Infrared Calibration for Climate: A Perspective on Present and Future High Spectral Resolution Instruments

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ABSTRACT

The new era of high spectral resolution infrared instruments for atmospheric sounding offers great opportunities for climate change applications. A major issue with most of our existing IR observations from space is spectral sampling uncertainty and the lack of standardization in spectral sampling. The new ultra resolution observing capabilities from the AIRS grating spectrometer on the NASA Aqua platform and from new operational FTS instruments (IASI on Metop, CrIS for NPP/NPOESS, and the GIFTS for a GOES demonstration) will go a long way toward improving this situation.

These new observations offer the following improvements:

1. Absolute accuracy, moving from issues of order 1 K to <0.2-0.4 K brightness temperature,
2. More complete spectral coverage, with Nyquist sampling for scale standardization, and
3. Capabilities for unifying IR calibration among different instruments and platforms.

However, more needs to be done to meet the immediate needs for climate and to effectively leverage these new operational weather systems, including

1. Place special emphasis on making new instruments as accurate as they can be to realize the potential of technological investments already made,
2. Maintain a careful validation program for establishing the best possible direct radiance check of long-term accuracy--specifically, continuing to use aircraft-or balloon-borne instruments that are periodically checked directly with NIST, and
3. Commit to a simple, new IR mission that will provide an ongoing backbone for the climate observing system. The new mission would make use of Fourier Transform Spectrometer measurements to fill in spectral and diurnal sampling gaps of the operational systems and provide a benchmark with better than 0.1K 3-sigma accuracy based on standards that are verifiable in-flight.

Key Words: Infrared, Calibration, Spectrometer, Validation, Spectral radiance

1. INTRODUCTION

The challenge is to provide highly sensitive climate reference observations that can be continued for decades to quantify global and regional climate change. Now that it is evident mankind can and is modifying our atmosphere on a global scale, there is a clear mandate to observe the forcing and the response in a way that quantifies the changes for future generations. The results will form a key part of the basis for planning societal approaches to mitigation and adaptation.

Earth radiation budget observations were the first measurements of the earth from space, performed by Verner E. Suomi's pioneering experiment on Explorer 7 in 1959. In the nearly half century since this visionary start to applying satellites to explore the factors that affect the balance of the earth radiation components, much progress has been made in both understanding this delicate balance and in our capability to observe the earth from space with ever improving spacecraft instruments. Fortunately, as society has advanced to the stage that it can alter the atmosphere, it has also advanced highly accurate tools that can be used to monitor these changes. We need to commit to making a range of carefully selected, highly sensitive climate benchmark observations that apply our most accurate remote sensing techniques to this task. These measurement should include detailed measurements of the solar reflected spectrum and the sun itself, the infrared emission spectrum, and other key measurements that can be made with exceptional accuracy (like atmospheric refraction that is highly sensitive to atmospheric structure and composition).

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This paper advocates adding benchmark measurements of the thermal emission spectrum of the earth that contains information on key factors forcing global change and on the response mechanisms, as well as, the overall radiative cooling of the atmosphere. In the next section, we recommend a general concept, then in Section 3 summarize the need for a new system based on shortcomings of existing and planned systems, and in Section 4 discuss the system requirements and general approach for a benchmark infrared system.

2. THE RECOMMENDED INRARED CONCEPT

Driven by applications for vertical temperature and water vapor sounding and atmospheric chemistry, high spectral resolution spacecraft instruments have been developed for infrared observing. Advanced techniques capable of resolving atmospheric absorption lines not only offer higher information content, but also offer significant advantages for accurate calibration. The fundamental advantage over lower spectral resolution measurements for radiometric calibration is discussed in Goody and Haskins (1). In addition, these techniques greatly reduce the uncertainty associated with spectral calibration (2,3). Fourier Transform Spectrometer (FTS) techniques that provide well defined and stable spectral Instrument Line Shape (ILS) and carry onboard laser spectral references are especially effective for delivering high absolute accuracy (4-7). Now we have the opportunity to apply these advantages to characterize climate change.

