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Real-time measurements and analyses of precipitation micro-structure and dynamics

W. L. Randeu[1,2], **M. Schönhuber**[1], **and G. Lammer**[1]

[1]Institute of Applied Systems Technology, Joanneum Research GmbH, Graz/Austria
[2]Institute of Communications and Wave Propagation, Technical University Graz, Austria

Abstract. Several scientific and applied research disciplines are developing increased interest in the objective determination of precipitation micro-structure and - dynamics parameters, i.e. particle shape and size, fall speed, material, spatial orientation and oscillation characteristics. Among these fields are e.g. calibration of precipitation sensors, remote sensing of precipitation, type of weather determination, soil erosion studies, snow and mixed-phase water equivalent determination, analysis of channel characteristics in radio communication and navigation systems, and scattering modelling and propagation correction in passive and active remote sensing.

This paper describes measurements and analyses performed by an instrument especially designed for such purpose, the so-called 2D-Video-Distrometer (2DVD), which delivers, in real time, front and side view, as well as fall speed, of each particle falling through a 10 cm by 10 cm wide sensing area, with a resolution in the order of 0.15 mm. Beyond individual particles' characteristics the bulk parameters (rainrate, size and shape distribution etc.) are generated online as well. Specifications of the 2DVD and calibration procedures are given, results from a number of events observed in different climates (Alpine mountain range, moderate mid-latitude, down to tropical regions) are shown as examples, including summer as well as winter precipitation. Prototype methods for deriving solid precipitation water equivalent information are described, as well as recent findings on the accuracy of rain drop canting angle measurements. Finally it is shown how 2DVD data can be applied for real-time comparison, calibration and/or validation of weather radar measurements, leading to Z-R relations deviating from usual models. The 2DVD is presently manufactured in a small series, with some ten units in operation now.

1 The Instrument (2DVD)

All results presented and discussed here below are based on measurements performed with a specially developed precipitation sensor, the 2D-Video-Distrometer ("2DVD"). This is a high-speed imaging system for retrieving contour data from each precipitation particle falling through a 10 cm by 10 cm wide capture area, defined by two crossing horizontal light sheets. Two high-speed line scan cameras, one looking south-north, the other west-east, retrieve and record shadow regions in these light sheets, generated by particles falling through. This results in having front as well as side-view information available at a rate up to 51 000 lines per second and camera, and a horizontal pixel number up to 700 (across 10 cm sheet width).

Figure 1 illustrates the resolution which can be achieved by the 2DVD. It shows front and side view of a 1 mm diameter steel sphere, thrown through the capture area (shown in upper right quarter, being 700 pixels wide in both views), just at the position of the yellow marker (the red markers are positions of earlier thrown spheres). Sphere contour line widths represent the resolution achievable, in this case in the order of 0.15 mm. Fall speed is also measured by means of a small (about 6 mm) vertical offset between the two light sheets, which allows to calculate speed via time lapse between the object appearing in both cameras.

Besides the cameras and associated illumination and optical components contained in a rigid, temperature-stable housing (the "sensor unit"), the 2DVD consists of two high-level personal computers, one outdoors close to the sensor unit, responsible for fetching line-scan camera raw data, the other one indoors, up to 180 m away from the sensor unit, providing the graphical user interface as well as all control and archiving functions. Powerful software allows to view single particle data (as in Fig. 1) as well as precipitation bulk characteristics derived therefrom, like size and oblateness distributions, velocity vs. diameter scatterplots and even horizontal wind components derived from particle trajectories slantness.

More detailed information on the 2DVD can be found e.g. in Schönhuber et al. (1997) and in http://www.distrometer.at.

