temperature measurement errors, contamination, etc.

GSE Calibration Maintenance

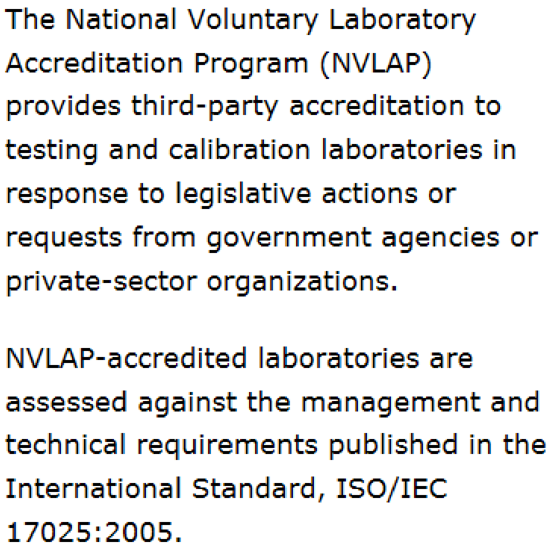
- The equipment used for calibration requires maintenance to ensure proper operation and to maintain traceability
  - For example, the Air Force requires contractors using calibration tools such as volt-ohm-current meters to calibrate the tools annually against known reference standards
    - Meters are then distributed among laboratories and used to test and calibrate higher-level sensors
- As the level of complexity of a calibration tool or reference increases, the level of calibration complexity is correspondingly elevated
  - For example, a sensor that will be used to measure the thermal infrared radiance emitted by the surface of the earth from space will need to be calibrated under vacuum and at space-based operational temperatures
  - The sensor will need to measure a radiance standard, with spectral calibrations being performed to obtain the relative spectral response

GSE Calibration Maintenance

- Challenges of maintaining traceability
  - A radiance standard can be established through knowledge of the emissivity and temperature of a surface
    - Although traceable to NIST standards, accurately calibrated, and stable:
      - PRTs must be in good thermal contact with the surface on which it is mounted to provide the correct temperature for the radiance calculation
      - PRTs are shock sensitive, which make their calibration uncertain due simply to handling
      - PRT calibration may shift due to the thermal cycling, rendering the calculated radiance from temperature incorrect
      - If the blackbody material is not in good thermal equilibrium, the temperature measured by the sensor may not be representative of the material under the paint layer
    - Emissivity of the coating of the blackbody may change under various conditions such as temperature cycling, contamination, or water absorption
- To minimize these uncertainties, some programs have adopted a transfer radiometer as the standard calibration tool for radiometric transfer and traceability to NIST standards

GSE Calibration Maintenance

- For specialized calibration equipment requiring expensive and time consuming calibrations, the challenge is to determine when recalibration is required
- Implementing a plan for monitoring and trending calibration can help define recalibration frequency
  - Includes comparing results to requirements and defining trending threshold(s) for recalibration
  - Ensures that the frequency of recalibration is driven by the monitoring of calibration performance rather than by pre-defined recalibration intervals
- NIST offers laboratory guidelines in their National Voluntary Laboratory Accreditation Program (NVLAP) for establishing laboratory procedures and general requirements



The National Voluntary Laboratory Accreditation Program (NVLAP) provides third-party accreditation to testing and calibration laboratories in response to legislative actions or requests from government agencies or private-sector organizations.

NVLAP-accredited laboratories are assessed against the management and technical requirements published in the International Standard, ISO/IEC 17025:2005.

http://www.nist.gov/nvlap/

Engineering Testing

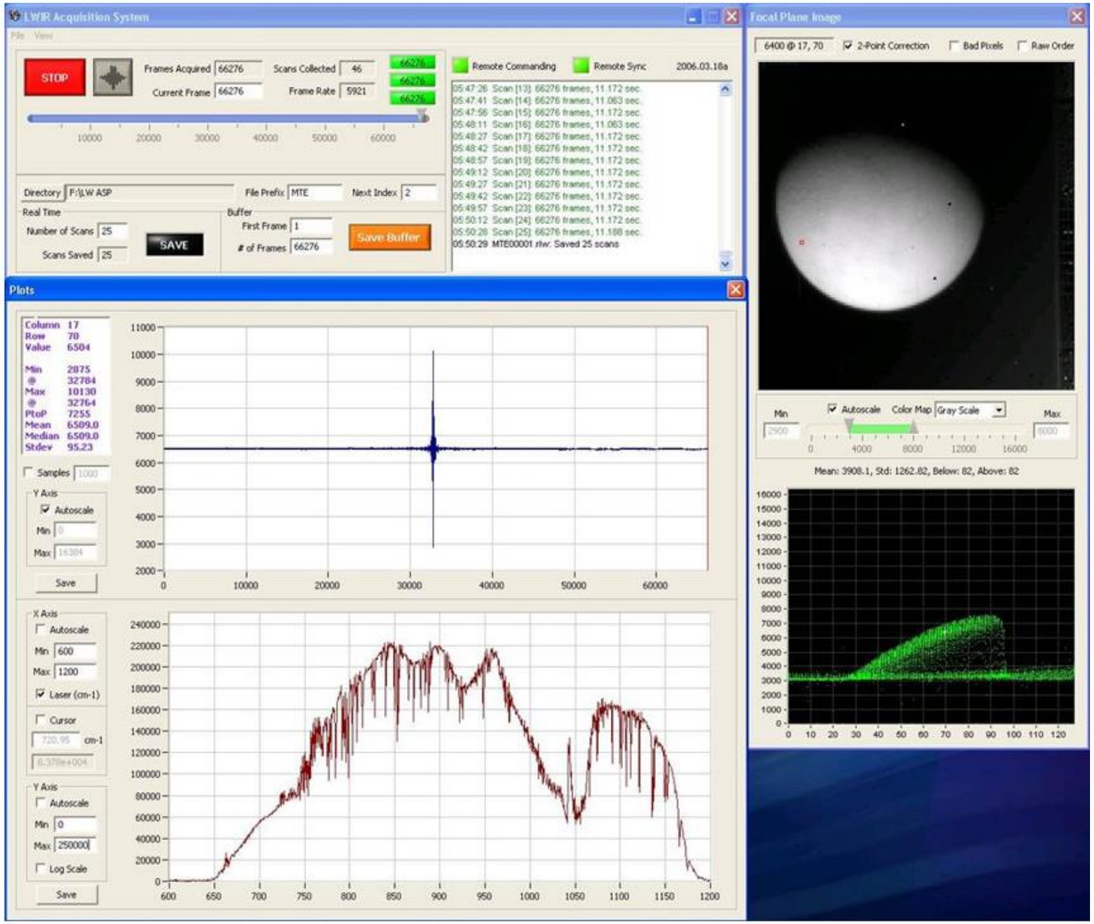
- Performed before the main calibration effort begins
- Primary goal is to identify calibration preparation shortcomings and make corrections before formal calibration begins
  - Minimizes collecting data that can NOT be used for the intended analyses
- Consists of:
  - Subsets of the planned measurement combinations
  - Special tests to establish sensor characteristics and data collection timing parameters
- Verifies
  - Functionality of the data collection and data management systems
  - Functionality and performance of GSE and calibration sources
  - Readiness of data analysis tools and quicklook display
  - Data collection scripts for acquisition of calibration data

