

Auto-calibration of the Zephyr Meteor Radar Network

Tori Field ^{*}, James Monaco , John Marino , and Scott Palo

University of Colorado Boulder, Boulder, United States of America

*Corresponding author: tofi1115@colorado.edu

Abstract

The Colorado based Zephyr meteor radar network is being used to study winds in the mesosphere/lower thermosphere (MLT) (70-120 km), which acts as an interface between space and the dense atmosphere. This region is difficult to study using in-situ methods, but ablating meteors provide radio reflective plasma trails that can be used to study the environment of the mesosphere/lower thermosphere. A single link consists of an array of transmitters and single receiver, enabling interferometry to be used to determine the location of the echo determined by the point of specular reflection. These interferometric links must first be calibrated before they can accurately estimate the location of trails. Aircraft can be used as calibration sources, enabling end-to-end calibration of the radar's entire processing chain.

This work provides a method for automating an existing method of radar calibration method, using ADS-B records from OpenSky's historical database. This method addresses the labor-intensive task of manually estimating the call signs of aircraft detected in radar data. First, a signal processing algorithm integrated with a clustering algorithm is used to locate planes in radar data. Next, ADS-B data from planes over Colorado for the time of detection is retrieved from OpenSky's databases and paired with plane detections in the radar data. Planes are matched between radar and ADS-B by determining which plane in the ADS-B data has the closest minimum bistatic range from that seen in the Range Time Intensity data product (RTI). The planes are then parsed through minimizing the error in bistatic range in a least squares sense. Finally, these pairings are used in an existing calibration script which compares expected phase, determined from the ADS-B, and the received phase, found in the radar data [1]. A set of calibration offsets can be determined for each link. It is labor intensive to identify the call signs of planes detected by radar, hence this work details methods to automate the process.

Keywords: keyword; keyword-two; keyword number three

Abbreviations: MLT: Mesosphere Lower Thermosphere, RTI: Range Time Intensity

1. Introduction

The mesosphere/lower thermosphere (MLT) acts as an interface between upper space weather and weather in the dense atmosphere. The MLT is a transitional region in which terrestrial weather interacts with space weather and is important to the propagation of heat from the lower atmosphere to the upper atmosphere [2]. Understanding the relationship between the upper and middle atmosphere are crucial to understanding the relationship between space weather and terrestrial weather [3]. Due to its high altitude and low density, the MLT exceeds the attainable range for weather balloons, but is too dense for satellite operation. Rockets can be used to determine wind speeds in the MLT, but are costly and spend limited time in the necessary atmospheric range. As a result, in-situ methods are unreliable and utilization of remote sensing systems is necessitated.

Ablating meteors can be used as tracers of opportunity for atmospheric conditions in the MLT. Most meteors ablate between 70 km and 120 km, leaving radio reflective ionization trails several kilometers long [4]. These trails can be carried by the wind and bulk motion of the atmosphere [1]. Though persisting for only a matter of milliseconds to seconds, the plasma trails resulting from ablating

meteors are used as tracers of opportunity to determine wind directions and velocities [5].

The Zephyr meteor radar network, located in Colorado, uses radar techniques to conduct atmospheric research. It consists of a transmitter array, with transmitters grouped closely together, and a single receiver. Each transmitter broadcasts a radio signal which will reflect off planes, meteors and other radio reflective objects in the atmosphere. This signal is then picked up by the receiver forming a single transmitter-reciever (tx-rx) link. Multiple tx-rx links are formed between individual transmitters and the receiver and can be used together to determine the locations of ablating meteors for use in determining wind speeds in the MLT.

Interferometry is a powerful tool Zephyr uses to determine the location of meteors, based on received signals from each tx-rx link. The total distance traveled from transmitter to receiver is known as the bistatic range. Receivers are only able to measure bistatic range to 1.5 km, but also record phase information from the received signal including received phase. Interferometric methods are used with range gate information to determine the location of objects by comparing the received phase of each tx-rx link [6]. When the bistatic range is known, it is possible to calculate the received phase expected at each link, known as the expected phase, based on the wavelength of radio wave being used.

