The NOAA Operational Hyper Spectral Retrieval Algorithm: a cross-comparison among the CrIS, IASI and AIRS processing systems

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Abstract

Scope of this paper is a cross-comparison among the AIRS/AMSU, IASI/AMSU/MHS and CrIS/ATMS retrieval results using the NOAA/NESDIS/STAR Operational Hyper Spectral Retrieval Algorithm. We perform a detailed analysis of the statistical and instrument performance of the three systems in order to assess their level of maturity and inter-consistency.

1. Introduction

Since February 2013, NOAA/NESDIS/OSPO has been running three hyper spectral sounding processing systems: 1) the Atmospheric InfraRed Sounder/Advanced Microwave Sounding Unit (AIRS/AMSU) retrieval product processing system, which has been running in near-real time since 2002; 2) the Infrared Atmospheric Sounder Interferometer/ Advanced Microwave Sounding Unit/Microwave Humidity Sounder (IASI/AMSU/MHS) NOAA unique cloud-cleared radiances and trace gas product processing system, which has been running operationally since 2008; and 3) the NOAA Unique Cross-track Infrared Sounder/ Advanced Technology Microwave Sounder (CrIS/ATMS) Processing System (NUCAPS), which has become operational in the Fall of 2013. The long term strategy of NOAA/NESDIS also involves the operational processing of the future JPSS and MetOp B and C missions, spanning a total period of ~30 years of hyper spectral remote sounding data processing.

The NOAA/NESDIS/STAR Operational Hyper Spectral Retrieval Algorithm is a modular architecture that was specifically designed to be compatible with multiple instruments (Figure 1). A pre-processor enables the reformatting of the sounder data record (SDR) into a common file format which is inputted to the retrieval code. The system runs the same exact executable for all instruments and employs the same underlying spectroscopy, sets of assumptions and look up table methodology. This property is of fundamental importance in guaranteeing homogeneity to a long term the multi-platform integrated dataset of retrieved Environmental Data Records (EDRs).

The CrIS instrument was launched in October 2011 and will ensure the continuity of the afternoon orbit sounding for the next decade in replacement of the AIRS instrument. The ongoing overlapping period between AIRS and CrIS will guarantee the inter-calibration between the two instruments. The combined sounding geometry of the Aqua, NPP and MetOp satellites (AIRS and CrIS have a 1:30pm equator crossing time; IASI has a 9:30 am equator crossing time) and the employment of the same retrieval system will provide an unprecedented uniform and long-term integrated database of six global atmospheric measurements per day.

Scope of this paper is a cross-comparison among the AIRS/AMSU, IASI/AMSU/MHS and CrIS/ATMS retrieved EDRs. We perform a detailed analysis of the instrument and retrieval statistical performance of the three systems in order to assess their level of maturity and inter-consistency.

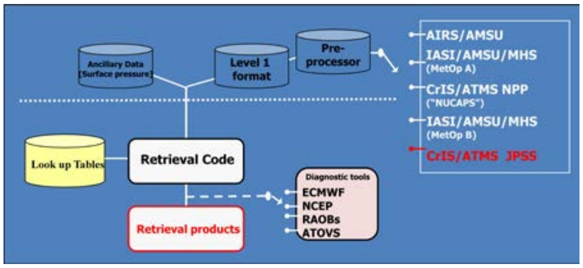

Figure 1. Modular architecture of the NOAA NESDIS hyper Spectral Retrieval System.

