6A.3

# CHALLENGES OF COMBINING REMOTE SENSING WITH IN-SITU MEASUREMENTS IN AIRBORNE SCIENCE AND ENGINEERING: A LOW-SWAP AIRBORNE RADAR SOLUTION

Jakob Fusselman*, Yan (Rockee) Zhang*, William Blake**, Mariusz Starzec**, Robert Miller***, Greg M McFarquhar**** and Steven D Harrah***** *

*Intelligent Aerospace Radar Team, Advanced Radar Research Center (ARRC), University of Oklahoma

**Garmin International, Inc., Olathe, KS

***Skydweller Aero, Inc;, Oklahoma City, OK

****Cooperative Institute for Severe and High Impact Weather Research and Operations, University of Oklahoma

*****NASA Langley Reseach Center, Hampton, VA

## 1. INTRODUCTION

Airborne weather radar as a remote sensor is extremely important for both scientific observations and aviation safety. Calibration of airborne radars has been done extensively by comparing them with ground radars. Recently, motivated by the challenges of verifying critical cloud physics models and developing radar standards for the high-ice-water-content (HIWC) detection, more flight operations combining forward-looking X-band radars with microphysical probes have been performed by NASA. This has initiated integrating radar and probe measurements at similar locations for modeling and verification. This operation was ground-breaking, but limited by the capability of the airborne radar used in the flight mission. As a follow-on effort of this verification operation, the Intelligent Aerospace Radar Team (IART) at the University of Oklahoma is developing a dual-polarized version of the forward-looking radar in collaboration with Garmin International, called PARADOX 1.5. PARADOX 1.5 can be installed on different existing aircraft platforms equipped with atmospheric probes and imagers. It uses a small, low-cost aperture with dual-polarization and can generate basic dual-polarized weather radar moment products in the required ranges. Although PARADOX 1.5 is suitable for joint remote-in situ missions in the near term, the newer version of the system, PARADOX 2.0, would use an electronic-scanning, low-cost, polarimetric phased array antenna as its RF aperture. This publication provides the current data collection from initial PARADOX ground tests, its multi-mission potential, and the concept designs for further improvement.

## 2. COMBINING IN-SITU AND REMOTE SENSING MEASUREMENTS IN AIRBORNE SCIENCE

An increasing call for combining in-situ measurements and remote sensing in airborne meteorological science has been evident in recent years. The in-situ measurement sensors support validation of radar measurements, especially the airborne radar measurements, and provide a microphysical basis for radar sensing modeling (Shrestha et al. (2023)). Joint in-situ and radar measurement also enhance the overall amount of features that can be used to support aviation safety. The radar sensing provides large airspace coverage that is not feasible to cover by a single aircraft. Part of the motivation is based on the studies of cloud physics, with the focus on ice particles or icing conditions, with direct application in aviation safety (RTCA (2018)).

There are two types of system solutions. One includes centralized, large aircraft and high-performance radar systems, such as APAR (Yaklich and Leifer (2022)) or NASA's DC-8 (Harrah et al. (2019)), another is distributed, small aperture, low-cost systems based on commercial air-platforms. Both system solutions support simultaneous measurements of onboard probes and airborne radars. The former is preferred for high quality scientific data production and in-depth storm penetration, while it is highly expensive and limited to the capability of a single aircraft. The latter is severely constrained by aperture size and weight by the aircraft, so the data quality is limited. However, it is supported by a large volume of commercial aircraft and general aviation (GA) aircraft across the world. This study focuses on the latter based on these reasons: (1) low-cost, distributed apertures and platforms are favored by the industry such as current airborne weather radar OEM or airline users, (2) the key requirements from FAA and RTCA standards are for aviation hazard detection and avoidance, rather than scientific modeling or physics analysis, and (3) one of the future trends of commercial aviation are distributed aircraft networks that are mostly uncrewed, electrically-powered (which is also lightweight) (Rakas et al. (2021)), and primarily focused on low to medium altitudes of airspace, which need a new generation of radar sensors onboard that are small, agile and multi-functional.

Nevertheless, there is still a lack of a practical airborne radar that is an upgrade of the existing commercial forward-looking radars for commercial aircraft that has the capability to fully support the latest DO-220B standards and enhance the capability of discriminating different types of hazards RTCA (2023). Polarimetric radar technology is a natural option and has been proven for ground-based radars (Ryzhkov and Zrnic (2019)), but due to the high cost and lack of verification in the data quality, its adaption has been a slow process.

