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Radiometric Stability of the SABER Instrument

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Abstract The SABER instrument on the National Aeronautics and Space Administration Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite continues to provide a long-term record of Earth’s stratosphere, mesosphere, and lower thermosphere. The SABER data are being used to examine long-term changes and trends in temperature, water vapor, and carbon dioxide. A tacit, central assumption of these analyses is that the SABER instrument radiometric calibration is not changing with time; that is, the instrument is stable. SABER stratospheric temperatures and those derived from Global Positioning System Radio Occultation measurements are compared to examine SABER’s stability. Global Positioning System Radio Occultation measurements are inherently stable due to the accuracy and traceability of the measured phase delay rate to the Système International de l’Unité de la Seconde. Differences in global annual mean SABER and COSMIC lower stratospheric temperatures show little significant change with time in the 11 years spanning 2007–2017. From this analysis we infer that SABER temperatures are stable to better than 0.1 to 0.2 K per decade.

Plain Language Summary SABER is an instrument that has been in orbit on the National Aeronautics and Space Administration Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite for over 18 years, observing temperature and composition of the atmosphere from 15 to over 100 km in altitude. Over this time the atmosphere has undergone changes. A key to diagnosing these changes is knowing that the SABER instrument itself has not been changing and so observed atmospheric changes are in fact real. This paper presents an analysis of SABER temperatures in the Earth’s lower stratosphere (15- to 35-km altitude) relative to those derived from Global Positioning System-Radio Occultation (GPS-RO) measurements of atmospheric refraction. The GPS-RO temperatures are inherently stable due to their traceability to the definition of the second. The analysis of SABER and GPS-RO temperatures shows that the SABER instrument is remarkably stable, better than 0.1 to 0.2 K per decade.

1. Introduction

The SABER instrument on the National Aeronautics and Space Administration Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite has been observing the terrestrial stratosphere, mesosphere, and thermosphere since its launch in December 2001. SABER is a radiometer that measures infrared radiance (W·m⁻²·sr⁻¹) in 10 distinct spectral intervals spanning 17 to 1.27 μm (Russell et al., 1999) for the purpose of understanding the energy balance of the mesosphere and lower thermosphere (Mlynczak, 1997). The spectral intervals for each channel are obtained through the use of interference filters that each pass a well-defined portion of the infrared spectrum for a particular measurement. The length and consistency of the SABER data set make it ideal for examining trends in the middle atmosphere. Recent studies have analyzed trends in temperature (Garcia et al., 2019), carbon dioxide (Yue et al., 2015; Rezac et al., 2018), and water vapor (Yue et al., 2019) using SABER data. A tacit but central assumption of these analyses is that the SABER instrument has remained stable; that is, its absolute radiometric calibration is unchanged, over the life of the instrument; or, that any changes with time are significantly smaller than the observed trends.
In principle, it is not possible to accurately quantify small changes in SABER's calibration using the SABER instrument alone. SABER and all other instruments presently observing Earth from orbit do not carry onboard, absolute radiance *standards* that can be used to diagnose calibration changes over time, traceable to Système Internationale (SI) units. Two new instruments now in development, CLARREO Pathfinder (Wielicki et al., 2013; Shea et al., 2017; Kopp et al., 2017) and TRUTHS (Fox et al., 2011), are designed for measuring the small changes in top-of-atmosphere radiation associated with changes in tropospheric climate and carry onboard reference standards for detecting instrument calibration drifts for the express purpose of diagnosing and correcting instrument drifts so they do not impact the observation of trends. SABER does carry a fixed-temperature (295 K) blackbody to provide a steady reference for calibrating most of its channels. The shorter wavelength channels (OH; 1.6 and 2.0 \(\mu\)m; O2(1\(\Delta\)) at 1.27 \(\mu\)m) are routinely illuminated by a near-infrared source to verify stability over time. The illumination from these sources may drift with time, for example, due to ageing or to exposure to the space environment. The temperature sensors that provide the blackbody temperature may also drift with time due to ageing or to changes in stress on their mounting points, effectively causing a drift in the calibrated radiances. It is also possible for slight shifts to occur (due to ageing) in the spectral filters used to isolate the infrared radiation admitted to the detector in each of SABER's channels, which could induce false trends as the SABER processing software would be using an incorrect spectral response. There is no reliable way to identify and accurately correct for any of these mechanisms if they are occurring. Note that large drifts (e.g., several kelvins per decade in temperature) would presumably be noted as the SABER temperatures would diverge from ongoing correlative measurement comparisons. In the case of large drifts, absent an onboard reference standard, the data could become largely unusable.

