First CLARREO Mission Study Team Meeting
Harvard IR/GPS Studies

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30 April – 1 May 2008

Langley Research Center

Earth Science and Applications from Space
National Imperatives for the Next Decade and Beyond

Committee found that fundamental improvements were needed to establish a disciplined structure linking:

- *Decision processes that serve societal objectives*
- *The analyses, forecasts and models that provide timely and coherent input to those decision processes, and*
- *Observations selected to test and systematically improve those forecasts*

Prioritization Process

The prioritization process for mission selection involved eight criteria used to set relative rankings:

1. Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration)
2. Contribution to applications and policy making (societal benefits)
3. Contribution to long-term observational record of the Earth
4. Ability to complement other observational systems, including national and international plans
5. Affordability (cost consideration, either total costs for mission or costs per year
6. Degree of readiness (technical, resources, people)
7. Risk mitigation and strategic redundancy (backup of other critical systems)
8. Significant contribution to more than one thematic application or scientific discipline


Ecology and Land Remote Sensing
Tony Janetos
Human Health, Infectious Diseases
Mark Wilson
Solid Earth Hazards
Brad Hager
Executive Committee & Panel Chairs
Water Sources, Hydrology
Dennis Lettenmaier
Land Cover Change
Ruth DeFries
Climate, Paleoclimate
Eric Barron
Meteorology Space Weather
Susan Avery

CLARREO addresses three key Societal Objectives

1. The essential responsibility to present and future generations to put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards

2. The development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically rigorous techniques to systematically improve those forecasts to establish credibility

3. Disciplined decision structure that assimilates accurate data and forecasts into intelligible and specific products that promote international commerce as well as societal stability and security

The magnitude and impact of climate change are not, at present, clearly defined. We do not presently observe Earth's climate system with sufficient accuracy to establish a climate record that is tested and trusted, nor are climate observations in place that can adequately constrain climate model predictions.

Important Sub-Fields Related to High Accuracy Long-Term Climate Records

Metrology	*Instrument Systems for High Accuracy Observations from Space*	*Climate Community and Climate Records*
• SI traceable standards • Technology and strategy for establishing absolute scales • Innovation for detection of systematic errors • Atomic clocks, phase transition cells, frequency stabilized laser	• Accuracy, precision and bias on-orbit • Blackbodies, frequency standards, temperature cells • Quantum cascade lasers, linear detectors, polarization of optical systems in space • Targets for calibration: Moon, stars, etc.	• Ground-based observations • Sondes, GEOSS • Use of weather data for climate • Intercomparison methods between satellites • *In situ* intercomparisons

If an observations is not initially SI traceable against an absolute scale, it cannot engage in the logic of testing for systematic error. If an observation cannot independently establish its time dependent bias against an SI traceable standard throughout its observing lifetime, it cannot, by the logic of metrology, provide independent evidence of trends in the climate record---it therefore ceases to constitute a climate benchmark.

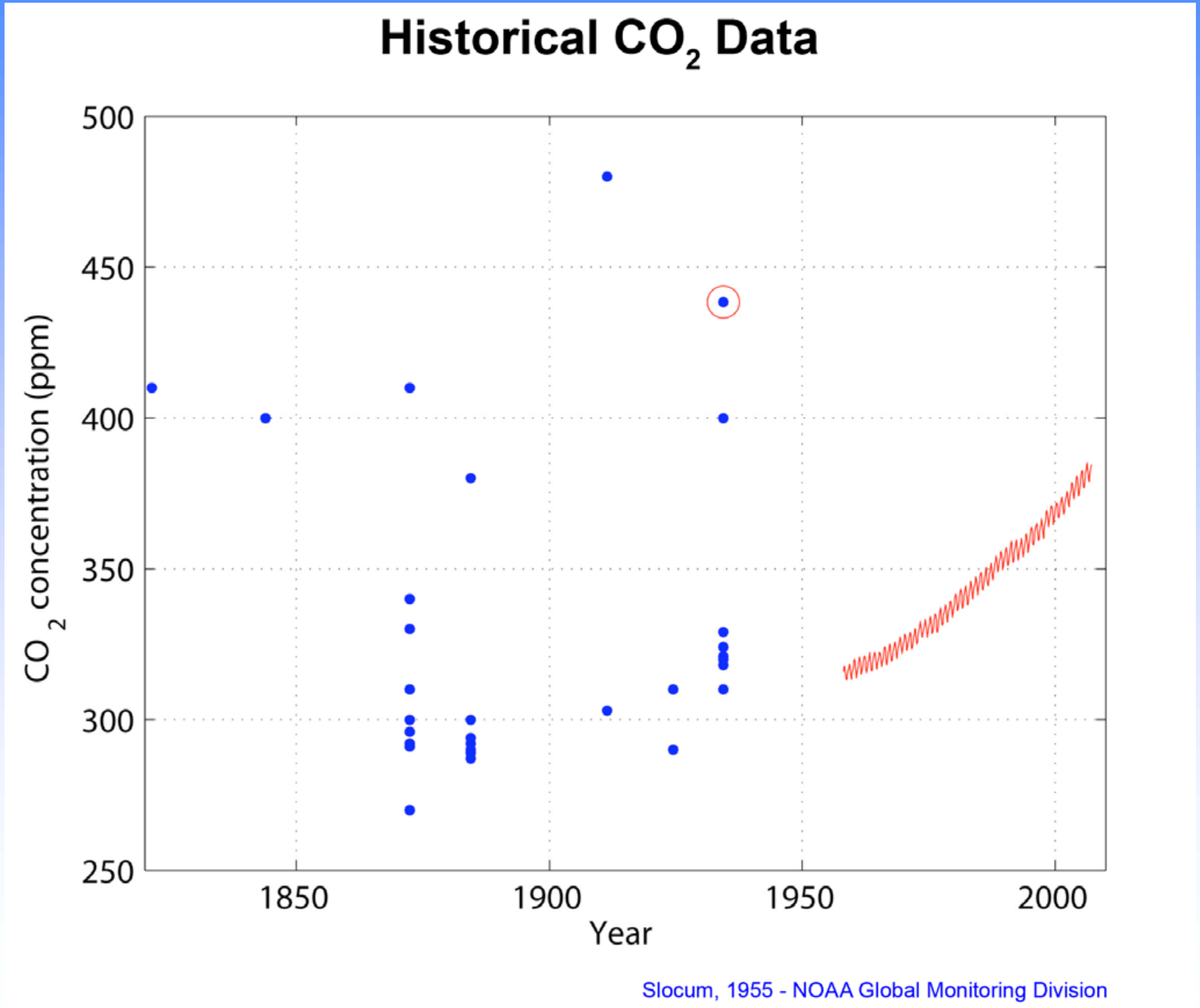
Accuracy, Precision, and Bias

Accuracy is the measure of the non-random, systematic error, or bias, that defines the offset between the measured value and the true value that constitutes the SI absolute standard

Precision, in sharp contrast, is the measure of reproducibility or repeatability of the measurement without reference to an international standard so that precision is a measure of the random and not the systematic error. Suitable averaging of the random error can improve the precision of the measurement but does not establish the systematic error of the observation.

Stability is a term often invoked with respect to long-term records when no absolute standard is available to quantitatively establish the systematic error - the bias defining the time-dependent (or instrument-dependent) difference between the observed quantity and the true value.

Keeling Record: Historical CO_2



Keeling Axiom

- ***Without*** an SI traceable (absolute) standard, time works ***against*** you.

- ***With*** an SI traceable (absolute) scale, time works ***for*** you.

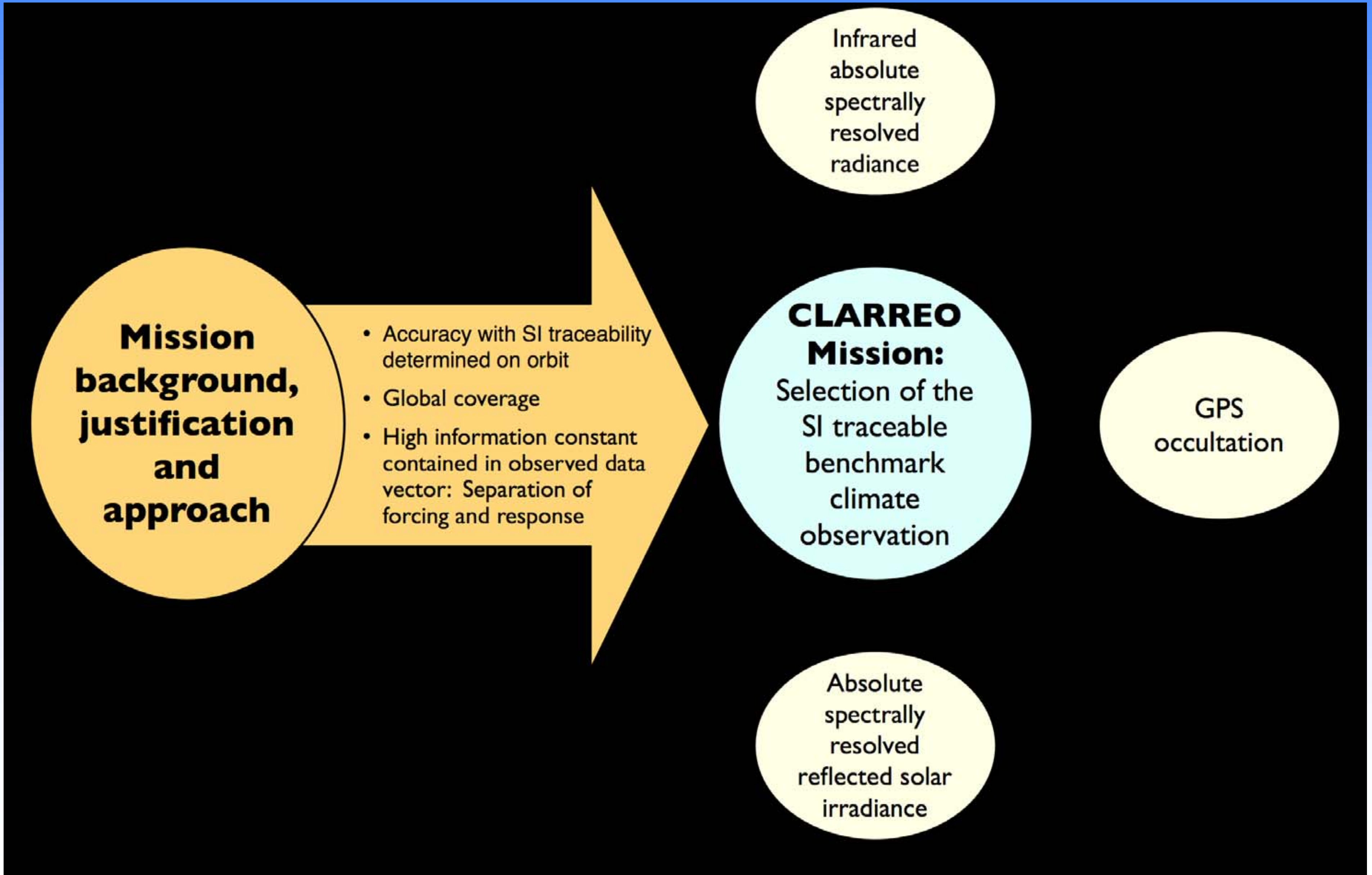
Keeling Axiom: CLARREO

- ***Without*** an SI traceable (absolute) standard *on-orbit*, time works ***against*** you.
- ***With*** an SI traceable (absolute) standard *on-orbit*, time works ***for*** you.

