Obtaining Continuous Observations from the Upper Stratosphere to the Lower Thermosphere Using the ALO-USU Rayleigh-Scatter Lidar.

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Abstract

The Rayleigh-scatter lidar at the Atmospheric Lidar Observatory at Utah State University (ALO-USU; 41.74° N, 111.81° W) started observations in 1993. In 2012 the original lidar system was upgraded with an array of larger mirrors and two lasers to enable observations of the upper mesosphere and lower thermosphere from 70 km to about 115 km in altitude. (Continued refinement should provide data to above 120 km.) Recently, the original system was reconfigured [*Elliott et al.*, 2016] to again observe the lower mesosphere between 40 km and 90 km. Initial data collected by these two parts of the Rayleigh system have been "stitched" together to obtain a full temperature profile from 40 km to about 115 km.

These extended profiles have been used to obtain relative neutral densities and temperatures through the entire mesosphere and well into the lower thermosphere. This extends the CEDAR goal of studying coupling between atmospheric regions. Furthermore, by normalizing the relative neutral densities between ~35 and 45 km to an advanced reanalysis model, absolute neutral densities become available from a ground-based, remote-sensing instrument all the way into the lower thermosphere. This opens that region to detailed studies for many research topics.

Background

Between 1993 and 2004 the ALO-USU Rayleigh-scatter lidar used a single 44 cm diameter mirror with a GCR series Spectra-Physics Nd:YAG laser operating at 30 Hz and 532 nm (with a PAP = 6.4 Wm^2) to make observations from which relative densities and absolute temperatures of the mesosphere could be derived between 40 and 90 km. The ALO-USU lidar system was later upgraded, adding another GCR series laser and four 1.25 m diameter mirrors (increased PAP = 706 Wm^2), Figure 1. It came into full operation in 2014. This big Rayleigh lidar opened up Rayleigh observations from the upper mesosphere well into the lower thermosphere, from 70 to 115 km [e.g., *Sox et al.*, 2016; *Wickwar et al.*, 2016]. In the spring of 2016, the 44 cm mirror was repurposed using a Dobsonian telescope design, a new photomultiplier tube, a chopper, and optics to make a small Rayleigh lidar to again observe the lower mesosphere from 40 to 90 km [*Elliott, et al.*, 2016]. The small and big lidars share the same lasers. The ALO-USU Rayleigh lidar system now has the capability of observing from 40 to about 115 km. The intent is to extend this range from 30 to about 120 km. The data from the big and small lidars then need to be combined to produce full profiles over this very extended altitude range. These, in turn, lead to full profiles of relative density, which can be reduced to full profiles of absolute neutral temperatures and absolute neutral densities.

Figure 1: Large telescope system. The four 1.25 m mirrors are mounted in the cage where the two laser beams pass through the center of the cage.

Future Research

With these new observational possibilities come both new and improved research opportunities. We now have neutral densities, in addition to neutral temperatures, extending from the stratosphere well into the lower thermosphere. This is the first time that neutral densities can be obtained all the way to 120 km from ground-based observations. These capabilities suggest numerous projects, a few of most interest to us are given below:

- Compare densities and temperatures at 120 km to the bottom boundary conditions for thermospheric models
  - Important input for satellite orbital-decay predictions.
  - Significant for examining ionosphere-thermosphere interactions
- Examine the significant differences that have been found between Rayleigh and Na lidar temperatures above 95 km at ALO-USU [*Sox et al.*, 2016a].
- Help to understand the Rayleigh-Na differences by comparing Rayleigh temperatures to those from TIMED-SABER (as in Fig. 3) and, later, to those from the OPAL CubeSat.
- Extend the search for effects from sudden stratospheric warmings, which have been seen at ALO-USU up to 90 km [*Sox et al.*, 2016b], to the thermosphere and to densities.
- Extend the search for coupling, which appears to have been seen between tropospheric weather and 45 km temperatures [*Moser et al.*, 2016], to 120 km and to densities.
- Examine the large amplitude waves that appear to be associated with mid-latitude noctilucent clouds sightings [*Herron et al.*, 2007].

Merging High and Low Altitudes

Because of weather and equipment challenges after the small Rayleigh lidar was completed, few nights of good data have been collected so far with the combined system. To illustrate what will be done, we will work with one night of lower altitude data from April 2016 and with one night of higher altitude data from a year earlier, from April 2015. The temperatures from these two nights are shown in Figure 2.

Three ways of merging the data are as follows:

a. Merge the signals from the two lidars in the overlap region.
b. Reduce the big lidar data to temperatures. Use one or more of the lowest altitude temperatures as seed temperatures to reduction the data from the small lidar.
c. Reduce the big and small lidar data to temperatures. Average temperatures from the lowest altitudes from the big lidar with temperatures from the same altitudes from the small lidar.

