The Challenges of 1% Uncertainty in Optical Ground Support Equipment Calibrations

CALCON

Space Dynamics Laboratory

Logan Utah, June 18 2019

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Overview

- Measurement requirements for EO missions are driving down uncertainty on orbit for long term studies
- Goal: <1% uncertainty on Optical Ground Support Equipment (OGSE) for calibration prior to launch
- Basic challenges: radiance levels, dynamic ranges, uniformity, and absolute traceable monitoring levels
- Advanced challenges: image quality assessment, spatial and spectral characterization, spectral line and in-band quantum efficiency, and sensor fusion (0.3-14um) calibrations
- Discuss challenges and solutions for recent space and terrestrial programs, and the new techniques needed to achieve the levels of uncertainty required by EO community

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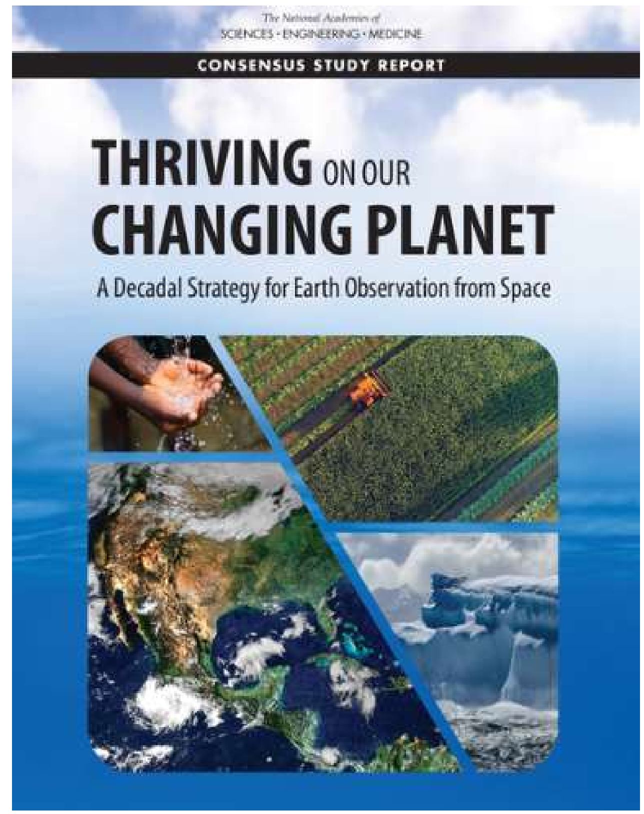
Earth Observation - The Importance of Long-Term Data

- Earth science and derived Earth information are integral to our daily lives, national and international economies, and society’s capacity to thrive. Understanding and reliably predicting planetary change critical.

- Decadal Community Challenge: Ambitious objectives and innovative solutions for space-based EO and analysis, to deliver great value under constrained resources and ensure dividends.



National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

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Earth Observation - The Importance of Long-Term Data

VERY IMPORTANT (summarized)	IMPORTANT (summarized)
(H-4) Influence of water cycle on natural hazards and preparedness **(W-3)** Influence of Earth surface variations on weather and air quality **(C-3)** Impacts of carbon cycle variations on climate and ecosystems **(C-4)** Earth system response to air-sea interactions **(C-5)** Impact of aerosols on global warming **(C-6)** Improving seasonal to decadal climate forecasts **(C-7)** Changes in decadal scale atmospheric/ocean circulation and impacts **(C-8)** Consequence of amplified polar climate change on Earth system **(S-5)** How energy flows from the core to Earth's surface **(S-6)** Impact of deep underground water on geologic processes and water supplies	**(H-3)** Fresh water availability and impacts on ecosystems/society **(W-6)** Long-term air pollution trends and impacts **(W-7)** Processes influencing tropospheric ozone and its atmospheric impacts **(W-8)** Methane variations and impacts on tropospheric composition and chemistry **(W-9)** Cloud microphysical property dependence on aerosols and precipitation **(W-10)** Cloud impacts on radiative forcing and weather predictability **(E-4)** Quantifying carbon sinks and their changes **(E-5)** Stability of carbon sinks **(C-9)** Impacts of ozone layer change **(S-7)** Improving discovery of energy, mineral, and soil resources

National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

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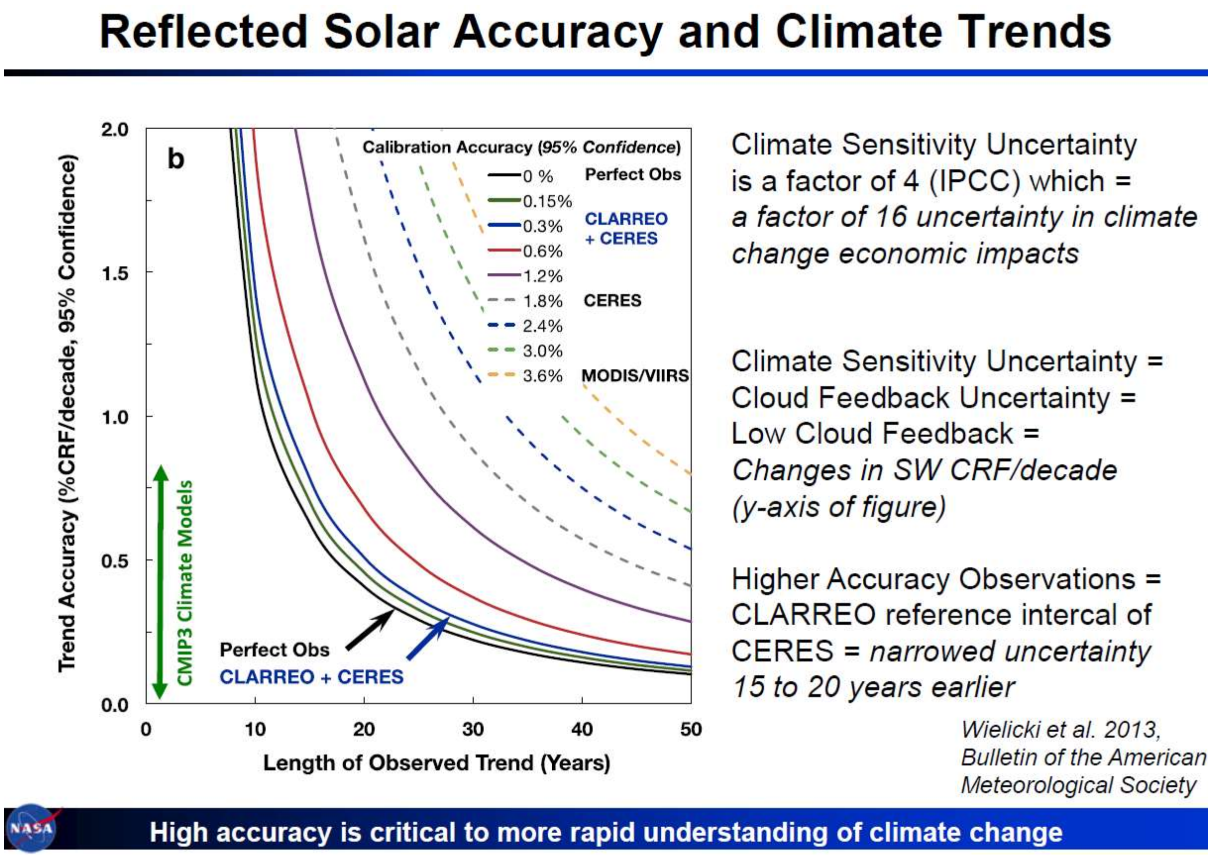
The Need for Low Uncertainty

- 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



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

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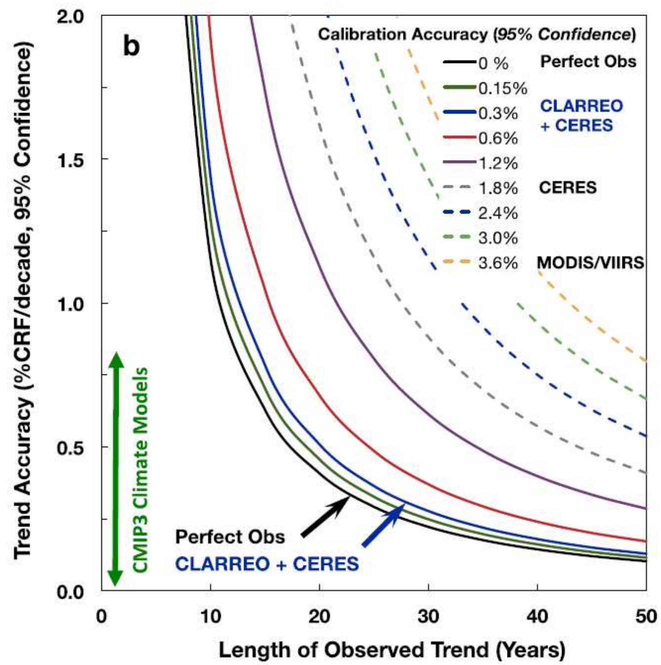
The Need for Low Uncertainty