This paper intends to introduce a low-C-SWaP (Cost, Size, Weight and Power), dual-polarized, X-band airborne radar concept and prototypes as an update of the latest effort to fill the above gaps. This system concept has been discussed in a previous publication (Shrestha

* *Corresponding author address:* Intelligent Aerospace Radar Team, Advanced Radar Research Center, 3190 Monitor Ave, Norman, OK 73071; E-mail: UAS@ou.edu.

et al. (2022)), but this is the first time that some of the initial polarimetric measurements are presented. Note that the system prototype presented here is only for proof of the basic system concept, and it is still being updated. It is not considered to be a final product for either scientific or navigational missions.

## 3. REQUIREMENTS AND OPERATIONAL SCOPE OF PARADOX

### *3.1. Concept of Operations*

The ultimate goal is to demonstrate a low-cost (lower than existing airborne weather radars), dual-polarized, dual-function (Detect-and-Avoid and weather avoidance) radar sensor that is suitable to be deployed on a long-endurance unmanned aerial vehicle being developed by Skydweller Aero, Inc (SKD). The sensor will be installed at the nose area of the aircraft, and can be configured to support other missions such as search and rescue, surveillance, and imaging. The motivation of applying dual-polarization techniques is based on the new RTCA requirements related to DO-220B, in which either pulse-to-pulse signal power variations or dual-polarization are considered as options for future ice detection capabilities (Shrestha et al. (2023)). The instrument can certainly make use of other aircraft platforms as well.

Figure 1 shows an example of the concept installation of PARADOX 1.5 on the nose of the SKD aircraft.

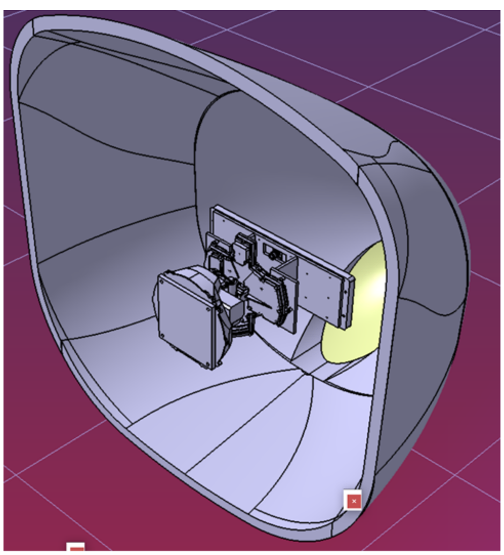

Figure 1: Mechanical drawing of PARADOX installation

### *3.2. Test System Parameters*

The test system is developed for proving the concept of polarimetric radar measurements based on ground tests. A low-cost, commercial grade dual-polarized array antenna, which has a single broadside beam, was used for the experiments. The antenna operates from 9.2 to 9.6 GHz frequency band, has approximately a $5^\circ$ (3 dB) azimuth beamwidth and approximately a $40^\circ$ (3 dB) elevation beamwidth (depending on the polarization channels). The one-way cross-polarization isolation was up to 35 dB in the main beam direction. Naturally, a major concern is the wide elevation beamwidth, which can lead to sampling volumetric mixing behavior from different species of the hydrometers from the stratified atmosphere. However, since the main purpose is proving the feasibility of polarimetric measurement with the C-SWaP constraint, the antenna is the best compromise at the current stage.

Table 1: PARADOX 1.5 Parameters

| Radar Parameter | Value |
|---|---|
| Antenna Size | 10 in. |
| Transceiver Diameter | 8 in. |
| Depth | 6.3 in. |
| Total Weight | <10 lbs. |
| Operating Frequency | 9.3 to 9.5 GHz |
| Antenna | Dual-pol ATAR |
| Field of View | $\pm 60^\circ$ Az |
| Transmitter | Solid-state 40 W peak |
| Beamwidth | $5^\circ$ Az, $40^\circ$ El |
| Scan Speed | PPI 4 sec, $\sim$3 sec RHI |

Basic link budget analysis of the system configuration parameters, for a single pulse and a 30 dBz weather target volume is shown in Figure 2. The analysis shows that we need to integrate 100 pulse returns to achieve the minimum detection capability at the 20 km range. This characteristic is further verified in the following data collection and processing, and can be certainly improved by using different antenna solutions.

