Georgia Tech Research Institute

Rayleigh-Scatter Lidar for Characterizing the Near-Earth Space Environment

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SPACE ENVIRONMENT TECHNOLOGIES

Space Research *Space Operations* *Space Standards*

Space Dynamics LABORATORY

Utah State University Research Foundation

Motivation

Thermospheric and satellite drag models need ***neutral density*** and ***temperature*** measurements at roughly 120 km to give real-time boundary conditions.





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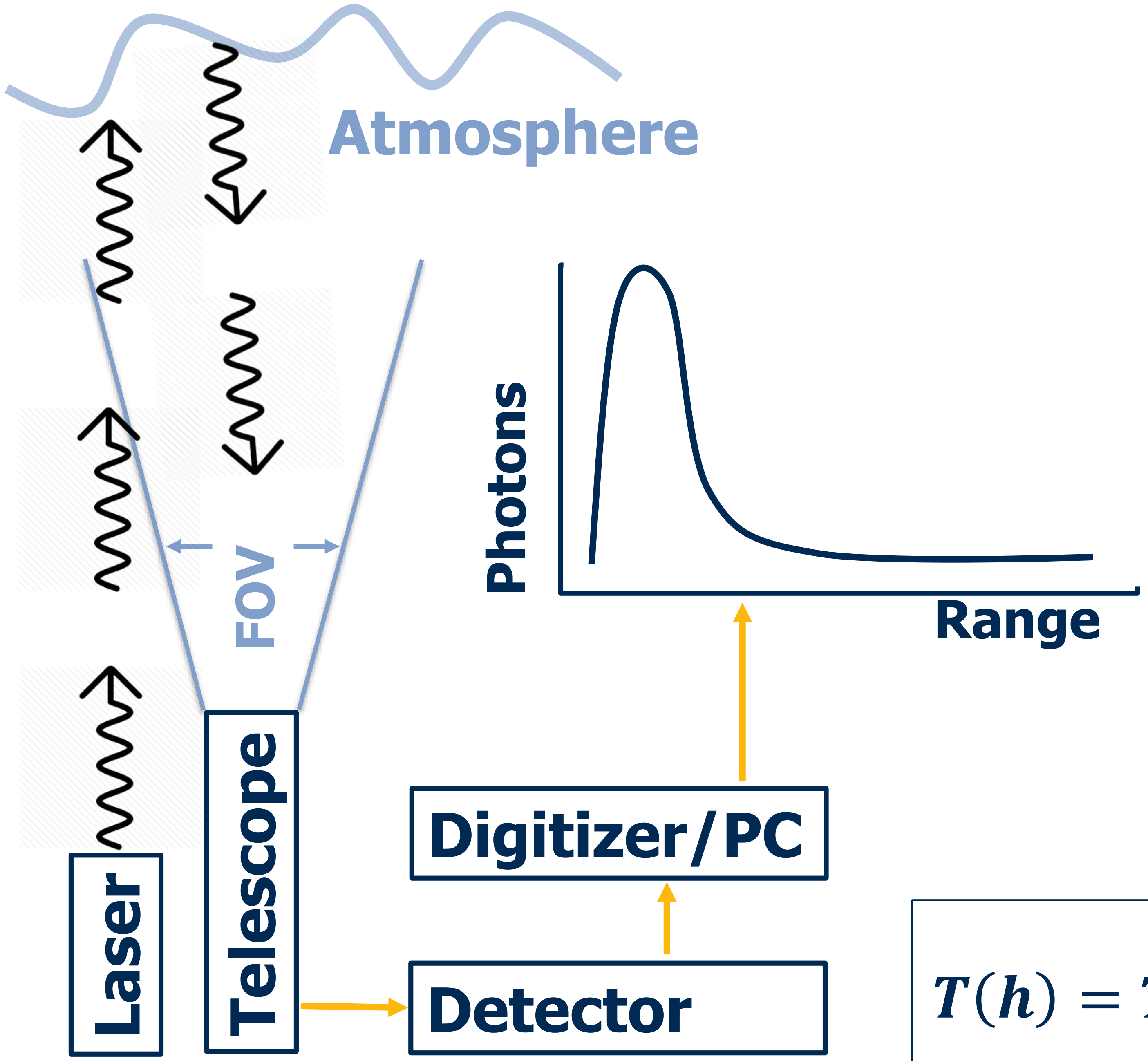
⇨ **High-power, large-aperture Rayleigh lidar systems can provide the fundamental thermospheric measurements for model boundary conditions**





Rayleigh Lidar Technique



1) Simplified Lidar Equation with lidar signal, $S(h)$:

$$n(h) = \frac{S(h)h^2}{C}$$

Assume:

- Hydrostatic equilibrium
- Well-mixed atmosphere

2) Plug into Ideal Gas Law:

