Communications Project

# Final Report

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7.7.2023

## Homework Tasks

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Nachrichtentechnisches Projekt - 2023

Tasks for the final project report
version June 23th

> RAW data analysis and signal processing <

> to be done in groups of about 5 students,
> either you work together on all tasks, or you split them and explicitely mention
who was working on which tasks.

Select the data files according to your group number.

Saura - array beam, 4x individual antennas

1) Plot the spectra for receiver 1 and one of the other four for all ranges
for magnitude and phase (use e.g. pcolor). Maintain a proper frequency axis
scaling... (also for the latter plots)

2) Compare the spectra for:
a) superposition of the time series of receiver channels 2-5
b) combination of the individual spectra of receiver channels 2-5

3) Apply a suitable number of coherent and/or incoherent integrations (CI/NCI) to
the data and show the spectra for the receiver 1 and one of the other four for all
ranges for magnitude and phase (use e.g. pcolor). Compare with 1) !

4) Derive and show the cross-spectra for receiver channel 2-5 in magnitude and
phase. Use the integrated data as CI/NCI applied in 3).

MAARSY - array beam, 3x subarray
1st RAW (vertical beam, 30s?)
5) Get the 1st MAARSY RAW file and Apply a suitable number of coherent and/or
incoherent integrations to the data and show the spectra for the receiver 1 and
one of the other three for all ranges for magnitude and phase (use e.g. pcolor).
Also derive and show the cross-spectra in magnitude and phase for receiver 2-4.

2nd RAW (vertical beam, 1day)
6) Get the 2nd MAARSY RAW file and
a) plot the echo power for all ranges for receiver 1 and the superposition of the
other three.
b) Derive the Angle-of-Arrival for the receiver channel 2-4 for each time sample
(e.g. pcolor plots for phi, theta).

7) Interferometry - the shared RAW is NOT used HERE! -> SYNTHETIC !
Create your own sensor layout (circular (ring), spiral, random) in x-y-plane.
Use 6 sensors and test those for 2 different distributions (distances/spacing  1
WL) between the sensors.
First, assume equal phasing for all sensors and verify the vertical looking angle.
(show corresponding plot)
Simulate the coverage area (possible AOA-positions), by e.g. test MANY random
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phases for the sensors and derive the positions.


Solve the given tasks in Python, use any library or source you like, but
mention/cite it!

Present your results in a report (PDF) with some explanations, findings,..., don't
put the Python scripts in the PDF! Add a ZIP file to your PDF, that contains your
Python scripts - name the scripts according your group and the task numbers!

Beautify the report as well as your plots - e.g. apply a reasonable SNR-threshold
in the plots and scaling to beautify them.

Use proper English!

