Monte Carlo Simulation to Estimate Meteor Radar Performance

Comparing Coverage and Counts of Increasingly Separated Specular Meteor Radar Links

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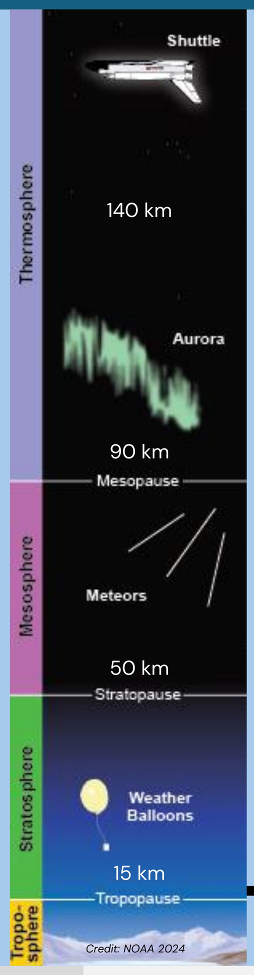
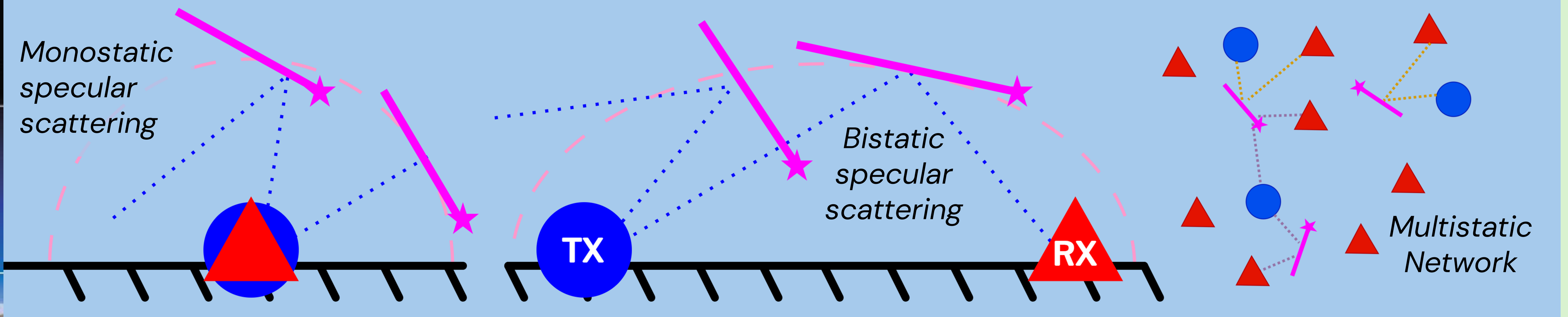
BACKGROUND



Specular meteor radar (SMR) utilizes ionized meteor trails as tracers of opportunity, **remaining one of the few techniques able to provide temporally and spatially dense environmental measurements** of the mesosphere/lower thermosphere (MLT, 70-110 km altitude).[1,2]

SMRs have blossomed from lone monostatic systems into multiple-in, multiple-out (MIMO) distributed networks of separated transmitters (TX) and receivers (RX).[3,4] Understanding the performance and converge of these networks enable informed network expansion and node placement, but little effort has been made so far to quantify the spatial coverage of separated TX-RX links.

This work uses Monte Carlo simulations of meteor radar echoes to investigate the relative performance (daily counts, spatial coverage, observation density) of differently separated RX-TX links.



SUMMARY

The performance of meteor radar transmit-receive links are estimated using a numerical scattering model. These results will inform the expansion of meteor radar networks and enable higher quality observations of the upper atmosphere's environment.

- A numerical model can be used to simulate the power scattered off a meteor with known characteristics to a receiver on the ground.[5,6]
- Power returned from a representative population of meteors is used to investigate the performance of a given transmitter-receive link.
- This method is validated by comparing observations of an actual meteor radar to its digital twin.
- Performance metrics like spatial coverage and fraction of observable meteors are investigated for a variety of TX-RX links of increasing separation distance.

Monostatic systems can observe about 3% of useful meteors lying >20° above the transmitter's horizon.[7-11] As TX-RX separation increases, **performance generally decreases,** although short links (<75 km) see a slight increase in total observations.

