Requirements for an Advanced Low Earth Orbit (LEO) Sounder (ALS) for improved regional weather prediction and monitoring of greenhouse gases

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ABSTRACT

Hyperspectral infrared atmospheric sounders (e.g. the Atmospheric Infrared Sounder (AIRS) on Aqua and the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp) provide highly accurate temperature and water vapor profiles in the lower to upper troposphere. These systems are vital operational components of our National Weather Prediction system and the AIRS has demonstrated over 6 hrs of forecast improvement on the 5 day operational forecast[1]. Despite the success in the mid troposphere to lower stratosphere, a reduction in sensitivity and accuracy has been seen in these systems in the boundary layer over land. In this paper we demonstrate the potential improvement associated with higher spatial resolution (1km vs currently 13.5 km) on the accuracy of boundary layer products with an added consequence of higher yield of cloud free scenes. This latter feature is related to the number of samples that can be assimilated and has also shown to have a significant impact on improving forecast accuracy. We also present a set of frequencies and resolutions that will improve vertical resolution of temperature and water vapor and trace gas species throughout the atmosphere. Development of an Advanced Low Earth Orbit (LEO) Sounder (ALS) with these improvements will improve weather forecast at the regional scale and of tropical storms and hurricanes. Improvements are also expected in the accuracy of the water vapor and cloud properties products, enhancing process studies and providing a better match to the resolution of future climate models. The improvements of technology required for the ALS are consistent with the current state of technology as demonstrated in NASA Instrument Incubator Program and NOAA's Hyperspectral Environmental Suite (HES) formulation phase development programs.

Keywords: Atmosphere, Sounder, Temperature, Water Vapor, Profile, Advanced

1. INTRODUCTION

Hyperspectral infrared spectrometers like the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua Spacecraft have demonstrated positive forecast improvement when assimilated into weather prediction models at major Numerical Weather Prediction (NWP) centers worldwide. AIRS has also been extremely valuable in understanding processes affecting climate, particularly with respect to water vapor and clouds and atmospheric composition of key greenhouse gases including CO_2, CH_4, O_3 and CO. Additional forecast impact is anticipated from the IR sounders as computing power at the NWP centers improves, but we are already seeing the limitations in these systems associated with the low (13.5 km) horizontal spatial resolution (HSR). A significant reduction in yield and accuracy occurs over land in the boundary layer indicative of lack of knowledge of the surface emissivity. Unfortunately NWP models have the lowest accuracy in the boundary layer where the sounders could have the most impact. Additionally, climate models require good knowledge of the surface atmosphere exchange of water vapor and of cloud process studies requiring higher HSR.

Higher accuracy and yield are all possible with the latest advancements in focal plane and optics technology developed over the last 10 years. Large format focal plane arrays allow slowing the scan rate to improve dwell time allowing smaller instantaneous fields of view. Wide field optics now image the large focal planes onto the scene collecting maximum illumination area while minimizing aperture size. The NASA Instrument Incubator Program funded the development of the Spaceborne Infrared Atmospheric Sounder (SIRAS) [2] and NOAA funded the Hyperspectral Environmental Suite (HES) both of which developed grating and large format focal plane technology with direct relevance to the ALS.

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2. IMPROVEMENTS

2.1 Current Sounder Performance

Temperature and water vapor accuracy of the AIRS instrument and retrieval system meet expectations as indicated in the literature[3]. Figure 1 shows the AIRS Version 5 temperature product accuracy compared to ECMWF along with the corresponding yield using the same technique discussed in the referenced document. Plots are given for land and ocean cases. From the RMS temperature the first obvious feature is that retrievals over ocean are much better than over land. There are two possible explanations for this behavior, of which most likely both are responsible. First, the surface emissivity over ocean is almost unity and subject to lower uncertainty. Second, the ocean scene is uniform causing less variability and correspondingly less uncertainty in the surface emissivity. The surface uncertainty then propagates up into the troposphere and increases overall uncertainty in the profile.