->>>
End of examination period: July 14

submission of the report by July 9 23:59LT

online defense - depends on students preferrence
->>>
```

# Contents

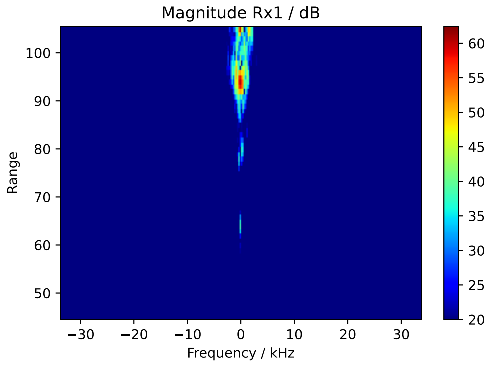


Figure 1: Task 1: Magnitude of Spectrum of Receiver 1.

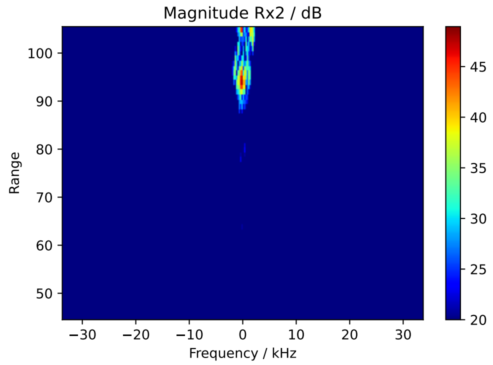


Figure 2: Task 1: Magnitude of Spectrum of Receiver 2.

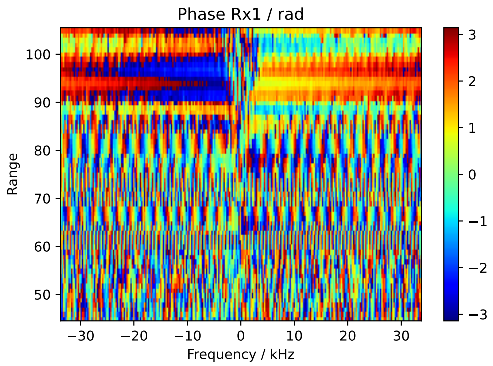


Figure 3: Task 1: Phase of Spectrum of Receiver 1.

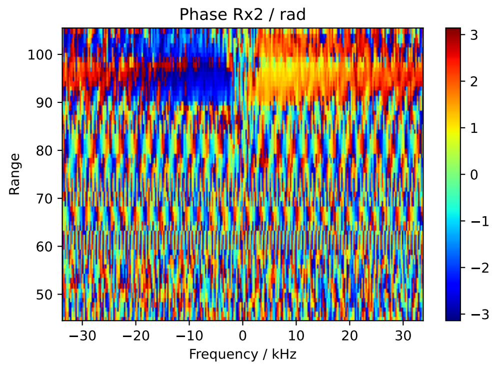


Figure 4: Task 1: Phase of Spectrum of Receiver 2.

# 1 Task 1

The Spectrum is calculated by performing the Fast Fourier Transform (FFT) over the data points for each range cell. Where sampling frequency is calculated from `datenums` (figures 1 to 4). Since, data is sampled at two different time intervals i.e. sampling intervals are not uniform. Hence, the average sampling frequency is calculated over the complete range of time. `numpy.fftshift` is used to plot the spectrum from `-Fs/2` to `Fs/2`. Comparing the magnitude plots of the spectrum corresponding to the array beam antenna (combined antennas) and individual antenna, the magnitude is higher for the target in the array beam as it sums the data from multiple antennas, thereby having additional gain. Looking at the phase, we can observe a change in pattern of phase where the target is present in the spectrum plots from the lower to the higher frequencies. The remaining regions of low signal-to-noise ratio are noisy and unreliable regarding the phase.

# 2 Task 2

Two different ways of combining the spectra of individual antennas are presented. One is combining the data in time domain by summation and calculating the spectrum afterwards and the other is combining the spectra calculated from the individual antenna data. Because of the linearity property of the fourier transform, the results or spectra of both these summations are the same (figures 5 to 8).

