4th URSI AT-RASC, Gran Canaria, 19-24 May 2024

Assessing 94-GHz Radar Estimates in Polar Regions through the K2W Methodology

A. Bracci(1), K. Sato(2), L. Baldini(1) and H. Okamoto(2)
(1) National Research Council of Italy, Institute of Atmospheric Sciences and Climate (CNR-ISAC), Italy
(2) Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-Koen, Kasuga, 816-8580 Fukuoka, Japan

Abstract

A methodology for estimating reflectivity and Doppler velocity at 94 GHz from K-band Doppler spectra collected by MRR and coincident disdrometer observations has been developed and tested in Antarctica using CloudSat overpass. This methodology, called K2W, is now evaluated in Artic, at the Ny Ålesund AWIPEV French-German research base using a co-located W-band. The three cases of snow precipitation analyzed highlight a fairly good performance of K2W.

1. Introduction

Precipitation, particularly in the form of snow, plays a crucial role in shaping Earth's hydrological cycle and energy budget, significantly impacting climate variability and sea-level rise. The Antarctic region, characterized by vast ice sheets, is a critical component of this global system. Therefore, understanding precipitation dynamics in Antarctica is essential for accurately modelling and predicting climate, but it brings unique challenges due to the complex nature of snowfall events, but also due to sparse ground-based measurements available.

Recent advancements in satellite observation technologies, namely the CloudSat NASA satellite equipped with a 94 GHz Cloud Profiling Radar (CPR) and the upcoming European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) EarthCARE mission whose payload includes a 94 GHz Cloud Profiling Radar (EC-CPR) with Doppler capability and a high spectral Resolution lidar, offer unprecedented opportunities for improving the knowledge of precipitation formation mechanisms in Antarctica and for quantifying precipitation at surface.

However, satellite precipitation estimates require careful calibration and validation activities that are particularly challenging over Antarctica due to ground clutter and the sublimation of snowfall affecting lower atmospheric levels. Validating satellite measurements necessitates ground-based research stations equipped with instruments for precipitation monitoring and for precipitation profiling. To ensure a fair comparison, an ideal validation site should include a radar profiler operating at the same frequency of the spaceborne radars (in this case W-band – 94 GHz). Unfortunately, potential validation sites are sparse in Antarctica, and some of them operates K-band radar profilers (e.g., the Metek Micro Rain Radar) rather than W-band radar. Stimulated by the availability of such K-band radars the K2W methods has been developed [1] to simulate reflectivity and Doppler measurements at 94 GHz using Micro Rain Radar spectra and co-located disdrometer data. This method was tested through a comparison between ground-based radar reflectivity (Ze) and spaceborne CPR reflectivities over Mario Zucchelli Antarctic Station during a CloudSat overpass, yielding promising results. However, direct comparisons between the K2W reflectivity and co-located ground-based W-band radar have not been conducted yet.

To address this gap, this paper utilizes data collected during three snowfall events at the Ny Ålesund Polar Station using co-located instruments (W-band radar, K-band radar, and disdrometer).

2. Site, instrumentation, and data

The data used in this paper have been collected during the winter/spring seasons 2018 at the AWIPEV French-German Arctic research base in the Norwegian archipelago of Svalbard, specifically in the village of Ny-Ålesund (from now on NyA) (coordinates 78.9N, 11.9E, 9m a.s.l.) that is positioned along the Kongsfjord, nestled near mountains that run parallel to the fjord from the northwest to the southeast [2]. The observations of 3 different snowfall events (7 February, 16 March and 16 April) are available through the Zenodo repository and contains measurements of the K-band MRR2 (Micro Rain Radar – Metek), the W-band radar MiRAC-A (from now on Mira) manufactured by RPG Radiometer Physics GmbH, and of the OTT-Parsivel disdrometer [3].

The MRR2 is a vertical profiling Doppler radar operating at the K-band (24 GHz). It generates Doppler power spectra across 64 bins within 32 vertical range bins. The instruments, thanks to low power consumption and robustness, is suitable for prolonged, unmanned deployment in remote areas [4]. MRR at NyA operates with a vertical resolution of 30 m and a temporal resolution of 1 minute [2]. This setup enables reliable measurements, free from clutter contamination, starting from the third range bin, just 30m above ground level (AGL). Routines from [5]

have been applied to enhance sensitivity. The Mira radar operating at 94 GHz, is configured with separate transmitting and receiving antennas. Its altitude coverage spans from ~100 m to a maximum of 12 km, with a vertical resolution of up to 3.2 m. For better alignment with MRR measurements, values are averaged over 1 minute [2].