2 Calibration

Imaging fidelity of the 2DVD is checked / calibrated by means of throwing a hand full of spheres of known diameters through the capture area, and evaluating (on-line) the

Correspondence to: M. Schönhuber
(michael.schoenhuber@joanneum.at)

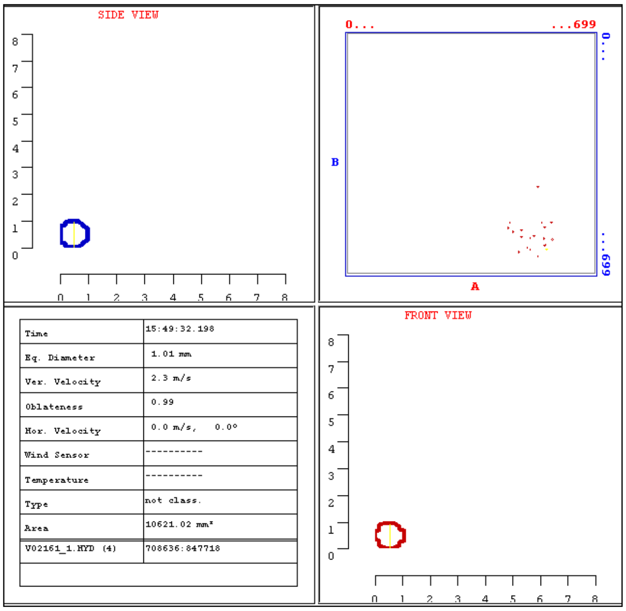


Fig. 1. 2DVD reproduction of 1 mm calibration sphere. Front, side view of sphere, as well as virtual top view of sensing area given.

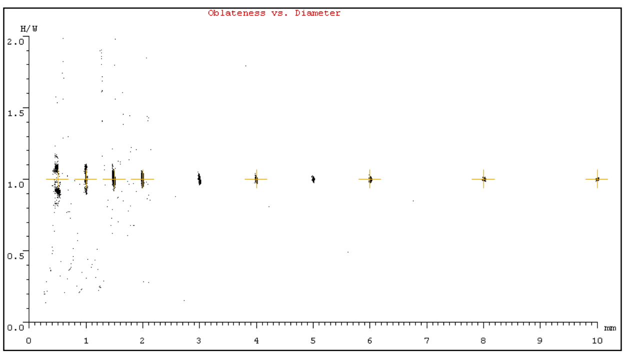


Fig. 2. Reproduction of calibration spheres in an oblateness vs. diameter diagram. 5247 objects counted, outliers often caused by two or more spheres clinging together.

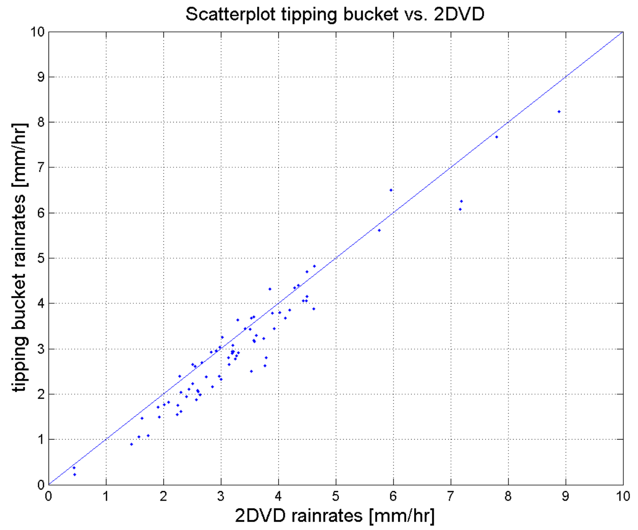


Fig. 3. Scatterplot of rainrates, tipping buckt vs. 2DVD. Data taken on 29 May 2000, after a wintertime field campaign on Mt. Erzberg, Styria, Austria.