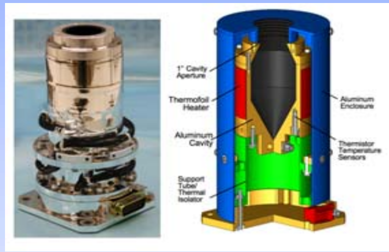
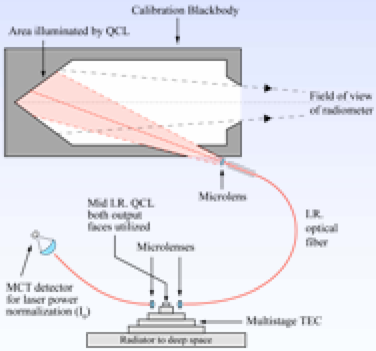
Some Guiding Principles for Satellite Climate Observations

1. Completely independent methods of observing the most critical climate benchmarks from space must be developed, each having accuracies that satisfy the requirements of climate (e.g., 0.1 K for temperature) and that are SI traceable on-orbit to absolute standards.
2. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array: Optical Designs, Orbits, Calibration, etc.
3. Trust in the accuracy of key long-term climate observations must be built upon: (a) open access to the details of experimental execution; (b) publication in the scientific and technical literature; (c) individual scientific responsibility; and (d) continuity in laboratory, airborne, and satellite analyses that together dissect systematic errors.
4. The experimental design and execution of long-term climate observations must be cost effective, responsive to emerging knowledge, and adaptable to technological innovation.
5. Calibration and associated subsystem development resources must be given high priority and the analysis of accuracy achieved by the observing systems must be systematically critiqued over the period of decades. Fundamental development of calibration facilities at NIST must be supported with ongoing commitment.
6. Primary long-term climate observations must be global in coverage, must provide required accuracies in both horizontal and vertical structure, and must be free of interference from uncontrolled boundary conditions.
7. Climate forecast testing and improvement places specific demands upon the data vector produced by the climate observation and upon the mathematical structure used to couple the observations to the forecast. Thus, selection of the highest priority observations must be done in concert with an understanding of the structure of the forecast model.

Establishing the Climate Benchmark Record: What are the Requirements?

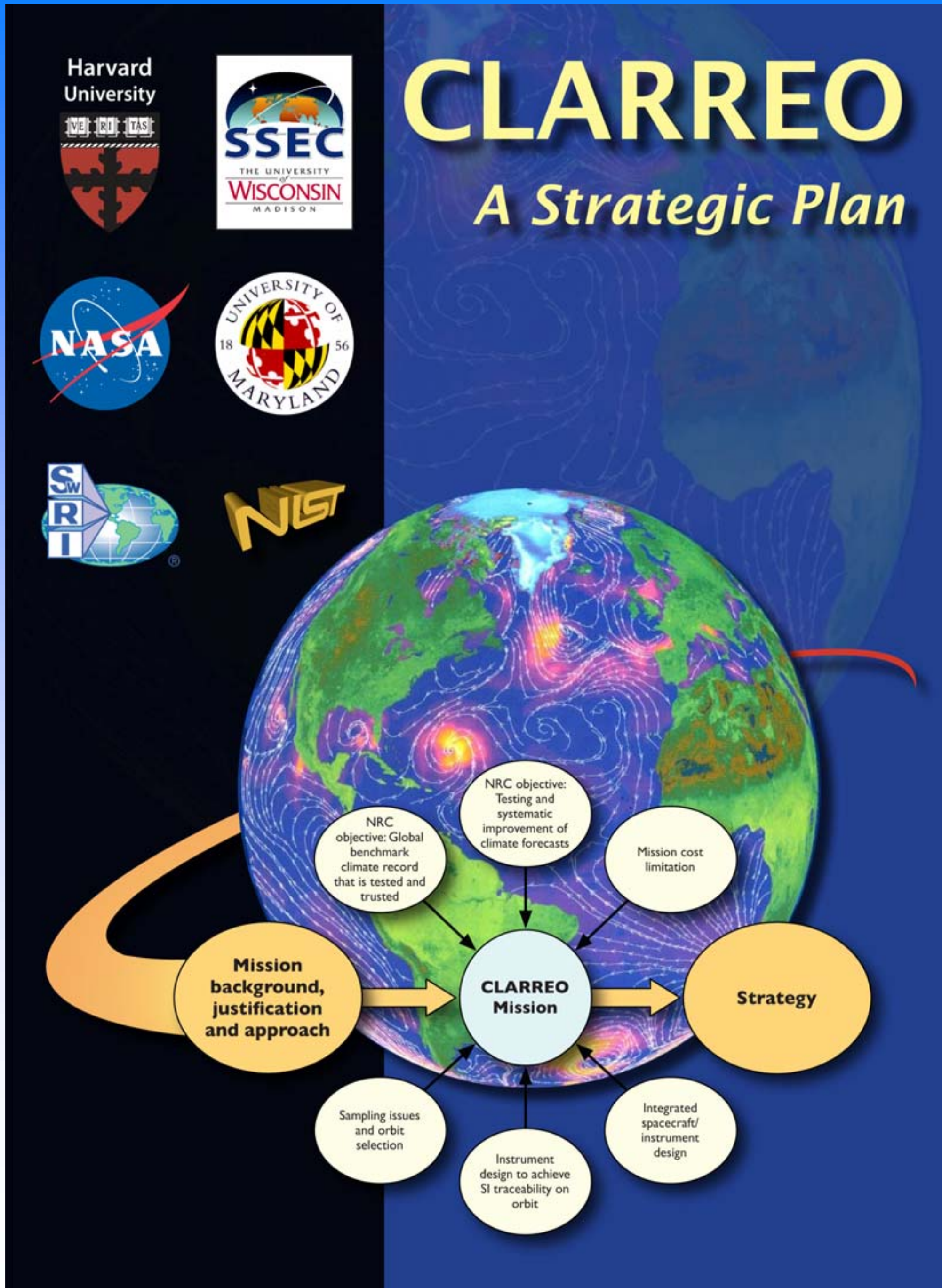


What is the Specific Manifestation of a Mission Objective in Terms of Instrument Design and Hardware Execution?

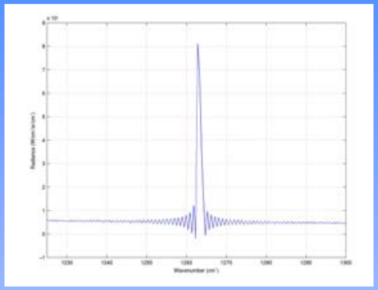
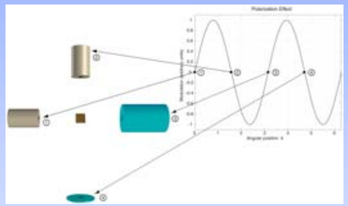
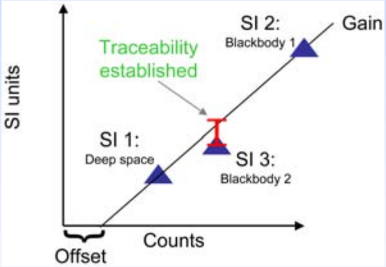
Specific Climate Objective	IR/GPS		Publications
Achievement of benchmark accuracy on-orbit: **Multiple Interferometer**	Independent cross check of systematic error on-orbit associated with thermometry, materials, linearity, emissivity, stray light, polarization		• Anderson, J.G., *et al.*, Arrhenius Proposal, 1996. • Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004.
Achievement of benchmark accuracy on-orbit: **Thermometry**	Incorporation of multiple phase transition cell into blackbodies to determine absolute temperature on-orbit		• Best, F., *et al.*, CORM 1997 Annual Meeting, NIST, Gaithersburg, MD, 20 April 1997. • Gero, P. J., J. A. Dykema, J. G. Anderson, A new blackbody design for SI-traceable radiometry, *J. Atm. Ocean. Tech.*, submitted 2008.
Achievement of benchmark accuracy on-orbit: **Emissivity**	• Incorporation of quantum cascade laser into blackbodies to determine cavity emissivity on-orbit • Heated source to perform emissivity measurement		• Gero, P.J., Realization of SI-traceable infrared radiance measurements from space for climate, PhD Thesis, Harvard University, 2007. • Dykema, J.A., and J.G. Anderson, *Metrologia* **43**, 287-93, 2006. • Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004.

Uncertainty (Error) Budget for Infrared

Subsystem	**Magnitude (mK)**
Thermometry	10
Blackbodies	
Homogeneity	20
Emissivity	9
FTS stray light and polarization	33
Detector chain nonlinearity	14
Other errors	10
TOTAL	44



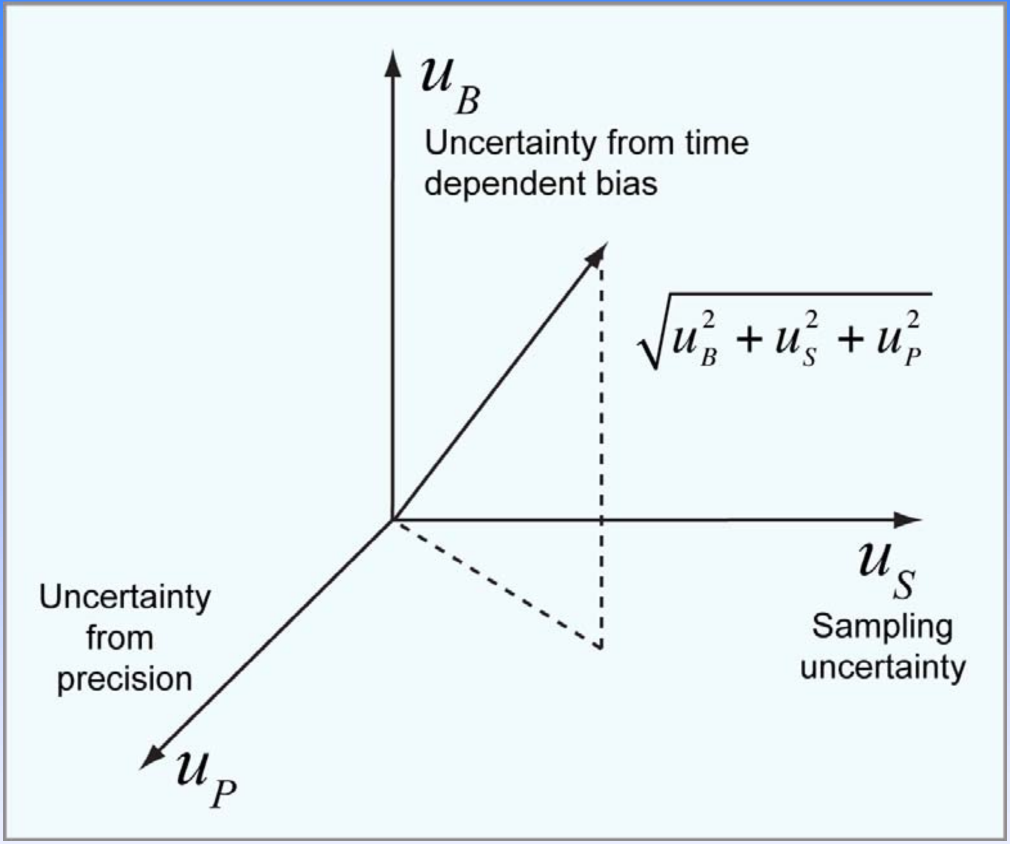
- Harvard University
  - Jim Anderson
  - John Dykema
  - Stephen Leroy
  - Jonathan Gero
  - Richard Goody
  - Joe Demusz
  - Norton Allen
- University of Wisconsin
  - Hank Revercomb
  - Robert Holz
  - Bob Knuteson
  - Dave Tobin
  - Fred Best
  - Joe Taylor
- University of Maryland
  - Dan Kirk-Davidoff
  - Renu Joseph
- NIST
  - Joe Rice
  - Carol Johnson
  - Jerry Fraser
  - Raju Datla
- Southwest Research Institute
  - Bill Gibson
  - Randy Rose
  - Kelly Smith
- NASA
  - Dave Young
  - Langley Research Center