Figure 4b shows the yield vs altitude. A rigorous quality control system in the AIRS retrieval system accepts retrievals with sufficient accuracy and rejects those without. The current retrieval system (version 5) shows a considerable drop in yield from over 60% over ocean to 15% over land. We have made improvements in the surface emissivity retrieval in Version 6 but the yield is not expected to improve substantially.

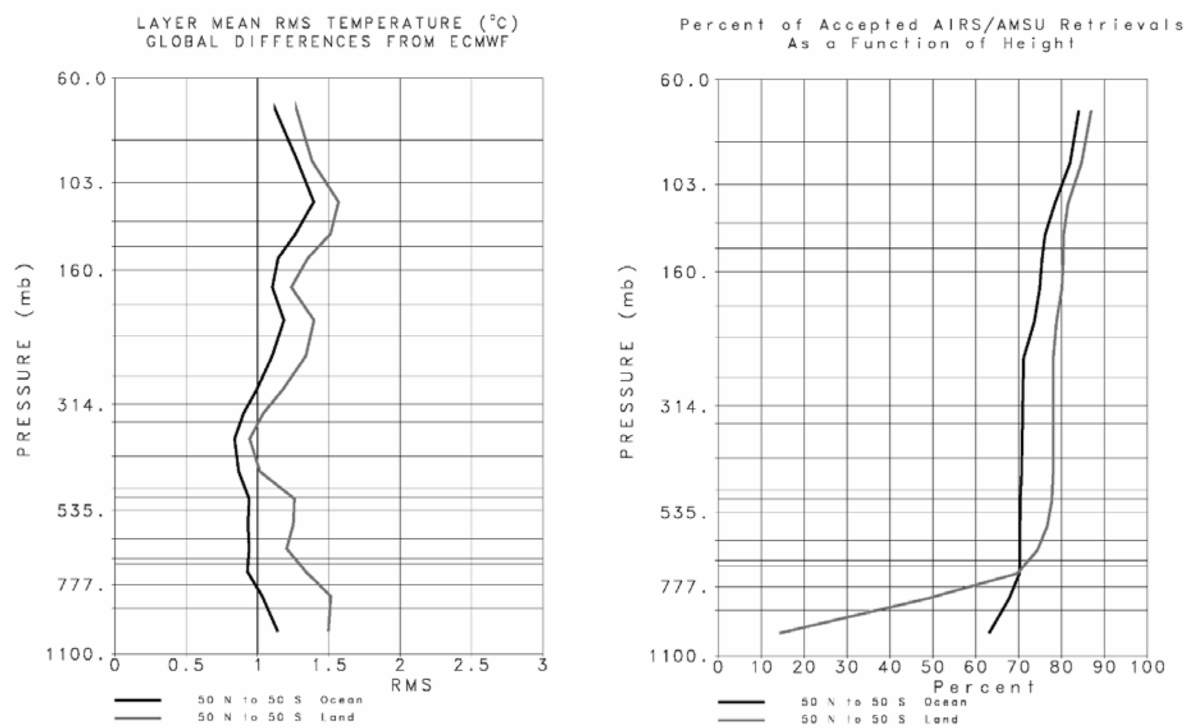

Figure 1 (left). RMS Accuracy of AIRS temperature profile over ocean (black curve) and land (grey curve). Corresponding yield for ocean and land surfaces

2.2 Boundary Layer Improvement

A factor of 2 or more improvement is anticipated in the accuracy of boundary layer products with higher spatial resolution. The improvement comes from the reduction in scene variability at the higher spatial resolution. Scene variability will contribute to the overall temperature error and consequently the uncertainty of all the geophysical products. We demonstrate the anticipated improvement by examining the variability of a clear scene taken from MODIS data. Figure 2 gives shows an image of MODIS surface temperature for the Southern California area on September 1, 2004. The MODIS Surface Temperature data from Version 5 are plotted in this image. Overlain on the figure is a route that the author takes from work at JPL in Pasadena to his home in Ventura county. This route was selected on this day because of the high temperatures and high variability traversing from the inland valley to the coastal region.

