THE CLIMATE BENCHMARK CONSTELLATION
A Critical Category of Small Satellite Observations

A collaboration:

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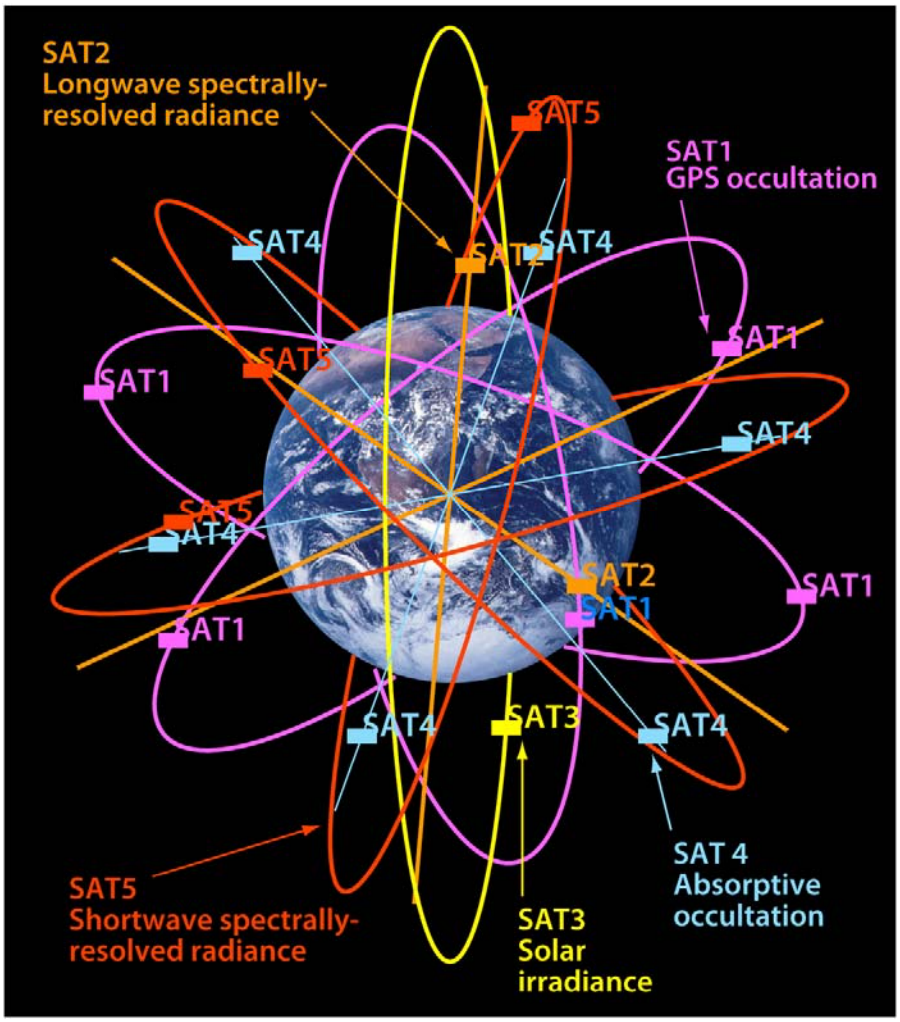
- High accuracy demonstrable on-orbit through traceability to international standards for absolute climate records in perpetuity
- Spatially resolved global coverage with orbits optimized to eliminate sampling bias
- Independently determined data requiring no auxiliary observing system or model
- Selected observations optimized for the testing and improving of climate models according to their decadal forecasting ability



- Absolute Infrared spectrally resolved radiance
- GPS radio occultation and millimeter-wave absorptive radio occultation
- Solar Irradiance and Absolute Shortwave flux reflected to space

I. Introduction

National objectives that balance strategic economic development, protection of life and property, and stewardship of the planet for this and future generations are increasingly dependent on the accuracy and comprehensiveness of observational data that establish the credibility of those forecasts that in turn inform decision structures. Two Presidential Initiatives—the 2001 U.S. Climate Change Research Initiative and the 2003 Global Earth Observation System of Systems (GEOSS) Initiative—underscore the importance of these objectives to the national agenda. Key decision support linked to climate change that addresses water resources, human health, natural resources, energy management, ozone depletion, civilian and military communications, insurance infrastructure, fisheries, and international negotiations depend upon accurate climate benchmarks and accurate, precise, and credible long-term climate forecasts. Current business decisions, economic projections, stability and security are strongly linked to our ability to forecast climate change decades into the future. Credible forecasts constitute the backbone of an effective decision support structure. However, climate forecasts that are tested and trusted engage a chain of strategic decisions required to establish fundamentally improved climate observations that are mathematically coupled to the direct testing and systematic improvement of long-term forecast performance.

Design of climate observing and monitoring systems must ensure the establishment of global climate data which are of *high accuracy, tested for systematic errors on-orbit, tied to irrefutable international standards* maintained in the U.S. by the National Institute of Standards and Technology (NIST). In addition, it is essential for societal objectives that require the long term climate record, that the accuracy of the core benchmark observations be verified against absolute standards *on-orbit* by fundamentally independent methods engaging a strategy such that the accuracy of the record archived today can be verified by future generations. Societal objectives also require a long-term record not susceptible to compromise by interruptions in that data record. For example, continuing debate over the reliability of surface temperature records and the community's inability to establish the upper air temperature record over the past several decades stem from inadequate adherence to fundamental principles that must be identified, understood, and incorporated in the strategic planning.

