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EarthCARE Doppler Velocity validation using ACTRIS ground-based cloud radar network

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Abstract. The Earth Cloud, Aerosol, and Radiation Explorer (EarthCARE), launched in May 2024 by ESA and JAXA, carries the first spaceborne Doppler cloud profiling radar (CPR) capable of providing global observations of hydrometeor vertical motion. The retrieval of Doppler velocities from space is technically challenging due to satellite motion–induced spectral broadening, non-uniform beam filling, low signal-to-noise ratios, and antenna mispointing. In this study, we evaluate EarthCARE CPR Level-1b (L1b) and Level-2a (L2a) uncorrected and best estimate Doppler velocity products during the first 18 months of the mission (June 2024–November 2025) using ground-based cloud radar observations from the European Aerosol, Cloud, and Trace Gase Research Infrastructure (ACTRIS) network. Ground-based measurements are forward-simulated with an orbital radar simulator to ensure geometric and sampling consistency with the CPR, enabling a harmonised, profile-based comparison across multiple sites in Europe and the polar regions.

After applying a harmonised preprocessing and filtering procedure to ensure dataset consistency, systematic Doppler velocity biases are quantified for individual overpasses and statistically across sites. The uncorrected L1b and L2a Doppler products exhibit biases that correlate with the ESA antenna mispointing estimate, confirming the dominant contribution of this effect. In contrast, the L2a best-estimate Doppler velocity product effectively mitigates these biases. For sites with sufficient overpass sampling for robust statistics, including Ny-Ålesund, Lindenberg, Jülich, and Neumayer Station, the median residual bias of the best-estimate product ranges from $-0.05\ \mathrm{m\,s^{-1}}$ to $0.01\ \mathrm{m\,s^{-1}}$, well within the mission requirement of $0.1\ \mathrm{m\,s^{-1}}$. Sensitivity analyses indicate only a weak dependence of the retrieved bias on spatial collocation distance (≤ 100 km) and temporal averaging window (± 30 min).

These results demonstrate the robustness of the EarthCARE CPR Doppler velocity retrieval following application of the L2a correction scheme and confirm the suitability of the ACTRIS cloud radar network for long-term validation. The validated performance of the L2a best-estimate product provides confidence in the use of EarthCARE data for global investigations of cloud dynamics and hydrometeor vertical velocity climatologies.

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1 Introduction

The Earth Cloud, Aerosol, and Radiation Explorer (EarthCARE) mission, jointly developed by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), was launched on 28 May 2024 (Illingworth et al., 2015). Its primary objective is to improve our understanding of the interactions among clouds, aerosols, precipitation, and radiation, and their roles in the Earth's energy budget. To achieve this, EarthCARE carries four co-aligned instruments: the Cloud Profiling Radar (CPR), the high-spectral-resolution lidar (ATLID), a Multispectral Imager (MSI), and a Broadband Radiometer (BBR) (Wehr et al., 2023). Together, these instruments provide vertically resolved cloud, aerosol, and precipitation properties along with co-located radiative fluxes on a global scale.

The CPR operates at 94 GHz (W-band), the same frequency used by a previous cloud radar satellite mission (CloudSat) (Tanelli et al., 2008; Stephens et al., 2008, 2018). It achieves a minimum detectable reflectivity of -35 dBZ at 20 km and throughout the troposphere. The transmitted pulse length and oversampling yield an effective vertical resolution of 100 m. Compared with earlier spaceborne radars, EarthCARE's CPR exhibits enhanced sensitivity, finer vertical sampling, and reduced surface clutter (Illingworth et al., 2015; Burns et al., 2016; Lamer et al., 2020).

A key novelty of EarthCARE's CPR is its ability to measure Doppler velocity, making it the first spaceborne radar to provide global observations of hydrometeor vertical motion (Illingworth et al., 2015; Wehr et al., 2023). These measurements offer new opportunities to investigate cloud microphysical processes and to derive global climatologies of hydrometeor terminal velocities (Lamer et al., 2020; Battaglia et al., 2020a; Kollias et al., 2022).

Retrieving accurate Doppler velocities from space, however, is particularly challenging. The high orbital velocity of the platform ($\sim 7.6\,\mathrm{km\,s^{-1}}$) induces substantial Doppler spectrum broadening (Kobayashi, 2002; Tanelli et al., 2005), which increases measurement uncertainty and may introduce biases, especially under low signal-to-noise ratio (SNR) or non-uniform beam filling (NUBF) conditions (Illingworth et al., 2015; Battaglia et al., 2020b; Kollias et al., 2020). Additional uncertainties arise from small mispointing errors of the antenna, which can lead to systematic Doppler biases if uncorrected (Tanelli et al., 2005; Battaglia and Kollias, 2015). The CPR Level-2 (L2) processing chain therefore applies a set of dedicated corrections—including NUBF mitigation, spatial averaging, and continuous antenna pointing adjustment—to derive quality-controlled Doppler velocity estimates (Kollias et al., 2023; Puigdomènech Treserras et al., 2025).

Given these complexities, independent validation of EarthCARE's Doppler velocity products is essential. This includes the assessment of Level-1 (L1) measurements and the evaluation of the corrections applied in the L2 processing chain.

A suitable reference framework for such validation efforts is provided by the Aerosol, Clouds and Trace gases Research Infrastructure (ACTRIS) (Laj et al., 2024). The ACTRIS cloud remote sensing network comprises 24 permanent stations, primarily in Europe but also in the Arctic (Ny-Ålesund), Antarctica (Neumayer Station III), the tropical Atlantic (Mindelo), and the southern Indian Ocean (Maïdo Observatory), see Figure 1. Each site operates a suite of ground-based remote sensing instruments, including Doppler cloud radars, microwave radiometers, Doppler lidars, and ceilometers. The diversity of these systems enables the generation of synergistic cloud products such as the Cloudnet target classification (Illingworth et al., 2007;

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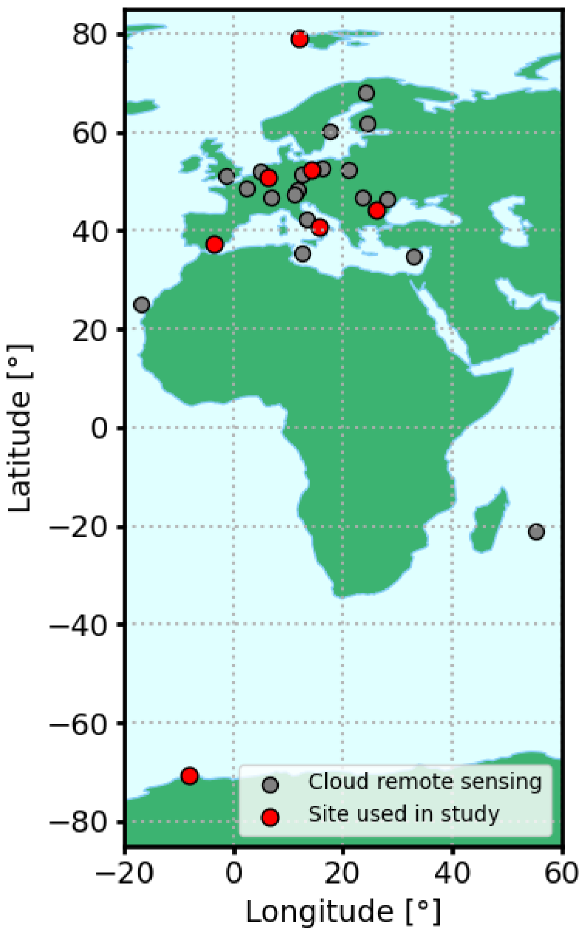

Figure 1. Map of the ACTRIS network of cloud remote sensing sites. Sites from which data are analysed during this study are displayed in blue

Tukiainen et al., 2020). The geographical coverage, standardised processing, and continuous quality control of ACTRIS make the network an ideal benchmark for validating EarthCARE CPR Doppler velocity retrievals.