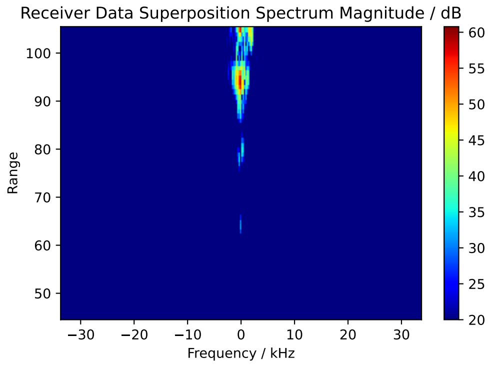


Figure 5: Task 2: Magnitude of spectrum of time series superposition of receivers 2-5.

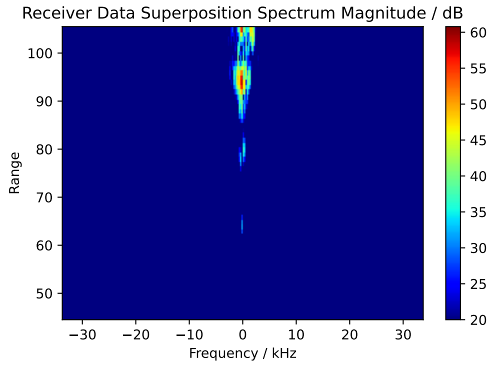


Figure 6: Task 2: Magnitude of individual spectrum combination of receivers 2-5.

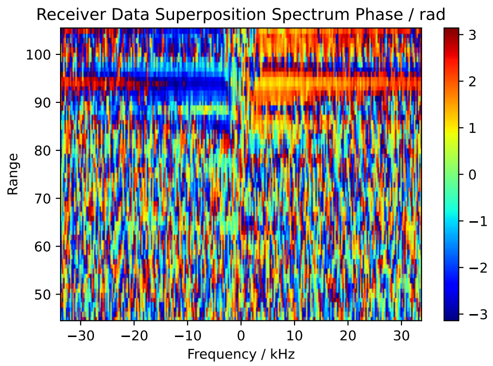


Figure 7: Task 2: Phase of spectrum of time series superposition of receivers 2-5.

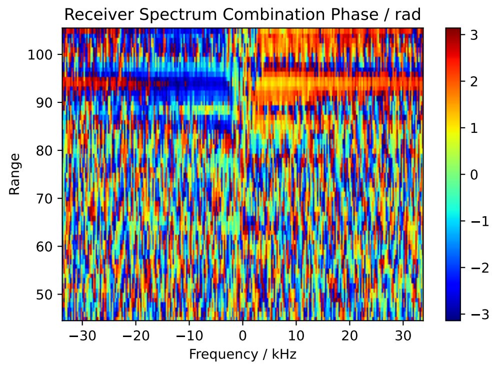


Figure 8: Task 2: Phase of individual spectrum combination of receivers 2-5.

The magnitudes of the spectra seem to be the same as the one of receiver channel 1 (combination) which can be seen in task 1.

# 3 Task 3

In our integration function, the mean is used so that the signal power will not increase but SNR should improve, since the noise is assumed to be gaussian with a mean of zero. After applying 8 coherent integrations, we see that a greater number of points in areas that are not high-SNR are lower after integration which means noise power is reducing (note the different color scaling). However, the drawback appears as the reduction in of the highest frequency in the spectrum since multiple time sample points are collected as one which increases their spacings (sample time or sample frequency). The above is for the combined antenna data, and the same can be said for any individual antenna data.

