Emerging Science Applications of Measurements from GPS/GNSS and GPS-like Signals: Recent Results and Future Possibilities

NOAA/GCOS Workshop to Define Climate Requirements
for Upper-Air Observations
February 9, 2005

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John Dykema
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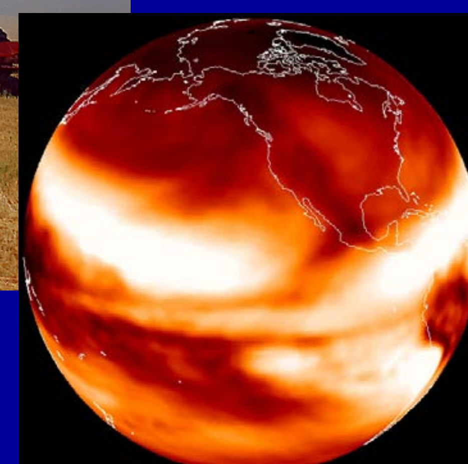
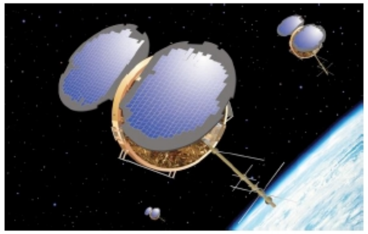
Societal Objectives

Climate monitoring must derive from societal objectives as stated in CCSP reports, NRC NASA decadal report, etc.

- Need to monitor geophysical variables relevant to economies and human welfare (precipitation, sea level, etc.)
- Need for credible climate forecasting ability



AGU Workshop Topics



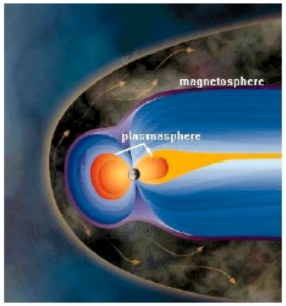
Emerging Science Applications Of Measurements From GPS/GNSS And GPS-like Signals: Recent Results And Future Possibilities

Date:	Thursday, December 16, 2004
Time:	7:00PM to 10:00PM
Location:	San Francisco Marriott 55 Fourth Street San Francisco, CA 94103 415-896-1600 Golden Gate A Room
Contact people:	Cinzia.Zuffada@jpl.nasa.gov James.Zumberge@jpl.nasa.gov

Workshop chair:Jim Anderson (anderson@huarp.harvard.edu).

Discipline-specific discussion leads:

Atmosphere/climate:	Stephen Leroy	leroy@huarp.harvard.edu
Ionosphere:	Paul Kintner	paul@ece.cornell.edu
Oceanography/Hydr		



Agenda:

7:00 - 7:10	Welcome a
7:10 - 7:40	Participant
7:40 - 8:10	Atmosphe
8:10 - 8:20	Break
8:20 - 8:50	Ionospher
8:50 - 9:20	Oceanogra
9:20 - 9:40	Action iten
9:40 - 10:00	Programm

Workshop on Emerging Science Applications of Measurements from GPS/GNSS and GPS-like Signals: Recent Results and Future Possibilities

J. Anderson, Y. Chao, P. Kintner, S. Leroy, C. Zuffada, and J. Zumberge

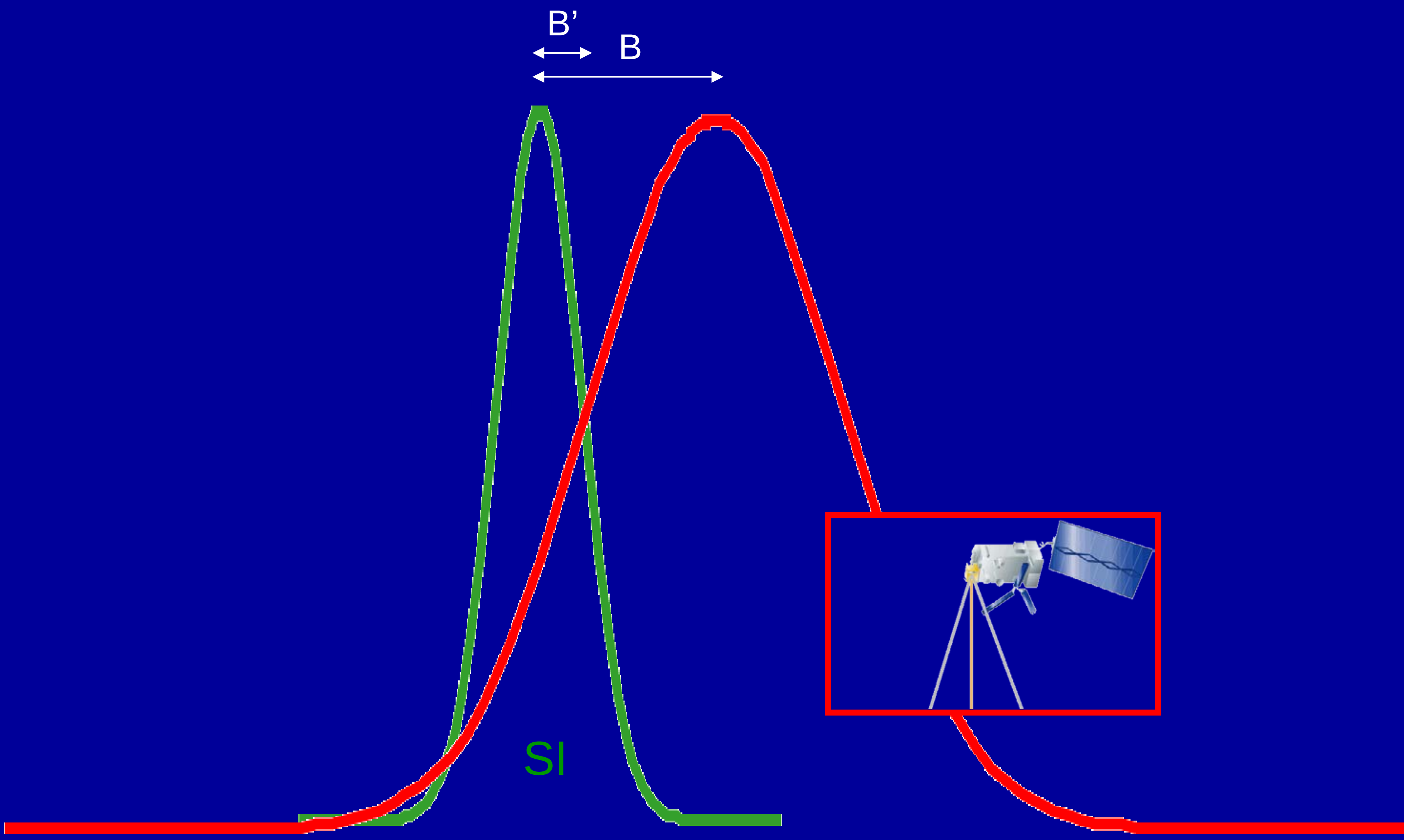
Program directions

It is now recognized that key societal objectives underpin the NOAA and NASA research and applications programs engaging Earth system change and climate studies and that the U.S. program is rapidly evolving in response to the imperative for high accuracy observations that are capable of providing accurate records in perpetuity. The U.S. Climate Change Science Program (CCSP) (http://www.climatescience.gov/) states the program objectives in terms of five hierarchical goals: Goal 1, "Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change"; Goal 2, "Improve quantification of the forces bringing about changes in the Earth's climate and related systems"; Goal 3, " Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future"; Goal 4, "Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes"; Goal 5, "Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change."

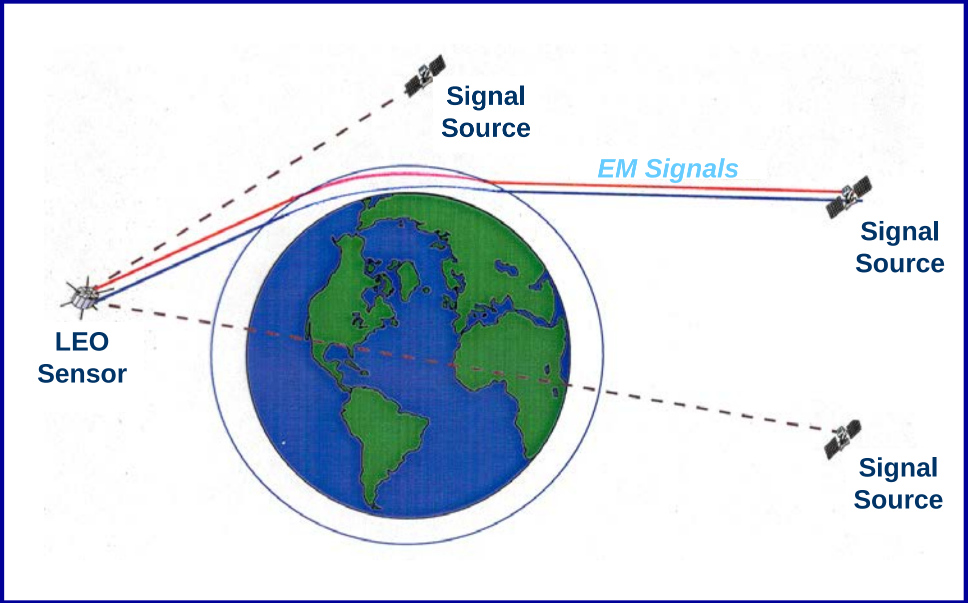
Climate Benchmarks: Why are they needed?

- Provide record of absolute values of key climate observations valid for all time
- Focus on accuracy referenced by independent methods to absolute standards
- Critical distinction between accuracy and precision
  - Accuracy: The measure of how close the result of the experiment comes to the "true" values
  - Precision: The measure of how exactly the result is determined without reference to any "true" value
- The importance of independent crosschecks; the importance of redundancy; the importance of transparency

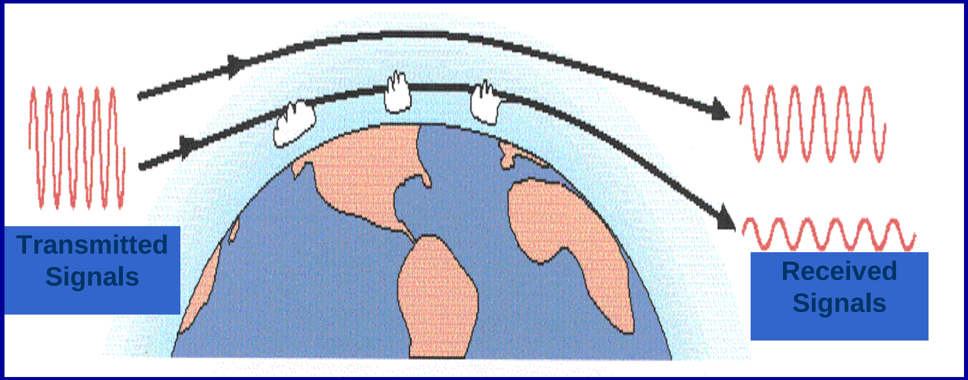
Accuracy and Precision



Global Climate Benchmark Measurements
Occultation methods: How they work



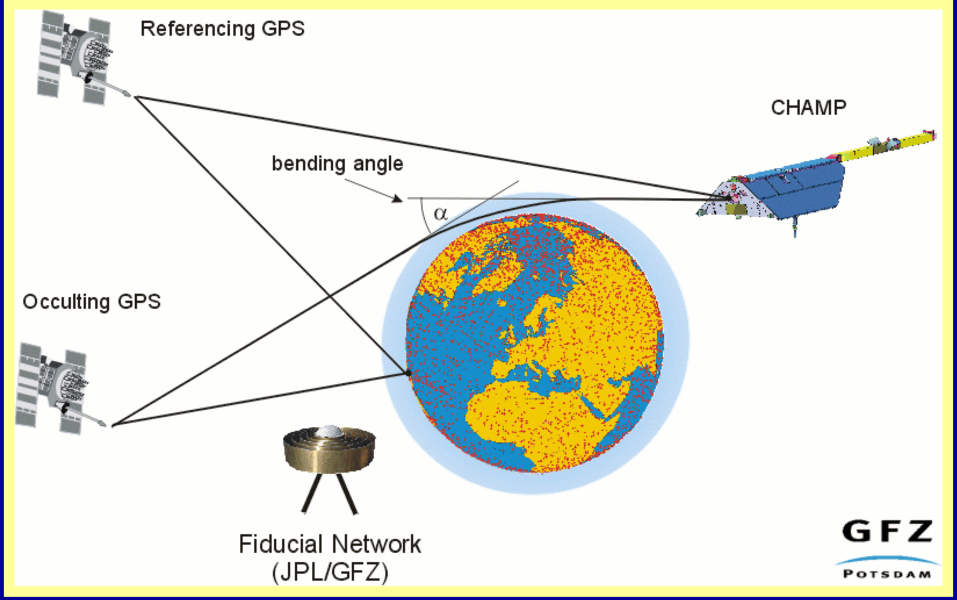
[Basic figures from D. Feng, Univ. of Arizona, private communications, 2001 (modified)]