In this study, cloud radar observations from the ACTRIS network are used to evaluate EarthCARE CPR L1 and L2 Doppler velocity measurements and the effectiveness of the applied corrections, adapting the method of Protat et al. (2010) across seven sites of the network. Section 2 describes the satellite and ground-based datasets. Section 3 outlines the methodological considerations made in the development of the Doppler velocity comparison algorithm. Finally, Section 4 provides the results of a case study and the CPR–ACTRIS comparison across the entire network. This section also provided a short discussion of the averaging and distance-to-site relation.

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2 Dataset description

In this section, we present the ground-based and satellite datasets on which our comparisons are based, and we introduce the products relevant to our study.

2.1 EarthCARE CPR L1b and L2a products

The validation of the EarthCARE Doppler velocity products includes two main aspects. Firstly, the validation of Doppler velocity measurements and secondly, the validation of the antenna mispointing correction reported in Puigdomènech Treserras et al. (2025). This validation is performed using EarthCARE L1b (CNOM) and the corresponding uncorrected Doppler velocity from ESAs L2a product (C-CD). Table 1 provides an overview of the EarthCARE products used and the corresponding acronyms.

The two products differ in their vertical integration along-track: $0.5\ \mathrm{km}$ for CNOM and $1.0\ \mathrm{km}$ for C-CD. Moreover, the noise in the CNOM product is separated from the signal using a reflectivity threshold $Ze_{noise} = -32.5\ \mathrm{dB}Z$. In addition, both products have a vertical resolution of $100\ \mathrm{m}$ created by an five times oversampling of the $500\ \mathrm{m}$ pulse of EarthCARE's Cloud Profiling Radar (CPR) (Kollias et al., 2014; Illingworth et al., 2015; Wehr et al., 2023).

Due to uncertainty and biases, under low signal-to-noise ratio (SNR) in the CPR Doppler velocity data (Battaglia et al., 2020b; Kollias et al., 2020), all datasets are again cut at an SNR-related threshold, $Ze_{SNR} = -21.\ \mathrm{dB}Z$ (Kollias et al. (2022) suggested a threshold of $Ze_{SNR} = -15.\ \mathrm{dB}Z$ but the first results and discussions in the community and during the EarthCARE workshops showed that it can be lowered down to $Ze_{SNR} = -21.\ \mathrm{dB}Z$). This threshold guarantees that uncertainties do not dominate the Doppler velocities used for validation.

The L1b C-NOM products used in this study are from the DA baselines. If this baseline was not available, a corresponding product from the CA-to-CD baseline is used instead. For the L2a C-CD products, we use baseline BA. These two baselines are selected because they are the latest baseline where all the data from the beginning of the mission were reprocessed. They are thus supposed to present an homogeneous dataset and to be the ones with the most available data.For a detailed description of the changes in the processing baseline, read the disclaimers at (European Space Agency (ESA), 2026a). In addition, the older

Table 1. List of EarthCARE data used in this study.

EarthCARE product level: name	acronym	resolution	description
C-NOM: Doppler Velocity	v_{L1}	0.5 km	L1b Doppler velocity direct CPR data without corrections
C-NOM: Radar Reflectivity Factor	Ze_{Sat}	0.5 km	L1b Radar reflectivity direct CPR data without corrections
C-CD: Doppler velocity uncorrected	v_{L2}	1.0 km	L2a Doppler velocity without correction
C-CD: Doppler velocity best estimate	v_{best}	1.0 km	L2a Doppler velocity best estimate corrections applied
C-CD: Doppler velocity pointing bias	$L2a_{\mathrm{MPB}}$	1.0 km	Antenna mispointing bias estimated by Puigdomènech Treserras et al. (2025)

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baselines do not include the antenna mispointing bias ($L2a_{\mathrm{MPB}}$) in the C-CD product (Puigdomènech Treserras et al., 2025). Puigdomènech Treserras et al. (2025) reported the $L2a_{\mathrm{MPB}}$ is related to the solar radiation hitting the CPR antenna. Therefore, the $L2a_{\mathrm{MPB}}$ varies for ascending and descending orbits (solar radiation hitting the CPR antenna is different for ascending and descending orbits) and over time, while the pattern does not repeat yearly. This leads to validation of separated orbits while the end statistics are performed for all orbits.

The data were analysed for a time period from the start of the mission in June 2024 until the end of November 2025. The data set was created using ESA's Multi-mission Algorithm and Analysis Platform (MAAP) portal (European Space Agency (ESA), 2026b), all data within a radius of $100\ \mathrm{km}$ were selected.

We would like to comment here that we were not able to download the full data set of overpasses for all the sites we wanted. The available data sets are dominated by ascending orbits, and at several sites no match could be found within the selected radii around the sites. Consequently, the analysis for some sites is limited, see section 4.2. We traced the issue down to incorrect geo-locations in the metadata, which occurred only in the EarthCARE's CPR data. These issues have been fixed in the latest baselines released after October 14, 2025. Older data will be corrected during the next reprocessing of the entire EarthCARE data set. This issue means that some data gaps exists in this study and will need to be addressed in the future. The final data used for the analysis are all the available data for which the nadir locations of the overpasses were within a radius of $100\ \mathrm{km}$ to the site.

2.2 The ACTRIS ground-based cloud remote sensing network

The ground-based radar data used in this study are provided by the ACTRIS Center for Cloud Remote Sensing (CCRES) and the Cloudnet Cloud Remote Sensing Data Centre Unit (CLU).

CCRES is an expertise centre responsible for overseeing calibration and operational procedures for all national cloud remote sensing facilities within the ACTRIS network. Its role is to develop robust quality control and data harmonization protocols, guaranteeing reliable and comparable data across all ACTRIS cloud remote sensing sites (Toledo et al., 2020; Jorquera et al., 2023; Feuillard et al., 2026; ACTRIS-CCRES, 2026). At the same time, CLU provides centralized data processing to generate multi-instrument observational and geophysical products, as well as tools for data access, quality control and long-term archiving. The processing software used for these large-scale operations is documented in detail by Tukiainen et al. (2020).

These services are essential for a heterogeneous network like ACTRIS, where cloud radars operate at either Ka- or W-band (35 GHz and 95 GHz, respectively) and originate from different manufacturers, having been installed at various times. Figure 1 shows the locations of the ACTRIS cloud remote sensing sites, with those used in this study marked in red. Table 2 provides the coordinates, radar type, Ze-offset between CPR and the ground radar, and overpass details for each site.

