Combining the High Altitude Lidar Observatory (HALO) and the Scanning High-Resolution Interferometer Sounder (S-HIS) for Thermodynamic Retrievals during the EcoDemonstrator Campaign

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1. INTRODUCTION

The 2017 Decadal Survey (National Academies of Sciences, Engineering, and Medicine 2018) designated improving thermodynamic observations of the planetary boundary layer (PBL) to be a priority for future observing missions. In response, the National Aeronautical and Space Administration (NASA) created the Decadal Survey Incubation Program to refine observing system requirements and perform trade studies to shape a future mission focused on providing these improved observations of the PBL. The NASA PBL study team report (Teixeira et al. 2021) highlighted both passive sensors: hyperspectral infrared (IR) and hyperspectral microwave, and active sensors: water vapor differential absorption lidars (DIAL) and radio occultation, as instruments that could achieve high technical readiness levels for a potential mission launch in the 2030s.

Previous studies (e.g. Toporov and Löhnert 2020, Loveless et al. 2022) have displayed the benefits of developing instrument synergies with IR sounders, where the synergy of two instruments outperforms a combination of single instrument retrievals. Turner and Löhnert (2021) have displayed the benefits of a synergy of a ground-based IR sensor with a ground-based DIAL. By introducing high vertical resolution measurements from the DIAL with low uncertainty, additional temperature information may be extracted from the IR radiance measurements. From the ground-based perspective, this resulted in improved representation of the capping inversion at the top of the PBL. This work will consider the combination of downward looking IR and DIAL sensors from an airborne platform.

2. INSTRUMENTATION

This study will focus on simulating a synergy of two airborne instruments: the Scanning High-Resolution Interferometer Sounder (S-HIS) and the High Altitude Lidar Observatory (HALO). These instruments flew together aboard the NASA DC-8 during the EcoDemonstrator campaign in the Pacific Northwest. Unfortunately, instrument issues with the HALO prevented this campaign from providing co-located data from these two instruments. Thus, this presentation focuses on a simulated synergy of the two instruments.

HALO is a downward pointing water vapor DIAL developed at NASA Langley Research Center. It uses four channels near 935 nm to ensure sensitivity over a wide dynamic range (Carroll et al. 2022). HALO retrievals provide water vapor profiles at 300 meter vertical resolution. By utilizing the strong surface signal and a total column water vapor retrieval, the profile in the lowest hundreds of meters can be estimated as well. For this study, we do not simulate HALO specifically, only a generic DIAL with a wide range of performances.

S-HIS is a passive downward looking interferometer maintained at the University of Wisconsin-Madison (Tobin et al. 2006). It is a Michelson interferometer is similar to the space-based Cross-track Infrared Sounder (CrIS) or Infrared Atmospheric Sounding Interferometer (IASI) instruments. S-HIS provides radiance measurements at 0.5 cm^{-1} between 580 and 2850 cm^{-1}. It does cross-track scans extending to 45^{o} from nadir in either direction. While this simulation study focuses on the nadir-nadir matched views for HALO (or a generic DIAL) and S-HIS (or a generic IR sounder), how the water vapor information at nadir from the HALO benefits IR retrievals at the other scan angles is a topic of future work.

3. SIMULATION METHODS

We utilize radiosonde profiles from the Atmospheric Radiation Measurement Program's Southern Great Plains site in central Oklahoma for simulation of the DIAL and S-HIS between middle of April 2019 through July 2019. These 703 profiles provide a wide range of thermodynamic environments for simulation of these two sensors. Within that period of time is approximately a one month intensive observation period where eight radiosondes were launched per day, instead of the typical four, providing us with a better representation of the diurnal variations in the PBL within our simulated dataset. Skin temperature is a critical variable that can significantly affect near-surface level information content from downward pointing IR sensors, so we utilize the skin temperature measurements at the time of each radiosonde launch from the infrared thermometer (IRT) for inclusion in these simulations.

To simulate S-HIS, we utilize a fast radiative transfer model called Optimal Spectral Sampling (OSS, Moncet et al. 2008, 2015). The OSS model is patented by the Atmospheric Environmental Research Inc. and calculates the radiance at each channel using a weighted set of monochromatic radiances calculated over a large training set. We allow OSS to account for absorption and emission of carbon dioxide, methane, nitrous oxide, and ozone, but these trace gas profiles remain the same in each simulation. The surface emissivity is also assumed to be known perfectly in this experiment. We use the NASA Combined Aster and MODIS Emissivity for Land (CAMEL; Borbas et al. 2018, Loveless et al. 2021) monthly climatology of surface emissivity at SGP for radiative transfer calculation. Skin temperature from the IRT, along with temperature and water vapor profiles from the radiosonde dataset, are also provided as model inputs. While OSS is not trained for S-HIS, we simulate IASI at an altitude of 10000 m above ground level (AGL) and then convert those radiances and Jacobians to S-HIS wavenumbers and spectral resolution.