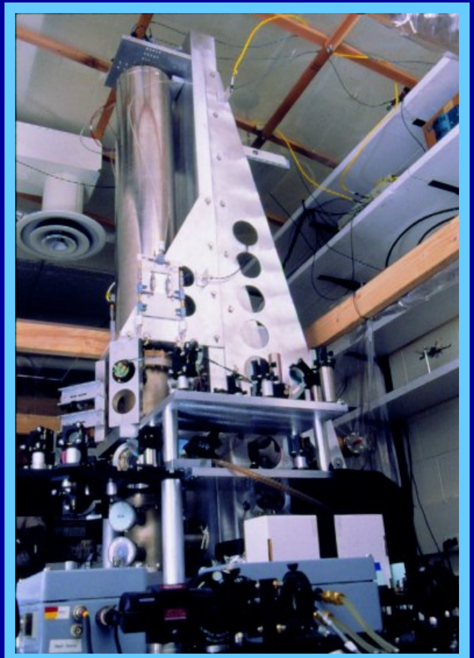
Occultation methods

- Exploit extinction and/or refraction of electromagnetic signals along limb paths
- Providing <u>self-calibrated measurements</u> of transmission and/or Doppler shift profiles
- Leading via opt. thickness or column density, bending angle, and (complex) refractivity
- To key atmospheric and climate parameters such as temperature, humidity, ozone, and geopotential height (among others)

GPS Occultation: The Time Standard



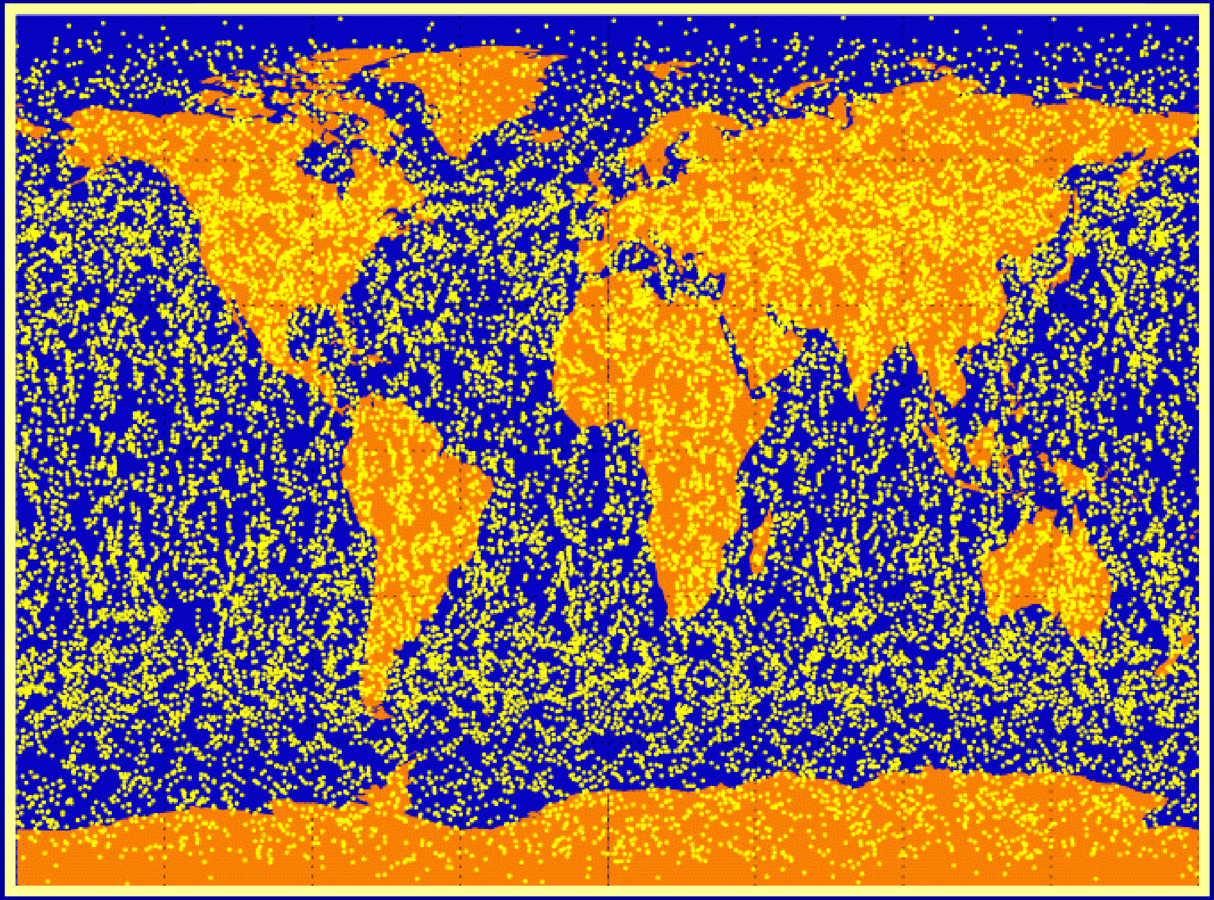
- GPS occultation is tied to ground-based atomic clock standards by double-differencing technique.
- NIST F1 measures time with fractional error of $1.7 \cdot 10^{-15}$ (as of 1999).



Critical Advantages of GPS

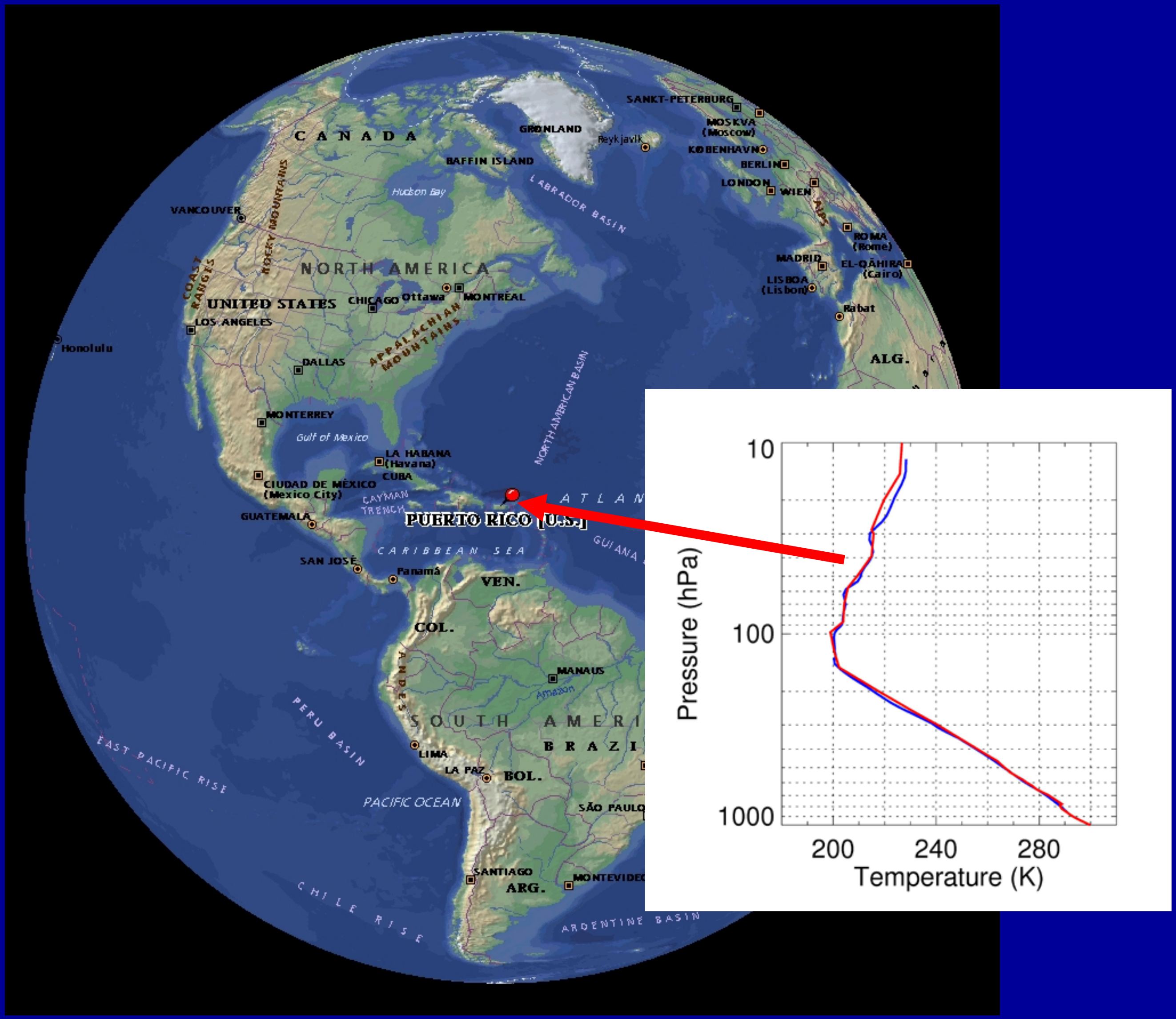
1. Absolute calibration: GPS occultation is based on a timing measurement using atomic clocks
2. Diurnal cycle coverage with compelling cost effectiveness
3. Unambiguous retrieval of temperature, from mid-troposphere up, with ~ 100 m resolution, meaning capability to observe tropopause temperature globally
4. All-weather capability: Insensitive to clouds
5. Insensitive to instrument generation: absolute record in perpetuity