- 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



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

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

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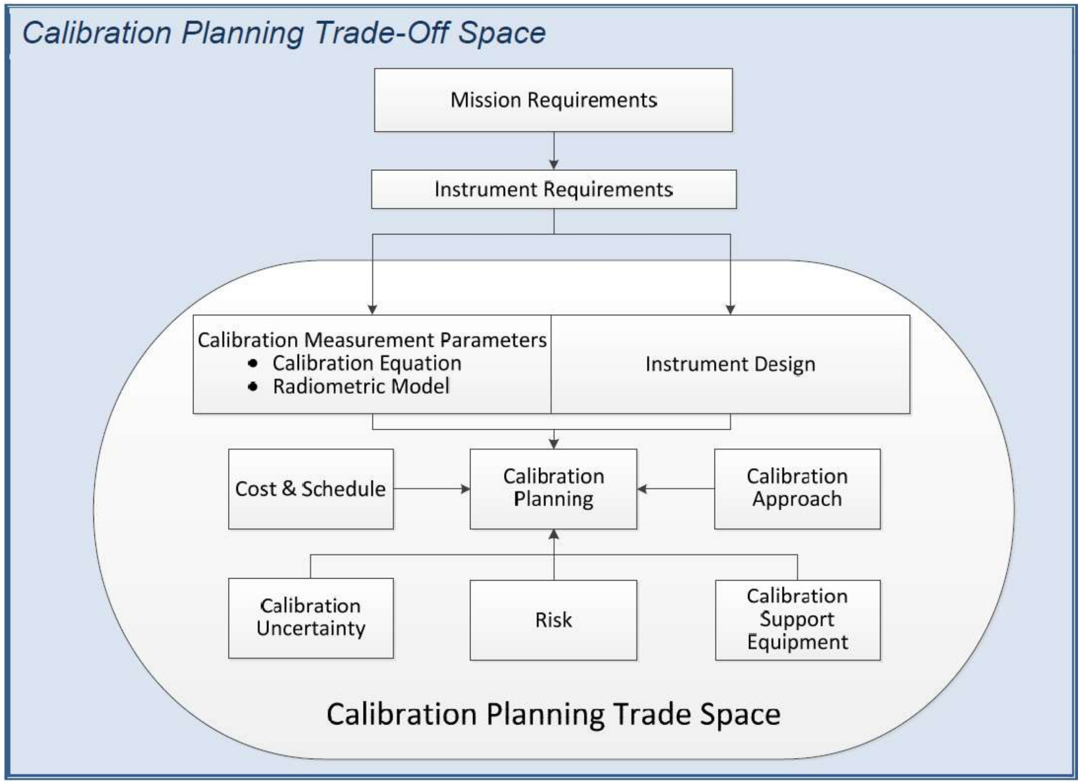
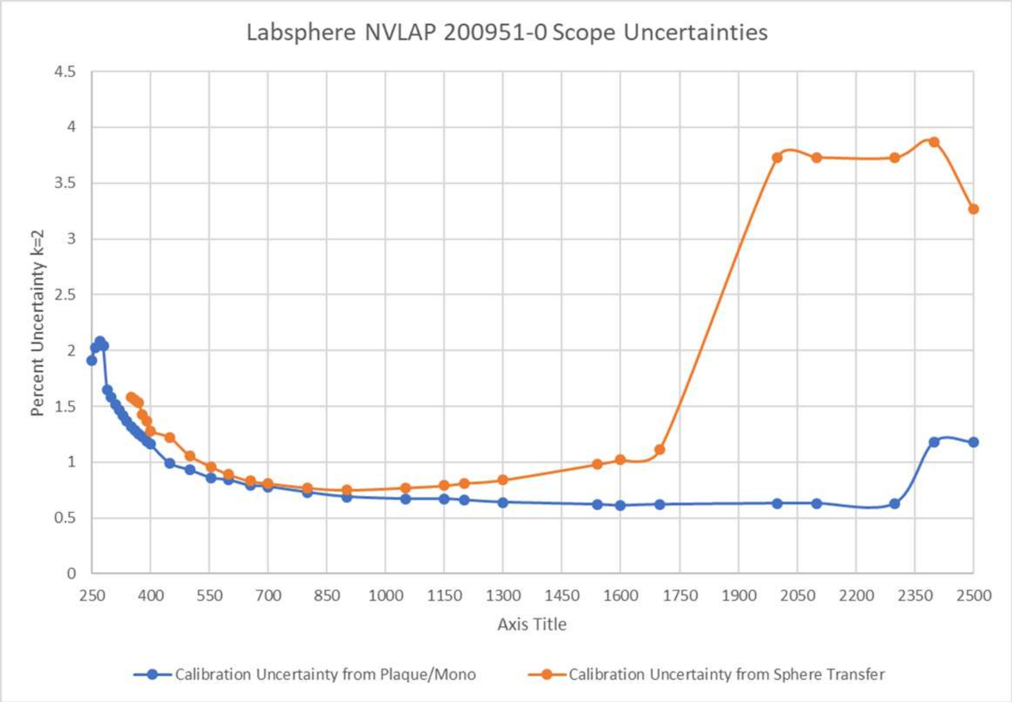
Sphere Based Cal Source OGSE and Uncertainty

- Uniform, stable, traceable radiance
- Spheres are not perfect
- How can uncertainty be reduced?
  - Traceable measurement methods
  - Spectral content
  - Radiance levels
  - System monitoring approach coating selection
  - Environment
  - Aperture size and physical design



Traceability for Integrating Sphere Calibration Source

- Begins with SI Units and the National Metrology Institutes
  - Transfer from NIST primary irradiance source off calibrated Lambertian plaque to monochromator detector
- Increases in NMI accuracy improves uncertainty across industry/EO community
  - NIST recently added (2018) 2500 nm, extends our capability
- Traceability chain to NIST - <1% relative uncertainty 555 – 1600 nm



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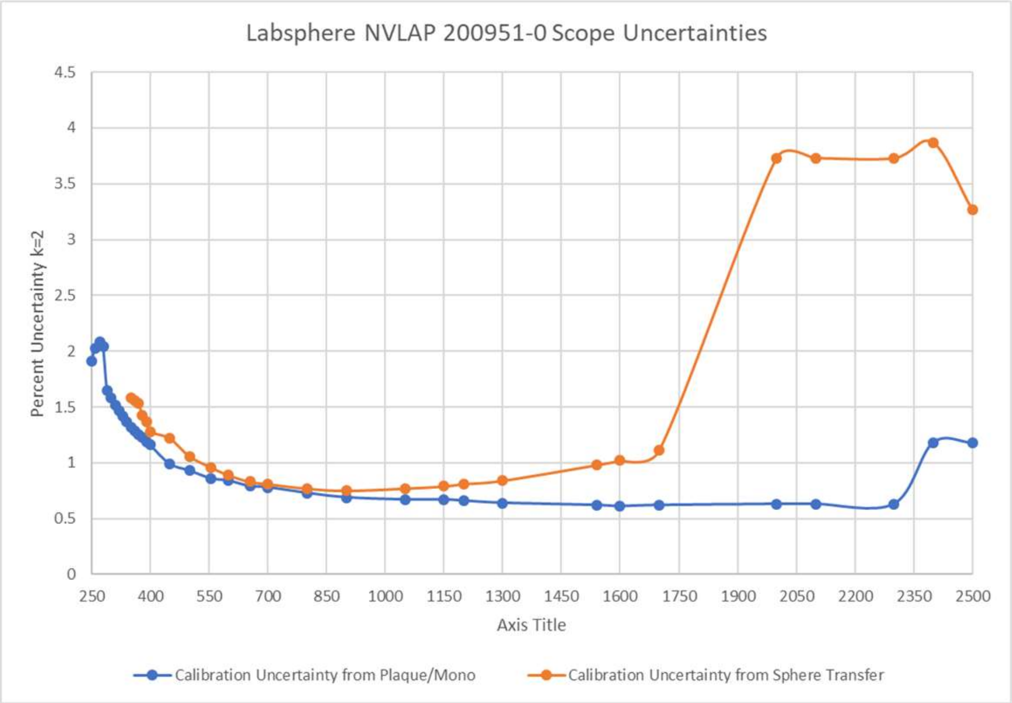
Traceability for Integrating Sphere Calibration Source

- National Validation Laboratory Accreditation Program (NVLAP)
- Direct, periodic audit by NIST/NVLAP accredited auditors
  - Instrumentation,
  - Measurements
  - Processes
- Highest level of accreditation that a commercial laboratory can achieve
- Required full uncertainty budget development



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Lamp Choice and Spectral Content

- "Test as you fly and fly as you test"
- Spectral content and output of radiometric calibration equipment should mimic expected target
- Natural targets illuminated by sunlight
- Reflectance – magnitude/λ varies widely
  - Ocean 6%, Snow 80%

Lamp Choice and Spectral Content

Typical or Estimated Source Performance and Features

Lamp Type	Normal Short term Stability (5 minutes)	Typical Rate of Decay	Calibration Duration	Stability options	Stabiity in Closed Loop	Dominant Frequency	Needs Real Time Power Monitor or Chopper	Burn in before Stable Use?	MTBF Lifetime	Approx. Radiance Temp	Approx. Lumens/W	High Flux Blue	High Flux UV (<320nm)	$ Per Lamp (includes Power Supply)	Use Atten-uators	Spectral Strucure	Spectral Peak Energy	Used for Low Uncer-tainty	Radiometric Power Mode
QTH	<0.01% P-P & RMS <0.01%	~1.5% over 50 hrs	50 hrs	Closed Loop	<0.1% P-P over 100hrs	DC	No	Yes	500-2000hrs	2600K-3200K Nominal 300K	15	Poor	Poor	$3k-5k	Yes	Blackbody-like (Greybody)	800-1000nm	Yes	Adj. DC Current
Xenon	<4.0% P-P & RMS <0.4%	~50% over 300hrs	10hrs	DC or Closed Loop	<4.0% P-P & RMS <0.4%	4-6kHz	Maybe	Yes	300-500hrs	5700-6600K Non-UV-6000K UV-6500K	40-60	Excellent	Excellent	$9k-12k	Yes	Some VIS and Lots of NIR	500-600nm	No	kV Start Pulse & DC Current
Microwave Plasma	<6.0% P-P & RMS <1.5%	15% over 12,000hrs	500+ Hrs	Stable Mode Closed Loop Staggered	<0.6% P-P & 0.06% RMS	0.1Hz	Maybe	No	12,000+ hrs	5000-6500K Nominal 5100K	80-100	Excellent	N/A	$9k-12k	Yes	Molecular VIS_NIR	550-650nm	Maybe	Adj. DC Voltage
Laser plasma	Unknown	10% over 10,000hrs*	500+ Hrs*	DC or Closed Loop	Unknown	DC	No	No	10,000+ hrs	N/A (flat)	30-50*	Low	Low	$10k to >$100k	Maybe	Flat with Absorption lines	Relatively Flat	Yes	Pulse Start & Adj. DC Current
Super Continuum	Unknown	Mode Dependant	100+ Hrs*	Pulsed (>100mhz) Closed Loop	Unknown	>75MHz	Yes	Unknown	>2000hrs	N/A (flat)	Flat	>400nm Low	Special Modes - Low	>$40k	Maybe	Flat with Absorption lines	Relatively Flat	Yes	Pulsed
Tuneable Laser	Variable	Variable	Use Dependant	Pulsed (>100mhz) Closed Loop*	Unknown	TBD	Yes	No	Product Dependant	Mono-chromatic	Variable	Good	Good	>$100k	Maybe	Mono-Chromatic	Mono-chromatic	Yes	Pulsed
Laser Diodes	Power Supply and Thermally Dependant	Diode Dependant	Power Supply and Thermally Dependant	DC or Pulse	Unknown	DC	Maybe	Maybe	Diode Depenant (>1000hrs)	Mono-chromatic	Variable	Excellent	Good	$2k->$10k	Maybe	Mono-Chromatic	Mono-chromatic	Yes	Adj. DC Current or Pulsed
LED	<0.1% P-P & RMS <0.01%	3% over 3,000hrs	1,000+ Hrs	DC or Pulse	<0.1% P-P over 100hrs	DC	No	Yes	10,000+ Hrs	Mono-chromatic or LED Dependant	Variable	Very Good	Good	$2k->$10k	Yes	Mono-chromatic or LED Dependant	Source Dependant	Yes	Adj. DC Current
IR Sources or BB	<0.01% P-P & RMS <0.01%	10% over 2,000hrs*	500+ Hrs*	DC	<0.1% P-P over 100hrs*	DC	No	Yes	5000 hrs	500-1500K	N/A	N/A	N/A	$3k-5k	Yes	Near Blackbody	>1000nm	Yes	Adj. DC Current