The gas and liquid attenuations of the ground observations are corrected by the ACTRIS network processing chain, we therefore assume the use of the best corrected radar products for our analysis and filter out data for which a correction was not possible.

The CLU product used in this study is the synthetic CPR product (Pfitzenmaier et al., 2025). It transforms ground-based radar data into CPR-comparable data by resampling the data using a function that accounts for the CPR's sampling geometry,

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following the EarthCARE CPR specification (CPR L1 data resolution is 100 m vertical resolution and 0.5 km horizontal resolution). This enables the use of similar datasets for the comparison of ground-based and spaceborne data. The synthetic CPR product takes into account the different additional disturbances coming from the satellite. Such effects are the platform motion and Doppler spectral broadening (Kobayashi, 2002; Tanelli et al., 2005), low signal-to-noise ratio (SNR) or non-uniform beam filling (NUBF) conditions (Illingworth et al., 2015; Battaglia et al., 2020b; Kollias et al., 2020) as well as mispointing errors of the antenna, which can lead to systematic Doppler biases if uncorrected (Tanelli et al., 2005; Battaglia and Kollias, 2015). We decided to not take these effects into account, the Doppler product used in this study can thus be regarded as an optimally corrected, noise-free CPR Doppler velocity obtained from ground-based radar observations. Other studies have shown that the right re-gridding or convolution method is key to compare data as best as possible (Pfitzenmaier et al., 2019; Lamer et al., 2020) because it directly affects the detectable signal as well as the cloud microphysical properties represented within the measurement volume.

As mention in Sect. 2.1 the satellite Doppler velocity data are cut at an SNR-related threshold of $Ze_{SNR} = -21.$ dBZ. To compare the ground and satellite Doppler velocities as effectively as possible the same threshold is to be used on ground data. However, the ground and CPR reflectivities are not necessarily calibrated the same way. To this end we evaluated a calibration offset for each site to correct the ground reflectivity values to best match the ones observed from the CPR. The Ze offset column from Table 2 contains these calibration offsets for each site using the method developed in Feuillard et al. (2026). The method consists in a statistical comparison of the ice cloud profiles reflectivities observed from the ground and from the satellite when passing in a 200 km radius from the site. From this data collection, height bins with the most statistical comparability are assessed. The satellite-ground offset and its uncertainty are then evaluated at these heights. Table 2 gives two values for the Lindenberg site, corresponding to a hardware and thus calibration change in July 2025. The evaluated Ze offsets are used to correct the ground reflectivities to be the closest to EarthCARE prior to the Doppler velocity cut at the $Ze_{SNR} = -21.$ dBZ threshold (see Sect. 3).

3 EarthCARE CPR Doppler velocity validation methodology

This section presents the processing of the satellite and ground-based radar observations as well as a harmonised pre-processing and evaluation strategy to ensure consistency between the datasets.

3.1 Satellite-based dataset: EarthCARE CPR

The satellite-based data set consists of observations from the EarthCARE CPR. Doppler velocities corresponding to radar reflectivity values below -21 dBZ were excluded, as their estimation exhibit an insufficient signal-to-noise ratio (SNR) below this threshold. EarthCARE L1 data are additionally noise-filtered using a reflectivity-based threshold; consequently, only observations of radar reflectivity (Ze) and mean Doppler velocity (V_m) satisfying

$$Ze_{sat} \geq Ze_{\text{L1-SNR}} \quad (1)$$

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Table 2. List of ACTRIS sites whose Doppler velocity data are analysed in this study from North to South. Given also the operating bands and reflectivity offset ($Z_{EarthCARE} - Z_{ground}$) calculated following (Feuillard et al., 2026). The last column shows the number of all overpasses during the analyzed time period within 100 km of the site, the CPR data available on MAAP (CPR), and the cases with ground-based data for comparison (combined).

Name site	Latitude [°]	Longitude [°]	Radar band	Ze-offset [dBZ]	Overpasses [all / CPR / combined]
Ny- Ålesund	78.923	11.922	W-band	-0.1 ± 1.4	499 / 275 / 204
Lindenberg before July 25	52.208	14.118	K$_a$-band	$+2.2 \pm 1$	172 / 41 / 15
Lindenberg after July 25	52.208	14.118	K$_a$-band	$+0.4 \pm 1.3$	60 / 14 / 5
Jülich	50.908	6.413	K$_a$-band	$+0.3 \pm 1.4$	223 / 55 / 33
Bucharest	44.348	26.029	K$_a$-band	-0.1 ± 1.2	113 / 2 / 2
Potenza	40.601	15.724	K$_a$-band	-0.5 ± 1.3	97 / 19 / 8
Granada	37.1640	-3.6050	K$_a$-band	-2.0 ± 1.3	114 / 38 / 17
Neumayer Station 3	-70.6600	-8.284	W-band	-6.2 ± 1.3	471 / 152 / 100

Both the reflectivity and Doppler velocity fields were subsequently examined for changes in the pulse-repetition frequency (PRF). Variations in PRF affect both the radar's vertical and Doppler velocity resolutions and were therefore accounted for during preprocessing.

To enable a meaningful comparison with ground-based observations, data segments corresponding to satellite overpasses of the ground-based radar sites were extracted. EarthCARE overpasses are selected when the minimum distance between the satellite nadir track and the ground site satisfied:

$$\Delta x \leq 100\ \mathrm{km}. \qquad (2)$$

All EarthCARE data available within a radius of 100 km around the ground sites of interest were thus retained for comparison. This window of selection is verified through the analysis presented in Sect. 4.3.

3.2 Ground-based data set: ACTRIS cloud radar

The ground-based observations were obtained from ACTRIS zenith-pointing cloud radar systems. To ensure comparability with satellite CPR measurements, ground-based radar data were forward simulated using the Orbital Radar tool (Pfitzenmaier et al., 2025). The simulation assumes a fixed horizontal wind speed throughout the troposphere of $v_h = 10\ \mathrm{m\,s^{-1}}$ and applies a vertical integration length of $x_{\mathrm{int}} = 500\ \mathrm{m}$. For the comparison, the noise-free, non-motion-influenced satellite-equivalent Doppler velocity field (v_{sat}), representing the best velocity estimate, was used.

Similarly to the satellite data, ground-based radar reflectivity values below $-21\ \mathrm{dB}Z$ need to be excluded to compare the same Doppler velocities from ground and satellite. However we need to ensure that the ground and satellite reflectivities are calibrated the same way before applying this threshold. As the calibration from the CPR is regularly monitored and stays con-

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stant it can be used as a reference to calibrate the ground radars. We thus evaluate a reflectivity calibration offset for each site, using the methodology developed in Feuillard et al. (2026), to get the calibrated ground based reflectivity ($Ze_{ground\ calibrated}$) (see Table 2). The ground-based Doppler velocities are thus filtered as follows:

$$Ze_{ground\ calibrated} \geq Ze_{\text{L1-SNR}} \tag{3}$$

The ground data are then selected in a $\Delta t = \pm 30$ min window around the overpass time of the satellite. The comparisons of CPR and ground Doppler velocities are statistical and are based on the mean Doppler velocity observations (v_m). It is then essential to have a sufficiently long time window of ground observations to build robust statistics. However, if the time window is too large, it could lead to observing very different Doppler velocities. We decided to use a time window of ± 30 min which is verified through the analysis presented in Sect. 4.3.