Specific Climate Objective	IR/GPS		Publications
Achievement of benchmark accuracy on-orbit: **Instrument Line Shape**	Incorporation of QCL into cell for observing optical performance directly		• Revercomb, H.E., *et al., SPIE Proc.* **6405** doi:10.1117/2.694084, Dec 22, 2006. • Gero, P.J., *et al.,* A quantum cascade laser based reflectometer for on-orbit blackbody cavity monitoring, *J. Atm. Ocean. Tech*., in preparation 2008.
Achievement of benchmark accuracy on-orbit: **Polarization**	• Design of optical system placing deep space, Blackbody and nadir at nodes of polarization • Rotation of scene mirror by 45° with deep space view		• Dykema., J.A., and J.G. Anderson, *Metrologia* **43**, 287-93, 2006. • Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004.
Achievement of benchmark accuracy on-orbit: **Linearity**	• Selection of detectors with basic physics of detector linear • deep space plus two blackbodies for each interferometer with temperature scan		• Dykema, J.A., and J.G. Anderson, *Metrologia* **43**, 287-93, 2006. • Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004.

What are the Advantages of the Fourier Transform Interferometer for climate studies?

- The ILS/SRF is defined over the entire instrument spectral widow by two wavelength-independent properties: The maximum optical path difference (OPD) and the stable optical field stop geometry. This principle has been directly proven with laser ILS measurements during testing of CrIS for NPOESS, TES for NASA Aura, and IASI for METOP1.
- The spectral resolution required by climate requirements (1.0 cm^{-1}), the optical core of the interferometer, is both small and simple yet the product of entrance aperture area and solid angle of acceptance (the étendue) is large. This provides the ability to employ redundant interferometers needed to test for systematic errors on orbit.
- Because of its integrated laser based metrology system, the ILS/SRF for the Fourier transform spectrometer is insensitive to instrument geometry and does not require the extremely precise thermal control needed for a grating instrument.
- The FTS delivers very broad spectral coverage to a single detector resulting in a very simple optical, thermal, and detector configuration.

Sampling: The Key to a Climate Strategy

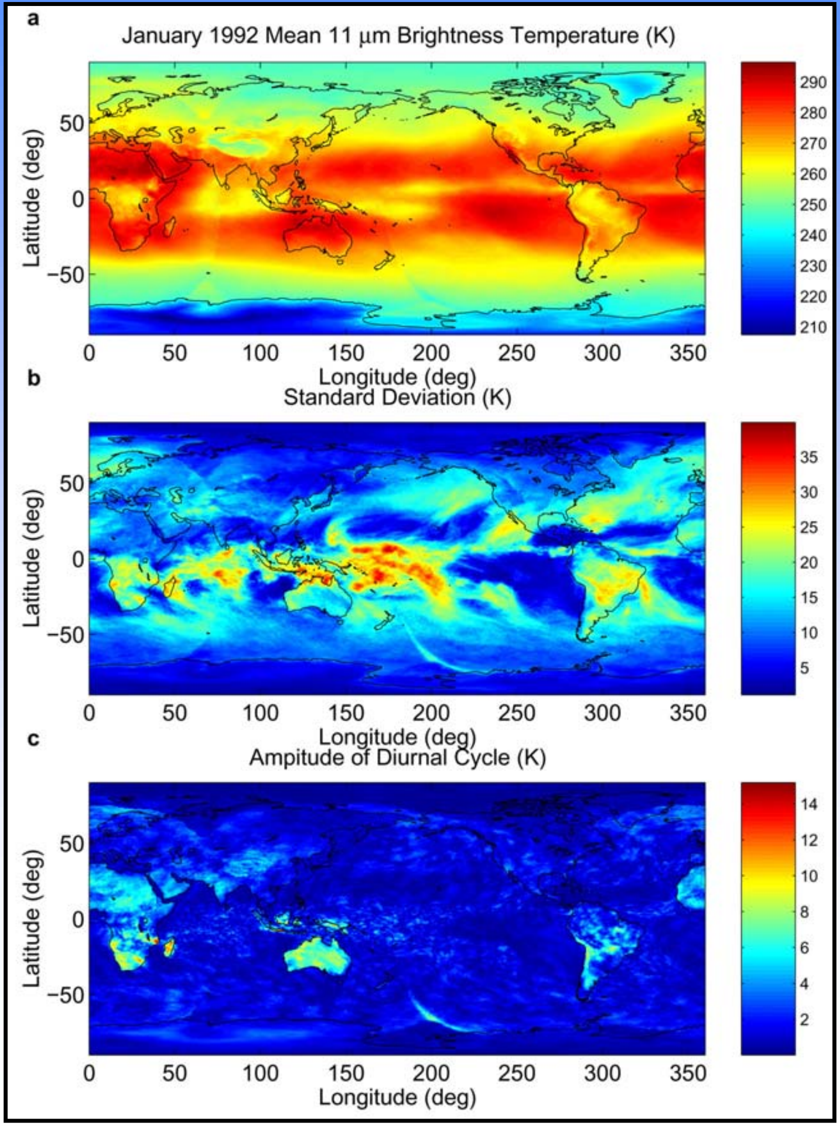


- The recovery of climate averages with an uncertainty of 0.1 K 3σ
- Recovery in the face of large diurnal and semi-diurnal amplitude, large variance resulting from weather "noise".