# 4 Task 4

The cross spectrum magnitudes were obtained by spectral multiplication of the regular spectrum of one receiver with the complex conjugate spectrum of the other receiver and are shown in figures 13 to 16. Here, only two cross spectra are shown. The rest can be found in the appendix A. Looking at the magnitude plots, one finds an increase in the signal amplitude values. So in comparison to the coherent integration

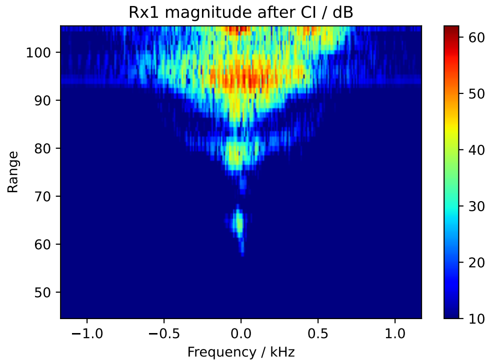


Figure 9: Task 3: Magnitude of receiver 1 spectrum after 8 CI.

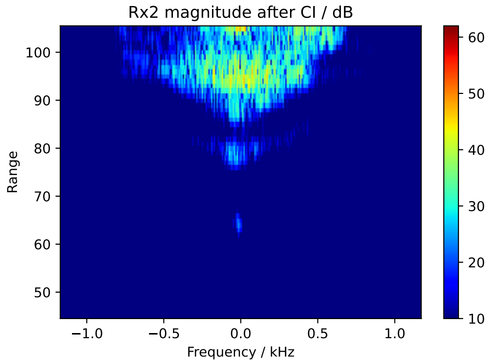


Figure 10: Task 3: Magnitude of receiver 2 spectrum after 8 CI.

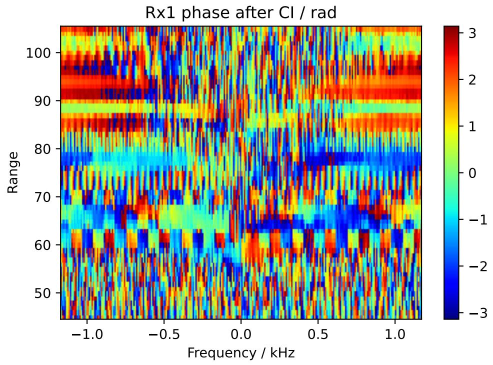


Figure 11: Task 3: Phase of receiver 1 spectrum after 8 CI.

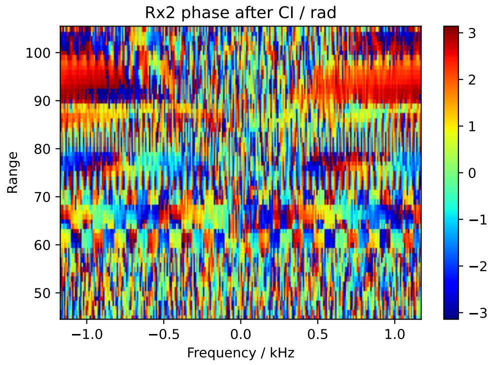


Figure 12: Task 3: Phase of receiver 2 spectrum after 8 CI.

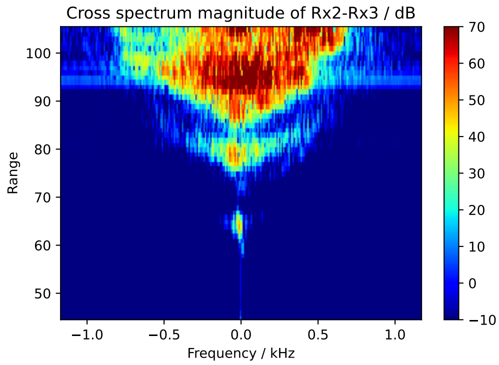


Figure 13: Task 4: Magnitude of cross spectrum of Receivers 2 and 3.

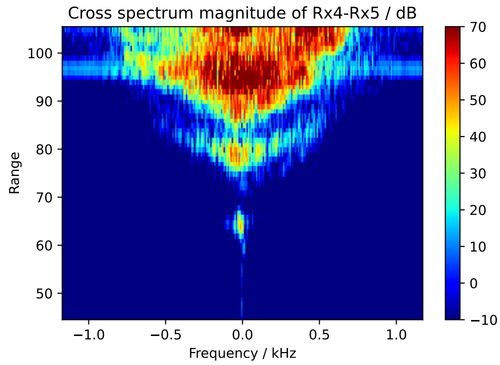


Figure 14: Task 4: Magnitude of cross spectrum of Receivers 4 and 5.

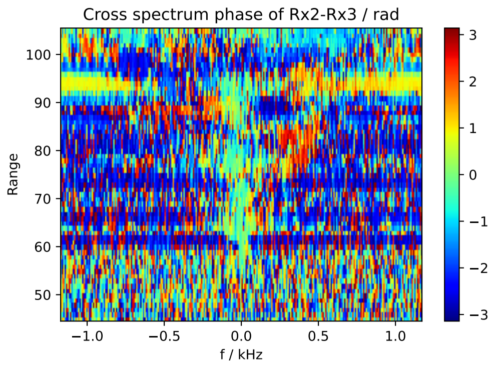


Figure 15: Task 4: Phase of cross spectrum of Receivers 2 and 3.

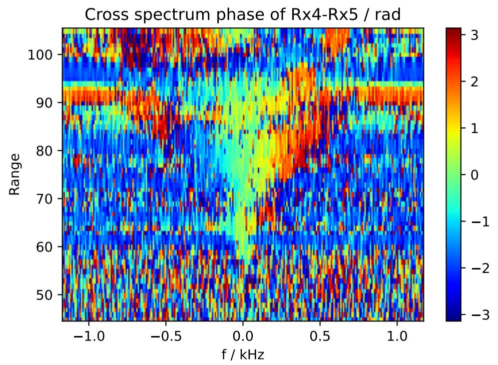


Figure 16: Task 4: Phase of cross spectrum of Receivers 4 and 5.

method, which does not increase the amplitude values, this cross spectrum method improves SNR by just that method.

# 5 Task 5

For the first MAARSY data file the data time duration is approximately 34 s. After compensating for the DC component in the complex data of each receiver, a coherent integration is applied to the timeseries data to improve the signal to noise ratio.

Further, the spectra of the individual receiver channels are calculated to obtain the magnitude and phase information vs frequency. Additionally, the cross spectra of the receiver pairs are calculated. These are the spectra of their cross-correlations. Since this is