COSMIC

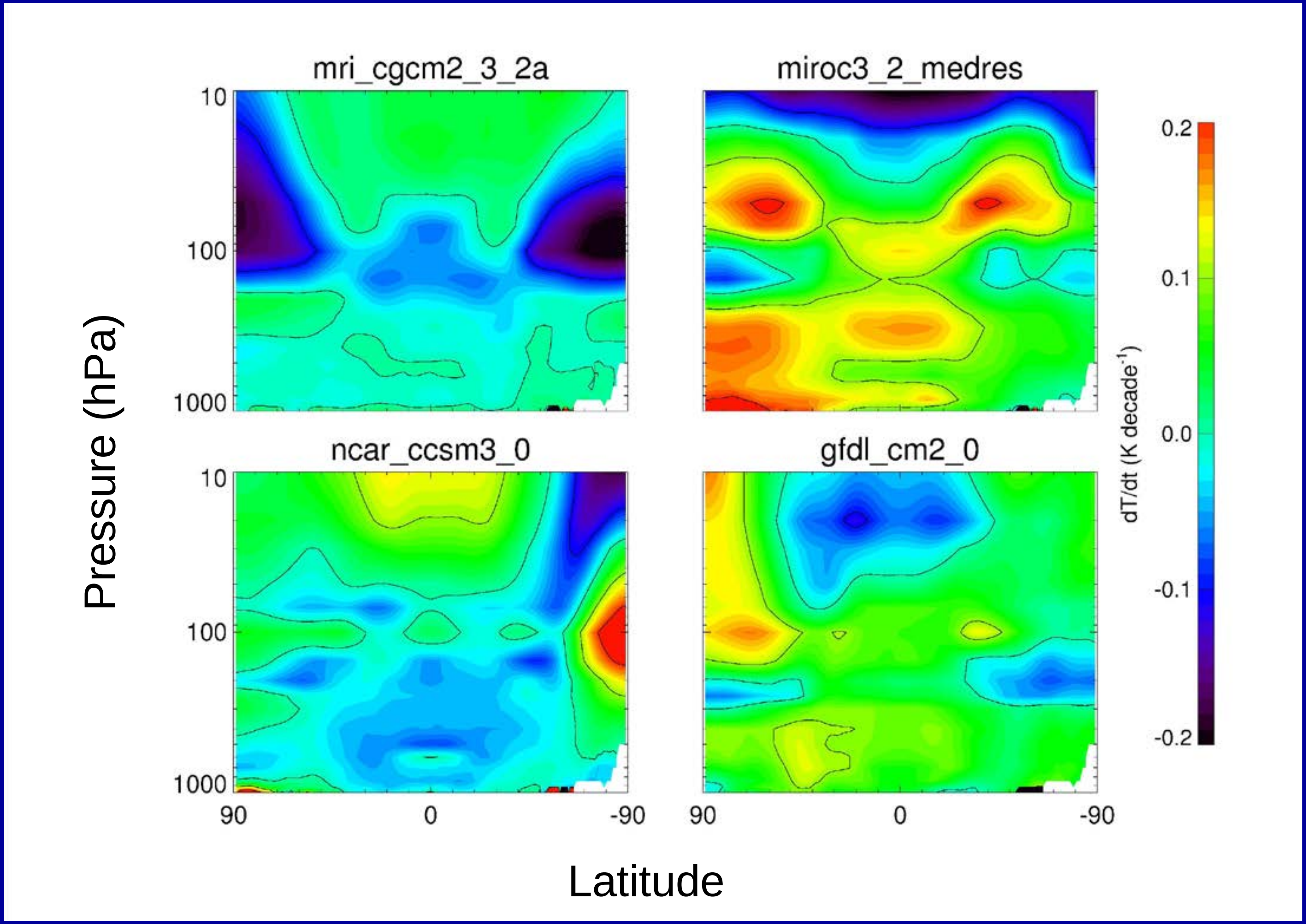


- Six satellites in three 72° orbit planes
- > 3000 soundings per day
- Launch in 2005
- Taiwan, NSF (UCAR)

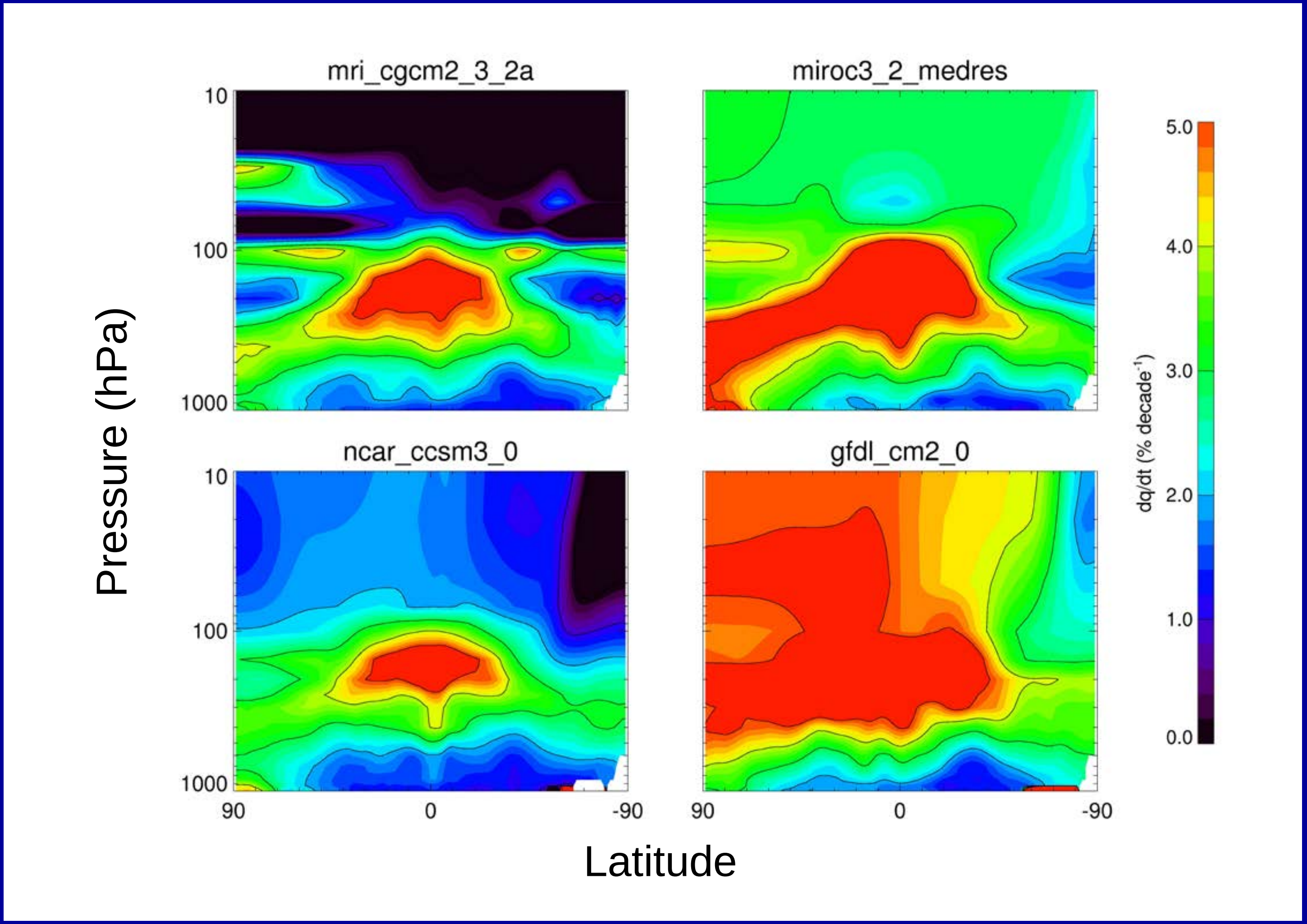
Radiosondes and GPS Occultation



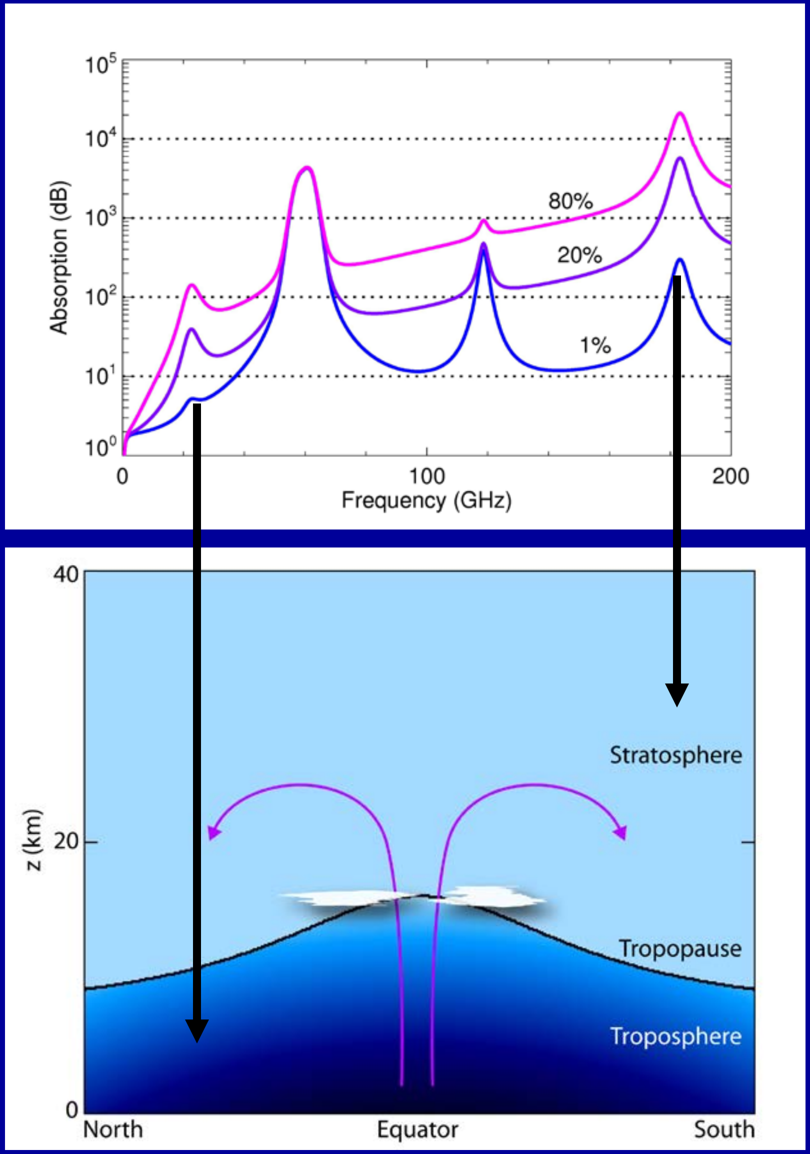
IPCC 4AR dT/dt: Difference Between Model Forecasts



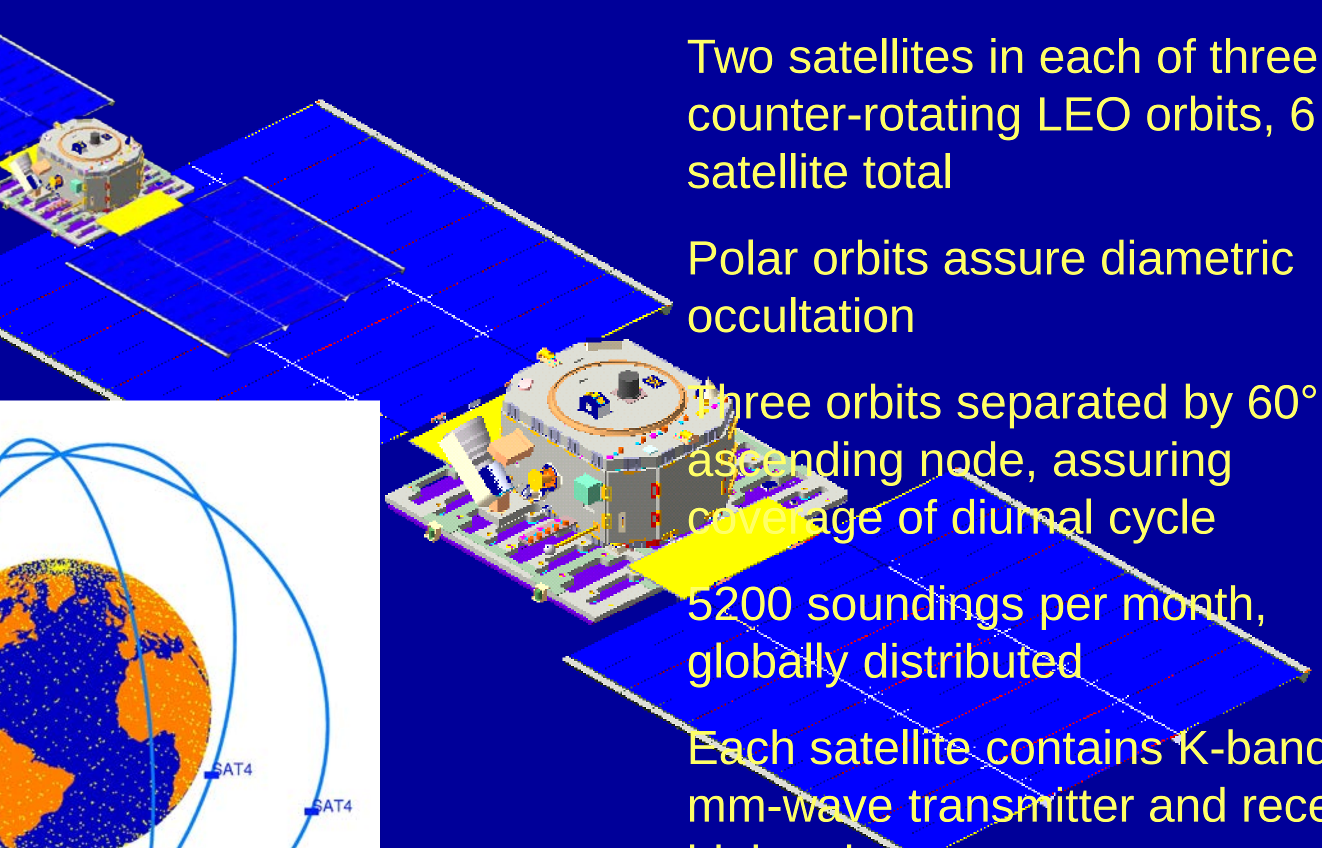
IPCC 4AR dq/dt: Difference Between Model Forecasts