Figure 3 shows the MODIS temperatures and the data taken by the author's car during his commute home that same day. The MODIS data are offset by -15F to match in-situ surface air temperatures taken by the car. The general trend of the surface temperatures from MODIS and the car temperatures are similar but the need to offset the MODIS data indicates there is a considerable gradient from the surface to the atmosphere just above the surface, or there is a problem with the MODIS surface temperature product in Version 4. Car temperatures are not expected to be off by more than 1-2 degrees. The variability in the MODIS surface temperature are used to determine the effect of HSR on the uncertainty in the local temperature of the scene.

We measure the surface temperature variability vs horizontal resolution by creating equal size bins along the route and filling them with the MODIS data that are within the range of the bin. We then take the standard deviation of the data in each bin and average them to get an overall average variability for a given HSR. We then repeat the process with a new bin size. The result is an average standard deviation as a function of HSR as shown in Figure 4. The standard deviation represents the scene variability that we will have to contend with in addition to the retrieval uncertainty. The observed standard deviation at the AIRS resolution (13.5km) is about 4K. When we reduce the horizontal bin size to 1km, the standard deviation is about 2K. This is major improvement is indicative of the benefits of horizontal resolution on accuracy of the temperature product. The benefit to surface air temperature most likely will not be as high since the mixing at the surface results in less horizontal variability as indicated by the car data.

2.3 Yield of Cloud Free Scenes

We anticipate a considerable improvement in yield of cloud free scenes with improved HSR. Krigner et. al use MODIS data to determine the fractional clear for a total of 1K radiometric contamination[4]. For this level of contamination, they found 2%, 12%, and 32% for 100km, 15 km, and 1 km HSR respectively. This level of contamination is considerably higher than what is needed for the atmospheric temperature retrievals. From these results we can expect a factor of 3 improvement in fractional cloud free scenes.

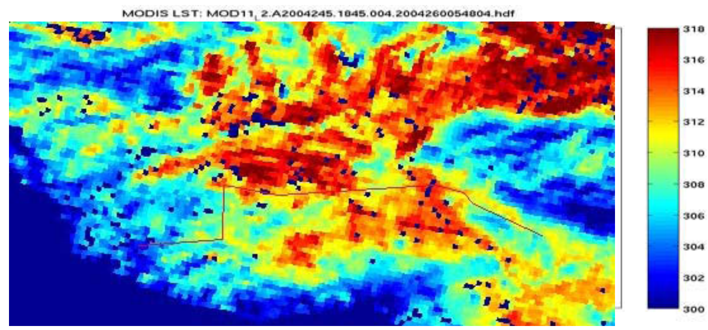

Figure 2. Image of Southern California Surface Temperatures as measured by MODIS. Overlain in red is authors commute route.

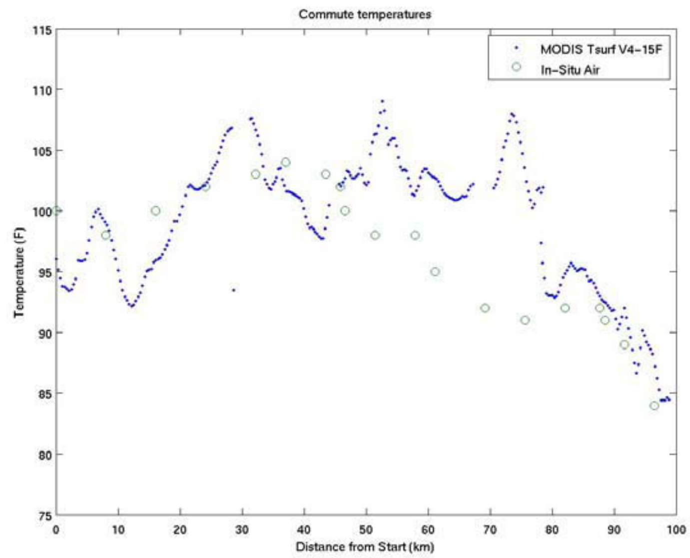

Figure 3. Surface Temperatures from MODIS for September 1, 2004 along commute route. Also shown are temperatures recorded by author's car on the same day.