a form of convolution in time domain, one can obtain the cross spectrum by performing the multiplication of the individual receiver spectra in frequency domain (Convolution Theorem) [1], albeit making sure that the second spectrum is in complex conjugate form (as seen earlier).

The phases, seen in figures 17 and 18 are very noisy outside of the range gates of high SNR but some patterns are visible. In these larger SNR regions, the phase shows low variability. The data has been aquired recently and the echo power vs range shows that this might be a polar mesospheric summer echo

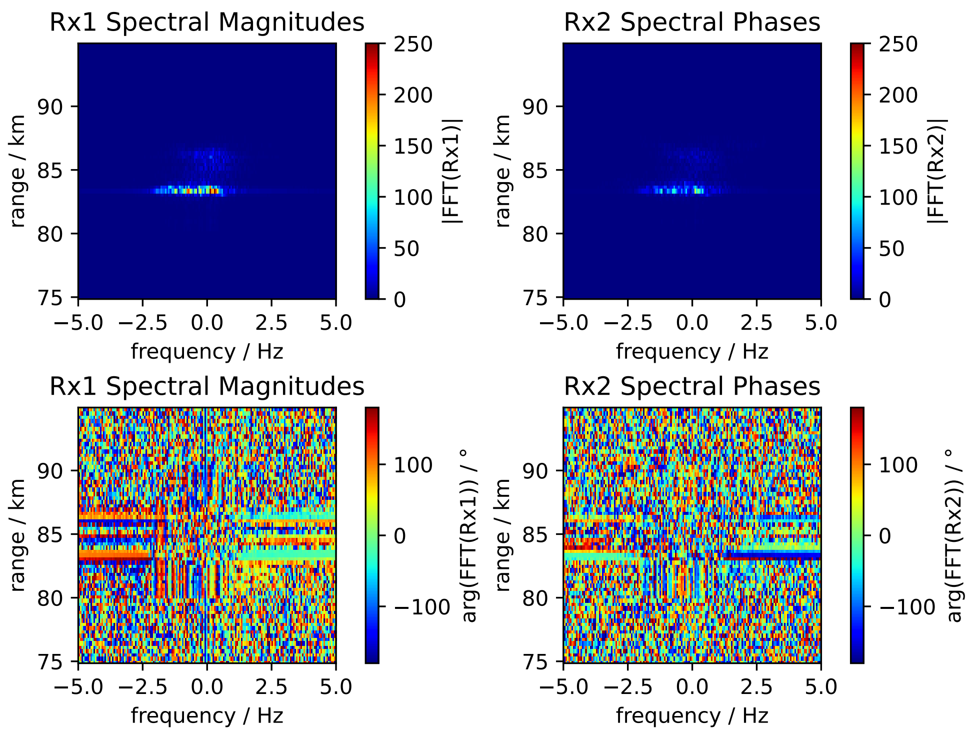


Figure 17: Task 5: Magnitude and phase plots of the time series spectra of channels 1 and 2.

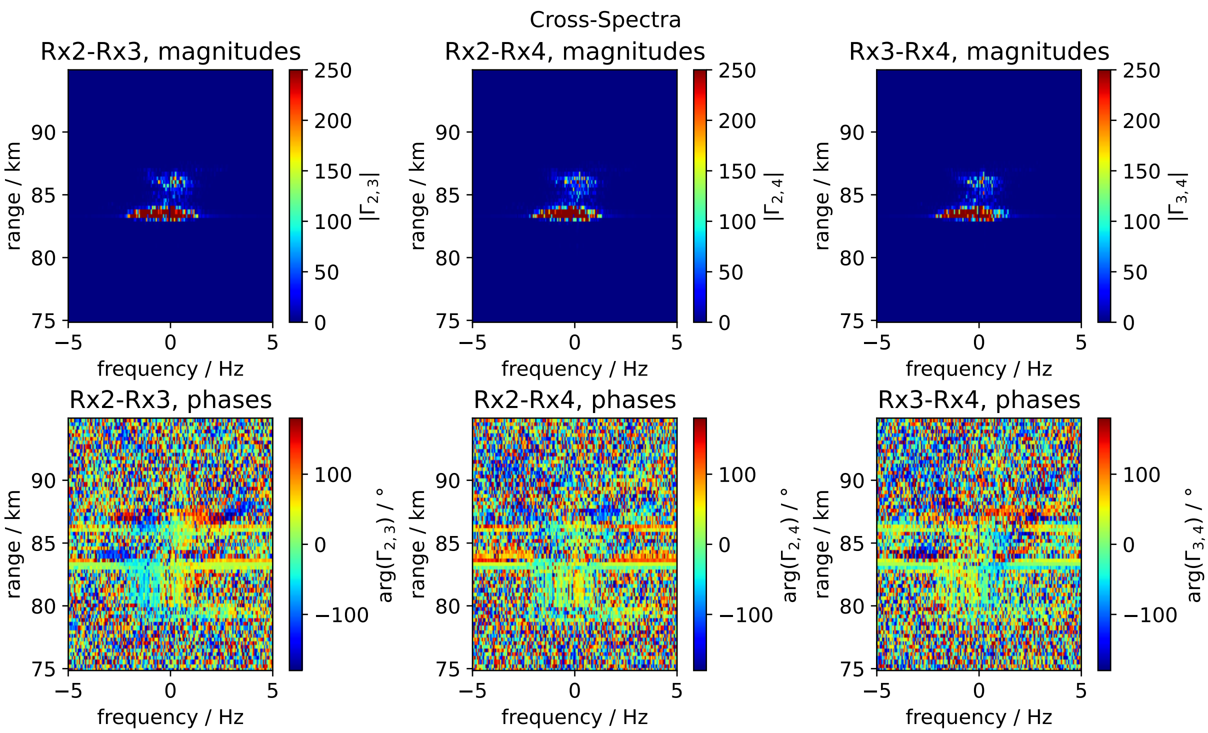


Figure 18: Task 5: Magnitude and phase plots of the cross spectra of all receiver channels.

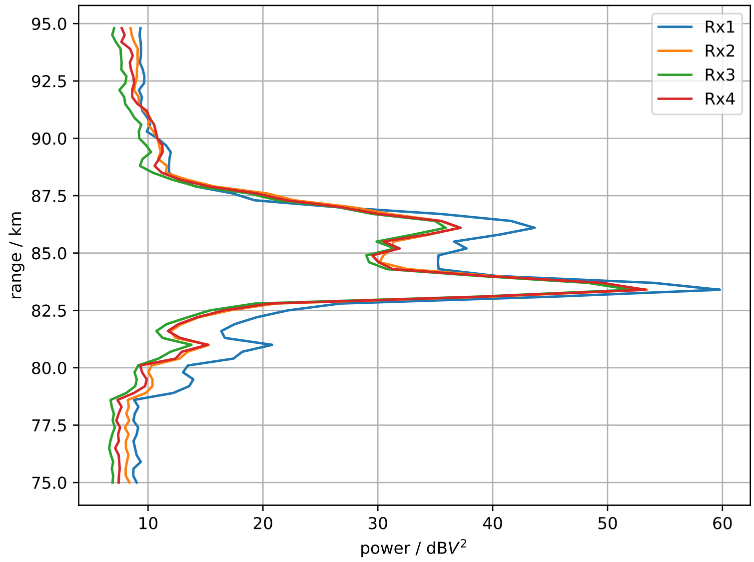


Figure 19: Task 5: Received power values over all range gates.

(figure 19) [2].

The color range in figures 17 and 18 are the same. Therefore an increase in the signal to noise ratio after applying the cross spectrum calculation is visible.

# 6 Task 6

The second MAARSY file holds preprocessed data over a time period of approximately 24 h. First, the provided calibration values were used to adjust the phase of the complex time series data. Then, the received power level over all ranges was determined for all ranges, this result is shown in figure 21 for the provided antenna combination (Rx0) as well as the superposition of the three receiver channels 1 to 4. The superposition of the receivers shows a similar shape to the array data but its noise power level appears to be higher. Again, the noise power is highest around the similar ranges to those in task 5.