Given that we are only illustrating the process, we will use the last method, which is the simplest. Taking into account that the two sets of temperatures will have very different uncertainties, the average temperature is given by

$$\langle T\rangle = (T_1/\sigma_1^2 + T_2/\sigma_2^2)/(1/\sigma_1^2 + 1/\sigma_2^2)$$

and its uncertainty by

$$\sigma^2 = 1/(1/\sigma_1^2 + 1/\sigma_2^2).$$

The merged temperature profile is given in Figure 3. This figure emphasizes that the ALO-USU Rayleigh lidar system can provide continuous coverage from the upper stratosphere into the lower thermosphere.

Using the first method will provide a continuous signal profile from which the relative density profile can be determined. This can then be used to derive a continuous temperature profile. In addition, the relative density profile can be normalized below 45 km against one of the reanalysis models (e.g., NCEP, MERRA, ERA-Interim) to obtain absolute densities all the way from the stratosphere, through the mesosphere, into the thermosphere. Having ground based observations of the neutral densities at 120 km would be a significant first.

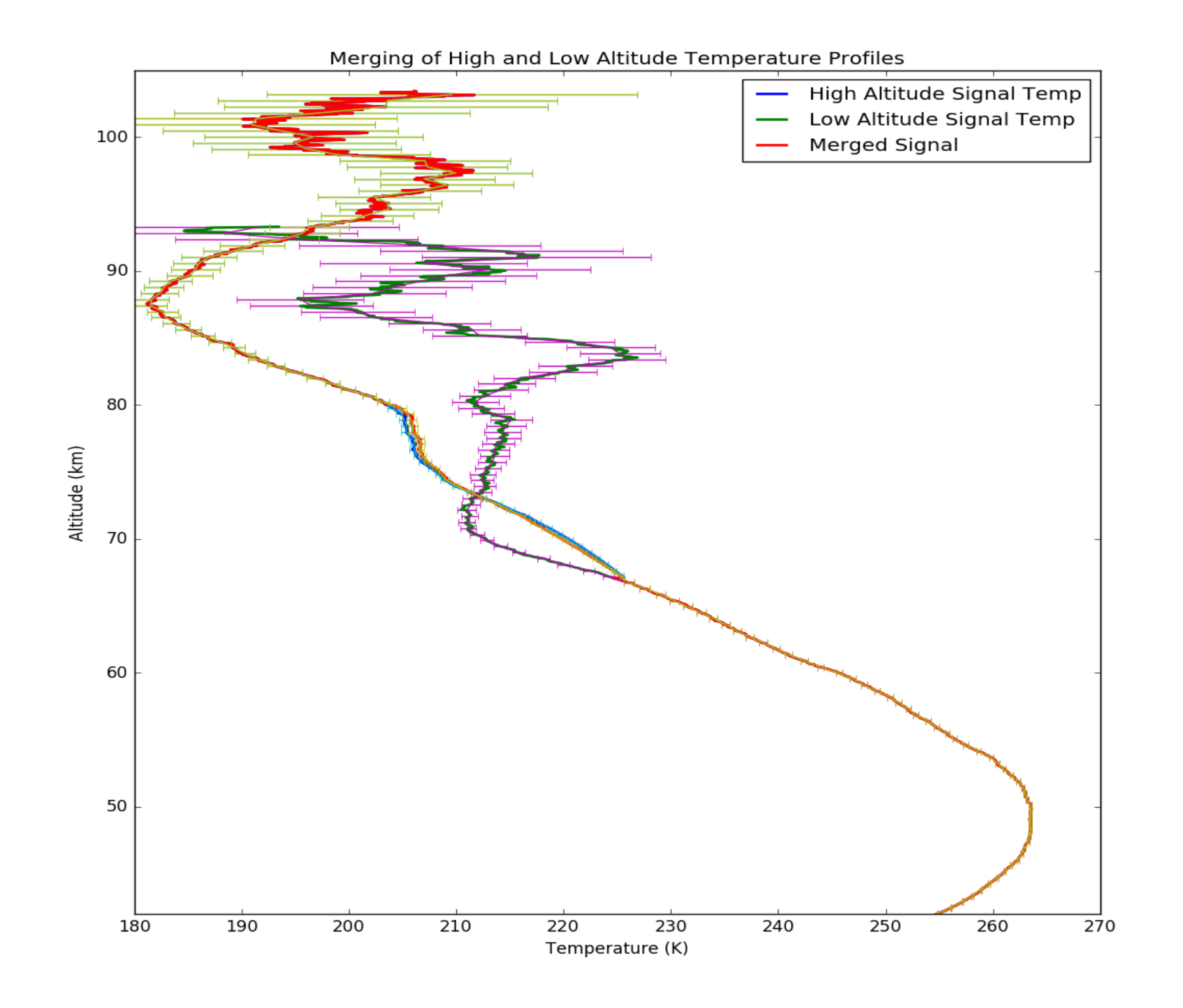

Figure 2: An all night averaged high altitude profile from 04/14/15 was merged with that of lower data observed on 04/07/16 to show proof of concept of the technique.

