PROCEEDINGS OF SCIENCE

Drone-borne calibration pulser for radio observatories detecting ultra-high-energy cosmic rays and neutrinos

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We report on the development of a drone-borne calibration pulser (cal-pulser) for radio observatories detecting ultra-high energy (UHE) cosmic rays and neutrinos. This system allows us to calibrate the radio detector in its field of view regardless of the accessibility of the site. The system is compact and sufficiently lightweight to be attached to a commercial drone. It consists of a solid-state high-power pulse generator, a programmable attenuator, a transmitting antenna, and a differential GPS (D-GPS) module. The drone, with the ~1.3 kg payload, has a typical flight time of around 25 minutes, corresponding to a maximum flight distance of around 10 km. After developing the first version of the system in 2019, it successfully demonstrated its calibration performance with the TAROGE stations in Taiwan and the TAROGE-M station in Mt. Melbourne, Antarctica. In 2022, the system was upgraded with a dual-band D-GPS for more reliable operation and more accurate determination of the coordinates of the cal-pulser. In addition to the cal-pulser, we investigated aerial photogrammetry using the built-in camera and the D-GPS, which is an efficient method to determine the coordinates of the detector. For objects within 10 m of the drone, an accuracy of a few millimeter was achieved. These drone-borne cal-pulser and the photogrammetry have become essential calibration procedures in the TAROGE-M experiment. We suggest these approaches may find application in many other radio experiments that detect UHE cosmic rays and neutrinos, such as ARIANNA, BEACON, GRAND, as well as IceCube-Gen2.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)512

1. Introduction

Detecting air showers induced by ultra-high energy (UHE, $E > 10^{17}eV$) cosmic rays and neutrinos using radio techniques is emerging as a highly promising method, thanks to the long attenuation length in the medium and recent significant advancements in RF technology, which provide an efficient way to explore the UHE regime [1]. To obtain a sufficient effective volume, experiments are being proposed with large-scale antenna arrays, such as IceCube-Gen2 Radio, comprising 200 antenna stations distributed over a 500 km^2 area [2]. As the area required for the experiment expands and the number of antennas increases, consequently, there arises a need for an efficient method of in-situ calibration. The cal-pulser system, comprising a high-power pulse generator and omnidirectional antennas, offers an appropriate solution. Multiple transmitter antennas built on high towers or in deep ice can serve as highly effective tools for long-term calibration and system monitoring [4]. On the other hand, calibration from various angles is required to understand the angular response of the system. Deploying a compact and lightweight cal-pulser system on a drone, flying above the airspace over the antenna array, and transmitting pulses is a feasible approach. Drones, due to the constraint of flight time, are not suitable for long-term calibration; however, they can offer a complementary calibration method when used in conjunction with other ground pulsers.

In this paper, we report on the successful development of the drone-borne cal-pulser system. Initially developed for the Taiwan Astroparticle Radio Observatory for Geo-synchrotron Emissions (TAROGE) experiment, wthat implementation faced limitations in ground pulser accessibility due to cliffside detector locations [6]. This system has played a vital role in detector characterizations, including receiver gain, trigger efficiency, timing, as well as radio propagation near the surface. Using the cal-pulser system, we successfully conducted the calibration of TAROGE-M during the austral summer seasons of 2019-20 and 2022-23, at the summit of Mt. Melbourne (2700m elevation) in Antarctica. This affirms the feasibility and capability of the system to operate even in the harshest environments.

The pulser system consists of a high-power solid-state impulse generator, a programmable attenuator, a transmitter antenna, and a differential GPS (D-GPS) [3]. The pulser system is designed to operate within the frequency range of 180-450 MHz for TAROGE-M. The expansion to wider frequency bands can be achieved with minor modifications to the antenna design. The D-GPS records the position of the drone during flight, which is essential for timing calibration and angular reconstruction of TAROGE-M receivers. The electronic components are placed inside a lightweight Faraday shield enclosure to reduce RF interference. Figure 1 shows the system diagram of the drone-borne cal-pulser. The total weight of the system is approximately 1.3 kg. It can be easily attached to a commercially available drone, as shown in Figure 2.

