Traceability and consistency of COSMIC radio occultation in comparison with NOAA-20 CrIS infrared sounder observations

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ABSTRACT

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellite system for the Radio Occultation (RO) mission provides advances in meteorology, ionospheric research, climatology, and space weather by utilizing the readily available Global Navigation Satellite System (GNSS) signals in conjunction with GNSS receivers in low Earth orbiting (LEO) satellites. COSMIC was launched in 2006 with six satellites in a constellation known as FORMOSAT-3 in low inclination orbits to provide global coverage. RO relies on the calculation of GNSS signal time delay in carrier phase due to the atmosphere in the L1 and L2 signals transmitted between the GNSS and receiving satellites in the LEO orbit, from which the bending angle, refractivity, and atmospheric profiles can be retrieved. Since the Atomic Frequency Standard (AFS) based GNSS signal is International System of Units (SI) traceable, is actively maintained, and the precise orbit of both the GNSS and the LEO satellites can be determined accurately, RO data from COSMIC have been recognized as stable references for data assimilation (DA) in Numerical Weather Prediction (NWP) models. Currently, NWP customers are eager to obtain similar data from COSMIC2 which will be launched in the next few months to mitigate the aging COSMIC constellation and diminishing number of ROs.

Meanwhile, the calibration of the hyperspectral sounders such as Cross-track Infrared Sounder (CrIS) on NOAA-20 relies on a high quality onboard blackbody which is also traceable to SI through prelaunch characterization relating to the laboratory blackbody with traceable calibration to NIST, and hyperspectral sounders have been recognized as on-orbit calibration references for other broad- or narrow-band infrared (IR) observations. In this paper we analyze the traceability of both systems in their raw measurements as well as retrieved geophysical variables. Comparisons are also made in spectral radiance/brightness temperature derived from the two systems. The objective is to gain a better understanding of the different paths of traceability to SI and ensure the consistency of the products for numerical weather prediction and other applications. This study directly supports the COSMIC2 verification and validation, as well as postlaunch calibration/validation of NOAA-20 CrIS.

Keywords: Radio Occultation, COSMIC, SI traceability, hyperspectral infrared sounder, NOAA-20 CrIS

1. INTRODUCTION

The GNSS (Global Navigation Satellite System) satellites operationally broadcast radio signals, which have become the backbone of modern navigation. In addition to a large number of common GNSS uses in our daily lives, a unique scientific application is the atmospheric radio occultation (RO) which relies on the detection of a change in the GNSS radio signal as it passes through the Earth's atmosphere. When this occurs, the signal is refracted (or bent) along the way, and then received by a GNSS receiver on a low-Earth orbit (LEO) satellite. The magnitude of the refraction depends on several factors but it is dominated by the temperature and water vapor concentration in the atmosphere. The bending can be calculated using the Doppler shift of the signal given the precise positions and geometry of the GNSS and LEO satellites. Then the amount of bending can be related to the refractive index by using the Abel transform on the formula relating bending angle to refractivity. For the neutral atmosphere (atmosphere below the ionosphere), the "dry" atmosphere temperature at the "tangent point" can be derived from the bending angle. As the LEO satellite moves rapidly, the tangent point changes in succession and "slices" through the atmosphere at different altitudes, thus providing measurements for retrieving vertical temperature profiles for atmospheric sounding. With additional information from weather models such as ECMWF (European Centre for Medium-Range Weather Forecasts), the "dry" atmosphere temperature can be resolved to retrieve atmospheric temperature, water vapor, and pressure, and thus gives the atmospheric sounding profiles. It is noted that RO is a limb sounding technique, as opposed to the nadir sounding by infrared and microwave sounders. The GNSS technology relies on very accurate time information, which is generated with atomic

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clocks traceable to the Atomic Frequency Standard (AFS) with very high absolute accuracy and precision [1][2][12]. As a result, it is inferred that the radio occultation (RO) is SI traceable (GNSS time). However, this SI traceability has limitations in the different levels of RO products. This paper analyzes the SI traceability of the GNSS RO measurements and limitations in the traceability. This is compared to the infrared sounder radiometric traceability. The advantages and limitations of each in terms of SI traceability are investigated by analyzing sample data.