In order for the Zephyr Meteor Radar network to function correctly, it must first be calibrated. Small differences in the physical system of transmit-eceiver links, such as variations in the lengths of electrical cables, can result in slight offsets in received phase [1]. The phase bias is used in interferometry to account for variations in the physical systems used to collect data. Without an accurate understanding of the phase biases, these discrepancies result in an inability to accurately determine the location of meteor plasma trails [1]. Any data collected based on uncalibrated meteor radar systems result in inaccurate measurements of wind fields.

Figure 1 displays the meteor detections by Zephyr before and after the calibration process [1]. Before calibration, meteors appear clustered with parabolic streaks. This data indicates a distribution that is not physically reasonable. When calibrated, meteors are centered around the transmitter and receiver, and taper off as distance increases. When uncalibrated, the meteors detected have incorrect relative locations, resulting in the parabolic shapes seen in 1, and incorrect wind speed data.

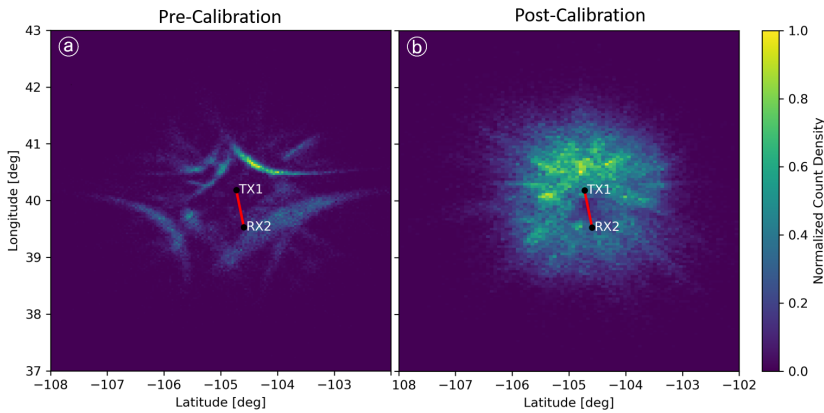


Figure 1. Zephyr meteor detections for uncalibrated (a) and calibrated (b) system. Figure taken from [1]

Several methods of calibrating meteor radar networks can be implemented in addition to the strategy being automated by this work. Such options include using celestial objects as calibration targets [7], assumed distributions of height variation [8], and the use of objects of known location as calibration

targets [9], all of which have the drawback of being considerably time consuming. Ideally, radar networks like Zephyr should be calibrated frequently, even multiple times a year but long calibration processes make this difficult. This work automates a previous calibration preformed on Zephyr [1].

During the previous calibration planes were used as objects of known location for calibration [1]. Each detected plane was manually matched with ADS-B data before being used in the calibration script. The corresponding planes were determined by matching general range gate and timing of minimum bistatic range of planes from the ADS-B data and the Range time Intensity (RTI) data. These values were used in the calibration script, developed in Zephyr's previous calibration [1], which compares RTI of identified planes and the planes corresponding ADS-B data to determine a set of calibration offsets. These offsets are then used to correct the timing differences and phase offset resulting from minor inconsistencies with the transmitter and receiver array setups.

Planes serve as optimal calibration targets due to the broadcasting of their location via ADS-B and their radio reflective properties. Airplanes are required to broadcast their location via ADS-B, providing information on location and speed [10], making their locations known for purposes of calibration. Planes are also very large, and are visible in RTI data for long periods of time making them easy to identify within RTI data and possible to detect automatically using methods outlined in this paper [11].

2. Methodology

Figure 2 depicts the steps of automating the calibration process. The calibration procedure begins with the detection of planes within the radar data. Relevant ADS-B data of planes in the area are pulled from OpenSky [12]. Planes visible in the radar data are paired with their corresponding callsign and ADS-B. The radar data and its corresponding ADS-B are then used in a calibration script to determine the calibration offsets [1].