*Approximated, Estimated or Values Not Tested

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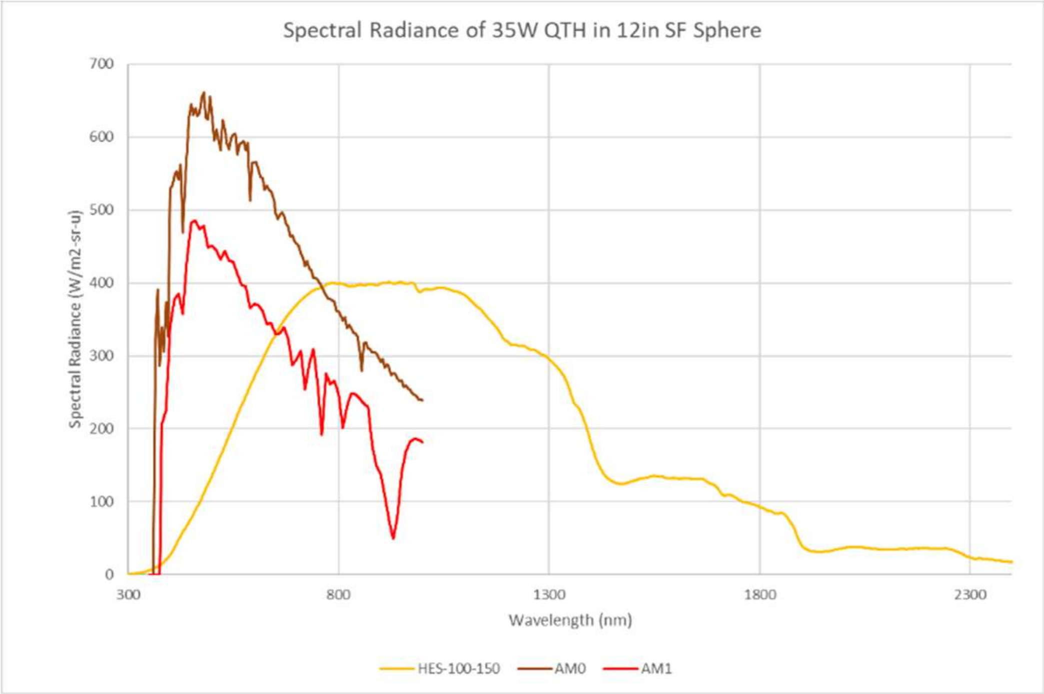
Quartz Tungsten Halogen - QTH

Advantages

- Standard calibration source for several generations of NMI and industry
- Radiometrically stable, predictable, smooth
- Blackbody-like curve at 2600-3400K
- Can achieve high flux levels



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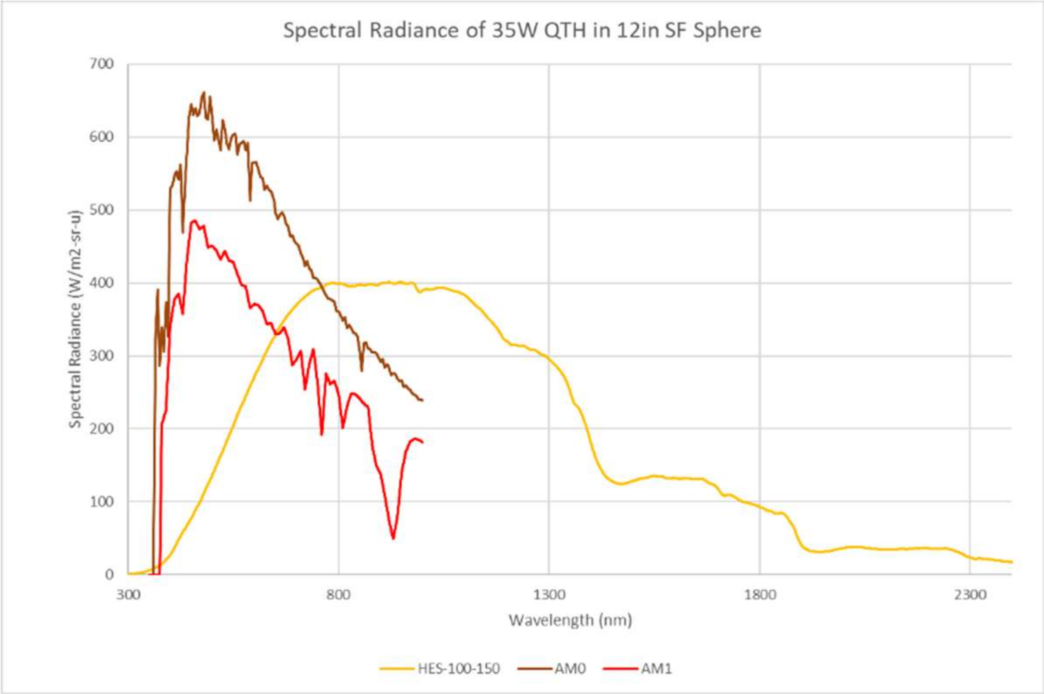
Quartz Tungsten Halogen - QTH

Challenges

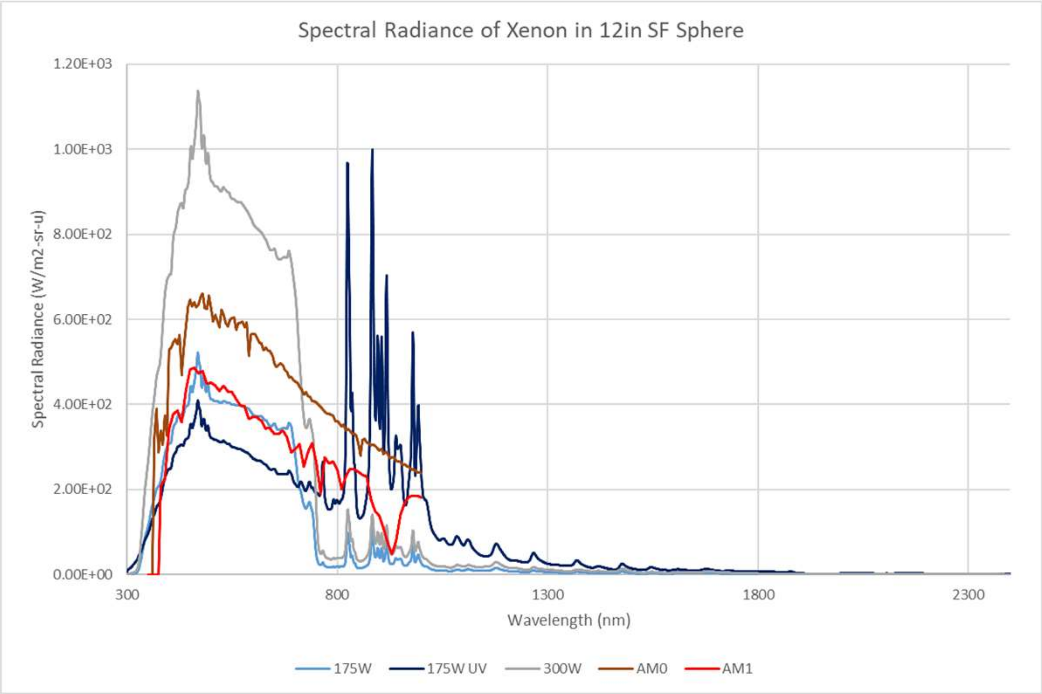
- Peak is 800-1000 nm (NIR), low spectral content below 500 nm
- Spectral mismatch to AM0/AM1
- Achieving adequate SNR in blue requires 1000s of Watts
- Blue-shift filters can be used, but have short lives, low energy
- Diminishing supply/quality



Xenon Arc Discharge

Advantages

- Higher color temp, significantly more blue than QTH
- Solar-like output: 6000-6500K
- Can be filtered for UV/NIR spectral content



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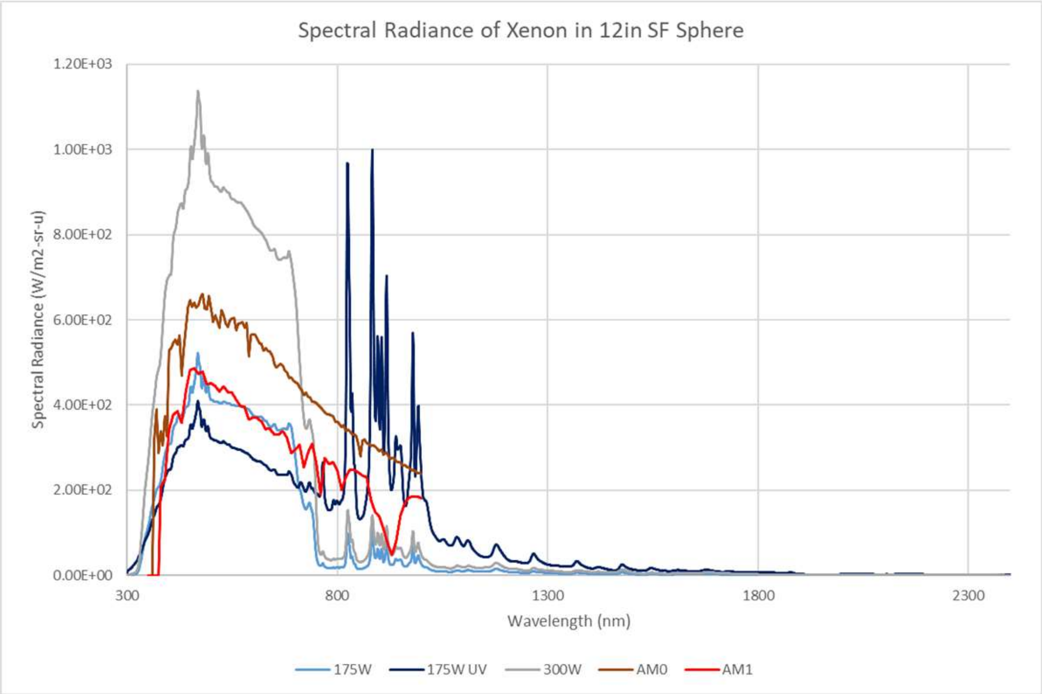
Xenon Arc Discharge

Challenges

- Few sources suitable for EOS calibration
- Undesirable structure in NIR
- Sharp features in visible – need high resolution sensor
- Inherent “flicker,” ~5KHZ instability which may be accepted if averaging, but may be untenable for pre-determined scan time systems like pushbroom/linescan imagers
- Instability can lead to increase in uncertainty for final calibration



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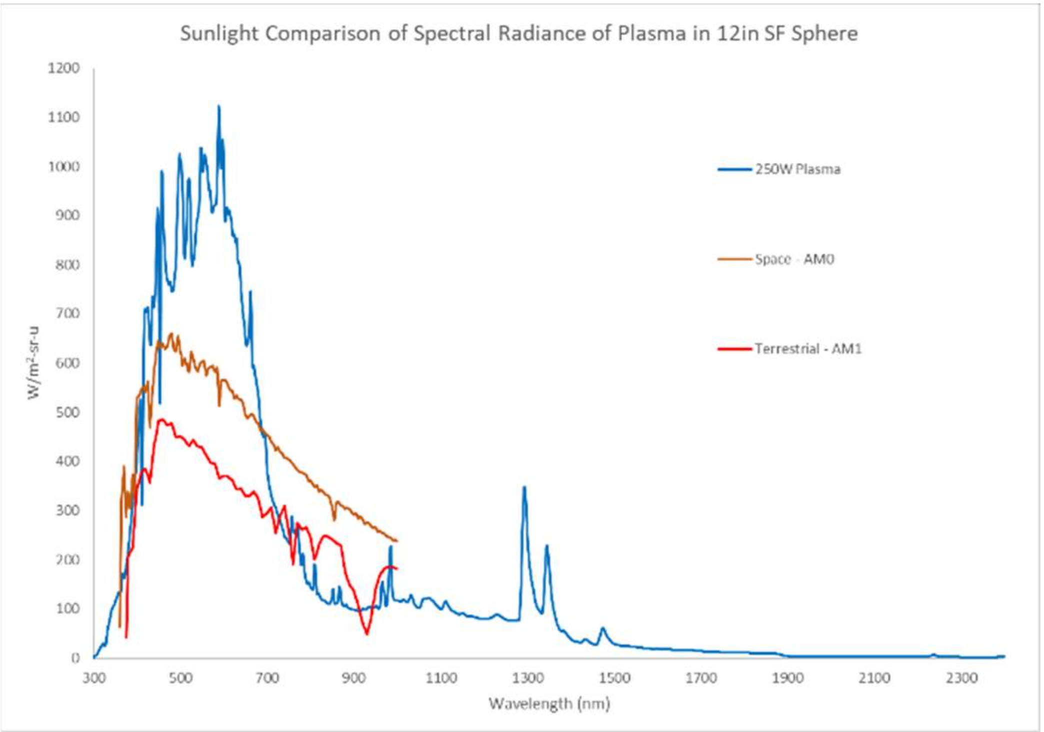
Microwave Stimulated Plasma