These societal requirements highlight the fundamental distinction between *accuracy* and *precision* and engage directly the issue of *stability* as it relates to the integrity and credibility of climate data records. *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 of, for example, time or temperature. *Precision,* in sharp contrast, is the measure of repeatability without reference to an international standard. While accuracy invokes unequivocal reference to absolute standards, precision engages, in various venues, the vocabulary of stability, reproducibility, repeatability, consistency, continuity, and data record overlap, but without reference to an absolute standard. Long-term records built upon precision (or stability, repeatability, continuity, etc.) rely upon efforts to reconcile time or instrument dependent biases without an international standard. As a direct result, they are seriously compromised by lack of continuity in the data record, and are notoriously open to criticism.

While geophysical measurements such as water vapor and temperature are being made (e.g., by the AIRS instrument on NASA's Aqua Mission) and will be made in the future (e.g., by AMSU and the CrIS instrument on NPOESS) these instruments are designed correctly for high spatial and temporal retrievals of meteorological variables from sun synchronous orbits for the purpose of weather forecast initialization, process studies, etc. But it is clearly recognized that

climate requirements are distinct from weather requirements, particularly with respect to the establishment of accurate long-term climate records. While *weather forecast* initialization and many process studies require sun-synchronous orbits, cross track scanning, hyper-spectral imaging, high throughput optics, high sensitivity detectors, small fields of view, and accurate pointing, *climate benchmarks* require orbit selection that systematically scans the diurnal cycle, absolute calibration demonstrable on-orbit, traceable to the international system (S.I.) of units, and sounding density sufficient to capture unbiased averages of the climate system. These climate requirements for accuracy are not the objective nor the capability of current systems. However, there is a compelling opportunity to significantly strengthen the contribution of planned operational systems such as NPOESS by incorporating high accuracy observations as part of the system.

The opening phase of critical government review is already emerging in the hearings before the senate committee on Commerce, Science and Transportation chaired by John McCain. In preparation for continued interrogation of the US climate program we first ask: *What would a Climate "Board of Inquiry" place at the top of the priority list?* A short list would include: (1) the fundamental responsibility to present and future generations to obtain a suite of climate benchmarks that are 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 improved using rigorous mathematical techniques to assure their credibility to commerce and public policy makers; and (3) disciplined decision structures that assimilate accurate data and forecasts into intelligible and specific choices that underpin international commerce as well as societal stability and security.

Moving to address these and other priorities for the U.S. Climate Program requires the establishment of clear principles for climate observations from space. Climate observations from Earth orbit are central not only to unbiased global coverage but also to long-term accuracy because such observations are mostly free from the environmental contamination that plagues in situ observations and because the relatively benign environment of space is uniquely compatible with recent developments in the physics of high accuracy measurements (metrology).

In Summary, the key attributes of a climate benchmark are:

- **High accuracy, verified on orbit, for use in perpetuity that are checked against fully independent observations traceable to the International System of Units (SI).**
- **Global coverage which minimizes sampling error and scans the diurnal cycle so as to remove bias.**
- **Observations selected to distinguish and test global climate models according to their decadal forecasting capability and provide for the systematic improvement of those global climate models.**
- **End-to-end scientific responsibility for accuracy testable by protocols accessible to all nations and to future generations**

In the sections that follow, we present a selected constellation of climate benchmark observations from low Earth orbit consisting of a unified, coordinated system specific to the demands of climate driven by the societal requirements discussed above.

II. Components of a Climate Benchmark Constellation

Important features of the Climate Benchmark Constellation are:

1. **Only observations that satisfy the Climate Benchmark criteria defined in the Introduction are included.**

2. **The Constellation can be constructed in stages such that large start-up costs are avoided and the imperative to move forward in response to national needs can be flexibly addressed.**

3. **The constellation can be added to, orbits adjusted, improvements executed, and the impact of failures minimized as an integral part of the strategy.**

4. **The instruments are small, low in mass, power and volume and thus characterized by highly confined cost following a path validated by the success of small Explorer Class systems.**

II.1 Absolute Spectrally Resolved Radiance in the Infrared

Absolute Spectrally Resolved Radiance in the Infrared measured with high accuracy (0.1 K brightness temperature) by downward-directed interferometers in Earth orbit, as shown schematically in Figure II.1, provides a key observation that can be obtained from space for the purpose of long-term climate benchmark measurements and for decisive testing of climate forecasts. Both the radiative *forcing* of the atmosphere resulting from greenhouse gas emissions and aerosols and the *response* of the atmospheric variables are clearly observable in the spectrally resolved signal of the outgoing radiance. The increase in greenhouse gas concentrations and aerosol loading imply changes in the spectral distribution of outgoing infrared radiation. Similarly, large differences among model projections of temperature, water vapor and cloud distributions imply, for each model, different predicted changes in outgoing radiation. The spectrum of IR radiance, if observed accurately and over the full terrestrial band, carries decisive diagnostic signatures in frequency, spatial distribution and time. At satellite altitudes, the boundary conditions on radiative processes can be measured without interference.