2. SI TRACEABILITY OF RADIO OCCULTATION VS. INFRARED SOUNDERS

According to BIPM (Bureau International des Poids et Mesures), the "SI" refers to International System of Units (or Système International d'unités in French). This system of units was developed to provide an error-free means of comparing measurements made anywhere in the world, at any time, to one another. To accomplish this task, SI Units are defined by basic properties of matter. For example, the second is defined by the quantum mechanical properties of the Cesium atom. These quantum mechanical properties will be exactly the same, regardless of at what laboratory, or when, they are measured. Therefore, SI traceability is the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." In this definition, calibration refers to "establishing a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, then, uses this information to establish a relation for obtaining a measurement result from an indication" (International vocabulary of metrology – Basic and general concepts and associated terms). In this context, the GNSS RO measurement is fundamentally traceable to time and AFS, while the infrared sounder measurement is traceable to blackbody radiance in the unit of W/(m^2-sr-μm).

In the context of satellite remote sensing, the NASA CLARREO project defines SI traceability as "a technique used for satellite observations that links a satellite's measurements to internationally-recognized measurement standards." Using this technique, measurements from different satellites can be merged into "one long-term observational record that is free from small drifts in measurements due to slight differences between satellites." https://clarreo.larc.nasa.gov/about-SITrace.html.

2.1 From GNSS, RTK, to RO

It is necessary to discuss the basic principles of GNSS to understand SI traceability. The GNSS is a satellite-based navigation system which provides geolocation and time information to a GNSS receiver anywhere on or near the Earth's surface where there is an unobstructed line of sight to four or more GNSS satellites. The GNSS is based on time and the known position of GNSS satellites. The satellites carry very stable and accurate atomic clocks that are synchronized with one another and with the ground clocks. Any clock drift and offset from the true time maintained by the ground segment is determined and broadcast. In the same manner, the satellite locations are known with great precision. GNSS receivers have clocks as well, but they are less stable and less precise [12].

GNSS satellites continuously broadcast data about their current time, clock drift and ephemeris. A GNSS receiver monitors multiple satellites and solves equations to determine the precise position of the receiver and its clock deviation from true time. At a minimum, four satellites must be in view of the receiver for it to compute four unknown quantities (three position coordinates and clock error). Conceptually, the receiver measures the Time of Arrival (TOA) (according to its own clock) of four satellite signals. From the TOAs and the Time of Transmission (TOT), the receiver forms four Time of Flight (TOF) values, which are (given the speed of light) approximately equivalent to receiver-satellite ranges. The receiver then computes its three-dimensional position and clock deviation from the four TOFs.

While conceptually the GNSS positioning "fixes" rely on the time of flight differences from the receiver to at least four GNSS satellites, more accurate positioning is achieved using the Real-time kinematic (RTK) positioning technique. As a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems, RTK uses measurements of the phase of the signal's carrier wave in addition to the information content of the signal, and relies on a highly accurate fixed reference base station to provide real-time corrections, providing up to centimeter-level accuracy. The system is commonly referred to as carrier-phase enhancement. The position of the moving target is referred to as the rover. The base station and rover work together to reduce the rover's position error (https://en.wikipedia.org/wiki/Real-time_kinematic).

The range to a GNSS satellite from the rover is calculated by multiplying the carrier wavelength by the number of whole cycles between the satellite and the rover and adding the phase difference. Determining the number of cycles is critical, since signals may be shifted in phase by one or more cycles (or cycle slips). This results in an error equal to the error in the estimated number of cycles times the wavelength, which is 19 cm for the L1 signal. Resolving this integer ambiguity is the key to centimeter precision. The error can be reduced with sophisticated statistical methods that compare the measurements from the coarse-acquisition (C/A) signals and by comparing the resulting ranges between multiple satellites [13]. The carrier phase approach provides significant improvements assuming a 1% accuracy in locking. This is because the L1 C/A code changes phase at 1.023 MHz, while the L1 carrier itself is 1575.42 MHz, which is at a much shorter wavelength. A ±1% error in L1 carrier-phase measurement thus corresponds to a ±1.9 mm error. At the base station, the GNSS receiver typically consists a high end instrument with dual frequency receivers that allows for ionospheric correction using the L2 band at 1227.60 MHz. Modern GNSS technology has made ionospheric correction the largest remaining source of error in the signal. Dual frequency receiver is the key to centimeter accuracy GNSS.