3.3 EarthCARE CPR and ground-based Doppler velocity comparison

The comparison between EarthCARE CPR Doppler velocity products and the ground-based radar observations was performed using vertically resolved mean profiles. These mean profiles are evaluated, for each overpass on the data selected using the $\Delta t = \pm 30$ min window for the ground data and the $\Delta x = 100$ km window for the CPR data. Profiles for the three variables of interest are evaluated in this study: v_{L1} for the L1 Doppler velocities, v_{L2} for the L2a uncorrected Doppler velocities and v_{best} for the L2a best-estimate Doppler velocity product.

Subsequently, Doppler velocity difference profiles $v_{\text{diff}} = v_m - v_{cpr\,product}$ are calculated between the ground-based mean profile (v_m) and each of the three CPR-derived profiles ($v_{cpr\,product}$ where $v_{cpr\,product}$ is v_{L1}, v_{L2}, or v_{best}). These different profiles are subjected to a two-step filtering procedure. First, values exceeding $\pm 2 \cdot \text{median}(v_{\text{diff}})$ are removed. This is introduced to remove outliers and liquid precipitation from the profile. Second, height bins are excluded if fewer than 5% of the maximum possible number of data points are available within the selected data set. A similar thresholding approach, using a 3% criterion for the total sampled data, was applied by Kim et al. (2025).

This filtering procedure effectively removes height ranges dominated by liquid precipitation, thereby retaining only the non-precipitating hydrometeor portion of the profiles for further analysis. As a result, known limitations and inconsistencies in both ground-based and satellite data sets are minimized. The resulting systematic offset between EarthCARE CPR Doppler velocities and ground-based observations is finally estimated as the median of the filtered Doppler velocity difference profiles.

Figure 2 presents an example of an EarthCARE overpass near the ACTRIS Ny-Ålesund site on 6 April 2025. The left column shows measurements from the ACTRIS zenith-pointing 94 GHz cloud radar (Küchler et al., 2017). The v_{sat} is forward-modelled with orbital-radar tool by Pfitzenmaier et al. (2025). The synthetic velocity serves as the reference dataset against which EarthCARE CPR observations are compared. The simulator convolves the ground-based radar measurements with the EarthCARE CPR antenna characteristics to enable a more consistent comparison.

The ground-based radar shows a stratiform cloud from 2.0 km till 5.5 km. For the EarthCARE measurements, in the middle column, the identical stratiform cloud is visible. In addition, in the EarthCARE observation low level clouds up to 1.5 km are

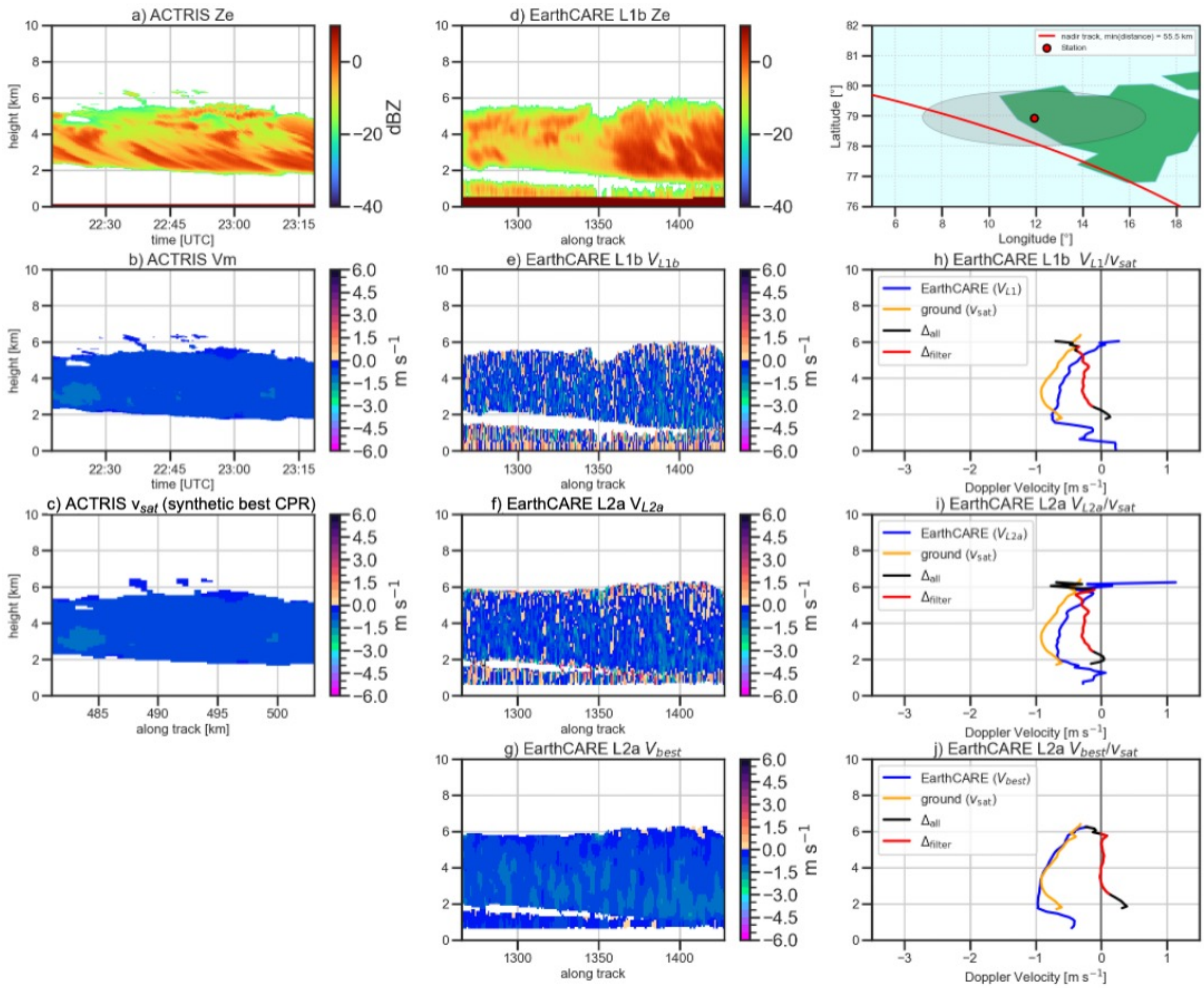

Figure 2. Overview of an EarthCARE overpass near the Ny-Ålesund ACTRIS site (6 April 2025, 22:47:48 UTC, EarthCARE frame 4870D; baselines: L1b = DA, L2a = BA). Left column: ground-based radar measurements, ±30 min around the overpass: a) reflectivity (Ze), b) Doppler velocity (Vm), c) synthetic CPR Doppler velocity (v_{sat}). Middle column: corresponding EarthCARE CPR measurements: d) L1b reflectivity above the L1 SNR threshold (Ze_{L1}), e) L1b Doppler velocity (V_{L1}), f) L2a uncorrected Doppler velocity (V_{L2}), g) L2a best-estimate Doppler velocity (V_{best}). Right column: Averaged Doppler-velocity profiles and corresponding bias profiles. The top map shows the Ny-Ålesund site (red dot), the 100 km radius around the site (grey shading), and the nadir ground track of EarthCARE (closest distance = 5.4 km). h)–j) show the median profiles of V_{L1}, V_{L2a}, and V_{best} relative to v_{sat}. Blue lines: EarthCARE, yellow: synthetic ground-based reference, black: full-profile differences, red: filtered ice-cloud differences.

present. The ground based radar at the Ny-Ålesund site did not measure exactly the same low level clouds as EarthCARE CPR

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because the satellite passed a few km away, over the open ocean. Hence, only the Doppler velocity measurements and products for the upper stratiform layer can be used for the validation.