Absorptive Radio Occultation: Millimeter-wave Spectrum



Cross-link: Technical Configuration



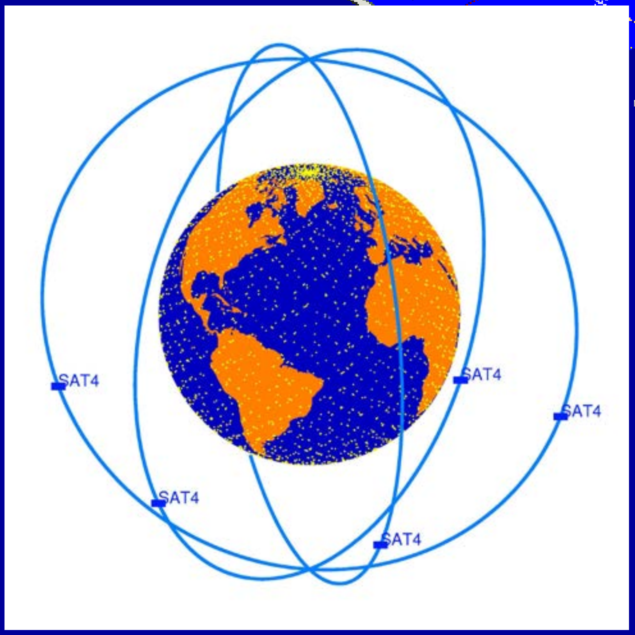
Two satellites in each of three counter-rotating LEO orbits, 6 satellite total

Polar orbits assure diametric occultation

Three orbits separated by 60° in ascending node, assuring coverage of diurnal cycle

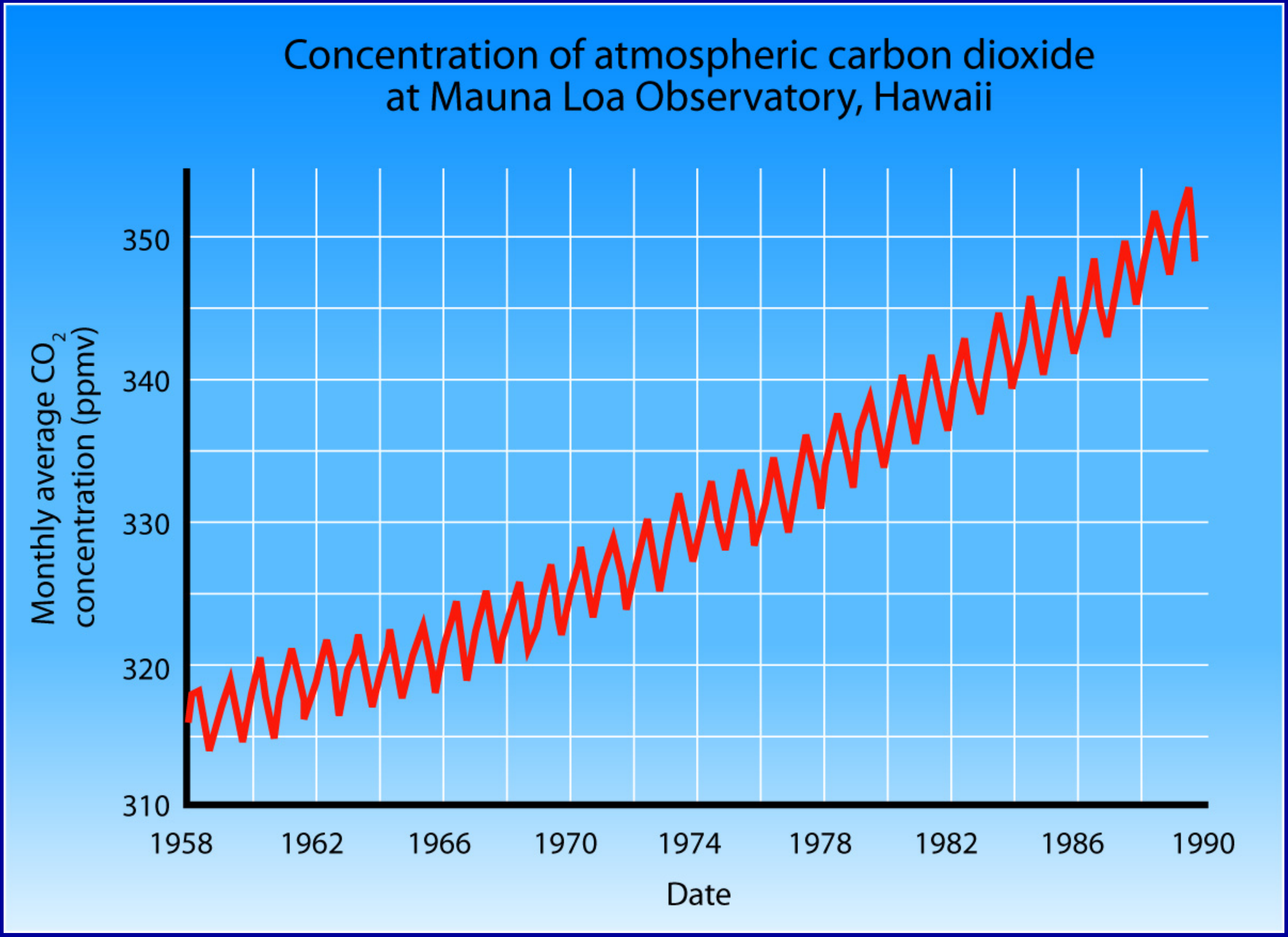
5200 soundings per month, globally distributed

Each satellite contains K-band and mm-wave transmitter and receiver, high gain array antennas, precision pointing