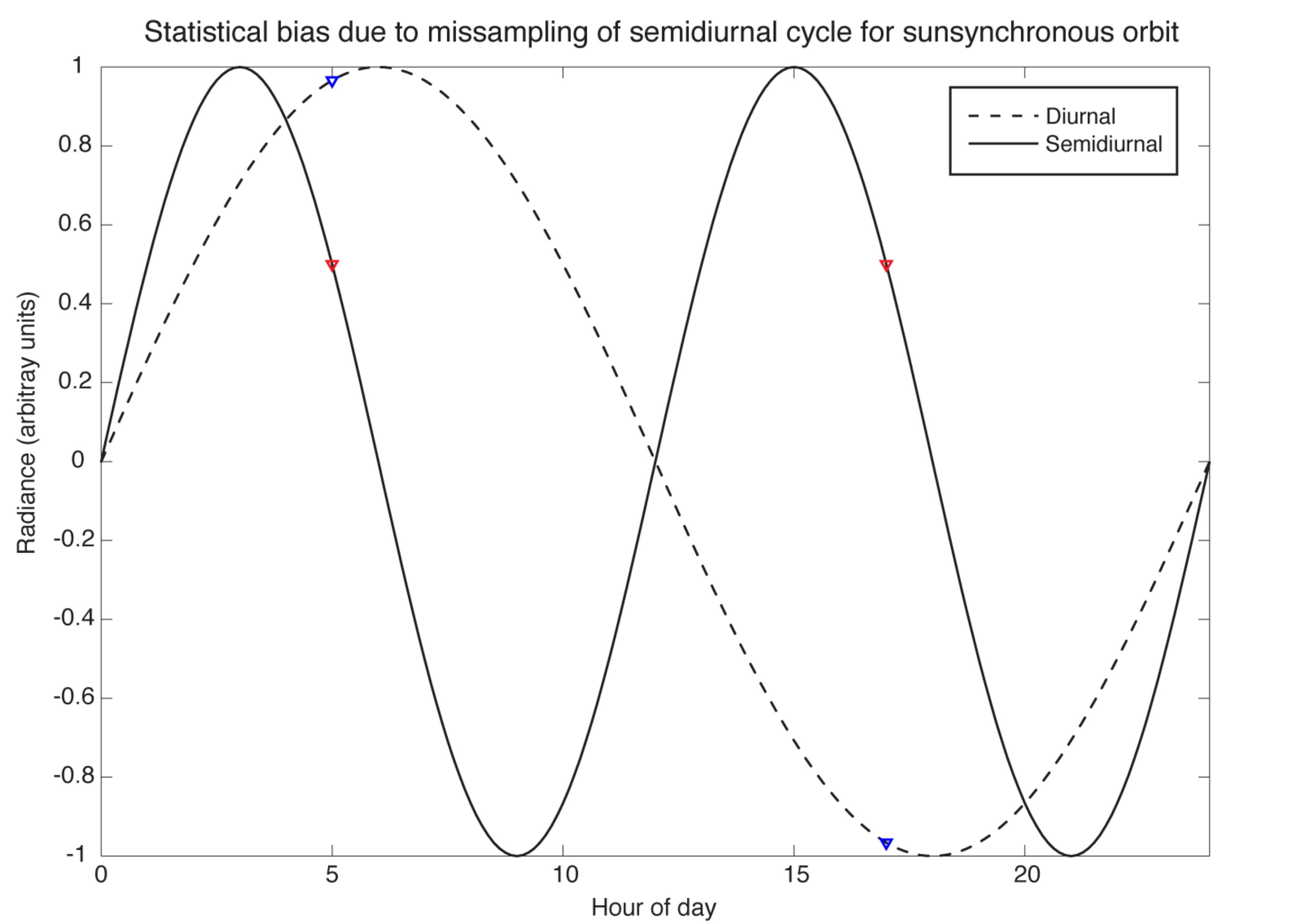
Original Work of D. Kirk-Davidoff

PRIORITY: Orbit Choice

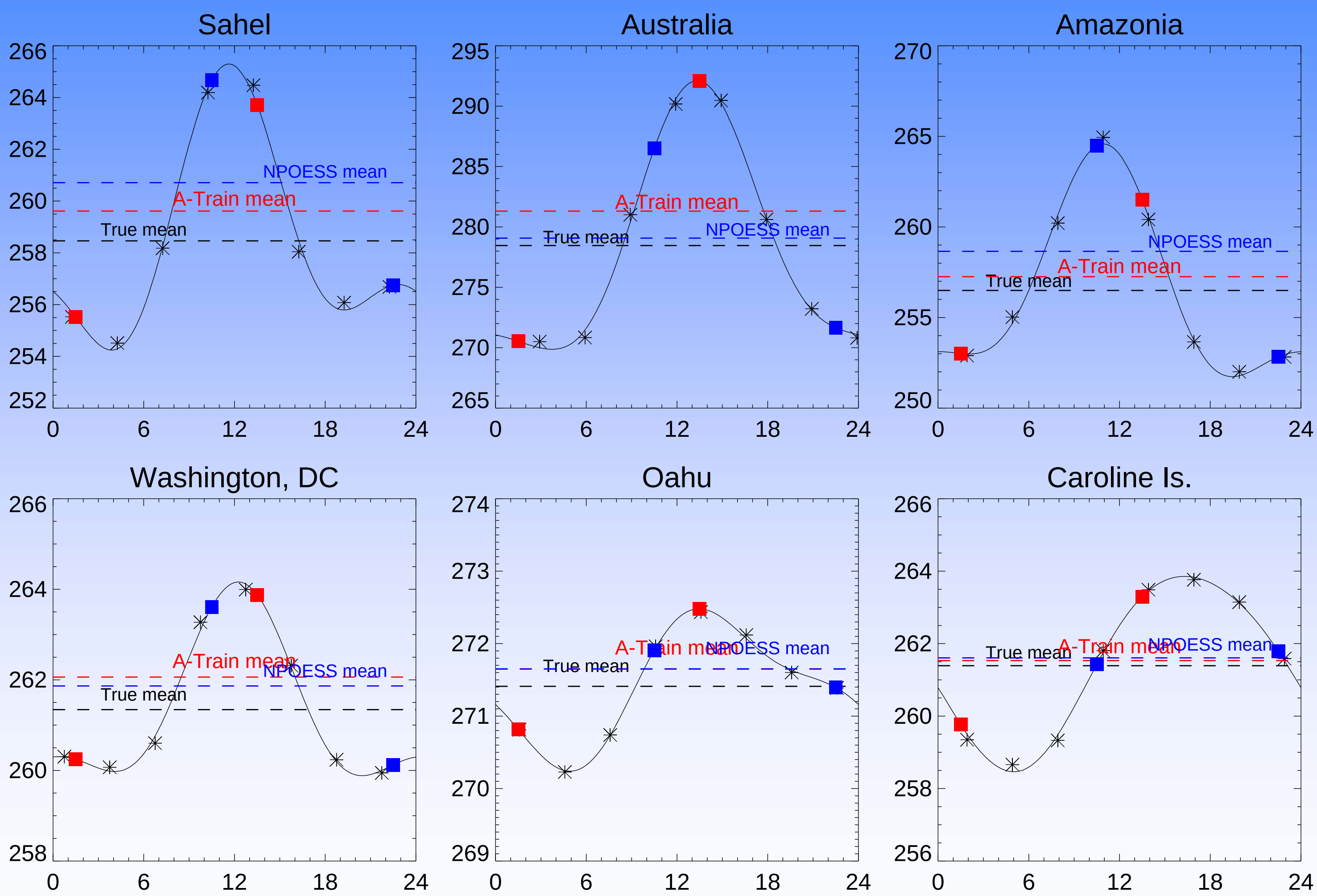
Salby cloud imagery data at 11μ



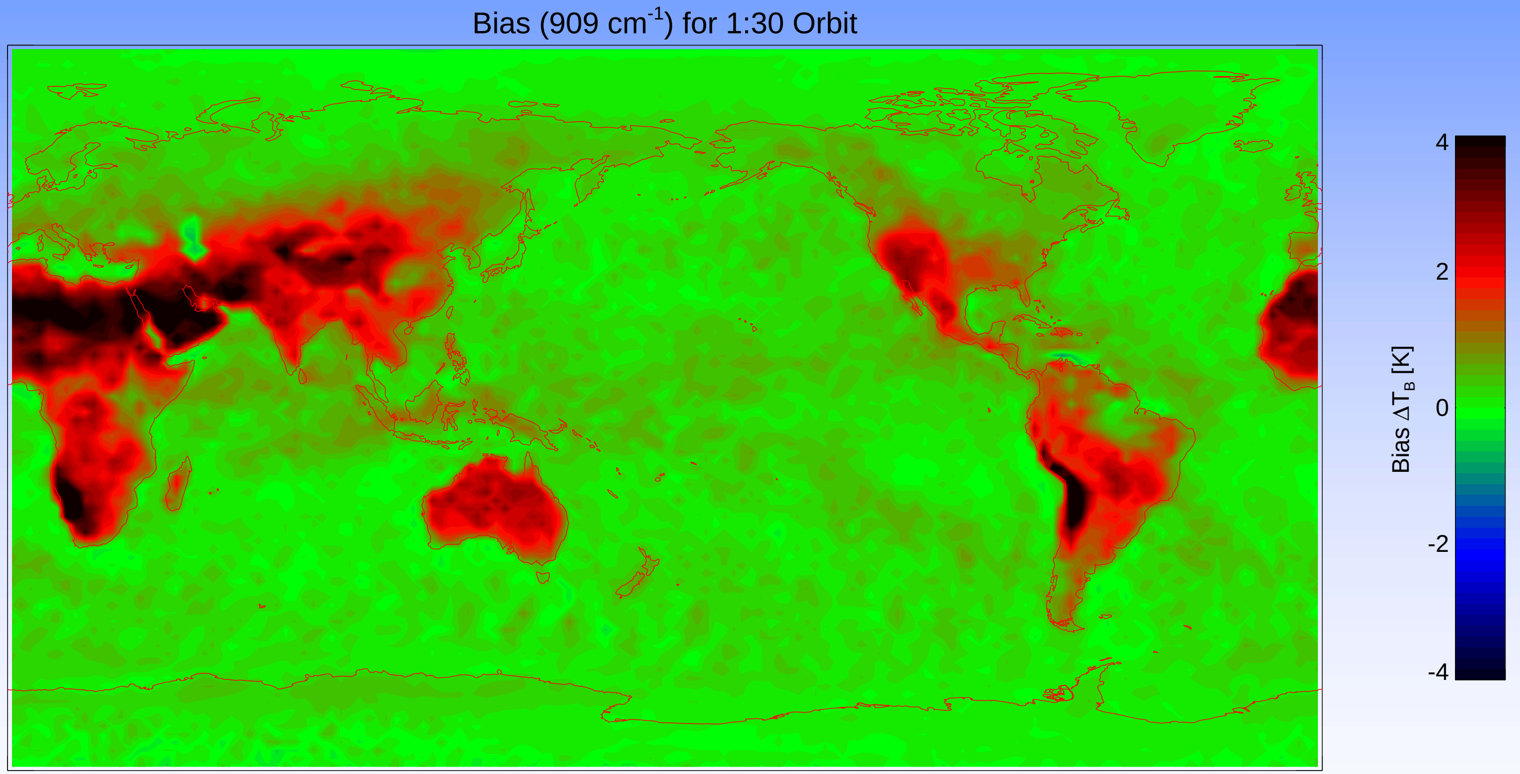
Distinction Between Diurnal and Semidiurnal

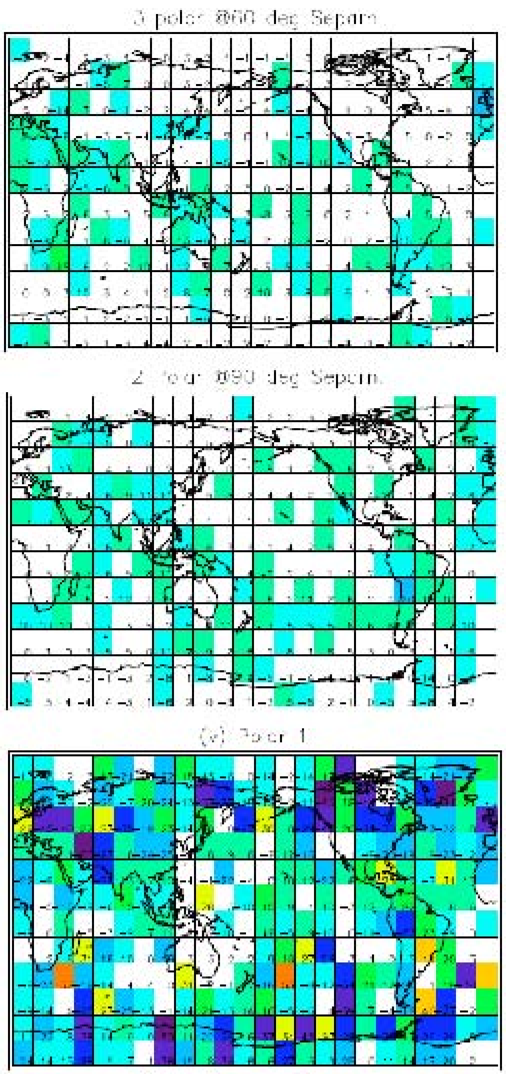


Bias Around the World

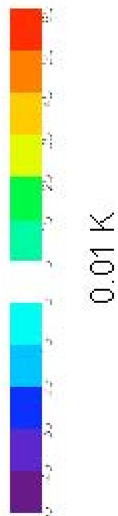


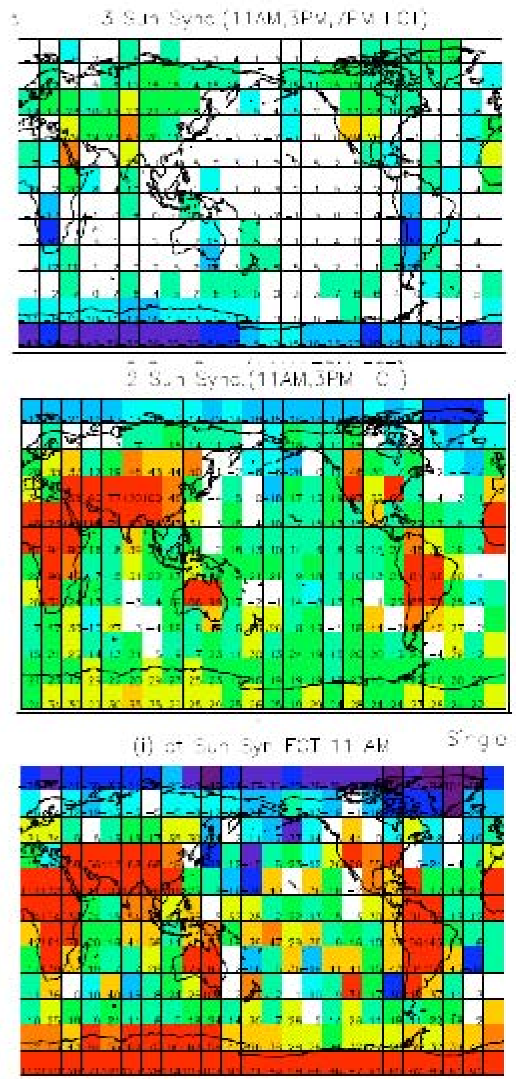
Semidiurnal Cycle Bias (1)





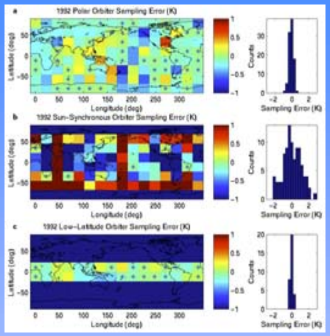
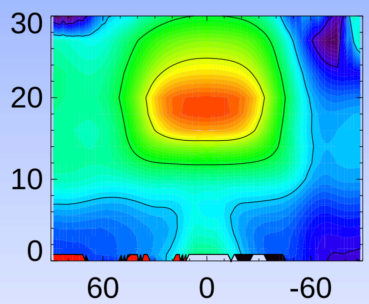
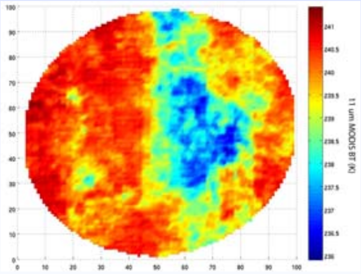
Sampling errors for 90° polar orbits (left) versus sun-synchronous orbits (right), for one, two or three satellites.