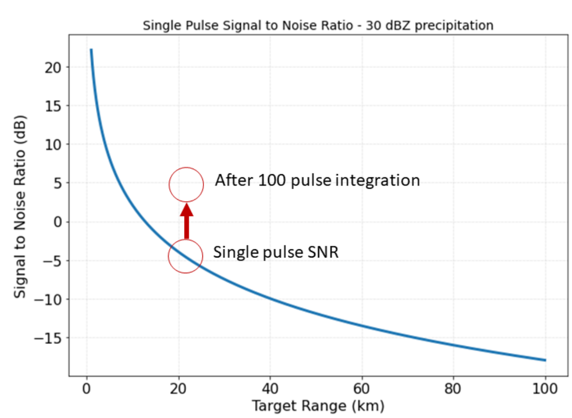


Figure 2: Basic system link analysis based on the PARADOX V1.5 test system parameters.

## 4. ENGINEERING DESIGNS

The engineering design is focused on a proof-of-concept system rather than a final product. The components currently used have minimized cost. These designs, however, are currently being upgraded, and will be updated in follow-on publications.

### 4.1. *Experimental Radar Sensor Structure*

The new dual-polarized antenna is interfaced with the existing GSX-70 airborne radar transceiver through customized RF frontend circuitry. The core of the frontend circuit is simply a switch controlled by a T/R sync signal coming from the T/R switching of the radar transceiver. This simple system structure is shown in Figure 3.

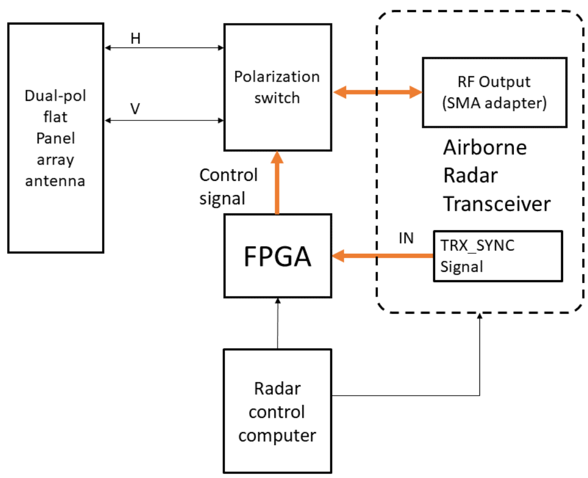


Figure 3: High level test system hardware architecture.

The system timing control, which is implemented using a low-cost FPGA, is depicted in Figure 4. Note this timing diagram is based on one specific setting of pulse width and PRF. The radar T/R sync signal triggers the timing signals to alternately switch between the H and V channels for both transmit and receive. The FPGA output timing signal is tuned carefully to allow for the rising/falling edge of transitions, as well as smooth transition of data collection.

### 4.2. *Resolution Considerations*

As a proof-of-concept and experimental system, the current PARADOX 1.5 system has spatial resolution limited to about $5^\circ$ in azimuth and $40^\circ$ in elevation. This limitation does not prevent us from evaluating the key dual-polarized data products and associated algorithms for airborne radars. Although the long-term solution would be a larger antenna aperture, there are some "super-resolution" solutions that are being tested at this stage.

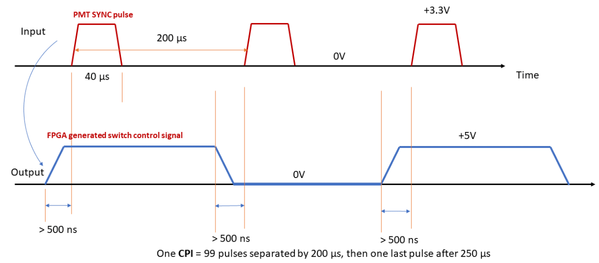


Figure 4: System Timing diagram.

### 4.3. *Backend and Overall System*

The complete V1.5 radar is shown in Figure 5. Each subsystem component of the test radar system is labeled in the photo. Using this rooftop test configuration, data collection during the Spring and Summer 2023 season has served as the main basis of the this presentation.