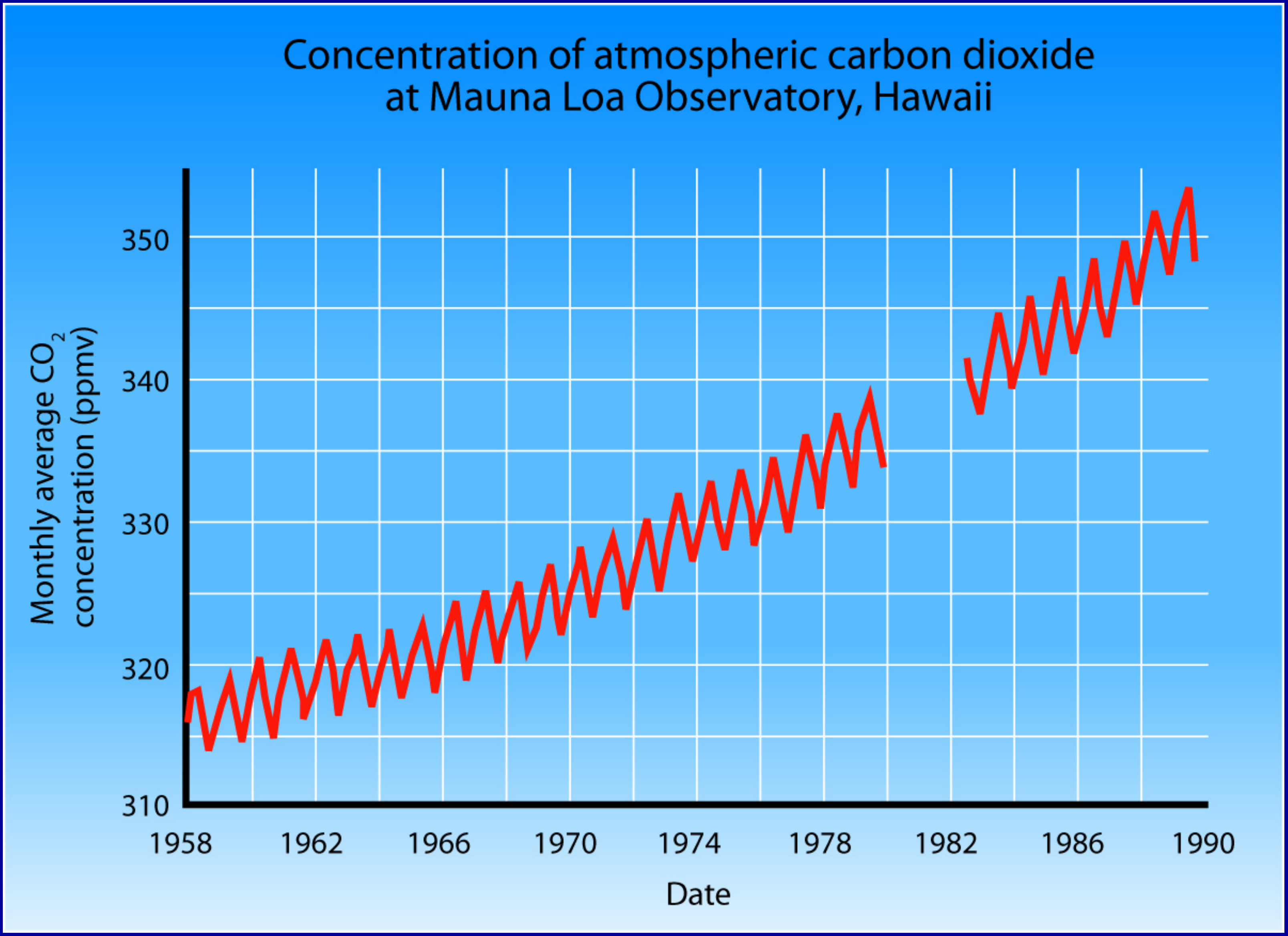


Distribution of occultations for one month

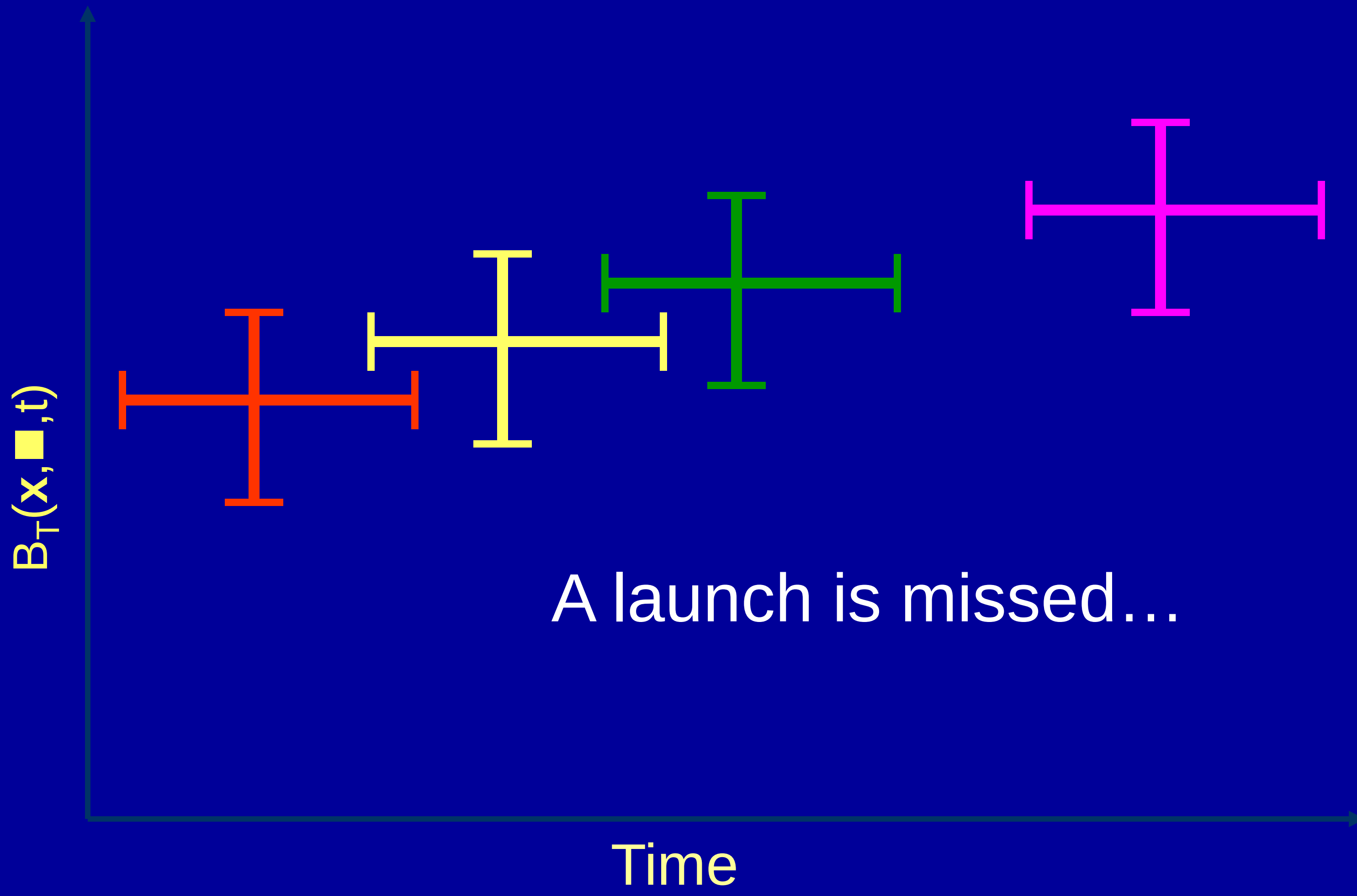
Keeling Record



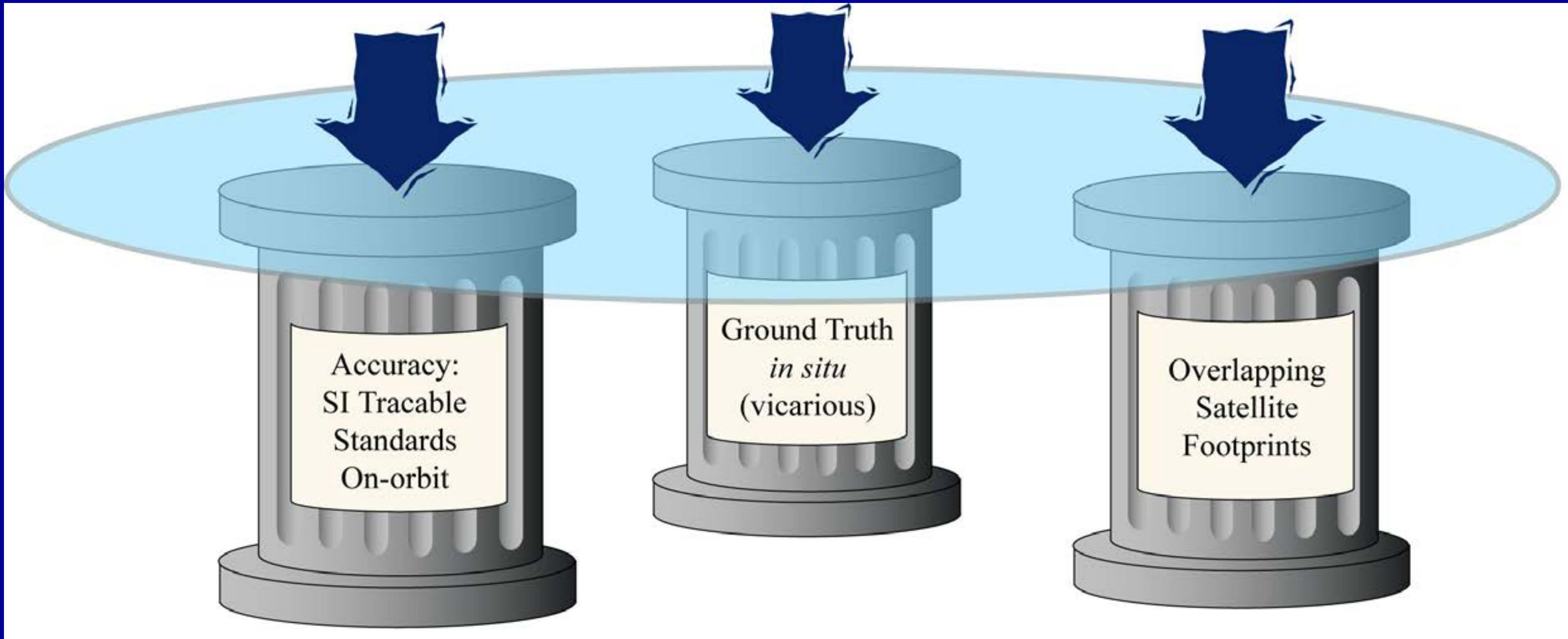
Keeling Record With a Break



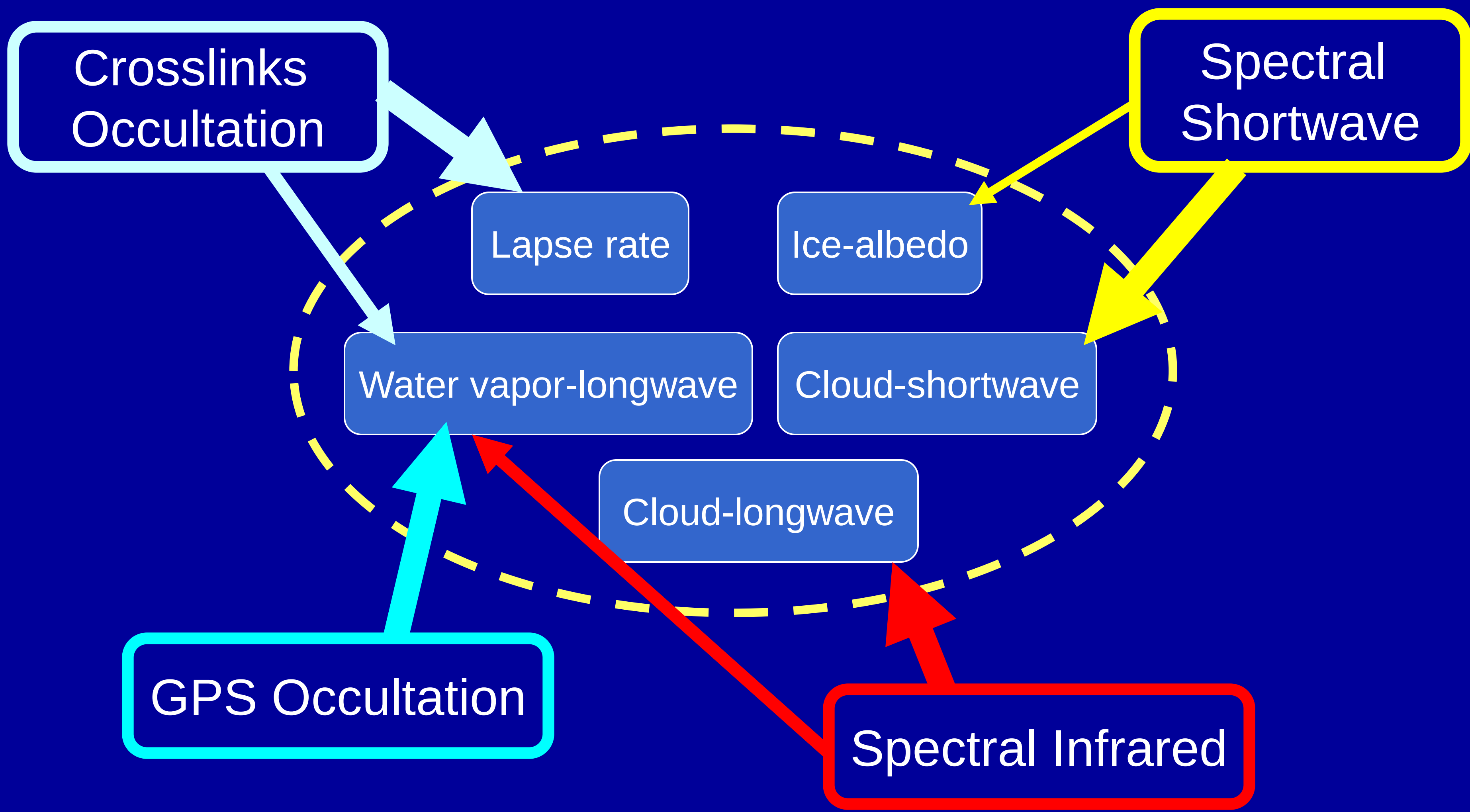
Further challenges for assembling long term record



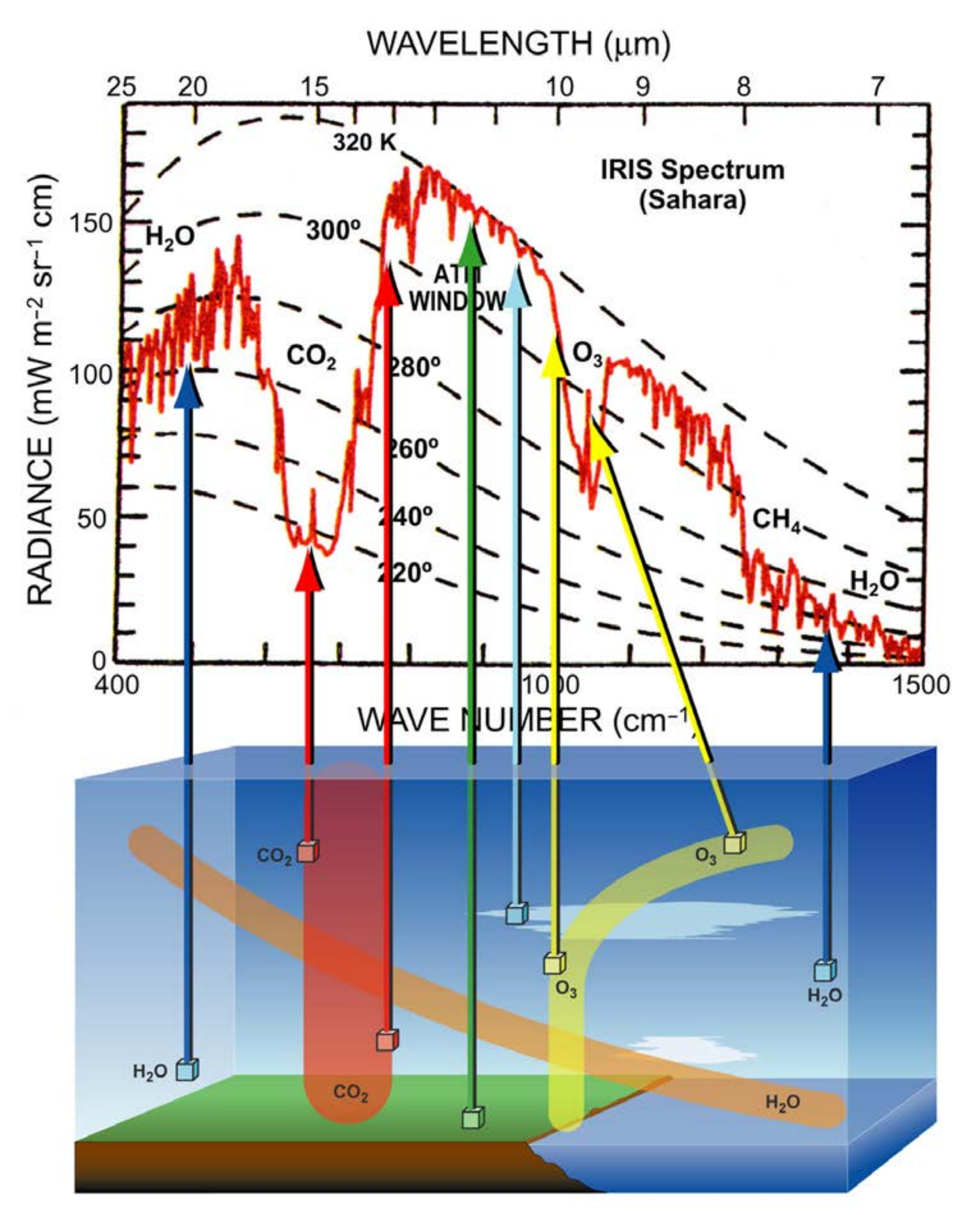
Upon what foundation must the long-term climate record for satellites be based?