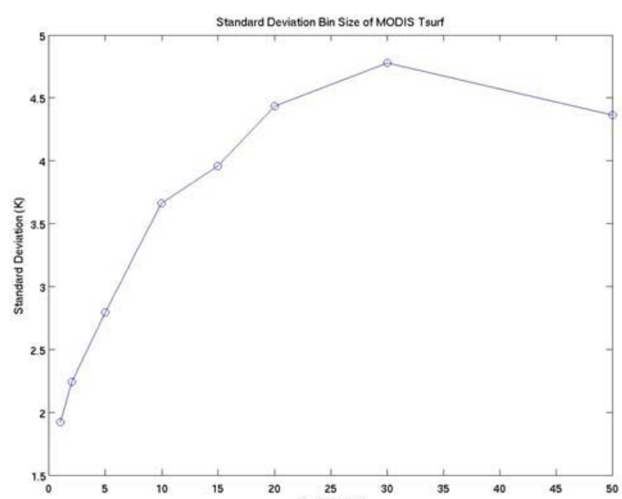

Figure 4. Standard Deviation vs Bin Size (HSR) for the route temperatures obtained by MODIS. A 2x improvement is seen with higher spatial resolution (smaller bin size).

Aumann et. al. show that at the AIRS resolution (appx. 15 km) only 0.2%-0.5% are truly clear for a radiometric cloud contamination of 0.2K[5]. These studies were performed to validate AIRS radiances using Sea Surface Temperature. Aumann shows 7000 cloud free pixels per day with AIRS resolution are truly cloud free. The ALS with 1km HSR will have 182x more samples than the AIRS per unit area. Combine this with the 3x improvement in probability of finding clear and we can expect 3.8M pixels that are totally cloud free. The total number of samples (clear and cloudy) obtained from AIRS is 2.9M. AIRS retrievals consist of 3 x3 AIRS raw footprints giving a total of 324000 retrievals per day. Of these 80% are passed with the "cloud clearing" process. That leaves 259200 retrievals remaining. This means that the ALS should be able to achieve 10x more samples at full 1 km horizontal resolution without the need of cloud clearing. If cloud clearing is used, a reduction of 9x will be obtained, but the yield will go from 0.2% to 80% giving almost 48M samples per day.

Table 1. Estimation of Yield per day for ALS

Parameter	Value
AIRS	
Total Number of AIRS L1B	2916000
Fraction Clear with AIRS	0.002400549
Number of True Clear from AIRS L1B	**7000**
3x3 Cloud Cleared Samples	324000
Fraction Passed with Clouds	0.8
Total Remaining AIRS L2 Retrievals	**259200**
ALS	
Number of AIRS/ALS L1B	182.25
Total Number of ALS L1B	531441000
Yield due to Clouds	3
Total Factor Improvement	546.75
Number of True Clear from ALS L1B	**3827250**
3x3 Cloud Cleared Samples	59049000
Fraction Passed with Clouds	0.8
Total Remaining ALS L2 Retrievals	**47239200**

3. IMPACTS

3.1 Weather Prediction

Improvements in the boundary layer temperature and water vapor accuracy from higher resolution infrared sounders are expected to have positive impact on the operational and regional forecast accuracy. Studies by Leibner et. al have shown that assimilation of "climatological information offshore in combination with observed conditions near the coast" produced a positive impact to the 12-hour and 24-hour forecast. Improvements were seen in PBL depth (by 65%) and marine inversion strength (by 41%)[6]. The fact that initialization of models with in-situ observations in the boundary layer has demonstrated a positive impact should be no different than assimilation of satellite data provided the satellite information is sufficiently accurate in this region. Temperature and water vapor accuracy of the AIRS products as shown above in Figure 1 have demonstrated the accuracy above 500-600 mb to have forecast impact, but the lowest levels have yet to be sufficient to have an impact over land.