The filtering removes areas affected by liquid precipitation and regions where Doppler velocity retrievals from both instruments are known to degrade. Only the filtered (red) section is used to estimate the bias via the median. This analysis is performed for each overpass where a comparison is possible.

For this example, comparing the median Doppler-velocity values yields the following results. The median of the Δ_{filtered} profiles shows a bias of $-0.26\ \mathrm{m,s^{-1}}$ for V_{L1}, $-0.25\ \mathrm{m,s^{-1}}$ for V_{L2}, and $0.02\ \mathrm{m,s^{-1}}$ for V_{best}. In the following section, the results are discussed. Furthermore, the influence of the track-to-site distance and the averaging time is elaborated.

4 Validation of CPR Doppler velocity

Here we discuss the results of the Doppler velocity validation. Data are analysed case-by-case and statistically to get a complete picture of EarthCARE CPR Doppler velocity performance. For the analysis, it is assumed that the ground-based radar Doppler velocity data are unbiased in a statistical domain.

4.1 Validation of ESA CPR Doppler velocity products for the single site of Ny-Ålesund

Figure 3 a) shows a time series of the validation results for the Ny-Ålesund site to the ESA EarthCARE CPR Doppler velocity products for ascending orbits. The descending orbit and the corresponding Doppler velocity information are shown in Figure 3 b).

In both a) and b) panels of Fig. 3 the comparison of the L1b CPR Doppler velocity with the ground-based cloud radars is shown as red stars. The blue line shows the estimated antenna mispointing bias (Puigdomènech Treserras et al., 2025). The difference between satellite and ground correlates with the estimated mispointing bias (red stars), indicating that the main source of bias in the Doppler retrieval comes from the mispointing error.

The yellow dots represent the comparison of the ESA EarthCARE L2a uncorrected Doppler velocity product with the ground-based radar. These comparisons are used as a self-consistency check of the method. The yellow dots and red stars are highly consistent with each other and overlap most of the time, which is the expected behaviour of these two products. The visible differences can be caused by the different along-track integration of the L2a products, which is $1\ \mathrm{km}$ instead of $0.5\ \mathrm{km}$ for the L1b. Before December 2024, the satellite was not fully stabilized; therefore, the spread between the estimated antenna mispointing and the uncorrected Doppler in L1b and L2a is larger than in later time frames.

This feature is also evident in the spread of the Doppler best estimates (blue crosses), which compare the ESA L2a best Doppler velocity product with the ground-based data. After December 2024, this comparison exhibits a smaller spread and the values are concentrated around the $0\ \mathrm{m\,s^{-1}}$ bias line. Before December 2024, the standard deviation of the $bias(L2a\ best)$ is $std(bias(L2a\ best_{DESC\ 24})) = 0.73\ \mathrm{m\,s^{-1}}$ for descending orbits and $std(bias(L2a\ best_{ASC\ 24})) = 0.89\ \mathrm{m\,s^{-1}}$ for ascending orbits. In contrast, after December 2024 the standard deviation of the bias is $std(bias(L2a\ best_{DESC\ 25})) = 0.67\ \mathrm{m\,s^{-1}}$ for descending orbits and $std(bias(L2a\ best_{ASC\ 25})) = 0.39\ \mathrm{m\,s^{-1}}$ for ascending orbits. These values shows a larger spread of

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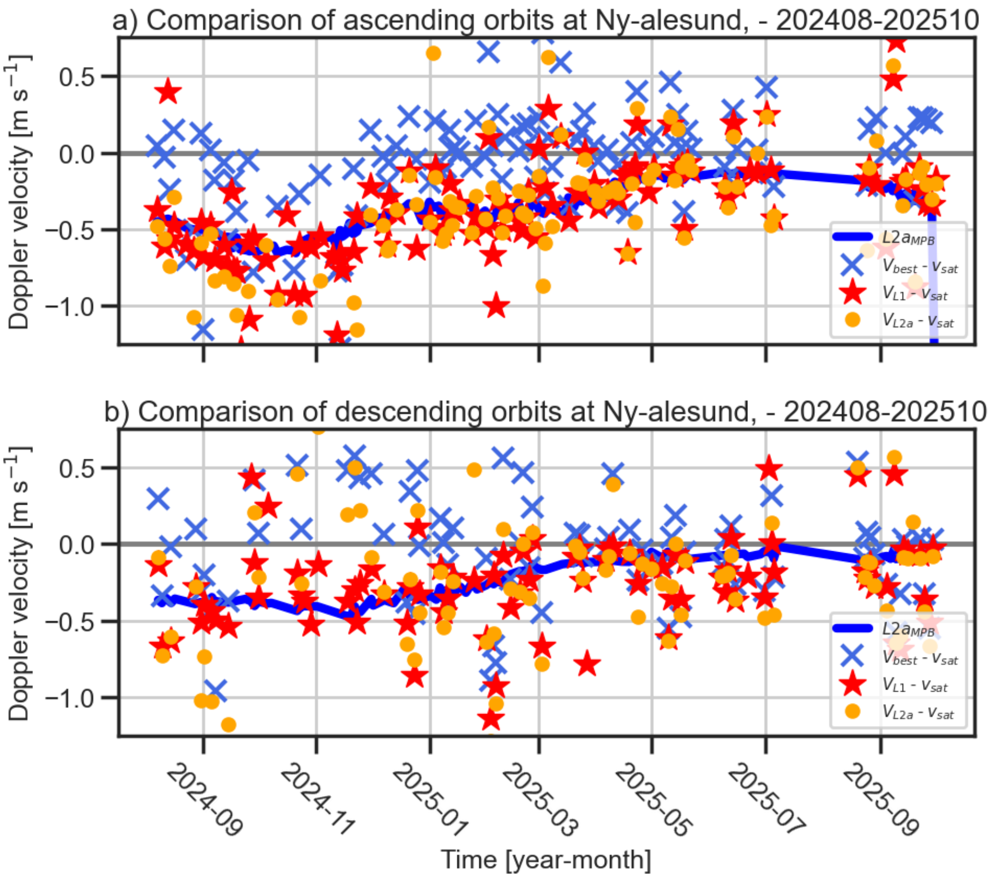

Figure 3. Time series of ESA EarthCARE Doppler velocity products for ascending orbits compared to the ground-based radar zenith pointing Doppler velocity at the ACTRIS site Ny-Ålesund, Svalbard, Norway. The blue line is the antenna mispointing correction as retrieved by (Puigdomènech Treserras et al., 2025), red stars are the median difference of the ground-based to CPR L1b Doppler velocity, yellow dots are the median difference of the ground-based to CPR L2a uncorrected Doppler velocity, and the blue crosses are the median difference of the ground-based to CPR L2a best estimated Doppler velocity product.

the bias before December 2024 as seen on Fig. 3 as we would expect from the stabilization of the satellite. Moreover the spread of the bias is far larger for $bias(L2a\ best_{DESC\ 25})$ than for $bias(L2a\ best_{ASC\ 25})$. This might be coming from the fact that less overpasses are used for descending orbits due to the data geo-locations problem mentioned in Sect. 2.1, making the statistics for the descending orbits is less robust.