There is a large number of RTK base stations available worldwide. A Continuously Operating Reference Station (CORS) network is a network of RTK base stations that broadcast corrections that can be used to improve the accuracy of GNSS positioning. Utilizing the corrections obtained from multiple base stations within a network potentially further reduces this error. The NOAA National Geodetic Survey (NGS) manages a network of CORS that provide GNSS data consisting of carrier phase and code range measurements in support of three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries.

In GNSS Radio Occultation, the continuous, high frequency (~50Hz) measurements of carrier phase from one or more locked GNSS satellites by receivers on the LEO satellite are recorded. These raw carrier phase measurements contain several pieces of information: the time delay between the receiver and the transmitter, the atmospheric path delay, the propagation time of the signal from transmitter to receiver, and the time delay caused by the referencing coordinate system change. With all time related corrections and subtraction of the direct distance between the transmitter and receiver from the raw carrier phase measurements, the so called “excess phase” can be calculated. The time derivative of excess phase (extra Doppler shift) and GNSS/LEO position/velocity information can be used to derive the bending angle [14]. Figure.1 shows a schematic depicting how the bending angles are derived.

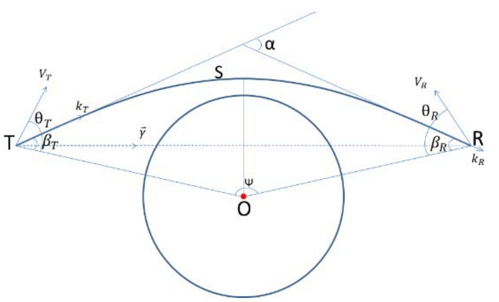

Figure 1. Schematic Plot of the Radio Occultation Bending Angle Calculation. T denotes the GNSS transmitter and R the LEO receiver (after Healy, S. B., 2001)[14]

To obtain the bending angle, the following equations need to be solved. The extra Doppler shift (after the Doppler shift due to relative movement between transmitter and receiver is removed) can be expressed as[14]:

$$f_d = \frac{f}{c}(V_T \cdot k_T - V_R \cdot k_R - (V_T - V_R) \cdot \vec{\gamma}) = \frac{f}{c}(v_T \cos(\theta_T - \beta_T) - v_R \cos(\theta_R - \beta_R) - (V_T - V_R) \cdot \vec{\gamma}),$$

where V_T and V_R are the velocity of GNSS transmitter and LEO receiver, respectively, k_T and k_R are ray propagation direction on the transmitter and receiver side, $(V_T - V_R) \cdot \vec{\gamma}$ is the relative speed along the direct line between transmitter and receiver. In this equation, given the position and velocity of both transmitter and receiver, the extra Doppler shift f_d is the time derivative of the excess phase. The two unknowns in this equation are the angles β_T and β_R illustrated in Figure 1.

The bending angle can be expressed as (see Figure 1 for illustrations of the angles):

$$\alpha = \beta_T + \beta_R + \Psi - \pi.$$

Assuming spherical symmetry, the following equation holds from Bouguer's formula:

$$nrsin(\beta) = impact\ parameter = n_T r_T \sin(\beta_T) = n_R r_R \sin(\beta_R),$$

where n is the refractivity index and r is the distance from transmitter/receiver to the Earth's center. Given the equations above, the position/velocity of the transmitter and receiver, and the extra Doppler shift (from excess phase), the bending angle can be solved using the Abel inversion.

However, the excess phase sometimes can lose track of lock when cycle slips occur. Processing from raw phase to excess phase must be performed, which includes cycle slip detection using GNSS bits information, clock/time correction using single/double differencing methods. Of course, the positioning and velocity also need to be accurately determined. The positioning/clock error can be propagated into the excess phase calculation and hence into the bending angle and higher level products in addition to errors from retrievals.