2. New upgrade of the system

The cal-pulser system has undergone several upgrades to improve its performance. One notable upgrade on the D-GPS system is to replace a single-band receiver with a dual-band receiver, which significantly enhanced the stability of position measurements. The D-GPS module comprises two identical parts, the base and rover units, which simultaneously receive GPS signals and store the

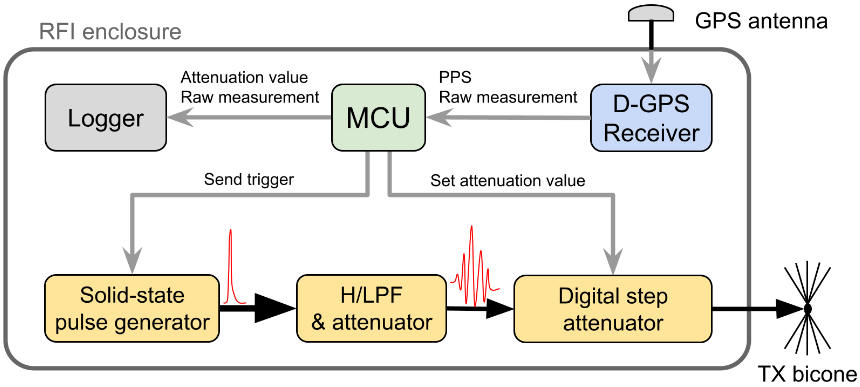


Figure 1: System diagram of the drone-borne cal-pulser system. Adopted from [3]

Figure 2: Drone-borne cal-pulser during the calibration of TAROGE-M system in Antarctica

measurement of its carrier phase signal, called raw measurements, in the SD card for post-processing in the lab. The base unit provides correction information on ionosphere interference to the rover unit, leading to improved position accuracy [7]. This offline process simplifies system design and eliminates possible RFI from communication links.

In addition to the D-GPS upgrade, other minor but valuable improvements were made to the system. One such upgrade involved introducing specially designed gloves for the remote controller, providing a warmer and more comfortable space for the pilot's hand during flight operations. This seemingly small enhancement significantly increased pilot comfort, especially during flights in challenging environments with cold temperatures. Furthermore, to extend the drone flight time, an additional set of batteries was prepared. This allowed for three consecutive flights and provide more coverage on the field of view.

The D-GPS upgrade from a single-band receiver to a dual-band receiver brought remarkable benefits. The dual-band receiver enabled the simultaneous observation of more GNSS signals from GPS, GLONASS, GALILEO, and Beidou constellations in both upper and lower L-band frequencies. This enhancement ensured more stable position measurements, especially in situations where the satellite signal was weak due to external factors such as high wind. Figure 3 illustrates the increased stability achieved with the dual-band receiver compared to the single-band receiver.

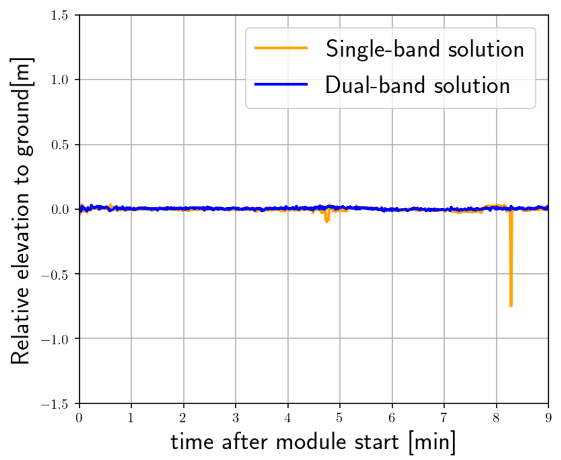


Figure 3: An example of the unstable position using a single-band signal and a corresponding stable position using a dual-band signal. The receiver is in a fixed position, so we expect to see the elevation of it stay at a fixed value.

Moreover, the new D-GPS module substantially reduced the initialization time required for a reliable position measurement. The previous single-band receiver necessitated several minutes for initialization, prompting a ten-minute setup to ensure proper measurement initialization. However, the upgraded module significantly shortened this initialization time to just a few tens of seconds, as demonstrated in Figure 4. Consequently, the preparation time required for the drone pulser in the field was greatly reduced, optimizing the overall efficiency of the calibration process.

