An Experiment Using High Spectral Resolution CrIS Measurements for Atmospheric Trace Gases: Carbon Monoxide Retrieval Impact Study

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***Abstract*—We perform a demonstration experiment using the National Oceanic Atmospheric Administration Unique Cross-track Infrared Sounder (CrIS)/Advanced Technology Microwave Sounder Processing System to assess the improvement on trace gas retrievals upon switching to high spectral resolution CrIS radiance measurements (0.625 cm^{-1}). The focus of this study is carbon monoxide retrievals. The experimental high spectral resolution CO retrievals show a remarkable improvement, of almost up to one order of magnitude in the degree of freedom of the signal, with respect to the low-resolution mode. Furthermore, high-resolution CO retrievals show similar skill with respect to existing CO operational products from the Atmospheric InfraRed Sounder, Atmospheric Sounder Interferometer, and Measurements of Pollution In The Troposphere instruments, both in terms of spatial variability and degrees of freedom. The results of this research provide evidence to support the need for high spectral resolution CrIS measurements. This is a fundamental prerequisite in guaranteeing continuity to the CO afternoon orbit monitoring as part of a multisatellite uniformly integrated long-term data record of atmospheric trace gases.**

***Index Terms*—Carbon monoxide, hyperspectral sounders, Suomi National Polar-orbiting Partnership Cross-Track Infrared Sounder (SNPP CrIS), spectral resolution.**

I. Introduction

THE Cross-track Infrared Sounder (CrIS) on board the Suomi National Polar-orbiting Partnership (SNPP) platform is a Fourier spectrometer covering the long-wave (655–1095 cm^{-1}), midwave (1210–1750 cm^{-1}), and short-wave (2155–2550 cm^{-1}) infrared spectral regions [1]. In current operations, the interferogram raw data record is truncated at maximum geometrical path difference L values of 0.8, 0.4, and 0.2 cm, and Fourier transformed into radiance spectra with Nyquist sampling $1/2L$, i.e., 0.625, 1.25, and 2.5 cm^{-1} in the three bands, respectively. The decision of truncating the interferogram at a shorter geometrical path difference in the midwave and short-wave bands rests on the restriction in the down-link bandwidth posed by the processing requirements of other onboard instruments. On March 12, 2013, after maturing more than a year of processing system upgrades, an experiment was attempted where five orbits of the CrIS instrument (from March 12, 15:46 GMT until March 13, 00:31 GMT) were configured to down-link full path interferograms truncated at a geometrical path difference L' of 0.8 cm in all three bands. Using a preliminary high spectral resolution sensor data record (SDR) code [2], [3], those files have been Fourier transformed into radiance spectra with Nyquist sampling $1/2L$ now equal to 0.625 cm^{-1} across the full spectrum. The scope of this experiment was to test both the upgraded processing streamline and the impact on retrieval applications.

In this letter, we assess the improvement on the retrieval skill of atmospheric retrieval products whose sensitivity falls in the midwave and short-wave regions, resulting from this increased spectral resolution. We perform Hamming apodization of the radiances for computational efficiency. Hamming apodization significantly reduces the spectral sidelobes (from 27% to less than 1%) of the instrument line shape function but increases the width of its central lobe to roughly $0.9/L$. For the high-resolution case, this corresponds to an effective spectral resolution of 1.25 cm^{-1} across the full spectrum, as opposed to the previous effective spectral resolution of 1.25, 2.25, and 4.5 cm^{-1}, respectively. Hamming apodization is a reversible process and, therefore, does not affect the information content of the spectrum [4].

Because carbon monoxide (CO) spectral sensitivity is found in the short-wave region, CO retrievals are expected to benefit the most from the high-resolution mode, now increased by a factor of four with respect to the operational resolution. For the scope of this letter then, we focus on the case study of CO retrievals.