Stratospheric temperature variations over time provide an ideal measure of SABER's stability. The radiative transfer in the 15-\(\mu\)m bands of CO2 observed by SABER and used to derive temperature is in local thermodynamic equilibrium in the stratosphere. The source function in the radiative transfer equation is the Planck blackbody function and thus is only a function of the kinetic temperature of the stratospheric gas molecules. Consequently, there is a very close relationship between instrument calibration, which is dependent on the instrument blackbody temperature, and the derived temperature of the atmosphere.

In order to assess the long-term stability of the SABER instrument, we compare global annual mean SABER stratospheric temperatures with those from COSMIC Global Positioning System Radio Occultation (GPS-RO) measurements. Temperatures derived from the GPS-RO technique are of benchmark quality (Goody et al., 1998; Leroy et al., 2006) due to the direct traceability of atmospheric refractivity to the SI definition of the second (Wielicki et al., 2013). Differences over time between SABER and COSMIC are then an indication of the long-term stability of the SABER instrument. Steiner et al. (2019) indicate that the structural uncertainty in trends derived from GPS temperature measurements is less than 0.05 K per decade for global mean data, making COSMIC temperatures ideal for the assessment of the stability of the SABER instrument.

**2. Analysis Approach**

COSMIC and SABER data between January 2007 and December 2017 (11 total years) are analyzed. COSMIC and SABER temperature data are obtained (see the Acknowledgments section) and the temperature profiles screened to eliminate profiles with missing data and profiles with anomalous temperature values, the latter being any temperature profile with values outside of the range from 173.15 to 283.15 K. The range of altitudes is limited to 15 to 35 km. This screening results in elimination of 0.04% to 0.48% of SABER temperature profiles and 0.57% to 1.99% of COSMIC data, depending on year. In any given year there are approximately 400,000 SABER profiles and between 496,000 (in 2007) and 82,000 (in 2017) COSMIC temperature profiles. “Global” annual mean temperature profiles are computed for both COSMIC and SABER within the range of latitudes from 50°N to 50°S, accounting for nearly 77% of atmospheric area. This range of latitudes corresponds to that continuously observed by SABER. Annual mean temperatures within this latitude range and shown in this paper will be referred to as “global” annual means.

To compare the SABER and COSMIC data, they must be placed on the same vertical spacing in altitude and the effect of the SABER field of view (nominally 2-km full width at half maximum) must be accounted for in the COSMIC data. SABER temperatures are nominally on an altitude spacing of 0.4 km, and a three-point spline interpolation is applied to place each temperature profile onto fixed altitude grid between 15 and
35 km in steps of 0.5 km. The vertical resolution of GPS measurements in the lower stratosphere is between 1.2 and 1.5 km (Kursinski et al., 1997; Khaykin et al., 2017). The COSMIC data sampling is nominally on a spacing of 0.02 km. The COSMIC data at this high spatial sampling are convolved with a 2-km full width at half maximum Gaussian function to simulate the average temperature over a vertical width corresponding to the SABER field of view. This process is applied to each COSMIC temperature profile in steps of 0.5 km to produce a new COSMIC temperature profile on the same vertical resolution and altitude grid as the SABER data.

Zonal annual averages of SABER and COSMIC temperature profiles are computed in 5° latitude bins on a monthly basis. Global monthly means are derived by computing the cosine-latitude weighted mean of the temperature profiles over the defined range of latitudes. Global annual means are computed from the twelve monthly means each calendar year.