Calibration Testing

- After engineering testing is complete and any adjustments are made, the main calibration effort begins
- The detailed test schedule should be followed as closely as possible
    - Some flexibility is required when issues or concerns arise
- Data collection engineer will follow the data collection procedure, fill in log entries, and make note of events or conditions that may affect the data
    - Becomes the red-lined version of the procedure
    - Completed data collection procedures, including any red-lined procedures and notes, should be archived as as-run procedures

Data Collection and Data Quality Assessment

- Ability to display EO sensor data in real time is critical to successful ground testing and calibration
  - Provides verification of
    - Proper instrument configuration
    - GSE configuration
    - Response levels



Frames Acquired 66276
Scans Collected 46
Current Frame 66276
Frame Rate 5921
Directory F:\LW ASP
File Prefix MTE
Next Index 2
Real Time
Number of Scans 25
Scans Saved 25
Buffer
First Frame 1
# of Frames 66276

2006.03.18a

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05:47:26  Scan [13]: 66276 frames, 11.172 sec.
05:47:41  Scan [14]: 66276 frames, 11.063 sec.
05:47:56  Scan [15]: 66276 frames, 11.172 sec.
05:48:11  Scan [16]: 66276 frames, 11.063 sec.
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05:50:29  MTE00001.rlw: Saved 25 scans
```

Column 17
Row 70
Value 6504

Min 2875
@ 32784
Max 10130
@ 32764
PtoP 7255
Mean 6509.0
Median 6509.0
Stdev 95.23

☐ Samples 1000
Y Axis
☑ Autoscale
Min 0
Max 16384

X Axis
☐ Autoscale
Min 600
Max 1200
☑ Laser (cm-1)
☐ Cursor
720.95 cm-1
8.378e+004
Y Axis
☐ Autoscale
Min 0
Max 250000
☐ Log Scale

6400 @ 17, 70
☑ 2-Point Correction
☐ Bad Pixels
☐ Raw Order
☑ Autoscale
Color Map Gray Scale
Min 2900
Max 8000
Mean: 3908.1, Std: 1262.82, Below: 82, Above: 82

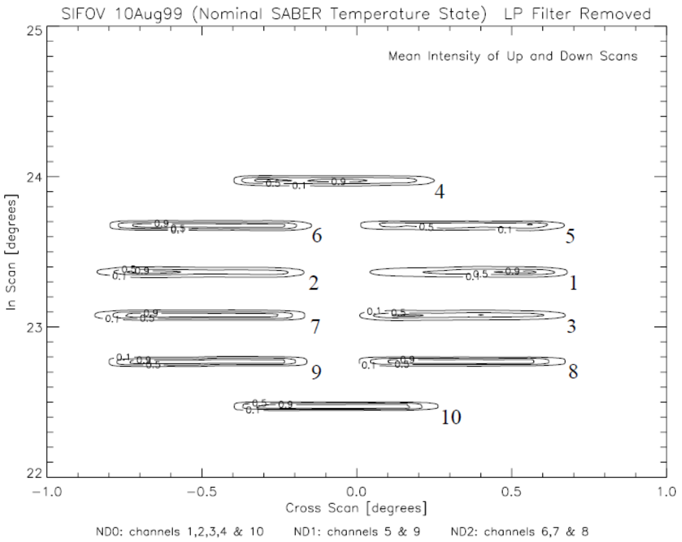
Courtesy of SDL

Data Collection and Data Quality Assessment

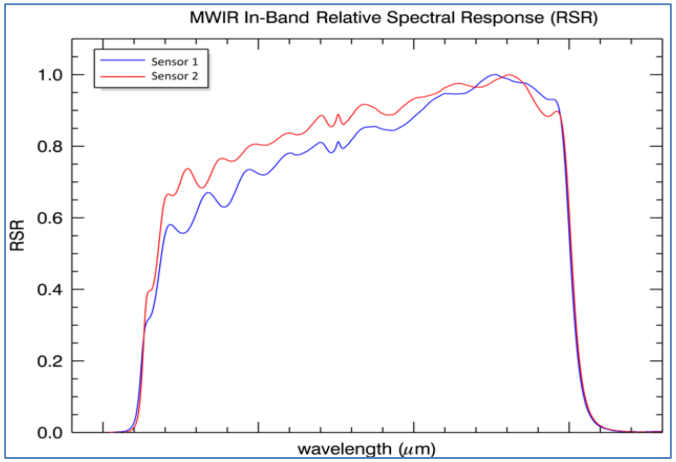
- Shortly after data collection
  - Process data through data processing or analysis software
  - Examine data for errors such as missing bytes, frame-to-frame discontinuities, sensor and source configuration errors, pixel and array response
    - Pixel statistics such as mean, median, standard deviation for each data file can be helpful
  - Report QA concerns where unique meta data (or housekeeping) parameters fall outside an acceptable range

Quick Look Analyses

- Quick look analyses are performed during testing shortly after data are collected (within a few days)
- Results will often be presented in the form of graphs and tables in a similar format to the intended final analyses
- Provide preliminary instrument performance results
- QA function
  - Provide confidence that the intended, more detailed analyses (usually performed post calibration testing) can be successfully completed



SABER Ground Calibration Tansock, CALCON 2000



Airborne Infrared (ABIR) sensor calibration (Tansock et al., 2012)

Post-Launch Calibration

Post-Launch Calibration

- Goals
  - Verify and validate calibration parameters determined pre-launch
  - Characterize or update parameters that are more successfully characterized from on-orbit measurements
  - Quantify on-orbit performance and update calibration uncertainties
  - Compare on-orbit performance to mission requirements
  - Create baseline(s) for on-obit trending during operations
  - Trend sensor performance and update calibration coefficients if necessary to meet measurement requirements

Post-Launch Calibration

- Typical phases of post-launch calibration
  - Early on-orbit calibration operations
  - Intensive calibration and validation (Cal/Val)
  - Sensor performance trending during planned operations
  - Recalibration efforts to address new missions, requirements, applications
- On-orbit calibration measurements are implemented using available resources to serve calibration
  - On-board devices, stars, moon, asteroids and other celestial objects, cross-calibration, and earth’s surface (land and water)

Early Operations Post-Launch

- Early calibration operations begin once the instrument reaches orbit, completes its initial bake out and checkouts, and is deemed functional
- Goal
  - Verify that the response measured on the ground is similar to that measured on orbit
  - Identify areas that may have changed and will need more work
- Activities may include (dependent on sensor design):
  - Performing test to evaluate initial performance values to determine if the sensor response is similar to ground testing
  - Updating parameters that can be uploaded and updated
  - Adjusting gains and settings that can be adjusted for optimal operation
  - Incorporating measured results into the temporal trending for mission life

Intensive Calibration and Validation

- Performed after completion of early operations