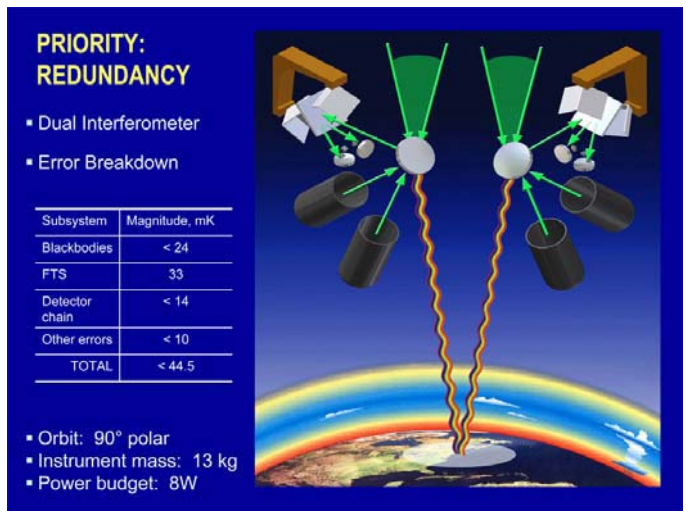


Figure II.1

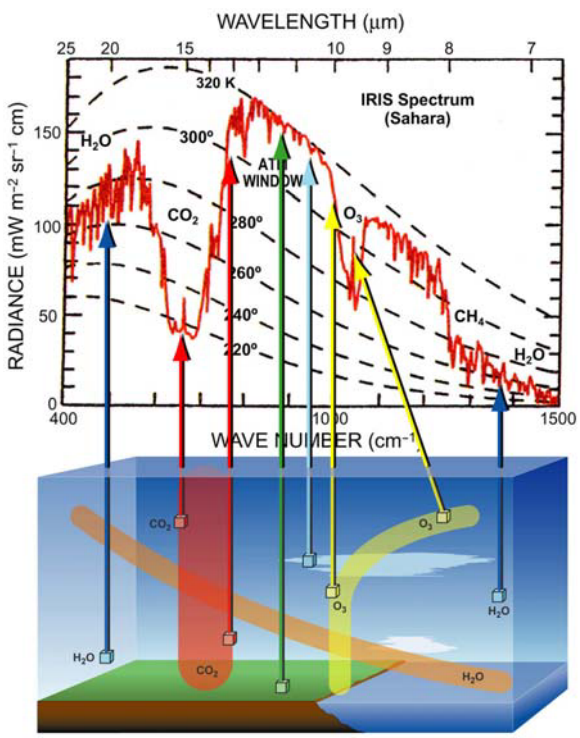


Figure II.2

Figure II.2 shows the spectrally resolved radiance encompassing the thermal IR emitted from Earth to space observed by a nadir viewing interferometer. The emission between 200 and 600 cm^{-1} is dominated by rotational lines of water vapor. This spectral interval in combination with the 800–1000 cm^{-1} spectral interval determine the presence of clouds. Spectral features of CH_4, N_2O, CFCs, etc., clearly reveal climate forcing from the release of these species over time. There is no other single measurement that can yield such a wide range of important climate information. Because of the dynamic range of individual line strengths of emission from water vapor, carbon dioxide, and ozone, temperature changes in the mid and upper, in the lower troposphere, and in the lower stratosphere may be determined, as shown in Figure II.3.

Figure II.3 shows changes in the infrared radiance spectrum if the lower troposphere warms by 0.7 K, when the upper troposphere warms by 0.2 K, and when the stratosphere cools by 2.5 K. These are the types of climate signals that infrared radiance spectra are expected to capture over a 20-year baseline and which global climate models should reproduce if they are to trusted as climate forecasting tools.

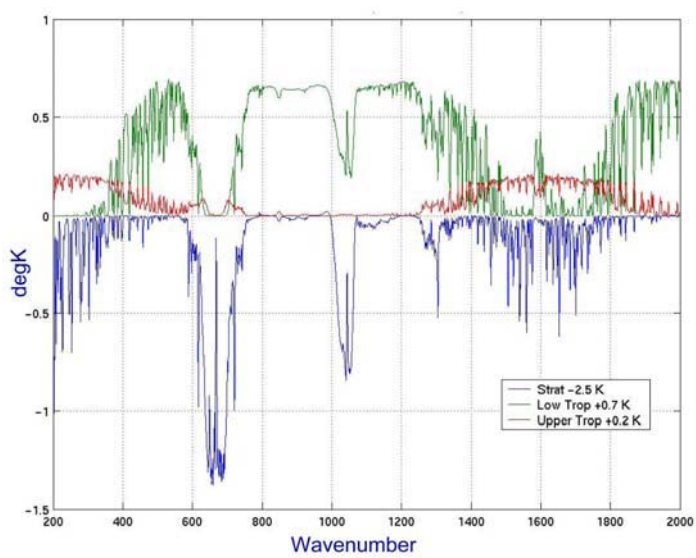


Figure II.3. GFDL Zonal average centered around 11°S clear sky radiance changes

One method of testing climate models according to their ability to forecast climate is to compare the anthropogenic signal of climate change as realized in data to the anthropogenic signal as simulated from forecasts by the most sophisticated climate models. While there are many examples to choose from, we briefly consider one that demonstrates the diagnostic power of absolute spectrally resolved radiance in the thermal infrared by comparing two important climate forecast models, the GFDL and ECHAM model at intervals of 20, 40 and 70 years using the method of difference spectra applied to the North East United States climate region. Figure II.4 displays difference spectra 20, 40, and 70 years out with a CO_2 increase of 1% per year for the GFDL model in the CMIP2+ ensemble for all sky conditions in the Northeast US (37–47°N latitude; 90–65°W longitude), showing the divergence of the forecast between the CMIP2+ protocol

ECHAM model and the CMIP2+ protocol GFDL model. In this case of forecast model intercomparison, shown in Figure II.4, clear differences are manifest across the spectrum. The ECHAM (MPI Hamburg) forecast shows greater warming in the high troposphere and in the boundary layer. The GFDL model displays less cooling in the stratosphere as revealed in the CO_2 and O_3 lines between 600–800 cm^{-1} and 1050 to 1150 cm^{-1} respectively. The forecast cloud structure between 800 and 1000 cm^{-1} shows large differences between the ECHAM and GFDL models 20, 40 and 70 years out.