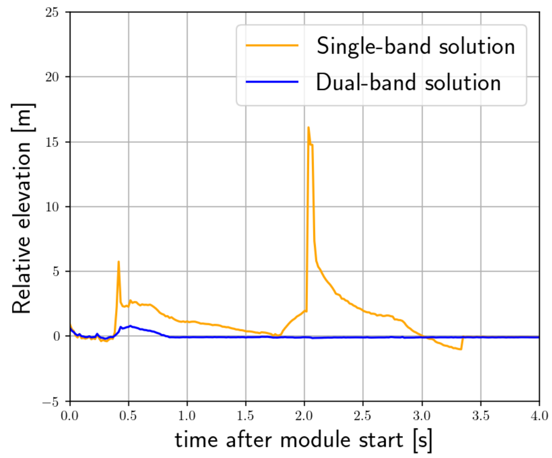
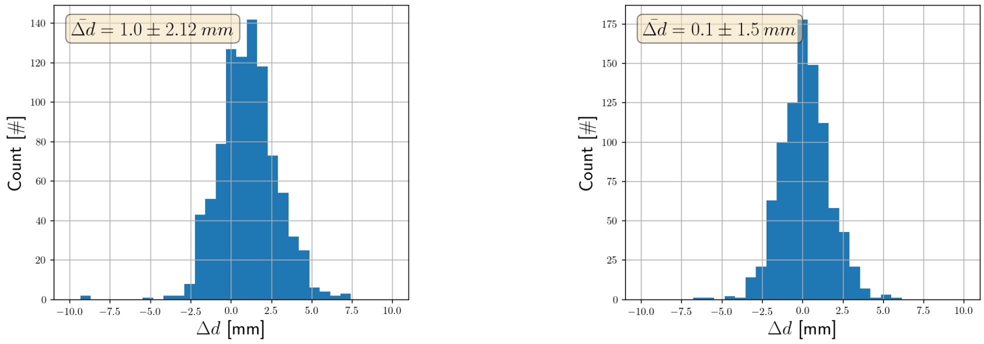


Figure 4: Comparison of convergence time of position solution processed using the single- and dual-band GPS signal. The typical convergence time for a dual-band solution is about 1 minute, while that for a single-band solution is about 5 minutes.

The dual-band receiver also exhibited a noticeable enhancement in position measurement accuracy compared to the single-band receiver, as depicted in Figure 5. Although both resolutions were sufficient for the purpose of the study, the dual-band receiver provided slightly better resolution, contributing to a more reliable and precise position output from the drone-borne cal-pulser system for later analysis.



(a) Single-band **(b)** Dual-band

Figure 5: A comparison of the length measurements by two GPS receivers using single- and dual-band signals. Two plots are generated using the same raw measurements at fixed positions. The only variations are the number of signal bands. Generally, the position using dual-band signals has a smaller RMS than the one using single-band signals. The 1 mm offset between the measurement using single- and dual-band is expected due to the offset of the antenna phase center.

A crucial parameter for D-GPS post-processing is the position of the base unit. In the previous design, we determined the position of the base unit through a long-term average of single-point GPS solutions, which was susceptible to significant elevation deviations. However, with this upgraded system, we can determine the base unit's position using the Precise Point Positioning (PPP) service provided by the Canadian Spatial Reference System (CSRS) [9]. This approach offers a static position accuracy at the centimeter level, reducing uncertainties in the post-processing of the relative position between the rover and base units.

In conclusion, the upgrades on the drone-borne cal-pulser system, which include the D-GPS module and the minor enhancements of gloves and additional batteries, have made substantial improvements in its stability, efficiency, and position measurement accuracy. These advancements have further solidified the system's reliability and utility in the calibration of radio detectors.