    - Consists of a focused calibration effort in preparation for mission operations
- Goals
    - Same as post-launch except the following, which is a goal of post-launch operations
        - Trend sensor performance and update calibration coefficients if necessary to meet measurement requirements
            - Assess temporal stability, compare to coefficient update plan, change as needed

Intensive Calibration and Validation

- Duration
  - Calibration operations begin once the instrument reaches orbit, completes its initial bake out and checkouts, and is deemed functional
    - Total duration varies with the mission objectives, planning, mission lifetime, and orbit
  - For example, sensors in low earth orbit, which are used for atmospheric research, may take over one year to complete testing due to the requirement for access to cloud-free ground targets
  - Satellites with short lifetimes may be forced to perform only a limited amount of characterization testing due to time constraints
    - Sometimes a satellite with a nominally short lifetime may go through a recalibration period after the top priority mission is accomplished, making it more useful in subsequent years – e.g., the pointing calibration on NFIRE

Intensive Calibration and Validation

- Activities dependent on sensor design (may include...)
  - Anomaly investigation (e.g., if responsivity or noise seems to have changed)
  - Spectral calibration check (e.g., using atmospheric lines or celestial emission line sources)
  - Detector linearity check and adjustment if required
  - Pointing calibration – boresight calibration and focal plane vector table checks
  - Pre- and post-launch assessment of on-board calibration source
  - Responsivity and sensitivity characterization: point and/or extended source
  - Spike/blinker analyses
  - Ice contamination analysis (especially using spectral information)
  - Correlated/uncorrelated noise characterization
  - Residual uncertainty tuning and analysis – “final” update to uncertainty budget
  - Cross comparison with other sensors
  - Establish on-orbit trending baseline
  - Update / finalize calibration monitoring plan for mission operations – required frequency of updates

Sensor Performance Trending

- Sensor performance trending tracks long-term changes in sensor performance
    - Objective is to demonstrate that mission measurements continue to meet the standards required for the sensor
    - Can be used to quantify calibration parameter correction if necessary
    - Critical to maintaining traceability and deriving target measurement uncertainties
    - Baseline sensor performance is established during pre-launch calibration and post-launch intensive calibration and validation
- Sensor performance trending consists of a mix of sensor responses to on-board and available external sources
- Sensor design and calibration plan included in planning, executing, and evaluating all on-orbit calibration operations

On-Orbit Trending Sources

Name	Description
Stars	A limited number of stars are available in the IR spectral region that also have stable intensity with proven/measured stability of ≤ ~3% (Russell et al., 2012)
Moon	Natural Earth satellite with stable surface reflectance and no atmosphere (spatially and temporally variable, modeled at shorter wavelengths – ROLO)
Other celestial objects	Sun, planets, galaxies, asteroids, dark space scenes
Vicarious	Natural or artificial sites on the surface of the Earth (Czapla-Myers 2011; Blonski et al., 2012; Schiller and Silny 2010)
Cross-calibration of on-orbit instruments	Comparison to a calibrated sensor in another orbit viewing the same Earth scene at the same time
Solar diffusers	On-board reflective surface that attenuates solar radiance to match sensor dynamic range (Xiong 2012; Guenther 2012)
Pseudo-invariant calibration sites (PICS)	Sites on Earth's surface (typically desert regions) that have repeatable radiant properties

Frequency of On Orbit Measurements

- On-orbit calibration measurements typically cannot be performed at the same time as mission data collections
  - From a programmatic viewpoint, it is desirable to minimize time needed for calibration to reduce the time taken away from the mission
  - On the other hand, the data collected for the primary mission must meet program uncertainty requirements
  - As a result, calibration measurements may be interwoven into the mission timeline
    - Can often be scheduled for minimal interference with the mission
- Frequency of on-orbit calibration measurements is dependent on:
  - Relationship between the current performance of the instrument and the programmatic performance requirements
  - Internal and external calibration source availability and stability
  - Sensor performance dependence on operating bounds
    - Dependence on electronics temperature, for example
    - Stability of FPA temperature, optics temperature