The key elements of the recommended concept are

1. Monitor <u>thermal emission spectra</u> with a resolution that resolves absorption lines,
2. Extend spectral coverage into the <u>far infrared</u>,
3. Emphasize <u>absolute</u> radiometric & spectral calibration (Stability is not enough),
4. Provide reference sources with <u>in-orbit verification</u> and incorporate measurement redundancy for heightened credibility, and
5. Improve global, temporal coverage using satellites in <u>non-sun-synchronous orbits</u>, which also provides orbit overlaps for calibration transfer.

Although measurement continuity will also be a goal, achieving high absolute accuracy is the best way to guarantee a continuously useful climate record.

The considerations that justify making spectrally resolved IR measurements a high priority for climate are

1. The IR constitutes a <u>fundamental component of the energy budget</u> of the earth,
2. <u>High Accuracy</u> for establishing small trends is relatively easy to achieve, because especially hot or cold reference sources are not needed and highly accurate spectral calibration is possible, and
3. <u>High information content</u> to characterize complex climate change is possible using spectrally resolved radiances.

Included in the high information content category, is the independent information about climate forcing from trace gas changes (CO_2, N_2O, CFCs), and the response (e.g. warming, moisture changes, cloud changes).

The wide range of complex conditions represented by spectrally resolved radiance observations is illustrated in Figure 1 that shows example spectra from the NASA Atmospheric Infrared Sounder (AIRS) instrument, launched on the Aqua platform on 2 May 2002 (8,9). Examples that serve as reminders of the high information content of IR spectral radiances include the sensitivity to vertical structure and atmospheric stability that motivate atmospheric sounding applications (Figure 2), sensitivity to cloud phase and microphysical properties (Figures 3 and 4), information about land surface properties (Figure 5), as well as sensitivity to trace gas distributions.

3. SHORTCOMINGS OF EXISTING AND PLANNED OBSERVATIONS

Infrared observations with climate applications fall into three basic categories: 1) Total, Solar, or IR integrated radiance or flux (e.g. ERB, ERBE, CERES), 2) Multi-channel imaging or sounding filter radiometers (e.g. AVHRR, HIRS, GOES radiometers, MODIS), and 3) High spectral resolution, down-looking sounders (AIRS, TES, IASI, CrIS, GIFTS, future GOES sounders). Only instruments in the first category were originally designed for climate applications, although there is growing use of the other types of measurements. Each has shortcomings that the new system described here would address.

The major problem with relying on spectrally integrated radiance or flux is that spectral integration obscures information content. It is not possible to separate changes in forcing from changes in response, because everything is lumped together. In addition, significant changes can create opposite effects that cancel, thereby masking the changes from detection. For example, one can envision a lapse rate change coupled with a surface warming, such that the total outgoing longwave flux does not change. Therefore, the information content of these integrated observations is quite limited and even for basic detection of change the accuracy requirement must be very high.