4.2 Validation of ESA CPR Doppler velocity products using the ACTRIS network

Figure 4 summarizes the Doppler velocity biases derived from comparisons between the EarthCARE CPR and seven ACTRIS sites for the period from the beginning of the mission until 18 November 2025. The three panels show the comparison results

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between the ground data and one of the EarthCARE products. Panel a), shows the box plots summarizing the difference of EarthCARE L1b velocity V_{L1} to the ground based velocity, v_{sat}, for the selected sites. b) shows the difference of ESA EarthCARE L2a uncorrected Doppler velocity product V_{L2s} to the ground velocity measurements to the ground velocity measurements, v_{sat}, , and panel c) depicts the comparison between the ESA EarthCARE L2a best estimate Doppler velocity product, V_{best}, and v_{sat} (blue). The details of series of the analysed overpasses is also shown for the sites of Jülich and Potenza in Fig. 5, as done for the Ny-Ålesund site in Fig. 3.

These results for the ACTRIS network can be grouped by data availability. The sites of Ny-Ålesund, Lindenberg, Jülich, and Neumayer have a sufficient amount of matching satellite and ground-based radar data available to analyse the Doppler velocity, while the sites of Bucharest, Granada, and Potenza have too few overpasses for a robust comparison (see Table 2). The results from sites with fewer matching overpasses should therefore be interpreted with caution and are included here primarily to illustrate the limitations of the statistical approach used. As noted in Section 2.1, some sites have significant data gaps due to misclassified geolocation in the files. In addition, these sites are closer to the equator and therefore have fewer potential overpasses within the selected $\Delta x \leq 100\ \mathrm{km}$. This leads to the low number of cases where ground and satellite Doppler velocities could be compared. The Figure 4 a) and b) show, that the the antenna miss-pointing bias contribution is still on of the main sources of the Doppler velocity of the CPR. The increased along track resolution from EarthCARE L1b $0.5\ \mathrm{km}$ to $1\ \mathrm{km}$ for L2a does not show a significant influence on the biases. Only the antenna miss-pointing correction and as well as the other velocity corrections within ESAs EarthCARE L2a best estimate Doppler velocity product, V_{best} show biases around $0.1\ mathrmm\, s^{-1}$ when comparing to ground based data, v_{sat}, when the data coverage is sufficient.

Figure 5 a) shows the time series for ascending overpasses for the Jülich site. Despite the relatively small number of analysed overpasses (20 overpasses contained matching data), the statistics obtained demonstrate excellent agreement with ACTRIS data for V_{best} (blue crosses). In contrast, the uncorrected CPR Doppler velocity products, V_{L1}–v_{sat} (red) and V_{L2a}–v_{sat} (yellow) exhibit substantially larger biases resulting from the uncorrected non-uniform beam filling (NUBF) and Doppler spectrum broadening and therefore correlate well with the antenna pointing bias (blue line). The corrections for these effects are applied in the generation of the V_{best} product (Kollias et al., 2023). So the V_{best}–v_{sat} (blue crosses) follow the $0\ m\, s{-}1$-line best.

Figure 5 b) shows the time series for ascending overpasses at the site of Potenza. Here, the analysed data shows only 8 matching cases out of the potential 97 overpasses (19 cases where CPR measured clouds). The Doppler velocity bias values here show a greater spread. As the sample size is very small, we cannot exclude potential influence of orography around the site. There also seem to be some incorrect $L2a_{MPB}$ values as we see with the decrease in the blue line. Based on the results of this case study and the other sites, we conclude that sites with fewer than 10% of overpasses analysed do not provide sufficient statistics for validation. The sites of Bucharest and Granada have an even lower data availability, the biases evaluated cannot be considered significant.

Considering the sites with more a sufficient numeber of overpasses, the Doppler velocity bias between ACTRIS ground-based measurements and ESA's EarthCARE CPR best-estimate product, V_{best}, ranges from $0.01\ \mathrm{m\,s^{-1}}$ at Neumayer Station to $-0.05\ \mathrm{m\,s^{-1}}$ at Lindenberg. These biases are very low and would come to validate the EarthCARE L2 Doppler velocity best estimate. Moreover these results are compatible with the observations made by Kim et al. (2025).

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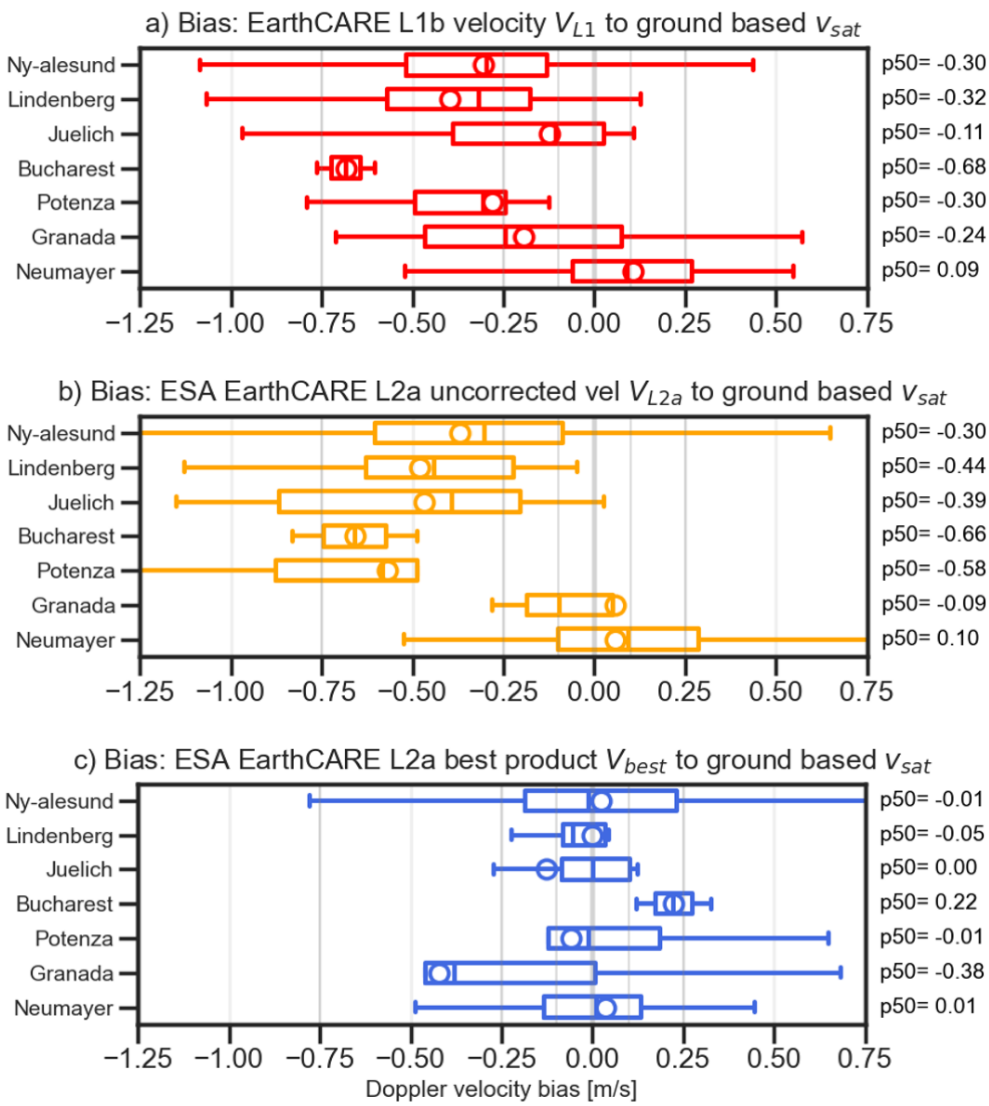

