Measuring atmospheric temperature and wind with Cabannes scattering at 589 nm with sodium vapor filters

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- Using a high temperature and a low temperature **two atomic vapor filters** (AVFs) as spectral analyzers, a group at Colorado State University (CSU) had proposed the use of their filtered Cabannes signal ratio for atmospheric temperature measurements in 1993 . They in fact made such measurements utilizing barium filters and iodine filters respectively in 1992-1993 and 2010. Recently, She et al.[1] has cited all these works and discussed why alkali potassium vapor filters are a better alternative for such measurements.

(1. She et al., , *Optics Express* **29**, 4338, 2021.)

- They also suggested that alkali sodium could be another candidate vapor for this application, though the larger ground state hyperfine splitting, 1.771 GHz in Na compared to 0.6418 GHz in K may be a concern.
- Thus, the first objective of this poster is to compare the performance between the use of sodium filters to those using barium, iodine and potassium filters along with the competing temperature lidar utilizing rotational Raman scattering. This comparison, along with the new CS_Na lidar, is shown in Table 1 below, where N_0 is the total received signal counts into the two channels (AVFs).

- Since a successful implementation of a Na Cabannes lidar (SCL) alongside an existing 3-frequency laser-induced-fluorescence (LIF) lidar, utilizing the same lidar transmitter with an independent receiver would allow temperature and wind profiling from ground to the upper mesosphere (~ 105 km), the second objective of this poster is to discuss different scenarios for simultaneous temperature and wind measurements with filtered Cabannes signal ratios below mesopause where the natural atmospheric Na atoms live.
- We define δT_1 and δV_1 respectively as single-photon temperature and wind uncertainties; when divided by $\sqrt{N_0}$, they become measurement uncertainties.

- Upper atmospheric lidar temperature and wind measurements is a challenge because of small Rayleigh cross-section and low atmospheric density between 40 and 80 km in altitudes. Currently, Since atmosphere is in hydrostatic equilibrium, one can use the very effective Rayleigh integration techniques only for temperature measurements $\delta T_1 \sim 300K$.
- For wind measurements, one must sense the associated Doppler shift in Cabannes spectrum ("edge technique"), which cannot take advantage of height integration. Since Cabannes spectrum depends on both temperature and wind, the edge technique measures wind only, leaving the contamination by (unknown) temperature un-assessed, unless both lidars are utilized.

- The technique of filtered scattering ratio discussed for simultaneous temperature and wind measurements in this poster measures both temperature and wind at the same altitude and time, thus avoiding this unknown contamination.

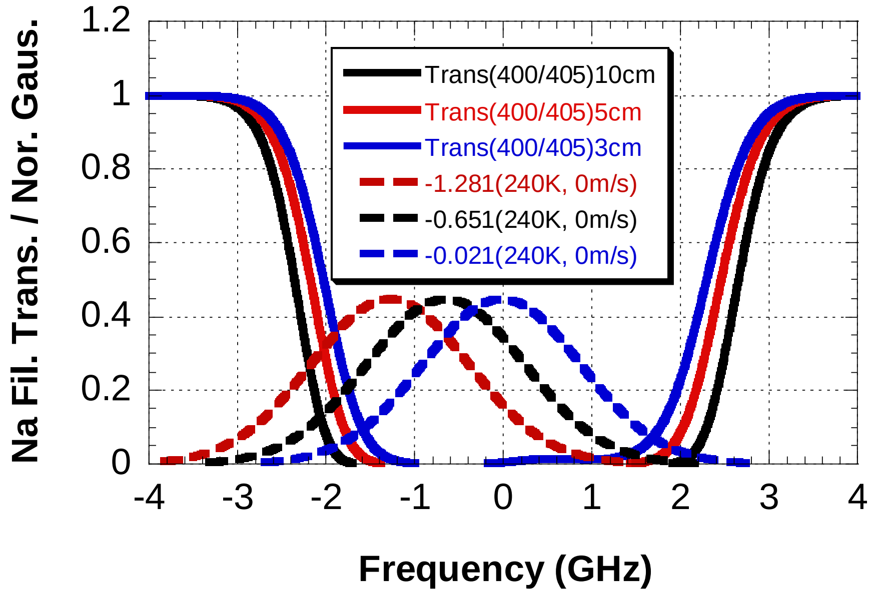
Table 1 Figure of merit comparison between 5 scattering temperature lidars

Lidar_Filter	CS_Ba (553.7nm)	CS_I_2/ (532nm)	RR_CIF (532nm)	CS_K (770nm)	CS_Na (589nm)
f_1/f_2	0.1951/ 0.4644	0.0033/ 0.0740	0.0150/ 0.0461	0.0374/ 0.2902	0.0098/ 0.0361
ξ_{opt} or ξ	3.73	21.1	9.38	7.03	15.38
$S_{T12}(\%K^{-1})$	0.18	0.42	1.16	0.72	0.42
$\delta T_1 \equiv \xi/\lvert S_{T12}\rvert$(K)	2.07 e3	5.02 e3	8.09 e2	9.76 e2	3.66 e3
N_0	100,000,000	100,000,000	3,420,000	100,000,000	100,000,000
$\delta T_{air}(K) = \delta T_1/\sqrt{N_0}(K)$	0.206	0.502	0.437	0.097	0.363
$\delta T_{air\_SCA} = [\lambda(nm)/532]$	0.219	0.502	0.434	0.169	0.423

Table 1 summarized the figure of merits of 4 lidars previously discussed[1,2] plus the SCL proposed here. The single-photon temperature uncertainty δT_1 is the single-photon uncertainty[2] ξ divided by temperature measurement sensitivity[2] S_{T12}.