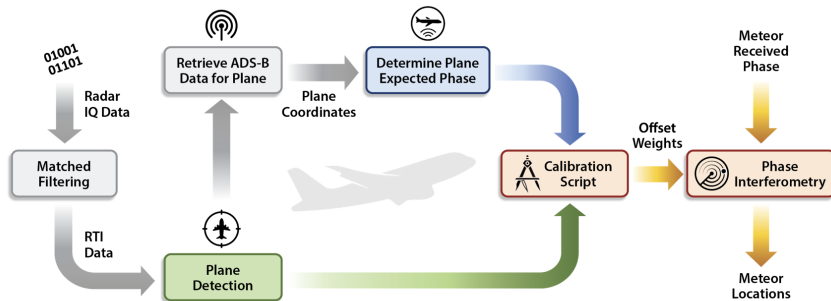


Figure 2. Block diagram of auto calibration script, courtesy of Lunar Designs, Inc.

2.1 Plane Detection in Radar Data

2.1.1 Detection in RTI Data

Raw radar data from Zephyr can be converted into RTI data, see figure 2: matched filtering, which is a 4 dimensional array including information about the phase and amplitude of each link across different gates and times. Range gates are 'listening windows' of about 1.5 km, representing bistatic range. RTI data is typically very large, and contains information which is used in CEV data.

Planes are typically visible in plots of RTI data across 1-2 range gates. The plane detection algorithm automatically determines the gates they occupy and the time period they are visible. Plane detection

is the first step of the auto calibration algorithm. The plane detection algorithm utilizes a Constant False Alarm Rate (CFAR) algorithm [13], resulting in points representing the times and gates planes may be present in. These points are then fed into a density-based spacial clustering of applications with noise (DBSCAN) algorithm which groups points into detections of planes and meteors [14]. Detections spanning less than 1.5 s are ignored representing meteor detections, and the remaining detections represent planes visible in the RTI data. The plane detection algorithm accepts RTI data, and determines the gates and times that planes are present in that data.

Some data preparation is done before using the plane detection algorithm to reduce the amount of RTI data used and to increase the accuracy of detection. Limits are placed to eliminate gates that are too high for planes and most meteors. This value is determined by using the distance between the TX and RX and the maximum height expected for meteors to calculate a maximum bistatic range. The calculated maximum bistatic range is then converted to a gate, above which meteors are not present.

First, a CFAR algorithm is used to determine pairs of times and range gates which of possible detections. The algorithm is run for each time in the 10-15 s interval across all gates to locate spikes in amplitude which can be indicative of planes or meteors. The CFAR algorithm was chosen due to it's ability to maintain a constant false alarm rate despite fluctuations in noise level [13]. This means that temporary atmospheric changes are rarely included as possible detections to be fed into the DBSCAN algorithm. Some possible detections not associated with planes or meteors are still included due to noise. The frequency of these detections can be altered by changing the CFAR parameters. It is possible to alter CFAR parameters to reduce the possible detections due to noise, but reducing this value too much could result in valid detections of planes being ignored. Likewise, if the CFAR algorithm produces too many possible detections, the DBSCAN will become less efficient.

After the CFAR algorithm, the potential detections are fed into a DBSCAN algorithm, that clusters them based on density. Inevitably, along with potential detections correlating to meteors or planes, the CFAR algorithm results in some noise included in potential detections. Meteors and planes are distinguishable from random noise as potential detections correlating to planes and meteors exhibit higher density in 1-2 range gates. The DBSCAN algorithm was chosen as it is robust to noise and cluster shape, and no preliminary information on the number of clusters is required [14] [15]. The range gate axis was scaled to prevent clustering over more than a couple gates. The results of the full plane detection algorithm is shown in figure 3. As planes are more persistent than meteors, any cluster spanning less than a few seconds in time are discarded, being either meteors or noise. If RTI data does not include any plane detections, it is not used in calibration.

2.1.2 Obtaining Required Pairing data from CEV Data

CEV data is derived from RTI data, representing data correlating to confirmed events. This can include both meteors and planes, but for auto calibration only CEV data containing planes is used. This data primarily covers a single gate, and includes similar information to that of the RTI. An existing calibration script from the previous calibration uses inputs of CEV data, and corresponding ADS-B data for to determine calibration offsets [1].

When a plane is detected in RTI data, information on it's range gate, and time of minimum bistatic range can be determined. Bistatic range range gate, but it will be somewhat inaccurate before the system is calibrated. The time of minimum bistatic range is independent on system calibration, as it is determined from CEV data and is evident in the phase wrapping. Since the individual transmitters in a transmitter site are very close together, the time of minimum bistatic range is almost identical for each link. Using the mean value is sufficient for use in the point pairing algorithm.