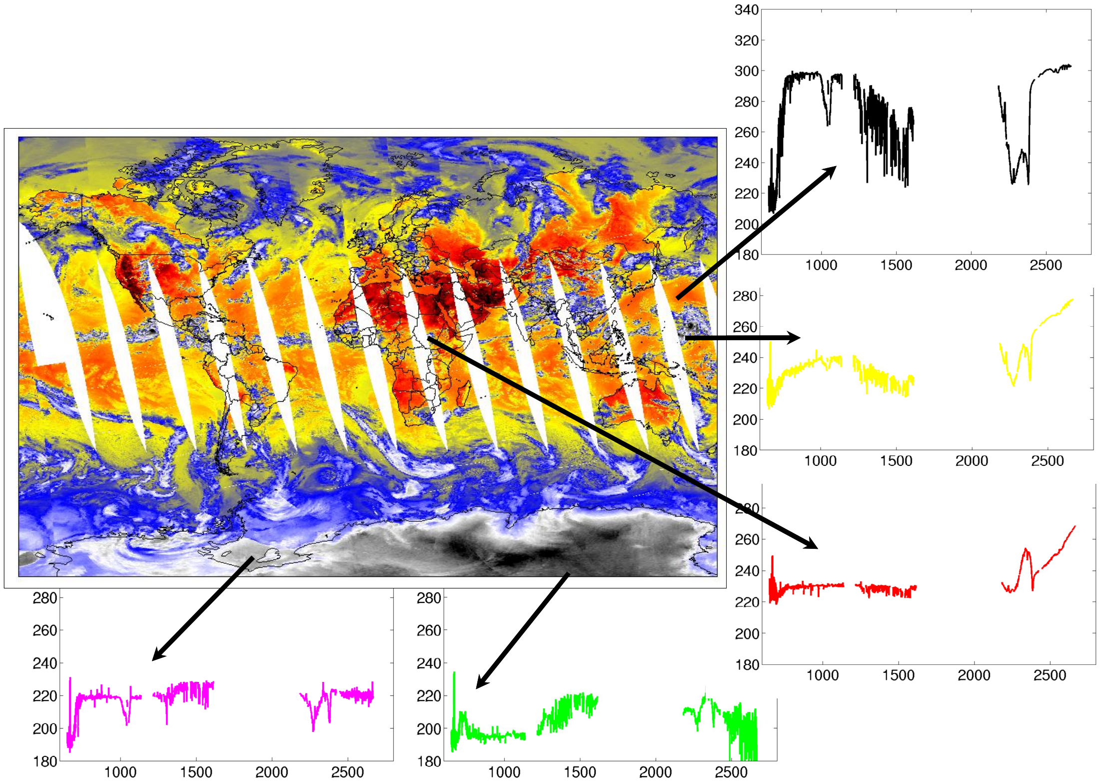


Figure 1. Sample brightness temperature spectra as a function of wavenumber from AIRS (20 July 2002), illustrating the complexity captured by high resolution IR emission spectra.

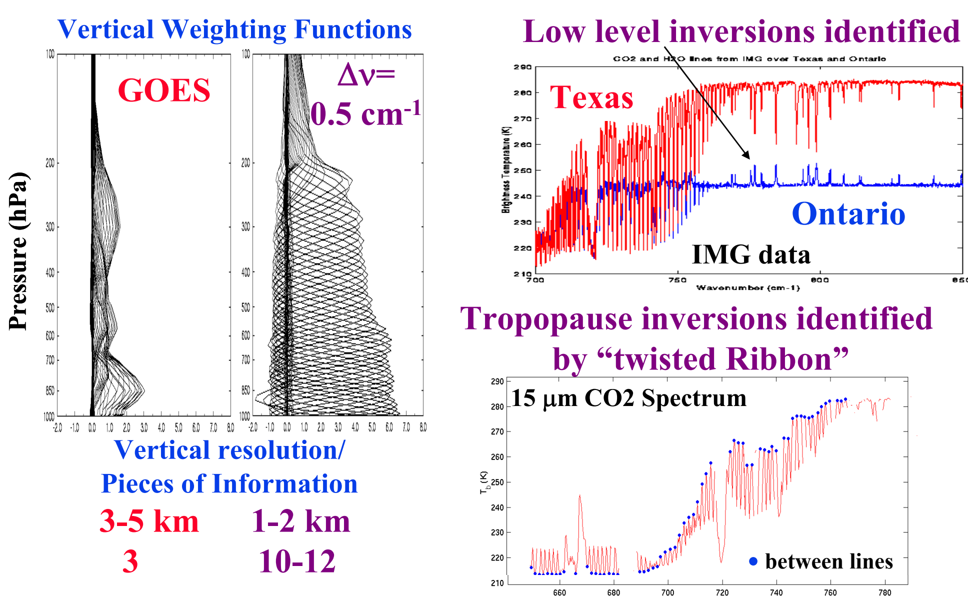
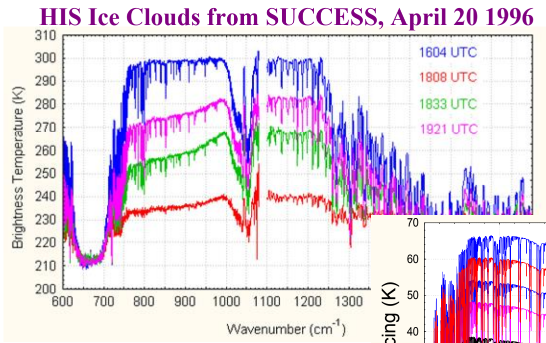


Figure 2. Examples illustrating the sensitivity to vertical structure of IR spectra with resolution capable of resolving individual spectral lines. This sensitivity is important to the characterization of climate change.