DIAL uncertainties are estimated to be a constant proportion of the ambient water vapor at each level of the atmosphere (1%, 2%, 3%, 4%, 5%, 10%, … 35%). This wide range of potential DIAL performances allows us to better visualize the range of benefits of the IR+DIAL synergy. As will be shown below, the DIAL water vapor uncertainties are needed to calculate the information content and estimate retrieval uncertainties for the synergy of sensors.

4. INFORMATION CONTENT AND VERTICAL RESOLUTION

The quantities used to assess information content of the S-HIS and DIAL are primarily derived from the averaging kernel **A**. Following Rodgers (2000) the averaging kernel **A** can be defined as:

$$\mathbf{A} = \mathbf{S}\,(\mathbf{K}^T\,\mathbf{S}_e^{-1}\,\mathbf{K}) \qquad (1)$$

where S_e is the model and measurement error covariance matrix, **K** is the Jacobian (change in measurement with change in state vector) and **S** is the posterior error covariance matrix:

$$\mathbf{S} = (\mathbf{K}^T\,\mathbf{S}_e^{-1}\,\mathbf{K} + \mathbf{S}_a^{-1})^{-1}. \qquad (2)$$

$\mathbf{S}_a$ is the a priori covariance matrix, which in this case is calculated from a 10 year climatology of SGP radiosondes and associated IRT measurements. The Jacobian **K** is a matrix with size being the number of measurements by length of the state vector (skin temperature along with temperature and water vapor at each level). **K** is calculated by the OSS model for S-HIS, and will vary by each input profile. **K** for the DIAL is simply one at each element where the respective water vapor measurement at level *n* corresponds with the water vapor at level *n* in the state vector.

Because of the difficulties quantifying model errors, S_e for S-HIS is estimated to be the instrument noise. The instrument noise for S-HIS is estimated from the blackbody calibration views during previous field campaigns. For the DIAL, S_e becomes the water vapor uncertainty estimated as 1% up to 35% of the ambient water vapor at each level. We can estimate 1σ retrieval uncertainties with this framework by taking the square root of the diagonal of **S**.

Following Hewison (2007), vertical resolution at height *i* may be estimated from the diagonal elements of the averaging kernel **A**:

$$vres_i = \frac{1}{2}(z_{i-1} - z_{i+1})\,(\mathrm{A}_{i,i})^{-1} \qquad (3)$$

where z_{i-1} and z_{i+1} is the height of the vertical grid at indices *i*-1 and *i*+1 respectively. Since the diagonal elements of **A** are the measure of information content at each level, this method effectively spreads the information content out across the vertical grid at each level to estimate the vertical resolution. Thus perfect information content of a level (diagonal element of **A** is 1), would result in the vertical resolution of the vertical grid.

5. RESULTS OF IR+DIAL

5.1 Case Study Profiles

A qualitative assessment of the 703 radiosonde profiles in this analysis reveal that there are largely two regimes that explain the behavior of the synergy of IR+DIAL. Figure 1 displays a case study of one of these regimes – a case where there are large vertical gradients in water vapor. In this profile, there are steep gradients in water vapor around 5500 m above ground level (AGL), 3000 m, and 1500 m. Figure 1 also displays the diagonal elements of the averaging kernel **A** for temperature for the IR only and for IR+DIAL. The diagonal elements of **A** provide a view the information content at each level. At each of those regions of sharp vertical water vapor gradients, IR+DIAL provides a significant increase in information content compared to the IR alone. The IR is sensitive to those gradients in water vapor through the vertical change in transmission at these levels, resulting in peaks of the weighting functions at those levels, and thus small increases in information content. However, the broad weighting functions of the IR spreads that signal out across several levels. Including the DIAL measurements helps to better extract that signal out of the radiance measurements. As a result, there are significant increases in information content, doubling at some levels, where these sharp water vapor gradients are located. These significant increases in information content are seen in the high DIAL uncertainty simulations as well. This suggests even a poorly performing DIAL would provide improvements to temperature retrievals out of IR radiances, not only water vapor retrievals.