Parsivel is an optical disdrometer manufactured by OTT GmbH that provide simultaneous measurements of the sizes and fall velocities of hydrometeors, categorized into 32 by 32 diameter/speed classes, that traverse the horizontal laser matrix spanning 54 cm² between the transmitter and receiver heads of the disdrometer [4]. Wind interference poses a significant challenge to disdrometer measurements in snow, and specific data analysis should be devoted to mitigating this issue [1, 4]

3. Methodology

To evaluate the effectiveness of the K2W, the following steps were undertaken using the data collected at NyA:

a) **Snow Particle Classification**: Snow particles were classified as either aggregate or pristine by comparing MRR radar reflectivity with radar simulations derived from disdrometer data and the DDA database [4].

b) **Velocity-Diameter Relationship:** Disdrometer data was analyzed to establish velocity-diameter relationships for the various snowfall events and different time windows[1];

c) **Application of K2W:** The K2W method was applied using MRR Doppler spectra, velocity-diameter relationships derived from disdrometer data, and the DDA scattering database, incorporating the snowfall particle classification obtained in step a);

d) **Comparison of Results:** The resulting K2W reflectivity values were compared with measured W-band reflectivity at the first reliable range gate (i.e., 90m AGL for MRR and 105m AGL for Mira).

By following these procedures, the effectiveness of the K2W methodology in estimating W-band reflectivity from K-band Doppler spectra under varying snowfall conditions was assessed.

4. Snowfall Classification

The scattering properties of ice particles change depending on the particle type, habit, density, and shape. One of the most crucial distinctions exists between particles formed through aggregation processes (referred to as aggregates) and single-crystal snowflakes (referred to as pristine). Following [4], one approach to snowfall classification involves comparing simultaneous observations of Ze_{MRR} and $Ze_{Parsivel}$ derived from disdrometer data. $Ze_{Parsivel}$ is calculated by combining the Particle Size Distribution (PSD) from the disdrometer with scattering properties from the Discrete Dipole Approximation (DDA) database [6].
Fig. 1a presents the results for the first studied snowfall event recorded in NyA. The upper panel displays the time series of Ze_{MRR} at the lowest range gate (90 m AGL) in black, alongside $Ze_{Parsivel}$ values calculated for aggregate particles (in red) and pristine particles (in yellow). The reflectivities measured by the disdrometer faithfully track Ze_{MRR}, irrespective of the observation height, except for two instances around 16:00 UTC. During these periods, Parsivel detects a minimal number of particles at ground level, resulting in very low radar reflectivities, while the MRR reflectivity remains relatively higher. The lower panel depicts density scatter plots between Ze_{MRR} and $Ze_{Parsivel}$ for aggregate (left) and pristine particles (right). A visual inspection indicates that the predominant falling particles during the snowfall on 7 February were formed by aggregate hydrometeors, leading to the utilization of this particle type for applying K2W.

Fig. 1b and 1c present the same analysis as Fig. 1a for the events of 16 March and 16 April. In both episodes, snow particle characteristics align with aggregate particles, with a more robust classification for 16 March due to the points in the scatter plot being clearly distributed along the bisector. The particle type classification for 16 April is less certain, as the combination of disdrometer and DDA fails to accurately mimic Ze_{MRR} for both aggregate and pristine snow types. However, when forced to choose between the two types, aggregate particles were associated with precipitation for that day.

5. Application of K2W

The MRR Doppler Spectra, velocity-diameter relationship, and DDA database have been employed in the applied K2W methodology for the case study under investigation. Fig. 2a, 2b, and 2c depict the outcomes of this conversion methodology for the three snowfall events and for a time window of 30 minutes [1]. It is important to note that the time window signifies the duration considered for deriving the velocity-diameter relationships from Parsivel measurements. It is well-known that several factors, with wind being the most significant, can adversely affect the reliability of laser disdrometer performance. Hence, utilizing appropriate time windows enhances the robustness of velocity-diameter retrieval, aiming to mitigate both changes in snowflake characteristics and strong winds leading variability in snowfall estimation by disdrometers. Each comparative plot includes time series of the measured MRR K-band reflectivity at 90 m AGL, the measured W-band reflectivity by Mira at 102 m AGL, and the converted W-band reflectivity at the height of the MRR through K2W. The conversion methodology appears to perform well, often accurately mimicking the W-band observations. However, K2W frequently fails to replicate the W-band reflectivity, with the reflectivities almost perfectly superimposed with Ze_{MRR}, indicating imperfect operation of K2W.