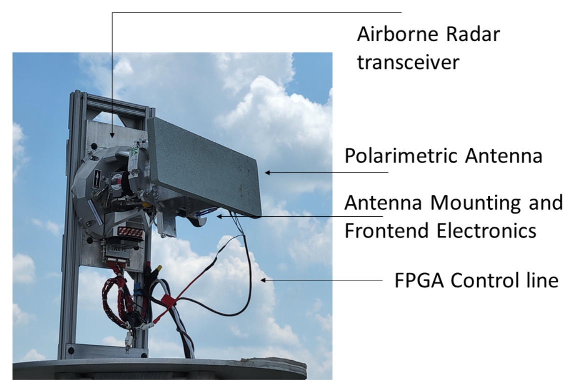


Figure 5: Photo of the complete radar sensor (roof test)

## 5. SIGNAL AND DATA PROCESSING OF PARADOX 1.5

The signal processing of PARADOX 1.5 follows similar schemes and algorithms as ground-based dual-polarized radars (Sachidananda and Zrnić (1989), Doviak et al. (2006)). The Alternate Transmit, Alternate Receive (ATAR) mode of processing is implemented by synchronizing the received data with the T/R switch. Currently, the data are saved to a host PC and later post-processed, but real-time data processing is under development.

## 6. INITIAL DATA ANALYSIS

The following example shows data collected from a weather event near Norman, OK on the evening of May 11, 2023. Figure 6 shows how we can draw comparisons between the data collected by NEXRAD (KTLX) and PARADOX by carving out the region of the NEXRAD scan that corresponds to the geographic region from which the PARADOX data was collected since PARADOX, being a much smaller radar built for a different purpose from NEXRAD, has a much smaller area of coverage. The two leftmost images in Figure 7 show a comparison between the reflectivity estimation of PARADOX and NEXRAD, and it can be seen that the general trends match quite well here despite the difficulty involved with getting the two scans to match up temporally. The center images of Figure 7 show differential reflectivity, and the rightmost images compare radial velocity. The radial velocity plots are difficult to compare, because the radars are not co-located so the observation angles are different. Spectrum width plots are shown in the leftmost images of Figure 8. There is reasonable agreement between these plots, showing the same general trends, which is to be expected. The center and rightmost images in Figure 8 show correlation coefficient and differential phase, respectively. The correlation coefficient plots show significant discrepancy, which is to be expected because the wide elevation beamwidth of PARADOX indiscriminately captures significant atmospheric stratification. The differential phase plots show similarities, but significant differences are also to be expected here due to a difference in transmit frequency and alternate vs simultaneous TR schemes.

## 7. NEXT STEP: PARADOX 2.0 AND DEPLOYMENT

Plans for future development of this system (PARADOX 2.0) include improvements to the antenna aperture which include a low-cost, custom, electronically-scanning phased array. It will also include the improvements to the data processing, especially specific differential phase (KDP), which is critical to HIWC detection. Real-time data processing is also under development. Planning for flight tests is on-going and we hope to begin flight tests of the current system on the Skydweller Aero's aircraft in the very near future.

## 8. CONCLUSION

The current status of PARADOX 1.5, a novel radar concept for airborne polarimetric observations, has been discussed. Initial results of ground-based tests of the current prototype instrument have been presented. It can be seen from the initial results that some promising data can be collected, despite limitations of the current antenna aperture. Now that the concept has been proved, further development is being conducted to improve the quality of the data being collected by the instrument. Additionally, plans for initial flight tests are underway.

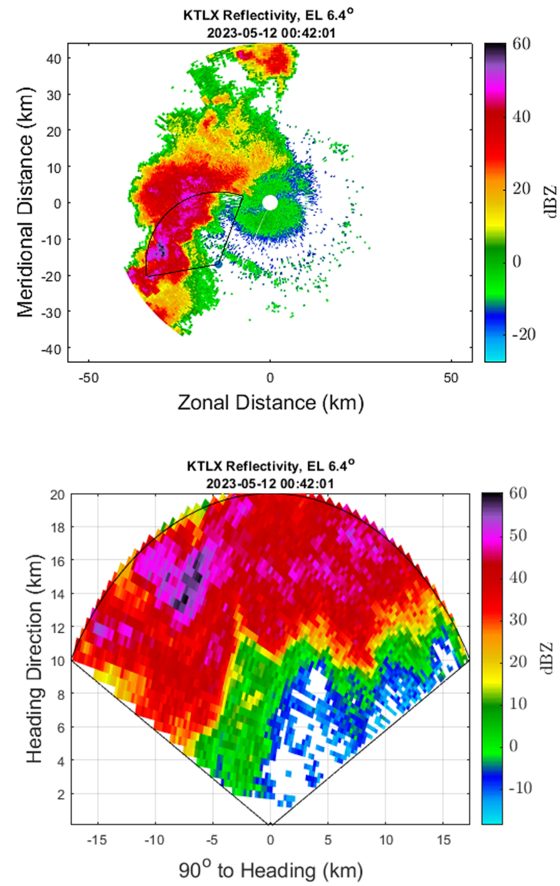


Figure 6: Preparation of the NEXRAD radar scan data for comparison.

