



A Ka/W-band dual-frequency millimeter-wave radar–thermal infrared radiometer system for cloud and precipitation observations over the Tibetan Plateau: design, performance evaluation, and preliminary observations

5 Yongheng Bi^{1,2}, Yinan Wang^{1,2}, Rui Qi³, Linjun Pan^{1,2}, Ming Li^{1,2}, Yufang Tian^{1,2}, Wei Zhao^{1,2}, Juan Huo^{1,2}, Daren Lyu^{1,2}

¹Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

²University of Chinese Academy of Sciences, Beijing 100049, China

³Sun Create Electronics Co., Ltd., Hefei 230088, China

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Correspondence: Yinan Wang (wangyinan@mail.iap.ac.cn) and Daren Lyu (ludr@mail.iap.ac.cn)

Abstract. Continuous observations of cloud and precipitation structure are important for characterizing atmospheric processes over the Tibetan Plateau, where long-term measurements remain challenging to obtain. We present a Ka/W-band dual-frequency millimeter-wave radar–thermal infrared radiometer system (KaW-TIR), developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences, and Sun Create Electronics Co., Ltd., and deployed at the Yangbajing Atmospheric Observatory in Tibet. The system integrates all-solid-state frequency-modulated continuous-wave (FMCW) radars, shared-aperture dual-frequency Cassegrain antennas, separate transmit and receive assemblies, and a thermal infrared channel on a common scanning platform. A common time reference supports synchronized observations with approximately aligned viewing directions. We evaluated system performance using internal monitoring, UAV-suspended metal-sphere calibration, weak cold-cloud consistency analysis, and long-term observation statistics. The metal-sphere calibration yielded mean apparent reflectivity biases of -0.75 dB for the Ka band and $+0.32$ dB for the W band, which were used to correct the corresponding radar constants. Selected weak cold-cloud samples had a median Ka–W dual-wavelength ratio of 0.34 dB. In the routine observing mode, the nominal range resolution is 30 m, and the product update interval is approximately 0.92 s. At 10 km above radar level, the observed statistical detection boundaries are approximately -44.43 dBZ for the Ka band and -43.20 dBZ for the W band. A representative case illustrates concurrent radar-observed cloud and precipitation structure and thermal infrared brightness temperature. These results demonstrate the KaW-TIR system's capability for continuous, synchronous observations of cloud and precipitation at a high-altitude site on the Tibetan Plateau.

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1 Introduction

30 1.1 Measurement needs for cloud and precipitation observations over the Tibetan Plateau

Cloud microphysical properties and phase govern particle growth and precipitation formation, while cloud macrophysical structure influences the atmospheric radiation budget, hydrological cycle, and material transport between the troposphere and stratosphere (Stephens, 2005; Bony et al., 2015; Bian et al., 2020; Morrison et al., 2020). These processes are closely coupled with cloud dynamics and thermodynamics across a wide range of scales, making their representation a continuing challenge in numerical weather prediction and climate models (Bony et al., 2015; Morrison et al., 2020). Continuous ground-based millimeter-wave cloud radar observations provide measurements of equivalent radar reflectivity factor, Doppler velocity, and spectral width within clouds at high temporal and vertical resolution. Such observations are valuable for investigating cloud processes and evaluating numerical model representations (Kollias et al., 2007; Kollias et al., 2020).

Owing to its strong orographic and thermal forcing, the Tibetan Plateau plays an important role in the Asian monsoon, regional moisture cycling, and troposphere–stratosphere exchange (Bian et al., 2020; Fu et al., 2020; Huang et al., 2023). The Tibetan Plateau's high altitude, complex terrain, harsh environmental conditions, and sparse observational network make long-term, continuous cloud and precipitation measurements at high vertical resolution particularly challenging. Consequently, ground-based observations that can resolve internal cloud structure and rapid evolution remain scarce (Gao et al., 2016; Zhang et al., 2020; Huo et al., 2021; Wu et al., 2024). Observing systems deployed on the Tibetan Plateau therefore require high sensitivity to weak cloud echoes, sufficient dynamic range for stronger cloud and precipitation returns, and accurate spatial and temporal co-registration among sensors. Continuous operation under low pressure and large temperature variations is also essential.

1.2 Existing measurement approaches and remaining instrument challenges

Millimeter-wave cloud radars provide continuous, range-resolved measurements of equivalent radar reflectivity factor (Z_e), radial Doppler velocity (V_r), Doppler spectral width (σ_v), linear depolarization ratio (LDR), and Doppler spectra ($S(v)$) within clouds (Illingworth et al., 2007; Kollias et al., 2007; Kollias et al., 2020). Vertical pointing provides time–height information, whereas range–height indicator (RHI), plan position indicator (PPI), and volume scans describe spatial structure (Kollias et al., 2014a; Kollias et al., 2014b). System sensitivity, hydrometeor scattering characteristics, and propagation attenuation control the effective detection range and quantitative interpretation of radar measurements.

Hydrometeor scattering and propagation effects differ between the Ka and W bands. Ka-band signals are generally less affected by gaseous, liquid-water, and precipitation attenuation, allowing deeper penetration when propagation attenuation is strong. In contrast, the shorter W-band wavelength produces a stronger frequency-dependent scattering response to particle size and is more susceptible to propagation attenuation (Lhermitte, 1990; Kollias et al., 2007).

The dual-wavelength ratio (DWR), defined as the difference between the Ka- and W-band equivalent radar reflectivity factors expressed in dBZ, provides information on frequency-dependent scattering and attenuation. Multifrequency measurements have been used to investigate snowfall microphysics (Kneifel et al., 2015), retrieve raindrop size distributions from dual-



frequency Doppler spectra (Tridon and Battaglia, 2015), and estimate melting-layer attenuation (Li and Moisseev, 2019). These approaches require relative calibration, attenuation correction, and comparable sampling volumes; DWR alone does not uniquely determine microphysical properties.

Thermal infrared brightness temperature ($T_{b,IR}$) complements radar backscatter by responding to atmospheric and cloud emission along the viewing direction. Radar–infrared studies demonstrate this complementarity, while accounting for cloud emissivity, optical thickness, and atmospheric transmission (Matrosov et al., 1992, 1994; Mace et al., 1998). Radar–microwave radiometer and radar–lidar studies further illustrate sensor synergy (Bell et al., 2022; Dias Neto et al., 2023; Vishwakarma et al., 2023). For quantitative use of combined radar and thermal infrared observations, differences in radiometric characteristics, sampling time, pointing, and field of view must be considered. These issues are particularly relevant for integrated systems designed to provide coordinated observations of cloud structure and thermal emission.

Developments in scanning millimeter-wave cloud radars, W-band FMCW systems, and combined W-band radar–radiometer instruments have enabled multi-frequency and active–passive cloud observations (Kollias et al., 2014a; Delanoë et al., 2016; Kühler et al., 2017).

Our earlier Ka/W dual-frequency radar studies on the Tibetan Plateau provided initial experience with high-altitude cloud measurements (Huo et al., 2021). However, the complex plateau environment and operational constraints limited the duration of valid observations. To improve long-term observing capability, the Institute of Atmospheric Physics, Chinese Academy of Sciences, and Sun Create Electronics Co., Ltd. developed KaW-TIR. It was deployed at the Yangbajing Atmospheric Observatory in Tibet. The system combines dual-frequency radar and thermal infrared measurements within a common scanning and timing framework. This study therefore focuses on the system design, measurement geometry, calibration, and performance demonstrated during high-altitude deployment.

1.3 Objectives and scope

This paper describes the integration of the radar, thermal infrared channel, and scanning platform; the signal processing used to generate the basic observables; and the calibration and evaluation procedures for assessing measurement performance. The study focuses on instrument design and performance evaluation, using coordinated observations to demonstrate the system's capability.

Section 2 describes the site, environmental requirements, system architecture, instrument hardware, and operating modes. Section 3 presents the generation of the basic observables, together with spatial and temporal alignment and quality-control procedures. Section 4 describes internal monitoring, absolute calibration using a metal sphere, and relative consistency checks based on natural targets. Section 5 reports detection sensitivity, operational availability, and representative simultaneous observations. Section 6 discusses the scope and current limitations of the measurement evidence. Section 7 summarizes the main results.



2 Measurement site and instrument design

2.1 Site characteristics and environmental challenges

The KaW-TIR system is deployed at the Yangbajing Atmospheric Observatory in Tibet (Lu et al., 2018). The site is located at 30.10° N, 90.52° E, approximately 4300 m above sea level, with a mean surface pressure of about 600 *hPa*. The site experiences large diurnal and seasonal temperature variations, intense solar radiation, strong winds, windblown sand, snowfall, and icing. Although atmospheric water vapor is generally low, the summer plateau monsoon and regional moisture transport produce diverse cloud and precipitation events (Wu et al., 2022; Zhao et al., 2024). These characteristics make the site well suited for long-term observations of cloud and precipitation processes over the Tibetan Plateau.

The high-altitude environment also places specific demands on instrument design and operation. Low pressure reduces natural convective heat transfer, while ambient temperature variations can cause drift in transmit power, receiver gain, and frequency references. Snow, ice, and water films can increase radome losses or contaminate infrared optics. Intense solar radiation can also alter the equipment's thermal state and affect infrared observations. Because maintenance at the high-altitude site is constrained by weather, transportation, and personnel availability, the system was designed for long-term reliable operation with minimal maintenance and limited need for on-site intervention. To support this, the system incorporates thermal management, environmental protection, and status monitoring. Their implementation is described in this section, and the measurement characterization and operational results are presented in Sects. 4 and 5.

2.2 System architecture and observational concept

KaW-TIR comprises Ka- and W-band dual-polarization all-solid-state frequency-modulated continuous-wave (FMCW) Doppler cloud radars, a thermal infrared radiometer, a common azimuth–elevation scanning platform, and data acquisition and processing units (Figs. 1 and 2; Delanoë et al., 2016; Küchler et al., 2017). The transmit and receive antenna assemblies are separate, and each uses a Ka/W dual-frequency shared-aperture Cassegrain configuration in which the Ka and W bands share the same primary and secondary reflectors. The two antenna assemblies are mounted on the common scanning structure to provide a consistent viewing geometry for simultaneous dual-frequency observations. The infrared radiometer is mounted on the same platform, with mechanical alignment, pointing calibration, and a common time reference to support simultaneous, approximately co-pointing observations. Because the infrared field of view is wider than the radar beams, the channels do not sample identical spatial volumes.

The common scanning platform supports vertical pointing (VPT), PPI, RHI, and continuous scans through the zenith. Radar operating modes and infrared integration times can be configured for each scan sequence. The system directly produces basic radar observables Z_e , V_r , σ_v , LDR, and $S(\nu)$, together with thermal infrared brightness temperature ($T_{b,IR}$). Cloud phase, particle size, and water content can be derived through synergistic retrievals but are not evaluated in this study.

