Multistatic Radar Development for the Colorado Zephyr Meteor Radar Network

Nicholas Rainville, Scott Palo, John Marino, and Ryan Volz

Abstract – The development of a multistatic radar system for the Colorado Zephyr Meteor Radar Network is described in this article. This system relies on recent developments in the field of meteor radar, including advancements in software-defined radio-based radar receivers, multistatic wind retrieval, coded constant-wave transmit signals, and transmit-side interferometry. We present the current status of a prototype multistatic radar transmitter deployed in Platteville, Colorado, and a forward look toward how it can inform the design of a large-scale radar network.

1. Introduction

Specular meteor radars estimate winds in the mesosphere and lower thermosphere (MLT) region of the atmosphere by observing the specular reflections of RF signals from drifting plasma trails produced by ablating meteors. Traditionally, specular meteor radars are monostatic systems capable of observing backscatter reflections from meteor trails, with a colocated transmit antenna and interferometric receive array. This arrangement simplifies the transmitter design at the cost of requiring relatively complex multichannel receivers and precisely positioned receive antennas. Although this configuration has a long history of providing wind data [1], by observing backscatter reflections, it can only provide Doppler wind velocity estimates in the direction radial to the radar and meteor line of sight. Retrieving an estimate of the full three-dimensional wind vector requires combining meteor trail echoes from across the entire field of view of the radar, an area that can extend more than 400 km in diameter [2]. Depending on the altitude resolution of the wind estimate, collecting the meteor trail observations necessary to calculate the mean wind can require 30 min to 60 min [1].

In contrast to monostatic radars, multistatic configurations capable of observing forward and backscatter reflections from multiple locations can increase the number and geometric diversity of meteor trail observations. This can increase the spatial resolution of the wind estimate and decrease the time required to calculate it [3]. These types of systems have become feasible due to several key technologies. The first is the ability to perform multistatic wind retrievals that take advantage of the increase in meteor trail observations at nonradial geometries [3]. Next is the use of orthogonally coded constant-wave (CW) transmit signals that can overlap in frequency and concurrently allow the reception of multiple echoes from different sources [4]. Transmit-side interferometry simplifies receiver construction and installation by placing the large array at the transmitter and allowing for a single antenna on receive [5]. When combined with commercial off-the-shelf (COTS) software-defined radios (SDRs) to provide flexibility in signal processing, these techniques enable large-scale multiple-input multiple-output (MIMO) meteor radar systems composed of multiple transmitters broadcasting to wide networks of receivers.

A prototype multistatic meteor radar is being built in the Rocky Mountains to develop and mature these MIMO meteor radar technologies. This test network is focused on refining transmitter and receiver deployment, real-time autonomous operation, and enabling science observations of the Colorado Front Range MLT winds. The broader goal for this network is to serve as a pathfinder for a larger western US network that can provide dense wind measurements over a wide geographic region. This can provide data to better understand mesoscale dynamics of the neutral atmosphere in the MLT region, such as gravity waves and stratified turbulence, which are otherwise challenging to observe from remote sensing platforms [6].

2. System Design

The prototype Zephyr radar has followed an iterative build and test approach, with the design based on experience with traditional meteor radar systems, such as the backscatter radar operated by the University of Colorado Boulder at McMurdo, Antarctica [2]. Similar to the McMurdo radar, the Zephyr radar operates at very high frequencies (VHF) with a five-element Jones configuration [7] interferometric array. The center frequency for all transmit channels is 31.25 MHz to avoid local interference and comply with licensing requirements.

The CW signal is based on a GPS coarse acquisition code that was truncated from 1023 chips to 1000 chips, to better align with the sample rate of the transmit and receive SDRs and to allow the reuse of GPS-derived code correlation and processing software. At a chipping rate of 200 KHz, this code length provides a 1499 km unambiguous range, which greatly

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Figure 1. The Zephyr 3 U receiver chassis.

exceeds the distances likely to be encountered with meteor trail echoes. Initial processing has focused on correlating the entire code length for meteor detection and to prioritize the postcorrelation signal-to-noise ratio, though the input signal is preserved for all detections to allow for later reprocessing.