*Acknowledgments.* We would like to acknowledge Morgan Lau, Hernan Suarez, and Brenden Wiley from the University of Oklahoma for their contributions to this project. Their efforts helped made this publication possible.

## REFERENCES

Doviak, R. J., and Coauthors, 2006: *Doppler radar and weather observations*. Courier Corporation.

Harrah, S. D., and Coauthors, 2019: Radar detection of high concentrations of ice particles-methodology and preliminary flight test results. Tech. rep., National Aeronautics and Space Administration (NASA).

Rakas, J., J. Jeung, D. So, P. Ambrose, and V. Chupina, 2021: evtol fleet selection method for vertiport networks. *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 1–10, doi:10.1109/DASC52595.2021.9594309.

RTCA, 2018: Minimum operational performance standards (mops) for airborne weather radar systems.

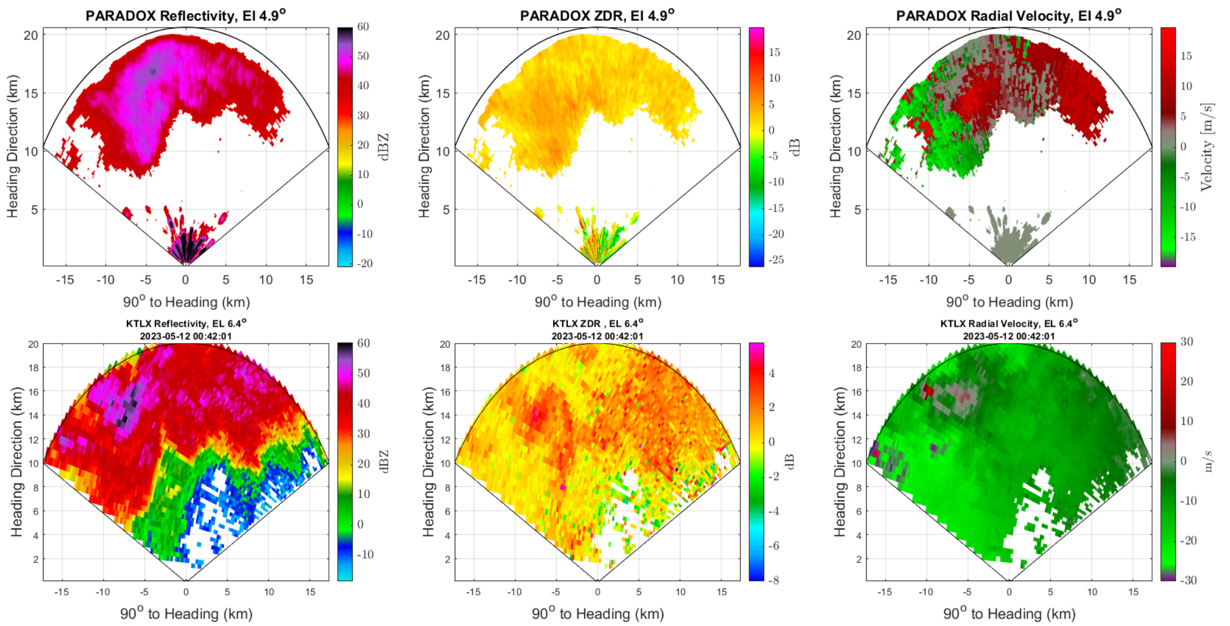


Figure 7: Comparison between PARADOX 1.5 scans and NEXRAD scan data for reflectivity (left), differential reflectivity (center), and radial velocity (right). PARADOX plots are top row, NEXRAD plots are the bottom row.