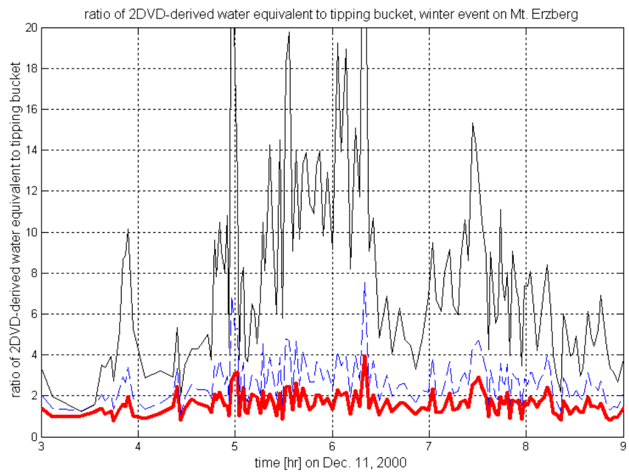


Fig. 4. Ratios of 2DVD-derived water equivalent to tipping bucket, wintertime event recorded on Mt. Erzberg, Austria on 11 December 2000. Thin black line refers to 2DVD derivation method (a), dashed blue to (b), thick red to (c).

distribution of these objects in an oblateness-versus-diameter diagram, where oblateness is defined as the height to width ratio.

Figure 2 shows the result of such a procedure, using steel spheres with 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0 and 10.0 mm diameter, counting 5247 objects in total. Results shown are quite acceptable, taking into account that a small number of obvious “outliers” below 3 mm diameter are mainly due to incorrect assignment between images in both cameras (a huge number of tiny spheres are crossing the light sheets more or less simultaneously), but also due to spheres clinging together, emulating non-spherical objects. Figure 3 shows a scatterplot of rainfall rates measured by 2DVD (abszissa) and by a tipping bucket raingauge (ordinate), during a rain event on Mt. Erzberg (Austria), on 29 May 2000, between 00:00 and 03:00. One can see good correlation and cumulative agreement between the two measurements. Rain totals yielded for this event are 8.0 mm by the 2DVD and 7.3 mm by the tipping bucket raingauge. A slight systematic overestimation by the 2DVD is probably caused by the ’matching algorithm’ (identifying elements in the data streams of the two cameras), improvements are underway. The correlation coefficient for the two time series of rainrates (2DVD and tipping bucket) for this event is 0.9714. Altogether the 2DVD’s rainfall rate typically differs less than 10% from those of tipping bucket rain gauges.

Table 1. Accuracy of drop canting angle measurement

2DVD tilt angle		Mean drop canting angle retrieved from 2DVD data		Mean canting angle error	
cam. A	cam. B	cam. A	cam. B	cam. A	cam. B
-5°	-5°	4.77°	4.89°	-0.23°	-0.11°
+2°	0°	-0.98°	0.62°	1.02°	0.62°
+5°	0°	-3.95°	1.85°	1.05°	1.85°

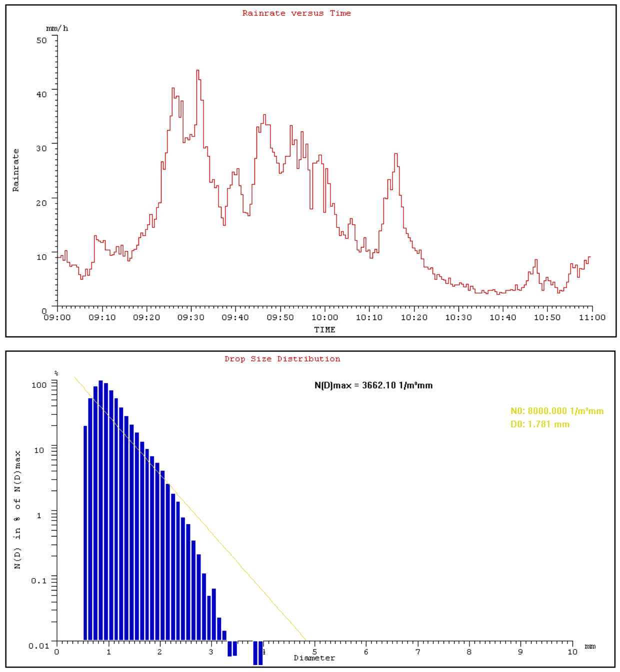


Fig. 5. Rainrate vs. time (09:00–11:00) and drop size distribution (09:25–10:05). Tropical rain event recorded in Lae, Papua New Guinea (geographical latitude 7 deg south)

3 Snow water equivalent determination

For snow particles the 2DVD retrieves contour data with the same precision as those of raindrops, but due to lack of unique snowflake shape models, and due to material mixing ratio uncertainties the equivalent rainfall rate (or snow water equivalent) can only be based on some estimates.