Figure 4. Summary of Doppler velocity biases between the EarthCARE CPR and seven ACTRIS sites for the period analysed. The Box plots show statistics for analysed overpasses containing data from satellite and ground. a) shows the statistics for V_{L1} (red stars in Fig. 3) to the ground based velocities v_{sat} , b), shows the statistics for V_{L2a} (yellow dots in Fig. 3) to the ground based velocities v_{sat} c) shows the statistics for the $L2a_{best}$ to the ground based velocities V_{sat} (the blue crosses in Fig. 3). In the boxes the vertical line indicates the median (p50), circles denote the mean, the boxes represent the interquartile range (25th–75th percentiles), while whiskers extend from the 1.5th to the 98.5th percentiles. Stations are sorted from North to South, top down on the left y-axis. On the right y-axis, the median (p50) of the bias probability density function is shown for each site.

The biases evaluated with the uncorrected Doppler velocity products affected by ESA's antenna mispointing bias ($L2a_{MPB}$) show that, with the exception of Neumayer Station, all sites exhibit an underestimation of Doppler velocities for both V_{L1} and

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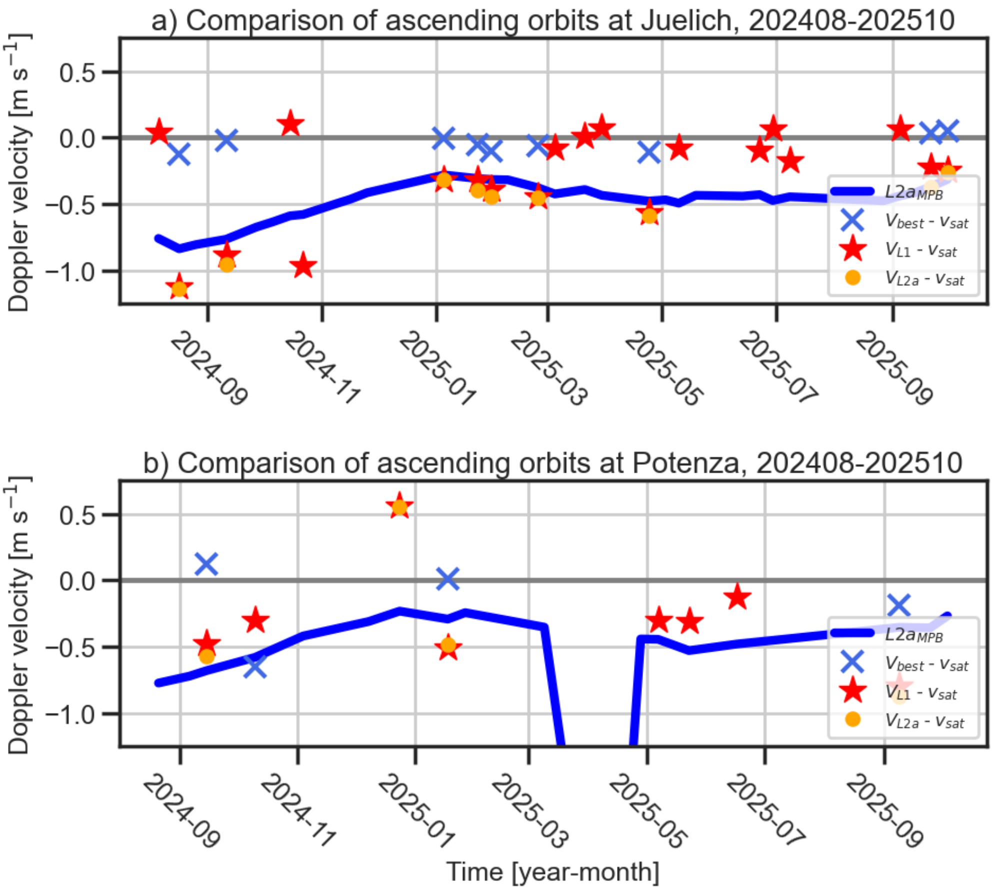

Figure 5. Ascending orbit for the sites of Jülich, Germany and Potenza, Italy. The labeling follows the one in Figure 3

V_{L2} relative to ground-based observations (Figure 4 a) and b). When biases of the uncorrected products are comparable, the spread of the V_{L2} data is typically wider. This behaviour is also observed for the three sites with low data availability. However, Figure 4 b) and c) demonstrate that the antenna mispointing is the largest bias for all of the analysed data sets, thus demonstrating how important this correction is.

Overall, these results demonstrate that the ACTRIS ground-based cloud radar network is well-suited to validating ESA EarthCARE CPR Doppler velocity products. Validation can be performed both on a case-by-case basis (Fig. 2 and Fig. 3) and a global statistical approach (Fig. 4).

4.3 Assessment of Δt and Δx for the validation

As direct satellite overpasses over a ground-based site are rare, previous studies have shown that, for sufficiently large spatial and temporal collocation windows, ground-based and spaceborne radar datasets exhibit statistically comparable characteristics (Protat et al., 2010; Kollias et al., 2019; Feuillard et al., 2026). These studies typically evaluate satellite radar reflectivity profiles

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Table 3. Root-mean-square error (RMSE) of the Doppler velocity bias relative to the antenna mispointing reference ($L2a_{MPB}$) for the CPR $L1b$ and $L2a$ products, and RMSE between the ground-based Doppler velocities and the best-estimate CPR Doppler velocity product ($L2a_{best}$). Results are shown for different temporal averaging windows applied to the ground-based data for the Ny-Ålesund and Neumayer stations.