The Ka/W radars provide range-resolved scattering, depolarization, and Doppler measurements, while the thermal infrared channel measures brightness temperature along an approximately co-pointing line of sight. Shared scanning and time

synchronization place the three channels in a common time–angle framework. Their beamwidths and sampling volumes differ,
 125 so the observations are approximately co-viewing but not strictly beam-matched. This mismatch is considered in the quality
 control and performance assessment below.

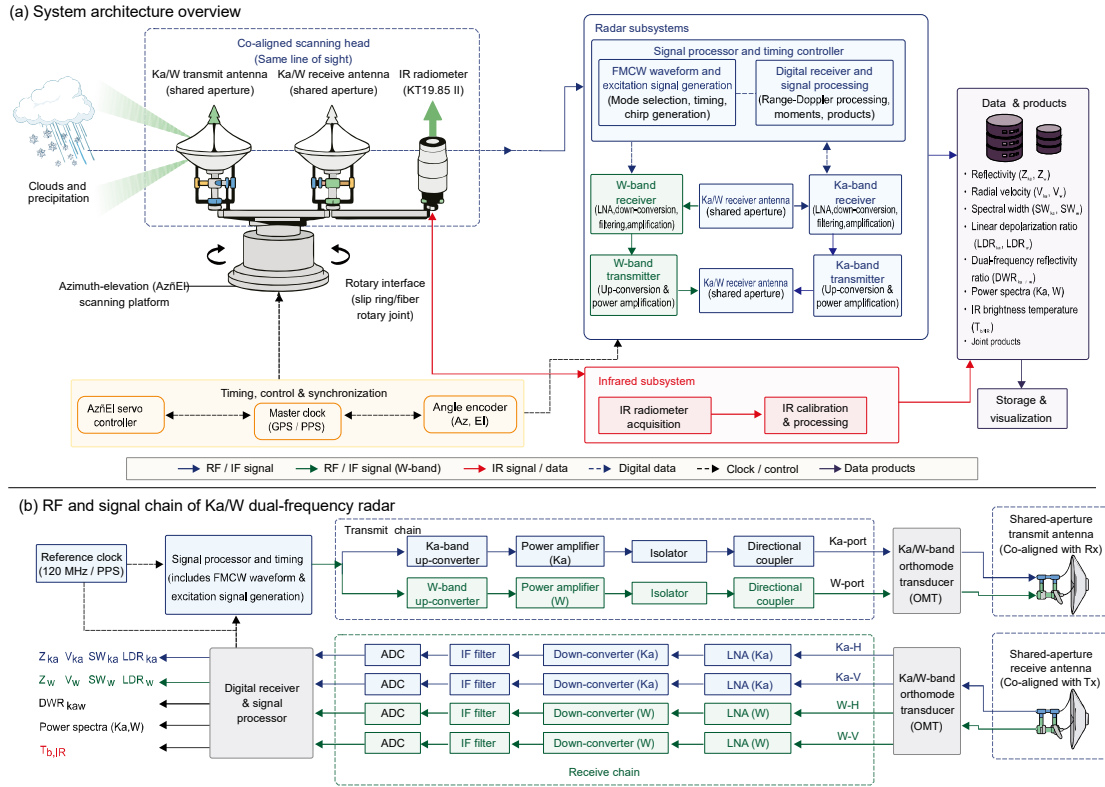


Figure 1: System architecture and signal flow of the KaW-TIR system.



Figure 2: Field deployment of the KaW-TIR system at the Yangbajing Atmospheric Observatory, Tibetan Plateau. The right panel shows the mounting position of the thermal infrared radiometer and its relative location with respect to the radar antenna.



Table 1: Main specifications of the KaW-TIR system.

Parameter	Ka-band radar	W-band radar
Frequency (GHz)	34.96	94.50
Measured transmit power (W)	≈ 65	≈ 12
Receiver noise figure (dB)	3.84	5.48
Receiver gain (dB)	≈ 35.5	≈ 35.5
Primary reflector diameter (m)	1.5	1.5
3 dB beamwidth ($^{\circ}$)	0.40	0.16
Tx/Rx antenna gain (dBi)	53.1/53.3	58.4/59.0
First sidelobe level (dB)	< -27	< -24
Cross-polarization isolation (dB)	> 30	> 30
Tx–Rx antenna isolation (dB)	> 100	$> 100^a$
Tx–Rx center spacing (m)	1.69	1.69
Statistical boundary at 10 km (dBZ) ^b	≈ -44.43 dBZ	≈ -43.20 dBZ
Spectral response of thermal infrared radiometer (μm)	9.6–11.5	
Temperature measurement range ($^{\circ}\text{C}$)	-100 to 200	
Sensor accuracy (manufacturer specification) ($^{\circ}\text{C}$)	$\pm [0.5^{\circ}\text{C} + 0.007 T_{\text{target}} - T_{\text{inst}}]^c$	
Field of view (FOV) ($^{\circ}$)	3	
Scanning modes	VPT / PPI / RHI / scans through zenith	
Azimuth range	0 – 360°	
Elevation range	0 – 180°	
Basic observables and products	Ka- and W-band: Z_e , V_r , σ_v , LDR, $S(v)$; thermal infrared: $T_{\text{b,IR}}$, T_{air}	

Table notes: Tx, transmit; Rx, receive; ^a W-band: estimated from system design; not independently verified. ^b Estimated at 10 km for Mode 3, with a 30 m range resolution and a 0.92 s profile update interval. ^c Manufacturer specification for the KT19.85 II sensor. T_{target} and T_{inst} denote the target and instrument temperatures, respectively.

2.3 Ka/W-band antennas and co-pointing design

Separate transmit and receive Cassegrain antennas are used, with the Ka and W bands sharing the primary and secondary reflectors within each antenna. A coaxially nested dual-frequency feed carries W-band signals through a central hollow circular waveguide and Ka-band signals through the surrounding coaxial waveguide. Dielectric rods and metal-ring loading are used to improve impedance matching and control the aperture illumination at both frequencies. The design is intended to provide adequate inter-band isolation, polarization performance, and consistent beam pointing. The resulting beam characteristics, gain, isolation, and transmission losses are evaluated below.



To achieve a high antenna gain, both the transmit and receive antennas employ 1.5 m diameter primary reflectors. Because W-band performance is more sensitive to reflector surface errors, different surface-accuracy requirements were applied across the reflector. The root-mean-square (RMS) surface error is limited to 0.03 mm within the central 1.0 m-diameter region and to 0.08 mm in the outer region extending from 1.0 to 1.5 m in diameter. Microwave anechoic-chamber measurements are summarized in Table 1. The Ka-band transmit and receive antennas have 3 dB beamwidths of approximately 0.40° , gains of 53.1 and 53.3 dBi, and first-sidelobe levels below -27 dB. The corresponding W-band beamwidths are 0.16° , the gains are 58.4 and 59.0 dBi, and the first-sidelobe levels are below -24 dB. The cross-polarization isolation of the Ka- and W-band antenna systems is 31.5 and 30.2 dB, respectively.

Separate transmit and receive antennas suppress direct leakage of the FMCW transmit signal into the receiver. Antenna spacing and the isolation structure were optimized together. Full-wave electromagnetic simulations at the Ka-band center frequency gave a transmit–receive antenna center spacing of 1.69 m and an isolation-cylinder height of 0.45 m. The simulated Ka-band isolation exceeded 120 dB; complete-system measurements at Ka band confirmed isolation greater than 100 dB, with the measurable upper limit constrained by the test setup's dynamic range. For the W band, an isolation above 100 dB is an engineering estimate rather than a direct complete-system measurement. Transmit–receive isolation reduces the effect of direct leakage on receiver dynamic range. Section 5 evaluates weak-echo detection using observations. Transmit leakage, receiver dynamic range, and antenna and waveguide losses affect the sensitivity and reflectivity calibration of millimeter-wave cloud radars. Laboratory characterization and complete-system tests assess these contributions (Ewald et al., 2019; Toledo et al., 2020).

The Ka- and W-band 3 dB beamwidths measured in the microwave anechoic chamber were 0.40° and 0.16° , respectively. Relative pointing offsets between frequencies and between transmit and receive antennas affect the geometric consistency of coordinated observations (Sekelsky and Clothiaux, 2002). During factory assembly, three-dimensional coordinate measurements guided adjustments to the relative positions of each antenna's primary reflector, secondary reflector, and feed to maintain the internal antenna geometry. Close-range photogrammetry was performed at the factory and repeated after installation at Yangbajing to measure and verify the three-dimensional geometry of the transmit and receive antennas. The relative angle between their mechanical axes was 0.028° , corresponding to approximately 17.5 % of the W-band 3 dB beamwidth. For an ideal Gaussian power beam, an angular offset of 0.028° corresponds to a single-beam off-axis gain reduction of approximately 0.37 dB at W band. This value is only a geometric estimate, assuming coincident mechanical and electromagnetic boresights. The photogrammetric measurements characterize the relative mechanical alignment of the antenna assemblies, whereas the Ka/W electrical boresights, infrared optical axis, and two-way radar gain are not directly determined by this method.

The polarization feed network comprises orthomode transducers (OMTs), waveguide power dividers, and waveguide switches. It supports dual-transmit, dual-receive and single-transmit, dual-receive modes. The latter mode is primarily used to measure LDR. The Ka/W transmitters, receivers, and waveguide connections are arranged compactly to reduce losses along the



millimeter-wave signal paths. Complete-system tests gave transmit–receive path losses of 3.03 and 3.66 dB for the W-band horizontal (H) and vertical (V) channels, respectively. The corresponding Ka-band losses were 1.30 and 1.20 dB.

2.4 Transmitters, receivers, and frequency generation

Both the Ka- and W-band radars use all-solid-state FMCW transmitters. The Ka-band transmit chain uses initial-stage units based on amplifier chips rated at approximately 7 W, the final power combining uses 3-dB waveguide hybrids, microstrip-to-waveguide transitions, and a six-way rectangular-waveguide power combiner. The design output power is approximately 70 W, and the measured output under the operating configuration was about 65 W. The W-band transmitter uses approximately 2 W gallium nitride (GaN) power amplifiers and a multistage waveguide power-combining structure. Its design output is approximately 20 W, and the measured output at initial installation was about 16 W. The typical monitored output during long-term operation was approximately 12 W. The 65 W (Ka band) and 12 W (W band) values listed in Table 1 represent typical operating values during the performance-evaluation period.

The radio-frequency (RF) chain in each band generates a linearly frequency-modulated drive signal of at least 10 dBm. After solid-state power amplification, the signal is fed to the transmit antenna. Directional couplers and R&S power meters continuously measure transmit power, and the measurements are stored synchronously with the observations. Section 4 describes the transmit-power correction method and its scope of application.

Both the Ka- and W-band receivers use a dual-channel superheterodyne architecture. Echoes undergo low-noise amplification and two down-conversion stages to an intermediate frequency of 140 MHz before entering the digital signal-processing unit. Complete-system measurements gave receiver noise figures of 3.84 dB at Ka band and 5.48 dB at W band. Internal test signals and noise sources monitor receiver gain, noise, and consistency between the two channels. Section 4 describes these tests and the relative correction methods.