References, Contact

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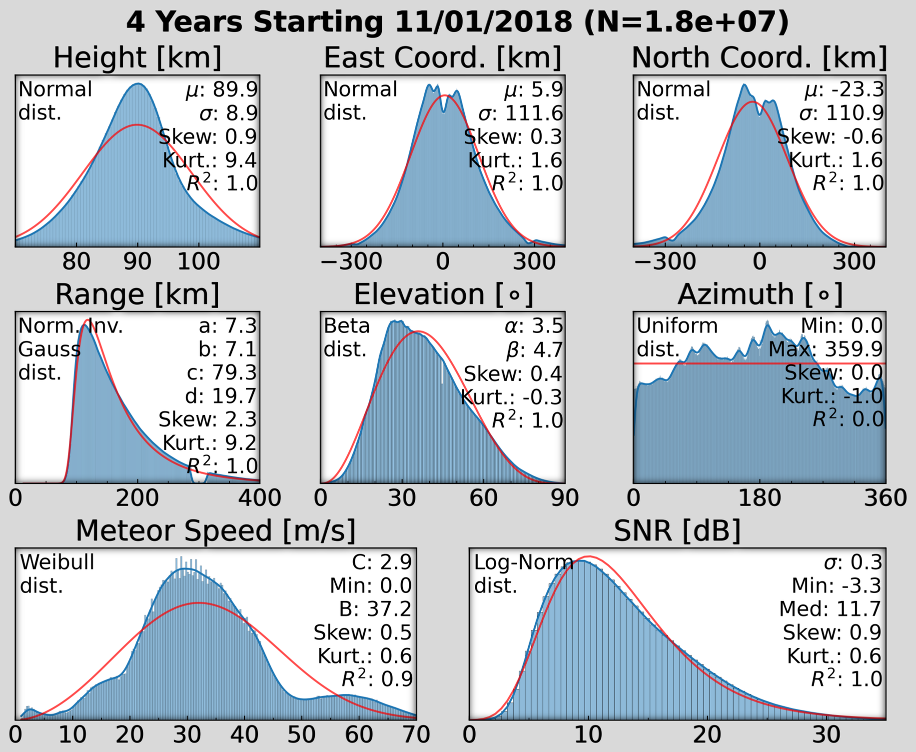
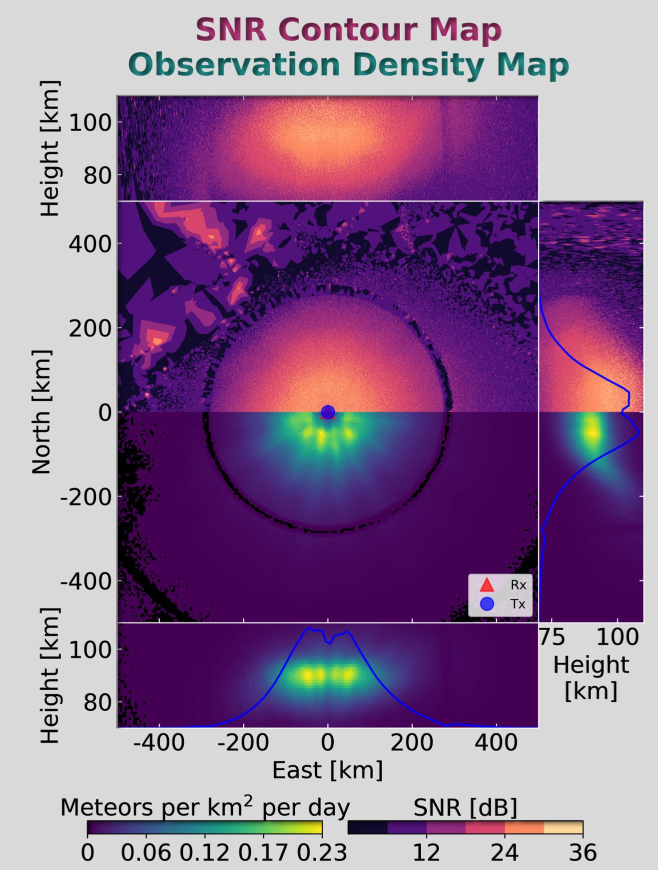
EMPIRICAL METEOR DISTRIBUTIONS



Observed meteor parameter distributions from a monostatic meteor at the McMurdo Antarctic research station are shown above.[12]

Stronger and more frequent observations occur closest to the instrument due to the short bistatic range. The receiver shuts off during the transmitting pulse, which results in a deficit of meteors at ~300 km range and may explain the blind spot directly over the instrument.[5] The interferometric position solution performs poorly at low SNRs, likely causing low SNR detections to be discarded.[0]