Considerations for choosing Internal and External Calibration Sources

- Internal and/or carried along external sources
  - Often available depending on design
  - May not sample all of the optical path, or may not use optics in the same way as mission target views
  - May be used to check, or even redo, linearity calibration
- External sources
  - Use the entire sensor optical train
  - Measurements within the operational FOV provide confirmation of, or updates to, radiometric as well as goniometric calibrations
  - Sources can be either modeled or simultaneously observed by reference sensors
  - May have limited availability depending on mission parameters
  - May have scheduling conflicts between the mission and calibration measurements
  - Have fixed radiance levels so that multiple sources are required to probe the entire dynamic range of the sensor
  - May need to be measured in wavebands that are different from those used for the mission

On-Board Internal Calibration Sources

- Provide the capability of periodically stimulating the sensor response with known and/or repeatable flux levels
    - Contained within an EO sensor’s optical path or
    - Moved in or out of the sensor’s optical path or
    - Viewed by means of a scan mirror
- Provide a critical link between AI&T, ground calibration, early on-orbit operations, and on-orbit operations over the life of the sensor
    - Long-term trending (LTT)
- At a minimum, these sources must be highly repeatable and can be linked to a calibration source during pre-launch calibration

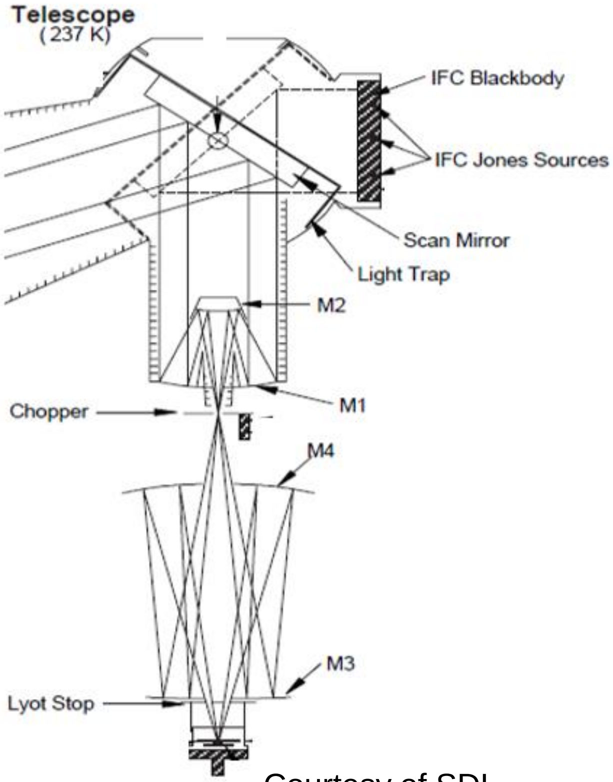
On-Board Internal Calibration Sources

- Operational considerations, requirements, and design trade-space for these sensors include:

- Volume, mass, and power
- Long-term source output repeatability, aging
- Magnitude, dynamic range, and stability
- Temporal properties (such as time required for source to be considered stable and repeatable)
- Radiation sensitivity to the on-orbit environment
- Spectral content
- Sensor response uniformity and repeatability over the sensor FOV
- Absolute traceability to standards
- Ability to exercise elements of system that have been identified to have potential degradation properties due to long term changes
- The extent of making internal calibration source measurements simulate on-orbit measurement

On-Board Internal Calibration Sources

- Implementations of on-board calibration sources cover a broad range of sensor/mission applications
- Detailed designs and requirements are of little general-purpose value (sensor design and mission requirements dependent)



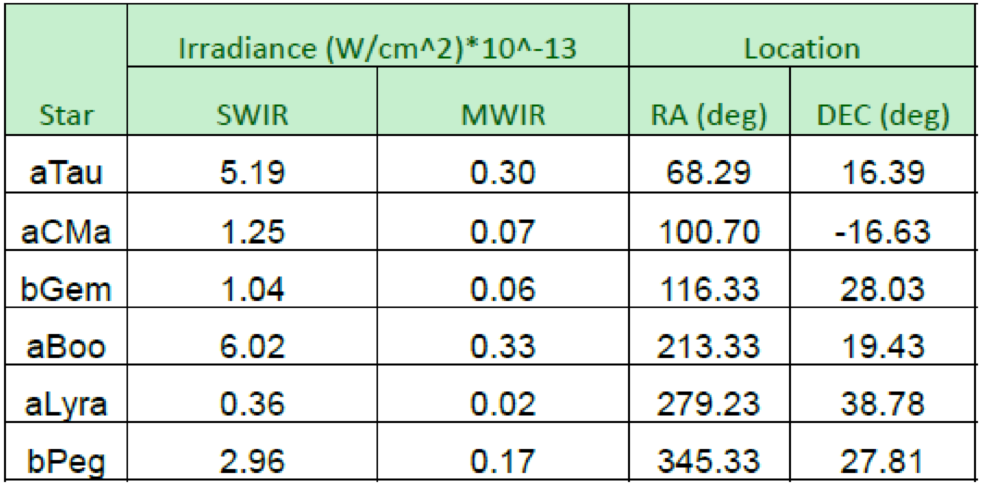
Courtesy of SDL

SABER example

- Rotate scan mirror to direct sensor FOV toward internal calibration source
    - Full aperture flat plate cavity enhanced blackbody for MWIR and LWIR bands
    - Jones source lamps integrated into the full aperture blackbody for NIR and SWIR bands

Stars - External Calibration Source

- Selected stars have been characterized and provide known IR irradiance (Russell et al., 2003)
  - bPeg recently shown to vary ~5%
- Stars provide true point sources that have been used for on-orbit calibrations
  - Data on reference standards span over 40 years

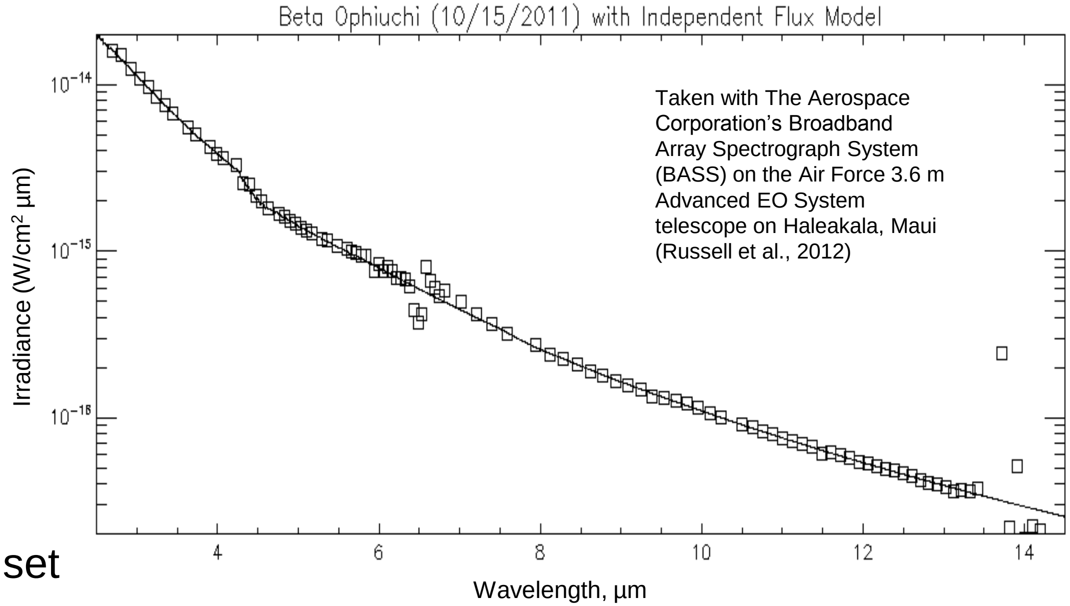


Star	Irradiance (W/cm^2)*10^-13		Location	
	SWIR	MWIR	RA (deg)	DEC (deg)
aTau	5.19	0.30	68.29	16.39
aCMa	1.25	0.07	100.70	-16.63
bGem	1.04	0.06	116.33	28.03
aBoo	6.02	0.33	213.33	19.43
aLyra	0.36	0.02	279.23	38.78
bPeg	2.96	0.17	345.33	27.81

- During this time, the absolute and spectral calibrations of the spectral energy distributions of the stars have improved dramatically in the infrared, and have been shown to be excellent in the visible (Russell et al., 2007)
  - Visible and near-infrared (near IR) calibration intensity accuracy is of the order of 1%
  - Infrared (IR) calibration (~ 2 microns out to 14 microns) is good to 5% or slightly better
  - Relative spectral accuracy is believed to be <1% in the visible and ~1% in the infrared

Stars - External Calibration Source

- Typically, an IR sensor will be tasked to view the brighter IR stars
  - Maximize signal-to-noise ratio (SNR) for the observation
  - Minimize the length of time required to perform the calibration
- For the IR, this often means using a variable star
- Near simultaneous ground-based observing equipment, techniques, and data analysis methods have been shown to provide high quality spectral energy distributions (SED) required for most programs (Russell et al., 2008)



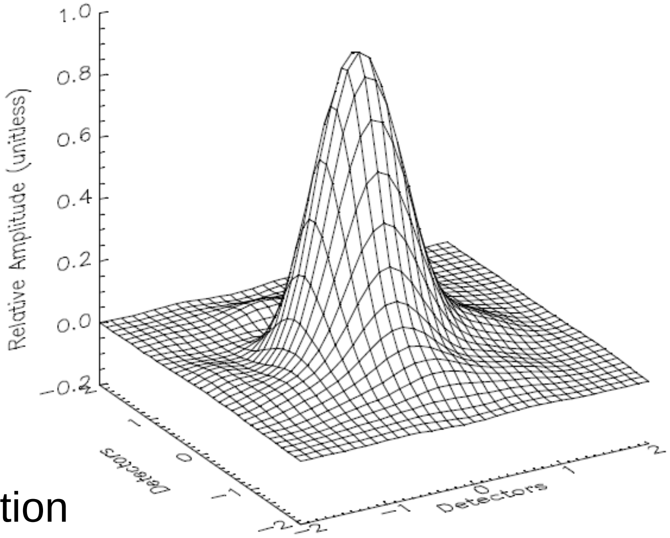
Beta Ophiuchi (10/15/2011) with Independent Flux Model

Taken with The Aerospace Corporation's Broadband Array Spectrograph System (BASS) on the Air Force 3.6 m Advanced EO System telescope on Haleakala, Maui (Russell et al., 2012)

Example SED for a ground-based data set

Stars - External Calibration Source

- Due to the true point source nature, stars are ideal for determining the point response function (PRF) of a sensor and checking focus