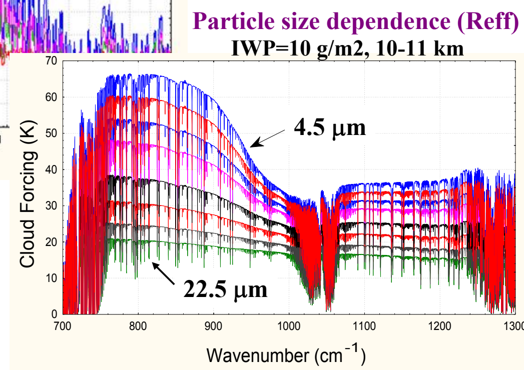


Figure 3. Examples illustrating the sensitivity to cloud phase and particle size, key climate parameters.

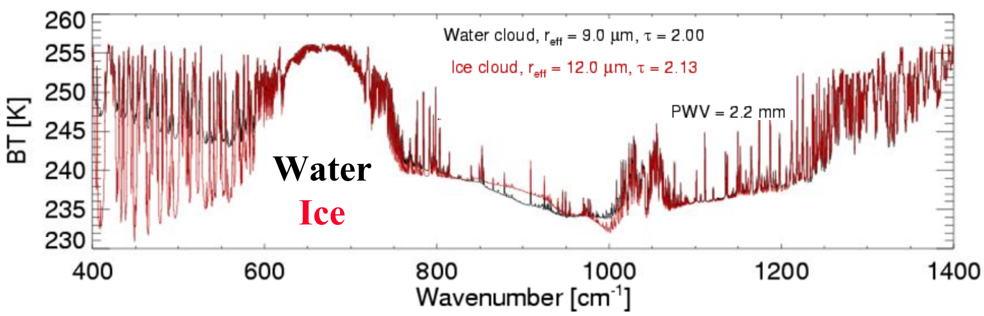


Figure 4. Calculated up-looking brightness temperature spectra illustrating the added information provided by extending the longwave limit of the IR spectrum beyond the normal 15 micron limit. The difference between these two cloud spectra, one for ice cloud and one for water, are hard to identify without the region between 400 and 600 cm^{-1}.

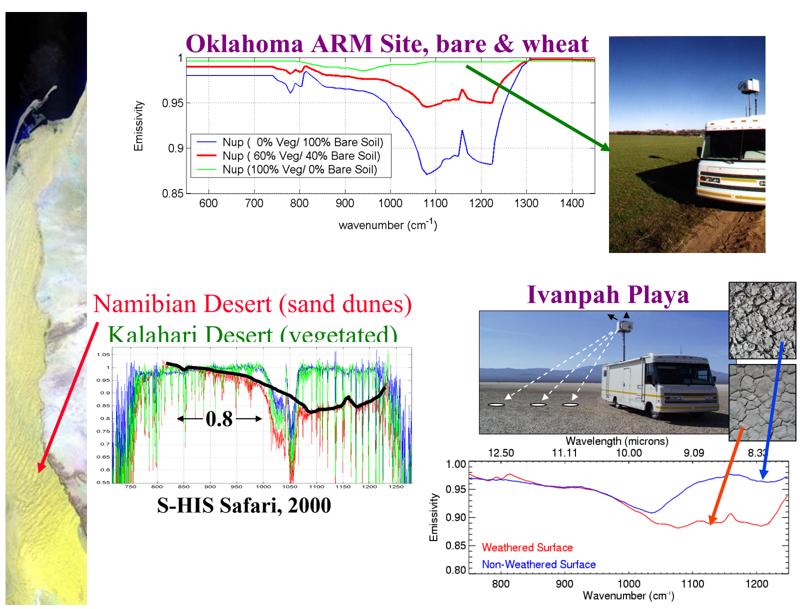


Figure 5. Illustration of land surface emissivity spectral properties that convey information about the effects of climate change on the land surface.

