A novel meteor radar network based on MIMO to study the MLT dynamics

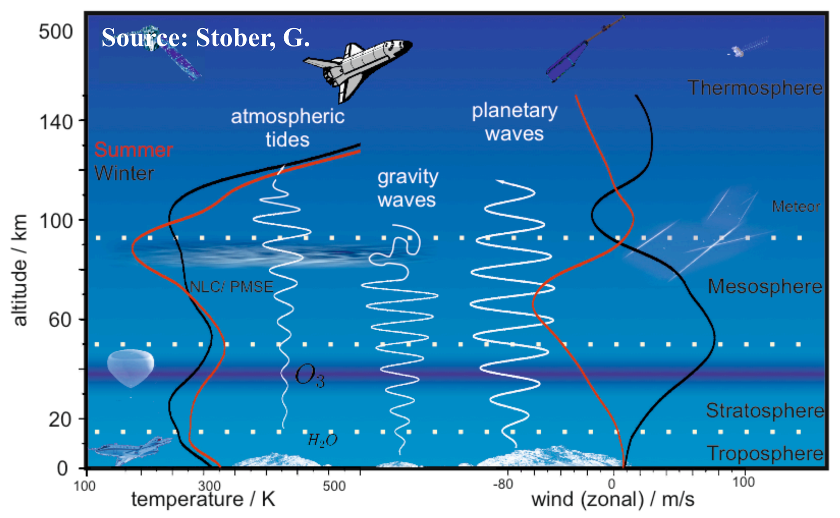
J. M. Urco[1], J. L. Chau[1], T. Weber[2], J. Vierinen[3], R. Volz[4]
[1]Leibniz Institute of Atmospheric Physics, Germany; [2]University of Rostock, Germany;
[3]University of Tromso, Norway; [4]MIT Haystack Observatory, USA;

Universität Rostock — Traditio et Innovatio

LEIBNIZ-INSTITUT FÜR ATMOSPHÄREN PHYSIK — IAP

Motivation

- Variability in the middle atmosphere is driven by a variety of **small and large scale** atmospheric waves.
- Specular Meteor Radars (SMRs) have been used for decades to study the middle atmosphere dynamics but with limited time, horizontal and vertical resolution due to the **limited number of meteor detections**

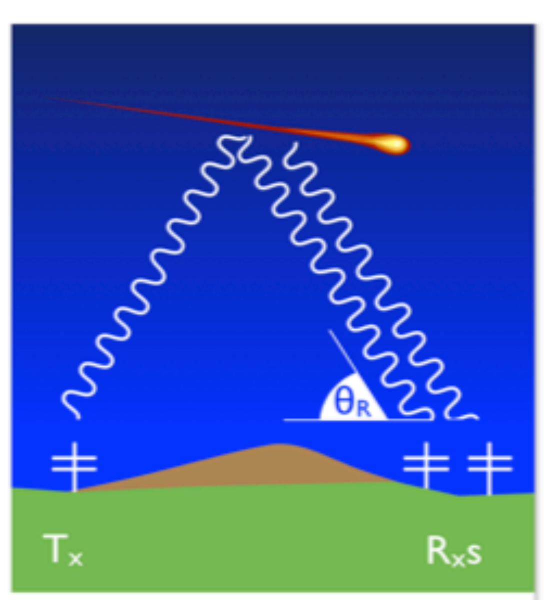


SMR: low resolution in time and space => not sensitive to small-scale wave dynamics
SMR networks allow to increase the number of meteor detections and improve resolution in time and space. Not all meteors are usable.
New simple and scalable SMR networks to increase the meteors' detections and to improve the measurement accuracy!!