- Only drawback in the use of stars is when a down-looking (nadir-viewing) sensor must slew away from the earth and the sensor state vector has changed
- Potential characterizations
    - PRF, Focus, EOD, NAS, MTF, EFOV, FOV, IFOV, line-of-sight (LOS, pointing, and goniometric calibrations)
    - The use of in-scene stars for real-time pointing information can be straightforward and accurate
    - Having multiple stars in the field of view (FOV) of the sensor at one time can provide a check on the focal plane vector table (FPVT) calibration obtained prior to launch, as well as the distortion map
    - Star pairs (real binaries or apparent LOS binaries) can be used to assess performance against closely spaced objects (CSOs)
    - Provide data sets for the development of point source extraction algorithms
    - Long-term trending providing diagnostic information about the condition of the optics, FPA, and electronics over time in the on-orbit environment



Other Celestial Objects - External Calibration Source

- In addition to the more obvious celestial sources, asteroids and planets can also be used as calibration sources
- Asteroids
  - Asteroids are bright, near room temperature targets that can be used as point sources for all but the highest spatial resolution sensors
  - Almost all asteroids rotate with a time scale of hours, and some of them exhibit spectral variations as a function of what part of the surface is being measured
    - Can be mitigated through simultaneous ground-based observations
  - Have orbits that change their distance from the sensor, and at times could be too far away to be used
  - Intensity can be fairly well represented by a Planck function but can be characterized with simultaneous ground measurements

Other Celestial Objects - External Calibration Source

- Planets
  - Mars (for example) can also be a point target or “fat spot” target, depending upon its distance from the sensor and the spatial resolution of the sensor
    - Has a temperature range around ~245 K
    - Intensity can be fairly well represented by a Planck function but also can be characterized with simultaneous ground measurements
- Line Emitting Regions
  - Planetary nebula, ionized hydrogen (H II) region, nova, Seyfert galaxy, or even a planetary atmosphere (Neptune has multiple molecular bands in the LWIR, for example)

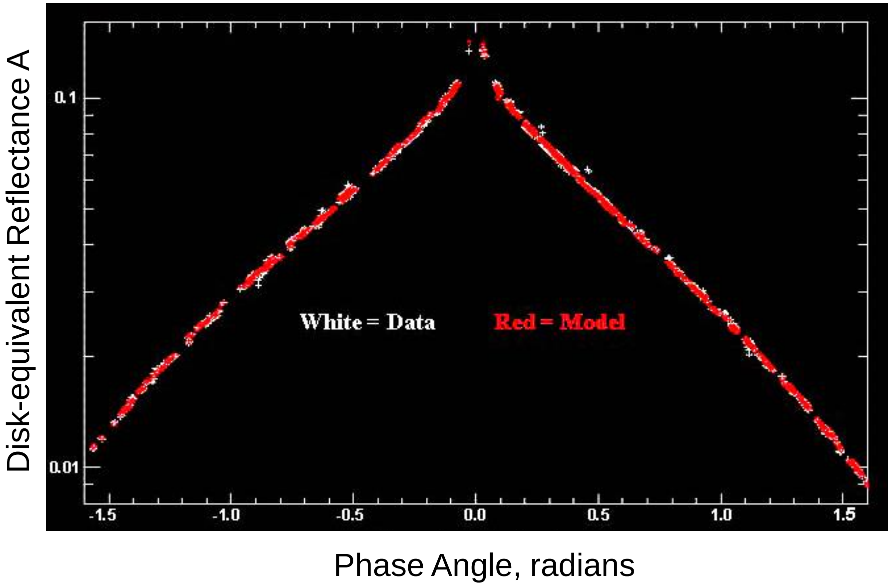
Lunar - External Calibration Source

http://sos.noaa.gov

- Several distinctive properties of the Moon make it an attractive and useful source for on-orbit radiometric calibration
  - At reflected solar wavelengths the Moon behaves as a solar diffuser with an exceptionally stable surface reflectance, considered photometrically invariant to under one part in 10^8 per year (Kieffer, 1997), the result of eons of exposure to the space environment
  - Sunlit Moon presents a spatially extended source with an overall brightness level similar to that of clear land surfaces
  - Lunar viewing is accessible from any Earth orbit
    - Spacecraft/ instruments must have a capability for off-Earth viewing angles
  - A particular advantage is the absence of intervening atmosphere between the source and the sensor

Lunar - External Calibration Source

- Observed brightness of the Moon is strongly dependent on the Sun–Moon–Observer geometry
  - Since observations from orbit can have any geometric configuration, the lunar radiometric reference is provided by an analytic model that is capable of continuous prediction of the lunar brightness with geometry
  - To date the most successful applications of lunar calibration have used the model for lunar spectral irradiance
    - Developed by the U.S. Geological Survey (USGS) Robotic Lunar Observatory (ROLO) project (Kieffer & Stone, 2005)
    - This USGS model covers wavelengths from 350 nm to 2450 nm and phase angles from eclipse to 90 degrees before and after full Moon



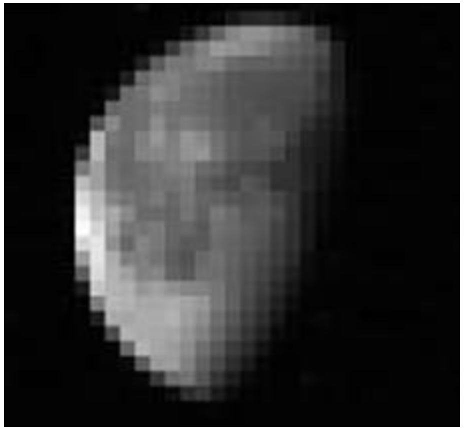
http://www.moon-cal.org/modeling/irradiance.php
(Courtesy of USGS)

Lunar – Practical Considerations

- Observing techniques for acquiring lunar calibration measurements vary depending on how the Moon is to be used, the sensor type, and the spacecraft orbit
- To use the lunar spectral irradiance, the entire disk of the Moon must be captured in some manner, with quantitative accounting for any oversampling
- The size and geometric shape of a sensor FOV can influence the scan sequence for acquiring a complete lunar disk and evaluating the oversampling factor
- Because the brightest features on the Moon have reflectances ~0.2 at solar wavelengths, saturation typically is not an issue for sensors designed for Earth observations
- Low signal-to-noise ratios can be encountered at the shortest wavelengths due to the combination of diminished solar irradiance and lower lunar reflectance