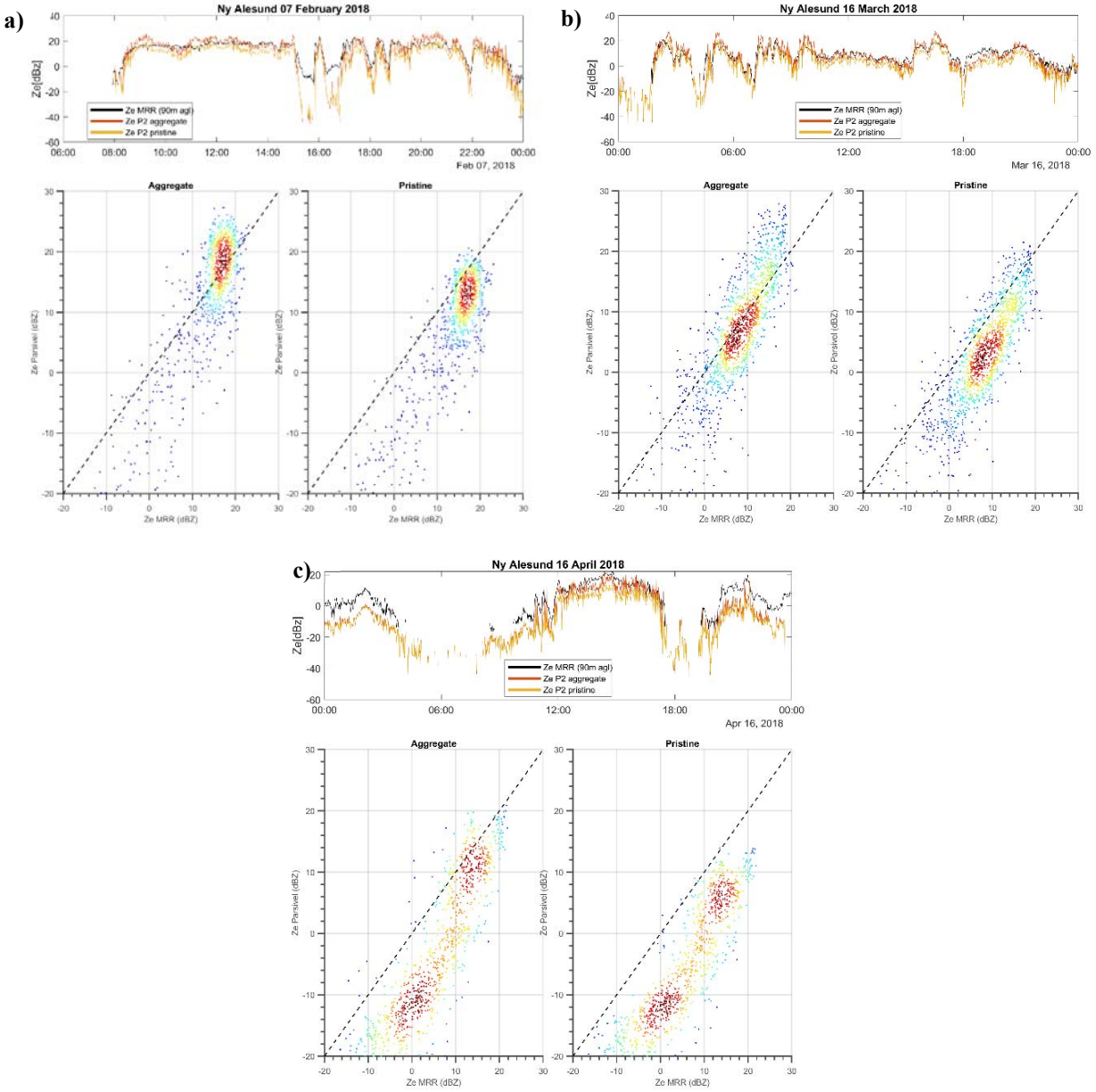

Figure 1 - For each plot a), b) and c) of the 3 snowfall events: in the upper plate the time series of Ze_{MRR} (black line) and derived $Ze_{Parsivel}$ using aggregate DDA particle model (red line) and pristine DDA particle model (yellow line) are depicted. The lower plate contains density scatter plots between Ze_{MRR} and derived $Ze_{Parsivel}$ using aggregate DDA particle model (left) and derived $Ze_{Parsivel}$ using pristine DDA particle model (right). Dots are colored according to the density of data (dark red = high density, dark blue = low density), whereas the dotted line stands for the bisecting line

We have thoroughly investigated this aspect, highlighting that two factors could have played a critical role: strong winds affecting Parsivel observations and calibration issues with the Mira. As previously mentioned, strong winds affect disdrometer measurements, leading to artifacts that can worse observations. This is why disdrometer observations have been carefully corrected both in the classification of hydrometeors [4] and in the K2W application [1]. Unfortunately, wind observations were not available for the NyA cases, and this aspect could not be further mitigated.

Instead, the possible calibration issue has been thoroughly investigated. A comparison between radar reflectivity of the Mira and radar reflectivity derived from disdrometer observations and DDA database for W-band has revealed a constant underestimation of the Mira values (not shown) for the 4 days considered. This is consistent with [7] which reports calibration offset values for Mira at NyA, of about 3 dB for the months of February, March and April 2018. Such value is consistent with what we have found in the Ze_{Mira} and $Ze_{Parsivel}$ comparison.