An internal direct digital synthesizer (DDS) generates a test signal, frequency-converts it to RF, and injects it into the horizontal and vertical receiver channels through switches. A digitally controlled attenuator sets the test-signal power. This interface checks the receiver electronics' performance and supports internal relative calibration. It does not provide full end-to-end absolute reflectivity calibration. Section 4 describes the test method and its scope.

The Ka/W receivers use closed-loop temperature control, with a set point of approximately 20 °C for key components. This control is intended to reduce the effects of plateau temperature variations on the receiver's gain, phase, and frequency response. Transmit power, receiver gain, noise level, and module temperatures are recorded synchronously with the observations to identify warm-up periods, abnormal thermal drift, and long-term changes in instrument status.

The Ka/W dual-frequency radar uses a shared 120 MHz reference clock and pulse-per-second (PPS) time reference. Local oscillators, chirp sources, and digital sampling clocks are derived from a common frequency reference to maintain timing consistency for waveform generation, sampling, and Doppler phase processing at both frequencies.



2.5 Thermal infrared channel

The thermal infrared channel uses a KT19.85 II narrowband radiation temperature sensor with a spectral response from 9.6 to 11.5 μm . During vertical pointing, the integration time is 0.92 s, corresponding to the routine radar product update interval.

210 During PPI and RHI scans, the infrared integration time is adjusted to match the angular scan speed. The effective angular resolution therefore depends on the optical field of view, integration time, scan speed, and angular sampling interval. The finite response time also introduces spatial smoothing and angular lag.

The sensor is mounted on the shared azimuth–elevation scanning platform. A gold-coated mirror directs its optical axis approximately along the Ka/W radar reference axis. The S925AR optics have an effective full field of view of approximately

215 3°, which is wider than the Ka- and W-band 3 dB beamwidths of approximately 0.40° and 0.16°, respectively. The three channels therefore have different angular sampling footprints and are not strictly beam matched. The system synchronously records thermal infrared brightness temperature, near-surface air temperature, relative humidity, radar observables, azimuth, elevation, and time. Angular registration of scan data also uses the scan speed and sensor response time.

The infrared channel reports band-equivalent thermal infrared brightness temperature in the 9.6–11.5 μm band along a given
 220 line of sight. This radiometric observable reflects emission from clouds and the atmosphere along the optical path. It cannot generally be interpreted as the physical temperature of the cloud at a specific geometric height. It depends on cloud temperature, emissivity, optical thickness, subcloud atmospheric conditions, including water vapor, and viewing geometry. These dependencies are particularly relevant for semitransparent clouds, multiple cloud layers, and slant-path observations. We therefore use thermal infrared brightness temperature as a basic observable for comparison with the Ka/W radar observations.

225 Because the sensor views the sky via a gold-coated mirror, quantitative interpretation must account for the mirror's finite reflectance and thermal emission. The system records ambient temperature and other auxiliary status parameters simultaneously. Quality flags identify rainfall, snowfall, mirror contamination, icing, and periods when the Sun approaches the line of sight; details are given in Sect. 3.

2.6 Scanning, timing, and environmental adaptation

230 The Ka/W radars and the thermal infrared channel share an azimuth–elevation platform for VPT, PPI, and RHI. In VPT mode, the radars provide continuous time–height observations, accompanied by line-of-sight thermal infrared brightness temperature. RHI scans include over-the-top scans through the zenith, while PPI provides azimuthal sampling. Each mode's coverage depends on the scan sequence, dwell time, and corresponding radar and infrared settings.

The system uses zoned thermal management and forced ventilation to support operation under low pressure, diurnal
 235 temperature variations, intense solar radiation, snowfall, icing, and windblown sand. It also monitors temperatures in key modules, transmitter output power, and receiver noise. The radomes have heating and air-purging devices, while the infrared channel has an optical protection assembly. Status parameters are recorded alongside the observations to identify warm-up



periods, abnormal thermal drift, and potential environmental contamination. Their effectiveness is evaluated separately using long-term operational records and calibration results.

240 2.7 Data acquisition and digital signal-processing hardware

The data acquisition system comprises separate field-programmable gate array (FPGA) processing units for the Ka and W bands, plus a central workstation. Each FPGA unit synchronously samples the 140 MHz intermediate-frequency signal from its respective receiver and performs front-end digital processing. The units share a reference clock and trigger signal to maintain timing consistency between the two frequencies. After range processing, complex in-phase and quadrature (I/Q) data are
 245 transferred to the central workstation for spectral processing and basic product generation, as detailed in Sect. 3.

Table 2 summarizes the waveform and processing parameters for the four configurable FMCW modes, including the sweep bandwidth B , chirp duration T_c , chirp repetition period T_r , range-FFT length N_r , Doppler-processing length N_D , and averaging number N_{avg} . These parameters determine the nominal range resolution, range-gate spacing, configured range coverage, native Doppler-velocity interval, accumulation time, and product update interval. Sweep bandwidths of 30, 15, and 5 MHz correspond
 250 to nominal range resolutions of approximately 5, 10, and 30 m, respectively, while the configured maximum range spans approximately 10–30 km across the four modes. These configurations therefore involve trade-offs among range resolution, range coverage, Doppler-velocity coverage, averaging, and temporal resolution. Windowing reduces spectral sidelobes but broadens the effective spectral response, while averaging reduces statistical variability at the expense of temporal resolution. The observed statistical boundary reported in Sect. 5 was evaluated for Mode 3 only.

255 Raw data and basic products retain timestamps, operating mode, scan angles, system status, and key processing parameters for dual-frequency registration, quality control, and reprocessing. Section 3 describes the measurement chain from range processing to spectral moments and dual-frequency products, including registration and quality control.

Table 2: FMCW operating modes and key processing parameters

Parameter	Mode 1	Mode 2	Mode 3	Mode 4
Sweep bandwidth, B (MHz)	30	15	5	5
Chirp duration, T_c (μ s)	245.76	245.76	256.0	204.8
Chirp repetition period, T_r (μ s)	315.1	348.1	358.0	407.0
Effective I/Q sampling rate, $f_{s,IQ}$ ($MS\ s^{-1}$)	16.67	16.67	4.00	10.00
Range FFT length, N_r	4096	4096	1024	2048
Doppler FFT length, N_D	256	256	256	256
Spectral averages, N_{avg}	10	10	10	10
Nominal range resolution, ΔR (m)	5	10	30	30
Configured maximum range, R_{max} (km)	10	15	15	30
Ka-band maximum unambiguous velocity, $v_{max,Ka}$ ($m\ s^{-1}$)	6.80	6.16	5.99	5.27
W-band maximum unambiguous velocity, $v_{max,W}$ ($m\ s^{-1}$)	2.52	2.28	2.22	1.95



260 3 FMCW operating modes and measurement processing

3.1 Range measurement and resolution

The four FMCW modes in Table 2 set the sweep bandwidth B , chirp duration T_c , and repetition period T_r . The chirp slope is $K = B/T_c$, and a target at range R has a round-trip delay $\tau = 2R/c$, where c is the speed of light. With the adopted signed-Doppler convention, the dechirped beat frequency is

$$265 \quad f_b \simeq K\tau + f_D = \frac{2KR}{c} + f_D \quad (1)$$

Neglecting the Doppler contribution gives the range assignment

$$R \simeq \frac{cf_b}{2K} = \frac{cT_cf_b}{2B} \quad (2)$$

The FPGA applies a window to each chirp and computes an N_r -point range FFT. The nominal unwindowed range resolution is

$$270 \quad \Delta R = \frac{c}{2B} \quad (3)$$

Thus, sweep bandwidths of 30, 15, and 5 MHz correspond to nominal unwindowed range resolutions of 5, 10, and 30 m, respectively. Windowing suppresses range sidelobes but broadens the effective range response. The output range-gate spacing is distinct from the physical range resolution; zero padding or output regridding can produce a finer range grid without improving the physical resolution.

275 The range coverage and gate counts in the original design are consistent with spacings of 5, 10, 30, and 30 m for Modes 1–4, respectively, assuming uniformly spaced output gates. The I/Q sampling rates listed in Table 2—16.67, 16.67, 4.00, and 10.00 MS s⁻¹—are specified in the same design records. These values are consistent with $f_{s,IQ} = N_r/T_c$ for a full-chirp FFT without zero padding.

Equation (2) introduces a coupling bias of magnitude $|\delta R_D| = \frac{cf_D}{2K}$. Its acceptability depends on the required range accuracy 280 relative to the gate spacing and effective resolution. Estimating Doppler frequency does not itself correct this bias; range reassignment requires a separate correction. The configured maximum ranges in Table 2 are distinct from both the sampling-limited ranges and the distance at which an echo is detectable.

3.2 Doppler processing and mode trade-offs

A slow-time FFT across $N_D = 256$ chirps estimates the Doppler frequency at each range gate. Radial velocity follows

$$285 \quad V_r = \frac{\lambda f_D}{2} \quad (4)$$

where λ is approximately 8.575 mm at Ka band (34.96 GHz) and 3.172 mm at W band (94.50 GHz). For uniformly spaced chirps, the native velocity interval is $[-v_{\max}, v_{\max})$, with $v_{\max} = \frac{\lambda}{4T_r}$ and FFT-bin spacing $\delta v = \frac{\lambda}{2N_DT_r}$. These relations connect



the two wavelengths and T_r to the band-dependent limits in Table 2; spectral windowing broadens the effective velocity response.

290 Mode 1 provides the finest nominal range resolution (5 m), a configured range of 10 km, and the widest native velocity intervals ($\pm 6.80 \text{ m s}^{-1}$ at Ka and $\pm 2.52 \text{ m s}^{-1}$ at W). Mode 2 extends coverage to 15 km with 10 m resolution and slightly narrower velocity intervals. Mode 3 retains 15 km coverage at 30 m resolution and is the configuration evaluated in Sect. 5. Mode 4 extends configured coverage to 30 km at the same nominal resolution as Mode 3. However, its longer repetition period narrows the velocity intervals to ± 5.27 and $\pm 1.95 \text{ m s}^{-1}$ and increases the accumulation duration.

295 The processor averages N_{avg} Doppler power spectra in linear units. For each spectrum, the nominal coherent processing duration is $T_{\text{coh}} = N_D T_r$. Assuming consecutive, non-overlapping spectra, the corresponding nominal accumulation time is $T_{\text{acc}} = N_D N_{\text{avg}} T_r$. With $N_D = 256$ and $N_{\text{avg}} = 10$, the accumulation times are approximately 0.807, 0.891, 0.916, and 1.042 s for Modes 1–4, respectively. For Mode 3, $T_{\text{acc}} = 0.91648 \text{ s}$, consistent with the observed product update interval of approximately 0.92 s. The product update interval describes the output cadence and is distinct from the accumulation time; the
 300 effective temporal response also depends on the averaging scheme, processing overhead, and scan dwell time.