Data collected for this paper only includes RTI and CEV data with known planes from the previous

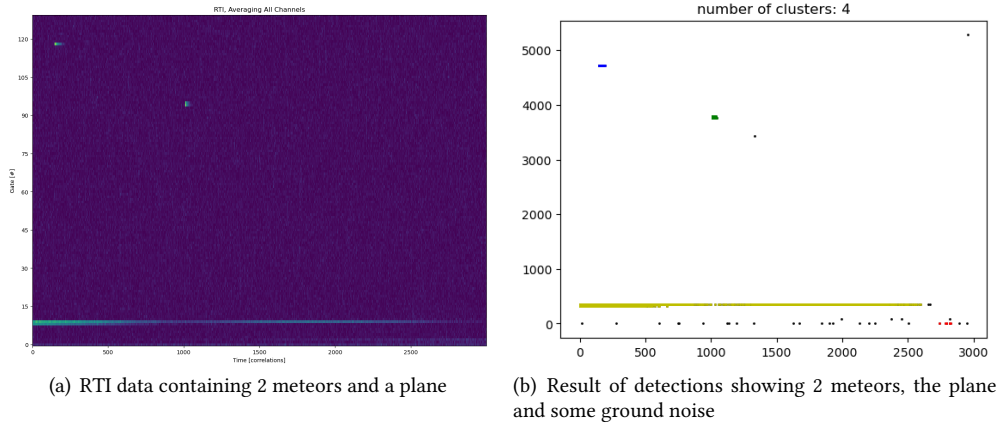


Figure 3. RTI data (a) compared to meteor and plane detections (b)

calibration [1]. This allows validation of results against that of a successful calibration. Only CEV data close to the minimum bistatic range was included, as the time of minimum bistatic range cannot be deduced without some phase cohesion.

2.2 Opensky Data

Using the time values from RTI data, and knowledge about the location and range of the transmitter receiver array, data is pulled from the OpenSky historical database for use in calibration [12]. Calls to the historical database are for 1 minute intervals, and focus on planes above the transmitter receiver site. Although RTI only lasts 15 s, pulling a full minute centered around the RTI provides ample data for use in the calibration script. The latitude and longitude ranges are determined based on the angle to the horizon Zephyr is able to collect data. Figure 4 shows the receiver, and both the current and previous transmitter sites. In this way the amount of data pulled from Opensky is kept to a minimal, both reducing the number of planes to be considered as possible targets, and reducing the load on Opensky servers.

With several airports surrounding Denver, Colorado, including Denver International Airport (DIA), planes taxiing, or within a few meters of the ground are not considered, despite frequently being included in the ADS-B pulled from Opensky. These planes are not visible in the RTI data more than buildings are in the form of ground noise and are not useful in calibration.

There are several other ADS-B resources available, but OpenSky was chosen due to its ease of use, extensive historical database and existing documentation and community. OpenSky has both a historical database through Trino, and a live API with current plane locations. For calibration, the historical database was used. The RTI data used to test the auto calibration is from 2023 when Zephyr was previously calibrate. Historical data will continue to be used, calibrating Zephyr for the new transmitter site, as beyond plane detection, calibration will not happen in real time. Important data from OpenSky includes the callsign, latitude, longitude, timestamp, velocity, altitude and vertical rate are used.

2.3 Analysis of Individual Flights

Once ADS-B data is retrieved from Opensky, information including the bistatic range at each time, and the time of minimum bistatic range should be found. The point pairing algorithm will be compare these values to those calculated in the radar data in order to determine which ADS-B belongs

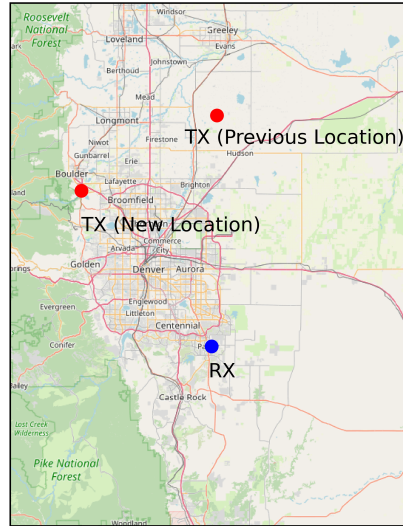


Figure 4. Current and previous transmitter sites, and receiver site

to the plane visible in the radar data.