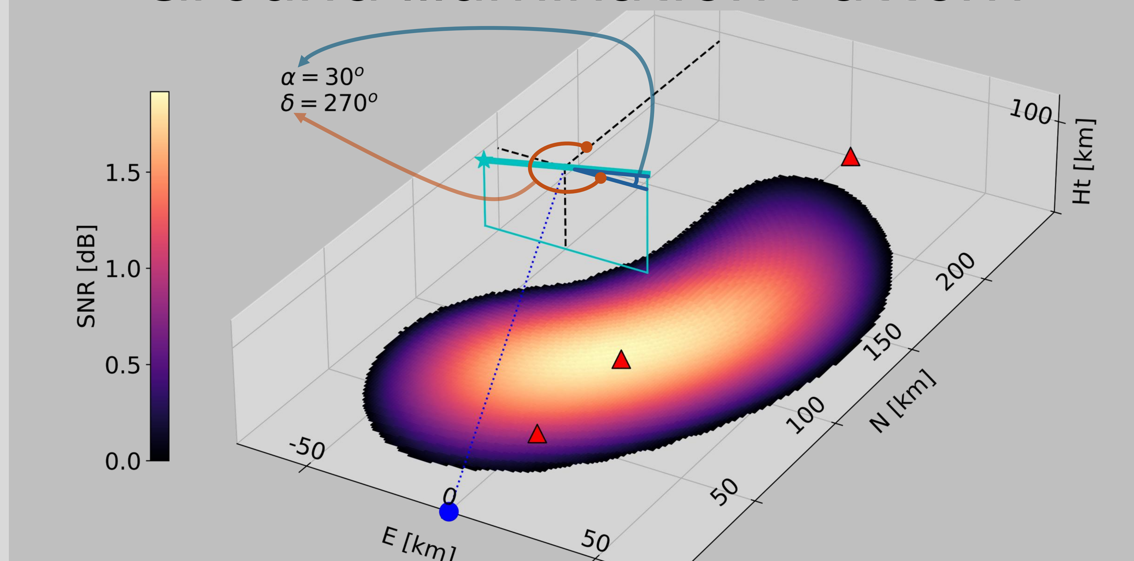


Left: The **pink-gradient** (top half) shows a filled contour map of echo signal-to-noise ratio (SNR) across space.

The **green-gradient** (bottom half) shows a heatmap of where meteor observations occurred.

SIMULATED SCATTERING

Ground Illumination Pattern



Above: **Simulated scattering** of a single meteor.[6,7] The **transmitter's** signal bounces off the **meteor trail**, and the gradient map shows the SNR at each point on the ground.

Some **receivers'** placement allows them to see this meteor; other **receivers** are placed where the reflected power is less than the noise power, or where no power is reflected at all.

The estimated SNR is dependent on the **noise power**, calculated based on the environmental temperature and the bandwidth of the receiver.[13]

$$P_N = 10\log_{10}(T_E k_B f_{BW}) + 30 \approx -113\ dBm$$

The simulation accounts for the antennas' directional gain and polarization, the polarization of the incident wave with respect to the trail orientation, and the polarization loss at the receiver.

Stochastic Meteor Parameters

The reflected power depends on the **geometry** of where the meteor, transmitter, and receiver are relative to one another, the **radar set-up** (frequency, power, antenna gain pattern, etc.) and the **physical characteristics of the meteor**. Some of these parameters are random, following known distributions.