Velocity dealiasing is performed sequentially. We first unfold Ka-band velocities using continuity constraints. Because the Ka-band measurements have a wider native velocity interval, the resulting dealiased Ka-band velocities then constrain the integer folding number for W-band unfolding. Candidate W-band velocities separated by $2v_{\text{max},W}$ are evaluated against the corresponding Ka-band velocity and continuity criteria, and samples that do not satisfy the prescribed constraints are flagged.

305 Because the W-band unfolding uses Ka-band information, the resulting Ka/W velocity agreement is not treated as an independent validation of dual-frequency velocity measurements.

3.3 Calibrated radar observables

After noise subtraction, the accepted echo power P_s is converted to equivalent radar reflectivity through the band- and mode-dependent calibration:

$$310 \quad Z_{\text{e,dB}}(R, t) = 10 \log_{10} P_s(R, t) + 20 \log_{10} R + C_{\text{rad}} + C_{P_t}(t) + C_{\text{corr}}(R, t) + C_{\text{ant}}(R) \quad (5)$$

where R is range, t is time, and C_{rad} is the radar constant determined from the metal-sphere calibration experiment for the corresponding radar band and operating mode. The transmitter-power correction is defined relative to the calibration reference state as

$$C_{P_t}(t) = 10 \log_{10} \left[\frac{P_{t,\text{cal}}}{P_t(t)} \right] \quad (6)$$

315 where $P_{t,\text{cal}}$ is the transmitter power measured during the external calibration and $P_t(t)$ is the synchronously monitored transmitter power during routine observations. The two powers in Eq. (6) are expressed in the same linear units. Thus, the absolute transmitter power at the calibration state is already represented in C_{rad} and is not applied again separately. C_{corr} represents propagation corrections relative to the calibration reference state. The Ka- and W-band radar reflectivities are



archived without correction for atmospheric gaseous attenuation. During post-processing, both are corrected for attenuation
 320 due to water vapor and oxygen using ERA5 reanalysis data, while C_{ant} accounts for the range-dependent incomplete overlap
 of the transmit and receive beams associated with the 1.69 m antenna separation (Sekelsky and Clothiaux, 2002).

For horizontal transmission, the linear depolarization ratio is

$$\text{LDR}_H = 10\log_{10} \left(\frac{P_{HV}}{P_{HH}} \right) \quad (7)$$

where P_{HV} and P_{HH} denote cross- and co-polar echo powers for the same band, mode, and gate. Its interpretation depends on
 325 channel calibration and valid cross-polar detection. After temporal and spatial registration, the dual-wavelength ratio is

$$\text{DWR}_{\text{Ka-W}} = Z_{\text{Ka}} - Z_{\text{W}} \quad (8)$$

where both reflectivities are in dBZ. DWR depends on scattering and differential attenuation as well as calibration, beam-
 volume differences, and unequal detection limits. The selected-cloud comparison in Sect. 4.3 is therefore a relative consistency
 check under its stated screening conditions.

330 4 Calibration and measurement characterization

4.1 Internal monitoring and relative calibration

Directional couplers and R&S power meters monitor Ka- and W-band transmit power synchronously with the radar
 observations. The recorded measurements are used to correct for transmitter-power changes relative to the external-calibration
 reference state. This correction is subject to uncertainties in coupling factors, power-meter measurements, and signal-path
 335 losses. External calibration with a standard metal sphere establishes the absolute reflectivity reference for the tested radar
 configurations.

A DDS source injects controlled test signals into the H- and V-polarized receive channels. Measurements at several input
 levels are used to monitor receiver gain and linearity and to determine the relative H/V gain correction used for LDR. These
 measurements characterize only those components downstream of the corresponding injection point and are therefore used as
 340 internal electronic checks rather than as an end-to-end radar calibration.

Both the Ka- and W-band receive chains contain solid-state noise sources. We monitor receiver noise performance by
 estimating the noise figure using the Y-factor method. Here, P_{on} and P_{off} are the receiver output powers in dBm, measured
 with the noise source switched on and off, respectively. Their difference, $\Delta P = P_{\text{on}} - P_{\text{off}}$, is expressed in dB. ENR is the
 excess noise ratio of the calibrated noise source, expressed in dB. The noise figure is calculated as

$$N_F(\text{dB}) = \text{ENR} - 10\log_{10}(10^{0.1\Delta P} - 1) \quad (9)$$

where N_F is the receiver noise figure in dB. The calculation requires a traceably calibrated ENR and corrections for switch and
 feedline losses between the noise source and receiver input. This test primarily monitors changes in receiver noise performance
 over time. Standard laboratory measurements remain the reference for the absolute noise figure.



Internal test signals characterize only the portions of the electronic chains downstream of their respective injection points. They do not include the complete antenna response or external propagation path and therefore do not establish an end-to-end absolute reflectivity reference. KaW-TIR consequently combines internal monitoring with external metal-sphere calibration. The initial link budget was established from independently measured transmitter power, receiver gain, and path losses. The metal-sphere measurements provide the external reflectivity reference for the tested radar configuration. The external calibration incorporates fixed system terms into the calibrated radar constant and does not reapply them individually during routine processing. Time-dependent transmitter-power variations are corrected relative to the calibration reference state, whereas propagation attenuation and other range-dependent terms are treated separately when required.

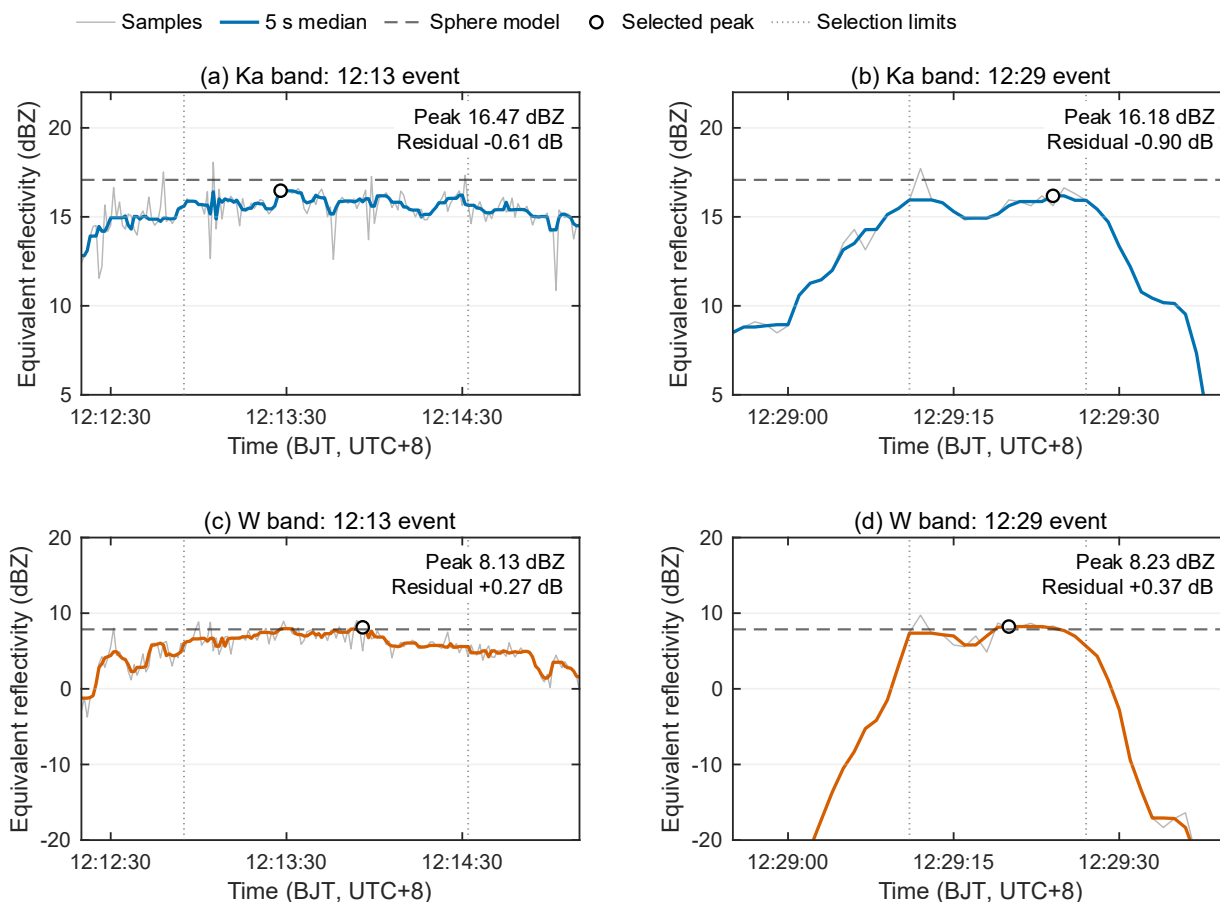
4.2 External calibration with a metal sphere

A UAV-suspended metal sphere provides a target with a calculable radar cross section (RCS). Its diameter and the radar wavelength determine the theoretical RCS, which is related to received power through the point-target radar equation. Calibration compares this reference with the sphere return processed using the specified radar mode. The reported apparent equivalent reflectivity is a representation of that point-target return on the radar product scale, rather than a volume-scattering property of the sphere (Williams et al., 2013; Yin et al., 2019).

During the KaW-TIR system tests in Huainan, we conducted an absolute calibration experiment using a metallic sphere. We suspended a standard metallic sphere with a diameter of 15.23 cm from a DJI M300 unmanned aerial vehicle (UAV) and positioned it in the far-field region. The target was located west of the radar, at an azimuth angle of approximately 277.15° , an elevation angle of 6° , and a horizontal distance of about 2.8 km. The metallic sphere was suspended approximately 50 m below the UAV. At the target range, the 3 dB beamwidths correspond to beam diameters of approximately 20 m for the Ka band and 8 m for the W band. The radar pointing was kept fixed, while the UAV was moved vertically and horizontally to allow the sphere to pass through the main beam several times. The peak response was identified using the target position time series.

Two sphere passages near 12:13 and 12:29 Beijing time on 20 March 2023 were evaluated. A centered 5 s median filter was applied, and the band-specific peaks were selected within common strong-echo intervals at the same range gate. The Ka-band peaks were 16.47 and 16.18 dBZ; the W-band peaks were 8.13 and 8.23 dBZ. At the nominal range of 2.88 km for gate 96, the theoretical apparent equivalent reflectivities were 17.08 and 7.86 dBZ. With bias defined as observed minus theoretical reflectivity, the mean biases were -0.75 dB at Ka band and $+0.32$ dB at W band. The between-passage sample standard deviations were 0.21 and 0.07 dB ($n = 2$), and the peak differences were 0.29 and 0.10 dB, respectively. We used these biases to adjust the radar constants for the corresponding tested configurations.

Calibration is affected by uncertainty in sphere RCS and position, range assignment, off-axis loss, suspended-target motion, background echoes, and system gain. The W-band beamwidth of approximately 0.16° makes target displacement particularly relevant. The repeatability of the two evaluated passages captures only part of this uncertainty and does not provide a combined uncertainty estimate for absolute reflectivity.