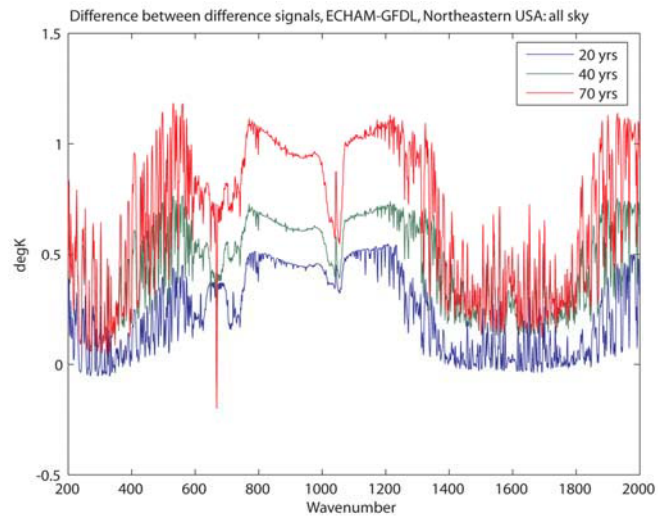


Figure II.4

Obtaining data accurate enough to reveal such minute differences and provide for the detection of trends and testing of climate models depends upon the details of the experimental design of the spectrally resolved climate benchmarking component of the Constellation. The calibration of the inter-ferometers is demonstrably tied *on-orbit* to the SI definition of frequency-dependent infrared radiance as realized by calibration protocol maintained at NIST. Because infrared radiance is based on multiple SI units as opposed to a single SI unit, it must be validated experimentally to support claims of absolute accuracy and traceability to the SI. The first validation of a thermal infrared scale against SI standards was published by Quinn and Martin (1985) for broadband measurements. The instrumental design discussed by Anderson *et al.*(2004) takes advantage of new NIST calibration technology to establish the absolute accuracy of the interferometer's calibration and provide independent on-orbit demonstration of radiometric performance (Dykema and Anderson 2005).

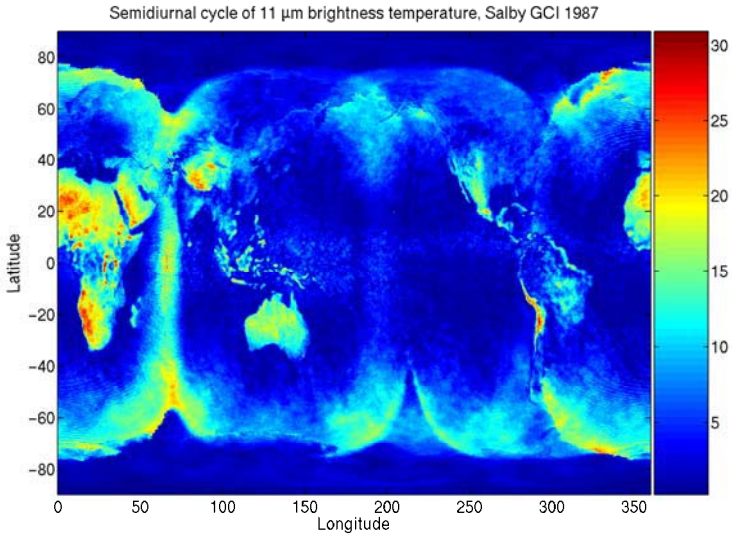


Figure II.5. Semi-diurnal cycle of 11µ brightness temperature

In addition to measurement bias, statistical biases also must be evaluated and/or eliminated to produce meaningful estimates of trends and to perform societally useful assessments of climate forecasts. An obvious requirement for trend estimation is that a remote sensing platform must obtain accurate mean radiances on climatically relevant temporal and spatial scales. Kirk-Davidoff *et al.* (2005) demonstrates that sun-synchronous orbits cannot determine 11 μm radiances to an accuracy of 0.1 K on annual time scales over most of the globe. The failure to reproduce the mean statistics accurately is due to the significant contribution of the semidiurnal cycle to the temporal pattern of infrared radiation, as shown in Figure II.5. Since sun-synchronous orbiters make measurements at fixed times at equatorial and mid-latitudes, the mean statistics are biased by the semidiurnal cycles. True polar orbiters avoid this problem by cycling through the diurnal cycle three times per year, as illustrated in the middle panel of Figure II.6. This sampling issue creates a serious conflict between weather sounders and climate benchmarking missions, emphasizing the need to deploy specialized measurements for climate to meet the needs of long-term forecast testing.