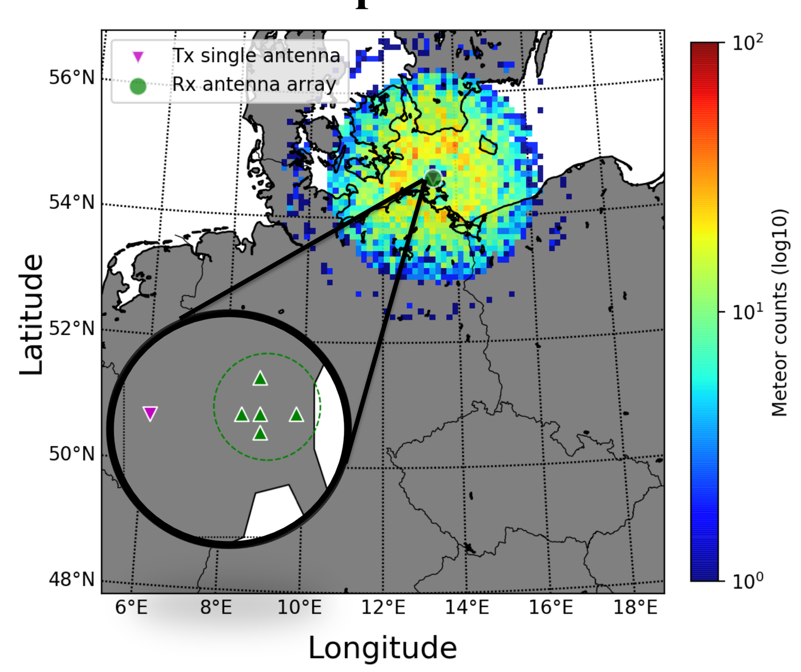
Background

Typical SMR (SIMO radar)

SIMO radar



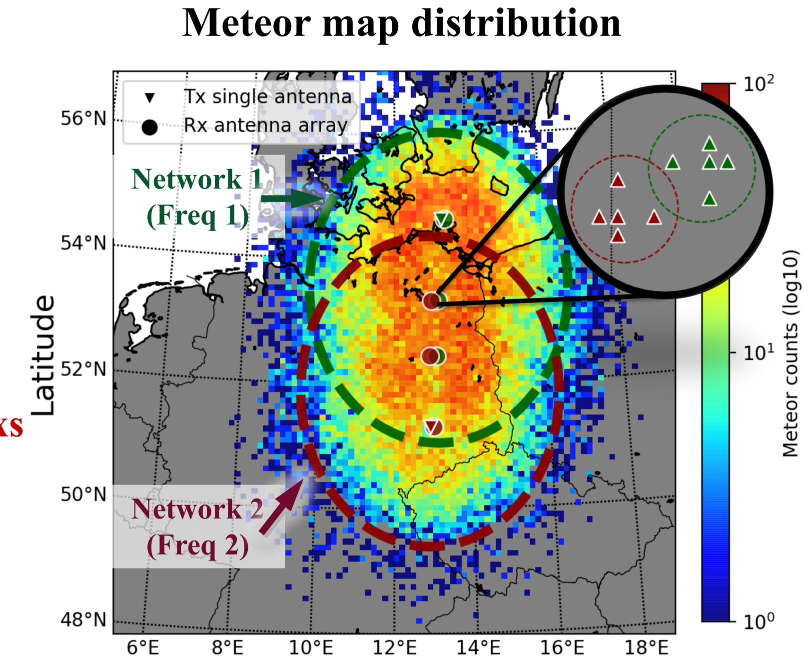
Meteor map distribution



- SIMO (Single-Input Multiple-Output): multiple Rx antennas (antenna array) to estimate θ_R (angle of arrival = meteor's location).
- **Limited number of meteor detections.**
- **Meteors with low elevation angles removed**
- Mean winds can be estimated

SMR networks based on SIMO

Meteor map distribution



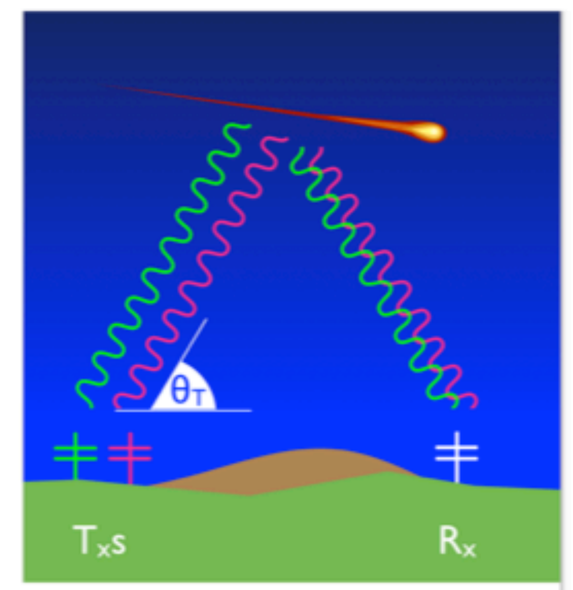
- Meteor counts increases by adding Rx sites around the Tx sites (Network).
- Area coverage increases by adding new networks (Tx + Rxs).
- **3D wind fields can be estimated.**
- Networks (Txs) are isolated by using different frequencies (diversity on Tx).
- **Frequency diversity does not allow Rxs (from Network 1) listen the Tx (from Network 2)**
- **Rx sites require large space.**
- **Tx sites require high power.**