20 March 2023 | Nominal slant range: 2880 m

Figure 3. Selected strong-echo episodes during the metal-sphere calibration experiment on 20 March 2023. Panels (a, b) show Ka-band equivalent radar reflectivity factors, and panels (c, d) show W-band measurements near 12:13 (left column) and 12:29 (right column) Beijing time.

4.3 Natural-target consistency check

Weak cold-cloud echoes provide a conditional reference for comparing Ka- and W-band reflectivity. For particles sufficiently small relative to both wavelengths, near-Rayleigh scattering gives approximately equal equivalent reflectivities when dielectric conventions, attenuation treatment, and sampling are consistent. Hogan et al. (2000) and Ewald et al. (2019) support this approach. The reference DWR_{Ka-W} is therefore approximately 0 dB for suitable targets, rather than for ice clouds in general. Candidate profiles were screened using ERA5 temperature. We rejected profiles if any valid echo occurred at $T > -38$ °C or lacked a corresponding temperature. This cold-cloud criterion reduces the likelihood of liquid-containing layers along the detected echo column and is motivated by homogeneous-freezing conditions (Koop et al., 2000). We also rejected profiles with reflectivity above -15 dBZ in either band. This is an empirical weak-echo filter, not a strict Rayleigh-scattering criterion,

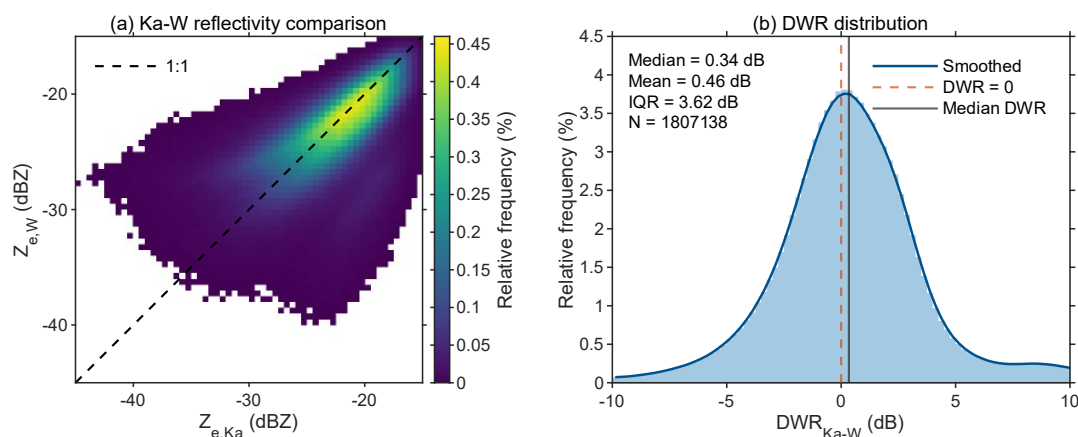


because reflectivity depends on particle concentration and size. The interpretation of weak targets therefore retains the
 395 scattering and attenuation qualifications discussed by Tridon et al. (2020).

We limited each contiguous cold-cloud layer to a geometric thickness of 1 km to favor thinner layers and reduce potential in-
 cloud propagation effects. A profile could contain several qualifying cold-cloud layers. We excluded regions within 150 m
 of each cloud base and top to reduce the effects of strong boundary gradients and sampling-volume differences on
 reflectivity comparisons. Candidate profiles required at least three cold-cloud range gates. Qualifying profiles had to form
 400 events lasting at least 10 s, with no more than 5 s between adjacent profiles, to exclude transient, isolated echoes. These
 thickness, boundary, and duration limits are operational filters for sample selection in this study. We removed invalid values
 and reflectivities affected by suspected range sidelobes, isolated echoes, or near-surface clutter. We corrected two-way
 gaseous attenuation by water vapor and oxygen using ERA5 temperature, pressure, and specific-humidity profiles.

Transmit–receive antenna overlap losses were also corrected. Finally, comparisons used paired range gates on a common 30
 405 m grid. Both bands had to provide valid equivalent radar reflectivity factors satisfying $Z_e \geq -45$ dBZ.

The screened dataset contains 1,807,138 paired reflectivities (Fig. 4). The joint distribution is concentrated near the 1:1 line,
 and DWR has a median of 0.34 dB, a mean of 0.46 dB, and an interquartile range of 3.62 dB. The near-zero center supports
 relative agreement for these selected targets, while the spread includes measurement noise, sampling differences, residual
 attenuation, and scattering effects.



410

Figure 4: Ka–W reflectivity comparison and DWR distribution for the selected cold-cloud samples. (a) Joint relative-frequency distribution of Ka- and W-band equivalent radar reflectivity factors. The black dashed line indicates the 1:1 relationship. (b) Relative-frequency distribution of DWR_{Ka-W} . The orange dashed and gray solid lines denote $DWR = 0$ dB and the median DWR, respectively. The median DWR is 0.34 dB, the mean is 0.46 dB, and the IQR is 3.62 dB ($N = 1\,807\,138$).



415 5 Field performance and observation examples

5.1 Observed statistical boundaries and theoretical reference sensitivity

We evaluated the observed statistical boundaries using observations collected from 1 January 2024 to 31 December 2025. The Mode 3 configuration had a nominal range resolution of 30 m, with a product update interval of approximately 0.92 s. Figures 5a and 5b show the accumulated sample counts of quality-controlled Ka- and W-band echoes on a logarithmic scale, while
 420 Figs. 5c and 5d show the corresponding conditional relative frequencies normalized independently at each range gate before masking and filtering. Because the analysis is based on vertically pointing observations, radar range approximately corresponds to height above radar level.

To determine the observed statistical boundaries, we retained the native 30 m range gates and grouped valid meteorological echoes that passed the standard quality-control procedure into 0.5 dBZ reflectivity bins. At each height, we defined the local
 425 boundary as the center of the lowest-reflectivity bin in a sequence of three consecutive bins, each containing at least 100 samples. We fitted $Z_{\text{obs}}(h) = Z_{\text{obs},10} + 20 \log_{10}[h/(10 \text{ km})]$ over 2–12 km, with the logarithmic slope fixed at 20. The initial intercept was the median of the height-dependent offsets after subtracting the prescribed range term. Offsets differing from this median by more than the larger of 0.5 dB and three unscaled median absolute deviations were excluded, and the final intercept was the median of the retained offsets. The fit used the original counts before display masking and median filtering.
 430 For the evaluated operating configuration, the observed statistical boundaries at 10 km were –44.43 dBZ for the Ka band and –43.20 dBZ for the W band, compared with theoretical reference sensitivities of –43.31 and –43.36 dBZ, respectively. The observed boundary was therefore 1.13 dB lower than the theoretical reference for the Ka band and 0.16 dB higher for the W band. The theoretical calculation used a threshold of twice the standard deviation of noise power fluctuations for integration over the full Doppler spectrum, assuming 256 Doppler samples, 10 independent spectral averages, rectangular processing
 435 windows, a 290 K input noise temperature, and no additional atmospheric attenuation. Both curves use the same prescribed range dependence, so their comparison concerns the fitted and calculated reference levels.

Valid cloud and precipitation echoes occurred mainly between approximately 0 and 13 km above the radar. At lower levels, Ka-band equivalent radar reflectivity factors reached approximately 40 dBZ, whereas retained W-band echoes reached approximately 27 dBZ. With increasing height, both distributions shifted toward weaker reflectivity. Between approximately
 440 8 and 12 km, most valid echoes were between –30 and –10 dBZ. These distributions reflect the combined effects of cloud and precipitation climatology, propagation, signal detection, and range-dependent sensitivity.

The observed statistical boundaries depend on echo occurrence, sampling duration, reflectivity bin size, and quality control. The minimum-count requirement can exclude infrequent weak echoes that have been detected, shifting the statistical boundary toward stronger reflectivities. The count in each bin represents accumulated observations and is distinct from the number of
 445 spectra averaged to produce an individual radar product. We report the observed statistical boundaries alongside the theoretical reference sensitivities to distinguish the retained echo distributions from the sensitivity predicted under the specified system and noise assumptions.

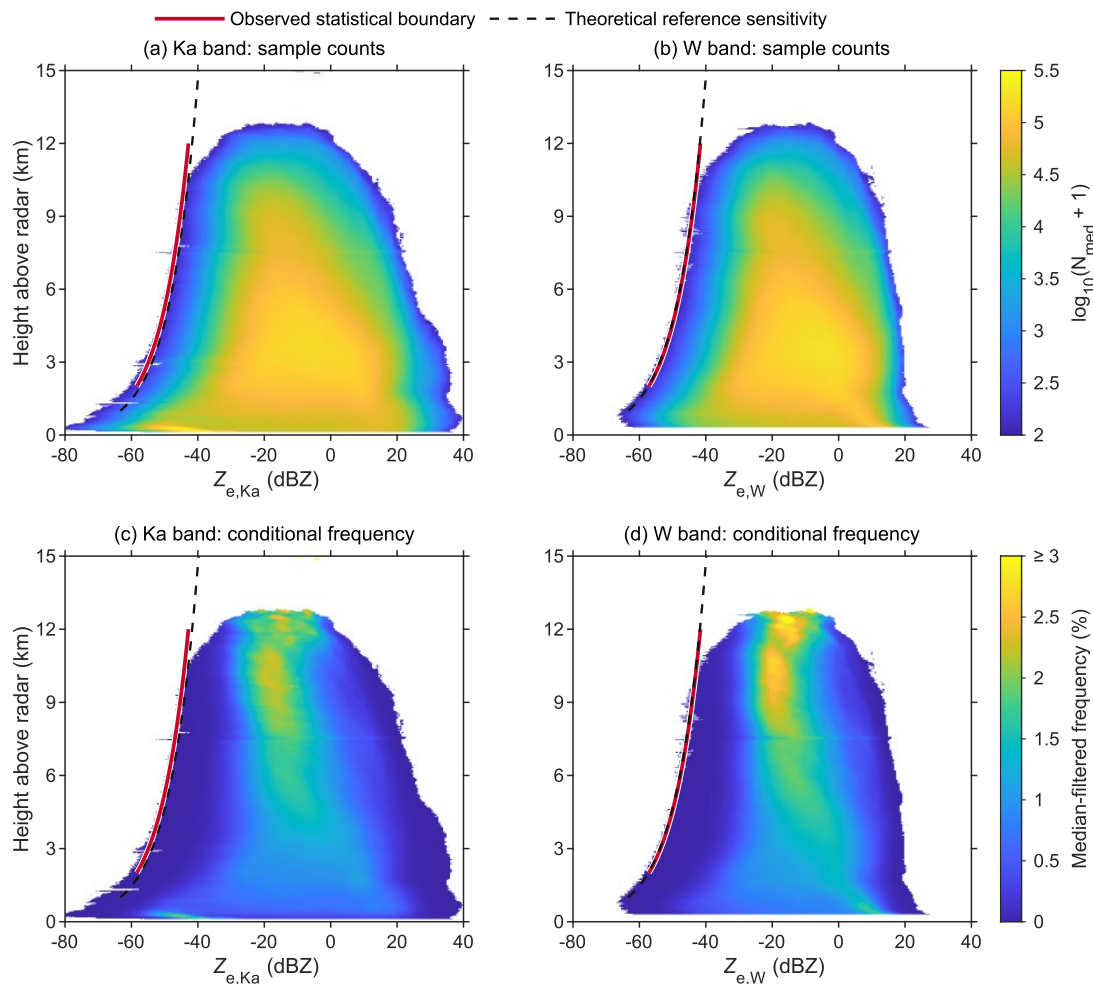


Figure 5. Height–reflectivity distributions of Ka- and W-band equivalent radar reflectivity factors from 1 January 2024 to 31 December 2025. Panels (a, b) show the occurrence counts, and panels (c, d) show the median-filtered conditional relative frequencies (%) for the Ka and W bands, respectively. Red solid curves indicate the observed statistical boundaries fitted over 2–12 km, and black dashed curves indicate the theoretical Mode 3 sensitivities.