### 3. Results

The SABER and COSMIC global annual mean temperature profiles are remarkably consistent over the 2007–2017 timeframe. Shown in Figure 1 is a plot of the COSMIC and SABER global annual mean temperatures and their difference for 2007. The difference plot shows that SABER exhibits a warm bias throughout the lower stratosphere relative to COSMIC. All other years are alike. A similar SABER warm bias relative to other lower stratosphere temperature records was noted by Remsberg et al. (2008). Figure 2 shows the average difference in global annual mean temperatures, COSMIC minus SABER, over 11 years, 2007 to 2017 inclusive. Although SABER has a warm bias relative to COSMIC, SABER’s stability is determined by examining the change in the difference between SABER and COSMIC with time. With COSMIC temperatures taken to be benchmarks, the change between the difference in COSMIC and SABER over time is an indicator of the stability of SABER.

![Figure 1. SABER (red) and COSMIC (black) global annual mean temperature profiles for 2007 (left frame) and the difference between COSMIC and SABER (right frame).](image-url)
Shown in Figure 3 is the difference between the COSMIC minus SABER global annual mean temperature in 2017 and the COSMIC minus SABER global annual mean temperature in 2007, that is, the SABER stability. The differences range from \(-0.05\) K at 15 km to as large as 0.25 K at 27 km. The absolute value of this “difference of differences” is less than 0.2 K over most of the lower stratosphere between 15 and 35 km. On this basis alone it can be stated that the stability of SABER relative to COSMIC is better than \(-0.2\) K per decade. This value is significant for stratospheric trends which are \(<0.4\) K per decade over this time period as shown by Khaykin et al. (2017) using COSMIC and AMSU data. Note that the stability is not the trend, the latter of which is derived first by removing the natural variability (e.g., the quasi-biennial oscillation, solar cycle, and El Niño-Southern Oscillation) from the signal before a trend is derived. Stability is the first and most essential measurement attribute for accurate trend detection and assessing trend uncertainty.

The vertical structure in Figure 3, however, is not consistent solely with a drift in the radiometric calibration of SABER instrument. That is, drift in radiometric calibration (e.g., due to a change in the blackbody or its temperature sensors) should not have a highly structured vertical dependence. A slow drift in radiometric calibration should manifest itself as a nearly uniform change in temperature with altitude, according to the temperature dependence of the Planck function at stratospheric temperatures. The more likely cause of the vertical structure in Figure 3 is other uncertainties in the SABER temperature retrieval process. Specifically, ozone is an interfering species in the carbon dioxide bands at 15 \(\mu m\) observed by SABER for temperature retrievals. SABER simultaneously measures ozone (at 9.6 \(\mu m\)), and this is used in the retrieval of SABER temperatures. The SABER ozone channel is optimized for mesospheric ozone observations and becomes optically thick below 25 km, resulting in larger uncertainties in the retrieved lower stratospheric ozone, which may then translate into uncertainty in SABER lower stratospheric temperature. It is possible that uncertainties in lower stratospheric ozone are reflected in some of the variations in Figure 3.

To determine if there is a consistent, year-by-year drift in the COSMIC-SABER temperature difference (i.e., the SABER stability relative to COSMIC), we have examined the differences in COSMIC minus SABER global annual mean temperatures as in Figure 3, but for each year relative to 2007. Shown in Figure 4 is the time history of SABER stability as given by the difference between the COSMIC minus SABER global annual mean temperature in “year” (e.g., 2008, 2009, and 2010) and the COSMIC minus SABER global annual mean temperature in 2007. There is no obvious, monotonic progression of SABER stability over the decade from 2007 to 2017. The stability appears nearly constant at each altitude through 2015. In 2016 the COSMIC minus SABER difference relative to 2007 in the very lower stratosphere was quite large (\(-0.8\) K at 15 km). This one year appears to be anomalous. We suggest that the effect is not due to instability in SABER. Rather, 2016 was the peak of the most recent El Niño, and we suggest that SABER temperature retrievals near 15 km might have been influenced by the presence of high clouds this year, particularly in the tropics which account for half of the global average area considered here.

Shown in Figure 5 is the average of the data shown in Figure 4, representing the average of the year-by-year differences from 2008 to 2017 in COSMIC and SABER with the COSMIC-SABER difference in 2007. The absolute value of this difference is less than 0.1 K except below 17 km. From this result and the data in Figure 3, we estimate that the actual SABER radiometric stability is between 0.1 and 0.2 K per decade.