2.2 SI traceability of radio occultation vs. infrared sounder

Although the GNSS and RTK applications discussed in the previous section were developed for navigation, the same basic principles are applicable to radio occultation. In fact, radio occultation and precision geolocation share many of the same algorithms. In geolocation, one of the considerations for improving geolocation accuracy is atmospheric correction, while in radio occultation, the atmospheric effect becomes the major subject of study. This is a classic example where one scientist's noise can be another scientist's signal. A major difference in radio occultation is that the GNSS receiver is on a LEO satellite which is moving at about 7 km per second, as compared to navigation on the ground where the rover would be moving at a slow speed or stationary on a Earth Centered Earth Fixed System. Nevertheless, the raw measurements in radio occultation share the same benefits of the SI traceability of GNSS time with un-paralleled accuracy of atomic clocks. Kursinski et al in 1997 [2] stated that GNSS "RO offers an independent, SI-Traceable, comparison for measurements derived from the spectrally resolved infrared and microwave emission spectrum." It follows that GNSS radio occultation has the advantage of that "no calibration is needed" because of its SI traceability[4][5][6].

While it is true that the GNSS time is more SI traceable than most other quantities in remote sensing, it is arguable that all radio occultation from different systems have the same data quality and SI traceability. For example, not all GNSS systems have the same clock stability [12]. Another potential problem is that the computation of excess phase, which is the key quantify in radio occultation, heavily relies on precision orbit determination (POD) [3]. As a result, an error on the order of 19 centimeters in the GNSS receiver satellite position can translate to an error of one cycle in the carrier phase, which can be a significant error in radio occultation. It is known that not all GNSS systems can provide centimeter level accuracy. The precise position of the GNSS satellite will also need to be well known within a few centimeters. As a result, it would be challenging for radio occultation systems with less accurate positioning knowledge to produce high quality, or SI traceable measurements.

It is noted that infrared sounder measurements should also be SI traceable, given the definition of "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." In prelaunch thermal vacuum tests, the onboard blackbodies of infrared hyperspectral sounders are calibrated against external blackbodies, which in turn are calibrated against national standard blackbodies through transfer radiometers, and the uncertainties are quantified in each step. This does potentially provide a "documented unbroken chain of calibrations, with each contributing to the measurement uncertainty." One noticeable difference here, though, is the fact that radio occultation has fewer unknown variables, while in the infrared sounder calibration, there are more unknown variables which may contribute to larger uncertainties, such as spectral knowledge and far-field response, in addition to the radiometric calibration. However, infrared hyperspectral sounders provide measurements for retrieving multiple quantities such as temperature, moisture, ozone, and trace gas, compared to the single quantity of bending angle in radio occultation.

3 Comparing RO and IR measurements and challenges in assessing SI traceability

The fundamental measurement in radio occultation is time delay (pseudo range) and raw carrier phase, from which receiver position/velocity and excess phase can be calculated using precise positioning algorithms, and then bending angle, refractivity, and dry temperature can be retrieved. For infrared sounders, the fundamental measurement is spectral radiances with a typical unit of W/(m^2-sr-μm). While both excess phase and spectral radiance are "measurement results" and have the shortest unbroken chain of calibration in their respective systems, these two quantities are not directly comparable. As a result, retrievals become necessary to make them comparable, and unfortunately more uncertainties will be introduced in the retrievals. Retrieved quantities are not direct "measurement results" as defined in the SI traceability. This raises the issue of whether the atmospheric profiles retrieved from either radio occultation or infrared sounding are still SI traceable, as discussed later.

Nevertheless, two approaches have been developed for comparing radio occultation profiles with those from the infrared sounders. In a study validating temperature profiles from hyperspectral infrared sounder AIRS using COSMIC radio occultation, Feltz et al.(2014) performed comparisons of the temperature profiles retrieved from these two systems matched in time and space[7]. They stated that GNSS "RO provides an estimate of atmospheric temperature with a traceable path to absolute standards and well charact erized structural uncertainty". And GNSS RO has the advantage of homogeneous global coverage that is unbiased toward land or ocean and has the potential of high absolute accuracy in the upper troposphere to middle stratosphere where little water vapor is present. The study concluded that the bias and RMS error profiles in the comparisons depend strongly on the vertical averaging applied to the different profiles but are relatively insensitive to horizontal and temporal mismatch.