5.2 Operational availability and maintenance recovery

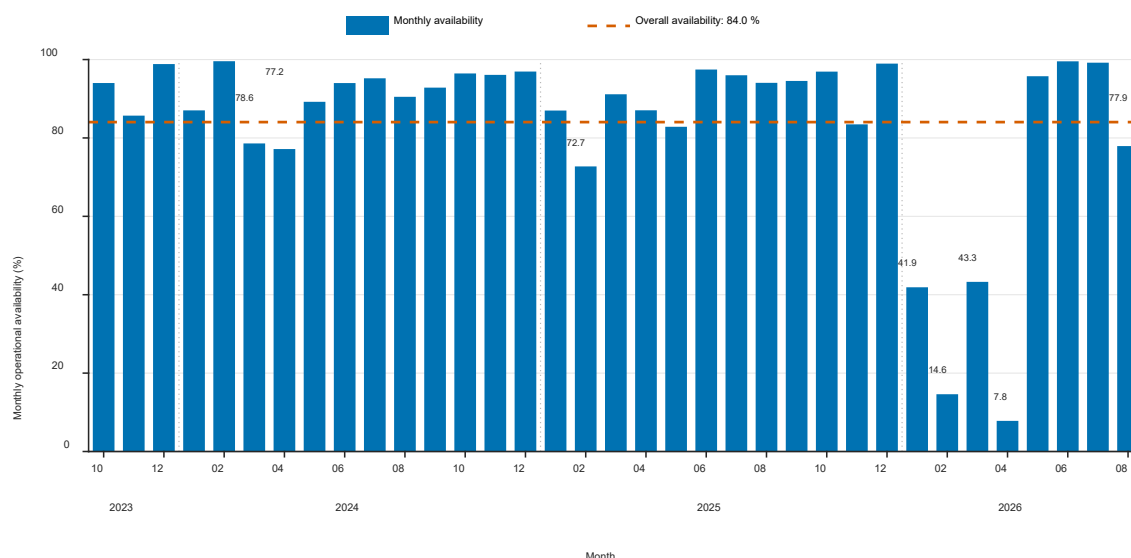
Monthly operational availability and system-status records from October 2023 to August 2026 were used to characterize KaW-TIR operation (Fig. 6). Monthly operational availability was defined as the ratio of valid observation time to total calendar time in each month. A period was counted as valid only when the Ka-band radar, W-band radar, and thermal infrared channel were all operating normally and simultaneously providing valid observations. Interruptions due to scheduled maintenance,



equipment repair, and unexpected shutdowns remained in the statistics, so the results describe observation coverage under actual operating conditions.

460 Mean monthly operational availability was 84.0 % over the full period, including maintenance and failures. Excluding January–April 2026, 27 of the remaining 31 months exceeded 80 %, and mean monthly availability for those 31 months was approximately 91.4 %. The full-period value describes overall observation coverage; the restricted statistic describes the months outside the main failure period.

Monthly operational availability from January to April 2026 was 41.9 %, 14.6 %, 43.3 %, and 7.8 %, respectively. Operating
 465 logs and diagnostic records linked the main interruptions during this period to the Ka-band receiver failure in January 2026. After factory repair and on-site reinstallation of the receiver, operational availability recovered to 95.5 % in May 2026 and approached 100 % over the next two months. These records document the recovery of observation coverage after receiver repair.



470 **Figure 6: Monthly operational availability of KaW-TIR from October 2023 to August 2026.**

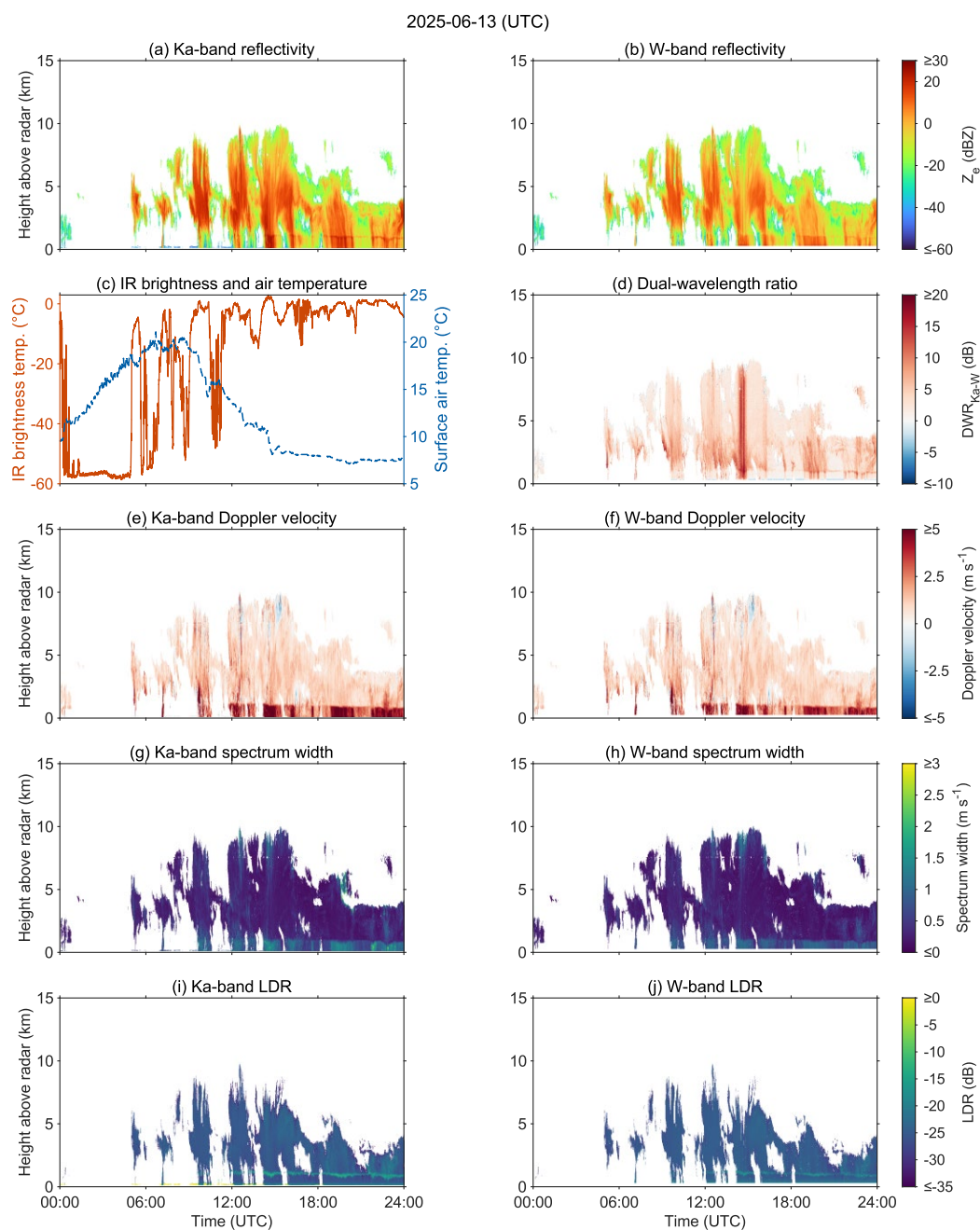
5.3 Representative simultaneous radar–infrared observations

Figure 7 shows coordinated observations on 13 June 2025. Both radars resolve the evolving cloud and precipitation structure, with echoes extending to approximately 8–10 km above radar level. Enhanced reflectivity near 1.5 km is consistent with a melting-layer bright band near the 0 °C level. DWR is generally small in weak upper-level echoes and larger in stronger echoes
 475 and lower-level precipitation, where frequency-dependent scattering and differential attenuation may both contribute. During approximately 02:00–05:00 UTC, when little or no radar cloud echo is detected, infrared brightness temperature remains near −55 °C. It varies more strongly when radar echoes appear and increases during precipitation. These variations



provide a radiometric view of the changing scene alongside the range-resolved radar observations; their interpretation also depends on atmospheric transmission and the quality status of the infrared optical path.

480 Larger Doppler spectral widths and enhanced LDR occur mainly in lower-level echoes and regions of greater vertical development. These observables indicate changes in the distribution of radial velocities and depolarizing backscatter, with contributions from particle properties and measurement conditions. The case demonstrates simultaneous sampling of cloud and precipitation evolution by the radar and infrared channels.



485 **Figure 7: Time–height observations on 13 June 2025: (a, b) Ka- and W-band equivalent radar reflectivity factors; (c) thermal infrared brightness temperature and surface air temperature; (d) Ka–W dual-wavelength ratio; (e, f) Ka- and W-band radial Doppler velocities; (g, h) Doppler spectral widths; (i, j) linear depolarization ratios (LDR). Height is measured above the radar, and time is in UTC.**



6 Discussion and limitations

490 The KaW-TIR system integrates the Ka-band radar, W-band radar, and thermal infrared channel on a common observation platform and uses a common time reference for synchronized acquisition. The three channels are therefore temporally synchronized and observe approximately the same direction. However, because the radar beamwidths and the infrared field of view differ, their spatial sampling volumes are not identical. This difference becomes particularly relevant near cloud boundaries and within spatially heterogeneous clouds, where the three channels may represent different spatial averages.

495 Photogrammetric measurements provide a practical and robust estimate of the relative mechanical alignment of the transmit and receive antennas. Under the present experimental configuration, this represents the best available estimate of the relative pointing geometry. Small differences may nevertheless remain between the mechanical axes, electromagnetic boresights, and infrared viewing axis.

To achieve high detection sensitivity, the Ka- and W-band transmit and receive antennas employ 1.5 m diameter high-gain
500 reflectors. The large antenna aperture results in relatively narrow main beams. Because the transmit and receive antennas are spatially separated, the two beams do not fully overlap at short ranges, reducing the effective two-way antenna gain relative to longer ranges, where the beams overlap more fully. This effect decreases with increasing range and mainly influences quantitative reflectivity estimates in the near range. As high-level ice clouds are an important target for studies of cloud–radiation interactions over the Tibetan Plateau, the system design prioritizes sensitivity to weak cloud echoes. The associated
505 near-range gain reduction caused by incomplete transmit–receive beam overlap is compensated using a range-dependent beam-overlap correction.