Advantages

- Xenon discharge – microwave emitter instead of conventional arc
- Qualified as cal sources with GSFC 2012
- High flux levels
- Solar-like blue/red ratio
- High stability under certain conditions



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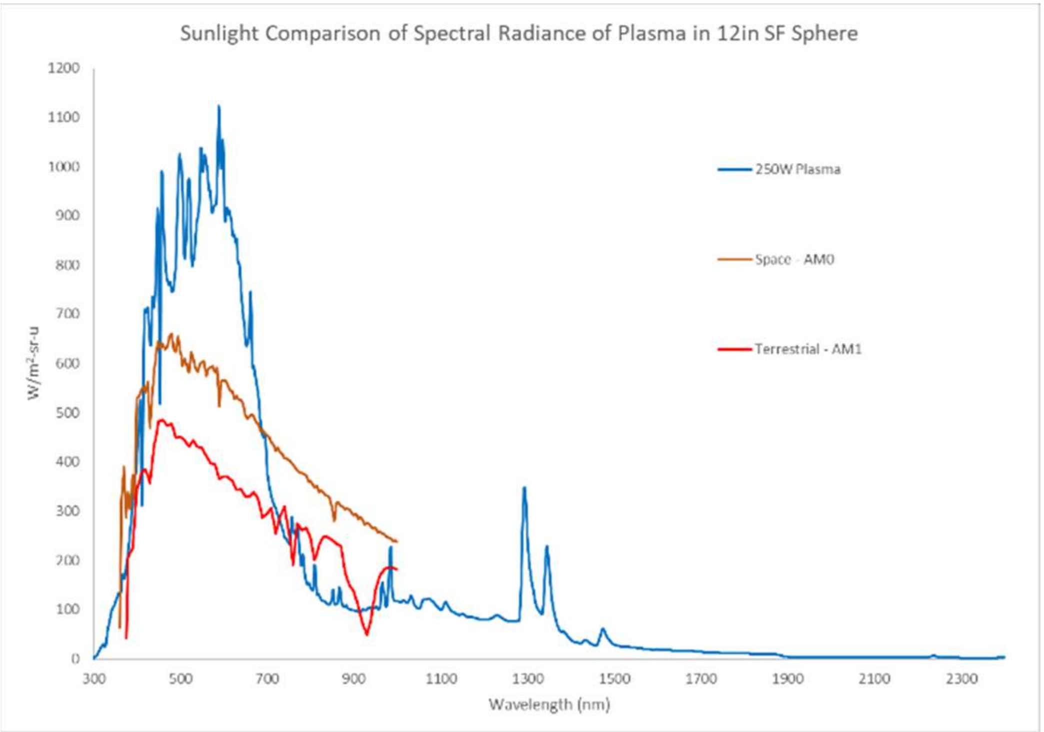
Microwave Stimulated Plasma

Challenges

- Sharp features in visible, “spikes”
  - High resolution sensor required,
  - Local slope can increase uncertainty/noise, curve fitting/differentiation artifacts
  - Especially problematic for hyperspectral systems
- “Flicker”
  - 0.1Hz waveform+/- 6% P-P
  - Possible to overcome with complex system



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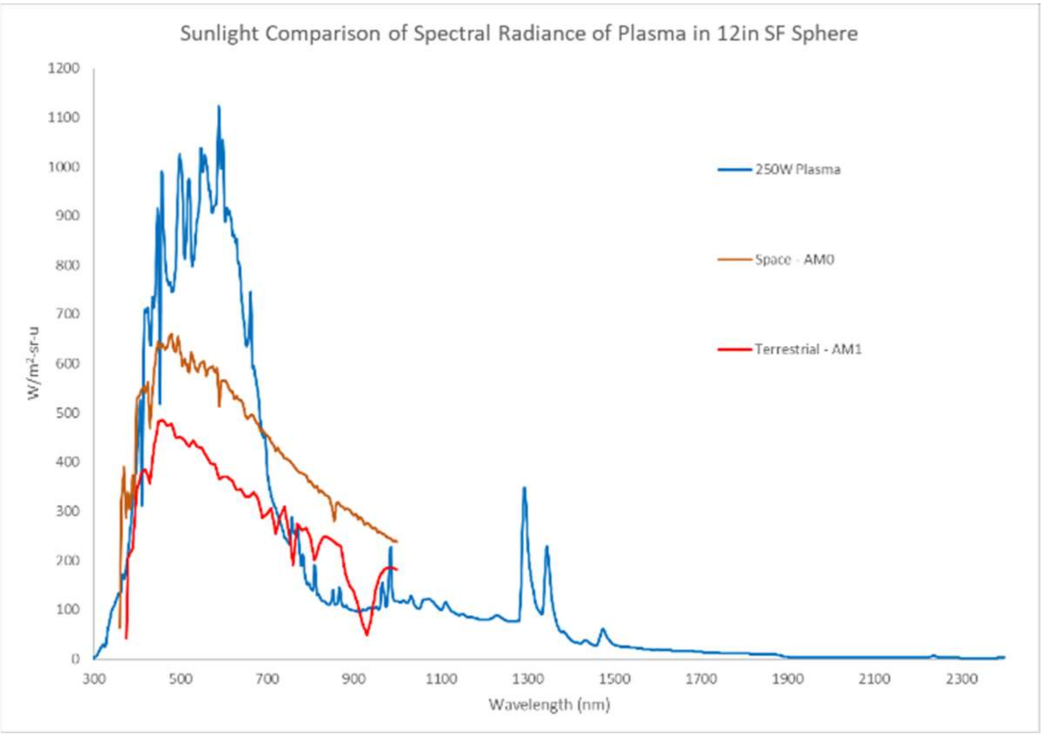
Microwave Stimulated Plasma

Large Uniform Source Systems

- Waveform can be “stabilized” for up to 30 min
- Recent successful use of plasma sources on large spheres > 20in diameter
- Controlled asynchronous operation with active feedback attenuation
- P-P variation reduced to <2% over 12 hour operation with radiance averaging of multiple sources

	3 Hours	12 Hours
P-P	1.70%	2.13%
SD/Mean	0.24%	0.22%



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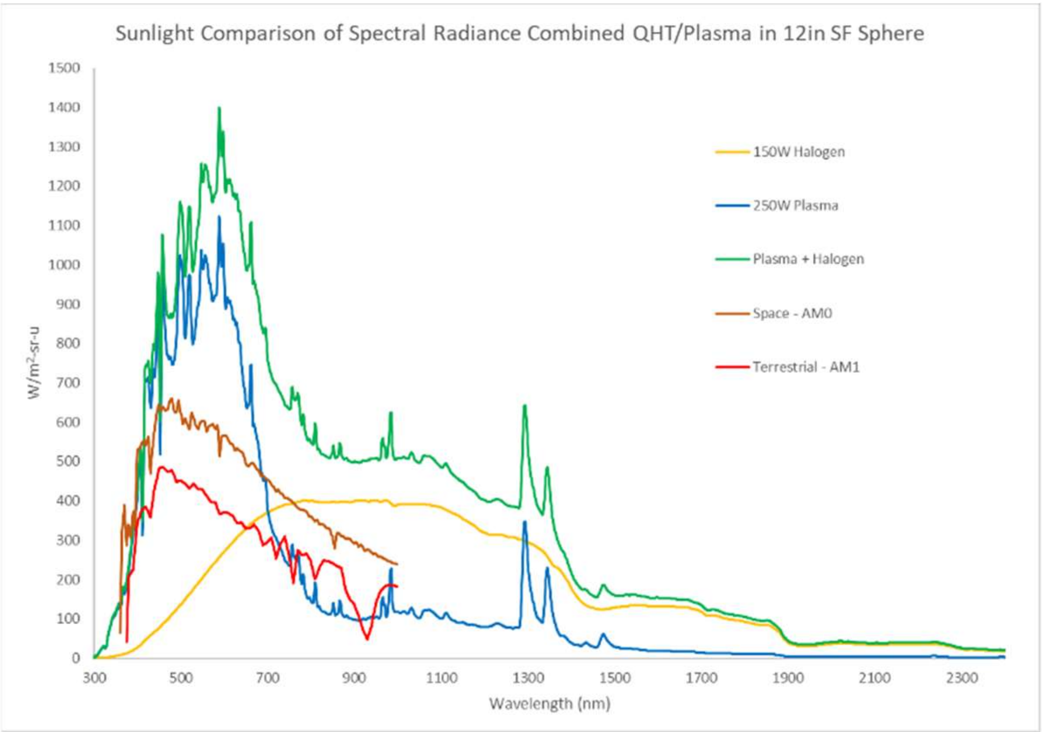
QTH/Plasma Combined Sources

“Best of Both Worlds”

- Enhanced blue/green output over QTH alone
- Smoother, higher red/NIR output over xenon/plasma
- Independent/controllable attenuation can allow for spectral tuning of system output
- Additional/advanced monitoring options should be considered as sharp structure can still be present
- Other combined sources may overcome structure



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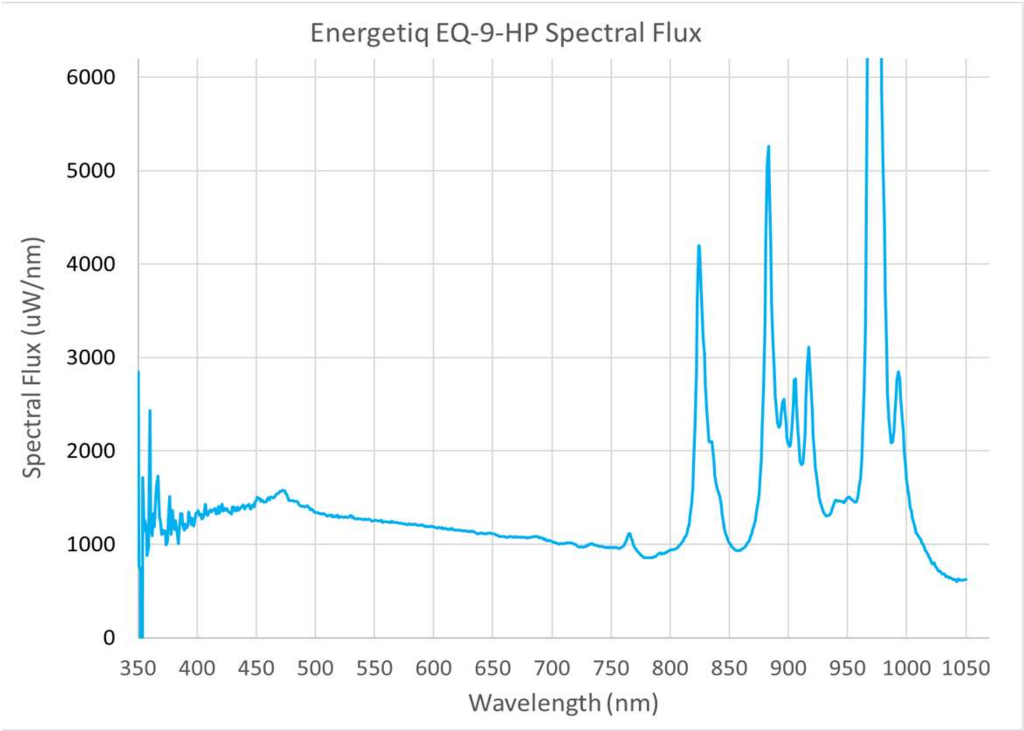
Laser Induced Plasma