2. The NOAA Hyper Spectral Retrieval Algorithm

The NOAA Hyper Spectral Retrieval Algorithm is a heritage algorithm originally implemented for the AIRS/AMSU suite of instruments by the AIRS Science Team. This retrieval scheme includes: 1) A microwave retrieval module which derives cloud liquid water flags and microwave surface emissivity uncertainty [Rosenkranz, 2000]; 2) A fast eigenvector regression retrieval for temperature and moisture that is trained against ECMWF analysis and CrIS all sky radiances [Goldberg et al., 2003]; 3) A cloud clearing module that combines a set of microwave and IR channels (along with, in the future, visible observations provided by the onboard VIIRS instrument) to produce cloud-cleared IR radiances [Chanine, 1974]; 4) A second fast eigenvector regression retrieval for temperature and moisture that is trained against ECMWF analysis and CrIS cloud cleared radiances [Goldberg et al., 2003]; 5) The final physical retrieval which employs the previous regression retrieval as a first guess [*Susskind, Barnet, Blaisdell*, 2003]. The final IR retrieval module is an iterated regularized least squared minimization performed on a selected subset of infrared channels. This channel selection follows the methodology described in *Gambacorta and Barnet* (2012) and is a physically-based procedure where channels are selected solely upon their spectral properties: high priority is given to spectral purity, avoidance of redundancy and vertical sensitivity properties, along with low instrumental noise and global optimality. Jacobians and radiative transfer calculations are performed by mean of the microwave MIT [Rosenkranz,2003] and infrared SARTA forward model [Strow et al., 2003].

Table 1. List of retrieval outputs from the NOAA hyper spectral retrieval algorithm (left) and sensitivity spectral regions (right).

Cloud Cleared Radiances	**660-750 cm-1** **2200-2400 cm-1**
Cloud fraction and Top Pressure	**660-750 cm-1**
Surface temperature	**window**
Temperature	**660-750 cm-1** **2200-2400 cm-1**
Water Vapor	**780 – 1090 cm-1** **1200-1750 cm-1**
O3	**990 – 1070 cm-1**
CO	**2155 – 2220 cm-1**
CH4	**1220-1350 cm-1**
N2O	**1290-1300cm-1** **2190-2240cm-1**
HNO3	**760-1320cm-1**
SO2	**1343-1383cm-1**

There is a need for identifying and removing those components of the residuals arising from modeling and calibration errors. This process, commonly referred to as *brightness temperature tuning*, is fundamental to achieve retrieval performance accuracy, in that it removes artificial systematic biases that could be otherwise ascribed to the atmospheric source of interest and erroneously confused with climatic trend signals [Gambacorta et al., 2012].

The full suite of retrieval products is summarized in Table 1 and includes cloud cleared radiances, cloud top pressure and fraction, skin temperature and vertical profiles of atmospheric temperature, water vapor and trace gases such as O3, CO, CH4, CO2, N2O, HNO.

Figure 2 shows an example of temperature (top) and ozone (bottom) retrieval maps at 500mb using the NOAA Unique CrIS ATMS Processing System (NUCAPS) data from January 5th 2014.

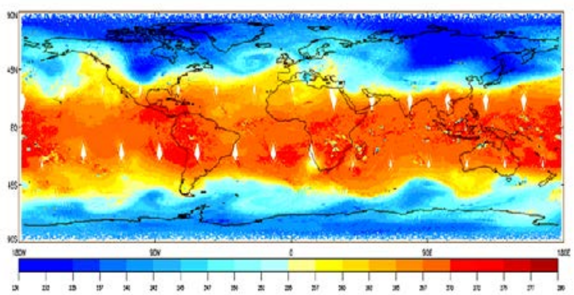

Figure 2. Temperature retrieval maps at 500mb using the NOAA Unique CrIS ATMS Processing System (NUCAPS) data from January 5th 2014.

3. Temperature and Water Vapor Retrieval Validation

We perform a validation analysis using a full ensemble of global AIRS/AMSU, CrIS/ATMS and MetOp A IASI/AMSU/MHS retrievals collected on May 15 2012. Figure 3 shows a RMS statistical analysis with respect to collocated ECMWF atmospheric profiles. Solid curves represent the final retrieval and dash curves represent the first guess statistics. We can notice that for both temperature (left) and water vapor (right) the retrieval performance is stable across the three platforms (green is AIRS/AMSU, blue is IASI/AMSU/MHS) and red is NUCAPS). As highlighted in Gambacorta et al. (2012), after only 7 months from the launch of the NPP platform, the performance of the NUCAPS system has proved comparable to the more mature AIRS/AMSU and IASI/AMSU/MHS systems. The vertical dark red bars on Figures 3 indicate the JPSS mission requirements. NUCAPS meets requirements almost entirely except for the temperature lower tropospheric and water vapor mid tropospheric regions. Improvements on the microwave module, first guess regression retrieval along with optimization of the retrieval parameters and rejection thresholds is underway and will be part of the NUCAPS version 2 upgrade.