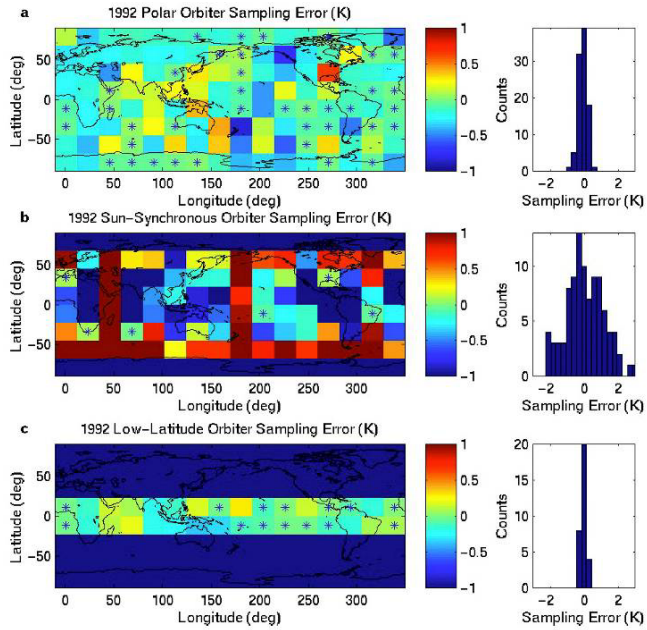


Figure II.6

II.2a. Benchmark GPS Occultation from low Earth orbit.

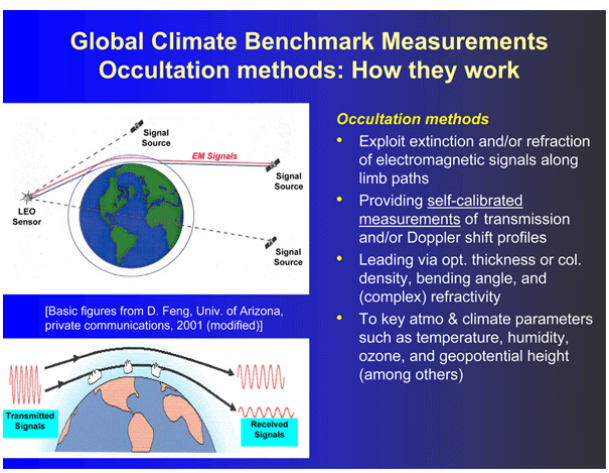


Figure II.7

GPS radio occultation offers an ideal method for benchmarking the climate system because the technique is a measurement of frequency shift against a time standard and is therefore simply traceable to international standards. Because much of the infrastructure for this active limb sounding technique already exists in the form of the Global Positioning System (GPS) satellites and because orbiting GPS receivers are comparatively inexpensive, GPS radio occultation is an obvious component of a Climate Benchmarking Constellation. GPS radio occultation profiles the refractive properties of the atmosphere by observing the timing delay of GPS signals induced by the atmosphere as the ray-path descends toward the Earth's surface in a limb-sounding geometry as shown schematically in figure II.7 (Kursinski et al. 2000). The index of refraction is directly related to pressure, temperature, and water vapor concentration such that the refractive index can be easily simulated from model output. Moreover, GPS occultation offers an accurate measurement of geopotential heights on constant pressure surfaces throughout much of

the troposphere and stratosphere and thus offers the opportunity to directly observe thermal expansion of the troposphere in response to forcing.

GPS radio occultation is traceable to international standards because the raw observable, the timing delay induced by the atmosphere on the occulted GPS signal, can be tied directly to the international definition of the second by a near real-time chain of calibration (Leroy et al. 2005a). The clock on board the orbiting GPS receiver satellite used for measuring the atmosphere-induced time delay of the GPS signal is generally of low quality and is calibrated by a reference link to a second GPS satellite. GPS satellites themselves have excellent and highly stable suites of cesium and rubidium atomic clocks on board, but even they are subject to minute instabilities over the timescale of a single occultation event. Thus, the clocks and the precise orbits of the GPS satellites are determined by constantly observing them from ground-based GPS receiving stations tied to hydrogen maser atomic clocks as shown in figure II.8. By maintaining a GPS receiving station tied to the clock at the National Institute of Standards and Technology in Boulder, Colorado, that defines the second with a fractional error of 1.7×10^{-15}, GPS radio occultation is made S.I. traceable. As a consequence, the accuracy of each occultation is independently testable by any scientist into the indefinite future and can be easily replicated by any observing community, whether it be in the Far East, Western Europe, or North America.

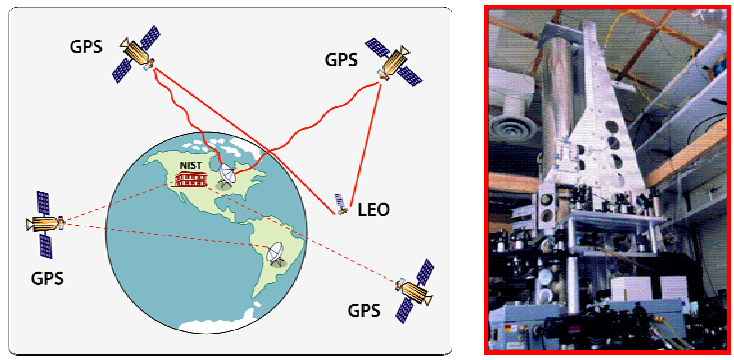


Figure II.8 Traceability of GPS radio occultation to the international definition of the second. On the right is one of the two most stable atomic clocks in the world, this one maintained at NIST.