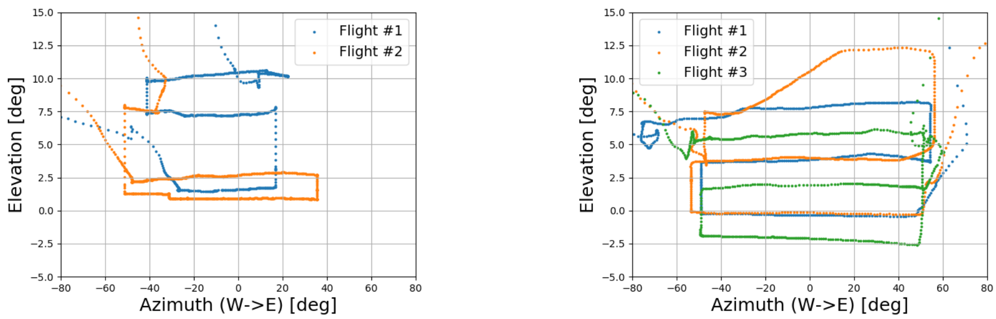
3. TAROGE-M calibration with upgraded drone-borne cal-pulser

During the 2022–23 season, the upgraded cal-pulser system was successfully employed for calibrating the TAROGE-M system. Equipped with three sets of batteries, the calibration was conducted from a distance of 500 meters away from the station, covering an azimuth angle range of $-50°$ to $50°$ and an elevation angle range of $-2.5°$ to $10°$. The calibration process involved a total of six flights conducted in two trials.

There're three flight in the first trial. The initial flight started from an elevation of $10°$, using a $5°$ grid in elevation. Subsequently, the second flight repeated the same flight path to cross-validate the measurements. The last flight began from an elevation of $7.5°$ with a $5°$ grid in elevation, making the flight path denser and providing coverage of the region below the horizon. However, during the first two flights, the ambient temperature of approximately $-25°C$, combined with windy conditions, caused the cal-pulser's battery to deplete rapidly within three minutes after take-off. Consequently, the data inside the SD card was corrupted due to the unstable power supply.

To address these challenges, additional thermal insulation foam was introduced outside the RFI enclosure, and a handwarmer was placed inside the foam to maintain the system's temperature during flight operations. With these modifications, the second trial was conducted in an ambient temperature of approximately $-30°C$ and wind speeds of around 2 m/s with gusts up to 10 m/s. Despite encountering a strong gust during the second flight, the team skillfully regained control, ensuring a safe completion of the flight. Notably, the flight paths of all three flights were accurately reconstructed with centimeter-level precision.

Comparing the drone calibration in the 2019–2020 season with this upgraded version, the flight path in 2022–23 season boasted a larger coverage area, denser grid lines, and smoother overall operation, as shown in Figure 6. As the calibration analysis is ongoing, we are optimistic about achieving superior results with these improvements. More detailed information about the TAROGE-M activity in the 2022–23 season can be found in [8].



(a) Flight path in 2019–2020 season. **(b)** Flight path in 2022–23 season

Figure 6: Comparison of the flight paths. The one in 2022-23 season cover more field of view with a denser grid line.

4. Photogrammetry survey of antenna array

In addition to the drone-borne cal-pulser, we further investigate the application of the drone and the D-GPS on the photogrammetry. Photogrammetry is a technique that uses 2D photographs to create 3D models of objects and environments. The process involves capturing photos in the field and then post-processing them in the lab to reconstruct a photogrammetric model. The process automatically or manually identifies common features in multiple images as tie points and then solves triangulation among these tie points to compute their positions and the camera's position in 3D space. Figure 7 shows the photogrammetric model of the TAROGE-M station taken in 2022–23 season. This approach enabled faster surveys of multiple points simultaneously, significantly reducing personnel exposure time, particularly in challenging high mountain and polar environments [5]. As a result, we apply this method in the survey of TAROGE-3,4 in Taiwan and TAROGE-M in Antarctica.