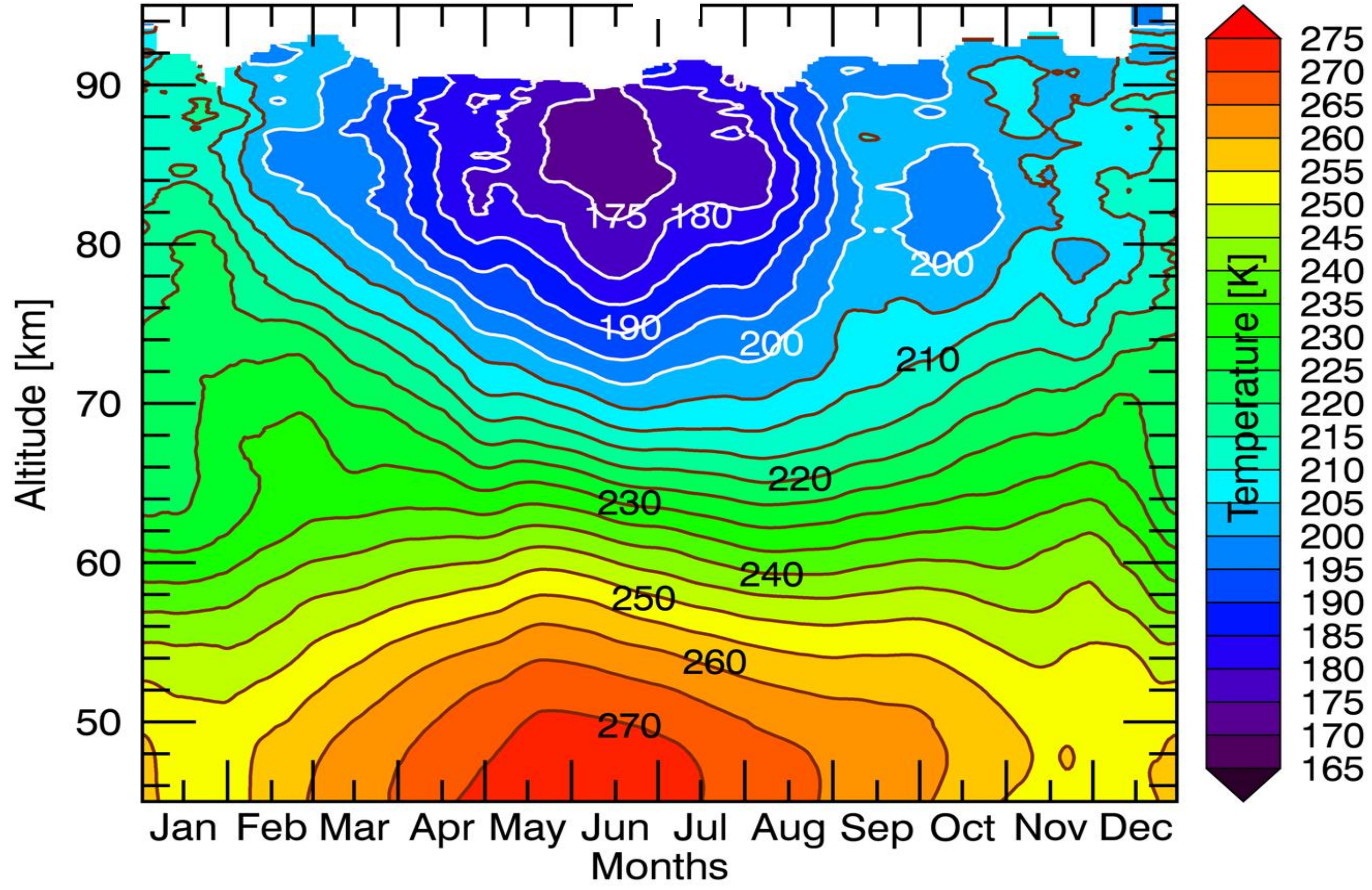
$$p(h) = n(h)kT(h)$$

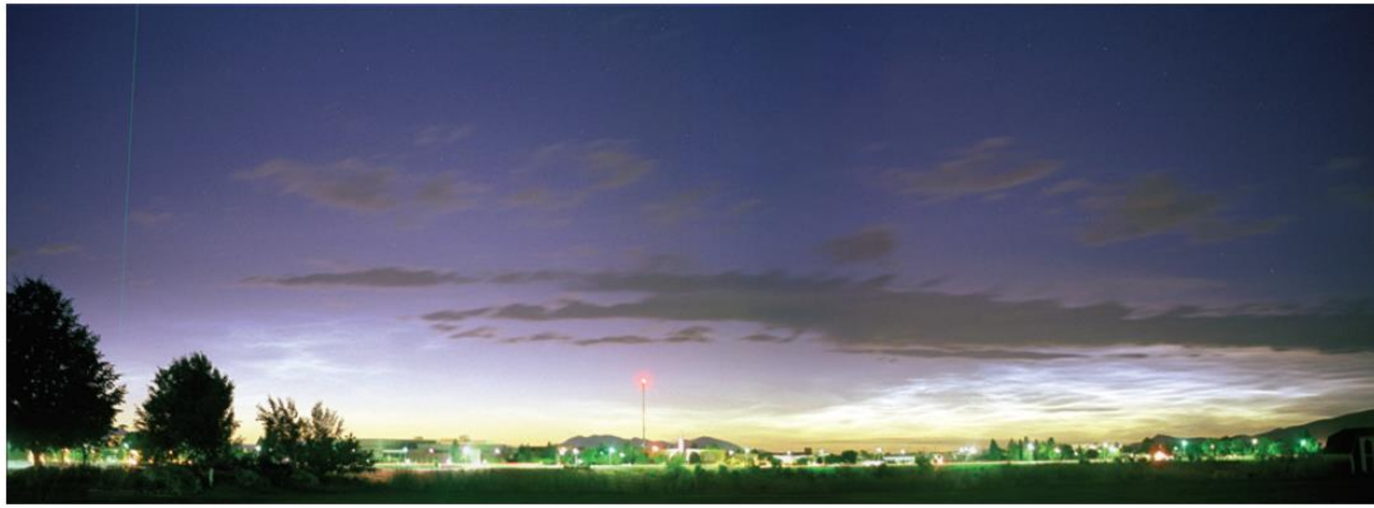
3) Rayleigh Lidar Temperature Integral Equation [Hauchecorne & Chanin, 1980]