[Stober and Chau 2015]

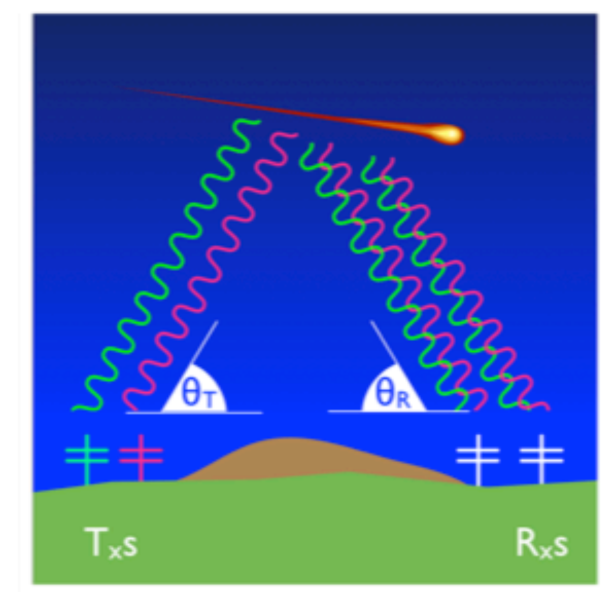
SMR networks increase number of meteor detections but they are not scalable.
Our SMR network based on MIMO => Scalable (All Rx sites listen all Txs) and simple (complexity located only in the Tx side)

SMR network based on (coherent) MIMO

MISO radar



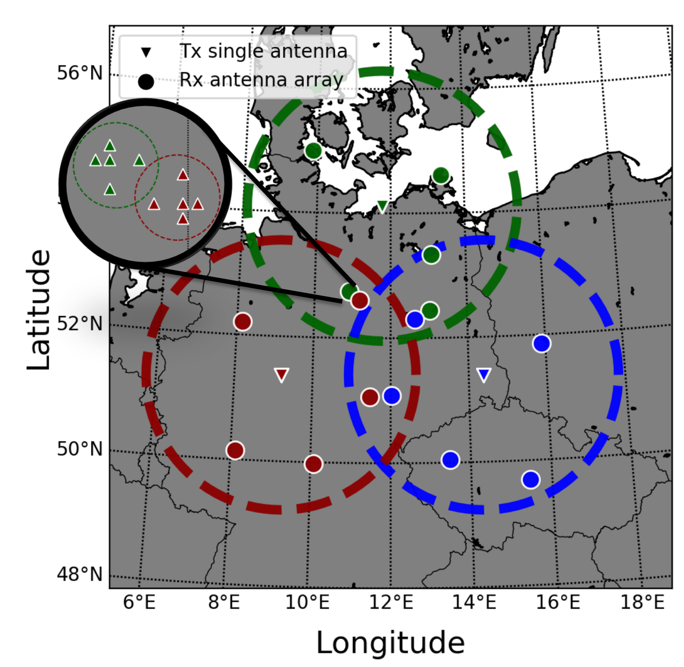
MIMO radar



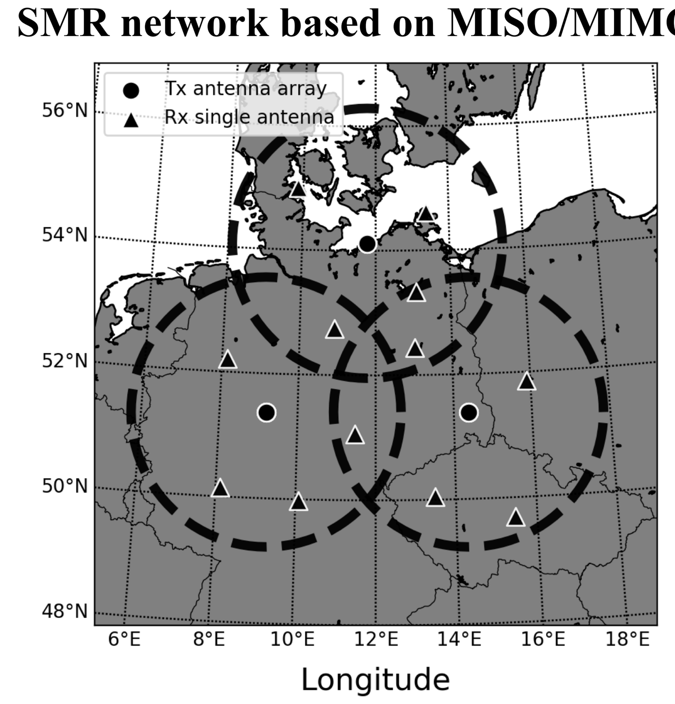
- MISO (Multiple-Input Single-Output): multiple Tx antennas to estimate θ_T (angle of departure).
- MIMO (Multiple-Input Multiple-Output): multiple Tx and Rx antennas to estimate θ_R and θ_T, respectively.