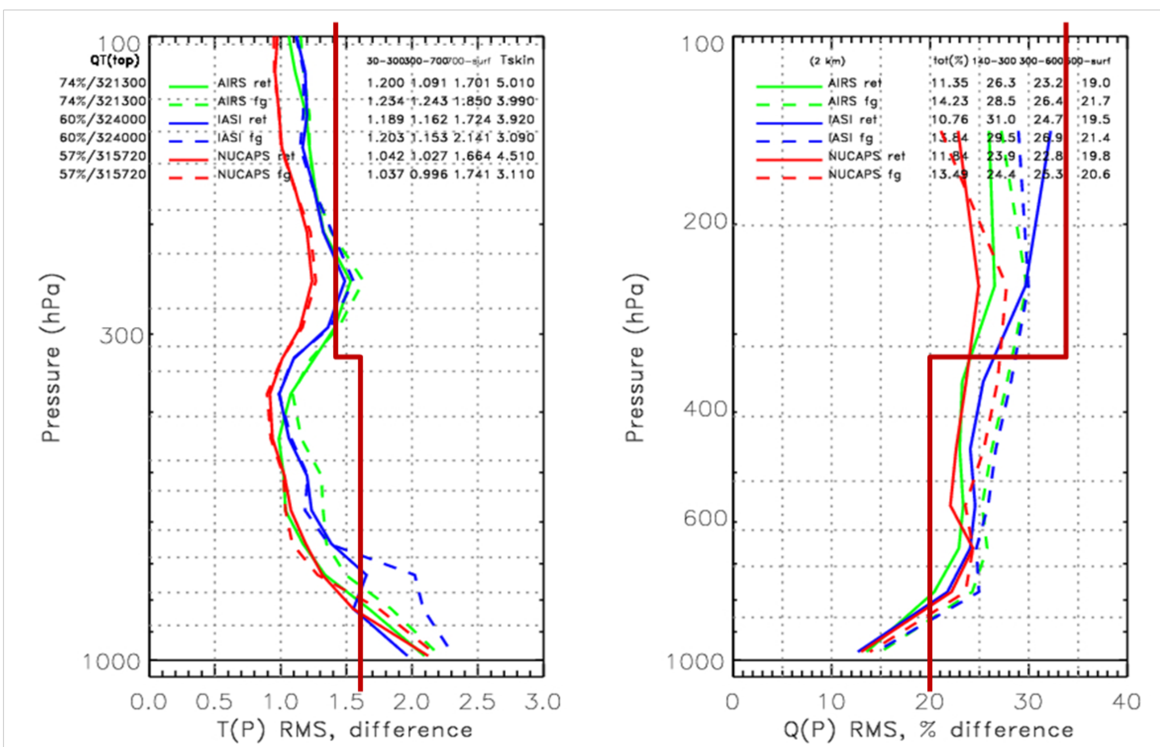

Figure 3. Temperature (left) and water vapor (right) global RMS statistics of the AIRS/AMSU, CrIS/ATMS and MetOp A IASI/AMSU/MHS retrievals collected on May 15 2012. See text for details.

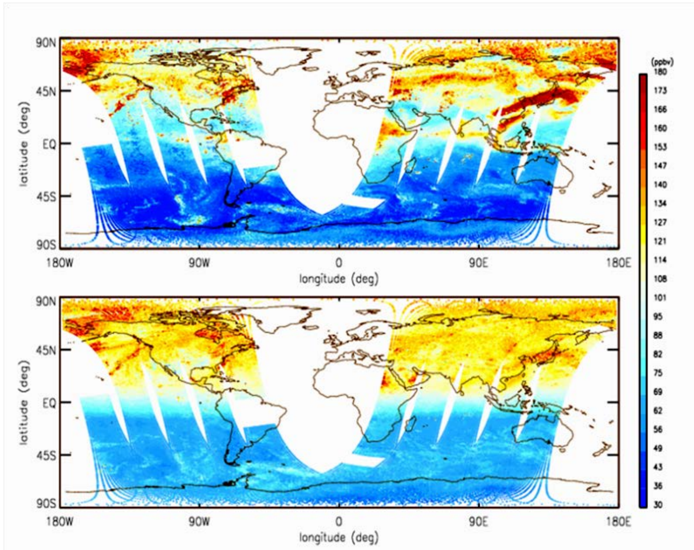

Figure 4. NUCAPS CO retrieval performed in high spectral resolution mode (top) with respect to the operational low resolution mode (bottom) from March 12, 2013 at 450mb.