- The expected radiance for a specified detector IFOV, wavelength, and phase angle can be predicted for lunar view planning

Lunar – Viewing Geometry

<u>Low Earth Orbit</u> An instrument that normally observes the Earth in nadir view from low Earth orbit must view the Moon either through an alternative optical path or by executing a spacecraft attitude maneuver



Moon Image Acquired by MODIS
(Courtesy of NASA)

<u>Geostationary Orbit</u> From a position in geostationary orbit the Moon appears regularly behind the Earth several times in a month, traversing the Earth disk diameter (~17.4 degrees) in about 80 minutes

GOES–13 Visible Channel Image
(Courtesy of NOAA)

Vicarious Calibration – External Calibration Source

- Over the years, the term ‘vicarious calibration’ has come to be closely associated with viewing the Earth and deploying a team to make ground level measurements of the test site at the time of satellite overpass (Helder et al., 2012)
- Advantages
  - Multiple locations on the Earth that can be acceptable sites
  - Calibration based on an actual Earth surface
  - Normal operation of the satellite sensor
  - Improving methodologies
- Disadvantages
  - (1) Expense and time of transporting people and equipment to the site, (2) susceptibility to cloud cover, and (3) site maintenance
- Schiller and Silny (2010) have pioneered an alternative technique using spherical reflectors
  - Doesn’t require ground characterization
  - Uses measured solar illumination to derive atmospheric transmission
  - Can be used in many different locations

Vicarious Calibration – External Calibration Source

- For classical vicarious calibration
  - Obtain estimates of the surface reflectance at a particular location
  - Simultaneous measurements are made of the atmosphere
  - In combination with a model for solar radiation, a prediction is made of the radiance present at the top of the atmosphere

Portable spectrometer for surface reflectance measurements at a vegetated site
(Image courtesy of Dennis Helder, SDSU)

Vicarious Calibration - External Calibration Source

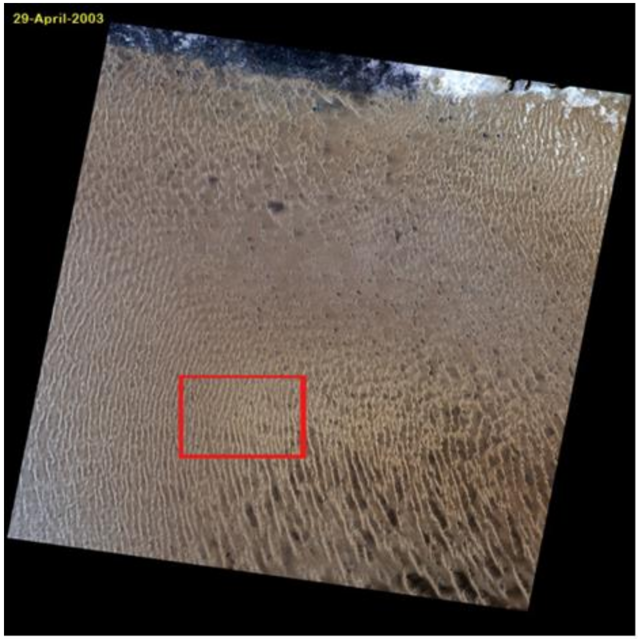
- To predict the top of the atmosphere radiance, a radiative transfer code is typically employed that uses the surface reflectance and atmospheric measurements as inputs (Moran et al., 1992)
- Calibration then occurs by comparing the measurement made by the satellite to the prediction and calculating a correction factor (Schott 2007; Thome et al., 2004; Naughton et al., 2011)
- Preferred site locations are those where the surface and the atmosphere are stable and easy to characterize
    - Brightness and spatial homogeneity are other considerations
- Well-known bright calibration sites
    - Railroad Valley and Ivanpah Playa in Nevada/California, and White Sands New Mexico (Bannari et al., 2004).
    - An example of a well used darker vegetative site is located at Brookings South Dakota (Thome et al., 2004)

Commonly used sun photometer to anchor atmospheric modeling

(Image courtesy of Dennis Helder, SDSU)

PICS - External Calibration Source

- Stable sites on the Earth's surface, known as pseudo invariant calibration sites (PICS) have been used in a variety of ways for the calibration of EO instruments for remote sensing over the past two decades
- Common PICS
  - Dry lakebeds, salt flats, and desert sand sites in arid regions
  - Low probability of cloud cover, are spatially homogeneous, and have constant surface spectral reflectance and BRDF over long periods of time.
  - They are typically inexpensive since no target maintenance or team deployment is required.
  - They have shown excellent stability and accuracy and can be used with a wide variety of sensor types



Landsat 7 image of the well known Libya 4 PICS which is located in the western Libyan desert. The red rectangle indicates the CEOS suggested region of interest

PICS - External Calibration Source

- Key to the usefulness of these sites is the concept that they don’t change radiometrically as a function of time
  - While in theory this is impossible, in practice it has been found to be a good approximation with an uncertainty in the range of 1-3% (k=1), which is significant given that the atmosphere is included in the overall PICS concept
- Some of the most stable sites in the world are found in the Sahara Desert (Cosnefroy et al., 1996; Helder et al., 2010)
- An excellent listing of PICS is maintained at the USGS EROS website: http://calval.cr.usgs.gov/rst-resources/sites_catalog/radiometric-sites/test-site-gallery/
- PICS applications
  - Long-term trending was the first use of PICS (Cosnefroy et al.,1996; Barsi et al., 2012; Chander et al., 2010)
  - Cross calibration of satellite sensors by viewing the PIC at essentially the same time (Lacherade et al., 2013; Helder et al., 2012; Chander et al., 2013) but can be difficult depending on the orbital characteristics of the sensors