$$T(h) = T(h_{max})\frac{n(h_{max})}{n(h)} + \frac{1}{k}\int_h^{h_{max}} \frac{n(h')}{n(h)} m(h')g(h')dh'$$

USU Rayleigh Lidar Temperatures from 1993—2004

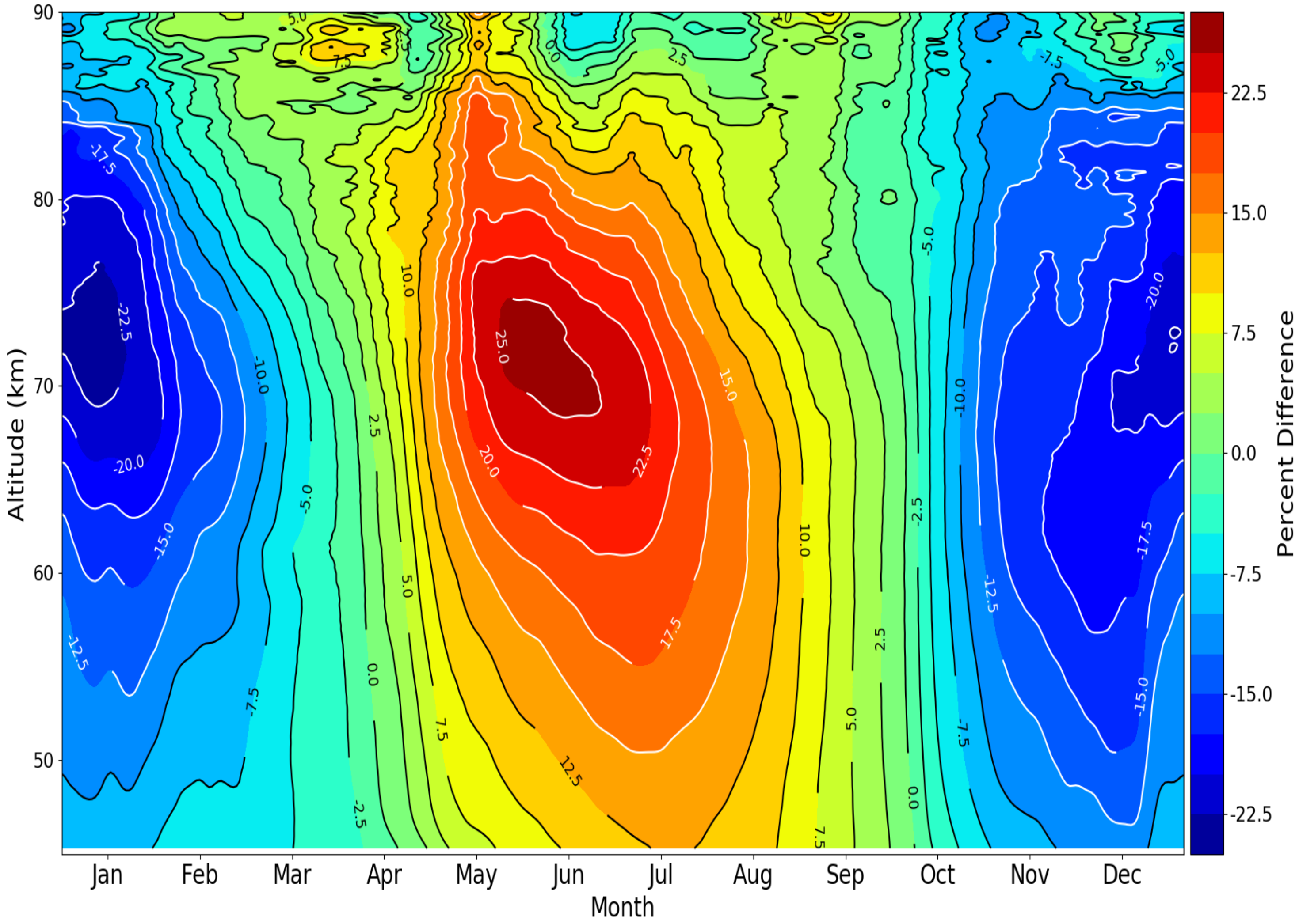
- Temperature climatology (below) [Herron, 2007]





- Mid-latitude (42ºN) noctilucent clouds (above) [Herron et al., 2007; Wickwar et al., 2002]
- 11-year temperature trends [Wynn & Wickwar, 2010]
- Gravity wave studies [Kafle, 2009]
- Mesospheric coolings in conjunction with sudden stratospheric warmings [Sox et al., 2016]