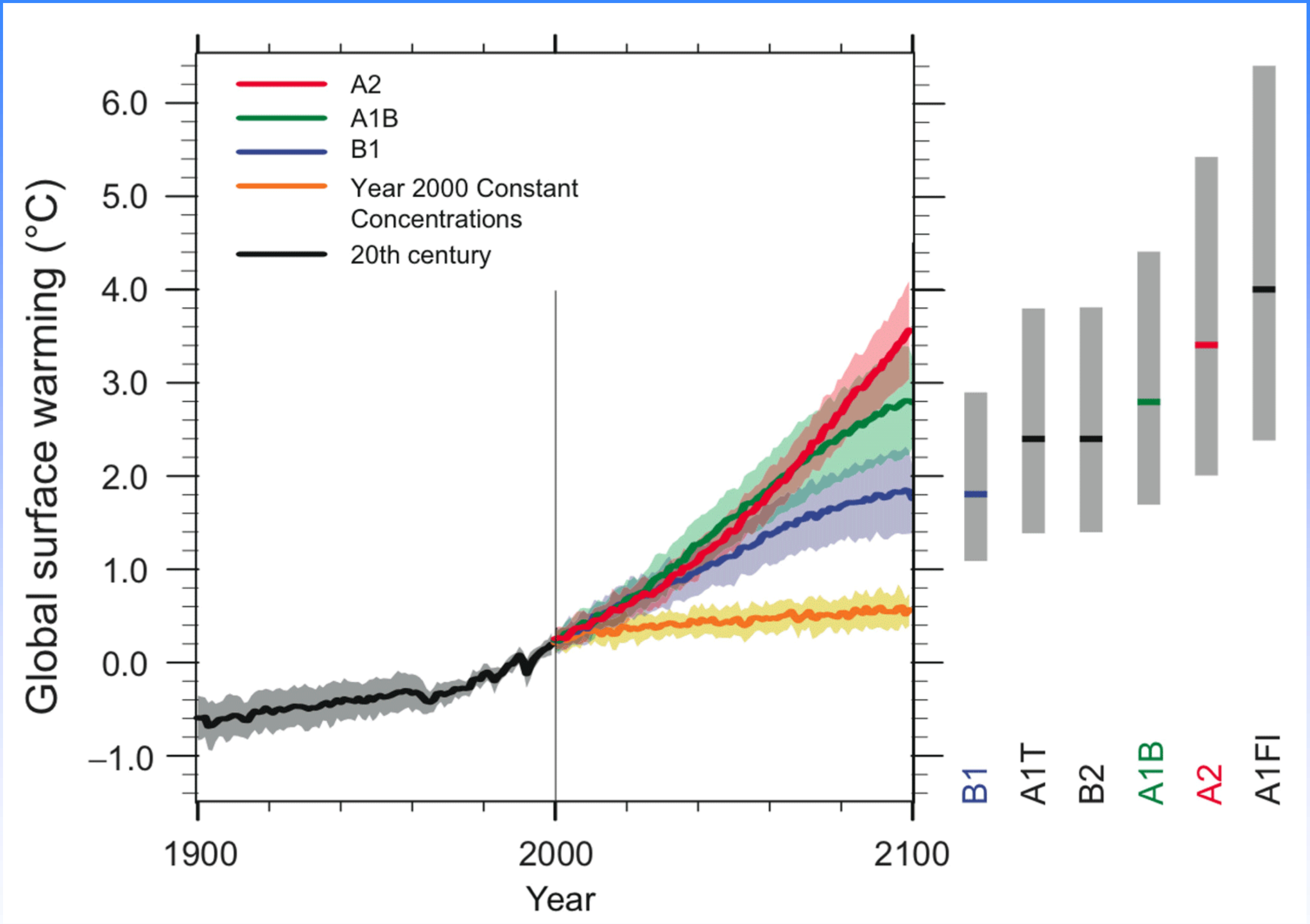
Conclusion

- Semidiurnal component is a critical issue for climate benchmark
- Precessing is important, faster precession is not necessarily better
- Three 90° polar orbits is key to global benchmark observation

Specific Climate Objective	IR/GPS		Publications
Achievement of benchmark accuracy on-orbit: **Sampling/Orbit Selection**	• True polar orbit to sweep diurnal dependence twice each year • Cost constraints on mission such that multiple orbits are used		• Kirk-Davidoff, D., R. Goody and J. Anderson, *J. Climate* **18**(6), 810-22, 2005. • Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004.
Achievement of benchmark accuracy on-orbit: **Overall Systematic Error by Completely Independent Methods**	• Direct overlap of absolute spectrally resolved radiance with GPS • Each with 0.1 K accuracy (absolute)		• Leroy., S., J. Anderson and J. Dykema, pp. 287-301 in *Occultations for Probing Atmosphere and Climate II*, Springer NY, 2006. • Leroy., S., *et al., J. Geophys. Res.* **111** D17105, doi:10.1029/2005JD0006145, 2006.
Calibration of other IR Sounders	• Analysis of sampling bias for simultaneous nadir observations		• Tobin, D.C., *et al., J. Geophys. Res.* **111** D09S02, doi:10.1029/2005JD006094, 2006. • Tobin, D.C., *et al., J. Geophys. Res.* **104** (D2), 2081-92, 1999. • Kirk-Davidoff, D., R. Goody and J. Anderson, *J. Climate* **18**(6), 810-22, 2005.

Conclusions: High Level Requirements

- High level requirements that emerge:
  - Orbits: Three 90° polar orbits spaced by 60° in orbital plane are required. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases.
  - Achievement of SI traceability (absolute) on-orbit: Redundant and fully independent determination of each variable of quantitative significance to the error budget dictates the selected instrument architecture and the choice of independent on-orbit observations.
  - For the separation of climate forcing and response—critical both for the climate record and for systematic testing of climate forecasts—absolute spectrally resolved radiance in the thermal infrared and GPS radio occultation constitute the foundation of the benchmark climate record.



Global surface warming (°C)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
A2
A1B
B1
Year 2000 Constant Concentrations
20th century
1900
2000
2100
Year
B1
A1T
B2
A1B
A2
A1FI

Testing Climate Models

Response = Forcing × Sensitivity

$$\Delta T = \Delta F_{\mathrm{rad}} \times \left(\Gamma - \sum_i \gamma_i^{\mathrm{LW}} - \sum_i \gamma_i^{\mathrm{SW}} \right)^{-1}$$

$$\Gamma = \Delta F_{\mathrm{RAD}} / \Delta T$$

Planck response to radiative forcing ΔF_{RAD}

Stefan - Boltzmann

$$F = \varepsilon \sigma T^4$$

$$\Delta F_{\mathrm{RAD}} / \Delta T = 4 \varepsilon \sigma T^3 = \Gamma$$

$$\gamma_i = \left(\frac{\partial F}{\partial x_i} \right) \left(\frac{d x_i}{d T} \right)$$

γ_1 = 1.7 w/m^2-K (water vapor)
γ_2 = –0.3 w/m^2-K (lapse rate)
γ_3 = 0.5 w/m^2-K (clouds)
γ_4 = 0.5 w/m^2-K (surface albedo in cryosphere)

Testing Climate Models

Response = Forcing × Sensitivity

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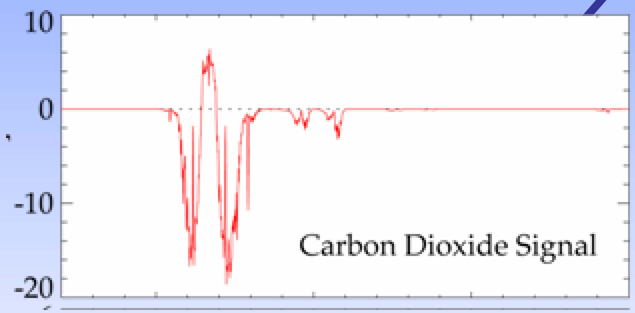