Thermal infrared brightness temperature is a band-equivalent radiometric observable determined by the radiance received along the line of sight. Atmospheric transmission, cloud temperature, emissivity, optical thickness, and viewing geometry influence it. In the installed configuration, the gold-coated mirror's finite reflectance and thermal emission may also affect the
510 measured radiance and must be considered in quantitative applications. The simultaneous case presented here therefore demonstrates the radiometric complementarity between infrared observations and radar-observed cloud structure. The measured brightness temperature is not interpreted directly as cloud-top or cloud-base temperature, cloud height, or cloud phase.

The long-term operational record quantifies observation continuity and availability under plateau conditions, including
515 scheduled maintenance, equipment failure, repair, and subsequent recovery. Operational availability, however, is distinct from the long-term stability of the measurement response. Evidence for measurement stability must instead be derived from the corresponding system-monitoring and calibration records. Within these sampling and calibration constraints, the performance assessment and synchronized multi-channel observations presented here provide a basis for subsequent quantitative evaluation and independent validation of synergistic retrievals.



520 7 Conclusions

This study presents the KaW-TIR system deployed at Yangbajing and its basic measurement workflow. The system integrates all-solid-state Ka- and W-band FMCW radars and a thermal infrared channel on a common scanning platform. Internal monitoring tracks the electronic response, metal-sphere measurements provide external reflectivity references for the two radar bands, and natural-target observations provide an additional check on their relative consistency. The metal-sphere
525 measurements yielded mean apparent reflectivity biases of -0.75 dB for the Ka band and $+0.32$ dB for the W band relative to the corresponding sphere references, and these measurements were used to derive band-specific corrections to the radar constants. Separately, the near-zero center of the Ka–W DWR distribution for the screened weak cold-cloud samples supports relative agreement between the two radar bands under the stated selection and correction conditions.

For the evaluated operating mode, the range resolution was 30 m, and the product update interval was approximately 0.92 s.
530 The observed statistical boundaries at 10 km were about -44.43 dBZ for the Ka band and -43.20 dBZ for the W band. This value represents the lower boundary of valid observations for the specified waveform, processing, detection, and quality-control configuration. Long-term height–reflectivity distributions characterize the observed echo population, while the representative case demonstrates concurrent Ka- and W-band radar profiles and line-of-sight thermal infrared brightness-temperature measurements.

535 Long-term operating records quantify operational availability under high-altitude conditions and document interruptions associated with maintenance and receiver failure, as well as the subsequent recovery of observation coverage after repair. Overall, the system design, external calibration results, measurement characterization, and coordinated multi-channel observations establish an observational basis for studies of cloud and precipitation structure over the Tibetan Plateau.

Data availability

540 The KaW-TIR data are available through the Chinese Meridian Project (<https://doi.org/10.12176/01.05.00081-V01>; <https://dcstatus.meridianproject.ac.cn/>).

Code availability

The code is available upon request from the authors.

Author contributions

545 YB and YW led the writing of the paper. YB, YW, RQ, and LP contributed to the instrument development and measurements. YB and YW performed the data processing and analysis. ML, YT, WZ, and JH contributed to the measurements and data analysis. DL supervised the project. All co-authors contributed to the discussion, review, and revision of the manuscript.



Competing interests

The authors declare no conflicts of interest.

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References

- Acquistapace, C., Coulter, R., Crewell, S., Garcia-Benadi, A., Gierens, R., Labbri, G., Myagkov, A., Risse, N., and Schween, J. H.: EUREC4A's Maria S. Merian ship-based cloud and micro rain radar observations of clouds and precipitation, *Earth Syst. Sci. Data*, 14, 33–55, <https://doi.org/10.5194/essd-14-33-2022>, 2022.
- Bell, A., Martinet, P., Caumont, O., Burnet, F., Delanoë, J., Jorquera, S., Seity, Y., and Unger, V.: An optimal estimation algorithm for the retrieval of fog and low cloud thermodynamic and micro-physical properties, *Atmos. Meas. Tech.*, 15, 5415–5438, <https://doi.org/10.5194/amt-15-5415-2022>, 2022.
- 565 Bian, J., Li, D., Bai, Z., Li, Q., Lyu, D., and Zhou, X.: Transport of Asian surface pollutants to the global stratosphere from the Tibetan Plateau region during the Asian summer monsoon, *Natl. Sci. Rev.*, 7, 516–533, <https://doi.org/10.1093/nsr/nwaa005>, 2020.
- Bony, S., Stevens, B., Frierson, D. M. W., Jakob, C., Kageyama, M., Pincus, R., Shepherd, T. G., Sherwood, S. C., Siebesma, A. P., Sobel, A. H., Watanabe, M., and Webb, M. J.: Clouds, circulation and climate sensitivity, *Nat. Geosci.*, 8, 261–268, <https://doi.org/10.1038/ngeo2398>, 2015.
- 570 Delanoë, J., Protat, A., Vinson, J.-P., Brett, W., Caudoux, C., Bertrand, F., Parent du Chatelet, J., Hallali, R., Barthes, L., Haeffelin, M., and Dupont, J.-C.: BASTA: A 95-GHz FMCW Doppler Radar for Cloud and Fog Studies, *J. Atmos. Ocean. Technol.*, 33, 1023–1038, <https://doi.org/10.1175/JTECH-D-15-0104.1>, 2016.
- Dias Neto, J., Nuijens, L., Unal, C., and Knoop, S.: Combined wind lidar and cloud radar for high-resolution wind profiling, *Earth Syst. Sci. Data*, 15, 769–789, <https://doi.org/10.5194/essd-15-769-2023>, 2023.
- Ewald, F., Groß, S., Hagen, M., Hirsch, L., Delanoë, J., and Bauer-Pfundstein, M.: Calibration of a 35 GHz airborne cloud radar: lessons learned and intercomparisons with 94 GHz cloud radars, *Atmos. Meas. Tech.*, 12, 1815–1839, <https://doi.org/10.5194/amt-12-1815-2019>, 2019.



- 580 Fu, Y., Ma, Y., Zhong, L., Yang, Y., Guo, X., Wang, C., Xu, X., Yang, K., Xu, X., Liu, L., Fan, G., Li, Y., and Wang, D.: Land-surface processes and summer-cloud-precipitation characteristics in the Tibetan Plateau and their effects on downstream weather: a review and perspective, *Natl. Sci. Rev.*, 7, 500–515, <https://doi.org/10.1093/nsr/nwz226>, 2020.
- Gao, W., Sui, C.-H., Fan, J., Hu, Z., and Zhong, L.: A study of cloud microphysics and precipitation over the Tibetan Plateau by radar observations and cloud-resolving model simulations, *J. Geophys. Res. Atmos.*, 121, 13735–13752, <https://doi.org/10.1002/2015JD024196>, 2016.
- 585 Hogan, R. J., Illingworth, A. J., and Sauvageot, H.: Measuring Crystal Size in Cirrus Using 35- and 94-GHz Radars, *J. Atmos. Ocean. Technol.*, 17, 27–37, [https://doi.org/10.1175/1520-0426\(2000\)017<0027:MCSICU>2.0.CO;2](https://doi.org/10.1175/1520-0426(2000)017<0027:MCSICU>2.0.CO;2), 2000.
- Huang, J., Zhou, X., Wu, G., Xu, X., Zhao, Q., Liu, Y., Duan, A., Xie, Y., Ma, Y., Zhao, P., Yang, S., Yang, K., Yang, H., Bian, J., Fu, Y., Ge, J., Liu, Y., Wu, Q., Yu, H., Wang, B., Bao, Q., and Qie, K.: Global Climate Impacts of Land-Surface and Atmospheric Processes Over the Tibetan Plateau, *Rev. Geophys.*, 61, e2022RG000771, <https://doi.org/10.1029/2022RG000771>, 2023.
- 590 Huo, J., Bi, Y., Liu, B., Han, C., and Duan, M.: A Dual-Frequency Cloud Radar for Observations of Precipitation and Cloud in Tibet: Description and Preliminary Measurements, *Remote Sens.*, 13, 4685, <https://doi.org/10.3390/rs13224685>, 2021.
- Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Brooks, M. E., Delanoé, J., Donovan, D. P., Eastment, J. D., Gaussiat, N., Goddard, J. W. F., Haeffelin, M., Baltink, H. K., Krasnov, O. A., Pelon, J., Piriou, J.-M., Protat, A., Russchenberg, H. W. J., Seifert, A., Tompkins, A. M., van Zadelhoff, G.-J., Vinit, F., Willén, U., Wilson, D. R., and Wrench, C. L.: Cloudnet: Continuous Evaluation of Cloud Profiles in Seven Operational Models Using Ground-Based Observations, *Bull. Amer. Meteorol. Soc.*, 88, 883–898, <https://doi.org/10.1175/BAMS-88-6-883>, 2007.
- 595 Kneifel, S., von Lerber, A., Tiira, J., Moisseev, D., Kollias, P., and Leinonen, J.: Observed relations between snowfall microphysics and triple-frequency radar measurements, *J. Geophys. Res. Atmos.*, 120, 6034–6055, <https://doi.org/10.1002/2015JD023156>, 2015.
- 600 Kollias, P., Clothiaux, E. E., Miller, M. A., Albrecht, B. A., Stephens, G. L., and Ackerman, T. P.: Millimeter-Wavelength Radars: New Frontier in Atmospheric Cloud and Precipitation Research, *Bull. Amer. Meteorol. Soc.*, 88, 1608–1624, <https://doi.org/10.1175/BAMS-88-10-1608>, 2007.
- Kollias, P., Bharadwaj, N., Widener, K., Jo, I., and Johnson, K.: Scanning ARM Cloud Radars. Part I: Operational Sampling Strategies, *J. Atmos. Ocean. Technol.*, 31, 569–582, <https://doi.org/10.1175/JTECH-D-13-00044.1>, 2014a.
- 605 Kollias, P., Jo, I., Borque, P., Tatarevic, A., Lamer, K., Bharadwaj, N., Widener, K., Johnson, K., and Clothiaux, E. E.: Scanning ARM Cloud Radars. Part II: Data Quality Control and Processing, *J. Atmos. Ocean. Technol.*, 31, 583–598, <https://doi.org/10.1175/JTECH-D-13-00045.1>, 2014b.
- Kollias, P., Bharadwaj, N., Clothiaux, E. E., Lamer, K., Oue, M., Hardin, J., Isom, B., Lindenmaier, I., Matthews, A., Luke, E. P., Giangrande, S. E., Johnson, K., Collis, S., Comstock, J., and Mather, J. H.: The ARM Radar Network: At the Leading Edge of Cloud and Precipitation Observations, *Bull. Amer. Meteorol. Soc.*, 101, E588–E607, <https://doi.org/10.1175/BAMS-D-18-0288.1>, 2020.
- 610 Koop, T., Luo, B., Tsias, A., and Peter, T.: Water activity as the determinant for homogeneous ice nucleation in aqueous solutions, *Nature*, 406, 611–614, <https://doi.org/10.1038/35020537>, 2000.
- 615 Küchler, N., Kneifel, S., Löhnert, U., Kollias, P., Czekala, H., and Rose, T.: A W-Band Radar–Radiometer System for Accurate and Continuous Monitoring of Clouds and Precipitation, *J. Atmos. Ocean. Technol.*, 34, 2375–2392, <https://doi.org/10.1175/JTECH-D-17-0019.1>, 2017.
- Lhermitte, R.: Attenuation and Scattering of Millimeter Wavelength Radiation by Clouds and Precipitation, *J. Atmos. Ocean. Technol.*, 7, 464–479, [https://doi.org/10.1175/1520-0426\(1990\)007<0464:AASOMW>2.0.CO;2](https://doi.org/10.1175/1520-0426(1990)007<0464:AASOMW>2.0.CO;2), 1990.
- 620 Li, H. and Moisseev, D.: Melting Layer Attenuation at Ka- and W-Bands as Derived From Multifrequency Radar Doppler Spectra Observations, *J. Geophys. Res. Atmos.*, 124, 9520–9533, <https://doi.org/10.1029/2019JD030316>, 2019.