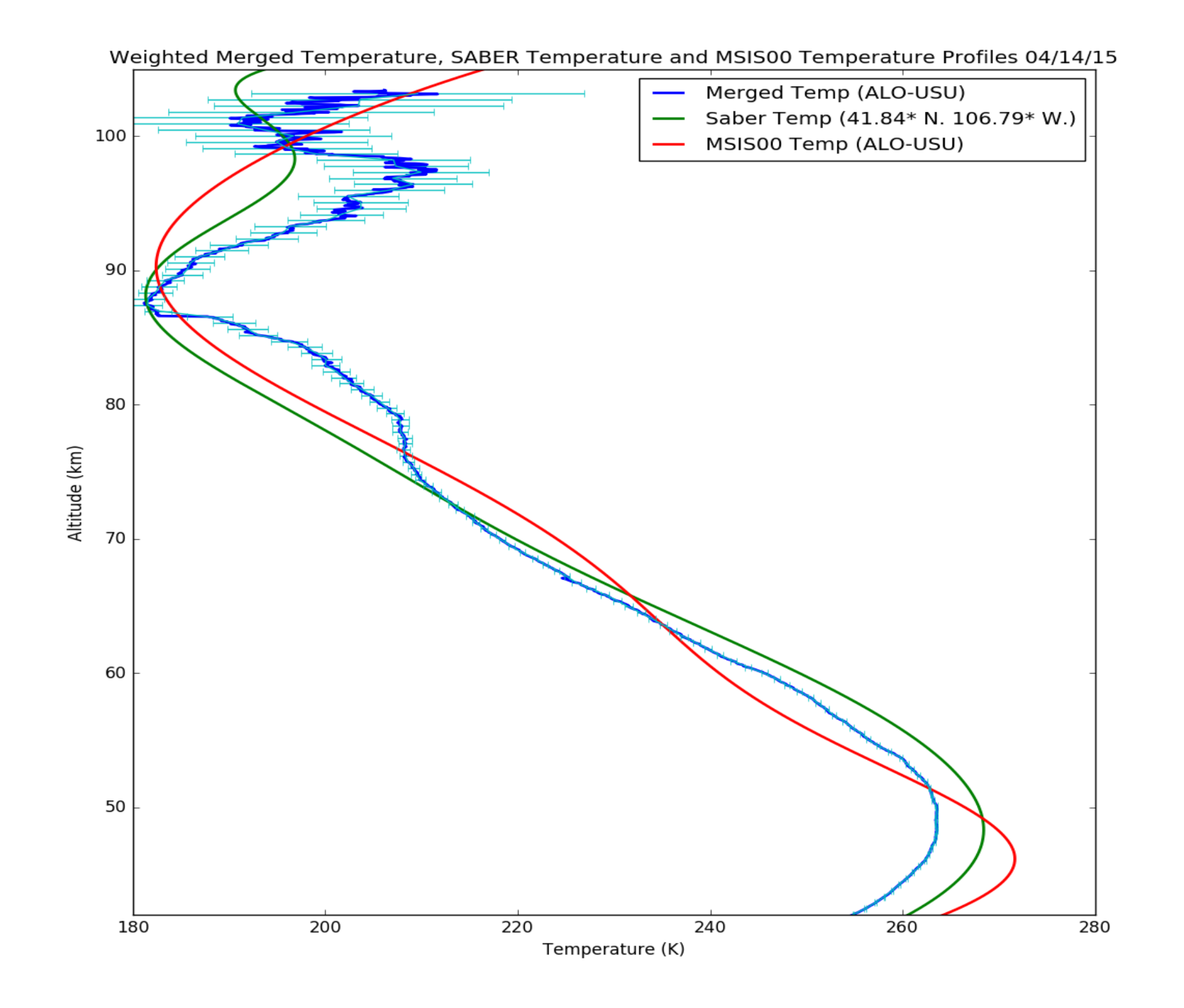

Figure 3: Illustrative profile of merged temperature data from the USU-ALO big and small lidars. This is compared with SABER data and the MSIS00 model.

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Conclusions

The altitude range of the large ALO-USU Rayleigh lidar is 70—115 km. This capability has just been significantly increased by adding a small Rayleigh lidar to the system. Its range is 40—90 km. Combined, the altitude range for Rayleigh-derived neutral temperatures is now 40—115 km.

Straightforward future work will extend the altitude range down to 30 km and up to 120 km, i.e., from the mid stratosphere to the lower thermosphere.

By extending the altitude range downward from 70 km to ~35 km, the ALO-USU Rayleigh lidar system can now, in addition to temperatures, provide neutral densities over 40—115 km.

Having these extended profiles of temperature and density opens many new research opportunities, some of which were described in the previous section.

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