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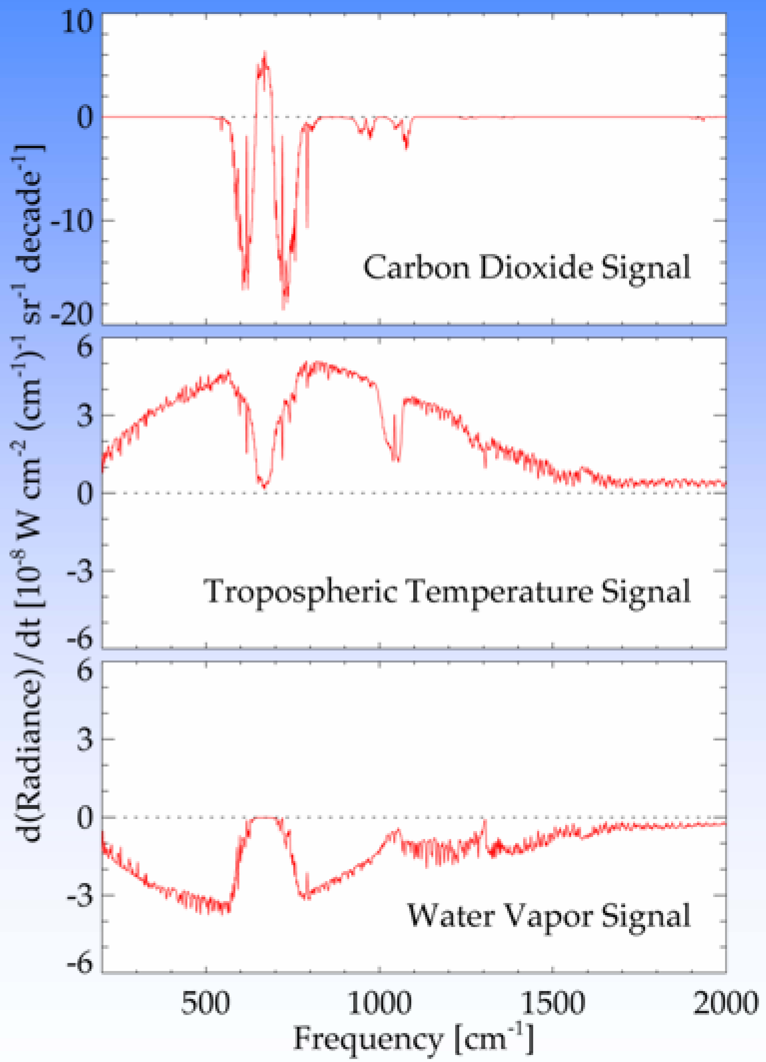
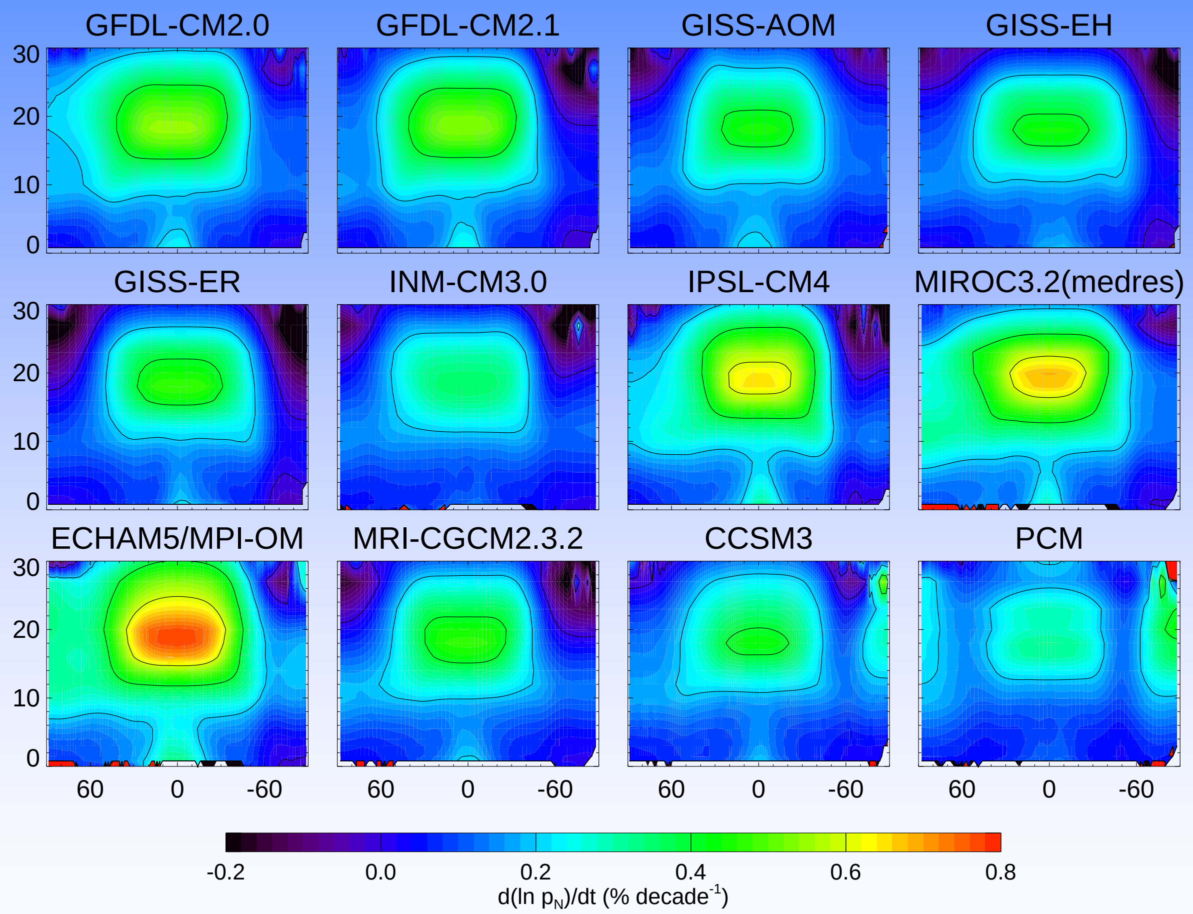
Information in Infrared



Obtain part of feedbacks

$$\gamma_i = \left(\frac{\partial F}{\partial x_i}\right)\frac{dx_i}{dt} \times \left(\frac{dT}{dt}\right)^{-1}$$

Information in GPS Occultation



Obtain climate "response" by observing jet stream migration, widening of Hadley cell, expansion of troposphere.

Obtain response to 10% uncertainty in 29 years (SRES-A1B).

$$\gamma_i = \left(\frac{\partial F}{\partial x_i}\right)\frac{dx_i}{dt} \times \left(\frac{dT}{dt}\right)^{-1}$$

Example from Haskins *et al.* (1999) Considered IRIS data in various geographic regions

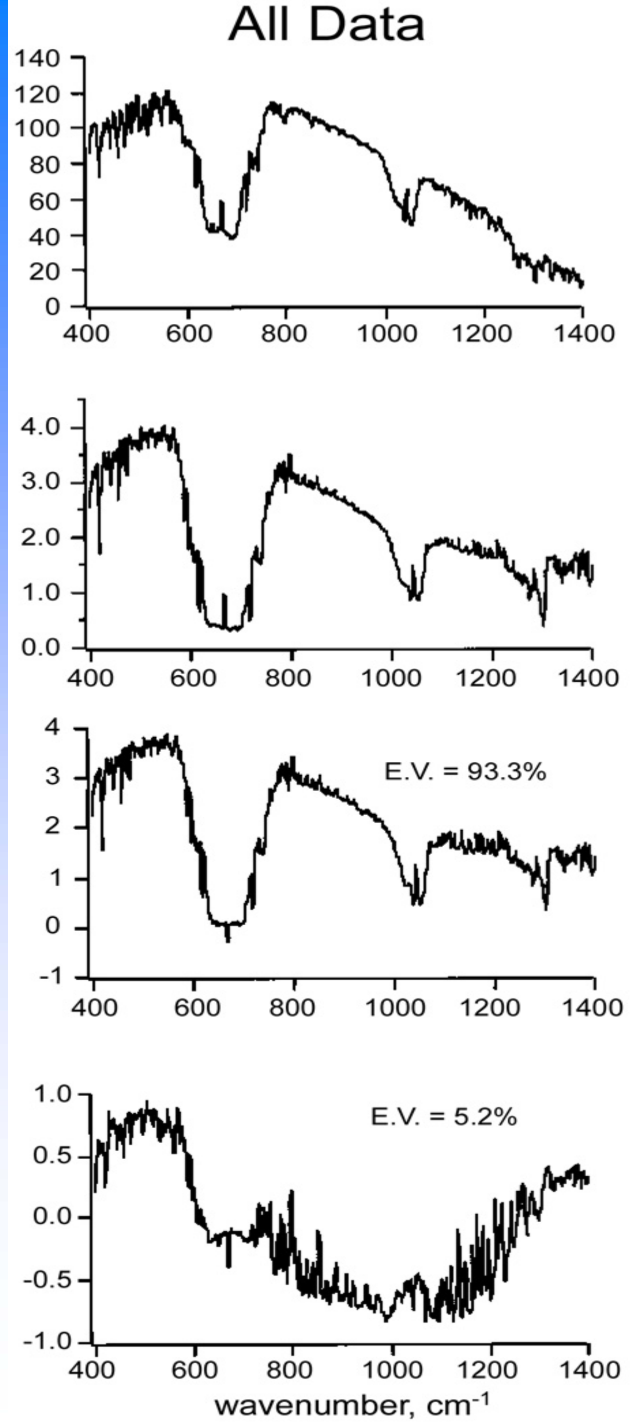
- IRIS data for Central Pacific, 9872 Spectra
  Elements in Jacobian calculated from differences between two spectra—one calculated before, one after a change of a parameter by a given amount in a given layer
  - Relative humidity: W2, W4, W6, W8 ,W12, W16
  - Temperature: T2, T4, T6, T8, T12, T16, T30, T40
  - Cloud fraction: C4, C8, C12, C16
- These Principal Components have clear signature

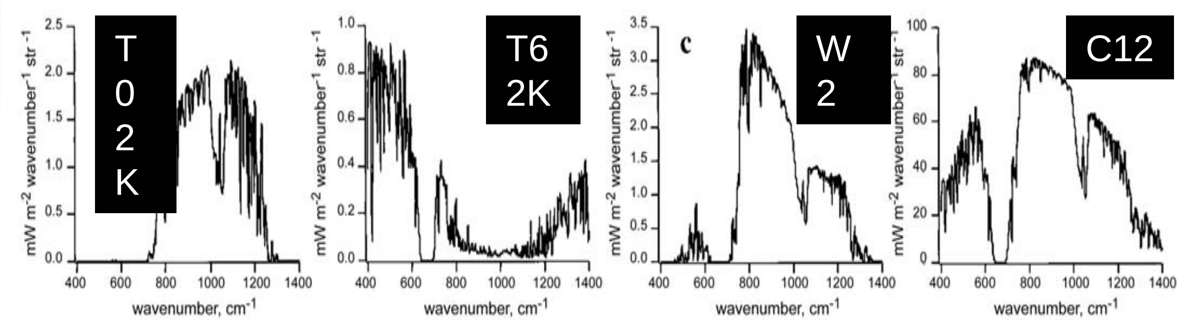
I_ν

σ

PC^1

PC^2





Optimal Fingerprinting

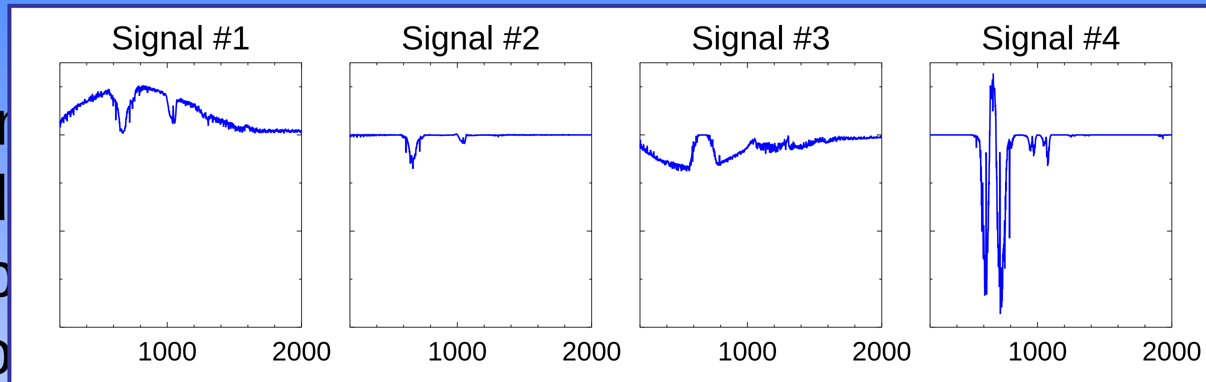
Find signal amplitudes (α_m) and uncertainty (Σ_α) in a data set (**d**) according to the signals' patterns ($\mathbf{s}_i$) against a background of natural variability, the eigenvectors and eigenvalues of which are $\mathbf{e}_\mu$ and λ_μ.