There are two additional benefits to higher accuracy. The higher yield of observations produces more cloud free observations, as well as more observations per unit area. The benefit of more observations per unit area is not from a noise point of view because there are correlations at all scales that limit noise performance. It is this correlation itself that we are trying to reflect in the boundary conditions of weather and climate prediction models.

The significantly higher yield from the ALS has the potential to greatly improve weather forecast. Early results from LeMarshal presented at an AIRS science team meeting showed another 6 hour improvement in the 5 day forecast with assimilation of all 18 FOV's of AIRS rather than 1 in 18 which was responsible for the 6 hour improvement already achieved. At this time, most NWP centers do not have the capacity to assimilate all AIRS footprints, but hopefully will within the next few years. We must also realize that as computing power increases the model resolution will improve and the current operational sounders will not have sufficient resolution to initialize these more advanced models.

3.2 Climate Processes: Water Vapor, Clouds and Greenhouse Gases

Infrared sounders have proven valuable in understanding the processes affecting water vapor transport and cloud formation in the atmosphere. For example, recent studies by Gettelman and Fu show using AIRS and model data that as surface temperatures increase, water vapor in the upper troposphere increases preserving a constant relative humidity and producing a positive feedback[7]. The question remains in how a positive water vapor feedback will react to make clouds. MODIS has proven highly effective in characterizing clouds with its 1km horizontal spatial resolution, however the added hyperspectral information in the AIRS has shown to be more capable of separating clouds into ice and liquid phases[8]. Discussions with the authors of this latter paper indicate that having the high spatial resolution of the MODIS combined with the hyperspectral resolution of the AIRS would be a major improvement in cloud process science.

A final major side benefit of the ALS will be the ability to monitor sources and sinks of greenhouse gases with unprecedented resolution and coverage. Currently the AIRS instrument has demonstrated the ability to observe carbon monoxide and methane at horizontal resolutions of 45 km, and carbon dioxide at horizontal resolutions of 200km all with global daily coverage. The ALS will have the ability to produce greenhouse gases at the scale of MODIS observations (Figure 5). The benefits include monitoring emissions from natural and anthropogenic burning, identifying sources and sinks of greenhouse gases for climate science and monitoring emissions for verification of compliance with government regulation and international treaty verification.

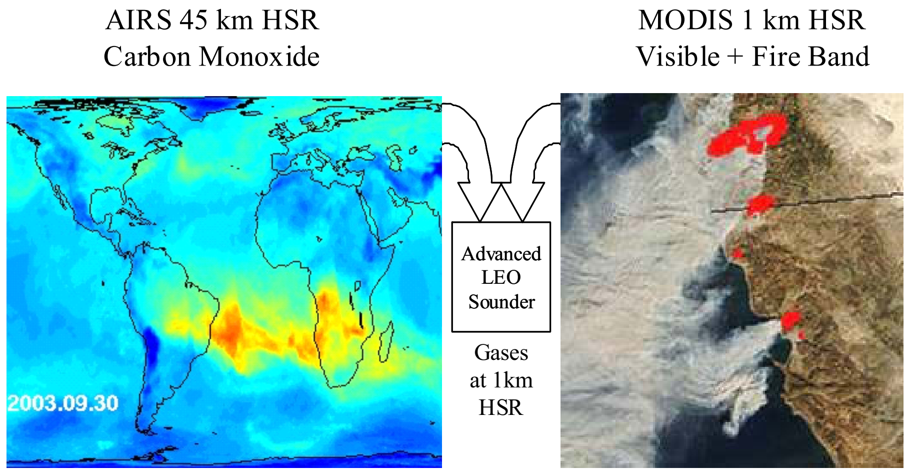

Figure 5. ALS will produce greenhouse gases like AIRS, but at high spatial resolution like MODIS

3.3 Validating Climate Models

AIRS data have proven highly effective in validating water vapor in climate models. Pierce et. al have observed a wet bias in the upper troposphere compensated by a dry bias in the lower troposphere in 9 of the major climate models used in the 2007 IPCC climate forecast predictions[9]. Although the consequences of this bias are unknown at this time, the bias was only found due to the hyperspectral information content in the AIRS data. Satellite systems provide the data sets from the global vantage point allowing comparison with global scale models.