2. She & Friedman, Atmospheric lidar fundamentals: Laser light scattering from atoms and linear molecules, Cambridge Univ. Press, 2022.

- Shown below are 3 Na vapor filters and 1 approximated Cabannes spectrum (at 240 K and 0 wind), represented by a Gaussian function centered at 3 LIF lidar frequencies relative to the Na D_2transition.



- Through each filter, we receive 3 filtered signals, from which we can form selected signal ratios for T and/or V measurements.

- For either T or V only measurement, we need only one ratio:

$$\frac{N_1}{N_2} = \frac{\eta_1 f_1(T,V)}{\eta_2 f_2(T,V)} \qquad \xi_{opt} = \frac{1}{\sqrt{f_1}} + \frac{1}{\sqrt{f_1}}$$

$$S_{T12} = \frac{\partial}{\partial \mathrm{T}}\left[ln\left(\frac{f_1}{f_2}\right)\right] \qquad \delta T_1 = \frac{\xi_{opt}}{S_{T12}}$$

$$S_{V12} = \frac{\partial}{\partial V}\left[ln\left(\frac{f_1}{f_2}\right)\right] \qquad \delta V_1 = \frac{\xi_{opt}}{S_{V12}}$$

- Measuring T and V simultaneously, we use two ratios below, with which, we obtain temp. and wind uncertainties as:

$$R_T = N_{T1}/N_{T2} \quad , R_V = N_{V1}/N_{V2}$$

$$\delta T = R_T \frac{\partial T}{\partial R_T}\left(\frac{\delta N_{T1}}{N_{T1}} - \frac{\delta N_{T2}}{N_{T2}}\right) + R_V \frac{\partial T}{\partial R_V}\left(\frac{\delta N_{V1}}{N_{V1}} - \frac{\delta N_{V2}}{N_{V2}}\right)$$

$$\delta V = R_T \frac{\partial V}{\partial R_T}\left(\frac{\delta N_{T1}}{N_{T1}} - \frac{\delta N_{T2}}{N_{T2}}\right) + R_V \frac{\partial V}{\partial R_V}\left(\frac{\delta N_{V1}}{N_{V1}} - \frac{\delta N_{V2}}{N_{V2}}\right)$$

- The uncertainty of each quantity is affected by the change of both ratios in an unpredictable but calculable way .

Title (Lightning Talk Slide 2)

- For example, if the 3 cm long filter is used, the transmission f and associated sensitivities S_T, S_V are :

Freq. (GHz)	f	S_T	S_V
|+> -0.0214	0.0326	0.0080	-0.0016
|0> -0.6514	0.0780	0.0050	-0.0059
|-> - 1.2814	0.2150	0.0020	-0.0047

- For T or V only measurement, the respective best ratio gives rise to

$$\delta T_1 = 984K \ \& \ \delta V_1 = -1531 m/s$$

- For both T and V measurements, we calculate δT and δV.

- Depending on the choice of signals, two terms in previous $\delta T, \delta V$ equations may be combined before squaring to evaluate temp. and wind variations. We then set photon counts of each signal respectively as f_i to get δT_1 and δV_1.
- The final values of δT_1 and δV_1 will depend on the choice of two ratios from 3 possible signals at – 0.0214, - 0.06514 and - 1.2814 GHz. We consider three different choices of ratios. For 3 cm filter, we obtain the results below:

Uncer-tainty	$R_T = N_+/N_0$ $R_V = N_-/N_0$	$R_T = N_0/N_-$ $R_V = N_+/N_-$	$R_T = N_+/N_-$ $R_V = N_+/N_0$
δT_1	**1989**	**1837**	**3025**
δV_1	**4379**	**3627**	**2425**

Discussion and Conclusion

- The δT_1 and δV_1 of simultaneous measurements of each choice are larger than either temperature or wind only measurement by more than a factor of two. However, the latter contain an unknown contamination, which could be quite large.
- With a given AVF, the signal choices (channel and transmitter frequency) for the two ratios make a difference in the resulting uncertainties. If we transmit light at +1.2814, 0, and -1,2814 GHz, δV_1 should be reduced, as seen below:

Uncertainty	$R_T = N_+/N_0$ $R_V = N_-/N_0$	$R_T = N_0/N_-$ $R_V = N_+/N_-$	$R_T = N_+/N_-$ $R_V = N_+/N_0$
δT_1	2053	5384	4832
δV_1	1044	1834	1116

- For single-photon uncertainty of 2000 for example, we need to receive 4×10^6 photons to measure temperature and wind with uncertainty of 1 K and 1 m/s.
- Using the received signal from the CSU sodium LIF lidar (PA = 0.05 Wm^2), we can judge the difficulty for measure temperature and wind in the upper atmosphere. The average photon counts collected between[3] 9 and 10 hr UT in Jan 19, 2009 at 30, 40, 50 and 90 km are respectively, 259077, 25615, 3988 and 493345. The temp. and wind uncertainty at 30 km (assuming δT_1=δV_1 = 2000) will be ~ 4 K (4 m/s). Since the measured uncertainties at 90 km are ΔT=0.44 K & ΔV=0.3 m/s, giving an effective LIF lidar dT_1=280K & dV_1=232 m/s
- We are reporting a study in progress.

[3]Krueger, D. A., C.-Y. She, and T. Yuan (2015), Retrieving mesopause temperature and line-of-sight wind from full-diurnal-cycle Na lidar observations, *Appl. Opt*. **54**, 9469-9489.