Neutral density measurement from simultaneous radar observation of meteors

Nicolas Lee[1] and Sigrid Close[1]

[1]Stanford University

November 21, 2022

Abstract

Observations of atmospheric neutral density and associated dynamics within the lower thermosphere has been a challenge to the atmospheric science and space community due to its inaccessibility to balloon-borne or orbital in situ instruments. We present a methodology to study the latitudinal and temporal variation of neutral density in this region through a simultaneous campaign at geographically distinct high-power large-aperture (HPLA) radar facilities to observe meteor trajectories. These meteors are formed by meteoroids entering the Earth's atmosphere; the deceleration they undergo due to atmospheric drag provides a source of information to determine the neutral density of the atmosphere at altitudes of 80 to 140 km. Through the measurement of meteor head echo trajectories using specialized radar waveforms and signal processing to enhance the range resolution, combined with novel statistical techniques to account for the distribution of meteoroid properties, the temporal evolution of atmospheric neutral density from 70 to 140 km can be characterized with sub-km altitude resolution. Initial results will be presented from the first of four observation campaigns planned during the 2019-2021 period using the HPLA radar sites at Jicamarca, Millstone Hill, and Resolute Bay, which span equatorial to polar latitudes at similar longitude. The simultaneous measurements across facilities complements other measurements of atmospheric composition and structure at similar altitudes to provide improved identification of latitudinal coupling and forcing from lower altitudes into the magnetosphere-ionosphere-thermosphere (MIT) system.

Poster SA43C-3218

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Nicolas Lee and Sigrid Close

Department of Aeronautics and Astronautics, Stanford University

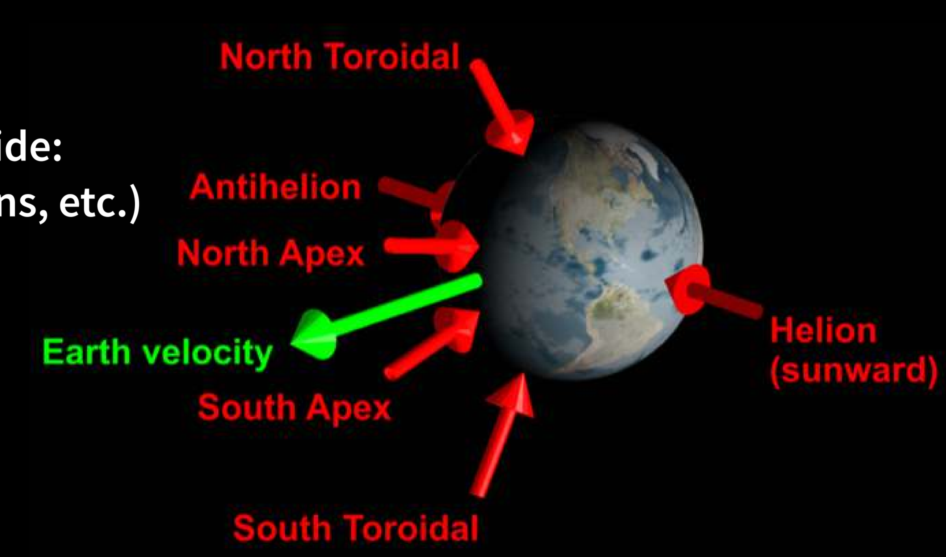
nnlee@stanford.edu sigridc@stanford.edu (650) 725-2863

Introduction

- Thermospheric neutral density difficult to measure directly
- Space-based in situ measurements down to ~360 km
- What is coming into the Earth system and what is it passing through?
- Meteoroids provide information on the properties and phenomena of the lower thermosphere

Meteoroids

- Plasma interactions throughout meteoroid lifetime
- Sporadic meteoroids entering the Earth's atmosphere provide:
  - A source function of extraterrestrial material (metallic ions, etc.)
  - A probe into the atmospheric conditions being traversed
- Ablation of meteoroids in atmosphere produces meteor plasma, which is detectable by ground-based radar



Radar facilities

- High-power large-aperture (HPLA) radar typically uses higher frequencies and narrower beams than dedicated meteor radar
- Track head plasma to determine deceleration of meteoroid subject to drag and ablation

Resolute Bay Incoherent Scatter Radar North face (RISR-N)

Location:	74.7296° N, 94.9058° W, 145 m
TX Frequency:	442.5 MHz
Antenna:	30 m x 30 m square array
Orientation:	26° azimuth, 86° elevation
Waveform:	MinSideLobe-51 1μs baud
Inter-pulse period:	1.4 ms
Sample frequency:	2 MHz

MIT Haystack Observatory (MHO)

Location:	42.6195° N, 71.4917° W, 146 m
TX Frequency:	440 MHZ
Antenna:	46 m steerable dish
Orientation:	270° az, 45° el
Waveform:	Barker-7 6 μs baud
Inter-pulse period:	2 ms
Sample frequency:	1 MHz (10 minutes at 25 MHz)

Jicamarca Radio Observatory (JRO)