The stability of SABER can also be assessed by computing the trend in the difference between the SABER and COSMIC global annual mean temperatures. Figure 6 shows the time series of COSMIC minus SABER global annual mean temperatures from 2007 to 2017, 11 years total, at altitudes of 15, 20, 25, 30, and 35 km. The dashed straight line through each of the time series is the least squares fit line, the slope of which is an estimate of the SABER stability. With the exception of data at 15 km, the slopes are all very
small. Figure 7 shows the stability computed this way from 15 to 35 km in 1-km steps. The stability is between 0.05 and 0.2 K per decade except at 28 km and below 16 km. Below 17 km the slope is being impacted by the data in 2016, the peak El Niño–Southern Oscillation year, as noted above in the discussion of Figure 4. This additional approach to assessing the SABER stability further illustrates that the instrument is stable to 0.1 to 0.2 K per decade, or better, depending on altitude.

4. Discussion and Summary

The above analysis demonstrates that the SABER instrument is exceptionally stable relative to COSMIC in the lower stratosphere in the decade spanning 2007 to 2017. This is remarkable for an instrument launched in 2001 and for a mission that was originally intended to last two years but is now past its eighteenth anniversary in orbit—with no apparent significant degradation in performance. The SABER radiometric stability in the stratosphere will also apply throughout the mesosphere and lower thermosphere. As the modeled and SABER-derived trends below 100 km are less than 1 K per decade (Garcia et al., 2019), SABER stability is a factor to be considered in overall trend uncertainty and in future instrument design (discussed below). We also note that lower stratospheric trends derived for SABER data (Garcia et al., 2019) over the 50°N to 50°S latitude region appear consistent with the global lower stratosphere trends presented in Khaykin et al. [2017], further supporting the case for SABER’s stability. The SABER team will continue to monitor SABER’s performance relative to COSMIC and will investigate stability as a function of latitude in a future publication in order to complement the quasi-global annual averages shown here.

Figure 3. SABER stability defined as the difference between the COSMIC minus SABER global annual mean temperature profiles in 2017 and the COSMIC minus SABER global annual mean temperature profiles in 2007.

Figure 4. The time history of SABER stability as given by the difference between the COSMIC minus SABER global annual mean temperature in “year” (e.g., 2008, 2009, and 2010) and the COSMIC minus SABER global annual mean temperature in 2007.
French and Mulligan (2010) suggested that there was significant instability approaching 7 K per decade in SABER temperatures. This suggestion was based on observed changes in the mesopause region temperatures observed by SABER over Antarctica relative to ground-based temperature observations and observations by the MLS instrument on the Aura satellite. The results presented above show that the SABER instrument is very stable on decadal time scales covering the period of the French and Mulligan observations. It is extremely unlikely that SABER would have an instrument instability that occurs only in a polar region. We suggest that French and Mulligan observed algorithm instability in the SABER Version 1.07 data set used in their analysis. Specifically, Version 1.07 of the SABER data set uses model values of carbon dioxide in the mesosphere where the concentration is significantly smaller (and more variable) than its well-mixed tropospheric value. SABER derives temperature using measurements of infrared emission from carbon dioxide and accurate values of the carbon dioxide mixing ratio are essential for SABER to deliver accurate temperatures. In particular, in polar night conditions observed by French and Mulligan, it is very likely the model carbon dioxide values were not indicative of the actual values and their long-term changes. This would translate into an apparent trend in SABER temperatures that is due to essential but incorrect parameters in the algorithm. The current SABER Version 2 data also use model carbon dioxide in the temperature retrievals both day and night. However, there is a version of the SABER data available in which temperature and carbon dioxide are simultaneously retrieved in the daytime (Rezac et al., 2015). Retrieval of CO$_2$ concentrations at night has not proven feasible with SABER. The CO$_2$ daytime concentration is derived from observations of emission from the 4.3-$\mu$m band of CO$_2$ in conjunction with observations of CO$_2$ emission at 15 $\mu$m, the

Figure 5. Average of data shown in Figure 4, of the global annual mean COSMIC minus SABER stratospheric temperature differences in years 2008, 2009, 2010, etc., to 2017 and the COSMIC minus SABER global annual mean temperature difference in 2007.