The drawback in this approach of comparing retrieved profiles from both radio occultation and infrared sounders is that after going through several steps of retrievals, it is difficult to prove that the chain of calibrations has not been broken. As a result, it is not clear whether the retrieved atmospheric profiles (temperature, water vapor, and pressure) are still SI traceable. Or do they at least become less SI traceable than the excess phase since more uncertainties are introduced.

An alternative approach for comparing GNSS RO and sounder measurements has been used at NOAA Center for Satellite Applications and Research (STAR). In this approach, the GNSS RO profiles are used as input to the Community Radiative Transfer Model (CRTM), together with other timely atmospheric information from ECMWF. Then the simulated spectral radiances (or forward calculations) are generated in the same spectral range as those of the infrared sounder such as NOAA-20 CrIS. In this approach, the comparison is made in the spectral radiances (or brightness temperature), without the need for retrieving the atmospheric profiles from the infrared sounders, although retrieval is still needed from the radio occultation since bending angle cannot be used in direct comparisons. On the other hand, this approach relies on the radiative transfer model CRTM and inputs, which faces the same issue of traceability to SI given its definition. An example output of this is presented in Figure 2 below.

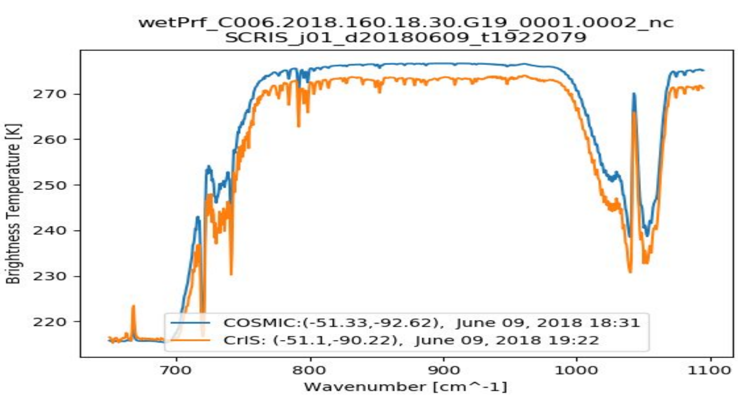

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Figure 2. Comparison between NOAA-20 CrIS spectral radiance and CRTM simulated radiance with COSMIC profile as input.

Figure 2 shows that the CrIS measured vs. CRTM simulated (with COSMIC RO input) agrees better in the spectral range below 700 cm^{-1} where CrIS observes the stratosphere (the CO2 bands), while the differences grow with the wavenumber between 700 and 800 cm^{-1} where CrIS observes several layers of atmosphere from the low stratosphere to the boundary layer. In the window channels (800 to 950cm-1), the figure shows that the difference can be several degree kelvin.

Several factors may have contributed to this difference: first, atmospheric sounding in the infrared cannot penetrate clouds, while radio occultation is not much affected by clouds. As a result, they may be observing different atmospheric phenomena even if they are collocated, except under clear sky conditions which is rare given the point measurement of radio occultation, with vertical atmospheric temperature profile over a distance of up to 250 km. Secondly, the "raw" measurement made by radio occultation is a single quantity of excess phase due to atmosphere which is used to calculate the bending angle. But this only allows the retrieval of “dry” temperature because the RO technique cannot solve two unknowns (or separate temperature and water vapor) with bending angle alone without a priori information. By comparison, infrared sounding measures the absorption and emission of gases in the atmosphere, such as CO_2 for temperature sounding in the 500-800cm^{-1}, water vapor and ozone in other spectral regions, which are measured separately but with vertical weighting functions. The third factor is collocation. Infrared sounding observations typically have pixel sizes on the order of 10-20 km, compared to RO point measurements (Figure 3) with a profile that spans up to 250 km. The collocation between the two will not be ideal given the heterogeneity of the atmosphere within such a large area. The fourth factor is the time difference. The coincidence of the observation in comparing RO vs. IR soundings is several hours, due to the sparsely distributed RO measurements globally (about 300 profiles per day from each satellite globally), as opposed to minutes or seconds, as in the Simultaneous Nadir Overpass (SNO) based comparisons[8]. With such a large time window, the atmosphere may have changed, especially in the case of major weather events.