The multi-channel filter radiometers contain more detailed information than spectrally integrating sensors, but this class of instruments has not traditionally been designed for the high absolute calibration accuracy needed to tightly constrain climate change. The radiometric calibration requirement has often been 1 K brightness temperature, interpreted as a 1-sigma requirement. While these instruments generally use 2-body on-orbit calibration (one onboard blackbody and space), few of the blackbodies used have an emissivity that is very well-known or exceptionally high (MODIS is an exception, employing a blackbody with emissivity between 0.987 and 0.994 with uncertainty between 0.0014 and 0.0035). Also, many of the long-wave radiometer channels use non-linear PC MCT detectors that can introduce significant uncertainty.

However, even when the basic radiometric calibration is reasonably good, spectral uncertainties limit the climate capabilities of filter radiometers. Spectral calibration issues include (1) the lack of reproducible instrument-to-instrument spectral channel response functions, and (2) spectral response uncertainty resulting from the uncertainty of the pre-launch characterization or in-orbit changes. For example, instrument-to-instrument differences have been assessed for the HIRS. Differences among the HIRS on NOAA 16, 17 and 18 are estimated to be order ±2 K (10), making consistent climate comparisons impossible without correction, and introducing uncertainties that are difficult to characterize even if corrections are used. The MODIS instrument provides an example of the effects of spectral response uncertainty. Differences that have the signature of spectral response function errors occur for MODIS compared to AIRS (11,12). These errors that have been attributed to MODIS are largest for spectrally opaque channels and exceed 1K for some CO_2 and water vapor bands.

Current and planned high spectral resolution, down-looking sounders like AIRS, IASI, and CrIS are capable of contributing to a climate observing system, but alone are not sufficient. While potentially well-suited to climate observing, current systems have not been optimized for this application. They lack diurnal coverage, do not cover the far IR, and have no capability for in-orbit verification of the reference blackbody temperature and emissivity. All of these deficiencies can be mitigated by the proposed satellite benchmark system, thereby leveraging planned operational systems to create a very capable climate observing system.

The radiometric and spectral calibration of AIRS, IASI, and CrIS have much better absolute accuracy than the filter radiometers. The absolute calibration uncertainty of this class should not exceed 0.5 K; AIRS is expected to be closer to 0.2 to 0.3 K and has been validated by comparison with flights of the UW-SSEC Scanning HIS aircraft instrument (11,13). The onboard blackbodies are all cavity designs with high emissivity (AIRS >0.999, IASI >0.996, CrIS > 0.995) and accurate temperatures (< 0.05-0.08 K). All responses are highly linear in radiance (AIRS <0.3%, <0.05 K corrected; IASI <1% LW & negligible in other bands, <0.15 K corrected; CrIS <0.1% or <0.07 K even uncorrected), and residual polarization errors after correction are small (AIRS <0.4 K worst case, <0.07K corrected; IASI and CrIS <0.05 %-gold mirror, <0.04 K even uncorrected). The information on CrIS was provided by Ron Glumb in personal communication and the IASI information is from Phulpin (14).

The uncertainty related to spectral sampling is very small for all of these instruments. The spectral Instrument Line Shape (ILS) for the FTS instruments is well established by the design geometry (verified by tests with laser sources); for AIRS, the ILS was measured in ground tests using a high resolution FTS. The spectral stability is established by very accurate thermal control for the AIRS spectrometer (<0.25 K annual variation), and by the onboard laser reference for the FTS instruments. Spectral calibrations for these instruments make use of atmospheric lines to realize less than 1 ppm uncertainty (<0.05 K for the 15 micron CO_2 band). Through atmospheric calibration, Larrabee Strow has tracked the small temperature-induced spectral shifts of AIRS (5 ppm p-p annual), demonstrating sub-1 ppm accuracy of calibration from the atmosphere.