Advantages

- Newly commercially available
- Extremely stable
- Flat spectral output



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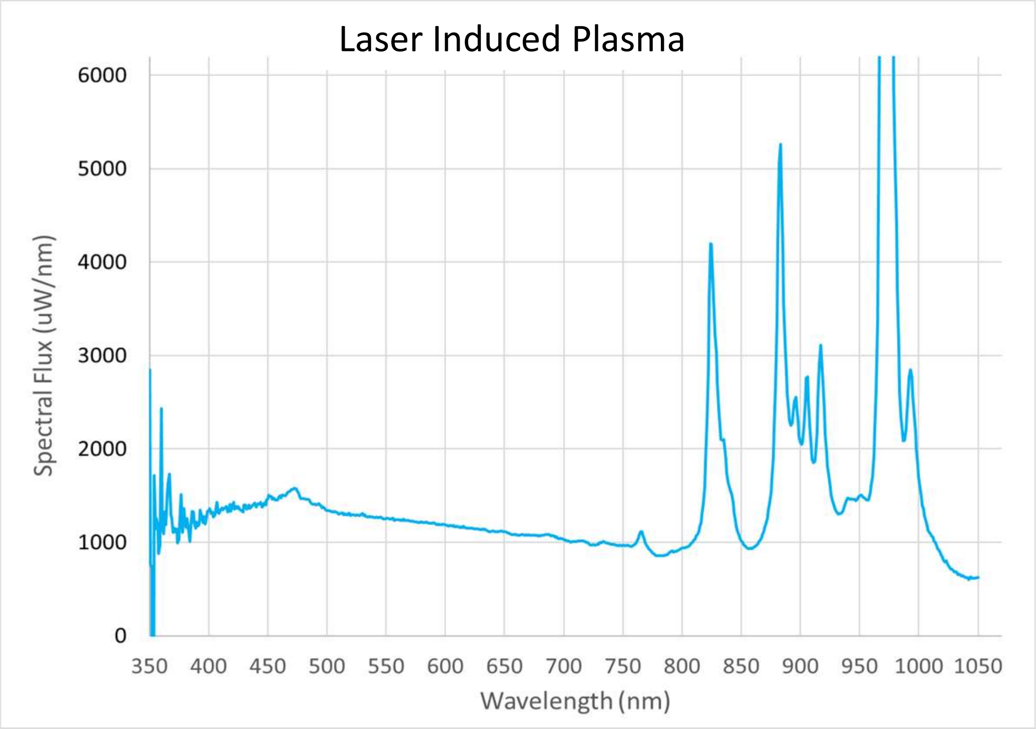
Laser Induced Plasma

Challenges

- Low flux
- Sphere attenuation
- Limited use in solar radiance level calibration
- Application limitations to sphere size/DUT FOV, uniformity, etc.



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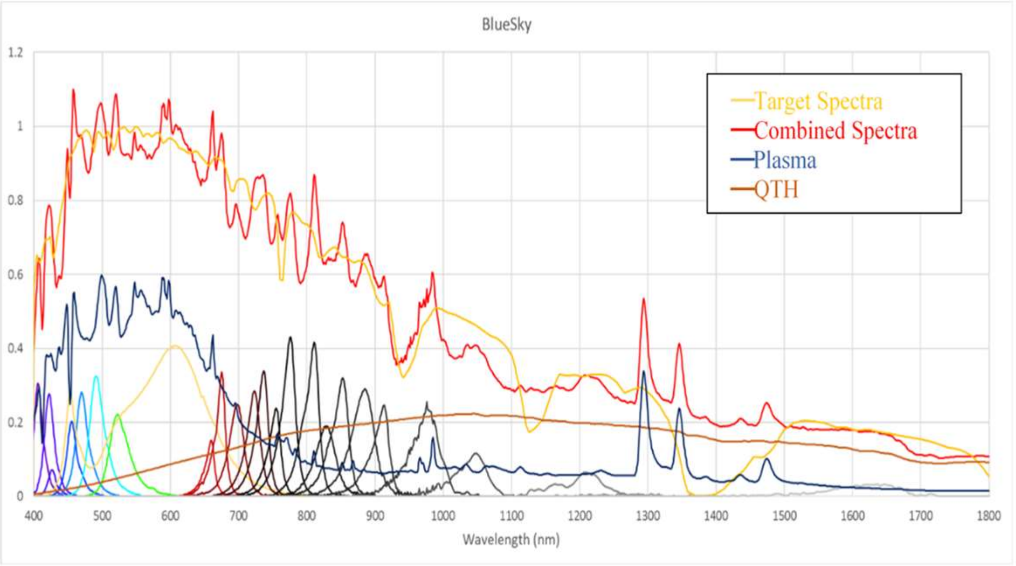
Light Emitting Diode Tunable Sources

- LED Technology Advancement
  - Power, performance, and wavelength selection
- LEDs Can Be Low Uncertainty Sources
  - DC mode operation
  - Thermally stabilized
  - Burn-in
- Large Arrays of LEDs
  - Provide high radiance in spheres
- Spectral Shaping for Tunability Systems
  - Independent control and flux integration
  - Global optimization using spectral fit objective functions provide match to target spectra
  - Can emulate many different sources including broadband through the visible and NIR
- Combining with broadband sources: a spectrally tunable calibration source 300-2500nm

Light Emitting Diode Tunable Sources

Challenges

- “Monochromatic” devices typically 10-30nm FWHM bandwidth
- “White Light” LEDs have limited wavelength ranges (visible) making them a poor choice for UV-VIS-NIR and SWIR
- Relatively low flux is an issue with LEDs and large spheres (>20”)
  - Hundreds of LEDs may be required to get to these radiances.
- Complex Electrical Systems
- Large Physical Foot-Print for Arrays



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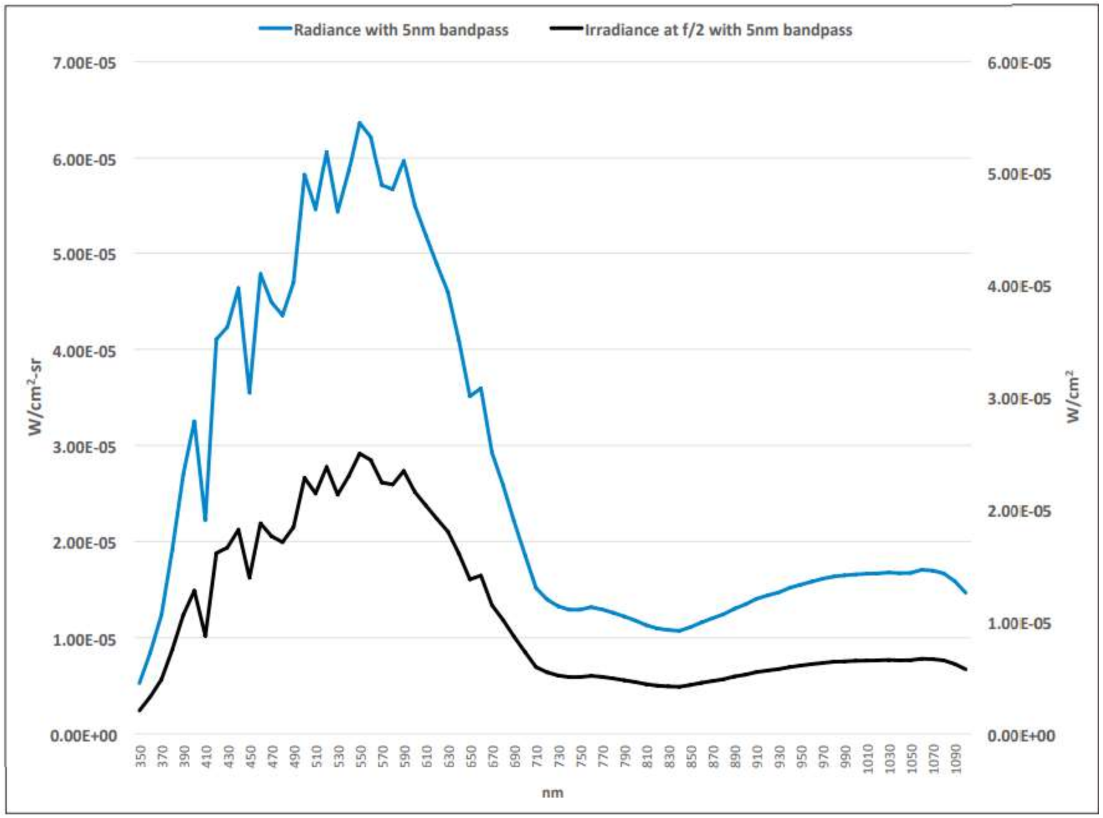
Monochromator

- May be deployed with multiple types of broadband sources, e.g. QTH and plasma
- Narrow band pass/fine wavelength resolution over selected range
- Allow for quantum efficiency testing
- Throughput loss order of magnitude – very low light in large spheres
- Characterization of FPA itself, and small imaging systems



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Prairie View A&M U Charged Particle Detector onboard JAXA's Ten-KOH 2.

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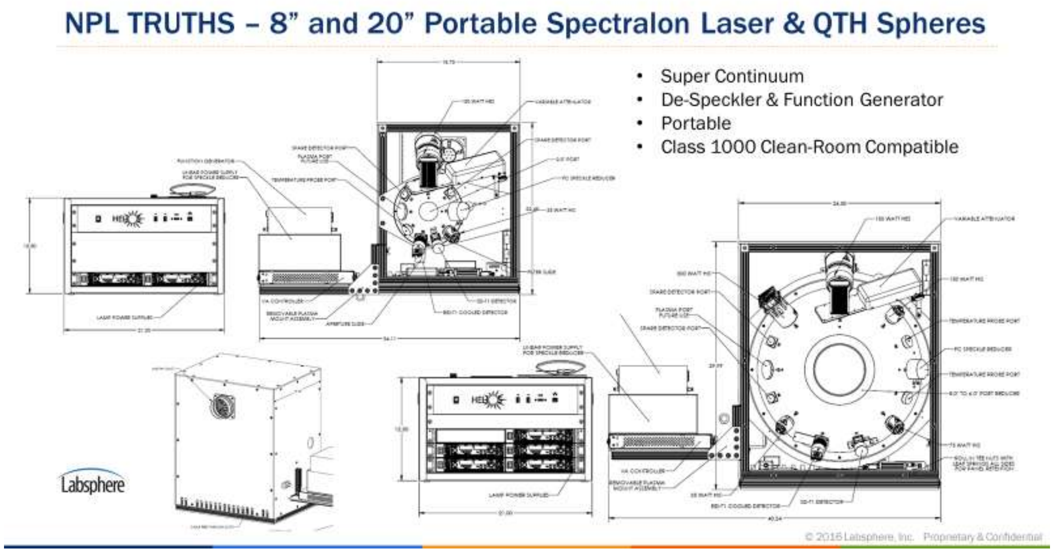
Super-Continuum Sources

- White-light laser
- > 50 MHz pulse rate, smoothed by sphere time constant
- Broad band, can be filtered (band pass, AOTF)
- Simple fiber-based coupling mechanisms
- Must be de-speckled
- Relatively low power



NPL proposed TRUTHS mission offering for lower uncertainty and portable calibration using broadband and supercontinuum sources.