The refractivity measured by GPS radio occultation, N, is expressed in terms of the index of refraction n, and the three terms that determine the index of refraction at each altitude are given in Equation 1.

$$N = (n - 1) \times 10^6 = 0.776\,(p/T) + 3730\,p_w/T^2 - 4.03 \times 10^7\,n_e/\nu^2 \qquad (1)$$

At the standard GPS frequencies of 1.2 and 1.5 GHz, the first term on the right-hand side of Equation (1), in S.I. units, represents the contribution to the microwave index of refraction resulting from atmospheric density at pressure p and temperature T in each altitude increment between the ground and 50 km altitude. The second term represents the contribution to the index of refraction by water vapor partial pressure, p_w, at temperature T and is significant as a climate signal only in the tropics in the lowest 4 km. The third term is the contribution to the index of refraction of the ionosphere for an electron density of n_e at frequency ν. A linear combination of the two GPS frequencies (at 1.2 and 1.5 GHz) is used to remove the ionospheric contribution.

Figure II.9 shows the zonal average trend of dry pressure as forecast by the NCAR CCSM3 over the coming decades. Dry pressure is the downward integral of the refractivity N in height. Figure II.9 shows thermal expansion of the troposphere, water vapor increases in the vicinity of the intertropical convergence zone, and poleward motion of the mid-latitude jetstream. It is the signal of the human influence in the upper air over the next 50 years. Optimal detection shows that the portion of this signal most important for optimal detection is poleward motion of the mid-latitude jetstream: when the jet is observed to migrate poleward, one can declare with confidence that a human influence on climate has been detected because the

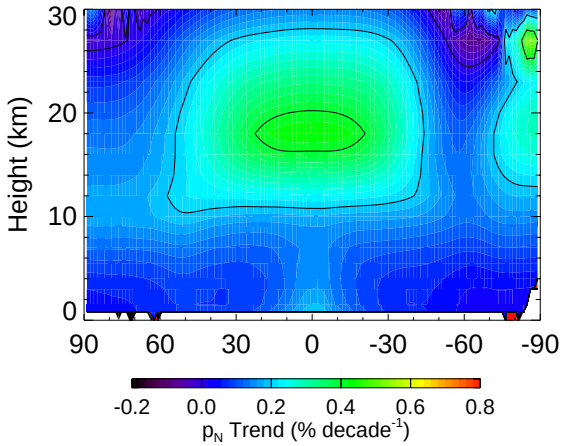


Figure II.9 Rates of increase of zonal average dry pressure expected over the coming decades as predicted by NCAR CCSM3. Taken from Leroy et al. 2005b.

atmosphere doesn't typically exhibit that type of behavior. Only credible climate models will demonstrate the same trends as those observed.

This component of the Climate Benchmarking Constellation is a direct follow-on to the COSMIC project, expected to launch in late 2005 (Rocken et al. 2000).

II.2b. Cross-Link Absorptive Radio Occultation

Fully understanding the behavior of water vapor throughout the troposphere is essential to credible and useful forecasting of climate change. Water vapor in the lower troposphere is responsible for 60% of greenhouse forcing, yet water vapor in the upper troposphere exerts disproportionate positive or negative greenhouse forcing because of its variability and its control over the flux of IR radiation to space in the middle/upper troposphere. Climate models indeed predict that upper tropospheric water vapor will increase dramatically in the coming years, as shown in figure II.10, but *in situ* data suggests that the coupling of upper tropospheric and lower tropospheric water vapor may not be as strong in reality as in models (Sun and Lindzen 2001). This makes model forecasts of trends in the climate, particularly the hydrological cycle in the upper troposphere, particularly unreliable. To lay a foundation for creating a system which correctly predicts trends in the climate system, it is absolutely necessary to benchmark tropospheric water vapor as soon as possible.

Absorptive radio occultation, by retaining the high performance of GPS radio occultation but at millimeter-wave frequencies with water vapor absorption, provides a benchmark measurement of atmospheric water vapor with accuracy directly traceable to international standards. While GPS radio occultation profiles the real part of the atmosphere's microwave refractive index using GPS satellites as transmitters, absorptive radio occultation profiles both the real and imaginary parts of the atmosphere's refractive index using receivers and transmitters in low Earth orbit. When the signals of an absorptive radio occultation are chosen near an absorption feature in the millimeter-wave spectrum, the combination of the real and imaginary parts of the refractive index provide all the information needed to create a benchmark for profiles of water vapor. The hyperfine vertical resolution obtained by diffraction calculations given occultation data enable even a benchmark of profiles of *relative* humidity. Next generation technology should profile the isotopes of water vapor by this same technique.

The lower altitude limit of an absorptive radio occultation is governed by

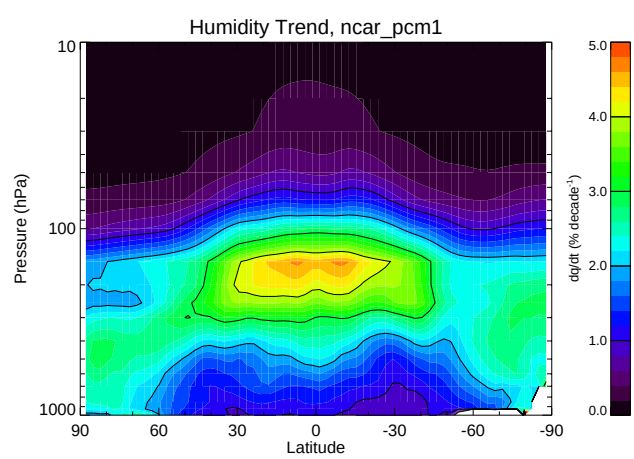


Figure II.10 Trend in specific humidity per decade for climate forcing scenario SRESA1B as predicted by the NCAR PCM model for the *IPCC 4th Assessment Report*. Units are percent per decade.