Location:	11.9515° S, 76.8745° W
TX Frequency:	49.9 MHz
Antenna:	300 m x 300 m square array
Orientation:	90° elevation
Waveform:	MinSideLobe-51 1μs baud
Inter-pulse period:	1.25 ms
Sample frequency:	1 MHZ

Neutral density estimation

- Simultaneously estimate relative neutral density profiles and meteoroid parameters
- Use order statistics with known meteoroid distribution to anchor density profiles to absolute density value
- Prior work by Li and Close [2016] using ALTAIR meteor data

Drag: $$\frac{1}{v^2}\frac{dv}{dt} = -\frac{3}{8}\frac{C_D\rho_a}{\rho_m R}$$

Ablation: $$\frac{dm}{dt} = -\frac{1}{2}\frac{C_H}{H^*}A\rho_a v^3$$

Combined: $$D = \frac{C_H}{6C_D H^*}$$

Matrix formulation:

$$\ln\left(\frac{a_2^2}{v_2^2}\right) - \ln\left(\frac{a_1^2}{v_1^2}\right) = D(v_1^2 - v_2^2) + \ln\left(\frac{\rho_{a2}}{\rho_{a1}}\right)$$

$$F_{i,j} = \ln\left(\frac{a_{i,j+1}}{v_{i,j+1}^2}\right) - \ln\left(\frac{a_{i,j}}{v_{i,j}^2}\right) \qquad W_{i,j} = v_{i,j}^2 - v_{i,j+1}^2 \qquad \rho_{rj} = \frac{\rho_{a,j+1}}{\rho_{a,j}}$$

$$\begin{bmatrix} F_{i,1} \\ F_{i,2} \\ \vdots \\ F_{i,m} \end{bmatrix} = \begin{bmatrix} I_{i,j=1} & 0 & \cdots & 0 & W_{i,1} \\ 0 & I_{i,j=2} & \cdots & 0 & W_{i,2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & I_{i,j=m} & W_{i,m} \end{bmatrix} \begin{bmatrix} \ln(\rho_{r1}) \\ \ln(\rho_{r2}) \\ \vdots \\ \ln(\rho_{rm}) \\ D_i \end{bmatrix}$$

Convex optimization problem:

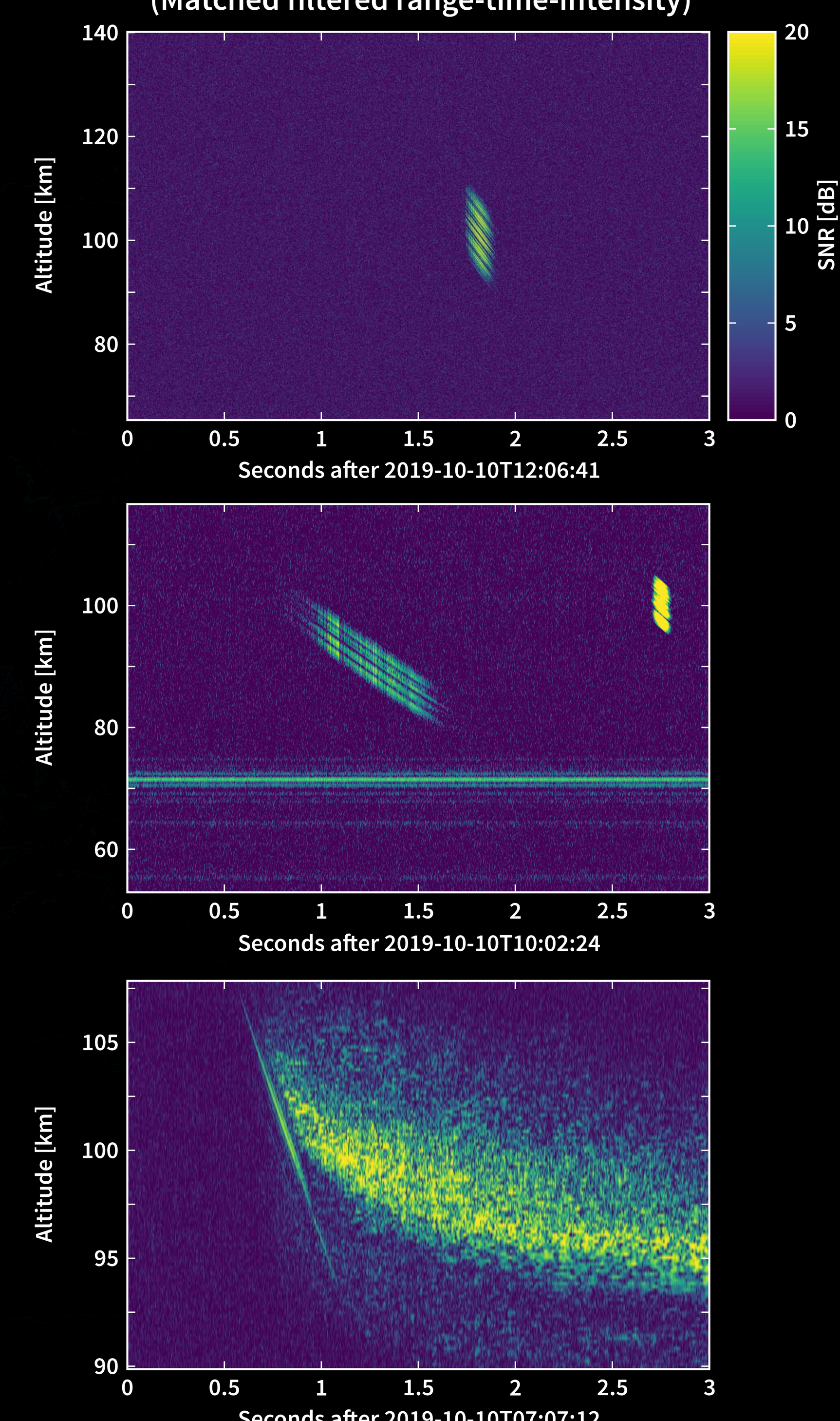
Minimize $$\sum_{i,j} \left| F_{i,j} - D_i W_{i,j} - \ln(\rho_{rj}) \right|$$