$$\begin{aligned} \boldsymbol{\alpha}_m &= \mathbf{G}^{-1}\mathbf{h} \\ \boldsymbol{\Sigma}_\alpha &= \mathbf{G}^{-1} \end{aligned}$$

$$\begin{aligned} h_i &= \sum_{\mu=1}^{k} \lambda_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{d} \rangle \\ G_{i,j} &= \sum_{\mu=1}^{k} \lambda_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{s}_j \rangle \end{aligned}$$

Optimal Fingerprinting

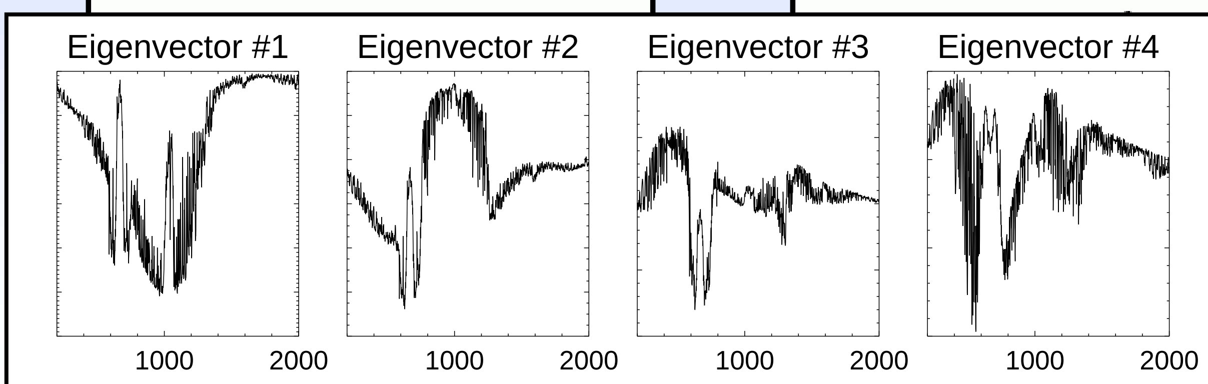
Find signal ar
data set (**d**
against a b
eigenvecto

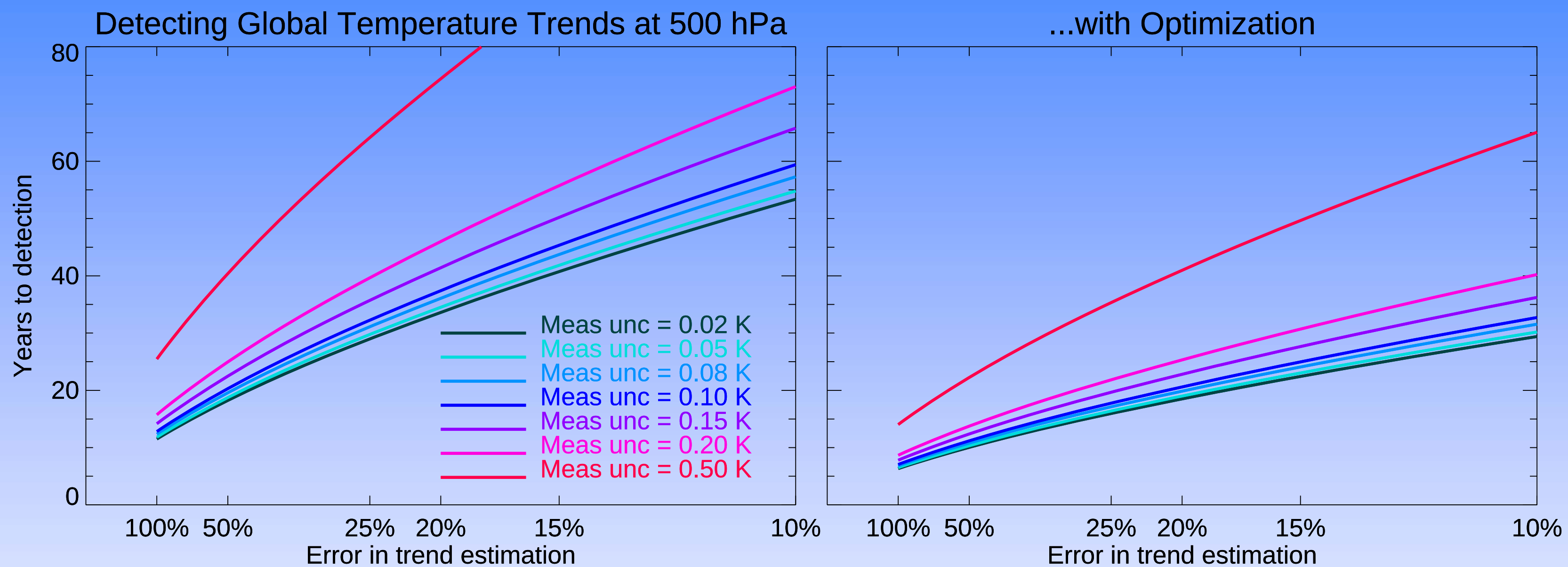


$$\boldsymbol{\alpha}_m = \mathbf{G}^{-1}\mathbf{h}$$

$$h_i = \sum_{\mu=1}^{k} \lambda_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{d} \rangle$$

$$\ldots {}_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{s}_j \rangle$$





Testing for human influence

Testing climate models

Testing for human influence

Testing climate models

Climate OSSE: The Science of a Benchmark

Benchmark Measurement

- Traceable to international standards
- Minimize sampling error

Climate OSSE

- Simulate trends in observable as produced by different models
- Explore information content with various contravariant fingerprints

Climate Uncertainty

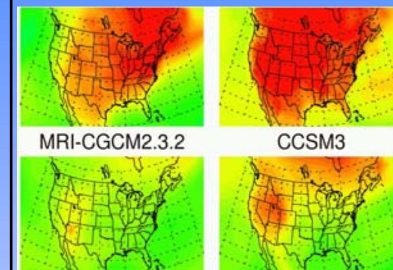
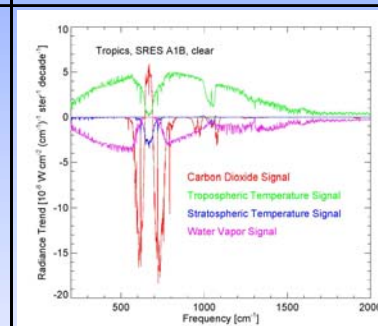
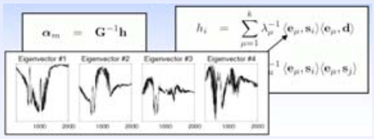
- Shortwave forcing
- Longwave forcing
- Climate feedbacks & processes
- Sensitivity & meteorology

Climate OSSE Results

- Detection time and accuracy requirements
- How measurement constrains climate predictability
- Information content: Relative redundancy with other benchmark data types

Conclusions

- Absolute Spectrally Resolved Radiance (ASRR) in the IR in Combination with GPS Constitute a Powerful Observational Foundation for far more Stringent Tests of Climate Forecast Models
- The Systematic Testing and Improvement of Decadal Climate Forecast Models is Mathematically Linked to the Data Vectors Provided by ASRR and GPS such that Both Trends and the Gain Terms in Climate Feedback can be Observed.
- Optimal Fingerprinting Provides both the Optimization of Time-to-Detect and a Quantitative Measure of the S/N Ratio of that Determination

Specific Climate Objective	IR/GPS		Publications
Testing climate forecast models: **Accuracy for Global and Regional Trends**	• Use of high accuracy radiance differences for selected 4AR models		• Anderson, J.G., *et al., J. Quant. Spectrosc. & Rad. Transf.* **85**, 367-83, May 15, 2004. • Leroy, S., *et al.,* Testing climate models using thermal infrared spectra, *J. Climate*, in press, 2008.
Testing climate forecast models: **Observation of Climate Feedbacks**	• Spectral resolution with decomposition into forcing and response • Direct observation of Partial Derivatives		• Leroy, S., *et al.,* Testing climate models using thermal infrared spectra, *J. Climate*, in press, 2008.
Testing climate forecast models: **Optimal Fingerprinting**	• Optimization using projection of signal shape on eigenmodes of natural variability		• Leroy, S., J. Anderson and J. Dykema, pp. 287-301 in *Occultations for Probing Atmosphere and Climate II*, Springer NY, 2006.

End Here

Summary of Conclusions

1. Using CLARREO FOVs with spatial standard deviations less than 3K, the uncertainty in the monthly mean brightness temperature differences (CLARREO minus IASI, CLARREO minus CrIS) due to differences in spatial and temporal sampling are less than 0.02 K.

2. To meet a monthly inter-calibration accuracy of 0.1 K 3σ, the maximum allowable instrument noise for individual CLARREO FOV is approximately 0.6 K, with no assumed spectral averaging. This assumes single channel calibration with no noise filtering or spectral averaging and three CLARREO satellites with sampling frequency of 10 seconds

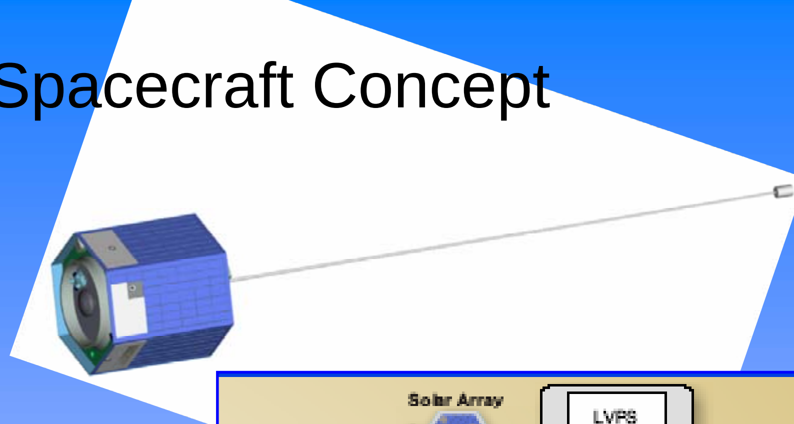
3. The number of usable monthly CLARREO Fields of view (BT STD < 2 K and 10 second sampling) during 2006 does not vary significantly by month with the number of FOV between 400–500. As result, the monthly CLARREO noise requirement (0.6 K) for intercalibration remains consistent during the year.