Site	RMSE of	±5 min	±15 min	±30 min	±60 min
Ny-Ålesund	bias($L1b$) to $L2a_{MPB}$	0.39	0.36	0.36	0.32
	bias($L2a$) to $L2a_{MPB}$	0.44	0.40	0.44	0.41
	$L2a_{best}$ to ground	0.47	0.48	0.53	0.50
Neumayer	bias($L1b$) to $L2a_{MPB}$	0.23	0.18	0.16	0.15
	bias($L2a$) to $L2a_{MPB}$	0.25	0.22	0.23	0.21
	$L2a_{best}$ to ground	0.26	0.22	0.23	0.23

using different time windows that include satellite overpasses and a spatial radius of up to 200 km around the ground-based site. The validation of CPR Doppler velocities shows no significant dependence on the site-to-overpass distance within a radius of 100 km (not shown). As mentioned earlier, the main prerequisite is that the cloud types and conditions match for Doppler velocity validation. Because this is already a hard-to-fulfill condition for all sites within the network, we decided to perform the analysis using a common 100 km radius around all sites.

Building on this framework, we investigate the sensitivity of the estimated Doppler velocity bias to (i) the horizontal distance between the ground-based site and the EarthCARE overpass (Δx) and (ii) the temporal averaging window applied to the ground-based observations (Δt). The analysis is based on collocated measurements from Ny-Ålesund and the EarthCARE CPR covering the period from December 2024 to September 2025.

In all cases, no systematic of the estimated Doppler velocity bias on the site-to-overpass distance was observed. Instead, the bias estimates are primarily driven by variations in cloud conditions rather than by spatial collocation distance. Likewise, the impact of the averaging time on the bias is not immediately apparent.

A quantitative assessment is provided in Table 3 for the Doppler velocity products and averaging windows. For Ny-Ålesund, the RMSE remains largely stable across the investigated averaging times, with only a slight reduction for longer averaging windows. Overall, the differences between the ±15 min, ±30 min, and ±60 min averages are small, indicating a weak sensitivity of the RMSE to the chosen temporal window.

To place these results in a broader context, the same analysis was performed for the Neumayer station in Antarctica (Table 3). While the absolute RMSE values at Neumayer are approximately a factor of two lower than those at Ny-Ålesund, the overall behaviour as a function of averaging time is similar. The lower RMSE at Neumayer can be attributed to several factors. First, the variability of the antenna mispointing bias $L2a_{MPB}$ is smaller at this site, as its magnitude depends on latitude, solar activity, and time (Puigdomènech Treserras et al., 2025).

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Second, the CPR operates with higher pulse repetition frequencies (PRF) in contrast to the latitude region at Ny-Ålesund. Doppler velocity estimates exhibit higher signal-to-noise ratios when the CPR is operating at a higher pulse PRF, resulting in improved Doppler velocity accuracy (Kollias et al., 2014, 2023; Imura et al., 2026). Finally, the flat surrounding orography at Neumayer contrasts with the complex terrain around Ny-Ålesund, where mountainous topography reaching elevations of up to $1\ \mathrm{km}$ can induce localised dynamical features that are not fully captured by the CPR sampling volume. Such effects affect the validation of Doppler velocities and the estimation of bias in ground-based radar data.

Of the four temporal windows tested, none seems significantly better than the other. However, to ensure a consistent validation strategy across the ACTRIS network, we adopt a temporal averaging window of $\pm 30\ \mathrm{min}$ centred on the EarthCARE overpass, thus providing a robust and comparable basis for good statistics and data availability for all sites analysed in this study.

5 Conclusions and outlook

In this study, Doppler velocity measurements from the EarthCARE Cloud Profiling Radar (CPR) were evaluated using ground-based cloud radar observations from the ACTRIS network. By applying a harmonised preprocessing and comparison framework, the analysis provides a comprehensive assessment of the performance of the L1b and L2a Doppler products throughout the first 18 months of the mission. The results demonstrate that, although the uncorrected CPR Doppler velocities are strongly affected by antenna mispointing, non-uniform beam filling, and Doppler spectrum broadening, these effects are effectively mitigated in the ESA L2a best-estimate Doppler velocity product. Across ACTRIS sites with sufficient sampling (namely Ny-Ålesund, Lindenberg, Jülich, and Neumayer Station) the residual Doppler velocity bias is consistently small, with median values typically between 0.01 and 0.06 $\mathrm{m\,s^{-1}}$, which lies well within EarthCARE's mission requirement of 0.1 $\mathrm{m\,s^{-1}}$.

The analysis further shows that neither the distance between the satellite ground track and the ACTRIS site nor the temporal averaging window exerts a strong influence on the retrieved biases. While some sensitivity to averaging time exists, the differences between ± 15 min, ± 30 min and ± 60 min windows are minor compared with the total variability across overpasses. For this reason, and to ensure methodological consistency across the heterogeneous ACTRIS network, a uniform averaging window of ± 30 min was adopted for this study.

The comparison between Ny-Ålesund and Neumayer Station illustrates that environmental conditions, including latitude-dependent effects on antenna mispointing, differences in PRF-related SNR, and local orography, modulate the absolute magnitude of Doppler velocity errors but do not alter the overall behaviour of EarthCARE CPR products. At both locations, the L2a best-estimate product provides a stable and unbiased representation of hydrometeor vertical motion within the ice-cloud regime.

Overall, the findings confirm the robustness of the EarthCARE CPR Doppler velocity retrievals after application of the L2a correction scheme. The demonstrated consistency across diverse ACTRIS sites underscores the suitability of the mission for producing global, vertically resolved Doppler climatologies of clouds and precipitation. Future work should focus on expanding the analysis to additional stations, including tropical and maritime environments, and on refining the treatment of complex

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dynamical features such as orographically driven vertical motions, where residual discrepancies between ground-based and satellite observations may still arise.

Next steps related to Doppler velocity validation are the continuity of the monitoring of CPR Doppler velocity and Doppler products throughout the expected 10-year mission lifetime. Therefore, in the short run, it is planned to collaborate with ACTRIS CCRES and CLU to implement this procedure, and extend it throughout the whole cloud remote sensing network. Another possible extension is to monitor the EarthCARE Doppler velocity products retrieved by JAXA using the ACTRIS ground-based cloud radar network.

Data availability. The ground-based radar data used in this study (synthetic CPR product) are generated by the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) and are available from the ACTRIS Data Centre using the following link: https://doi.org/10.60656/3504f9e9e383470c, (Adam et al., 2026). EarthCARE L1b and L2a data are available on the MAAP portal European Space Agency (ESA) (European Space Agency (ESA), 2026b).

Author contributions. The methodology used in this work was defined by authors LP, NF, FT and BP. The code and figures were created by LP. The article was written by LP. It was reviewed by NF, FT, BP. The calibration of the ACTRIS ground sites was done by NF and FT. The conception of this CalVal project and the funding proposal were made by LP and FT. ST and EOC helped during the development of the project, providing the ground-based data, and will implement the code at the ACTRIS Cloud Remote Sensing Data Centre Unit (CLU) for continuous monitoring of the EarthCARE data.

Competing interests. The authors declare that they have no conflict of interest.

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