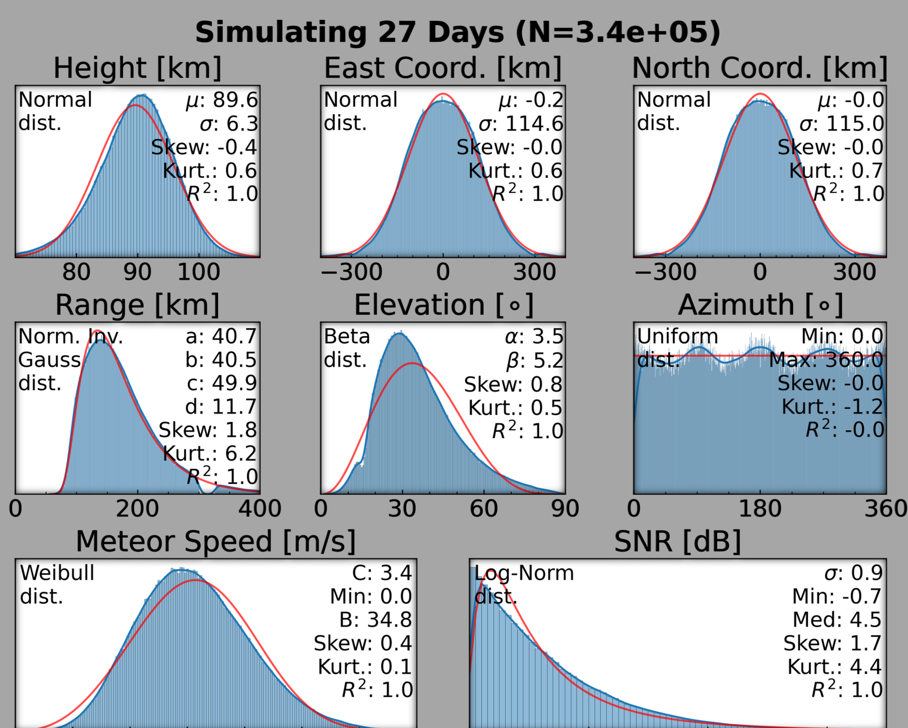
Orientation and Position

δ: Trail orientation in east/north plane [deg]	Azimuth. Sporadic meteors are generally randomly oriented. 0° points north, 90° points east. (Uniform Distribution; Trail Yaw (δ) [deg])
α: Trail orientation in east/up plane [deg]	Pitch; 90° is straight down, 0° is parallel to the ground.[14,15] (β Distribution, $\beta = 5$, $\alpha = 3$; Trail Zenith (α) [deg])
h: Altitude [m]	Roughly normal, with some dependence on radar frequency.[16] (Normal Distribution, Ht [km] $\sim \mathcal{N}(100, 18)$; Altitude (h) [km])
E, N: East, north ground coordinate [m]	Sporadic meteors are equally likely to occur anywhere over long periods of time. Bounded by instrument field-of-view. (Uniform Distribution; Ground Coordinate [m])

Physical Characteristics

$l_\parallel$: Trail length [m]	Length of first Fresnel zone, dependent on trail zenith.[15]	$l_\parallel = \frac{9}{4} H \sec(\alpha)$
$l_\perp$: Trail width [m]	Altitude and speed dependent.[17]	$\log_{10}(l_\perp) = a_1 + b_1(h - 110e3) + c_1 \log_{10}\left(\frac{V_\infty}{40e3}\right)$
q_e: Electron line density [e^-/m]	Zenith, mass, and speed dependent.[14]	$q_e = \frac{4}{9}\frac{a_2 V_\infty^{2.25} m_\infty}{\overline{\mu_A}\, H}\cos(\alpha)$
m_∞: Initial Mass [kg]	Based on published empirical distributions.[18]	Log-Norm Distribution, $\bar{m}_\infty = 10^{-6.3}$, $\sigma = 0.3$; Initial Mass (m_∞) [kg]
V_∞: Initial Speed [m/s]	Based on distribution measured at McMurdo.	Weibull Distribution; Initial Speed (V_∞) [km/s]