For MISO or MIMO:
- **Recovery (decoupling) of transmitted signals on the Rx side requires the use of orthogonal waveforms on transmission.**
- **CW radar + pseudo random coded sequences (quasi-orthogonal signals) allows to minimize cross-interference between Txs.**
- **Meteors' locations can be estimated respect to the Tx side (θ_T).**

SMR network based on SIMO



SMR network based on MISO/MIMO



SIMO:
- Meteor's location respect to the Rx site.
- Different networks use different frequencies.
- New networks (Txs) require new Rx sites.
- Rx sites require multiple antennas (large space and various digital receivers).
- Use of a broad spectrum bandwidth.
- Tx sites require one single antenna.
- No interference between Txs

MISO/MIMO:
- Meteor's location respect to the Tx site.
- Different networks use different waveforms (pseudo-random sequences)
- New networks (Txs) can use previous Rx sites.
- Rx sites require one single antenna and one digital receiver (small space). Ideal to be installed in school, gardens.
- One single frequency for all networks.
- Tx sites require multiple antennas.
- High interference between Txs.

MISO with waveform diversity:
- **Complexity moved to the Tx site.**
- **Rx sites are simple and can be installed in schools, gardens, etc.**
- **Only one working frequency needed.**

MIMO with waveform diversity:
- **With MIMO, meteor location estimated respect to both the Tx and Rx site (more accurate). Number of usable meteors increases.**
- **Problem: High cross-interference between transmitted waveforms!!**

Signal recovery in a MIMO-SMR network

MIMO-SMR: System model

$$y = \Phi X + \eta$$

with $\Phi = [A_1 \quad A_2 \quad \dots \quad A_t]$

and $X = [x_1 \quad x_2 \quad \dots \quad x_t]^T$,

where:
$y \in \mathbb{C}^M$: measurement vector at Rx.
$x_j \in \mathbb{C}^R$: scattered echo from transmitter j.
$A_j \in \mathbb{C}^{MxR}$: sensing matrix due to waveform j.
N = t*R.

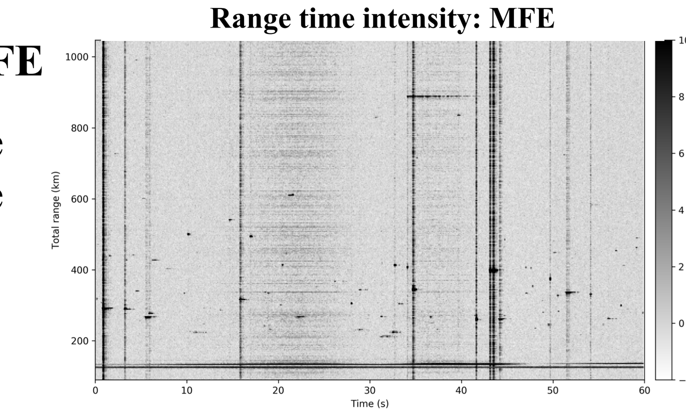
High interference and an undetermined problem M<N

Traditional Matched Filter estimator (MFE

Nyquist requires a sampling twice the signal bandwidth. MFE requires more measurements than unknowns (M>N)

$$\hat{X}^{MFE} = \Phi^H y,$$

Range time intensity: MFE

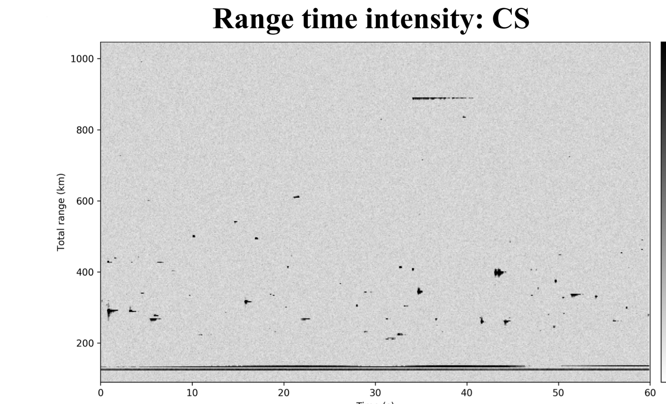


Compressed sensing approach (CS)