II. High Versus Low Spectral Resolution CO Sensitivity Analysis

Fig. 1(a) shows the results of a sensitivity analysis aimed at quantifying the expected improvement in the sensitivity

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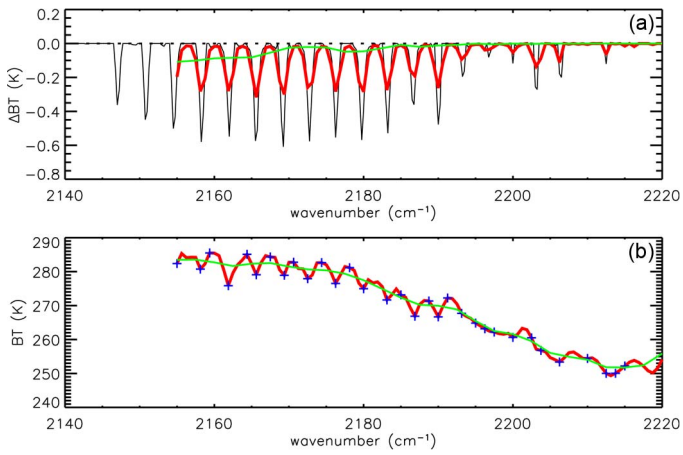

Fig. 1. (Top) Sensitivity analysis to a 1% perturbation in CO using spectral resolutions of (green) 2.5-, (red) 0.625-, and (black) 0.25-cm^{-1} spectral resolutions. (Bottom) Comparison of (green) low- and (red) high spectral resolution CrIS measurements from March 12, 2013, at the same location (32.10 °N-127.87 °E). The blue cross symbols indicate the selected subset for the CO retrieval in high-resolution mode.

of the CrIS instrument to CO, when switching from low- to high-resolution mode. We use a standard midlatitude atmospheric profile to compute a 1% perturbation in the CO vertical profile and simulate the brightness temperature response measured by CrIS using the current low (2.5 cm^{-1}, green curve) and the experimental high (0.625 cm^{-1}, red curve) spectral resolution. The 1% perturbation applied on the CO profile is on the order of magnitude of the observed CO diurnal variation over the equatorial Pacific Ocean [5] and of the annual trend oscillation measured over the Northern Hemispheric high latitudes [6]. For the brightness temperature computation, we use the Stand-alone Atmospheric InfraRed Sounder (AIRS) Radiative Transfer Algorithm [7]. CrIS has a spectral sampling gap in the 1750–2155 cm^{-1} band, hence the missing P branch (2000–2150 cm^{-1}) of CO absorption in the spectrum. The black curve in Fig. 1(a) is a third perturbation performed using a finer spectral resolution (0.25 cm^{-1}) and is used as a theoretical reference to better highlight the spectral features of the CO absorption lines.

The results shown in Fig. 1(a) indicate an increased sensitivity in the high-resolution measurement of up to three times higher with respect to the low-resolution case. More importantly, the large nonlinear structure observed in the high-resolution response is an indication of the higher information content present in the high-resolution measurement and represents a key feature for the accuracy of the retrieval in that it allows the separation of CO from other interfering atmospheric species [8], [9].

Fig. 1(b) shows a brightness temperature measurement acquired by the CrIS instrument in (thin) low- and (thick) high-resolution modes on March 12, 2013, at the same exact location (32.10 °N−127.87 °E) We can notice that the large structure present in the high-resolution spectrum (red curve) carries the distinctive signature of the CO absorption lines observed in the sensitivity study shown in Fig. 1(a). On the contrary, in low-resolution mode (green curve), these CO absorption features are almost entirely suppressed.

The blue crosses in Fig. 1(b) indicate the set of channels selected to perform the CO retrieval in high-resolution mode. A description of the channel selection methodology is provided in Section II. Section III of this letter is devoted to an in-depth study of the increased information content and the impact on the retrieval results upon switching to high-resolution mode.

III. NUCAPS

The National Oceanic Atmospheric Administration (NOAA) Unique CrIS/Advanced Technology Microwave Sounder (ATMS) Processing System (NUCAPS) [10] is the operational retrieval system developed at the NOAA National Environmental Satellite, Data and Information Service Center for Satellite Application and Research to produce cloud-cleared radiances and atmospheric temperature, water vapor, and trace gas profiles from CrIS in conjunction with the ATMS. These retrieval products are accessible in near real time (about 3-h delay) through the Comprehensive Large Array-data Stewardship System [11].