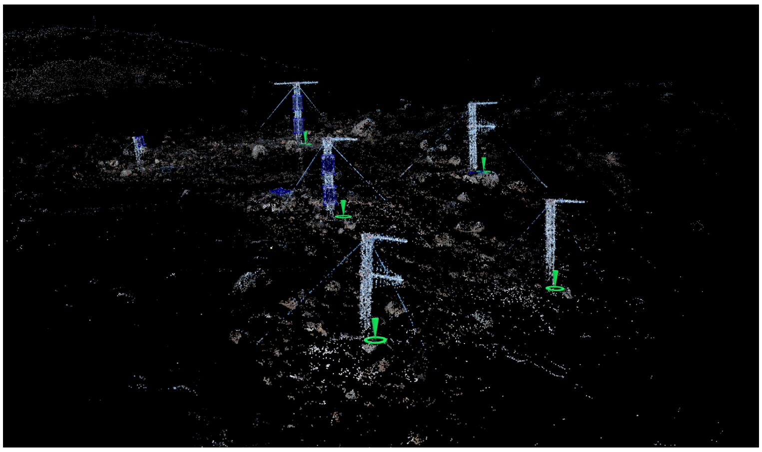


Figure 7: Photogrammetric model of TAROGE-M station taken in 2022–23 season. The colored point, called tie point, is a common feature seen in at least three photos. In this photogrammetric model, there are about 54000 tie points. The green markers indicate the GCPs that constrain the scale and orientation of the model.

4.1 Aerial photogrammetry with the drone

Photogrammetry involves capturing photos using either a hand-held camera or a drone for surveying antenna arrays. The hand-held camera takes horizontal photos with a lot of featureless sky, while drone-captured photos are taken from an inclined angle, providing a better view of the antenna array and ground with more features. Having more features in the photos reduces the effort to label tie points between them. Therefore, photogrammetry with drones simplifies post-processing and increases the success rate of building accurate models. Moreover, photogrammetry surveys can be conducted swiftly, with TAROGE-2 taking only 25 minutes for three towers and TAROGE-4 taking 30 minutes for four towers, both achieving millimeter accuracy compared to theodolite measurements.

4.2 Constrain absolute scale and orientation using D-GPS measurement

In photogrammetry, the initial model lacks scale and orientation. To address this, Ground Controlled Points (GCPs) are applied to establish absolute scale and orientation in the model. GCPs are specific tie points in the model with known real-world coordinates (often obtained through GPS measurements like latitude, longitude, and altitude). While a minimum of three GCPs is recommended, having more GCPs further enhances the accuracy. Applying multiple GCPs enables the photogrammetry software to effectively compensate for scale variations and orientation discrepancies, aligning the GCPs with their real-world coordinates [10]. Consequently, this process leads to the generation of more precise, realistic, and geographically referenced 3D models.

The dual-band D-GPS of the cal-pulser enables precise determination of Ground Controlled Points (GCPs) coordinates, thanks to its rapid convergence time. The system can be detached from the drone, and its GPS antenna is used to measure GCP coordinates, significantly reducing field time and required equipment. This method was successfully applied to model the TAROGE-M system during 2022–23 season, with the survey campaign conducted immediately after drone pulser calibration on the same visit. Capturing photos of 6 towers with a handheld camera took approximately 30 minutes, while an additional 15 minutes were allocated for measuring 5 GCPs. The accuracy of the resulting scaling uncertainty, validated using the length of the LPDA boom, was 0.63 mm. The orientation uncertainty of the model, validated using summits of distant mountains within the field of view, achieved an accuracy of 0.08 degrees in azimuth and 0.05 degrees in elevation. These results show the practicality of photogrammetry combined with GCP measurement using the pulser module as an effective survey method in the field.

5. Conclusion

The performance of the drone-borne cal-pulser system has improved this year with the incorporation of a more stable and accurate dual-band D-GPS module. During the 2022-23 season, the system was effectively applied in the TAROGE-M project in Antarctica, leading to broader and denser coverage within its field of view compared to previous seasons. As a result, better calibration results are expected. Additionally, our investigations into photogrammetry using the existing drone and D-GPS module can apply to accurate survey of antenna array, with precise reconstructions of the model down to millimeter scale and 0.01° orientation accuracy. These promising findings affirm the feasibility of utilizing drone-borne techniques not only for the TAROGE experiment but also for other radio detectors like IceCube-Gen2.

6. Acknowledgement

We gratefully acknowledge the financial support in the TAROGE-M project from the National Science and Technology Council (NSTC) for their grant 111-2112-M-002-034. We would like to express our sincere appreciation to the Korea Polar Research Institute (KOPRI) for their exceptional logistical and in-ice field support in 2018–2019, 2019–2020, and 2022–23 seasons.

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