After this, the angles of arrival could be calculated for each time sample as well as using an average phase for each range gate and receiver pair as comparison.

The verticality of the angle of arrival can be seen well in the plots of figure 24. Here, the theta-angle only varies by a few degrees while the phi angle varies a lot more, basically going around the full circle, indicating a vertical pointing beam direction. The same can be seen for the plots of the non-averaged data, where an angle of arrival was calculated for each time sample (figure 22 and 23). Theta and phi again vary in the same manner (note the color limits in both plots).

The effect of the phase averaging which results in a single AOA phase difference for a particular range gate and antenna pair can be seen in figure 25. The angle-variability decreases further.

# 7 Task 7

For this task, artificial complex data was created to test two different antenna array layouts to obtain AOA coverage data: one with a circular and one with a spiral antenna distribution, each having 6 anten-

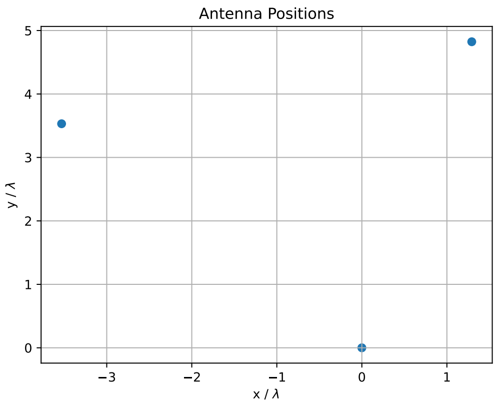


Figure 20: Task 6: Antenna positions.

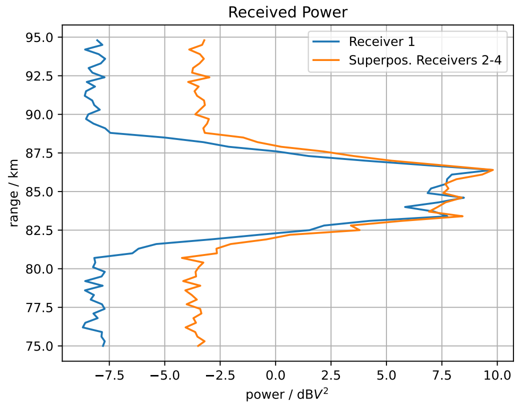


Figure 21: Task 6: Received power values over all range gates.

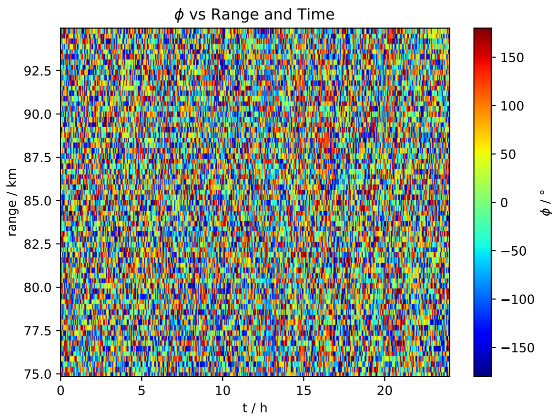


Figure 22: Task 6: AOA angle $\phi$ versus time and range.

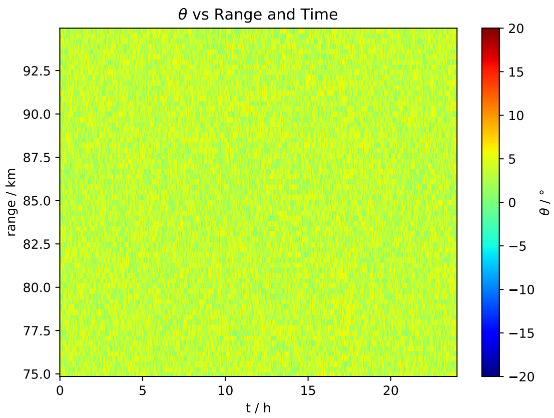


Figure 23: Task 6: AOA angle $\theta$ versus time and range.

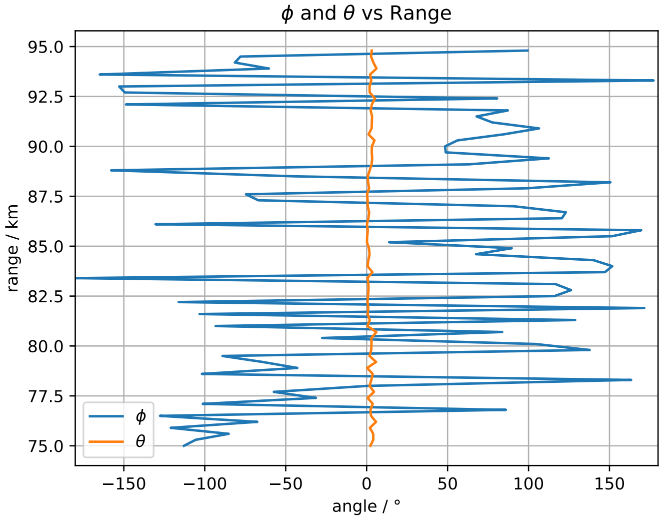


Figure 24: Task 6: Plot of the angles of arrival versus range (averaged phase calculation).

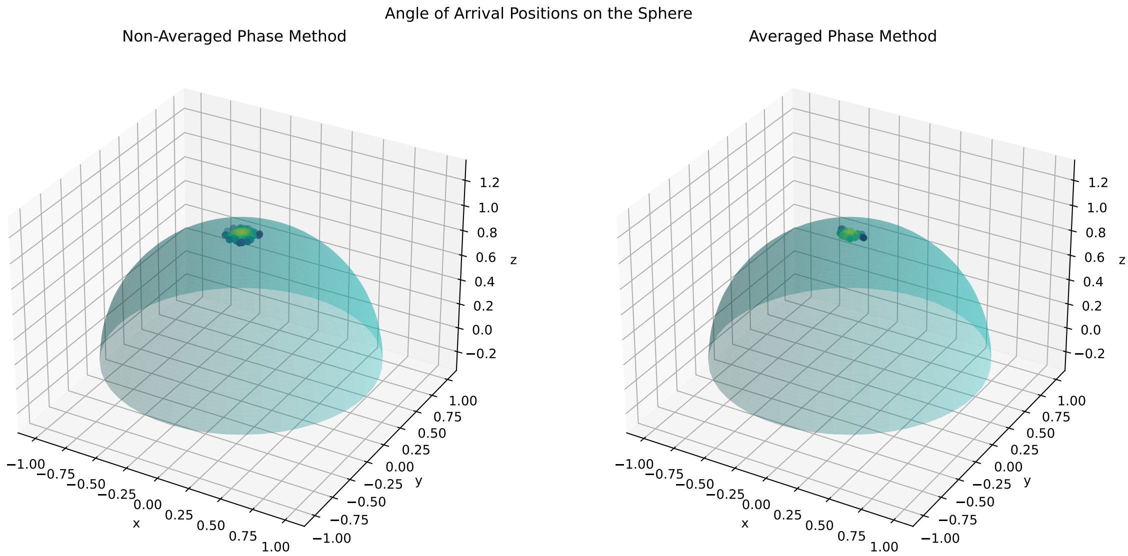


Figure 25: Task 6: Scatter plots of the AOA positions on a hemisphere above the antenna plane.