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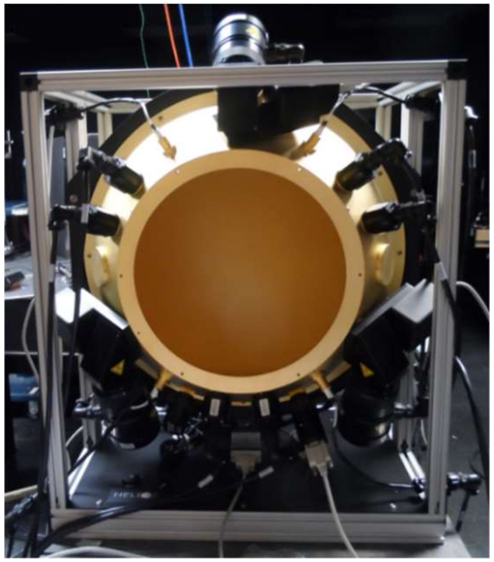
Thermal Sources

- Small emissive sources, 800 - 1200° C
  - Can be integrated like other light sources
  - Water-cooled hull - 270°
- Close emulation to black body
  - SWIR and MWIR
- Sphere material must be optimized – gold or PTFE
- Wide FOV MWIR/LWIR systems create uniform cavity radiance, but uncertainty not developed yet



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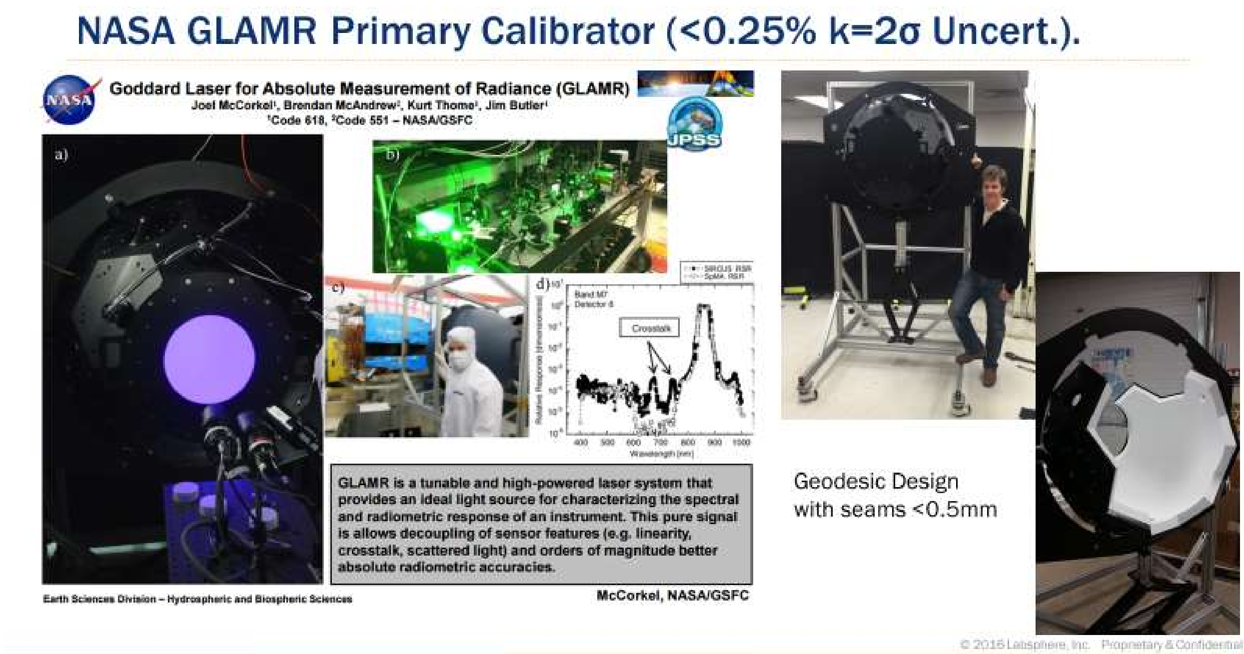
Discrete/Tunable Lasers

- NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) and NASA GLAMR systems
- Thousands of independent laser lines
  - Quantum efficiency
  - Radiometric testing
  - Spectral feature characterization – filter edge, stray light, etc.
- Expensive, complex, difficult to operate systems but enable < 1% absolute calibration
  - Portable versions exist for final instrument characterization
- Discrete laser diodes can be utilized for specific instrument performance request
- Throughput/coupling and speckle must be considered



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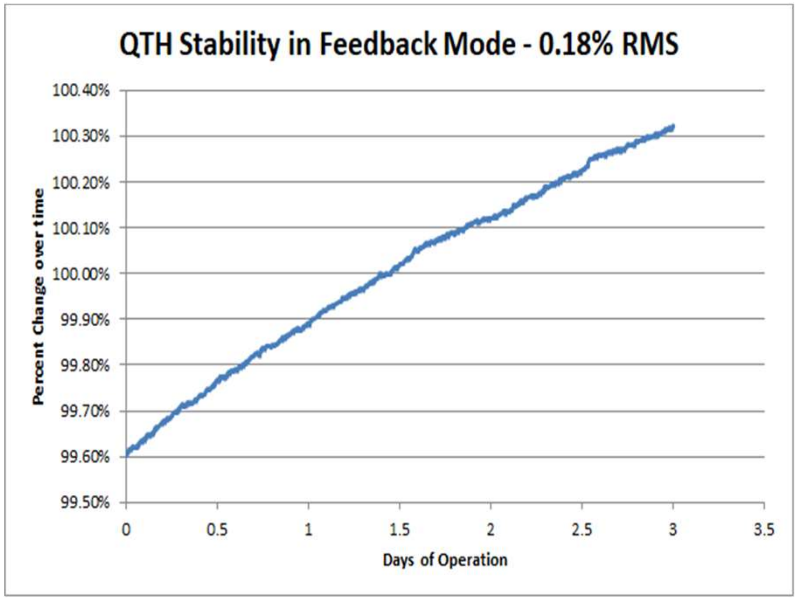
Radiance Levels – Stability and Dynamic Range

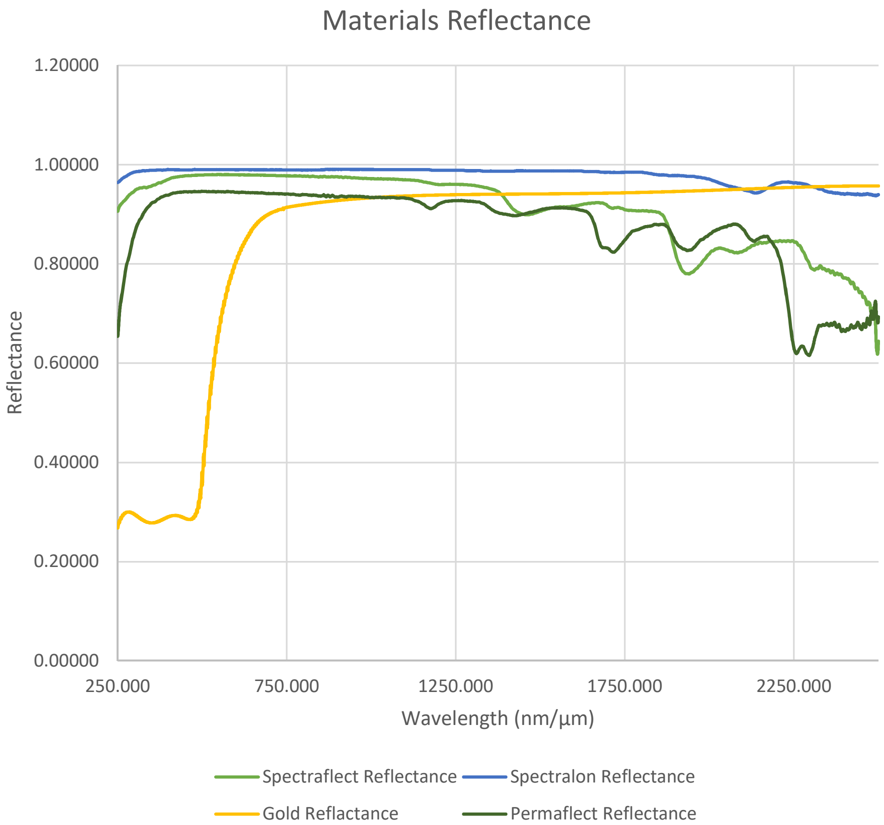
- EO targets can range over orders of magnitude in radiance
  - Day/night
  - Ocean/snow cover
  - Specular targets
- OGSE must have orders of light output
  - Multiple light sources (dozens)
  - Multiple types/spectra
  - Variable attenuation
- Detectors/spectrometers for active feedback – high stability over long duration (days). Similar systems were also employed in thermal vacuum (TVAC) testing over 27 days with the Landsat 8 program
- System monitoring and lamp selection/placement critical



QTH lamp stability in a sphere operated over three days of operation in closed loop mode.

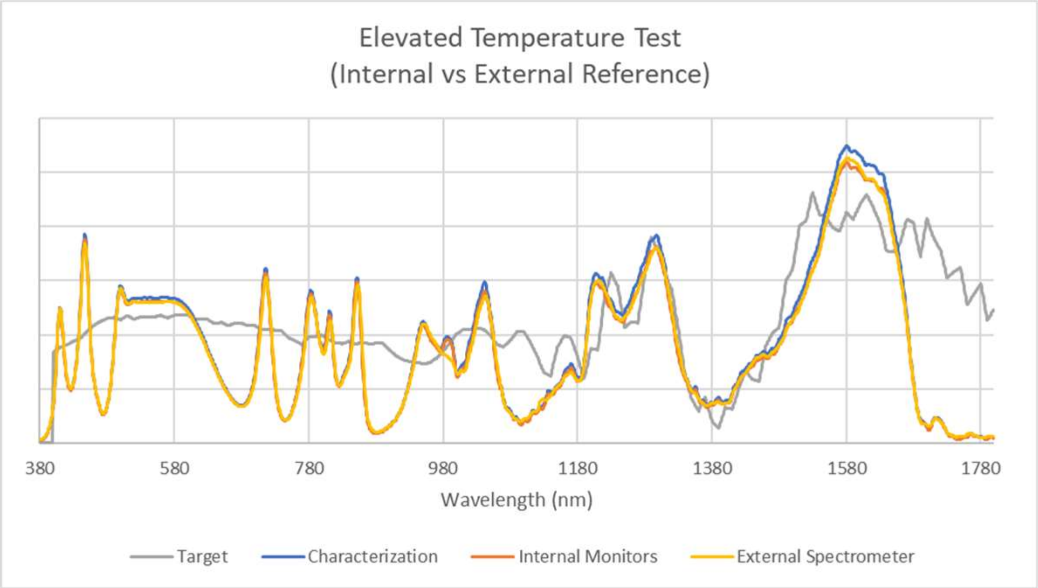
Coating Selection

- Spectralon (PTFE)
  - Spectrally flattest (250-2500nm)
  - Thermal, UV, moisture stable
  - Highly Lambertian – highest uniformity
  - Higher R/throughput
- Spectraflect ($BaSO_4$)
  - Lower cost
  - 375-2500nm
- Diffuse Gold
  - Highly reflective (IR)
  - Low R in VIS