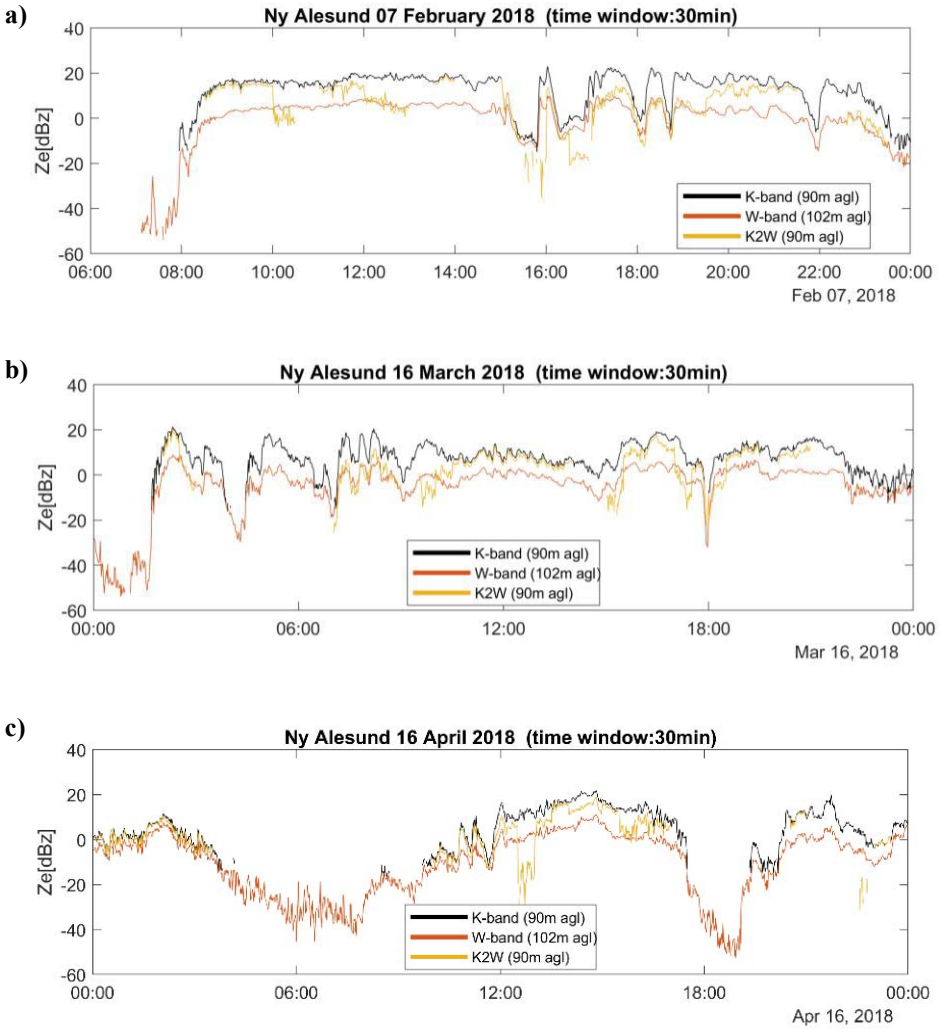

Figure 2 – Time series of radar reflectivity for the 3 case studies: the black line represents K-band reflectivity (Ze_{MRR}), the red line represents W-band reflectivity (Ze_{Mira}), and the yellow line depicts converted W-band reflectivity (Ze_{K2W}).

Hence, to properly test the K2W methodology, we have added a value of 3 dB to Mira reflectivity measurements. The final comparison between W-band Ze_{K2W} and Ze_{Mira} is reported in Fig. 3, which contains all data for the three snowfall cases using 30-minute time windows, as reported to be optimal for comparison [1]. Applying the correction significantly improved the correspondence. K2W values now correctly replicate W-band reflectivity probed by Mira, particularly for the lowest reflectivity values, but also for the higher values. However, for the most frequent values (dark red dots), K2W seems to overestimate radar observations, that could be linked to the not correction of disdrometer data.

6. Conclusions

Satellite observations from missions like CloudSat and EarthCARE, equipped with W-band CPR, are crucial for global precipitation estimation due to their ability to cover vast areas. A key aspect of satellite missions is the validation and calibration of measurements, which relies on independent measurements typically collected by ground-based observational sites. These sites are sparse in harsh environments like the Antarctic continent. Since several stations in Antarctica are equipped with a MRR K-band profiler and a disdrometer, the K2W methodology enhance the opportunities to validate 94 GHz radar measurements. K2W simulates W-band profiles