Interlocking of Absolute Benchmarks



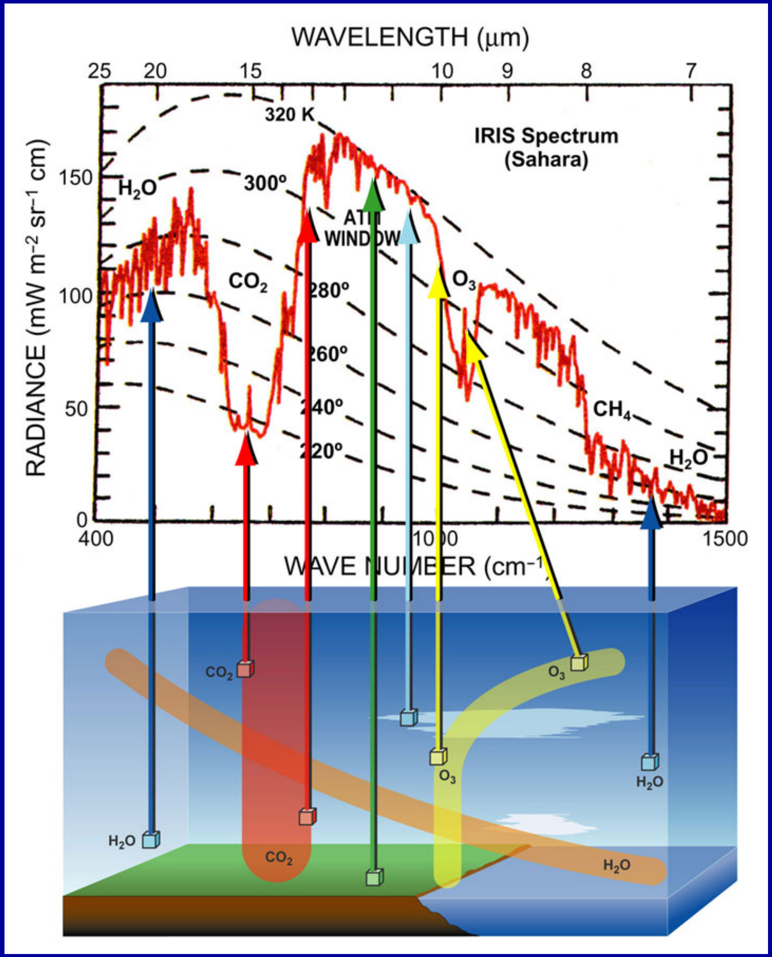
Why is spectrally resolved absolute radiance so fundamental to climate diagnostics?



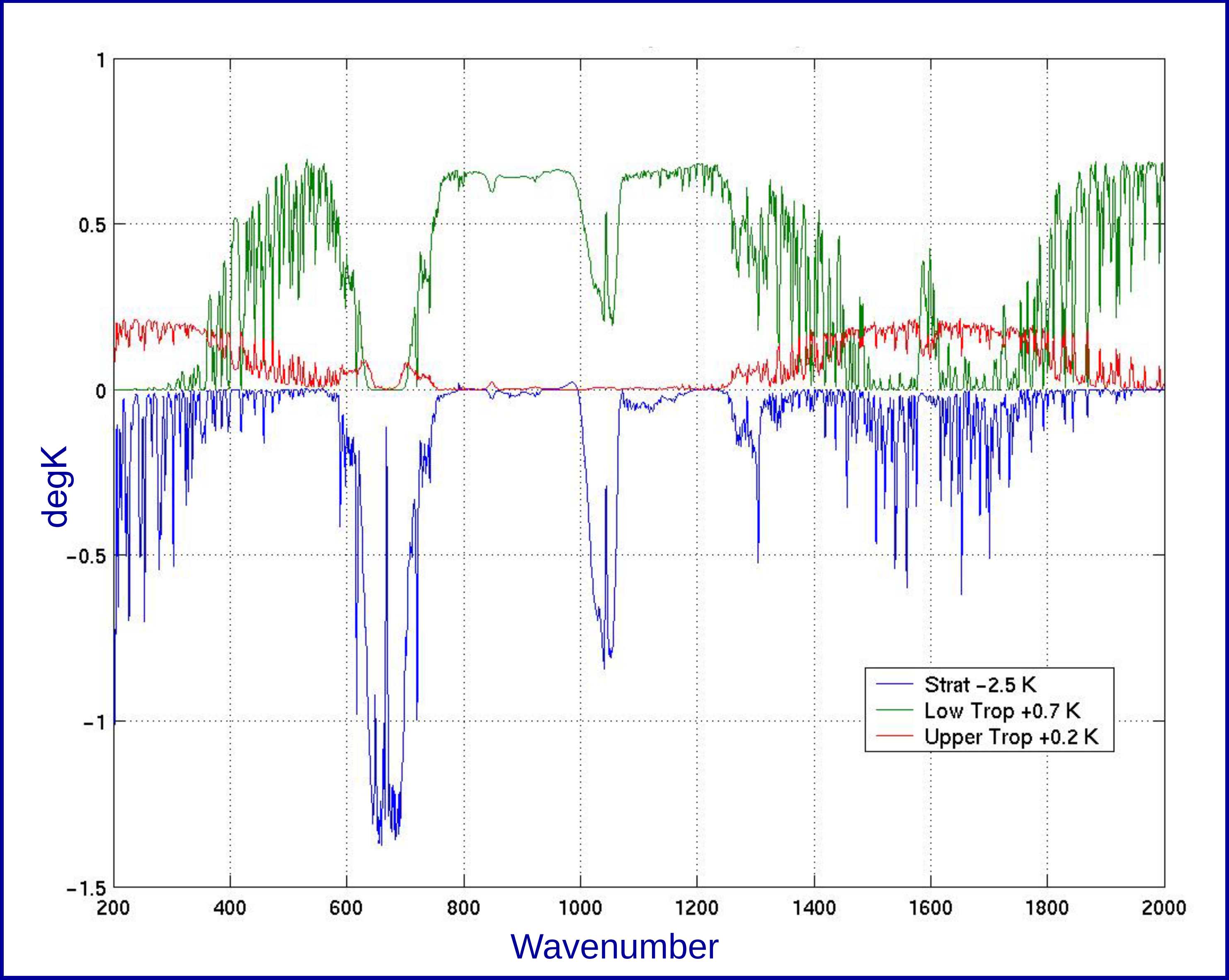
Upwelling Radiance

$$I_\lambda^{\uparrow}(z) = I_\lambda^{\uparrow}(z^*)\,\tau(z^*, z) + \int_{z^*}^{z} B_\lambda(z')\,W_\lambda(z', z)\,dz'$$

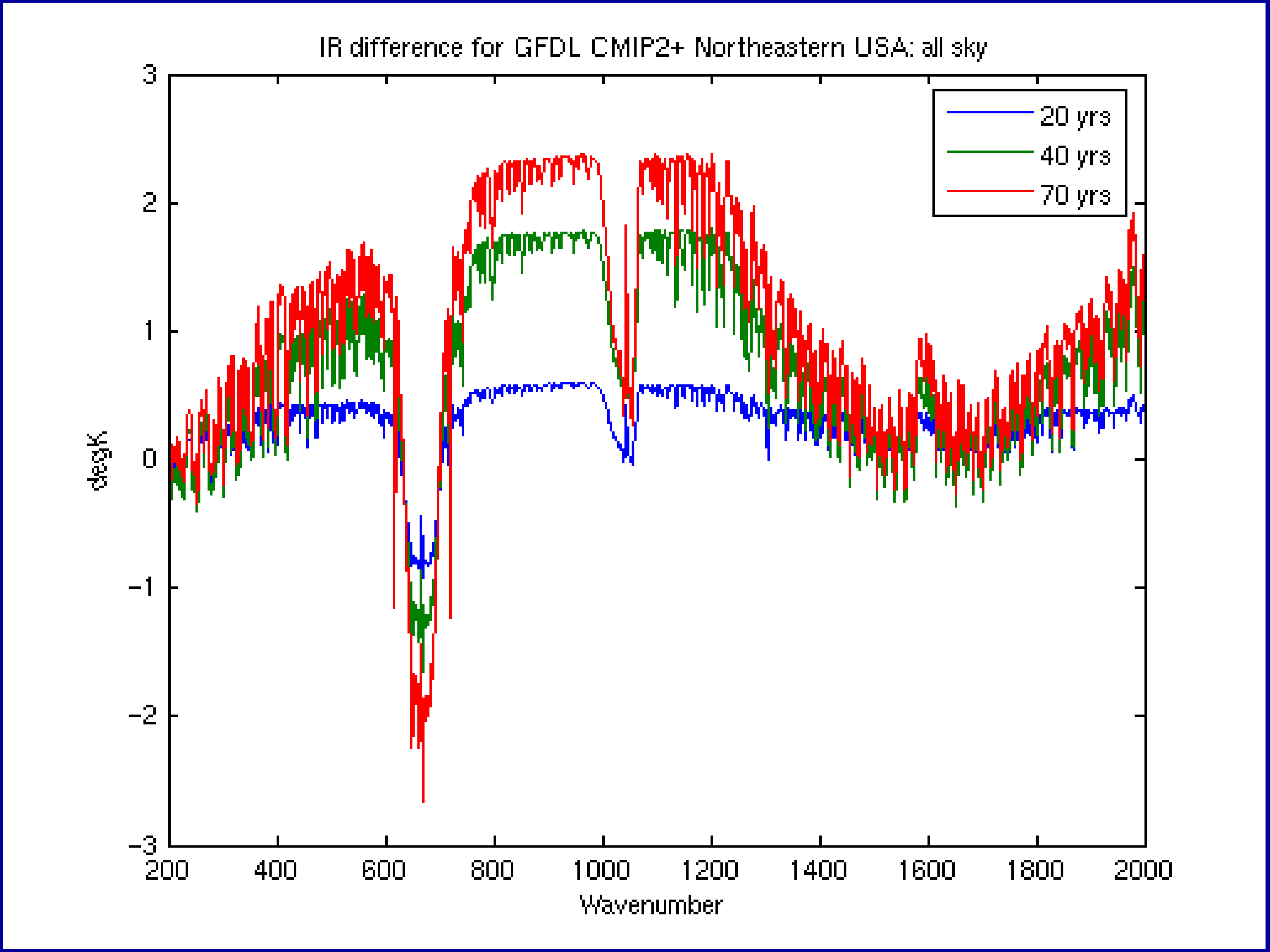
Radiance as a language of model intercomparison