System Monitoring Approaches

- Real-time monitoring critical to operating low uncertainty uniform sources
  - Specialized optical monitors can offer orders of magnitude better stability than any lamp sphere coatings
  - Calibrated, traceable, and stable optical monitors offer users real-time data, reduce DUT measurement uncertainty even as systems age and environmental conditions change
- Broadband detectors (Si – VIS, InGaAs – IR)
  - Simple, robust
  - Highly stable (long term), high dynamic range
  - Monitor total radiance but not spectral content
- Spectrometers
  - Spectrally resolved data – monitor both total radiance and spectral shift (due to age, thermal state, etc.)
  - Generally lower dynamic range than broadband
- Multiple monitor types
  - Combining detector types to cover full range



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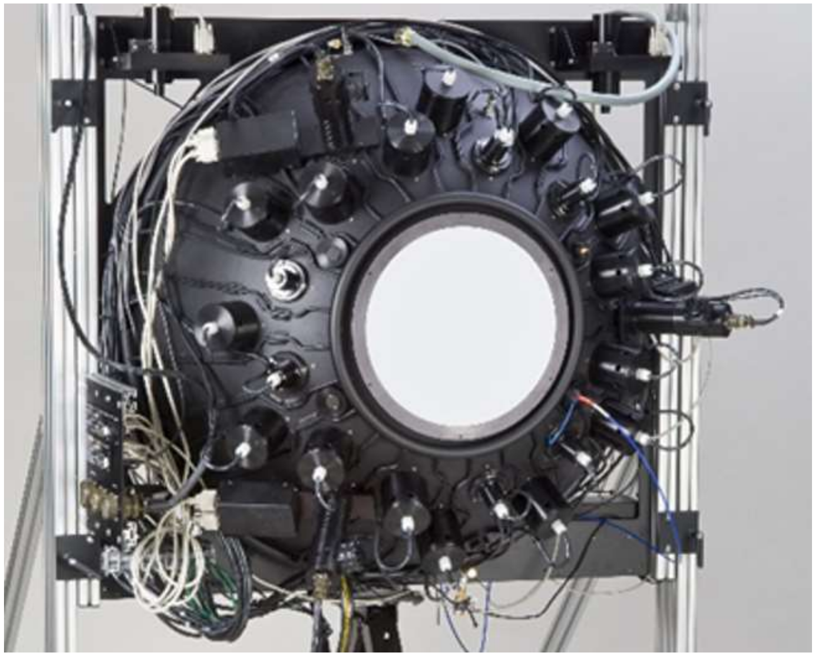
Ambient, Vacuum, Special Environments

- "Test as you Fly"
  - Harsh conditions like vacuum, purging or thermal extremes
  - Atmospheric gases can create calibration problems in SWIR bands
- $N2$, dry-air purge, or vacuum
- Water cooled sphere-hull solution allows much higher wattage, but requires gas containment
- Thermal vacuum (TVAC) on orbit, can recreate in OGSE
  - Landsat, RBI, Sentinel and other programs
  - Lack complete range of test capability, increase complexity (thermal, radiometric) but perform vital stability and radiometric test
  - Save 1-2% on uncertainty by placing cal in test environment, removing windows and other artifacts



40" Water Cooled Sphere with 9kW QTH for Landsat 8 & 9 Calibration

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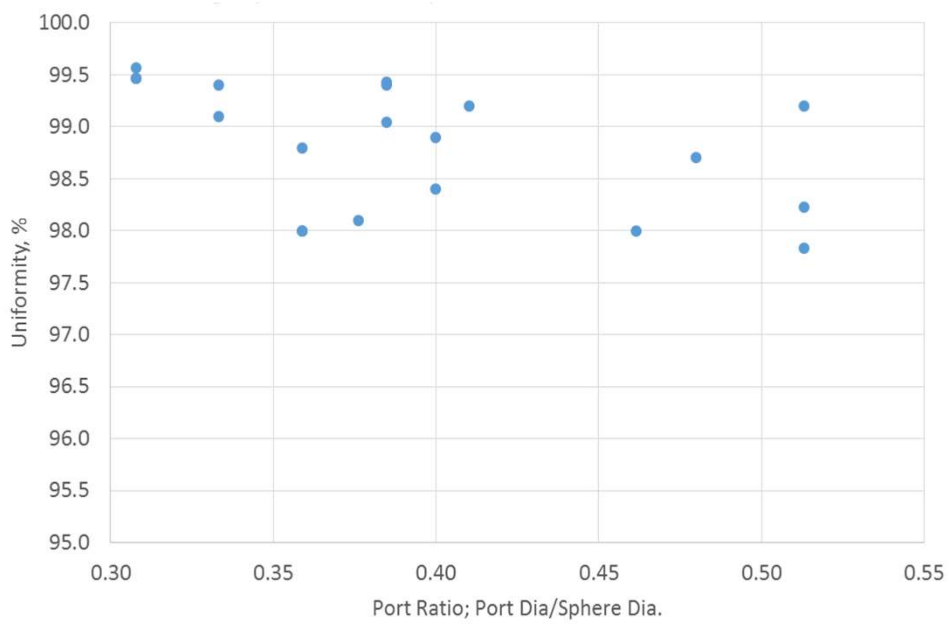
Sphere Size, Aperture Size, Symmetry and Uniformity

- Purpose of an integrating sphere
  - Quantified radiance for all sensor elements with a highly uniform output field.
- Real spheres cannot produce perfect uniformity
  - Light sources, detectors, etc.
  - Predicting uniformity using ray-tracing won't provide sufficient resolution to targeted uncertainties for OGSE calibration.
- Characterization of real spheres
  - Port ratio (port dia/sphere dia) has major impact
  - For given ratio, uniformity can be influenced by sphere configuration
  - #, position of sources, % output



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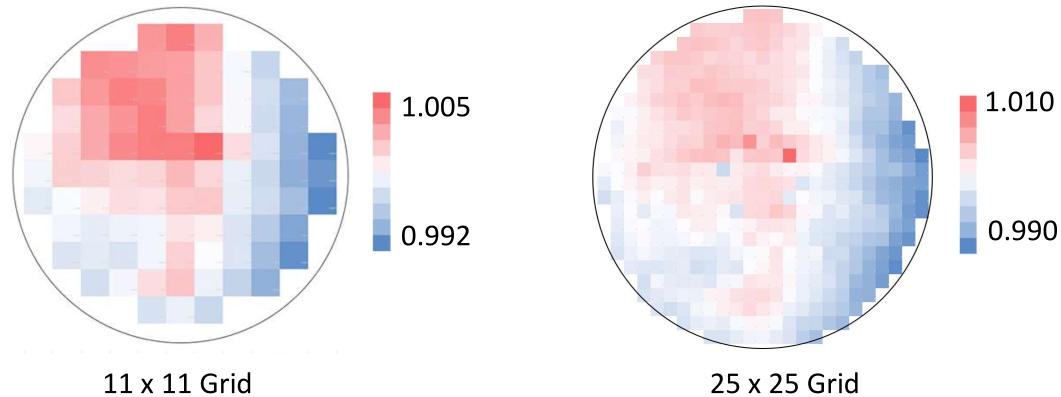
Perfectly Understood Non-Uniformity

- Labsphere legacy systems: ± 2%
  - Entire budget of new OES missions
- Cannot manufacture perfect uniformity
- Recently developed new method of determining uncertainty of non-uniformity measurements
  - Measure/estimate uncertainty at every point in chain
  - Propagate error to measured (non) uniformity of source
  - Pixel-by-pixel mapping to DUT for radiance and uncertainty (for < 1%)
- Uncertainty increases with resolution of output field (lower pixel averaging)

	11 x 11 Grid		25 x 25 grid	
Calculation Method	Uniformity	Expanded Uncertainty, k=2	Uniformity	Expanded Uncertainty, k=2
Max Deviation	98.71%	±0.068%	98.0%	±0.32%
Deviation Method	98.71%	±0.069%	97.9%	±0.33%
Mean Deviation	99.35%	±0.034%	99.0%	±0.17%
CoV	99.687%	±0.0046%	99.667%	±0.0080%

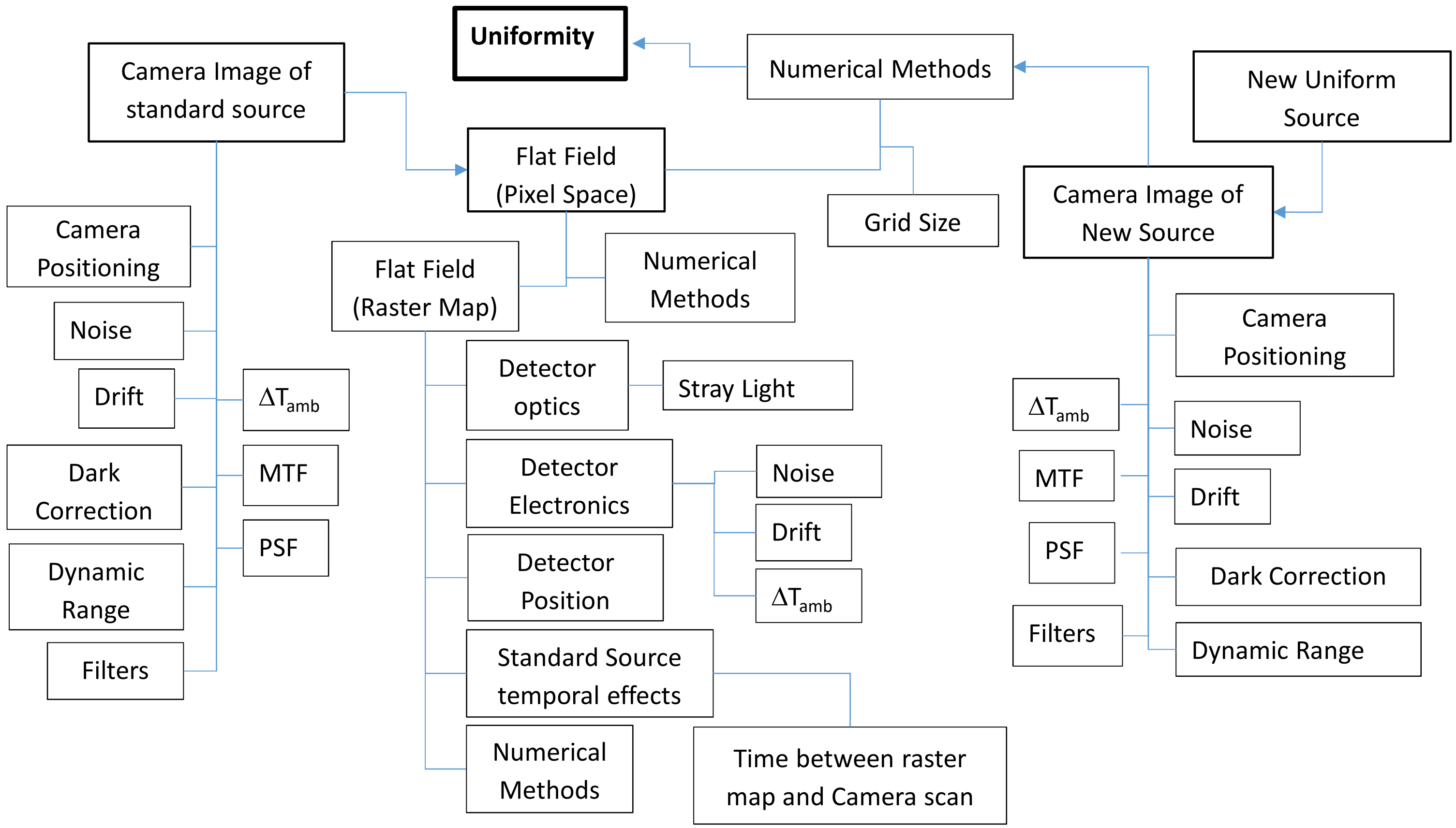


Uniformity Map for 20" test sphere at different grid spacings.