The second regime is displayed by the case profile in Figure 2. In this case the vertical gradients in water vapor are much smaller throughout the profile, than the first case in Figure 1. Without the sharp water vapor gradients, the DIAL provides only small improvements to the temperature retrieval. These information content gains are on the order of 20-30% and contained in the middle to upper troposphere, around 7000 to 8000 m AGL.

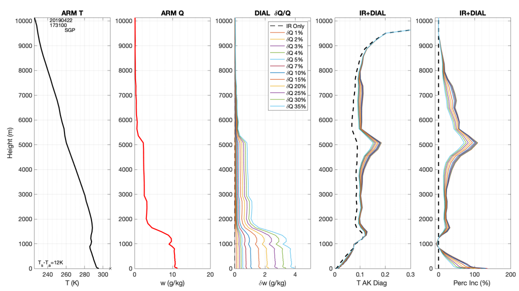

Figure 1. ARM SGP radiosonde temperature (left) and water vapor (left middle) profiles. DIAL uncertainty/noise estimates for each assumed state (middle). Diagonal elements of the averaging kernel (middle right) and the percent increase in the value of those diagonal elements at each height shown (right).

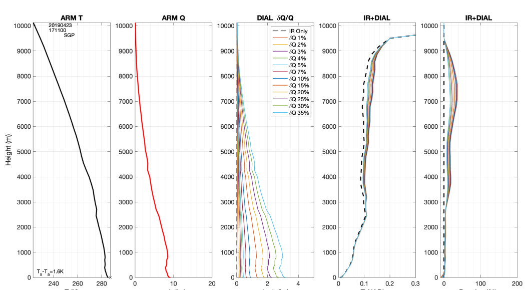

Figure 2. ARM SGP radiosonde temperature (left) and water vapor (left middle) profiles. DIAL uncertainty/noise estimates for each assumed state (middle). Diagonal elements of the averaging kernel (middle right) and the percent increase in the value of those diagonal elements at each height shown (right).

These two cases presented display the variations seen in this 703 profile set. The IR+DIAL synergy does not provide much benefit compared to the IR alone when there are small vertical gradients in the water vapor profile. However, in cases with sharp vertical gradients in water vapor, notably environments that would have capping inversions, the IR+DIAL benefit is quite large.

5.2 Composite View of Synergy Gains

We compute averages across each level for the IR alone and IR+DIAL 1σ temperature retrieval uncertainties and vertical resolutions. The 1σ uncertainties are displayed in Figure 3. The IR alone has high uncertainty at the surface due to the inclusion of skin temperature in the state vector. The IR+DIAL synergy provides a reduction of about 0.3 to 0.5 K from 300 m AGL up to about 9000 m. With a simulated flight level of about 10000 m AGL the IR instrument is very sensitive to the 9000 to 10000 m AGL layer, therefore the DIAL provides less benefit in that region. The low water vapor at that height likely affects the synergy benefit as well. The combination of IR+DIAL results in uncertainties less than 1 K goal of the 2017 Decadal Survey above 1000 m AGL.

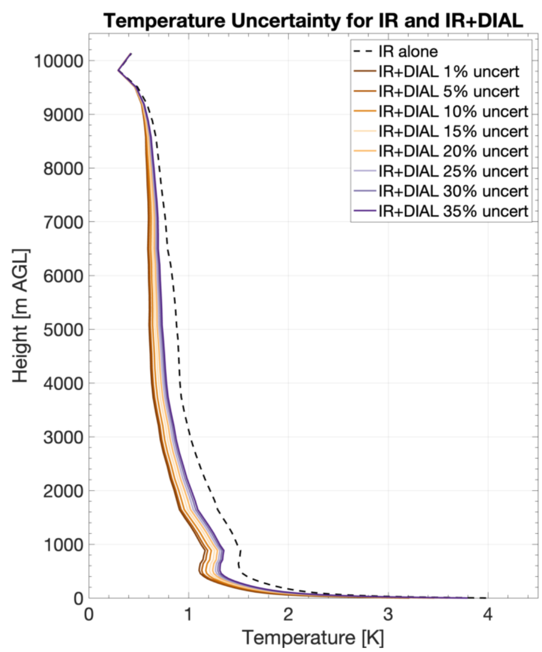

Figure 3. Mean 1σ temperature uncertainty for all 703 profiles in this analysis.

The vertical resolution of IR and IR+DIAL is displayed in Figure 4. The greatest improvements to vertical resolution are between 5000 and 7000 m AGL. The IR alone is shown to achieve the 1000 m resolution in the lowest 1000 m AGL, as desired by the 2017 Decadal Survey. However, the lack of improvements in the near-surface layer suggests the need for ground-based platforms to fully achieve the objectives of the Decadal Survey.