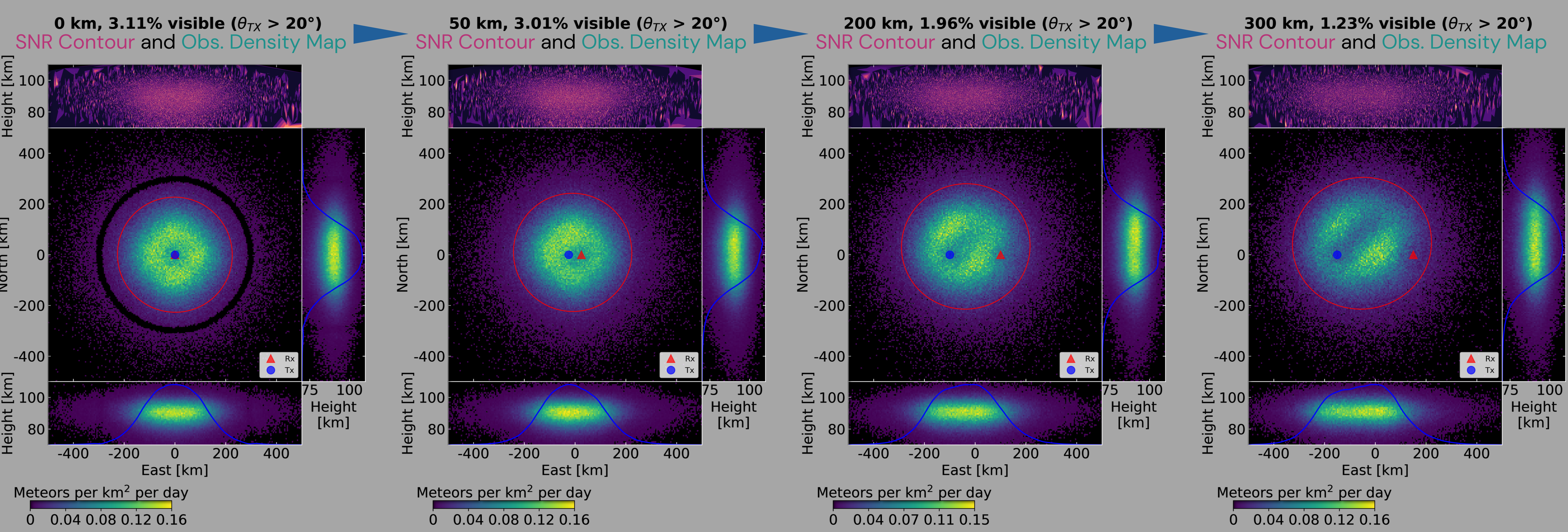
SIMULATED METEOR DISTRIBUTIONS



800 million **simulated meteors** whose characteristics follow expected distributions undergo simulated scattering using McMurdo radar parameters.

The distribution of meteors observed by the real-life McMurdo SMR closely match its digital twin, giving insight into the fidelity of the Monte Carlo simulation.

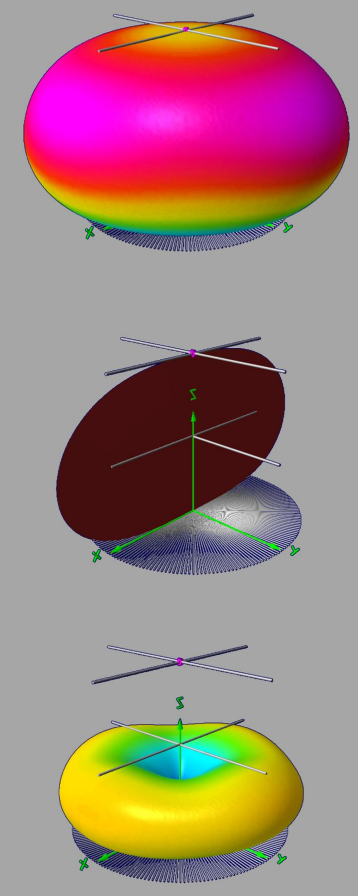
INCREASING SEPARATION DISTANCE



Interferometric positioning performs poorly for meteors at low elevations with respect to the transmitter. **Useful meteors are at least 20° above the transmitter's horizon.**[7-11]

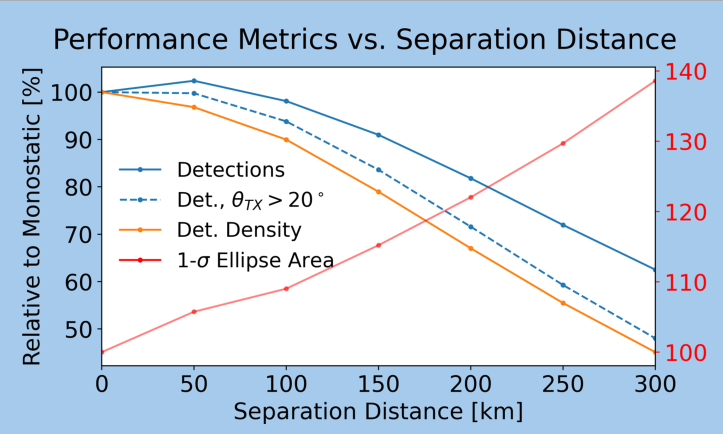
Trends: As the separation between TX and RX increases...

- **SNR of all echoes generally decrease** due to increased bistatic range.
- **The rate of useful detections decrease**
- The **area covered increases** steadily. This means that...
- **Observation density decreases** steadily.



Simulations take into account azimuth and elevation dependent antenna gain and polarization state.

CONCLUSIONS



For short separations (<75 km), slightly more meteors are observed, although about the same number of useful (>20° elevation) meteors are seen. **Performance metrics fall as distance increases,** consistent with previous estimates.[13] Fewer observations are distributed over larger areas of coverage, leading to poorer fidelity of estimated winds over the covered area.

FUTURE WORK

These simulations provide key insights into link performance, enabling **more informed decisions about the placement of instruments in a network**. This information can be used to create network topologies that optimize some performance metric given finite resources. This could include maximizing the area of dense coverage or daily counts for the number of nodes used, resulting in the most economical or densely covered network.

This could support the informed design of new network configurations that enable **new analysis techniques.** Simultaneous and geometrically diverse observations of a single meteor may allow for the point-like estimation of the full wind vector. These distributions could inform the design of a network that maximizes these observations, giving more precise estimates of MLT winds using fewer observations.