  - Efforts have been under way to use PICS for absolute radiometric calibration (Govaerts et al., 2012; Helder et al., 2013; Mishra et al., 2014)

Cross Calibration - External Calibration

- Even though best practices are followed during ground calibration, similar sensors in post-launch measurements between satellites do not necessarily agree within uncertainty
  - Affects the inter-operability in global earth observations, as well as climate change detection
- Over the years, many methods have been used for cross-calibration between earth observing satellite sensors
  - One particular method, the simultaneous nadir overpass (SNO) method, has gained popularity in the past decade (Cao and Heidinger 2002; Heidinger et al., 2002; Cao et al., 2004, 2005; Zou et al., 2006)
- SNO method is simple and robust
  - Based on the fact that any pair of polar-orbiting satellites flying at different altitudes regularly observes the earth at their orbital intersections at nearly the same time
  - Frequency of occurrence is a function of the orbital period differences driven by altitudes

www.asic3.sdl.usu.edu/papers/cao.ppt

Cross Calibration - External Calibration

- SNO Method (cont.)
  - Observations from the two satellites at the SNOs can then be collocated pixel by pixel and the biases between them can be quantified
  - Time series of the biases at the SNOs further reduce the uncertainties and allow for the long-term trends to be studied
- Since the SNO method was introduced more than a decade ago, it has been accepted for inter-satellite calibration
  - Method was first used for the operational monitoring of intersatellite biases at NOAA
  - It was then introduced to the climate community for constructing time series for decadal climate change detection (Zou et al., 2006; Zhao et al., 2008; Cao et al., 2005b)
  - In 2005, the World Meteorological Organization initiated the Global Space-based Inter-Calibration System (GSICS) (Goldberg et al., 2011) and adopted the SNO as one of the key methods, which greatly facilitated its use across countries and agencies

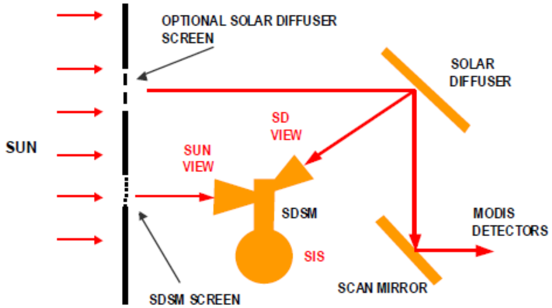
Cross Calibration - External Calibration

- SNO method has been applied to all major categories of instruments
    - Microwave, visible/near-infrared, thermal infrared, and ultraviolet
    - Launch of hyperspectral sounders in recent years greatly reduced the uncertainties in spectrally induced biases due to different spectral response functions, which also makes the SNO method useful for atmospheric sounders (Wang et al., 2007, 2008, 2009, 2011; Chen and Cao 2011)
- One weakness of the SNO method is that it relies on the assumption that a stable reference satellite can be used in the cross calibration
    - As a result, the SNO method should be used in conjunction with other methods for cross-calibrating on-orbit instruments
    - CLARREO team has carefully studied the opportunities for cross-calibration and intend to serve as an on-orbit reference (Weilicki et al., 2013), although its realization may still be many years away
- Other calibrations that add value to cross calibration
    - Aircraft underflight, ground-based Cal/Val, Marine Optical Buoy for ocean color and sea surface temperature

Solar Diffuser - External Calibration

- Solar diffusers have been used as on-orbit calibration targets in a number of earth-observing sensors in the reflective solar spectral range, from UV to SWIR
- Types of solar diffusers
    - Aluminum plates painted with YB71 white paint as used in SeaWiFS and Landsat ETM+
    - Space-grade spectralon panels as used in MODIS and VIIRS
    - Grounded aluminum diffusers and volume diffusers as used in the ozone monitoring instrument
- Solar diffusers can be used for absolute or relative radiometric calibration purposes
    - In either case, the solar diffuser (or its bi-directional reflectance distribution function (BRDF)) should be fully characterized at the illumination and viewing geometries

(Courtesy of NASA)



Xiong et al., 2005

Solar Diffuser - External Calibration

- There are more stringent calibration and characterization requirements if the solar diffuser is used as an absolute calibration device
  - Assure its BFDF measurements are traceable to a national/international reflectance standard with calibration uncertainties meeting the design requirements
  - Have on-orbit monitoring capability, such that any changes of the solar diffuser BRDF can be accurately determined and corrected
- Both MODIS and VIIRS use an on-board solar diffuser stability monitor (SDSM) to track the solar diffuser on-orbit degradation
  - Ratioing device that makes alternate measurements of the direct sunlight and the sunlight reflected from the solar diffuser on a regular basis
- Sometimes a solar attenuator is used in front of the solar diffuser to prevent saturation, depending on application and design specifications
  - A typical attenuator is made of a metal plate with small pinholes