Table 1 summarizes some of the key characteristics of these high resolution instruments.

So, in light of the small estimated absolute uncertainty of these new sensors, why do we need even higher absolute accuracy for the benchmark system? The answer is

1. Time to unequivocally quantify climate change is proportional to uncertainty (30 years can go to 10 years by reducing uncertainty from 0.3 to 0.1 K),
2. We can do better, if it has the priority, and
3. Results need to be unassailable to have societal impact: This implies the need to achieve assured high absolute accuracy by employing redundancy and in-orbit verification of the critical in-flight blackbody reference properties.

Table 1. Key properties related to absolute calibration for AIRS, IASI, CrIS and GIFTS. The arrows signify that the property given in the column to its left applies to that column also.

Property	AIRS	IASI	CrIS	GIFTS
Spectral Calibration 1. Absolute Reference 2. Stability 3. ILS knowledge	1. Atmospheric lines 2. ΔT control of spectro-meter/aft optics (2.2% $\nu\Delta$ shift/K) 3. Prelaunch tests with FTS source	1. → 2. Stable laser controls interferogram sampling (< 1ppm over 14 days) 3. fundamental instru-ment design, verified with laser sources in ground testing	1. → (&/or Ne source) 2. → 3. →	1. → 2. → 3. →
Radiometric Cal. 1. Absolute Accuracy 2. BB emissivity 3. Blackbody T error	1. < 0.2-0.3 K at scene T 2. >0.999 3. <0.05 K	1. < 0.5 K at scene T 2. >0.996 3. <0.08 K (?)	1. < 0.4 K at scene T 2. >0.995 3. <0.08 K	1. < 0.2-0.4 K at scene T 2. >0.999 internal 3. <0.056 K 3-sigma
Linearity	<0.3% over much of spectrum, < ~1% peak; **error assumed < 0.05 K after correction**	< 1% longwave, negli-gible mid- & shortwave **error < ~0.15 K after correction*** stability verifiable in orbit from out of band features	<0.1% longwave & negligible elsewhere **error < ~0.07 K even uncorrected** stability verifiable in orbit from out of band features	TBD
Polarization	±worst case 0.4K (9 & 15 μm); **error assumed < 0.07 K after correction**	<0.05% (gold scene mirror with overcoating) **error < 0.04 K even uncorrected**	→	±worst case ~0.2K (9 & 15 μm); **error assumed < 0.05 K after correction**
Reference	Pagano et al, ITWG, 2003	Thierry Phulpin, 2006 & Denis Blumstein	Ron Glumb, ITT	

In summary, among existing and planned sensors, the new high resolution sensors are by far the best candidates for making highly accurate climate observations. However, even using these effectively will depend on the development of a new benchmark satellite as the key element of a definitive climate observing system.

4. BENCHMARK CLIMATE OBSERVING SYSTEM REQUIREMENTS AND APPROACH

The need for small, climate-focused satellites to observe spectrally resolved IR radiance was first proposed in the early 1990s by Jim Hansen under the name CLIMSAT (15, 16). Then, in the 1996 Jim Anderson introduced the notion of a climate benchmark mission named Arrhenius, with strong emphasis on direct connections to international standards (17) and was later augmented with in-flight source verification (18). Now, a generalized version of this concept is emerging as one of three key recommendations from a May 2006 workshop, Achieving Satellite Instrument Calibration for Climate Change (ASIC[3]). The workshop was called by NOAA, NIST, NPOESS/IPO, NASA, NSF, and the WMO to formulate a national roadmap for a calibration system to achieve the requirements for long-term global monitoring.