Neutral densities from stratosphere to thermosphere



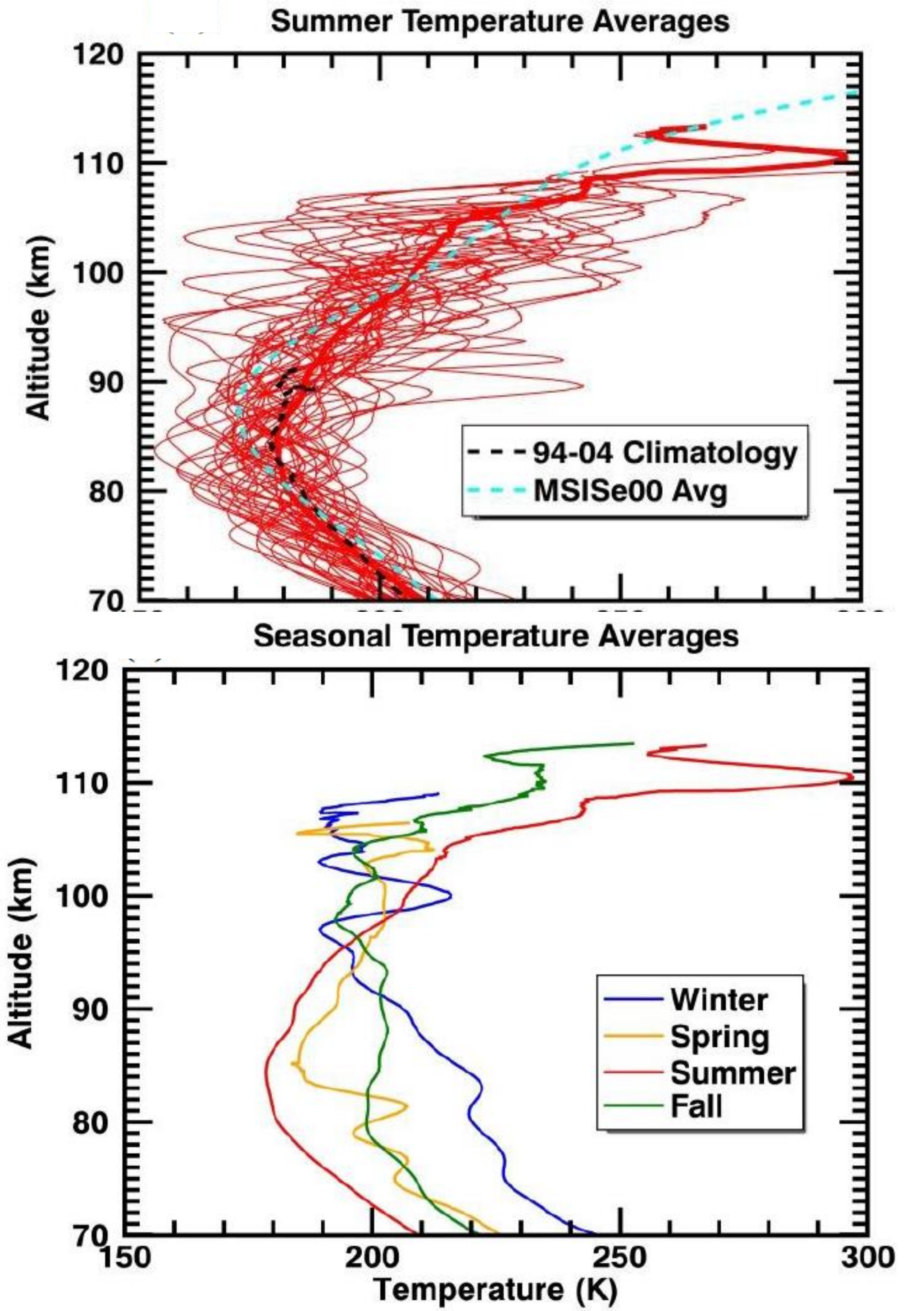
[Price et al., 2018]

- 11-year climatological relative densities normalized to NASA's MERRA2 densities at 45 km
- Can normalize to other datasets (e.g. JRA-55, ERA-20C)
- Percentage difference shows temporal and altitudinal variations
- In real-time could scale densities to data from collocated lower altitude lidar or other instruments