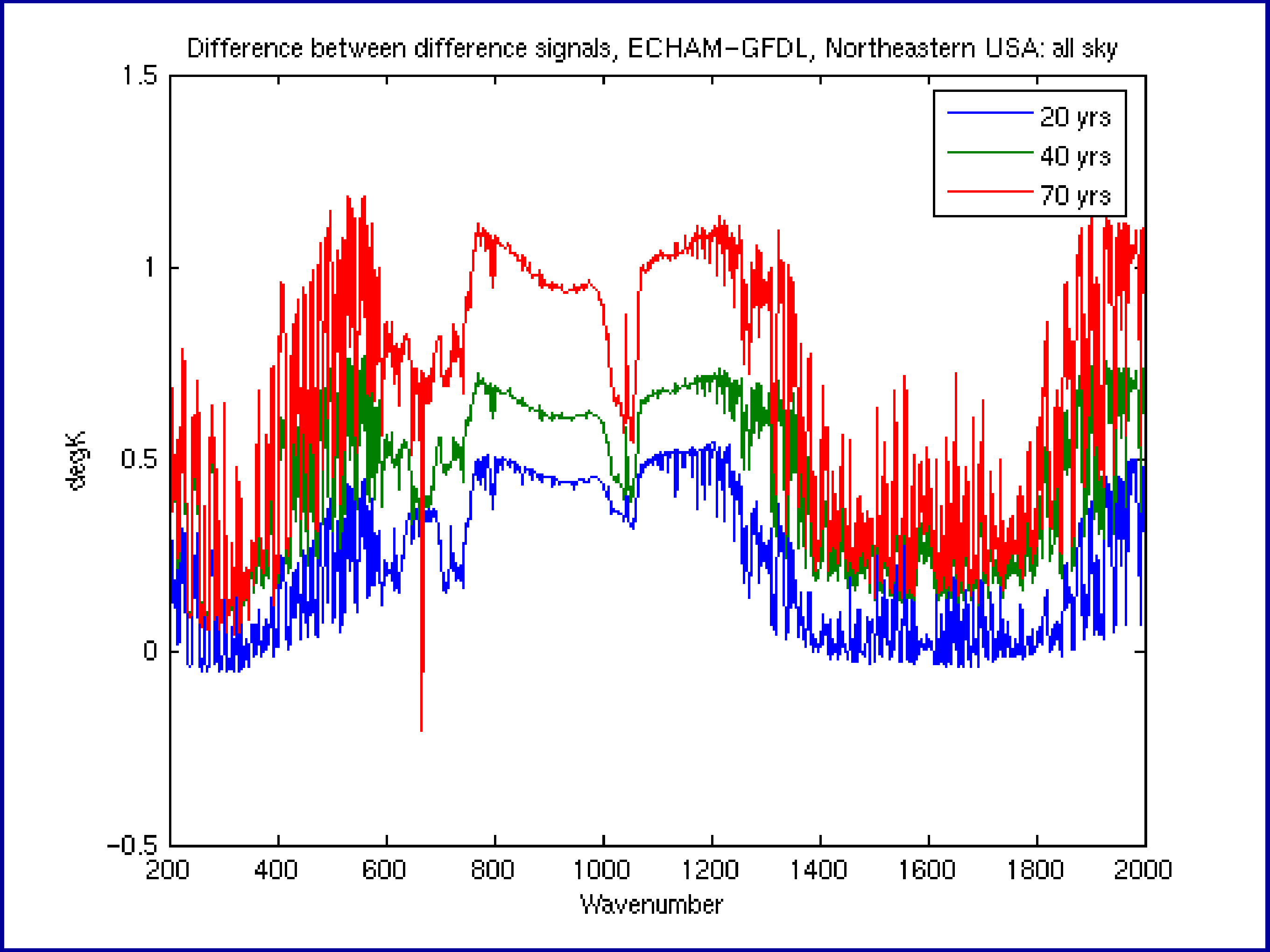
GFDL Zonal Average Centered around 11°S Clear Sky Radiance Changes



Temporal evolution of infrared radiance after 20, 40, 70 years of forced run



Model Intercomparison (ECHAM-GFDL)
difference between radiances after 20, 40, 70 years

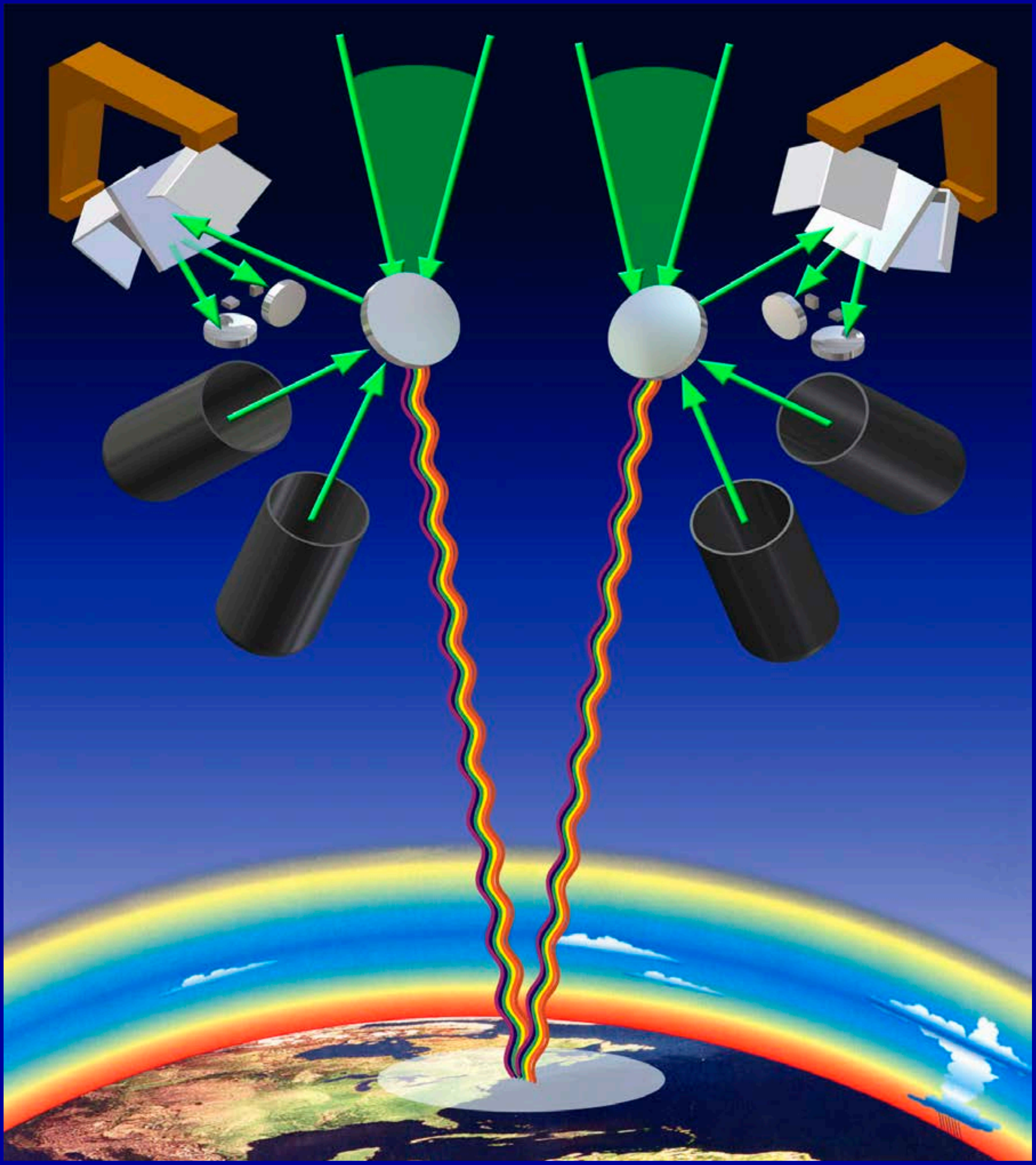


PRIORITY: REDUNDANCY

- Dual Interferometer
- Error Breakdown

Subsystem	Magnitude, mK
Blackbodies	< 24
FTS	33
Detector chain	< 14
Other errors	< 10
TOTAL	< 44.5