The basic mission for providing an IR Spectral Measurement Standard includes the following key elements:

1. Far IR spectral coverage (to 50 or 100 microns) to capture most of the emitted energy and unique information on cirrus clouds
2. Orbit providing local time coverage and crossing operational sun-synchronous orbits to allow inter-comparisons (e.g. 90-degree polar)
3. Fourier Transform approach with stable laser reference providing an accurate spectral standard
4. Dual instruments to detect unexpected drifts
5. Overall absolute calibration uncertainty (3-sigma) < 0.1 K
6. Highly linear detectors, with on-board non-linearity monitoring, using out-of-band response
7. 2 or more full-aperture, high-emissivity calibration reference blackbodies
8. On-orbit verification for key radiometric properties (e.g. Blackbody T, ε)
9. Multiple temperature monitoring standards for robustness
10. Polarization: Design to eliminate or measure in-orbit

Recent developments have demonstrated that this demanding calibration requirement can be met as shown in Figure 6. This analysis is based on making use of an onboard calibration reference similar to the blackbodies built by the UW-SSEC for the GIFTS internal calibration (19).

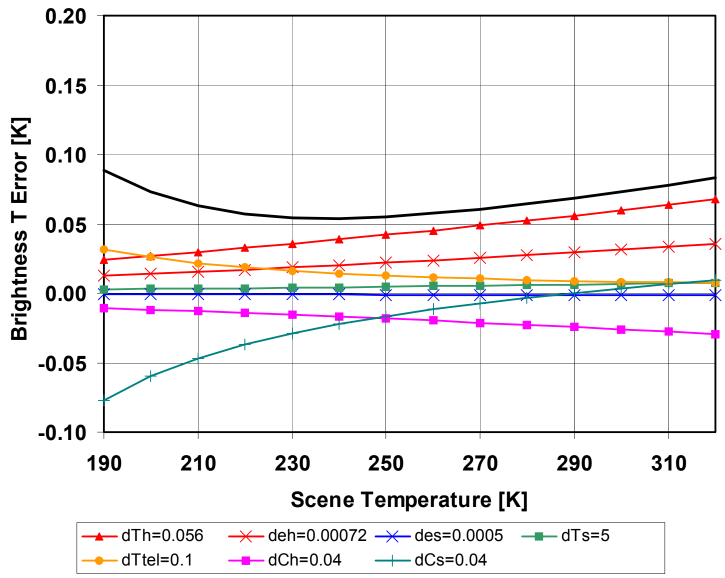


Figure 6. Estimated absolute, 3-sigma brightness temperature error for an instrument employing an onboard blackbody reference with parameter uncertainties matching those realized for the GIFTS program. The estimate assumes the use of a space view, very linear detectors, and a design that strongly suppresses uncertainty stemming from polarization issues. This performance meets the absolute calibration requirement for the benchmark system with significant margin.

In-flight verification approaches will be used to test the normal assumptions of stability for the basic properties needed to establish absolute calibration. Phase change materials will be used to verify the absolute temperature of the blackbody reference, and reflection sources will be used to monitor any changes in blackbody emissivity. The linearity will also be verified by monitoring harmonic contributions outside of the sensitive spectral band.

All of the key elements of this system are achievable with present-day technology, and systems with many of the combined characteristics have been demonstrated. It is time to proceed with a detailed design and to move forward toward flight as soon as possible.

5. CONCLUSIONS

High spectral resolution infrared measurements have demonstrated potential to greatly improve space-borne measurements of the forcing and response associated with climate change. The type of mission described here offers very high absolute accuracy with high information content. It would greatly enhance the value of upcoming operational systems for climate applications, by filling in spectral and diurnal sampling gaps and by acting as a benchmark with improved ties to fundamental standards in-flight. Therefore, it would go a long way toward unifying the entire international complement of IR observations from different instruments and platforms.

With the vision of this unified operational weather and climate observing system in mind, we need to

1. Endorse the climate role of our operational systems and put special emphasis on making new instruments as accurate as they can be, so as to realize the potential of technological investments already made,
2. Maintain a careful radiance validation program for establishing the best possible direct radiance check of long-term accuracy, including the continued use of aircraft- or balloon-borne instruments that are periodically checked directly with NIST, and
3. Commit to a simple, <u>new IR mission</u> that will provide an ongoing backbone for the climate observing system.

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