using K-band Doppler Spectra and v(D) relationships from disdrometer observations leading to direct comparison with CPR data. The effectiveness of K2W is evaluated against a ground-based W-band radar in Ny Ålesund, building upon the original comparison conducted during a CloudSat overpass over the Mario Zucchelli Station in Antarctica.

Results indicate that even if disdrometer data could not be corrected for wind artifacts (as recommended by K2W), the comparison between Ze_{K2W} and Ze_{Mira} at the first exploitable range gates shows promising results provided that the Mira calibration issue is addressed, demonstrating the feasibility of K2W, which should be further tested with a longer dataset and refined for continuous improvement.

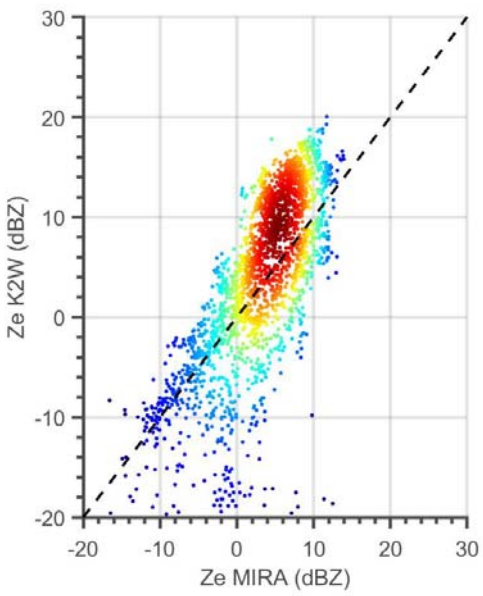

Figure 3 – Density scatter plot between Ze_{Mira} at 102 m a.g.l. (after calibration correction) and converted Ze_{K2W} at 90 m AGL. Dots are colored according to the density of data (dark red = high density, dark blue = low density), whereas the dotted line stands for the bisecting line

7. Acknowledgements

This study received partial support from the Antarctic Precipitation Properties (APP) project, funded by the Italian National Antarctic Research Program (PNRA). K.S. acknowledges support from The Japan Aerospace Exploration Agency [EORA3]; JSPS [KAKENHI grants JP22K03721, JP17H06139]; Shiseido Female Researcher Science Grant; Initiative for Realizing Diversity in the Research Environment and the Collaborative Research Program of the Research Institute for Applied Mechanics, Kyushu University (Fukuoka, Japan).

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