USU Rayleigh Lidar 2014-2015

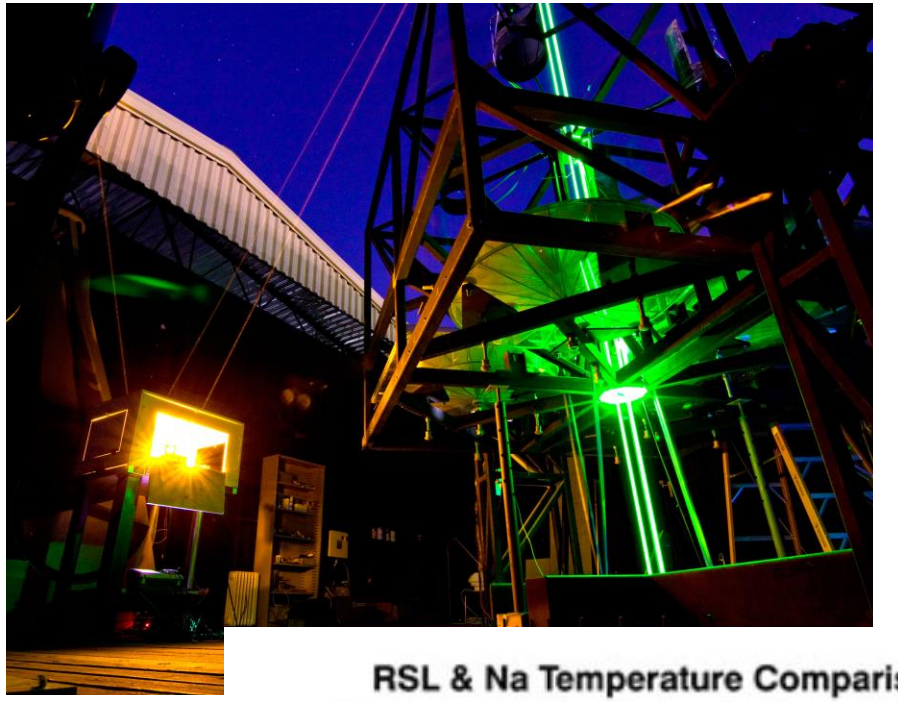
- Pushed Rayleigh lidar temperature measurements into the thermosphere (~115 km) [Wickwar et al., 2016; Sox, 2016]
- Uncertainties much smaller than oscillations shown here
- Accounted for changing atmospheric composition (atomic oxygen) above 90 km

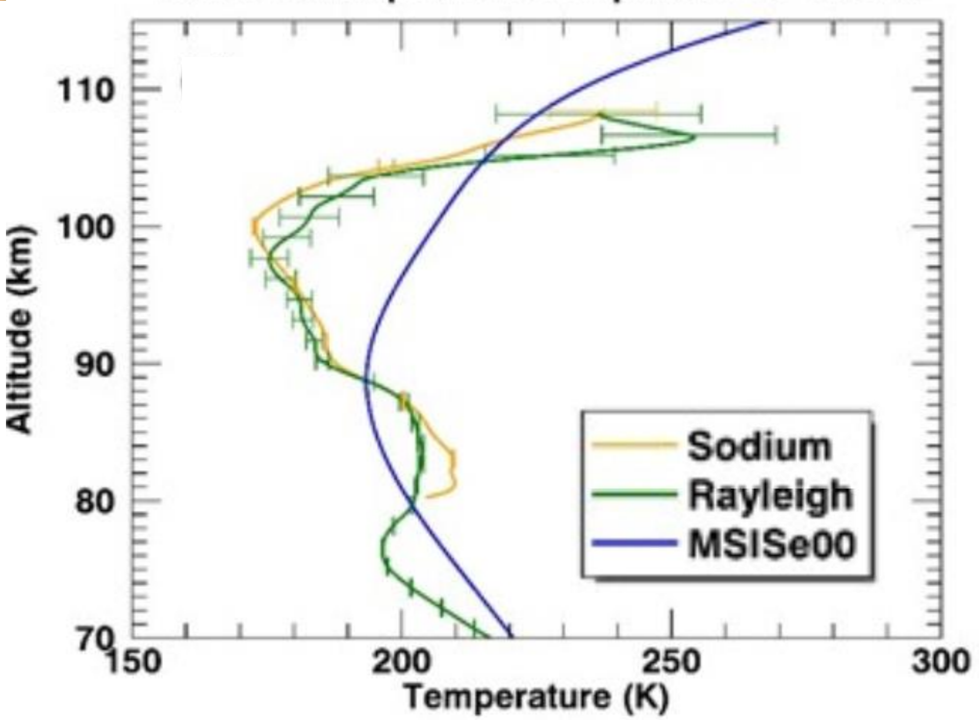
	1993-2004 Value	2014-2015 Value
Laser Power	24 W (18 W)	42 W
Telescope Area	0.44 m^2	4.9 m^2
Power-Aperture Product	3.6 $W \cdot m^2$ (2.7 $W \cdot m^2$)	206 $W \cdot m^2$
Top altitude in Temperature Profile	~95 km	~115 km