NUCAPS is a multistep retrieval algorithm consisting of the following: 1) a microwave and infrared radiance bias tuning which corrects for uncertainties in the radiative forward model [12], [13]; 2) a microwave retrieval module which derives temperature and water vapor retrievals along with cloud liquid water flags and microwave surface emissivity uncertainty [14]; 3) a fast eigenvector regression retrieval for temperature and moisture that is trained against the European Center for Medium Weather Forecast (ECMWF) analysis and CrIS all sky radiances [15]; 4) a cloud-clearing module that combines a set of microwave and infrared channels (along with, in the future, visible observations provided by the onboard Visible Infrared Imaging Radiometer Suite instrument) to produce cloud-cleared infrared radiances [16]; 5) a second fast eigenvector regression retrieval for temperature and moisture that is trained against ECMWF analysis and CrIS cloud-cleared radiances [15]; and 6) the final infrared physical retrieval, which employs the previous regression retrieval as the first guess of an iterated regularized least squared radiance minimization based on the methodology developed in [8]. In this experimental setup, we have replaced the temperature and water vapor regression-derived first guess used in operations [15], with an ATMS-derived "microwave-only" retrieval [14] to avoid the need for training. The CO *a priori* is a 12-month set of two single CO profiles, for the northern and southern hemispheres, respectively, computed from the Measurements of Pollution In The Troposphere (MOPITT) version 4 CO monthly averages [17], [18]. These profiles are temporally and spatially interpolated during the retrieval. For the CO retrieval step, we employ ans optimal estimation approach [19], following the methodology developed in [20].

The final infrared retrieval module employs a selected subset of infrared channels in order to expedite near-real-time data distribution and assimilation. We adopt the methodology described in [9] which consists in a physically based procedure where channels are selected upon their spectral properties: Priority is given to spectral purity, avoidance of redundancy, and vertical sensitivity properties, along with low instrumental noise and

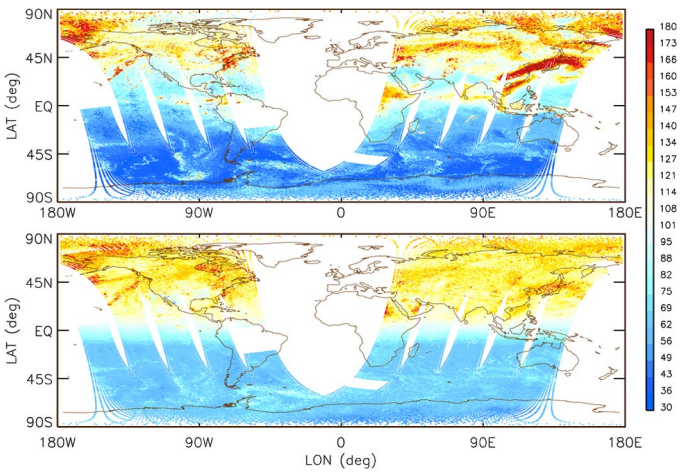

Fig. 2. NUCAPS CO retrieval (440–460-mb pressure layer) for five test orbits on March 12, 2013. (Top) High spectral resolution. (Bottom) Low spectral resolution. Units are in ppbv.

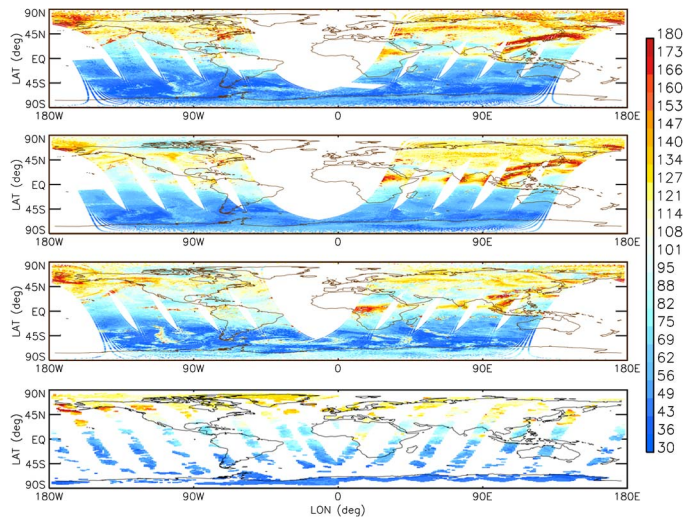

Fig. 3. (From top to bottom) High-resolution NUCAPS, AIRS, IASI (at 440–460 mb), and MOPITT (at 400–500 mb) CO retrievals on roughly the same five test orbits from March 12, 2013. Units are in ppbv.