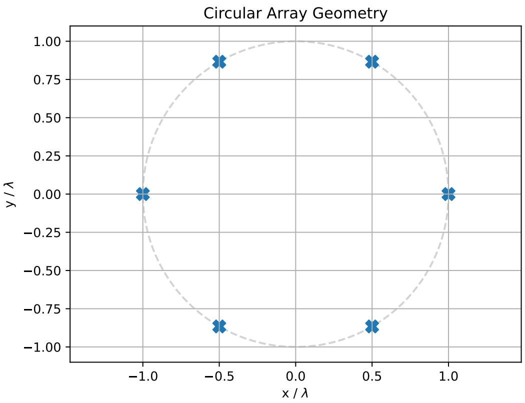


Figure 26: Task 7: Array geometry of the circular array.

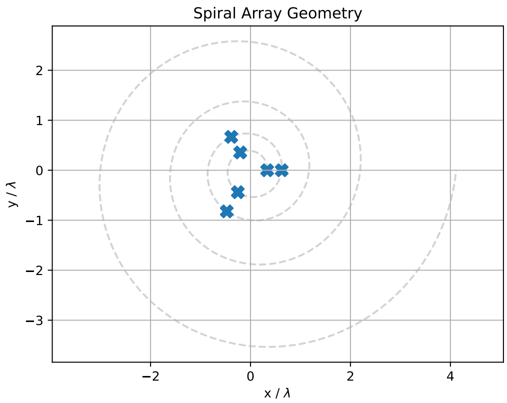


Figure 27: Task 7: Array geometry of the spiral array.

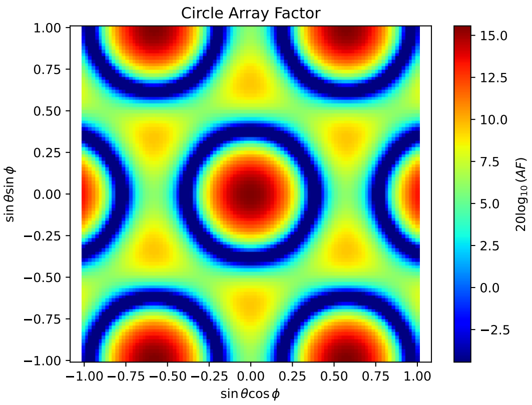


Figure 28: Task 7: Array factor of circular array.

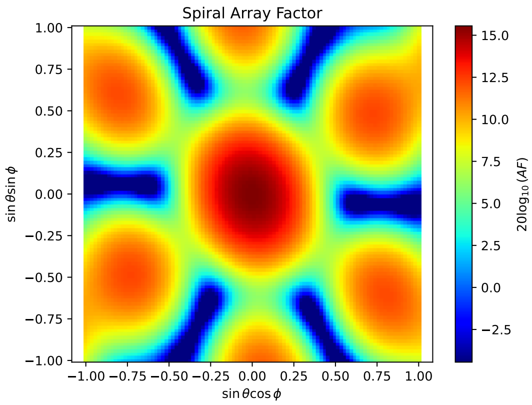


Figure 29: Task 7: Array factor of spiral array.

nas. The array geometries can be seen in figures 26 and 27.

Due to the low number of antennas, the main lobe in the antenna factor is relatively broad for both array types. The spiral array factor has a broader main lobe since the antennas along the spiral are spaced closer together. In any case, the vertical angle can be clearly seen from the array factor patterns (figures 28 and 29) when steering the antennas with equal phases.

The result of the AOA calculations with the random data can be seen in figures 30 and 31. As expected from the array factors, the spiral array shows a broader AOA coverage than the circular array type and both are pointing vertically. The grating lobes of the circular array show greater magnitude, so that aliasing might be greater. But in both array cases, the grating lobes lie almost on the edge of the horizon, which might result in negligible aliasing effects.

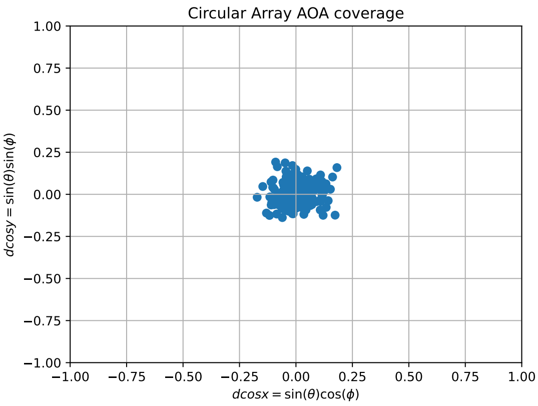


Figure 30: Task 7: AOA coverage of circular array.

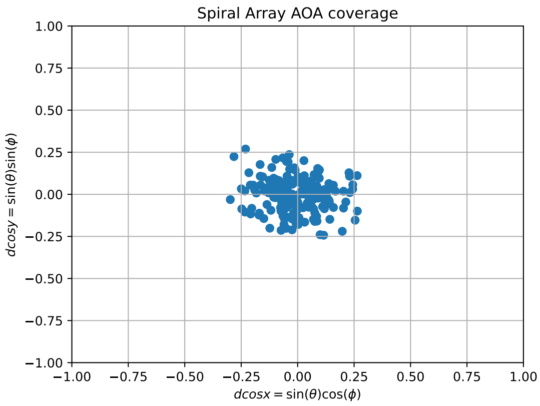


Figure 31: Task 7: AOA coverage of spiral array.

# References

## Web

[1] Wikipedia, The Free Encyclopedia. *Convolution Theorem*. 2023. URL: https://en.wikipedia.org/wiki/Convolution_theorem (visited on 07/03/2023).