Subject to $D_i > 0$

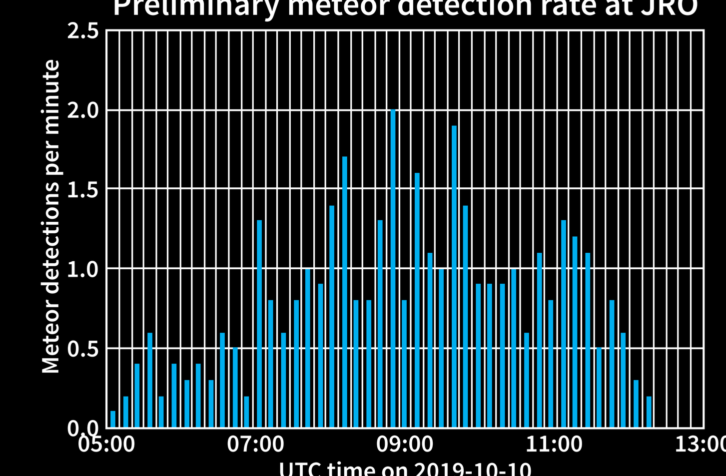
Meteor campaign

- Simultaneous measurement from multiple facilities spanning equatorial to polar latitudes
- Four-hour windows spanning period of maximum sporadic meteoroid flux:
  - 2019-10-10T09:00Z to 2019-10-10T13:00Z
  - 2019-10-11T09:00Z to 2019-10-11T13:00Z
- Binary phase coded pulse compression selected based on Volz and Close [2012]

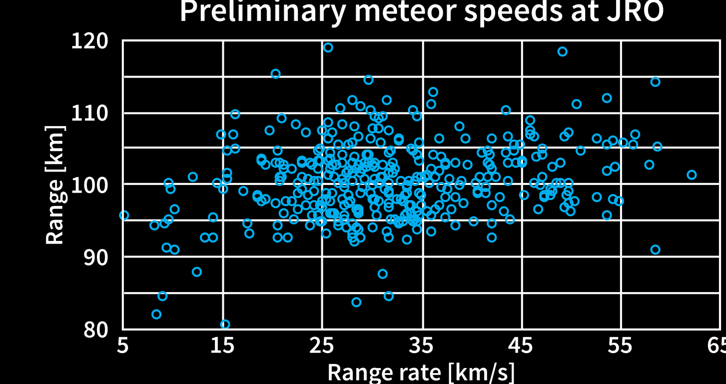
Meteors at RISR-N, MHO, and JRO (Matched filtered range-time-intensity)



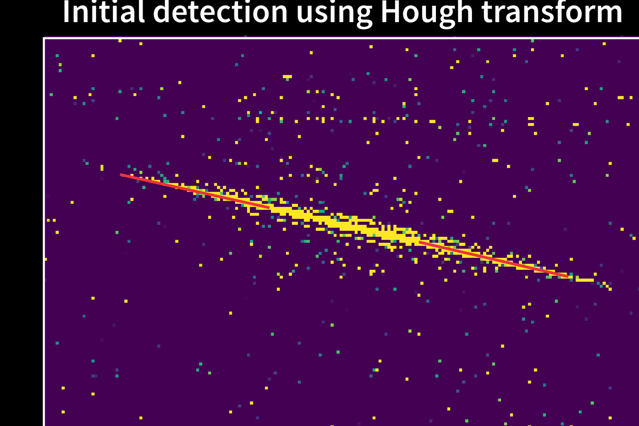
Preliminary meteor detection rate at JRO



Preliminary meteor speeds at JRO



Initial detection using Hough transform



Conclusion

- Meteor-derived atmospheric density measurements provide a technique for continuous monitoring using existing facilities that complements measurements of other atmospheric parameters
- Upcoming/ongoing meteor radar campaigns will yield new data set of meteor trajectories for population studies

Acknowledgment

- Funding for this research was provided by NSF under award number AGS-1920383
- Experimental support at JRO: Marco Milla, Karim Kuyeng Ruiz
- Experimental support at MHO: Phil Erickson, Ryan Volz
- Experimental support at RISR: Roger Varney

References

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