As model resolution improves it will be necessary to improve the observations as well. Current grid scales of models are in the 100 km range, but models developed for process studies can be as high as 4 km today. These models cannot be validated with a system observing at 13.5 km and producing products at 45 km as is the case with AIRS. A prior work by Pagano, et. al demonstrates that validation of a model of a given resolution must have observations as good or better than the model itself in order to minimize errors due to the observations filtering out process in the model of spatial frequencies higher than the Nyquist frequency[10].

4. REQUIREMENTS SUMMARY AND TECHNOLOGY ASSESSMENT

Table 2 gives the spectral and spatial resolution and coverage for the ALS[11]. The ALS should scan ±55° to give full global coverage twice daily in support of tracking hurricanes, monitoring transport of water vapor and greenhouse gases and monitoring emissions of carbon dioxide. The spectral ranges allow for measuring the key greenhouse gases as done with AIRS but extended to do a better job of carbon monoxide, N_2O and HNO_3.

Designs and rationale for the ALS have been examined in the past under the instrument name of the Advanced Remote-sensing Imaging Emission Spectrometer (ARIES)[12,13,14,15,16]. The instrument will make use of area arrays of HgCdTe of modest size (512x512) to produce a wide field of view allowing a slow can rate for signal integration. This makes up for the small instantaneous field of view and slightly higher spatial resolution than AIRS. Focal plane assemblies and optical systems have been demonstrated in the NASA Instrument Incubator Program and NOAA's GOES-R Hyperspectral Environmental Suite Formulation Phase demonstrations. A number of space qualified cryocoolers are available with sufficient capacity and flight heritage to be useful for the ALS applications. Raw internal data rate will by high for the ALS consistent with the high information content. Techniques for data selection have been investigated and also presented in the same references.

Table 2. ALS Spectral, Spatial and Radiometric Requirements Summary[4]

	SWIR	MWIR	LWIR1	LWIR2
ν_{max} (cm^{-1})	2100	1150	880	650
ν_{max} (cm^{-1})	2950	1613	1150	880
λ_{min} (μm)	3.39	6.20	8.70	11.36
λ_{max} (μm)	4.76	8.70	11.36	15.38
$\lambda/\Delta\lambda$	2227	2585	1887	1552
$\Delta\lambda$, $\Delta\nu$	1.1 cm^{-1}	0.5 cm^{-1}	0.5 cm^{-1}	0.5 cm^{-1}
N_{chan}	787	999	637	674
IFOV (km)	1.00	1.00	1.00	1.00
NEdT	0.15K	0.3K	0.3K	0.5K

5. CONCLUSIONS

The Advanced Low Earth Orbit (LEO) Sounder will provide a significant improvement in boundary layer accuracy and sensitivity while also providing the higher spatial resolution and improved accuracy of all currently available infrared sounder products. These products include higher spatial resolution temperature and water vapor profiles, surface temperature and emissivity, cloud properties and trace gas properties. A significant improvement in forecasting regional and global weather and severe storms including hurricanes and tropical cyclones is expected. Improvements are expected also in climate and weather process descriptions and in validation of the next generation of climate models.

Work must begin now on the ALS in order for it to be ready for the post NPOESS generation of sensors by the Integrated Program Office, and for the anticipated need for monitoring greenhouse gases in support of carbon trading legislation, and finally for the lives it will save by improving hurricane prediction worldwide.

6. ACKNOWLDEGEMENTS

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