[2] Wikipedia, The Free Encyclopedia. *Polar Mesospheric Summer Echoes*. 2022. URL: https://en.wikipedia.org/wiki/Polar_mesospheric_summer_echoes (visited on 07/03/2023).

## Software Used

[1] Charles R. Harris et al. “Array programming with NumPy”. In: *Nature* 585.7825 (Sept. 2020), pp. 357–362. DOI: 10.1038/s41586-020-2649-2. URL: https://doi.org/10.1038/s41586-020-2649-2.

[2] J. D. Hunter. “Matplotlib: A 2D graphics environment”. In: *Computing in Science & Engineering* 9.3 (2007), pp. 90–95. DOI: 10.1109/MCSE.2007.55.

[3] Python Core Team. *Python: A dynamic, open source programming language*. Python version 3.7. Python Software Foundation. 2019. URL: https://www.python.org/.

[4] Pauli Virtanen et al. “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python”. In: *Nature Methods* 17 (2020), pp. 261–272. DOI: 10.1038/s41592-019-0686-2.

# A Task 4: Additional Cross Spectra

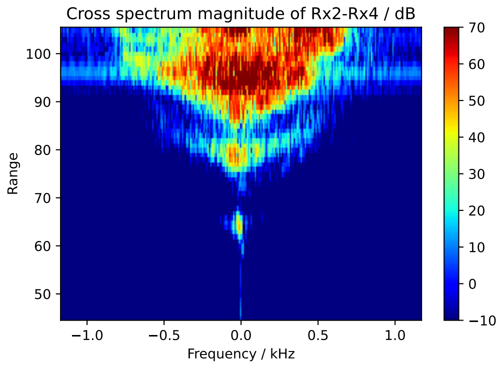


Figure 32: Task 4: Magnitude of cross spectrum of Receivers 2 and 4.

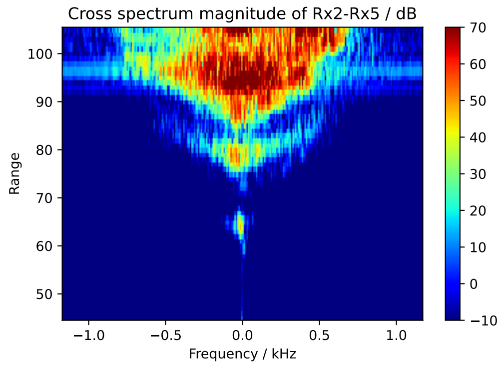


Figure 33: Task 4: Magnitude of cross spectrum of Receivers 2 and 5.

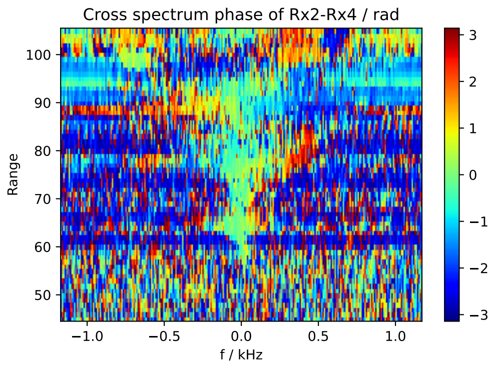


Figure 34: Task 4: Phase of cross spectrum of Receivers 2 and 4.

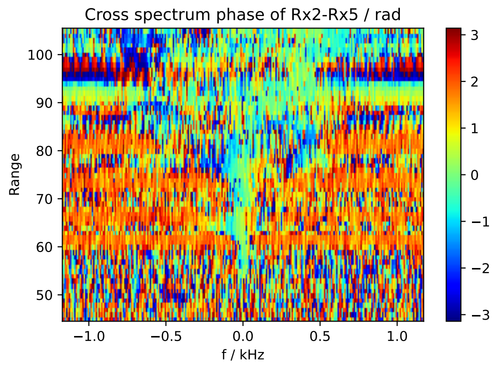


Figure 35: Task 4: Phase of cross spectrum of Receivers 2 and 5.

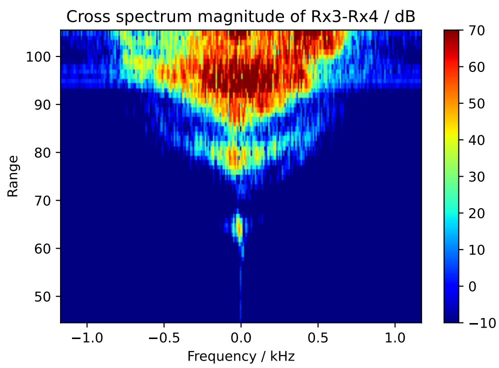


Figure 36: Task 4: Magnitude of cross spectrum of Receivers 3 and 4.

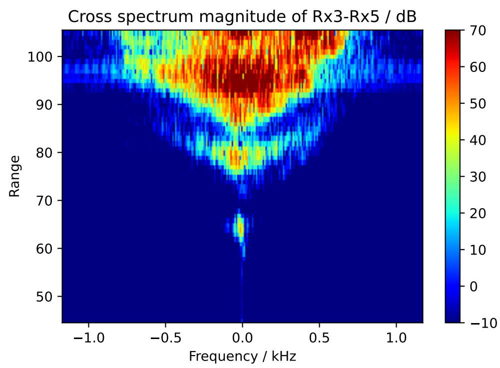


Figure 37: Task 4: Magnitude of cross spectrum of Receivers 3 and 5.

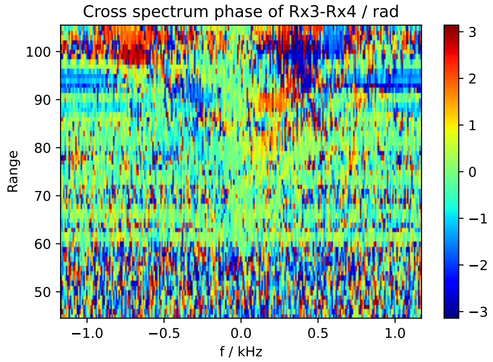


Figure 38: Task 4: Phase of cross spectrum of Receivers 3 and 4.

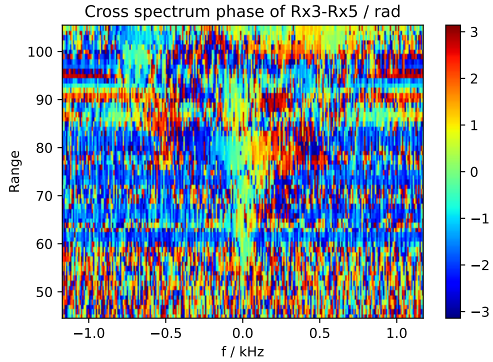


Figure 39: Task 4: Phase of cross spectrum of Receivers 3 and 5.