3. Receiver Development

To support a network requiring a large number of independent receivers, the goal for the receiver design is to provide a flexible and easily deployable radar receiver, with a pathway to a lower cost version that could be built in bulk. Early testing included a low-cost LimeSDR. However, the LimeSDR applies a down-conversion of the input signal prior to sampling and was seen to introduce a phase bias in the raw signal data. For this reason a National Instruments N200 SDR was instead selected. Although a higher cost, when paired with a BasicRX daughterboard, the N200 directly samples the RF input without requiring additional downconversion or upconversion, unlike most comparable SDR alternatives. The N200 also does not include any amplification stages on the RF front end, which allowed us to select amplifiers best suited for VHF frequencies.

The RF front end had several revisions and provides more than 28 dB of gain with either connectorized Mini-Circuits ZFL-500LN+ amplifiers or a custom amplifier printed circuit board with two Mini-Circuits Gali-74 integrated circuits. Prior to the amplifier, the signal passes through a bandpass filter and bias tee that provides the 8 V dc required by the receiver antenna.

To locally control the SDR and store data, the receiver includes a Seeed Odyssey single-board computer (SBC), based on an Intel J4125 processor. This is a low-power x86 processor that runs Ubuntu 20.04 LTS Linux. This provides a consistent development target for the Zephyr detection software, in addition to the telemetry and data transfer utilities necessary for remote operation. A Jackson Labs Mini-JLT GPSDO provides the timing signal for both the SDR frequency and time tagging.

The receiver antenna is a low-frequency array (LOFAR) low-band antenna (LBA), originally developed for radio astronomy [8]. This is a wideband antenna that covers 10 MHz to 80 MHz, with two independent linearly polarized outputs. Deployments have typically set the antenna mast in a portable tripod with a wire ground mesh placed underneath, as seen in Figure 2.

Figure 2. LOFAR LBA antenna at the Longmont, Colorado, receiver location.

4. Transmitter Development

Similar to the receiver design, the transmitter was built around COTS hardware. The amplifiers are HPA32-500, which can each transmit 500 W of CW power per channel at 32 MHz. The receive array includes three two-channel amplifiers for six total channels of amplification. The CW signal is provided to the transmit amplifier by six N200s with BasicTX daughterboards. Each N200 is controlled by a Seeed Odyssey SBC identical to the one in the Zephyr receiver but with the capability to monitor and control the amplifier status. The transmitter amplifiers and control electronics are seen in Figure 3.

The antenna array consists of five antennas in a Jones configuration with 2 λ and 2.5 λ spacing, with all but the center antenna circularly polarized. The center antenna's two dipoles are independently driven but are otherwise identical to the rest of the array. By transmitting orthogonal codes on each element of the center antenna, we can observe the impact of polarization on meteor trail echoes.

The individual antenna elements are constructed of wire in an inverted V dipole configuration that matches the geometry, but not the length, of the receive antennas. In contrast to the wideband LBA antenna, the transmit antennas are tuned to the transmit frequency of 31.25 MHz. The center antenna of the array is shown in Figure 4.

5. Zephyr Radar Testing

Initial testing was performed at several sites near Boulder, Colorado. The transmit array is located at the

Figure 3. The Zephyr transmitter, including three two-channel amplifiers and six SDRs to generate the transmit waveforms.

Platteville Atmospheric Observatory in Platteville, Colorado. Zephyr receivers are located at two sites in Longmont, Colorado, one suburban and one rural, approximately 10 km west of the transmitter, and at a rural site in Parker, Colorado, approximately 80 km south of the transmitter.

For early testing, the array operated with a single transmit antenna and a single receiver that supported the iterative design of the radar system but only allowed for nondirectional meteor trail observations. However, since August 2022, operations have expanded to the full six-channel array and now fully support interferometric data collection.

An example of a meteor detection from the full transmit array can be seen in Figure 5. This figure shows a meteor trail reflection observed at the Parker, Colorado, receiver on the two receive channels correlated against the six transmit codes. The amplitude

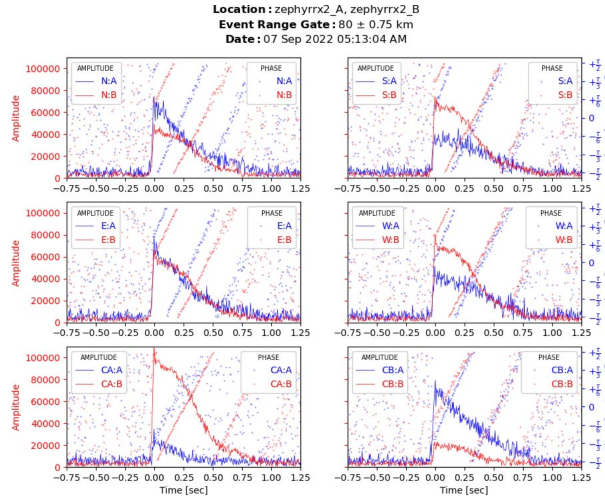

Figure 5. Postcorrelation signal amplitude and phase during a detection at the Parker, Colorado, receiver. Starting at the upper left, the plots show results from the north, south, east, west, center A, and center B transmit signals correlated with receiver channel A in blue and channel B in red.