As noted earlier, the sum of the diagonal elements of the averaging kernel **A** is the degrees of freedom of signal (DOF) for that layer. Figure 5 displays the DOF for temperature for IR only compared to IR+DIAL for both the full profile (surface to 10000 m AGL) and the surface to 2000 m AGL. IR+DIAL provides an improvement of 0 – 0.5 DOF for temperature in the surface to 2000 m AGL layer, and 1 – 2 DOF across the full profile. The IR+DIAL synergy is always better than the IR alone, but as discussed earlier, there are environments where those benefits are quite small and other environments where those benefits can be pronounced.

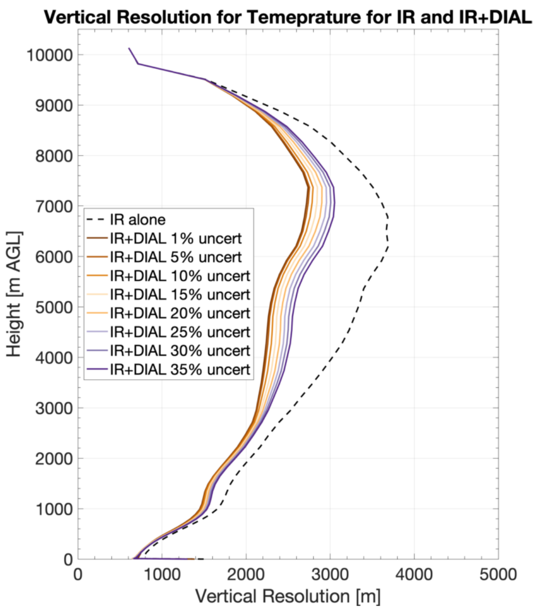

Figure 4. Mean temperature uncertainty for all 703 profiles in this analysis.

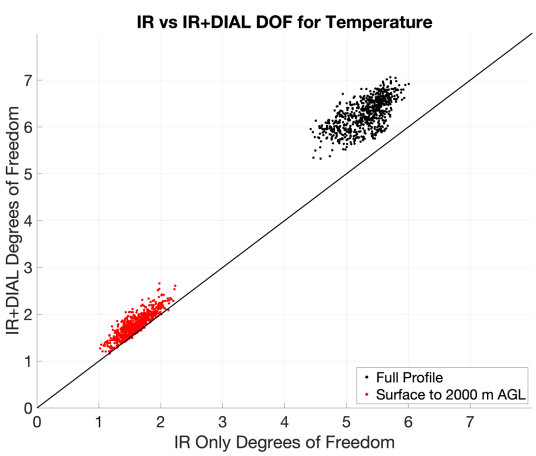

Figure 5. Degrees of freedom (DOF) for temperature for IR only and IR+DIAL assuming a 5% water vapor uncertainty. DOF values for the full profile are shown in black, surface to 2000m above ground level shown in red.

6. CONCLUSIONS

We have presented a simulation of the potential benefits of a synergy of IR sounders with water vapor DIAL measurements for improved sounding of the PBL. DIAL measurements would significantly improve water vapor measurements at nadir, compared to what IR and microwave soundings provide at current moment. What is less clear is the improvements to temperature retrievals that a better observation of water vapor would have on the observing system. The assumptions and design of this study provides a reasonable estimate of the theoretical maximum performance of these instruments.

We have designed this study to consider a wide range of uncertainties to the DIAL measurements. A key result here is that even very uncertain DIAL measurements (water vapor uncertainties of 35% of the ambient water vapor) would, on aggregate, result in reductions of about 0.3 K in temperature retrieval uncertainty above 300 m AGL, along with improvements to vertical resolution in the middle troposphere. We have identified that in thermodynamic environments in which vertical water vapor gradients are quite small, the DIAL benefits on the temperature retrievals are quite small. However, in environments that have sharp water vapor gradients, we have found that the DIAL benefit is quite significant – with those benefits concentrated on those regions where the gradient is largest in magnitude. Critically, these are the environments that are most important for severe convection where these measurements could provide important insight on atmospheric stability.

The results here suggest that the IR+DIAL synergy from a space-based platform would provide important benefits to thermodynamic sounding. This result is key for design of a future NASA PBL observing mission. However, we do find that this synergy still fails to provide improvements to temperature retrievals in the near-surface layer. This suggests that ground-based platforms are going to be critical to achieving the objectives of the 2017 Decadal Survey, as has previously been shown by Loveless et al. (2022).

Acknowledgments

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