For each plane present in the ADS-B data the bistatic range is calculated based on the position coordinates in ADS-B. The latitude, longitude and altitude coordinates from each planes ADS-B are converted to ECEF coordinates in preparation for calculations. Next, it is possible to calculate the bistatic range of the plane at each point in time. By using trigonometry to calculate the distance from the transmitter to the object, and from the receiver to the object and adding the two values the bistatic range is found. The gate can also be found by dividing the bistatic range by the width of each gate. Since most planes used in calibration do not rapidly change direction, quadratic interpolation is used to find the approximate bistatic range of the plane at every point in time the radar data has values.

The time of minimum bistatic range for each plane is crucial in determining the correct pairing with planes visible in RTI data. This value can be calculated using the interpolated dataset, as the time at which the minimum bistatic range is achieved. This is the time which the plane is closest to the transmitter and receiver, and in most cases is flying directly between them.

2.4 Pairing radar data with ADS-B

The collection of candidate planes with known location and time can be matched with the plane detected in the radar data. The plane detected in the RTI will have a gate, or gate range, and time of minimum bistatic range. Since the meteor radar network is not yet calibrated, the bistatic range determined from the radar data will be inaccurate, but still close to the actual range. The time of minimum bistatic range determined will be very accurate before calibration as it is not dependent on the phase biases and is determined by locating where phase wrapping stops increasing and begins decreasing.

By comparing the range gates and time of minimum bistatic range between the ADS-B and radar data, a pairing between radar data and ADS-B can be produced. The differences in time of minimum bistatic range between what is calculated in the RTI and each planes minimum bistatic range as determined by ADS-B is calculated. The plane with the closest time of minimum bistatic range is

taken to be the correct pairing with the RTI data. This value can then be checked by comparing the estimated gate from the RTI to that determined from the ADS-B using a least squares method. While several planes may have similar gates with time, as discussed above, the correct plane pairing should not be off by more than a couple gates. If this is the case, there is an issue with the pairing and calibration.

2.5 Data Product

The desired data product is a set of files containing matches CEV and ADS-B data for planes to be used in the calibration script. Once each plane detection in the RTI has a corresponding pairing of ADS-B data and known call sign, the ADS-B data and RTI data will be saved for use in a calibration script. The calibration script uses pandas Dataframes of ADS-B data, including latitude, longitude, altitude, time, velocity and CEV data derived from RTI data.

3. Results

In order to validate results, calibration values from a previous calibration on Zephyr were used. The previous calibration, resulted in accurate measurements, making it ideal for testing the auto calibration script as seen in figure 1. Currently, there is no new radar data being collected, as Zephyr's transmission site has been moved, and is in the process of being fully set up. In this work we are able to use the same RTI data used in the previous calibration and compare the phase offsets of the previous calibration to those of the auto calibration algorithm [1].

Overall the full algorithm was successful in acquiring the necessary information for calibration. For each RTI file, the algorithm determined a plane that had a time of minimum bistatic range, and bistatic range over time most closely aligned with that viewed in the RTI. If there is not a suitable plane, the algorithm will state so, and exit the program on an error. The algorithm signed planes correctly for 11 of the 15 planes tested, and produced erroneous results for four of them. Of these four erroneous results, three were due to the time of minimum bistatic range being at the edge of the RTI, one was due to an error pulling planes from OpenSky. While the algorithm cannot yet detect these circumstances on its own, they are easy to spot overseeing the algorithm's function. Whenever the algorithm paired a plane in RTI with an incorrect plane ADS-B data, it was not used in the next step to determine phase offsets.

Figure 5 is an example of the unwrapped phase of UA1896 radar data which was incorrectly paired to another plane. The algorithm incorrectly determined UA2145 to be the correct plane pairing, because the minimum bistatic range of the airplane occurred very close to the end of the 15 s of RTI data. The algorithm then determined the time of minimum bistatic range for this data to be the timestamp representing the end of the RTI data. As such, an inaccurate time of minimum bistatic range was calculated from the RTI data. This value was then used to determine the plane with a similar time of minimum bistatic range. At this time, several planes bistatic ranges were decreasing, so their minimum value present in the dataset also occurred at the end time for the RTI, and the plane UA2145 was chosen. This was an erroneous pairing, indicating the need for further work, but was not difficult to detect for a human operator.