- Solar diffuser absolute calibration uncertainties are limited by the pre-launch BRDF characterization uncertainties and on-orbit degradation characterization uncertainties

Data Analysis and Reporting

Data Analysis Software

- Prepare & test data analysis software before calibration testing starts
    - Quick look analysis (near real-time data collection verification and authentication)
    - Final data analysis (complete in-depth analysis for calibration report)
- Data analysis software requirements depend on calibration plans
    - Develop calibration and test plans early in program
        - Allow time for data analysis software development and testing
    - Size and scope of the calibration effort drives software development
    - Small team of analysts may process specific data sets in area of expertise using self-produced software
    - Large team of analysts and users may require dedicated software team for more robust software design and greater attention to documentation
- Implement revision control to maintain traceability & reproducibility for long-term verification and validation purposes

Calibration Report

- Detailed calibration report presents final analysis results
  - Calibration report contents are unique to each project
  - Often a primary reference for investigating and answering questions
- Calibration report overview
  - Instrument overview
    - Relevant sensor capability to give context to calibration measurements
    - Sensor requirements flowdown to calibration requirements
  - Calibration approach and summary
    - Scope of calibration – ground, on-orbit, lifetime of sensor
    - Measurement equations – sensor response model
    - Data collection algorithms – special tests, operational envelope
    - Uncertainty budgets – irradiance, radiance, goniometric
    - Calibration equipment – chambers, sources, specialized hardware
    - Data management – storage volume, data movement and processing

Calibration Report

- Calibration Report Overview
  - Data Analysis & Results
    - As-run test schedule
    - As-run data collection procedures – test logs, sensor state, data identification
    - Data verification review – quick look analysis results
    - Data analysis review – data used, algorithms & software, intermediate results
    - Uncertainty analysis review – assumptions, uncertainty propagation
    - Calibration parameters & uncertainty – calibration equation terms, radiometric model quantities
    - Cross checks & traceability
    - Sensor anomalies & response dependencies
    - Contamination control results – impacts to calibration data

Cross Checks and Traceability

- Multiple calculations or analyses of a single parameter provide cross checks
  - Equivalent results within calculated uncertainties validate the calibration and increase confidence
- For example, comparison of radiance and irradiance responsivity through effective FOV solid angle

$$\frac{PRR}{PIRR} = EFOV$$

PRR = Peak radiance responsivity
PIRR = Peak irradiance responsivity
EFOV = Effective field of view solid angle

  - Derive PRR and PIRR from blackbody measurements
  - Derive EFOV from full-field point source measurements (include near-angle scatter)
- Perform simple calculation to cross-check independent measurements of 3 terms

Cross Checks and Traceability

- Other cross-check possibilities
    - Compare system-level RSR from individual component measurements with end-to-end measured system-level RSR
        - RSR calibration is of primary importance for space-based sensors where direct RSR characterization is not possible after launch
    - Sensor response comparison between ground and on-board calibration sources
    - Performing cross-calibration of on-orbit sensors (Tobin et al., 2006)
    - Round robin calibration comparisons between laboratories (typically at the component or subsystem level) (Wilthan and Hanssen, 2011)
- An evaluation of potential cross-checks, along with schedule, cost, uncertainty, and risk should be addressed during the calibration planning trade

Long Term Repository of Calibration Data

- Calibration and characterization of contemporary EO sensors generate large amounts of data
- Preservation of calibration data in original form adds value and maximizes opportunity
  - Follow-on data analysis of calibration data often produces new insight
    - New questions, improved algorithms
  - Comparison of in-flight results with similar measurements from calibration
    - Processing of calibration data with flight data analysis tools and vice versa
    - Use calibration analysis software for mission data analysis if possible – same algorithms, source levels, data density
- Analysis of the ensemble of data from all phases of the mission together maximizes insight and understanding for future
  - Share lessons learned with the community

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