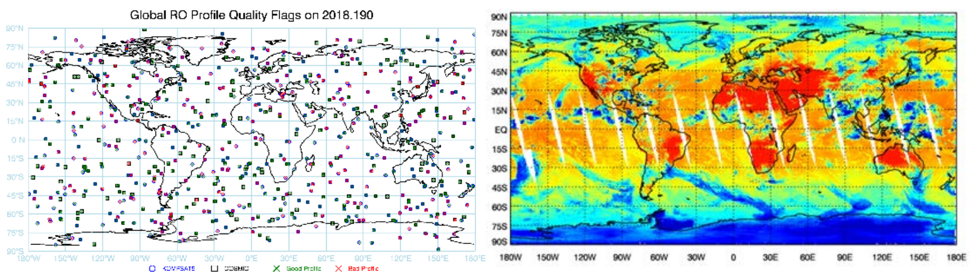

Figure 3. Comparison of global measurements from RO(left) and infrared hyperspectral sounder (right).

Therefore, there are several challenges in assessing and comparing the traceability of the GNSS RO and Infrared sounder measurements. Fundamentally, the SI traceability of GNSS RO is established with the unit of time, which can be irrefutable. However, from time delay, excess phase, to the derived quantities (as opposed to measurements) bending angle, refractivity, and further into dry and wet atmospheric profiles, the uncertainty assessment becomes complex. Essentially, the GNSS RO measurement provides time delay and carrier phase, which at most can solve one variable in the atmospheric profiles, i.e., the dry atmospheric temperature profile. To obtain the real wet atmosphere variables, other model input is utilized. At this stage, additional uncertainties can be introduced in the wet atmospheric profiles due to assumptions, model input, and atmospheric variability within the sampling scheme, thus contributing to the overall uncertainty in the GNSS RO atmospheric profiles.

While GNSS RO is accurate in the mid troposphere to low stratosphere, the measurement accuracy decreases in the low troposphere due to a number of factors including low signal to noise ratio, GNSS signal multi-paths, and the increased water vapor content. In a study of co-planar and nearly co-incidental profiles from the six COSMIC satellites shortly after launch in 2006, Alexander et al. (2014) found that the best precision for temperature profiles (about 0.1%, or 0.2-0.3K) was found between approximately 8 and 25 km height. In their study, precision is defined as the level of ”reproducibility” of an instrument, or the root-mean-square (RMS) difference between a large number of pairs of independent observations from the different COSMIC satellites. They found that precision degrades significantly (>1%) with height above 30 km. They also found that a vertical resolution of about 0.1 km may be reached at the lowest heights and it gradually increases to about 1.5 km in the upper troposphere or lower stratosphere [9].

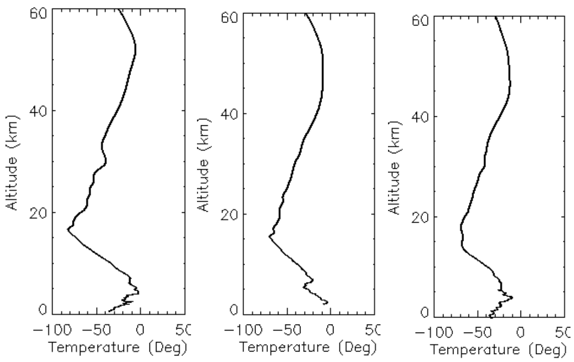

Figure 4. Sample dry temperature profiles from COSMIC Radio occultation (uncertainties grow near the boundary layer)

For infrared hyperspectral sounding, in addition to prelaunch SI traceable calibration, significant efforts have been devoted to postlaunch calibration/validation, especially using the SNO method for intercomparisons between satellites [8], such as IASI, AIRS, and CrIS. Several studies have shown that the agreement between these instruments are typically at 0.1K level across the temperature range [10], especially under WMO's Global Spacebased Inter-satellite Calibration System (GSICS). It has been demonstrated that the measurement accuracy for infrared hypspectral sounding is as good, if not better, than the radio occultation. On the other hand, in the event of blackbody degradation, the calibration will likely to drift. Therefore, continued intercomparison between hyperspectral sounders is necessary to ensure the longterm stability of the measurements (Table 1).