On planes that received the correct pairing, phase offset values closely matched those of the previous calibration data. One such example is that of NKS947 in figure 1, but others can be found in Appendix 2. In this case, the algorithm correctly determined that the plane visible in the RTI data was NKS947. In the previous calibration, this plane is referred to as NK947 due to different labeling standards used by another ADS-B source. For NKS947, almost all determined phase values were within .06 rad of the values from previous calibration. The largest recorded error under d7 was a difference of .34 rad, but notably, when determining final phase offsets for Zephyr on its previous calibration, this value

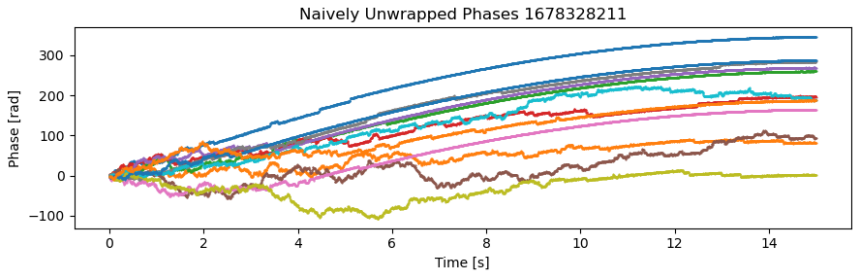


Figure 5. Unwrapped phase determined for each link of each link of UA1896 with time of minimum bistatic range occurring at the edge of the RTI. Wrapped phase is approaching it’s maximum value corresponding to minimum bistatic range, but RTI data ends before time of minimum bistatic range is reached resulting in incorrect pairing.

was dropped from for being too far out of the other calculated phase offsets for this link.

Table 1. Auto calibration phase biases compared to previous calibration phase biases determined from NKS947/NK947 in radians [1]

NKS947/NK947	d0	d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	d11
Previous Calibration	0	-.94	-.28	-.6	3.01	1.88	3.11	2.77	-2.02	-.46	1.17	.52
Auto Calibration	0	-.87	-.3	-.66	3.06	2.22	3.12	2.81	-2.1	-.49	1.18	.57
Difference	0	.07	.02	.06	.06	.34	.01	.04	.02	.03	.01	.05

4. Discussion

Overall, the auto calibration algorithm effectively determines plane pairings, and calibration offsets based on previous calibration data. Although not entirely interdependent of human interaction, the auto calibration algorithm is able to effectively determine calibration offsets for most input RTI.

Further work will address further automation, error detection and further automation of determining final link calibration offsets. As seen above, errors can arise when minimum bistatic range occurs at the edge of a set of RTI, further work should include determining when RTI and CEV data which includes minimum bistatic range, in order to reduce poor callsign approximation due to issues with minimum bistatic range.

5. Conclusion

This auto calibration algorithm will aid in the automatic calibration of Zephyr meteor radar network and other simular networks. It will speed up the process of calibration, and allow for more frequent calibration by reducing the need for human intervention in the calibration process to primarily reviewing errors and validating results.

Appendix 1. Supplementary figures

Appendix 2. Supplementary tables

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Python libraries including Numpy, Scikit-learn and Pandas were used to implement many of the algorithms described in this work [16],[15], [17].

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Author contributions

- Tori Field: Conceptualization, Software, Validation, Formal analysis, Investigation, Data curation, Writing Original Draft) , Writing (Review and Editing)
- James Monaco: Conceptualization, Resources, Writing (Review and Editing), Visualization.
- John Marino: Software, Validation, Formal Analysis, Resources, Writing (Review and Editing), Data curation, conceptualization, methodology
- Scott Palo: Writing (Review and Editing), Supervision, Project administration, Funding acquisition, **Principle Investigator**

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Open data statement

RTI data is available upon request.

Reproducibility statement

Code including plane detection, plane pairing, and tools for analyzing single flights available upon request.

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