CS claims that a signal can be recovered even when M<N, if the signal X is K-sparse and the sensing matrix ϕ satisfies the RIP condition.

$$\hat{X}^{CS} = \arg\min_X ||y - \Phi X||_2^2,$$
subject to $||X||_0 < K,$

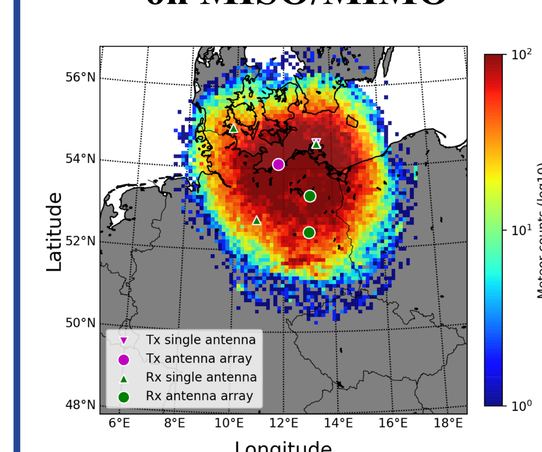
Range time intensity: CS



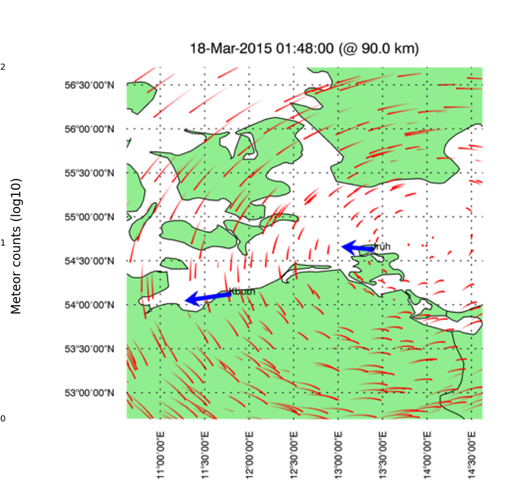
- **CS allows us to recover meteor signals in a interference environment even when the number of measurements is much less than the number of unknowns.**

Results and applications

SMR network based on MISO/MIMO

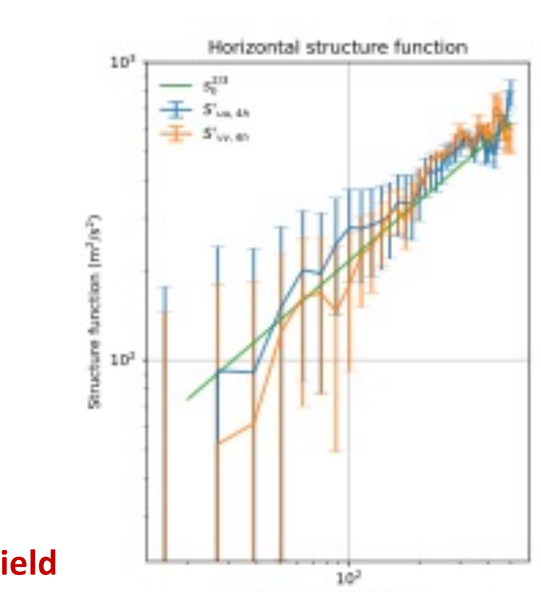


3D wind flow



SMR: mean wind
SMR network: 3D wind field

Mesospheric turbulence



References

Urco, J. M., Chau, J. L., Milla, M. A., Vierinen, J. P., and Weber, T.: Coherent MIMO to Improve Aperture Synthesis Radar Imaging of Field-Aligned Irregularities: First Results at Jicamarca, IEEE Transactions on Geoscience and Remote Sensing, PP, 1–11, 2018.

Chau, J. L., Urco, J. M., Vierinen, J. P., Volz, R. A., Clahsen, M., Pfeffer, N., and Trautner, J.: Novel specular meteor radar systems using coherent MIMO techniques to study the mesosphere and lower thermosphere, Atmos. Meas. Tech. Discuss. 2019.

Urco, J. M., Chau, J. L., Weber, T., Vierinen, J. P., and Volz, R.: Sparse signal recovery in MIMO specular meteor radars with waveform diversity, IEEE Transactions on Geoscience and Remote Sensing, 2019 [accepted].

J. Vierinen, J. L. Chau, N. Pfeffer, M. Clahsen, and G. Stober: "Coded continuous wave meteor radar," Atmospheric Measurement Techniques, 2016