global optimality. The sensitivity analysis shown in Fig. 1(a) represents an example of the first step of this channel selection methodology, in that it allows a prescreening of the channels most sensitive to an atmospheric species of interest (in this case, CO). No channel selection though was performed in the CO band for the current operational retrieval (low-resolution mode). We employ the full set of 27 consecutive channels present in the CO band, in order to maximize the information content present in the low-resolution retrieval. For the high spectral resolution experiment instead, we employed the methodology described in [9] and selected 32 channels in the CO band [blue cross symbols in Fig. 1(b)]. This high-resolution CO channel selection captures the cores and wings of the CO absorption lines shown in Fig. 1(a), enabling full sounding of the CO absorption curve of growth. It is important to notice that the high spectral resolution mode enables the selection of nonadjacent channels, thus reducing the spectral correlation noise introduced upon radiance apodization (62.5%, 13.3%, and 0% for adjacent, alternate, and every other two channels, respectively, in the case of Hamming apodization) [9].

IV. High- Versus Low Spectral Resolution CO Retrievals

Fig. 2 shows a comparison of the NUCAPS CO retrieval performed in high spectral resolution mode (top) with respect to the operational low-resolution mode (bottom) for the five test orbits. For brevity, we only show results from the 440–460-mb layer, where most of the instrument CO sensitivity is originated [21]. As expected from the sensitivity analysis in Fig. 1(a), high-resolution mode retrievals show significantly more structure in the global distribution of CO abundance with respect to the low-resolution mode. The extended regions of heightened CO peak values on the high-resolution map are indicative of anthropogenic emissions, biomass burning, and atmospheric circulation patterns. These key features of the source and sink climatology of carbon monoxide are predominantly missed in the low-resolution retrieval map, which is subject to a minimal departure from the *a priori*. This will be shown in the next section, by quantification of the information content present in the retrieval.

V. Comparison With Existing Operational CO Products

Although we are still working on the optimization of the quality control flag of the high spectral resolution NUCAPS CO product, we show an initial comparison with respect to two other hyperspectral products, the AIRS version 6 [22] [Fig. 3(b)] and the Infrared Atmospheric Sounder Interferometer (IASI) NOAA Phase II [23] [Fig. 3(c)] CO operational retrievals, on the same five test orbits and pressure layer as NUCAPS. For completeness, we also show results from the MOPITT version 5 [24] [Fig. 3(d)] CO operational retrievals.

Compared to the low-resolution case (Fig. 2, bottom), NUCAPS high spectral resolution CO retrievals [Fig. 2, top, and Fig. 3(a)] show a significantly improved agreement to all three CO satellite products. The observed differences among the four instruments are consistent with what has been previously observed in [21] and have been attributed to differences in retrieval methods, *a priori*, to thermal contrast diurnal cycle, and, more importantly, to differences in instrumental spectral resolution and coverage [25]–[27]. While IASI covers the full roto-vibrational spectrum of the atmospheric CO molecule, (2000–2250 cm^{-1}), both CrIS and AIRS have spectral gaps. As anticipated in Section I, CrIS has a spectral gap between 1750 and 2155 cm^{-1} and misses the entire P branch (2000–2150 cm^{-1}) but covers the majority of the R branch (2150–2250 cm^{-1}). AIRS presents a spectral gap between 1614 and 2182 cm^{-1} and also misses the entire P branch and a larger part part of the R branch of the CO band. The interferogram of IASI is truncated at 2 cm, corresponding to a 0.25-cm^{-1} Nyquist spectral sampling and roughly 0.5-cm^{-1} effective resolution after Gaussian apodization. AIRS has a spectral resolving power of 1200, corresponding to a spectral resolution of roughly 0.9 cm^{-1} in the CO band. Reasons for differences with respect