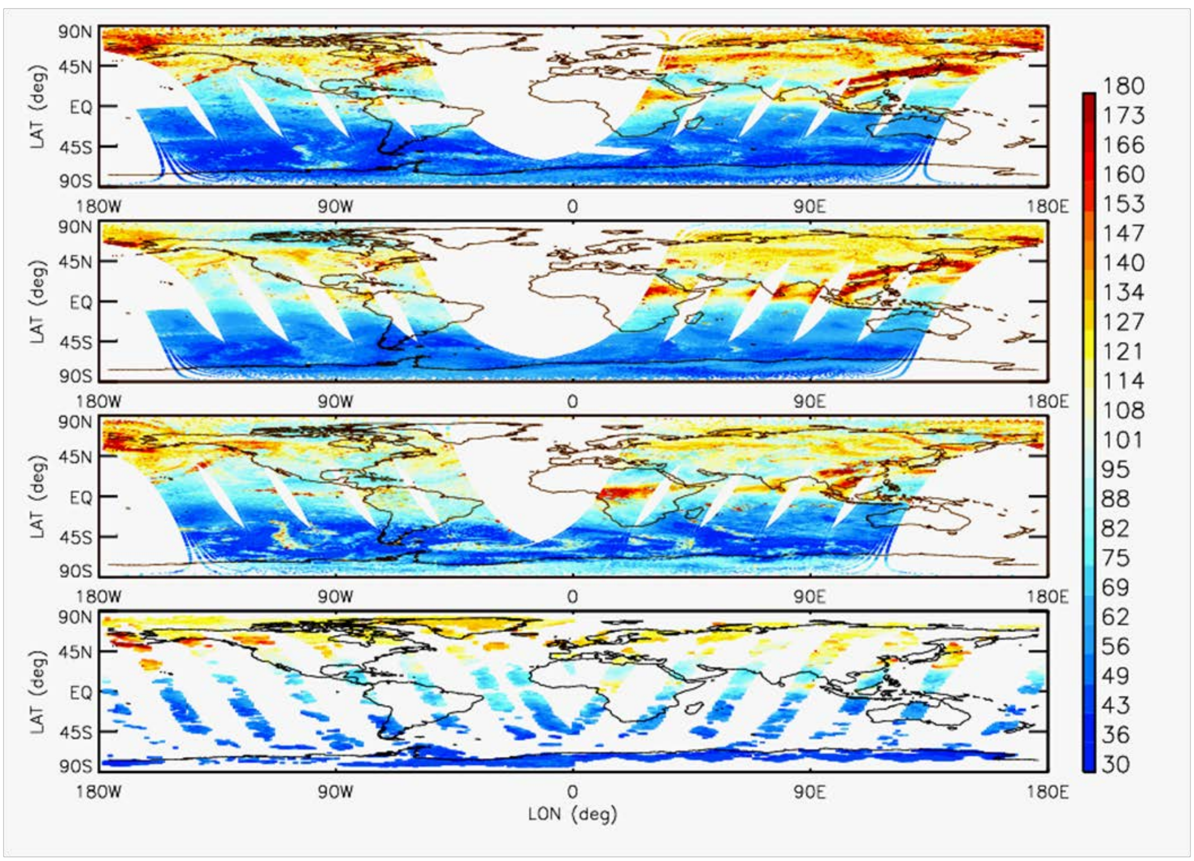

Figure 5. From top to bottom: high resolution NUCAPS, AIRS, IASI (at 440-460mb) and MOPITT (at 400-500mb) CO retrievals on roughly the same five test orbits from March 12, 2013. Units are in ppbv.