Table 1. Comparison of Radio Occultation with infrared hyperspectral sounding measurements

	Radio occultation	Infrared Sounder
Satellite Systems	COSMIC, COSMIC2, GRAS	CrIS on NOAA-20 & SNPP; IASI, AIRS
SI traceable measurement	Time or Atomic Frequency Standard (AFS)	Blackbody radiance (W/m2-sr-um)
Stability	Maintained by GNSS atomic clock with routine corrections and differencing algorithm can reduce the clock error.	Affected by blackbody emissivity, and thermal dynamics on-orbit; knowledge of longterm emissivity change
Possible errors	Smaller errors in the 8-25 km altitude, Spherical Symmetric Assumption in Bending Angle Calculation, Positioning errors. Retrieval Errors.	Measurement typically is not scene temperature dependent but retrieval may introduce errors
Coverage	Global point profiles (or line integrals)	Global area profiles
Other features	All RO systems can use the same GNSS signals which eliminates the source error in traceability and consistency.	Prelaunch traceability to different blackbodies depending on the program; relies on postlaunch intercalibration to assess consistency.

Given the challenges in assessing the SI traceability of the retrieved temperature profiles, in this study we investigated the sensitivity of CRTM generated spectral radiance to a small change in bending angle. The idea is that this sensitivity, although not a substitute for the "unbroken chain of calibration" as required by SI traceability, does provide a rough estimate of the uncertainty. The procedure is as follows: given a sample COSMIC bending angle profile, perturbations of different amount (0.2%, 2%, 0.5micro radian, and 5 micro radian) are introduced. Then the ROPP (Radio Occultation Processing Package) was used to generate the wet atmosphere profiles. Finally, the perturbed temperature profile is compared with the original version to quantify the differences. Results from Figure 5 shows that a 0.2% perturbation led to a maximum change in temperature profiles of 0.2K at 600 hPa, while a 2% perturbation resulted in a 2.5K change at the same pressure level. Therefore, with a bending angle precision of 0.1% as found in Alexander et al., the best case scenario would be a 0.1K uncertainty for the radio occultation temperature profile retrievals.