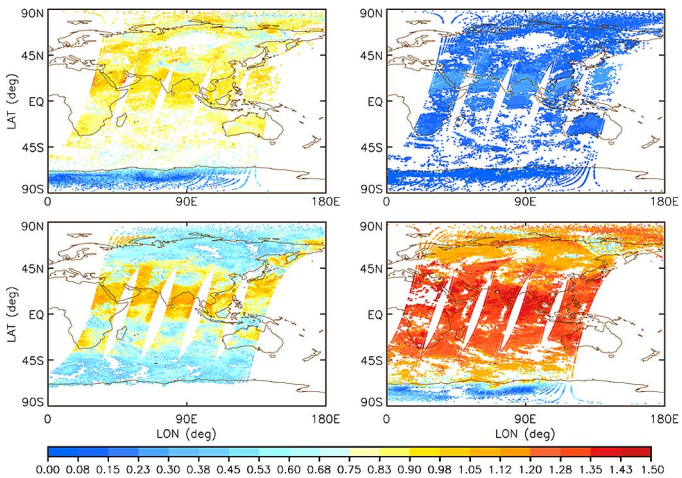

Fig. 4. Comparison of (top left) NUCAPS high-resolution, (top right) NUCAPS low-resolution, (bottom left) AIRS, and (bottom right) IASI CO DOFSs.

to MOPITT (10–20 ppbv) also rest in the coarser pressure slab of the MOPITT retrievals used for this study (400–500 mb).

The analysis shown in Fig. 3 is intended to provide a performance demonstration in support of the robustness of the NUCAPS high spectral resolution CO product, in terms of both spatial variability and order of magnitude.

In Fig. 4, we compare the degrees of freedom of the signal (DOFSs), a metric used to measure the number of independent pieces of information available from the retrieval [19]. We focus on the nighttime NUCAPS descending orbits which, at this preliminary stage of the high spectral resolution retrieval setup, show a higher quality-controlled acceptance yield with respect to the daytime ensemble. This enables a more rigorous comparison with respect to the colocated AIRS (bottom left) and IASI (bottom right) results. For NUCAPS and IASI, which share the same retrieval algorithm, we have employed a midtropospheric temperature quality flag as described in [23]. For AIRS, we have chosen only cases flagged as "best" and "good," as described in [22].

NUCAPS high spectral resolution CO DOFSs (top left) are observed to consistently improve across all latitudinal regimes, up to one order of magnitude, with respect to the low-resolution mode (top right). This is consistent with the results found in Fig. 2, where the higher information content enabled a larger departure from the *a priori*, hence the increased spatial variability observed in the high spectral resolution map (top part of Fig. 2) with respect to the low-resolution case (bottom part of Fig. 2). Furthermore, the NUCAPS high-resolution CO DOFS performance appears by far more comparable to both AIRS and IASI CO DOFS performances.

VI. Conclusion

Using the NUCAPS, we have assessed the improvement on the retrieval skill of atmospheric CO upon switching to high spectral resolution CrIS SDRs of 0.625 cm^{-1} across the full spectrum. The higher spectral resolution improves the information content present in the CO retrieval up to one order of magnitude, enabling a larger departure from the *a priori* and an increased spatial variability in the retrieved CO global distribution, with respect to the low-resolution case. Moreover, high spectral resolution NUCAPS CO retrievals prove comparable to the existing operational CO retrievals from the MOPITT, AIRS, and IASI instruments, in terms of spatial variability, order of magnitude, and DOFS.

The results of this research provide evidence to support the need for high spectral resolution CrIS measurements. This is a fundamental prerequisite in guaranteeing continuity to the afternoon orbit monitoring of atmospheric CO as part of a multisatellite uniformly integrated long-term data record of atmospheric trace gases. NUCAPS high spectral resolution trace gas retrievals from CrIS on SNPP will also serve in preparation of future advanced satellite missions under the Joint Polar Satellite System [1] for which atmospheric trace gases, such as ozone, carbon monoxide, methane, and carbon dioxide, are listed as operational requirements. The modular architecture of NUCAPS has proven that there is no risk of disruption to the operational processing upon switching to high spectral resolution mode.

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