4. Trace gas validation. A case study on carbon monoxide retrievals

The CrIS instrument is a Fourier spectrometer covering the longwave (655-1095 cm-1), midwave (1210-1750 cm-1), and shortwave (2155-2550 cm-1) infrared spectral regions. In current operations the interferogram raw data record (RDR) is truncated at a maximum geometrical path difference, *L*, of 0.8 cm, 0.4 cm and 0.2 cm, and Fourier transformed into radiance spectra with Nyquist sampling *1/2L*, that is 0.625 cm-1, 1.25 cm-1 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 shortwave bands rests on the restriction in the down-link bandwidth posed by the processing requirements of other on-board instruments.

On March 12th, 2013, after maturing more than a year of processing system upgrades, an experiment was attempted where five orbits of the CrIS instrument (from 12 March 15:46 GMT until 13 March 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 [Yong et al., 2013], 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.

We have assessed the improvement on the retrieval skill of atmospheric retrieval products whose sensitivity falls in the mid and shortwave region, resulting from this increased spectral resolution. Because carbon monoxide (CO) spectral sensitivity is found in the shortwave region, CO retrievals are expected to benefit the most from the high resolution mode, now increased by a factor of 4 with respect to the operational resolution. For the scope of this paper then, we focus on the case study of CO high vs low resolution retrievals and perform additional comparison with the operational AIRS and IASI CO product. Figure 4 and 5 are taken from Gambacorta et al. 2014. Compared to the low resolution case (Figure 4, bottom), NUCAPS high spectral resolution CO retrievals (Figure 4, top and Figure 5 top) show a significantly improved agreement to all three existing CO operational products derived from the AIRS (second), IASI (third) and MOPITT (bottom) instruments. The observed differences among the four instruments are consistent with what has been previously observed by *Warner et al.,* (2007) and have been attributed to differences in retrieval methods, a priori, thermal contrast diurnal cycle and, more importantly, to differences in instrumental spectral resolution and coverage [George et al., 2009; Warner et al., 2010, Clearboux et al., 2008]. 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 1, 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. IASI's interferogram 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 to MOPITT (10-20 ppbv) also rest in the coarser pressure slab of the MOPITT retrievals used for this study (400-500mb).

More details and explanations on the NUCAP high resolution CO retrieval experiment can be found in *Gambacorta et al.* (2014). Here we provide a summary on the results obtained from this 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. This is a fundamental prerequisite in guaranteeing continuity to the afternoon orbit monitoring of atmospheric CO as part of a multi-satellite, uniformly integrated, long term data record of atmospheric trace gases. NUCAPS high spectral resolution trace gas retrievals from CrIS on Suomi NPP will also serve in preparation of future advanced satellite missions under the Joint Polar Satellite System [Goldberg et al., 2013] 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.