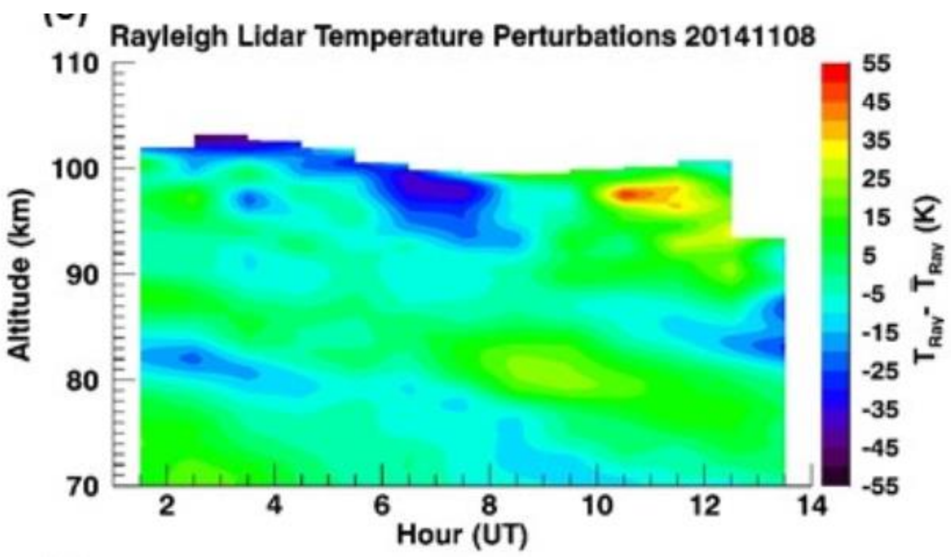


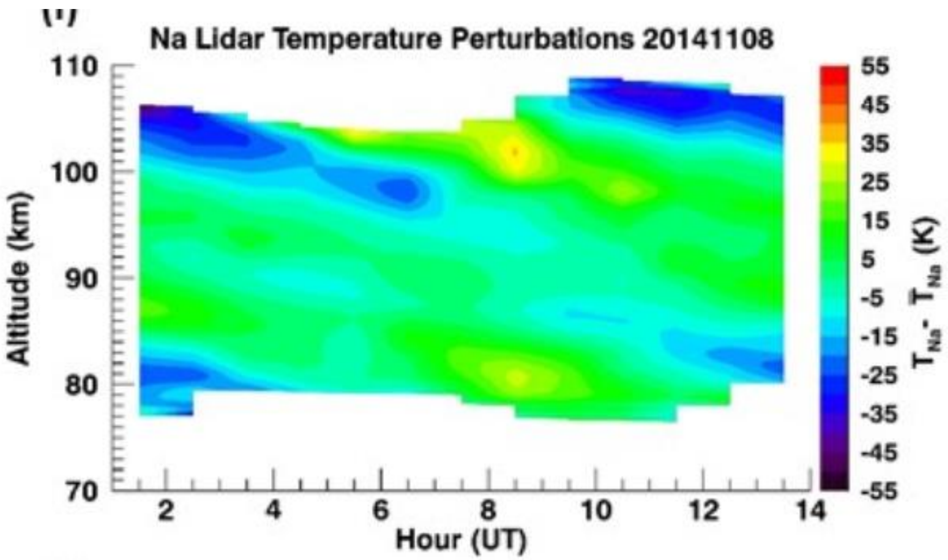
USU Rayleigh and Na Resonance Lidar Comparison [Sox et al., 2018]

- Throughout 2014-2015, direct comparisons were made to the collocated Na resonance lidar at USU
- Results show best agreement over 85-95 km, with larger differences above and below
- Same gravity wave structure in both datasets