saturation: when too much of the signal is absorbed in the atmosphere, the signal disappears. Conversely, the upper altitude limit of an absorptive radio occultation is governed by sensitivity: if too little of the signal is absorbed, the signal-to-noise ratio of the measurement precludes extending the profile above a certain altitude. There is a water vapor absorption at 22 GHz which permits profiling of water vapor from the surface to 12 km, and there is another, much stronger water vapor absorption at 183 GHz which permits profiling of water vapor from 12 km through the stratopause as displayed in figure II.11. This component of the Climate Benchmark Constellation incorporates both spectral features.

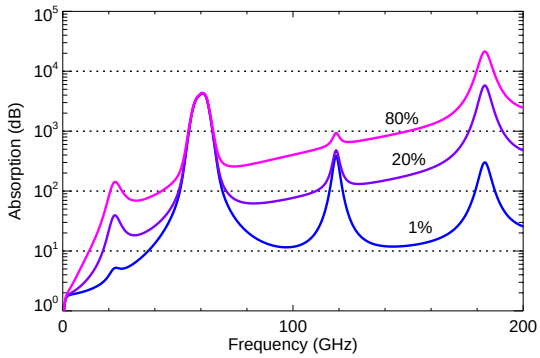


Figure II.11 The millimeter-wave spectrum of moist air. Conditions are for surface pressure and temperature, and different curves are for three different relative humidities.

As opposed to GPS radio occultation, absorptive radio occultation requires deployment of both LEO satellites for reception *and* LEO satellites for transmission (Kursinski et al. 2002). The measurement must obtain a high signal-to-noise ratio in order to profile water vapor over the widest possible range in altitude. Also, the measured amplitude of the signal must not be affected by any changes in total system gain throughout the course of a single occultation in order to assure an accurate measurement traceable to S.I. standards. The high gain and the total system stability demands lead to a requirement of high gain antennas on both the transmitting and receiving satellites with accurate and precise knowledge of spacecraft pointing. The simplest possible implementation, which also leads to global coverage, is to have purely fore and aft looking antennas on both the transmitter and receiver LEO satellites, with transmitter LEO and receiver LEO in counter-rotating polar orbits. For each pair of satellites in counter-rotating orbits, 4 occultation soundings per orbit period are obtained, amounting to roughly 3,000 per month. Considering that there exists a substantial diurnal cycle in upper air humidity, a benchmark of atmospheric humidity must cover the diurnal cycle, so an absorptive occultation benchmark should consist of three pairs of satellite in counter-rotating orbits, separated by 60° in longitude of the ascending node. Such a configuration will generate 9,000 soundings of atmospheric water vapor every month, with global coverage and coverage of the diurnal cycle.

For absorptive radio occultation, traceability to S.I. standards demands multiple occultation tones to sound every layer of the atmosphere. The raw observable of an absorptive occultation measurement is signal amplitude as a fraction of the signal amplitude measured outside the atmosphere. One tone would allow a retrieval of water vapor when near a water vapor absorption feature spectrally, but an extra tone is needed to unambiguously separate cloud from water vapor, and still another to be serve as a strong check on the calibration; hence, three tones for every atmospheric layer are necessary. The fully incorporated system will benchmark specific humidity from the surface through the stratopause with < 1% absolute accuracy.

II.4 Absolute Incident and Reflected Solar Irradiance

Energy from the Sun sustains both life on the planet as well as the structure and function of the climate and weather systems on Earth. Measurements of total solar irradiance (TSI) have occupied a central part of scientific investigation since the mid-nineteenth century, but until balloon-borne research carried instruments to high altitudes in the middle decades of the twentieth century, atmospheric absorption frustrated attempts to achieve the required accuracy to

establish an absolute scale for the solar "constant" that was recognized as an essential quantity in the historical record of climate and cultural change over recorded history and within the geologic record. TSI observations began with the launch of NIMBUS 7 in 1978 using electrical substitution radiometers, followed by the application of Active Cavity Radiometer Irradiance Monitor (ACRIM) on the Solar Maximum Mission and by Earth Radiation Budget Experiment (ERBE). These were followed by ACRIM instruments on the Solar and Heliospheric Observatory (SOHO). Space-based observations obtained over the past 20 years (see, for example, Lee et al. 1995, Fox et al. 2003, Woods et al. 2004; Lawrence et al. 2003) have converged to first order demonstrating that the amplitude of sunspot induced changes in TSI are about 0.2%, and that decade-long variations of TSI are on the order of 0.1%. The emerging conclusions are based on evidence that tied together, on an absolute scale, the results of ERB, ACRIM I, ACRIM II, and ERBS.

Because of the potential susceptibility of climate, and of surface temperatures in particular, to decadal variability in solar forcing, it is of critical importance that high accuracy, long term observations of total solar irradiance be established as a Benchmark Climate Observation. Continuing efforts to develop on-orbit accuracy has emerged (see Lawrence et al. 2003) with the Solar Radiation and Climate Experiment (SORCE) that includes efforts to improve accuracy (absolute) on-orbit to ±0.01%.