- Lu, D., Pan, W., and Wang, Y.: Atmospheric Profiling Synthetic Observation System in Tibet, *Adv. Atmos. Sci.*, 35, 264–267, <https://doi.org/10.1007/s00376-017-7251-7>, 2018.
- 625 Mace, G. G., Ackerman, T. P., Minnis, P., and Young, D. F.: Cirrus layer microphysical properties derived from surface-based millimeter radar and infrared interferometer data, *J. Geophys. Res. Atmos.*, 103, 23207–23216, <https://doi.org/10.1029/98JD02117>, 1998.
- Matrosov, S. Y., Uttal, T., Snider, J. B., and Kropfli, R. A.: Estimation of ice cloud parameters from ground-based infrared radiometer and radar measurements, *J. Geophys. Res. Atmos.*, 97, 11567–11574, <https://doi.org/10.1029/92JD00968>, 1992.
- 630 Matrosov, S. Y., Orr, B. W., Kropfli, R. A., and Snider, J. B.: Retrieval of vertical profiles of cirrus cloud microphysical parameters from Doppler radar and infrared radiometer measurements, *J. Appl. Meteorol.*, 33, 617–626, [https://doi.org/10.1175/1520-0450\(1994\)033<0617:ROVPOC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1994)033<0617:ROVPOC>2.0.CO;2), 1994.
- Mech, M., Kliesch, L. L., Anhäuser, A., Rose, T., Kollias, P., and Crewell, S.: Microwave Radar/radiometer for Arctic Clouds (MiRAC): first insights from the ACLOUD campaign, *Atmos. Meas. Tech.*, 12, 5019–5037, <https://doi.org/10.5194/amt-12-5019-2019>, 2019.
- 635 Morrison, H., van Lier-Walqui, M., Fridlind, A. M., Grabowski, W. W., Harrington, J. Y., Hoose, C., Korolev, A., Kumjian, M. R., Milbrandt, J. A., Pawlowska, H., Posselt, D. J., Prat, O. P., Reimel, K. J., Shima, S.-I., van Diedenhoven, B., and Xue, L.: Confronting the Challenge of Modeling Cloud and Precipitation Microphysics, *J. Adv. Model. Earth Syst.*, 12, e2019MS001689, <https://doi.org/10.1029/2019MS001689>, 2020.
- 640 Myagkov, A., Nomokonova, T., and Frech, M.: Empirical model for backscattering polarimetric variables in rain at W-band: motivation and implications, *Atmos. Meas. Tech.*, 18, 1621–1640, <https://doi.org/10.5194/amt-18-1621-2025>, 2025.
- Ohara, K. and Masunaga, H.: Evaluation of ice hydrometeor retrieval using multi-band radar and millimeter-wave radiometer measurements from the IMPACTS campaign, *Atmos. Meas. Tech.*, 19, 4099–4119, <https://doi.org/10.5194/amt-19-4099-2026>, 2026.
- 645 Sekelsky, S. M., and Clothiaux, E. E.: Parallax Errors and Corrections for Dual-Antenna Millimeter-Wave Cloud Radars, *J. Atmos. Ocean. Technol.*, 19, 478–485, [https://doi.org/10.1175/1520-0426\(2002\)019<0478:PEACFD>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0478:PEACFD>2.0.CO;2), 2002.
- Socuellamos, J. M., Rodriguez Monje, R., Lebsock, M. D., Cooper, K. B., Beauchamp, R. M., and Umeyama, A.: Multifrequency radar observations of marine clouds during the ECAPE campaign, *Earth Syst. Sci. Data*, 16, 2701–2715, <https://doi.org/10.5194/essd-16-2701-2024>, 2024a.
- 650 Socuellamos, J. M., Rodriguez Monje, R., Lebsock, M. D., Cooper, K. B., and Kollias, P.: Dual-frequency (Ka-band and G-band) radar estimates of liquid water content profiles in shallow clouds, *Atmos. Meas. Tech.*, 17, 6965–6981, <https://doi.org/10.5194/amt-17-6965-2024>, 2024b.
- Stephens, G. L.: Cloud Feedbacks in the Climate System: A Critical Review, *J. Climate*, 18, 237–273, <https://doi.org/10.1175/JCLI-3243.1>, 2005.
- 655 Teisseire, A., Seifert, P., Ohneiser, K., Maahn, M., Spirig, R., and Henneberger, J.: Evaluation of the Vertical Distribution of Particle Shape (VDPS) method with in situ measurements and assessment of the impact of non-Rayleigh scattering, *Atmos. Meas. Tech.*, 19, 2897–2921, <https://doi.org/10.5194/amt-19-2897-2026>, 2026.
- Toledo, F., Delanoë, J., Haeffelin, M., Dupont, J. C., Jorquera, S., and Le Gac, C.: Absolute calibration method for frequency-modulated continuous wave (FMCW) cloud radars based on corner reflectors, *Atmos. Meas. Tech.*, 13, 6853–6875, <https://doi.org/10.5194/amt-13-6853-2020>, 2020.
- 660 Tolentino, M., Bravo-Aranda, J. A., Guerrero-Rascado, J. L., Navas-Guzmán, F., Pérez-Ramírez, D., Alados-Arboledas, L., and Granados-Muñoz, M. J.: Long-term cloud characterization at the AGORA ACTRIS-CCRES station using a novel classification algorithm, *Atmos. Meas. Tech.*, 19, 2079–2102, <https://doi.org/10.5194/amt-19-2079-2026>, 2026.
- Tridon, F., and Battaglia, A.: Dual-frequency radar Doppler spectral retrieval of rain drop size distributions and entangled dynamics variables, *J. Geophys. Res. Atmos.*, 120, 5585–5601, <https://doi.org/10.1002/2014JD023023>, 2015.



- 665 Tridon, F., Battaglia, A., and Kneifel, S.: Estimating total attenuation using Rayleigh targets at cloud top: applications in
multilayer and mixed-phase clouds observed by ground-based multifrequency radars, *Atmos. Meas. Tech.*, 13, 5065–5085,
<https://doi.org/10.5194/amt-13-5065-2020>, 2020.
- Vishwakarma, P., Delanoë, J., Jorquera, S., Martinet, P., Burnet, F., Bell, A., and Dupont, J. C.: Climatology of estimated
liquid water content and scaling factor for warm clouds using radar–microwave radiometer synergy, *Atmos. Meas. Tech.*,
670 16, 1211–1237, <https://doi.org/10.5194/amt-16-1211-2023>, 2023.
- Vogl, T., Maahn, M., Kneifel, S., Schimmel, W., Moisseev, D., and Kalesse-Los, H.: Using artificial neural networks to predict
riming from Doppler cloud radar observations, *Atmos. Meas. Tech.*, 15, 365–381, [https://doi.org/10.5194/amt-15-365-](https://doi.org/10.5194/amt-15-365-2022)
2022, 2022.
- Vogl, T., Radenz, M., Ramelli, F., Gierens, R., and Kalesse-Los, H.: PEAKO and peakTree: tools for detecting and interpreting
675 peaks in cloud radar Doppler spectra – capabilities and limitations, *Atmos. Meas. Tech.*, 17, 6547–6568,
<https://doi.org/10.5194/amt-17-6547-2024>, 2024.
- Williams, E. R., Hood, K. T., Cho, J. Y. N., Smalley, D. J., Sandifer, J. B., Zrníc, D., Melnikov, V. M., Burgess, D. W., Forsyth,
D., Webster, T. M., and Erickson, D.: End-to-end Calibration of NEXRAD Differential Reflectivity with Metal Spheres,
36th Conference on Radar Meteorology, Breckenridge, CO, USA, 16–20 September 2013,
680 <https://ams.confex.com/ams/36Radar/webprogram/Paper228796.html>, 2013.
- Wu, J., Sun, Q., and Bi, Y.: Study of Diurnal Variation of Cloud Macro Parameters in Three Important Weather Systems over
the Tibetan Plateau Using Ka-Band Cloud Radar, *Chinese Journal of Atmospheric Sciences* (in Chinese), 46, 1030–1040,
<https://doi.org/10.3878/j.issn.1006-9895.2009.20103>, 2022.
- Wu, Y., Gao, J., and Zhao, A.: Cloud properties and dynamics over the Tibetan Plateau – A review, *Earth-Sci. Rev.*, 248,
685 104633, <https://doi.org/10.1016/j.earscirev.2023.104633>, 2024.
- Yin, J., Hoogeboom, P., Unal, C., Russchenberg, H., v. d. Zwan, F., and Oudejans, E.: UAV-Aided Weather Radar Calibration,
IEEE Trans. Geosci. Remote Sens., 57, 10362–10375, <https://doi.org/10.1109/TGRS.2019.2933912>, 2019.
- Zhang, F., Yu, Q. R., Mao, J. L., Dan, C., Wang, Y., He, Q., Cheng, T., Chen, C., Liu, D., and Gao, Y.: Possible mechanisms
of summer cirrus clouds over the Tibetan Plateau, *Atmos. Chem. Phys.*, 20, 11799–11808, [https://doi.org/10.5194/acp-20-](https://doi.org/10.5194/acp-20-11799-2020)
690 11799-2020, 2020.
- Zhao, W., Wang, Y., Bi, Y., Wu, X., Tian, Y., Wu, L., Luo, J., Hu, X., Qi, Z., Li, J., Pan, Y., and Lyu, D.: Unveiling Cloud
Vertical Structures over the Interior Tibetan Plateau through Anomaly Detection in Synergetic Lidar and Radar
Observations, *Adv. Atmos. Sci.*, 41, 2381–2398, <https://doi.org/10.1007/s00376-024-3221-z>, 2024.