SPIE Proceedings 2019 paper 10980-42

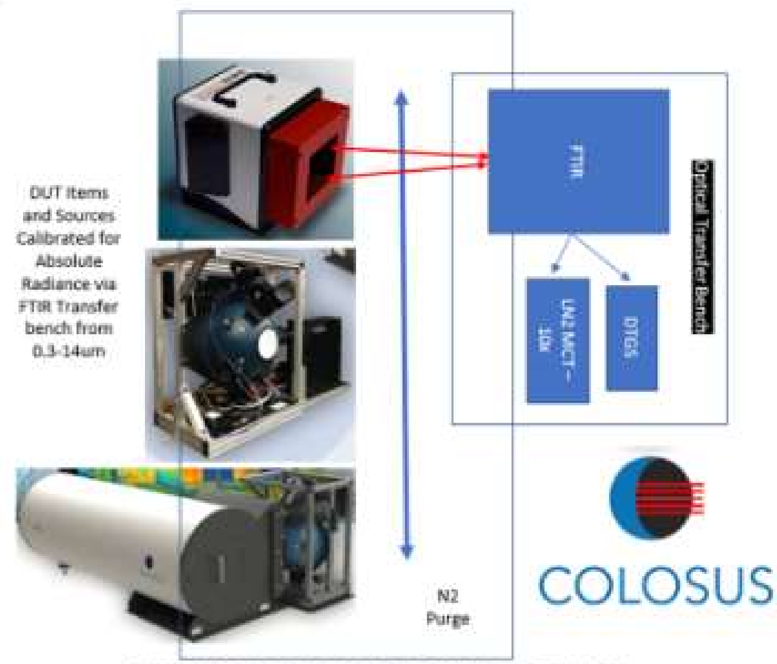
Labsphere

Measuring Uniformity



Extending Radiance Calibration to 0.3-14 µm

- Improving detector technology enabling Earth energy budgets in 0.3-30um and beyond
- Natural break point at 2.5um due to the use of radiant sources and radiance (like lamps) and emissive sources (like blackbodies) and temperature
- New highly absorptive materials, like Carbon Nano Tubes (CNTs) make radiance calibration from 2-14um a possibility
- COLOSUS
  - Labsphere/NIST potentially traceable chain of radiance joining spheres and blackbodies in radiance space
  - Labsphere is still developing transfer uncertainty
  - Commercial service for NIST traceable calibration from 0.3-14um using N2-purge
  - Native sources/collimators for image quality testing.
  - Sensor fusion to a common calibration baseline



TRANSFER RADIANCE CALIBRATION TO COMMERCIAL FLOOD AND COLLIMATED SYSTEMS.

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Extending Radiance Calibration to 0.3-14 µm

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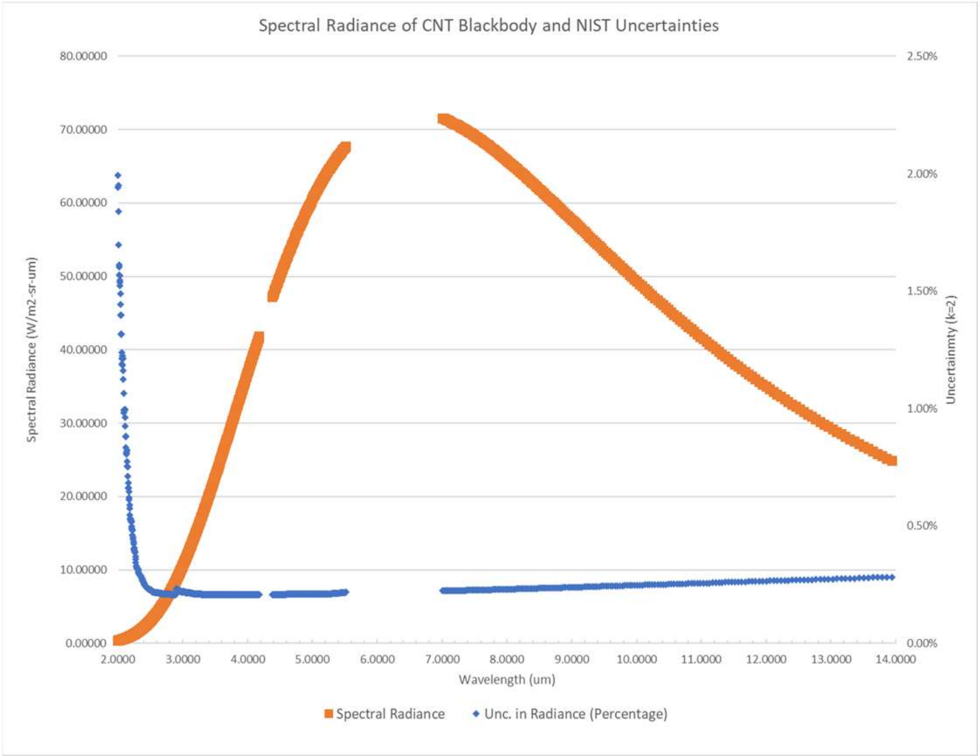

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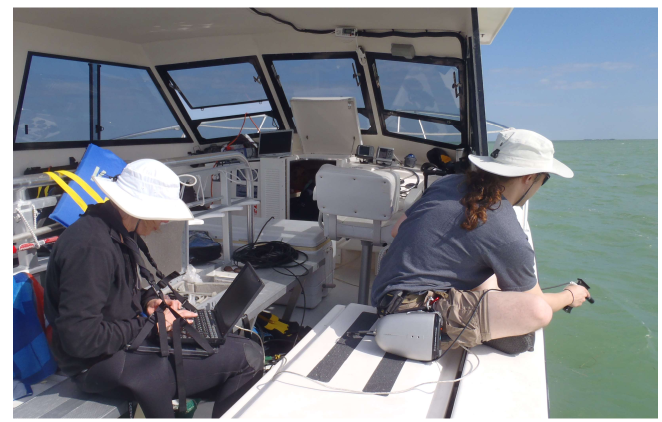
Vicarious Cal: Materials Improvement and Innovation

- Variety of techniques utilized for vicarious calibration
  - Individual targeted measurements
  - Natural targets
  - Pseudo-Invariant Cal Sites
  - Man-made targets
  - Atmospheric/radiometric monitoring
  - Moon
  - Sun
  - Other astronomical objects
- Uncertainties on order of >2.5%
  - 0.5% achievable
  - Methods constantly sought to improve – uncertainty, frequency, etc.

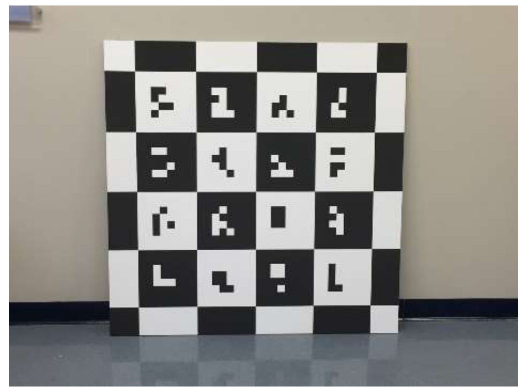


https://earthscience.arc.nasa.gov/sunsat/content/SunSat_AERONET

Labsphere

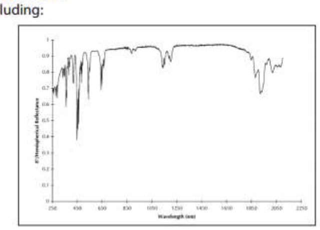
Vicarious Cal: Materials Improvement and Innovation

- Spectralon used for in-situ (<1%), other options needed for large GSD
- Permaflect
  - Spray coating for large, structured targets
  - 5 – 94% R (+/- 1%)
  - UV, weather resistant
  - Flexible version in development
- Doped Spectralon
  - PTFE with rare earth oxides
  - Strong absorption lines for λ verification



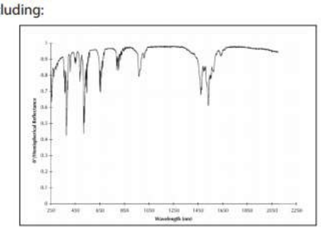
Holmium Oxide Standard

With wavelengths including:
447.6 - 449.6 nm
453.6 - 455.6 nm
1134.1 - 1138.1 nm
1198.6 - 1202.6 nm
1932.5 - 1936.5 nm



Erbium Oxide Standard

With wavelengths including:
378.9 - 380.9 nm
521.4 - 523.4 nm
1009.5 - 1013.5 nm
1470.0 - 1474.0 nm
1476.0 - 1478.0 nm



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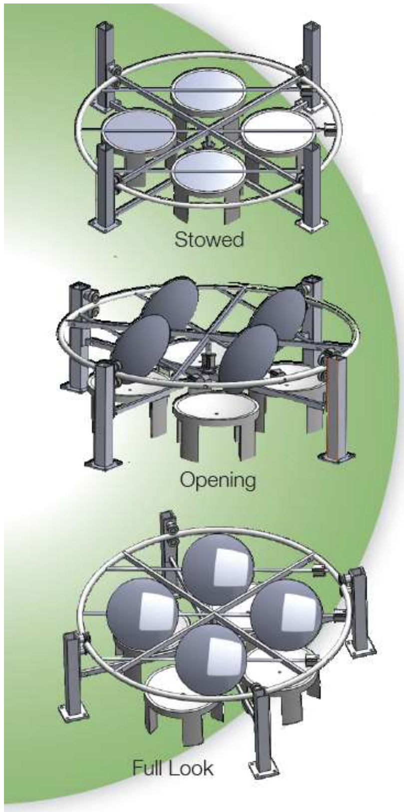
Vicarious Calibration on Demand - FLARE

- Utilizing Specular Array Calibration Method (SPARC)
  - Mirror point sources for radiometric, atmospheric, spatial information
  - At-sensor radiance equivalent to 80% Lambertian Reflector
  - Tailored Ground Sampling Distance (GSD)
- Automated network of “on demand” calibration tailored to any satellite resolutions requirements
  - Look is scheduled, mirrors open, track
  - Weather/image quality metrics
- High frequency, instrument tailored, on-demand calibration
  - Reduce uncertainty, improve image quality and facilitate Analysis Ready Data (ARD)



Labsphere

Thank You

- EO mission requirements driving down uncertainty on orbit for long term studies
- Translates to <1% uncertainty on Optical Ground Support Equipment (OGSE)
- Spectral content, radiance levels, dynamic range, uniformity, and absolute traceable monitoring levels must be considered in equipment design and matched to DUT
- Propagation of uncertainty critical to highest possible accuracy