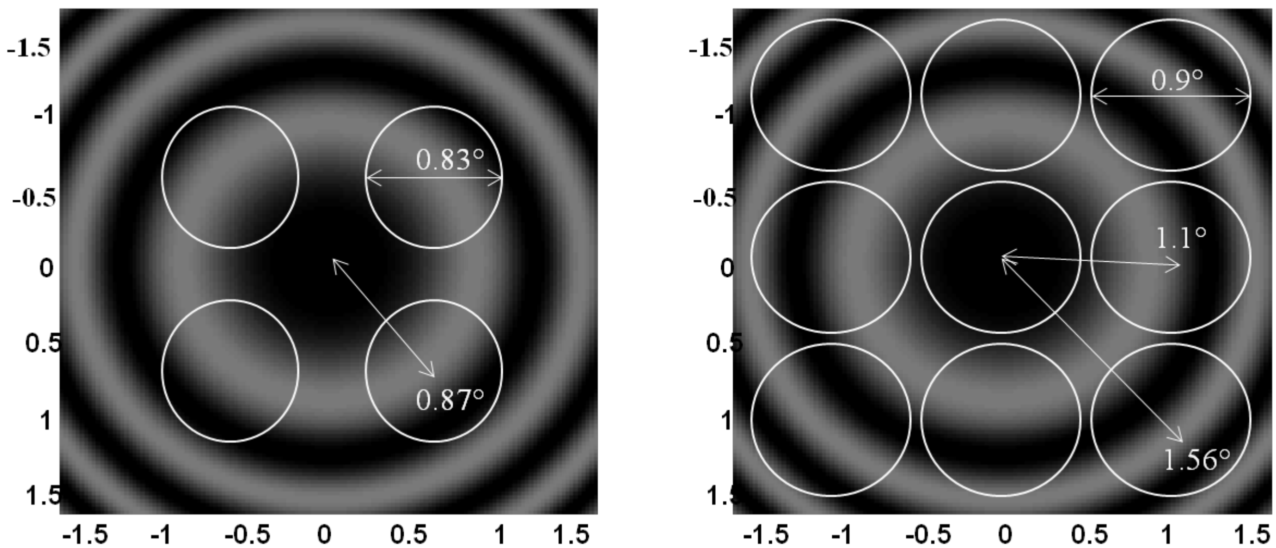

Figure 6. IASI (left) and CrIS (right) acquisition geometry.

5. Nominal field of view instrument line shape distortion in presence of scene inhomogeneities

At any given position of the mirror displacement (optical path difference, OPD, of the interfering beams) the signal measured by the detector is attributed to the frequency *v* whose interference pattern on the focal plane reaches a maximum in the center of the FOV. In clear scenes, the geometric center of the FOV coincides with the source radiometric center and this attribution is correct. The presence of clouds though will introduce an inhomogeneous distribution of the signal across the FOV surface and induce a shift in the radiometric center of the FOV. This displacement induces an error in the determination of the OPD and the corresponding maximum interference frequency associated to each sampling, introducing a spectral calibration error, a phenomenon usually addressed as ``ISRF shift" (the effect of deformation is minor). We investigate the effects of scene in-homogeneities on the IASI instrument line shape (ILS) in the attempt of assessing the spectral characteristics and order of magnitude of the error induced in the radiance spectrum.

By mean of the infrared imager (IIS) on board METOP, we measure the sub-pixel brightness temperature to compute the shift in the radiometric centroid and derive the corresponding frequency shift of the instrument line shape. We then re-sample the interferogram (via zero filled transforms) to the corrected frequency spectrum and finally evaluate the brightness temperature differences. We assume that the displacement in the radiometric centroid measured by the IIS instrument for IASI is the same for CrIS. This implies assuming that their climatology for scene in-homogeneities and interference fringing pattern is close enough. Figure 6 provides a summary on the acquisition geometry of the two instruments. More details on the methodology employed in this study can be found in Gambacorta et al., 2010. In summary, we find that for both the IASI and CrIS instrument the frequency shift is of the order of 3 ppm and the induced radiance error to be generally smaller than the instrumental noise within a large statistical sample of real data, hence negligible. There are occasions where the effect is larger than the noise, but these are very rare and would be considered very difficult scenes for infrared sounding.

6. Conclusions and future work

We have performed a cross-comparison among the AIRS/AMSU, IASI/AMSU/MHS and CrIS/ATMS NOAA/NESDIS/STAR operational hyper spectral retrieval systems. We performed a detailed analysis of the statistical and instrument performance of the three systems in order to assess their level of maturity and inter-consistency.

After only 7 months from the launch of the NPP platform, the performance of the NUCAPS system has proved comparable to the more mature AIRS/AMSU and IASI/AMSU/MHS systems. NUCAPS meets requirements almost entirely except for the temperature lower tropospheric and water vapor mid tropospheric regions.

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. High spectral resolution NUCAPS CO retrievals prove comparable to the existing operational CO retrievals from the 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 multi-satellite, uniformly integrated, long term data record of atmospheric trace gases. NUCAPS high spectral resolution trace gas retrievals from CrIS on Suomi NPP will also serve in preparation of future advanced satellite missions under the Joint Polar Satellite System [Goldberg et al., 2013] 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.

We investigate the effects of scene in-homogeneities on the IASI instrument line shape (ILS) in the attempt of assessing the spectral characteristics and order of magnitude of the error induced in the radiance spectrum. We find the effect to be generally smaller than the instrumental noise – within a large statistical sample of real data, hence negligible.

Improvements on the microwave module, first guess regression retrieval along with optimization of the retrieval parameters and rejection thresholds in underway and will be part of the near future system upgrade.

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