- Orbit: 90° polar
- Instrument mass: 13 kg
- Power budget: 8W

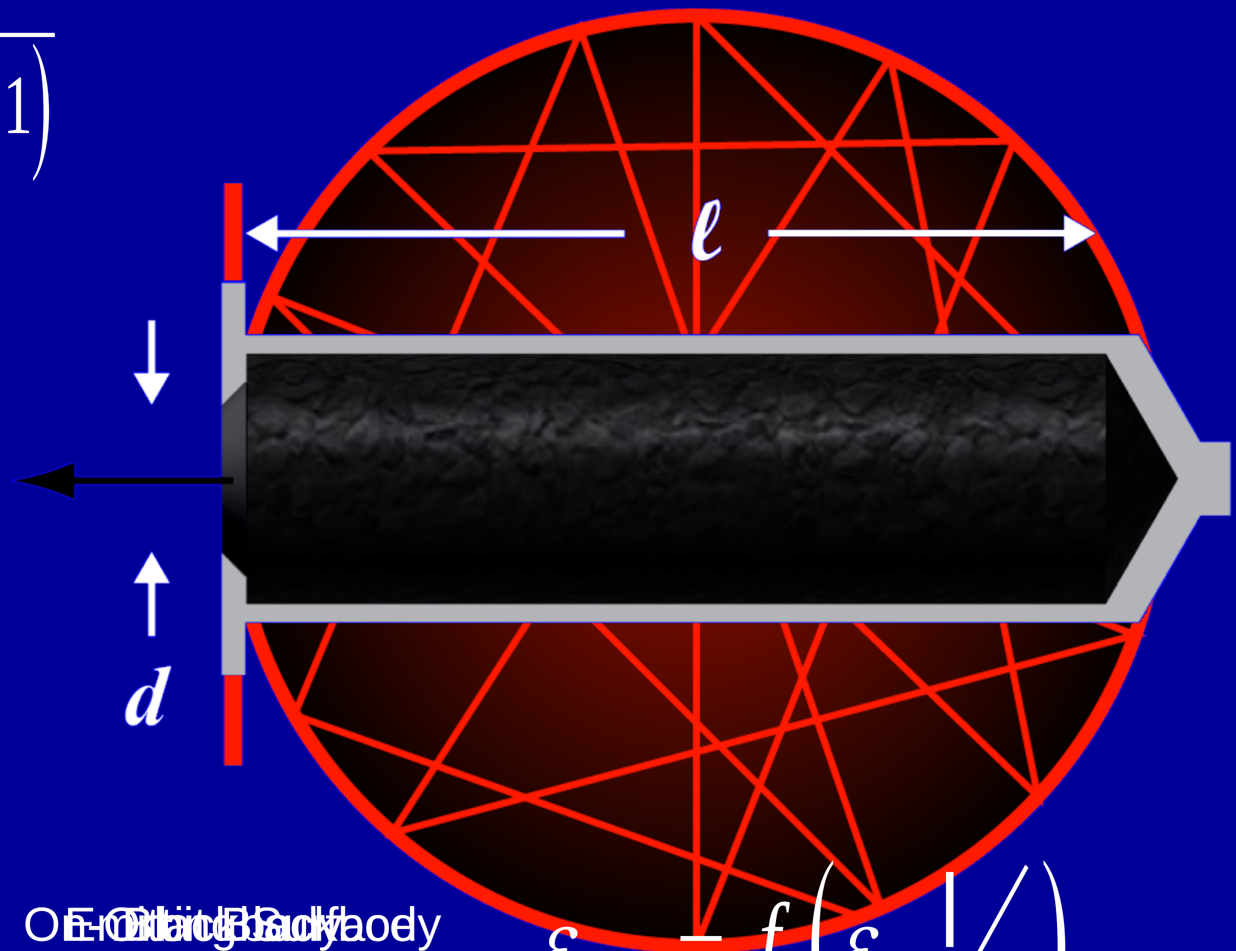


Priority for Climate Radiance Measurements: Blackbodies

$$B_\nu(T) = \frac{8\pi h}{c}\frac{\nu^3}{\left(\exp^{(h\nu/kT)} - 1\right)}$$

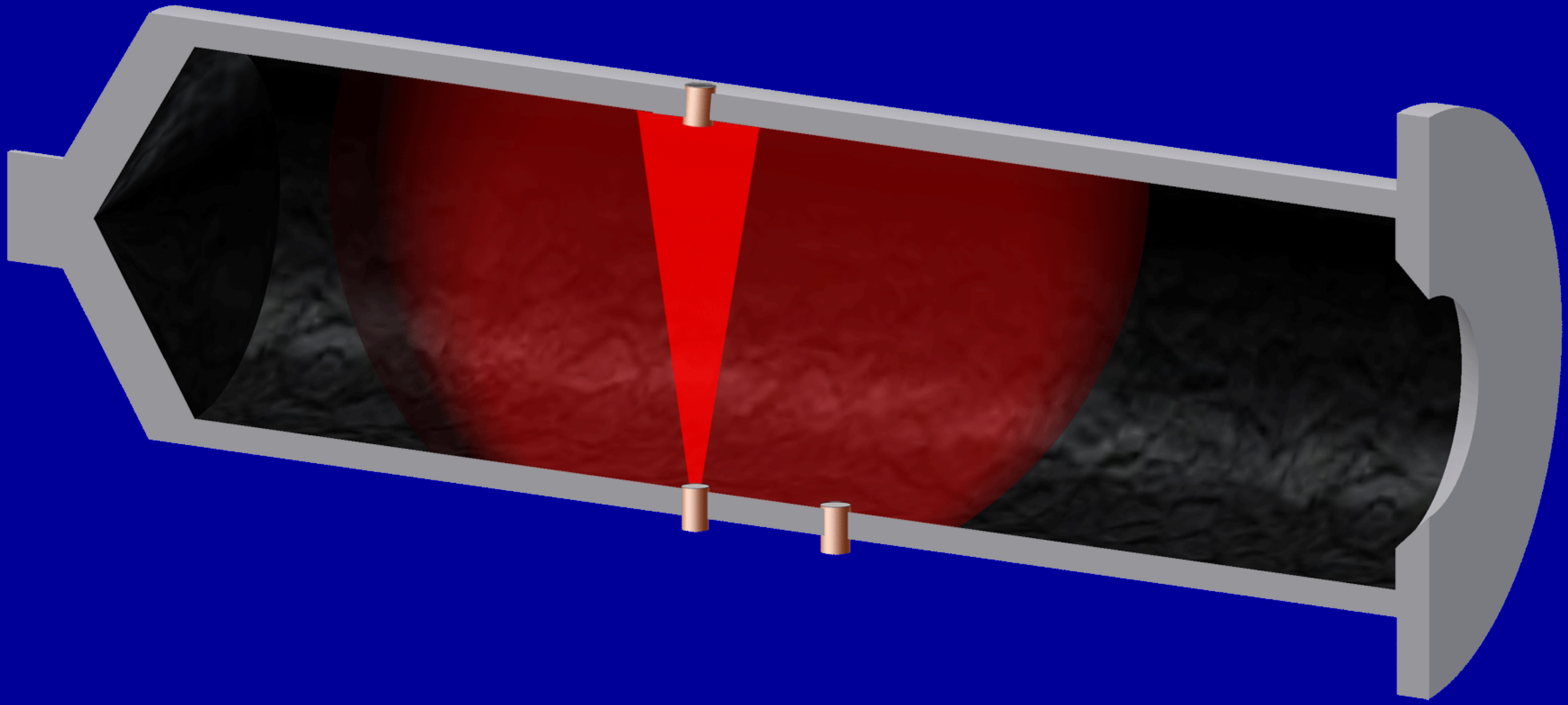
$$\varepsilon_s B_\nu(T)$$

$$\varepsilon_{axis} B_\nu(T)$$

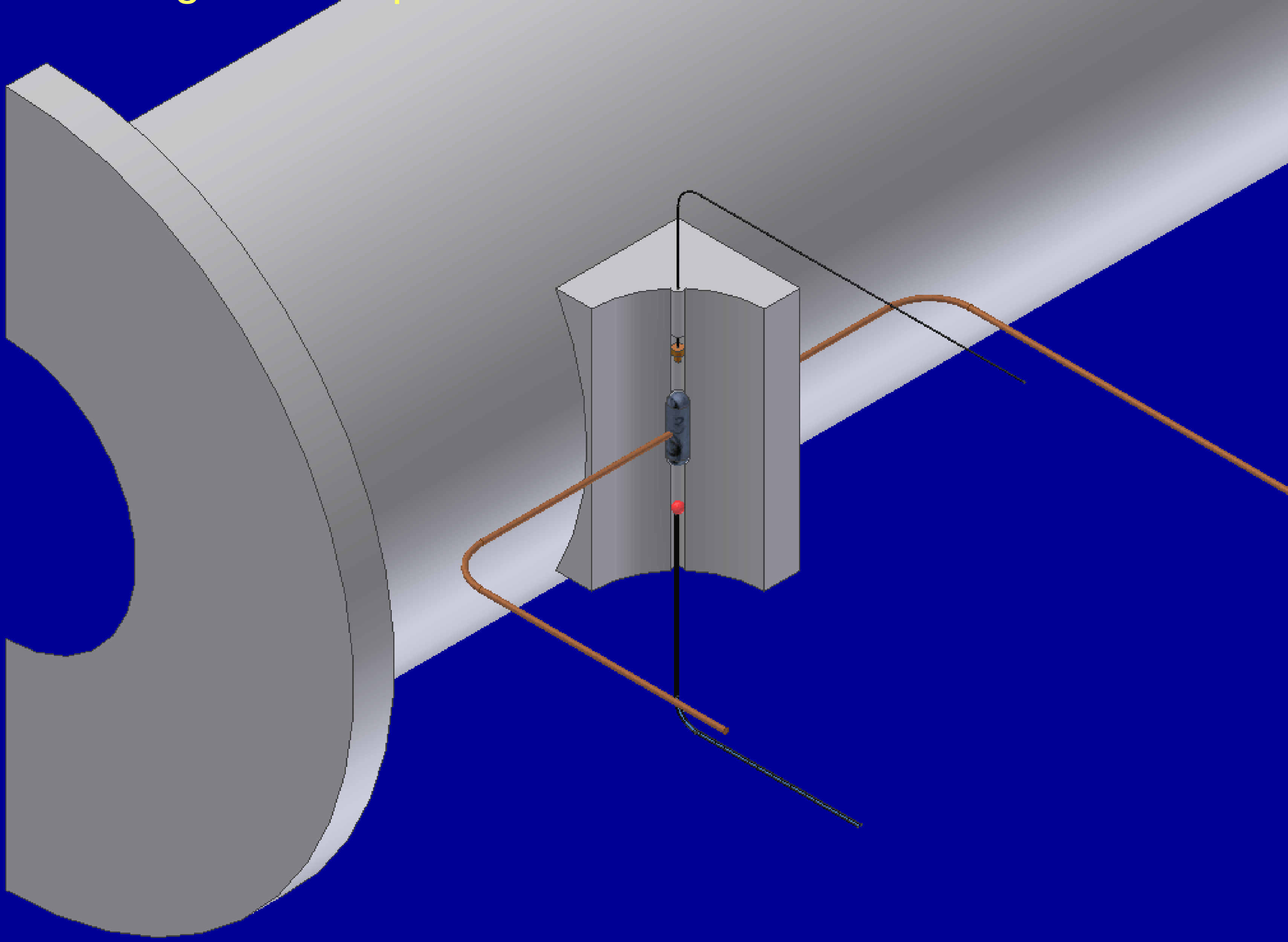


$$\varepsilon_{axis} = f\left(\varepsilon_s, {}^{l}\!/_{d}\right)$$

Checking on-orbit emissivity with a quantum cascade laser



Locking the Temperature Scale: Phase Transition



Board of Inquiry: Principles for Climate Observations from Space

1. Completely independent methods that each have accuracies (absolute) that satisfy the requirements of climate (e.g., 0.1 K) must be employed to test for systematic errors in the long-term global climate record.
2. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array.

Climate Board of Inquiry: Principles for Climate Observations from Space

1. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array.
2. The foundation for long-term climate observations must be built upon international standards, must be built upon SI units, that define the absolute scale of the core measurements.
3. Climate observations must be tied to SI units on-orbit with specified error budgets defining, for example, thermometry, blackbody emissivity, polarization, stray light, linearity, etc., that can be redundantly tested on-orbit.
4. Completely independent methods that each have accuracies (absolute) that satisfy the requirements of climate (e.g., 0.1 K) must be employed to test for systematic errors in the long-term record.
5. Orbits must be chosen such that diurnal and semi-diurnal components are properly observed on an annual basis in order that the first statistical moment (mean) is recovered to the accuracy required for climate (0.1 K).

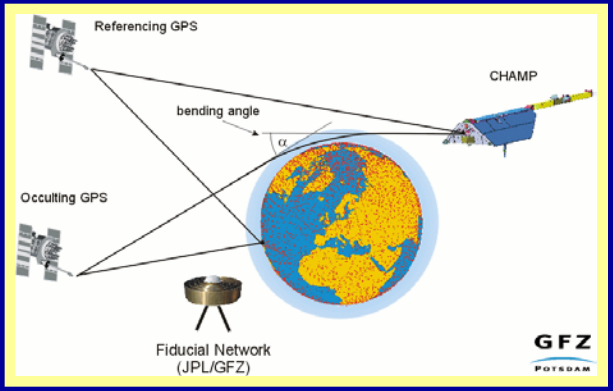
Climate Board of Inquiry: Principles for Climate Observations from Space

6. 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; (d) continuity in laboratory, airborne, and satellite analysis that together dissect systematic errors
7. A “Board of Inquiry” must be formed from a core of critical and independent scientists and engineers and engaged systematically in the critical appraisal of the strategy and execution of long-term climate observations
8. Primary long-term climate observations must be global in coverage, must provide required accuracies in both horizontal and vertical structure, must be free of interference from uncontrolled boundary conditions on the measurements, must contain essential information defining both the forcing and the response of the climate system, etc.
9. 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.
10. The experimental design and execution of the long-term climate observations must be cost effective, responsive to emerging knowledge, and adaptable to technological innovation.

Benchmark Observations: A Critical Category of Climate Observables

- GPS occultation measurements
- Absolute spectrally resolved radiance in the thermal infrared
- Absolute spectrally resolved radiance in the visible
- Solar irradiance
- Sea Level Height

GPS Occultation: The Time Standard



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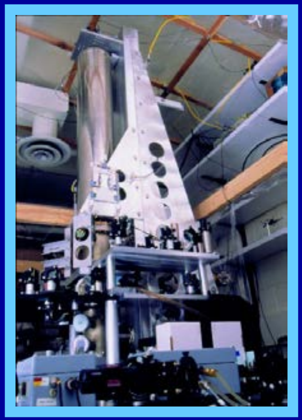

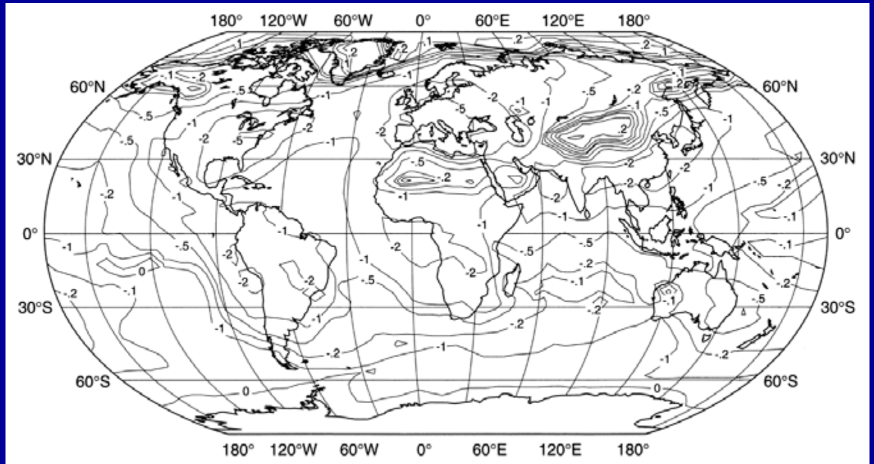

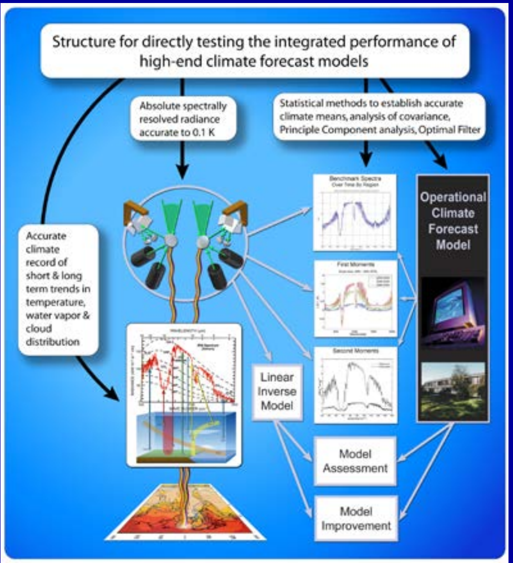

CONCLUSIONS

- Critical component of a climate program is the initiation of climate benchmark observations: distinguished by accuracy (absolute) tied to international standards on-orbit with independent, redundant dissection of systematic errors – highlights importance of GPS and ASRR
- Recognition that sharp criticism will be the growing reality in climate studies
- Benchmark component, while obviously very different in design objectives, highly complementary to NPP and NPOESS programs