Figure 6. Time series of the difference (COSMIC minus SABER) in global annual mean temperatures at 15, 20, 25, 30, and 35 km (solid) lines from 2007 to 2017. The dashed lines are the least squares fit to each of the time series, the slope of which lines provides another estimate of the SABER stability.
Figure 7. SABER stability (K per decade) as a function altitude (in 1-km steps) determined from the slope of the least squares line fit to the time series of the difference in global annual mean temperatures (COSMIC minus SABER) from 2007 to 2017.

latter of which provides temperature. During daytime the 4.3-μm band is strongly excited by the absorption of sunlight and generates a bright radiative signal that is readily measured. At night, in the absence of sunlight, the 4.3-μm band emission is substantially weaker, such that there is not sufficient signal-to-noise ratio to allow retrieval of carbon dioxide.

It is important to consider reasons that the SABER instrument is so stable. First and foremost, accurate absolute radiometric calibration of the SABER instrument was established as a priority from the beginning of the project (Tansock et al., 2003). Establishment of calibration as a priority played a major role in the instrument optical, thermal, and mechanical design, in parts selection for flight, and in test procedures, all of which ultimately led to a stable instrument. For example, SABER’s optical system stability is enhanced by its cylindrical symmetry and the SABER telescope cooling path is designed to minimize asymmetrical radial heat loads that would otherwise distort the long optical train.

Regarding parts selection and testing, the SABER calibration blackbody temperatures are measured and controlled with precision thermistors having a 0.02% stability per year specification (~0.06 K/year at SABER’s blackbody temperature). This is likely a conservative estimate because the specified stability is from a characterization at a much higher temperature than the stable in-flight operating temperature of the blackbody (295 K). Before selecting the flight thermistors, representatives from the flight lot went through a rigorous test program where temperature stability was tracked while inducing the effects of thermal cycling, mounting strain, moisture, and vibration (all three axes). Throughout this testing, no significant resistance shift was observed providing evidence of the robust nature of these thermistors and their ability to reliably measure and control the SABER blackbody temperature. Finally, the set of flight thermistors was thermal cycled to achieve the desired state of stability before mounting in the SABER flight blackbody.

SABER’s uniform and continuous mode of operation also plays a key role in achieving its stability. SABER routinely scans the Earth’s atmosphere with regular observations of the calibration blackbody—this is its nominal operational science mode which it has been in for over 98% of the mission. As such, SABER has essentially constant power dissipation which results in stable electronics temperatures on orbit. This is a key factor in minimizing voltage reference drifts which could cause trends in the instrument response. In addition, the SABER instrument is housed in the center of the TIMED spacecraft, providing overall thermal stability and affording minimal exposure to the space environment. Every 60 days the spacecraft undergoes a “yaw” maneuver to keep SABER on the cold side of the spacecraft. During this maneuver the SABER scan mirror is turned to face the calibration blackbody and effectively serves as a shield against any contaminants that may enter the telescope as the spacecraft rotates 180° in yaw. Finally, the focal plane of infrared detectors has been kept within 0.25 K of its 77-K setpoint for the entirety of its mission, with the exception of occasional thermal cycling early in the mission to drive off volatiles that were accumulating on the cold focal plane window. The cooler is presently cycled off every three years for this purpose; otherwise, the SABER instrument has run continuously since its launch in 2001.

In summary, the design of the SABER instrument and the TIMED spacecraft effectively minimizes perturbations to the instrument, enabling stability, while SABER’s location and viewing geometry minimize the degrading effects of the space environment. SABER’s routine operational mode minimizes parts degradation. The deliberate emphasis on calibration of SABER led to design choices that maximized the probability of long life and radiometric stability and are now recognized as best practices in development of radiometric sensors (Tansock et al., 2015). These design aspects are critical considerations for future sensors, particularly if independent onboard SI-traceable calibration standards [e.g., Wielicki et al., 2013] are not included. Under these circumstances, continued reliance on exceptional radiometric stability is required to produce a new data set of sufficient quality for continued analysis of long-term trends and changes. As noted above, the SABER stability is a component of the temperature trend uncertainty in the stratosphere, mesosphere, and lower thermosphere. Therefore, new infrared instruments, particularly those intended for smallsats
or cubesats, must place emphasis on calibration and must develop designs that enable long-term, high-stability performance in order produce measurements capable of credibly continuing the long-term SABER record.

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References