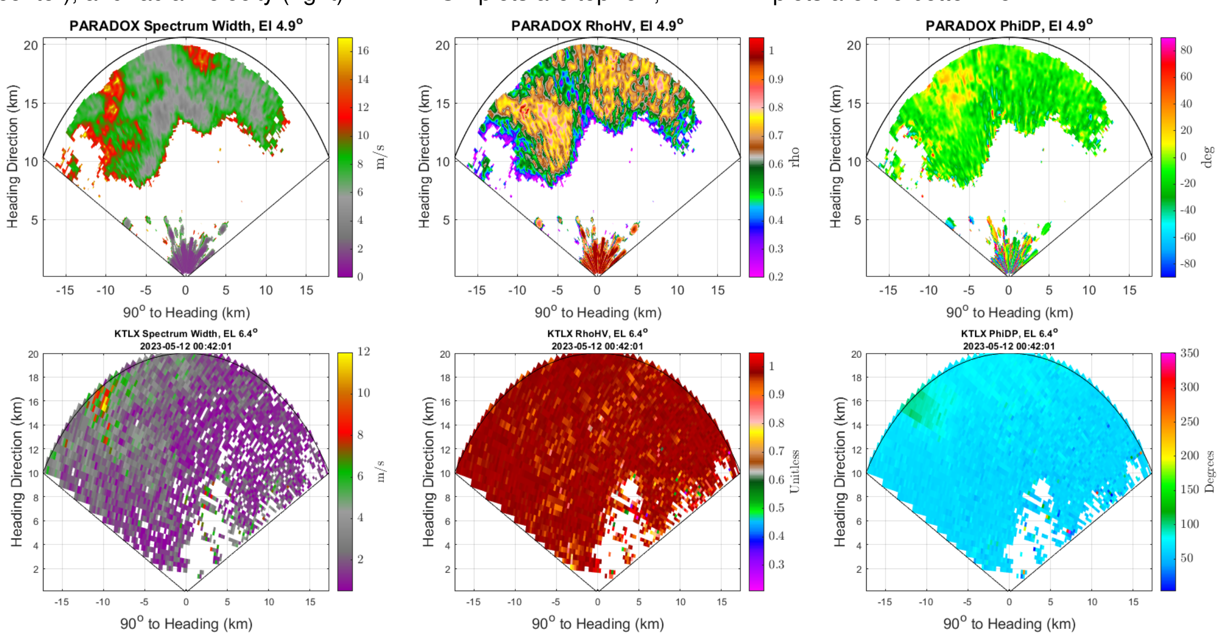


Figure 8: Comparison between PARADOX 1.5 scans and NEXRAD scan data for spectrum width (left), correlation coefficient (center), and differential phase (right). PARADOX plots are top row, NEXRAD plots are the bottom row.

Standard DO-220A, Radio Technical Commission for Aeronautics (RTCA), Washington DC. URL https://global.ihs.com/doc_detail.cfm?&csf=ASA&item_s_key=00201969&item_key_date=810414.

RTCA, 2023: Minimum operational performance standards (mops) for airborne weather radar systems. Standard DO-220B, Radio Technical Commission for Aeronautics (RTCA), Washington DC. URL https://www.rtca.org/products/do-220b-electronic/.

Ryzhkov, A., and D. Zrnic, 2019: *Radar Polarimetry for Weather Observations*. Springer, doi:10.1007/978-3-030-05093-1.

Sachidananda, M., and D. Zrnić, 1989: Efficient processing of alternately polarized radar signals. *Journal of Atmospheric and Oceanic Technology*, **6 (1)**, 173–181.

Shrestha, Y., Y. Zhang, J. Fusselman, G. M. McFarquhar, W. Blake, and S. D. Harrah, 2022: Potential application of paradox (polarimetric airborne radar operating at x-band) to high ice water content (hiwc) monitoring. *2022 IEEE Radar Conference (RadarConf22)*, 1–6, doi:10.1109/RadarConf2248738.2022.9764298.

Shrestha, Y., Y. Zhang, G. M. McFarquhar, W. Blake, M. Starzec, and S. D. Harrah, 2023: Development of simulation models supporting next-generation airborne weather radar for high ice water content monitoring. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **16**, 493–507, doi:10.1109/JSTARS.2022.3227124.

Yaklich, M., and M. C. Leifer, 2022: Airborne phased array radar (apar) program status & critical requirements analyses. *2022 IEEE Radar Conference (RadarConf22)*, IEEE, 1–4.