of each correlation shows the distinct sharp rise and exponential decay of a meteor plasma trail reflection [9]. The difference in phase between each code represents the delayed arrival time due to the direction of arrival of the meteor trail echo. The phase rate of change of any one correlation represents the bistatic velocity of the trail due to atmospheric wind [10]. The Zephyr system will use the data from multiple directions and altitudes to estimate the full three-dimensional wind field in the MLT region [1, 3, 5]. Additionally, this reflection shows a difference in amplitude between the two center channel codes, highlighting the effect of transmit polarization on the returned signal.

The nearly continuously operating array provides real-time detections across six channels since initial operation in August. Daily counts from the Parker location are shown in Figure 6, with the gaps representing the times the transmitter was under maintenance.

Figure 4. An inverted V dipole transmit antenna at the Platteville, Colorado, transmitter location.

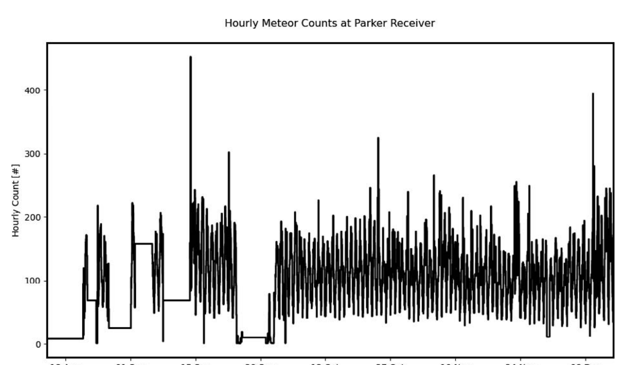

Figure 6. Hourly meteor detection counts between August 14, 2022, and December 14, 2022, at the Parker, Colorado, receiver.

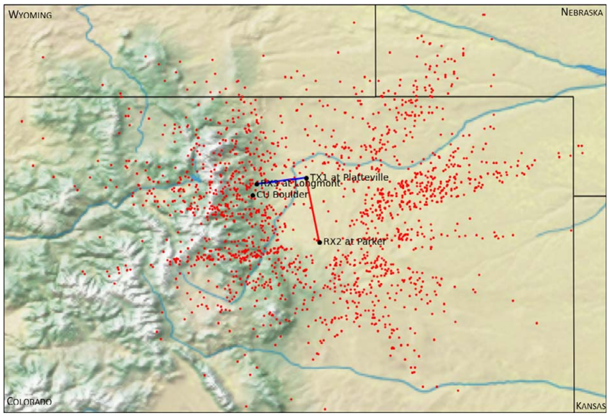

Figure 7. Map projection of meteor trail locations, as seen from the Parker, Colorado, receiver.

6. Calibration

The calibration effort for the Platteville array is ongoing. The initial calibration was based on physical measurement of the as-built array configuration, as well as time domain reflectometry testing of the array cabling. These calibration values result in the meteor detections shown in Figure 7, as seen from the Parker receiver between 12:00 A.M. to 3:00 P.M. local time on December 12, 2022. Additional calibration tuning will attempt to include bias from antenna phase center locations, as well as from signal generation timing and amplification, to further refine the accuracy of the meteor trail locations.

7. Future Work

With a calibrated transmitter array, focus will shift toward performing wind retrievals from the data currently being collected. Methods from [3] will be implemented on the receiver SBCs for real-time wind retrieval. This will provide MLT wind data for the Boulder region and further inform the radar system design. The shift to real-time wind estimation will greatly reduce the data transfer requirements for each receiver, because processed wind data are more compact than either the six-channel detection data or the raw RF signals. This will enable an expansion of the receiver deployments to locations with lower bandwidth network connections.

Continual operation of this network will prove out the design requirements for a larger scale network. A component of this will be to add an additional transmit location with overlapping coverage of the Platteville location. This will increase the meteor trail geometries seen at each receiver, similar to what is seen in a large-scale network, and will inform the receiver performance requirements for real-time data processing.

8. References

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