Conclusions for Establishing the Benchmark Climate Record

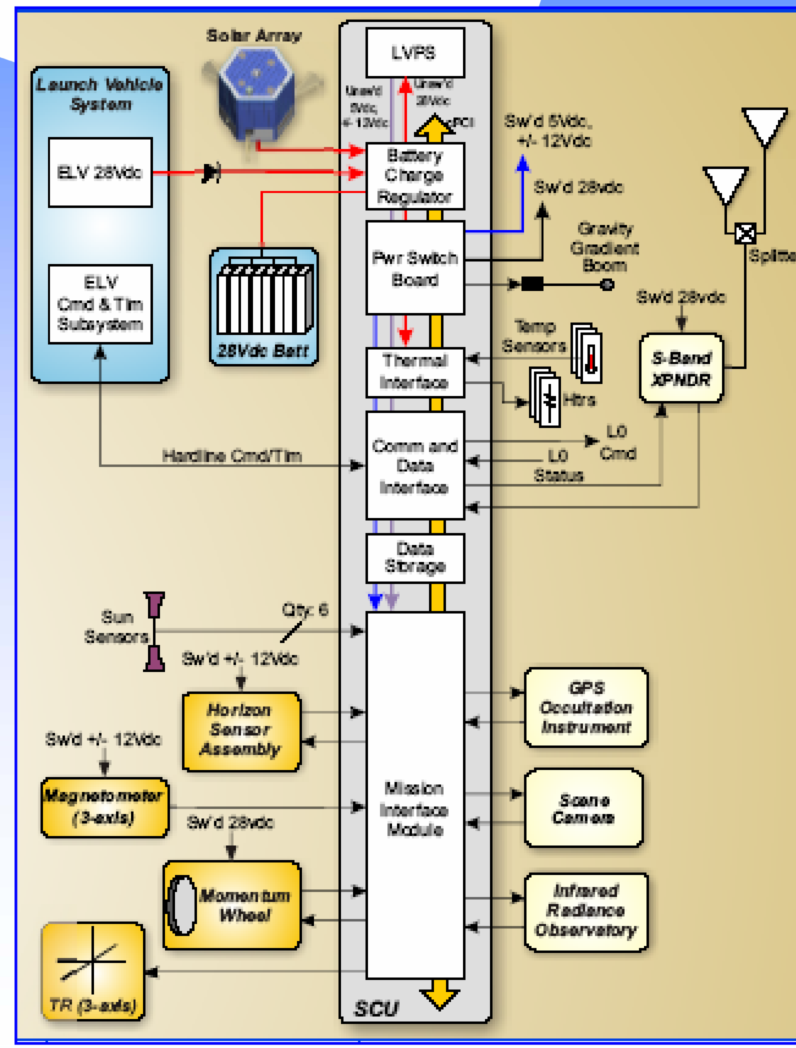
– Orbits: Three 90° polar orbits spaced by 60° in orbital plane are recommended. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases.

– The best strategy for the objective of intercalibrating of other IR sounders is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains.

CLARREO Spacecraft Concept



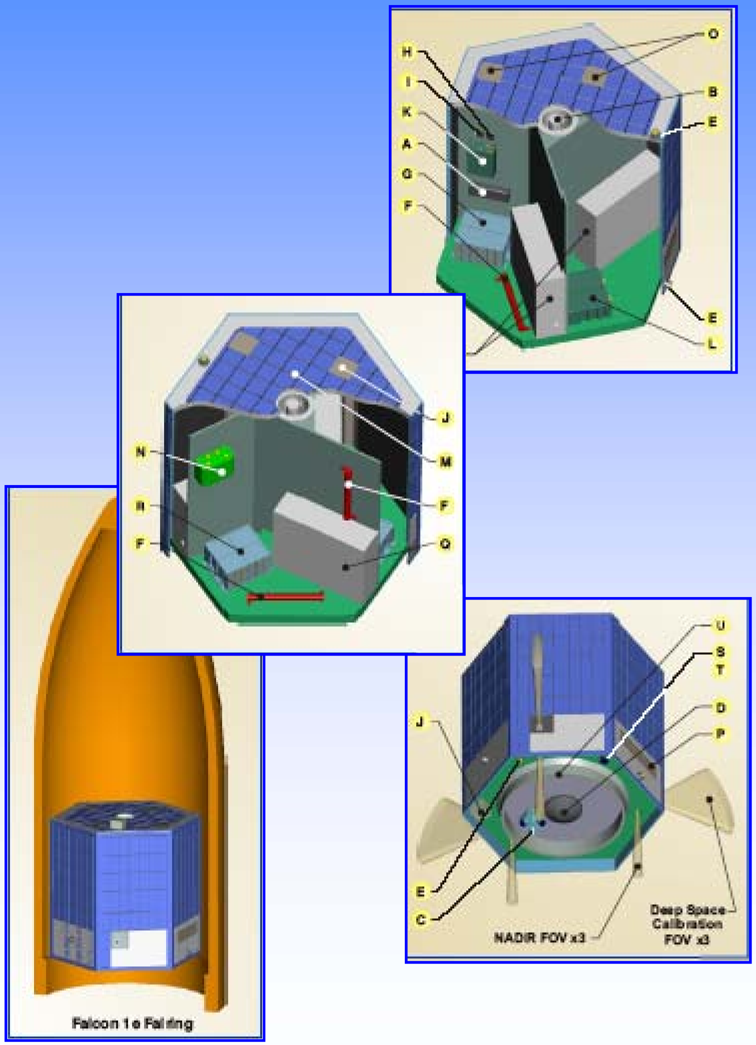
- Launch and Orbit
  - SpaceX Falcon 1e
  - 750km circular, 90deg inclination
  - 30krad TID
- Mechanical
  - 122cm-dia x 129cm (launch) Al honeycomb
  - 124.7kg
  - Passive thermal control
  - Isolated Instrument interface
- Electrical Power
  - 255W rigid body mount S/A
  - 10.5A-hr Li-ion battery
- Communication and Data
  - 16MIP computer
  - 512Mbyte data storage
  - S-band CCSDS 2.5Mbps data downlink
- Attitude
  - Knowledge: 0.2deg GPS with Horizon Sensor, Mag, CSS backup
  - Control: Gravity gradient pitch/roll with momentum biased yaw



All EPS, CDS, and ADCS components have flight heritage

Robust Margins Exist In All Subsystems

- Mechanical
  - Fairing volume margin
    - 27% (girth)
    - 36% (non-tapering height)
  - 217% launch mass margin
- Electrical Power
  - 27% (EOL) Power Margin
  - 13.2% (EOL) Battery DOD
- Communication and Data
  - 7.5dB Science downlink margin
  - 26.4dB Status downlink margin
  - 44.4dB Uplink margin
  - 24hr data storage margin
- Attitude
  - 0.2deg knowledge (3-axis)
  - 1.5deg control (3-axis)
- Fault Protection
  - Gravity-gradient stabilized
  - Full body S/A (nadir exception)
  - Selective redundancy in ADCS, thermal, and power



Mission and Payload

- The mission is built upon three satellites, each of which requires a specific orbit, and each of which includes an occultation GNSS receiver. In the first category of climate benchmark radiance measurements, two of the satellites contain redundant interferometers that have a spectral resolution of 1 cm^{-1}, and encompass the thermal infrared from 200 to 2000 cm^{-1}, are in true 90° polar orbits to provide a full scan of the diurnal harmonics as well as high latitude coverage from low Earth orbit,

- The components of the CLARREO mission include (1) two small satellites to obtain absolute, spectrally resolved radiance in the thermal IR and a GPS receiver; (2) a third small satellite to continue the IR absolute spectrally resolved radiance measurements but with the addition of benchmark observations to obtain the reflected solar irradiance and a GPS receiver; and (3) re-flight of the incident solar irradiance and CERES broadband instruments on NPP and NPOESS

Conclusions: First Order Objectives

- First order objective is to initiate a new generation of high accuracy, SI traceable on-orbit, climate benchmark measurements that will be continued in perpetuity, systematically improved and open for cross check and verification.
- A closely associated primary objective is the testing and systematic improvements of climate forecast models using a strategic balance between prioritization of new benchmark climate observations and mathematical tools that link those observations to climate forecast model testing.
- It is expected that by achieving high accuracy (absolute) and by a strategic combination of satellite orbits a combined measurement and sampling uncertainty (< 0.1 K 2σ brightness temperature for $15^\circ \times 30^\circ$ latitude/longitude regional, annual mean) that the long-term trend can be definitively separated from more rapid variations in the 10–20 year time frame.
  - The best strategy for the objective of intercalibrating of other IR sounders is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains.

Conclusions: Requirements for Instrument Architecture

- SI traceable, absolute calibration on orbit, by the logic of fundamental metrology, requires the determination of systematic error on-orbit. Determination of systematic error in turn requires an independent determination of each term in the error budget. For the determination of absolute spectrally resolved radiance in the thermal infrared this requires:
  - Redundant spectrometers on-orbit to reveal systematic errors
  - Absolute thermometry such as the phase transition of an element embedded in multiple blackbodies for each spectrometer
  - Direct determination of blackbody emissivity
  - Direct determination of instrument line shape applicable across the spectrum
  - Direct measurement of instrument polarization
  - Detector chain linearity determination
  - Foundation of continuous calibration of flight subsystems against NIST primary infrared standards and evaluation of flight blackbodies in NIST facilities

Conclusions: Specific Instrument Requirements

- **Spectrometer Design**: Fourier transform spectrometer. This requirement follows from the need for simplicity, broad nyquist sampled spectral coverage, redundant spectrometers on the same spacecraft, instrument line shape determination across the full spectrum, polarization determination.

- **Spatial Footprint and Angular Sampling**: Order of 50-100 km, nadir viewing only

- **Spectral Resolution and Sampling**: Order 1 cm^{-1} with nyquist sampling across interferogram

- **Spectral Range**: 200-3000 cm^{-1} the spectrum coverage is meant to include broad coverage of key parts of the infrared spectrum that contain significant information about the state of the atmosphere and that can be observed with high accuracy.

- **Pointing Accuracy and Knowledge**: Within 5° of nadir; < 0.1° uncertainty

- **Temporal Resolution and Sampling**: < 15 sec resolution and < 60 sec intervals

Conclusions: Specific Instrument Requirements (continued)

- **Detectors**: Chosen to meet NEΔT requirements with high level of linearity. Unlike most applications, detector sensitivity is not a major issue for this application. Many samples will be averaged, making noise requirements reasonably easy to achieve using pyroelectric detectors for 200 to 1200 cm^{-1}, photovoltaic MCT for 650 to 2000 and sandwiches InSb from 1825 $\rightarrow$ 3000 cm^{-1}

- **Blackbody Design**: Two blackbodies for each spectrometer, plus deep space view. Each blackbody equipped with phase transition cells for a range of absolute temperatures and direct emissivity measurements on-orbit. One of the blackbodies would be a warm blackbody references (~ 300 K); one would be a variable temperature with a range 200-320 K.

- **On-Orbit Performance Characterization**: Absolute temperature, cavity emissivity, instrument line shape, linearity, polarization, stray light

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