These ongoing efforts to establish the long-term record of absolute total solar irradiance address the following objectives:

- Bring developments in optical innovation, materials research, electronics systems, precision metrology, and on-orbit aging of components to bear on establishing TSI to 100 parts per million referenced to international standards defined in SI units on-orbit.
- Obtain measurements of solar irradiance between 0.3 and 2 μ with a spectral resolution of at least 0.03 cm^{-1} with and accuracy (absolute) of 0.03%.
- Press forward with an analysis of the factors that govern variability in TSI through the use of spectral resolution to improve the credibility of forecasts of solar behavior.

A key aspect underlining the need to put in place a high accuracy record of solar irradiance, independently tested on-orbit against international standards, is the repeated uncertainty introduced into the climate debate, by the lack of trusted records to the level of accuracy required for the diagnoses of causes responsible for observed responses of the climate system to various forcings.

Equally important, solar radiation reflected from the Earth-atmosphere system back to space is the final linchpin in understanding how the climate system attains radiative balance and how that balance changes with time given changes in snow cover, sea ice, agricultural practices, aerosol and cloud properties, pollutant deposition, and deforestation. Expressed in terms of albedo, the dramatic differences between ice/snowpack, ocean, terrestrial vegetation and desert areas is depicted in Figure II.12. Systematic, spatially resolved observations of the time series of absolute spectrally resolved flux of near ultraviolet, visible and near infrared radiation returned to space by the Earth system tied to NIST standards in perpetuity underpin a credible climate record of the changing Earth system.

Planetary Albedo:

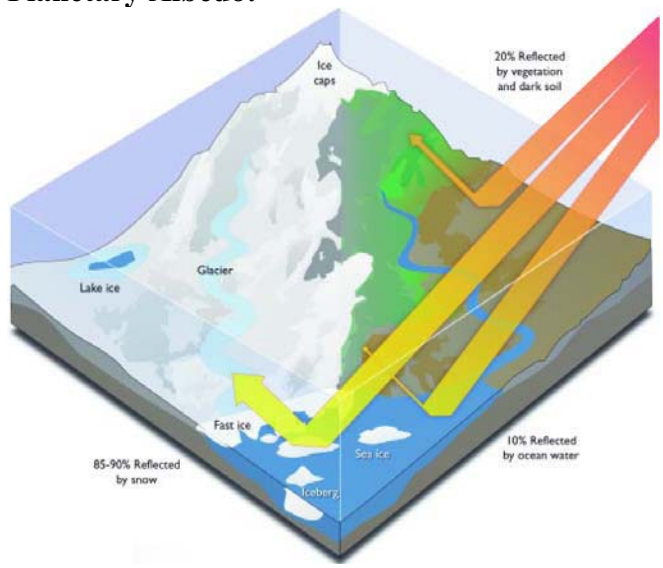


Figure II.12

There are three key components needed for the establishment of high accuracy, long-term records of the reflected component of solar irradiance from space. *The first* is the establishment of SI traceable absolute calibration on-orbit that can be verified at any future time by any nation of the world. This requires a standard for absolute radiance. Continuing work at NIST has significantly improved the accuracy (absolute) of radiance measurements in the visible and near IR through the use of detector based technology using helium cooled bolometers in combination with the Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) approach that provides accuracies to 3 parts in 10^3 in the visible and near IR. These standards can be flown to the middle stratosphere for direct determination of lunar irradiance that in turn will provide an evolving absolute benchmark for high (absolute) accuracy small satellites in Earth orbit.

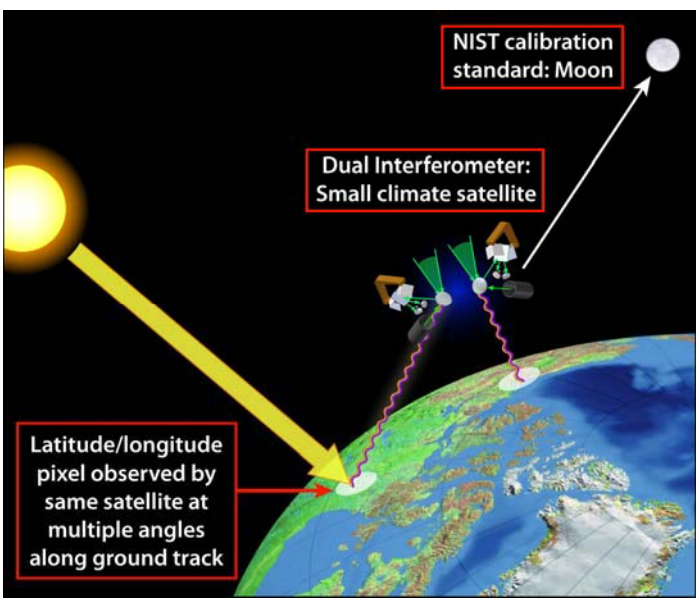


Figure II.13

The second key component is the use of spectral resolution intrinsic to the interferometer that not only contributes to the accuracy (absolute) of the radiance measurement itself, but also provides critical spectral information on the character of the observed scene that distinguishes between ocean, vegetation types, clouds, desert, snow-pack, etc. This is an important strategy to optimize the method by which determination of the hemispheric flux from each latitude/longitude pixel is determined from the observed radiance obtained from low Earth orbit.

The third key component is the use of small, multiple interferometers contained within the same small climate satellite capable of simultaneously observing the reflected radiance from the same footprint at different angles as shown in Figure II.13.

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