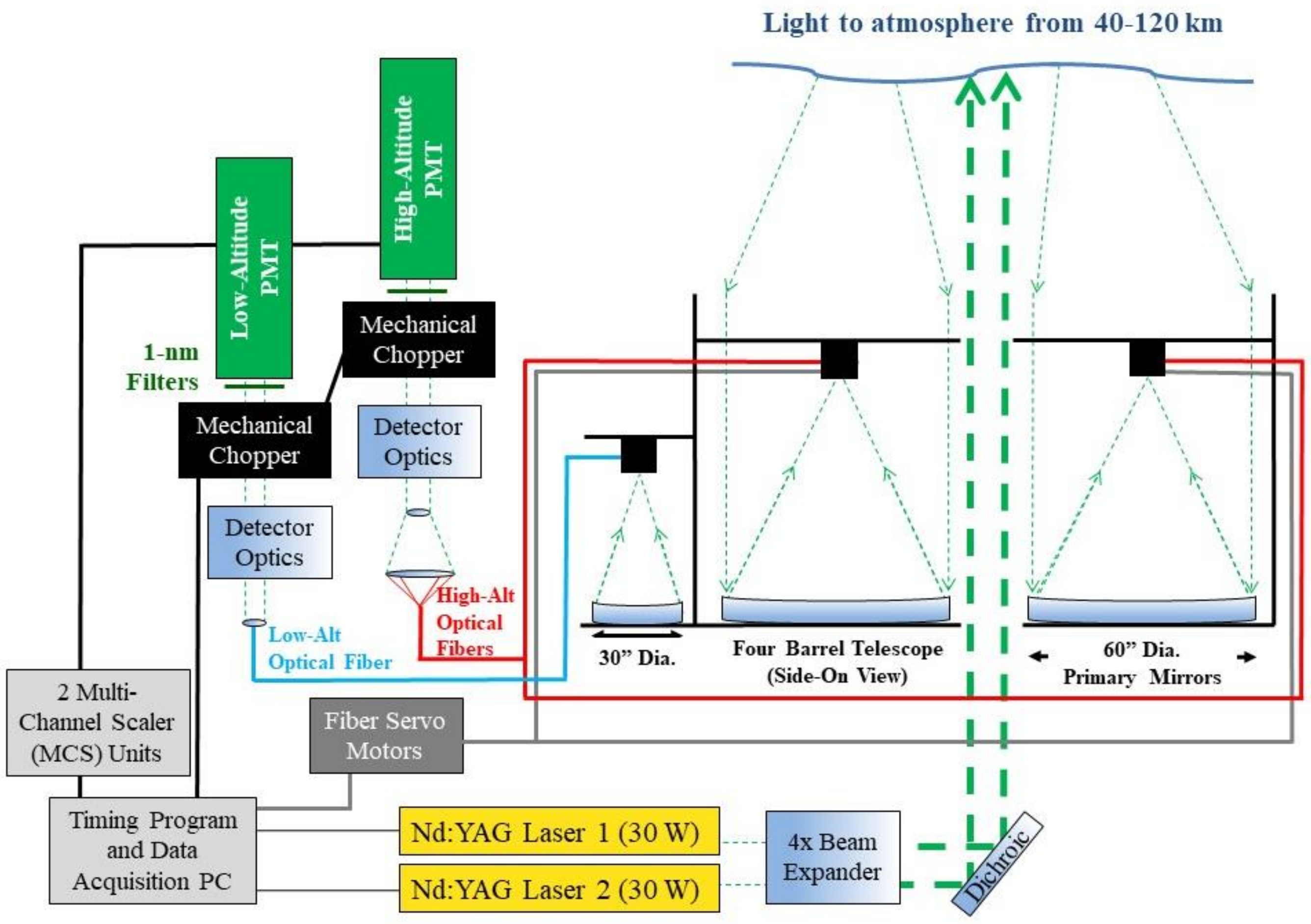






Rayleigh lidar for thermospheric model inputs

- With lessons-learned from USU Rayleigh lidar, extend neutral density and temperature measurements from 40 to 135 km
- Data ingested in real-time to satellite drag and thermospheric data assimilation models, for example:
  - Jacchia-Bowman 2008 [Bowman et al., 2008]
  - DRAGSTER [Crowley & Pilinski, 2017]
  - Others!



Toward a thermospheric lidar network

- GTRI has expertise in engineering deployable, ruggedized atmospheric lidar systems like the Integrated Atmospheric Characterization System [Roberts et al., 2014]
- Chain of such Rayleigh lidars located at a number of latitudes and longitudes can provide global coverage and complement existing techniques at large research facilities (e.g. Arecibo, Poker Flat, etc.)
- SET can provide thermospheric model and data assimilation expertise

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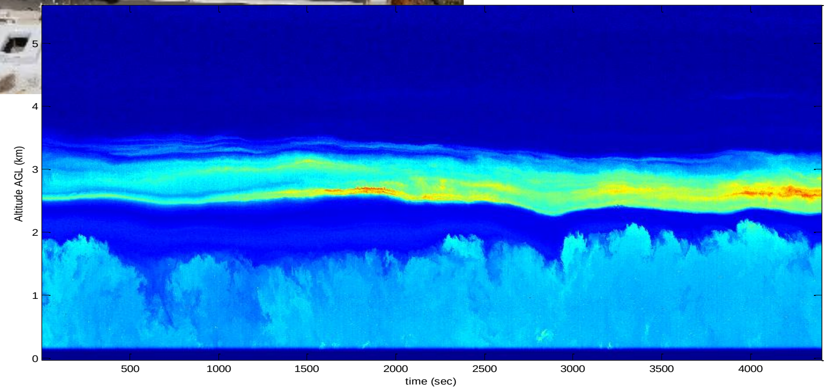

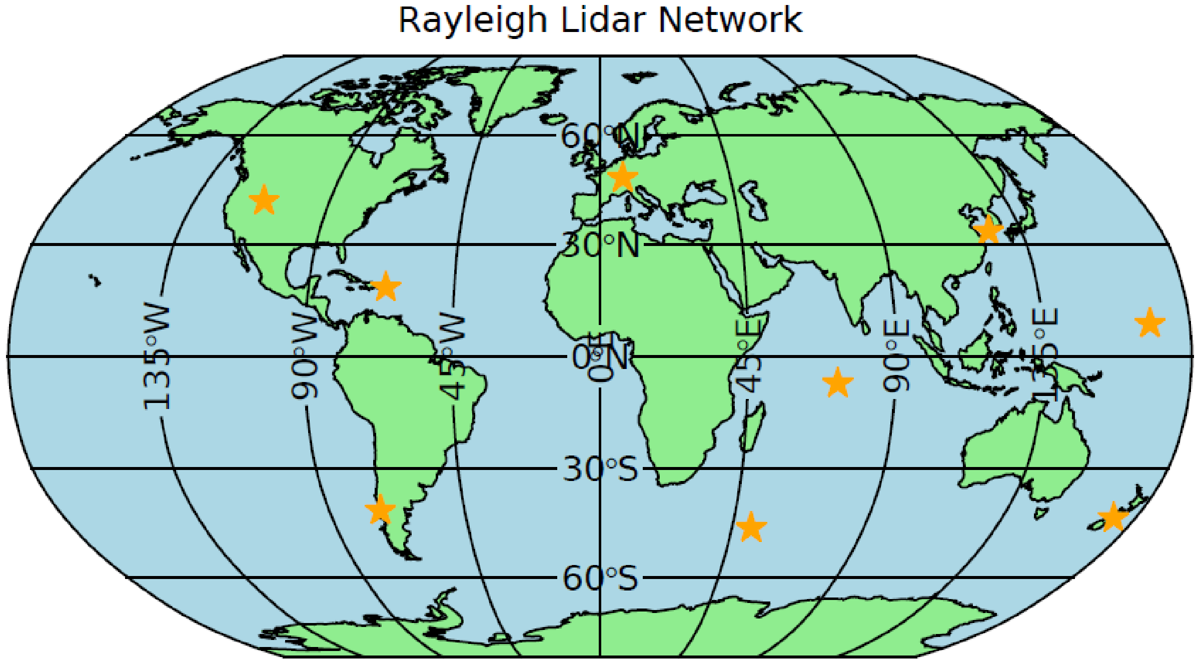

Take-Aways:

- Group at USU has extended Rayleigh lidar-derived temperatures to 115 km and densities up to 95 km
- GTRI can leverage atmospheric lidar engineering expertise to further extend USU's Rayleigh technique to 120 km or above, while assuring rugged, deployable systems that provide real-time data products
- SET has extensive experience in using the lower BCs to improve thermospheric models

References

Bowman, B., Tobiska, W. K., Marcos, F., Huang, C., Lin, C., & Burke, W. (2008). A New Empirical Thermospheric Density Model JB2008 Using New Solar and Geomagnetic Indices. *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, (August). https://doi.org/10.2514/6.2008-6438

Crowley, G., & Pilinski, M. (2017). Reducing conjunction analysis errors with an assimilative tool for satellite drag specification introduction : satellite drag and orbit prediction, (5), 1–17.

Hauchecorne, A., & Chanin, M.-L. (1980). Density and Temperature Profiles Obtained by Lidar Between 35 and 70 km. *Geophysical Research Letters*, *7*(8), 565–568.

Herron, J. P. (2007). *Rayleigh-Scatter Lidar Observations at USU's Atmospheric Lidar Observatory (Logan,UT) - Temperature Climatology, Temperature Comparisons with MSIS, and Noctilucent Clouds*.

Herron, J. P., Wickwar, V. B., Espy, P. J., & Meriwether, J. W. (2007). Observations of a noctilucent cloud above Logan, Utah (41.7°N, 111.8°W) in 1995. *Journal of Geophysical Research Atmospheres*, *112*(19), 1–12. https://doi.org/10.1029/2006JD007158

Herron, J. P., Wickwar, V. B., Espy, P. J., & Meriwether, J. W. (2007). Observations of a noctilucent cloud above Logan, Utah (41.7°N, 111.8°W) in 1995. *Journal of Geophysical Research Atmospheres*, *112*(19), 1–12. https://doi.org/10.1029/2006JD007158

Kafle, D. N. (2009). *Rayleigh-Lidar Observations of Mesospheric Gravity Wave Activity above Logan, Utah*.

Price, J. L., Wickwar, V. B., & Herron, J. P. (2018). Obtaining Absolute Neutral Densities in the Mesosphere Using Rayleigh-Scatter Lidar Observations with Reanalysis Models. In *American Geophysical Union Fall Meeting*.

Roberts, D. W., Albers, K. R., Brown, E. A., Craney, T. A., Hosain, M. M., James, R. K., … Whiteman, D. N. (2014). The integrated atmospheric characterization system (IACS). In *Proc. SPIE 9080, Laser Radar Technology and Applications XIX; and Atmospheric Propogation XI*. https://doi.org/10.1117/12.2050600

Schunk, R. W., Scherliess, L., Sojka, J. J., Thompson, D. C., Anderson, D. N., Codrescu, M., … Howe, B. M. (2004). Global Assimilation of Ionospheric Measurements (GAIM). *Radio Science*, *39*(1), n/a-n/a. https://doi.org/10.1029/2002RS002794

Sox, L. (2016). *Rayleigh-Scatter Lidar Measurements of the Mesosphere and Thermosphere and their Connections to Sudden Stratospheric Warmings*. Retrieved from http://digitalcommons.usu.edu/etd%0Ahttp://digitalcommons.usu.edu/etd/5227

Sox, L., Wickwar, V. B., Fish, C. S., & Herron, J. P. (2016). Connection between the midlatitude mesosphere and sudden stratospheric warmings as measured by Rayleigh-scatter lidar. *Journal of Geophysical Research: Atmospheres*, *121*(9), 4627–4636. https://doi.org/10.1002/2016JD025907

Sox, L., Wickwar, V. B., Yuan, T., & Criddle, N. R. (2018). Simultaneous Rayleigh-Scatter and Sodium Resonance Lidar Temperature Comparisons in the Mesosphere-Lower Thermosphere. *Journal of Geophysical Research: Atmospheres*, *123*(18), 10688–10706. https://doi.org/10.1029/2018JD029438

Wickwar, V. B., Sox, L., Emerick, M. T., Herron, J. P., & Barton, D. L. (2016). Early Temperatures Observed with the Extremely Sensitive Rayleigh Lidar at Utah State University. *EPJ Web of Conferences*, *119*, 13007. https://doi.org/10.1051/epjconf/201611913007

Wickwar, V. B., Taylor, M. J., Herron, J. P., & Martineau, B. A. (2002). Visual and lidar observations of noctilucent clouds above Logan, Utah, at 41.7°N. *Journal of Geophysical Research*, *107*(D7), 4054. https://doi.org/10.1029/2001JD001180

Wynn, T. A., & Wickwar, V. B. (2010). Temperature trends and episodic changes of the middle atmosphere over Logan Utah with consideration to model specification. In *Utah Space Grant Consortium Conference*.