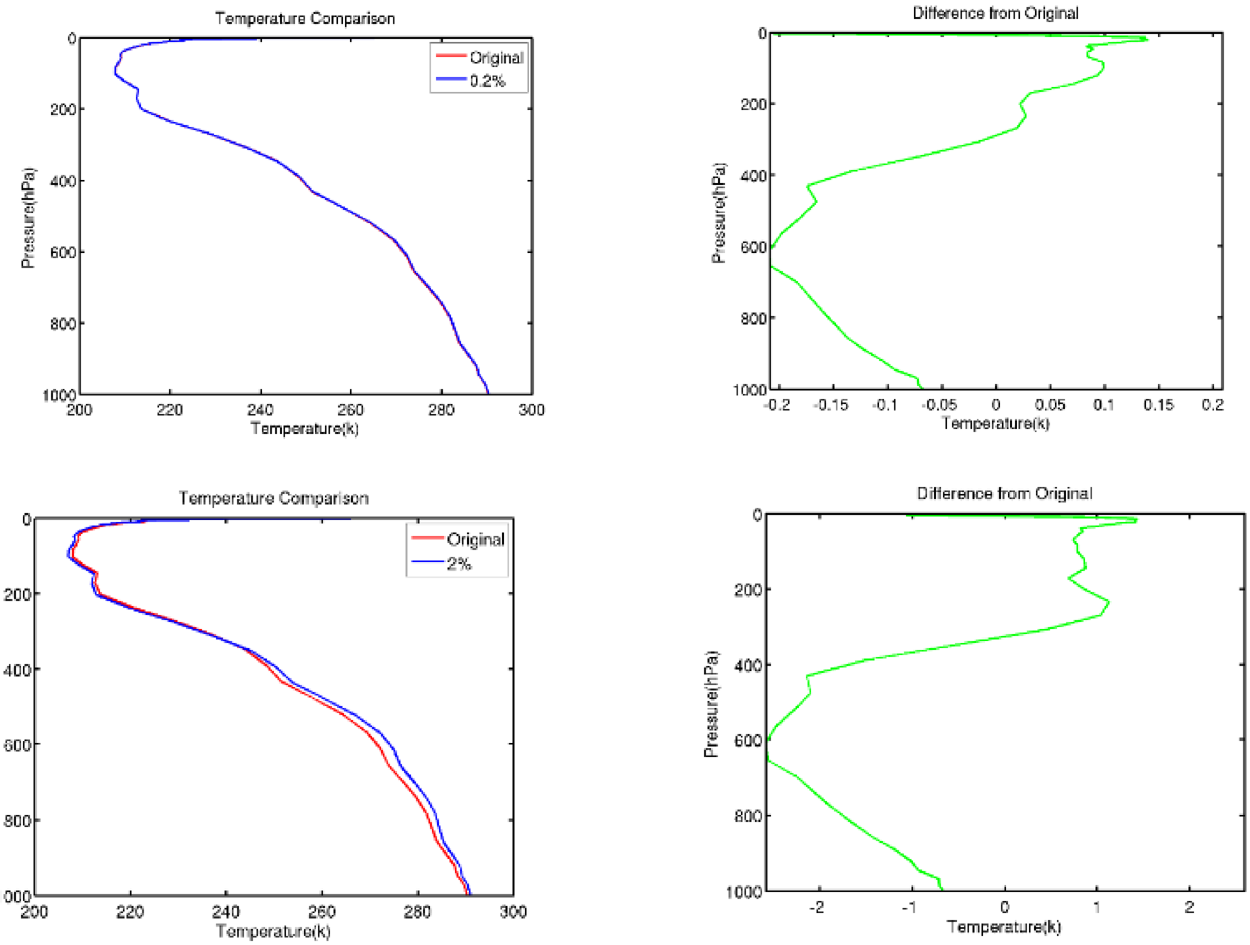

Figure 5. Sensitivity analysis of bending angle versus temperature profile

Finally, it is recognized that the COSMIC GNSS receiver is based on the technology that is more than a decade old. For COSMIC2, a new generation GNSS receiver (TriG) will be used with significant improvements in all major aspects which will address some of the issues existed in COSMIC. The higher signal to noise ratio will allows more accurate measurements in the low troposphere, and the ability to use all GNSS signals will significantly increase the number of RO profiles generated. In addition, the SI traceability is further improved with both an upgraded ultra-stable oscillator (USO), and the ability to use external USOs if better ones are available [11]. As the NOAA-20 CrIS is reaching validated maturity, the COSMIC2 cal/val team looks forward to the satellite launch and postlaunch calibration/validation in the next few months.

4. SUMMARY

Radio occultation is often quoted as a technique that is SI traceable, requires no calibration, and thus is particularly well suited for use as a stable reference for numerical weather prediction and other applications. Meanwhile, infrared hyperspectral sounding is also recognized as being SI traceable and produces highly accurate global measurements. This study investigated the SI traceability claims of each, and analyzed their advantages and limitations. Based on the definition of SI traceability of BIPM, we found that the GNSS time and excess phase in radio occultation is highly traceable to the

SI unit of Atomic Frequency Standard, and is unlikely to drift due to the atomic clocks used as well as routine bias corrections to the clocks. In addition, since all radio occultation systems will be using the same GNSS signals, consistency is expected to be very high across missions and over time. By comparison, spectral radiances in infrared sounding are also traceable to SI through blackbody calibrations to standard blackbodies. However, both RO and IR sounding have caveats in the SI traceability.

For RO, uncertainties may be introduced by other factors such as the GNSS and/or LEO satellite positions which introduces errors in the excess phase, or cycle slips in open-loop tracking, especially when the signal to noise ratios is low. The SI traceability from excess phase to bending angle and vertical temperature profiles is not well defined, since one measurement of excess phase cannot solve several unknowns even with the best atmospheric model. On the other hand, our sensitivity analysis shows that the uncertainty introduced in the retrieval of temperature profile from bending angle perturbation is small.

For infrared hyperspectral sounding, the SI traceability through rigorous blackbody calibration is required prelaunch, which is not a trivia effort. The blackbody emissivity, associated thermal dynamics effects, as well as spectral calibration may introduce biases. Longterm blackbody emissivity change, although small and unlikely, will introduce calibration drift. As a result, continuous longterm monitoring through intercomparisons between all hyperspectral infrared sounders is important to ensure the stable calibration. Both RO and IR sounding have their unique advantages and limitations and they complement each other in contributing to the numerical weather prediction and other applications.

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