Having at hand the front- and sideview of each snowflake entering the 2DVD, it is practically impossible to reconstruct its full 3D shape information. Small holes and cavities do not necessarily reflect unshadowed regions in the view, only straight tunnels through the whole particle, being aligned in parallel with the light beam, would produce holes in the shadow. So there is surely additional information necessary in order to determine the particle's mass. In case of the 2DVD the additional information is the fall velocity.

In order to demonstrate the effect of several mass reconstruction methods on the accuracy of snow equivalent water content, 2DVD and simultaneous (heated) rain gauge measurements on Mt. Erzberg, performed on 11 December 2000, have been analysed in this respect. The "mass" reconstruction techniques applied are (in ascending complexity order):

(a) No volume correction, process snowflake like raindrop: Each particle's volume is reconstructed from the measured shadow areas (summation of horizontal ellipses with axes given by shadow widths). The particles' rain contribution (yielded via the 2DVD capture area which is slightly different for different particle sizes, since only fully visible particles are considered) is integrated over a selected integration time interval, arriving at a total rain amount having fallen into the 2DVD's capture area. This total rain amount divided by the time interval gives the "rainfall" rate in millimeters per hour. It is like assigning each particle the density of water.

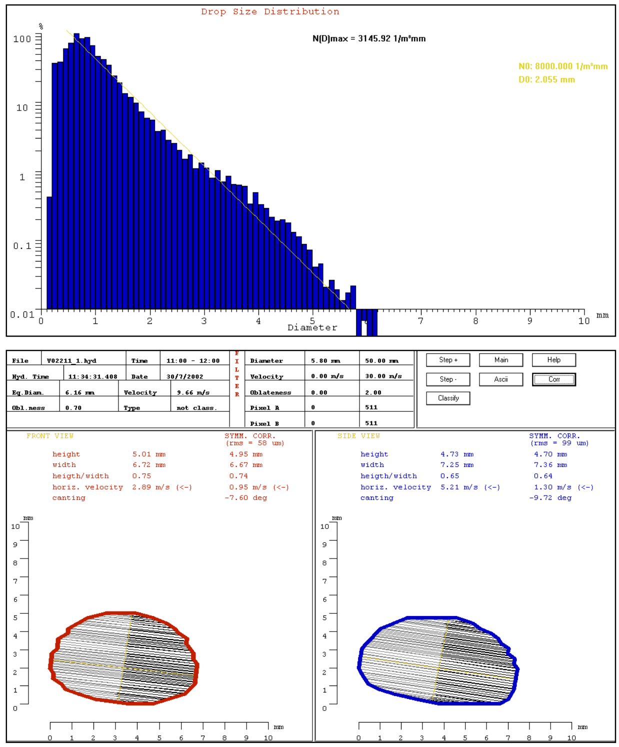
(b) Correction for slower fall velocity (compared to that of raindrop of equal volume) is applied: The measured fall velocity is used as an (approximative) indicator of lower-than-water density being actually present. This means that the particle volumes obtained under a) are multiplied by their associated ratios (measured_fall_velocity / fall_velocity_of_equivolumetric_rain_drop), in order to account for the snow-flake's lower density.

(c) In addition to (b): Correction by ratio (shadow area)/ (area of smallest circumscribed convex polygon), also providing a measure of shape compactness (contour smoothness). There are two polygons, one for the front and one for the side view. In consequence one has two ratios (actual_shadow_area / polygon_area), which are multiplied to give a correction factor being small for rather structured flakes (with many arms and legs, expected to have rather low density), while being close to 1 for more "compact" particle shapes. This additionally accounts for the actual material density. The number of polygon angles follows from the observed shadow shape (there exists only one SMALLEST circumscribed convex polygon for each shape), the edge number is therefore varying from particle to particle and from view to view.

Figure 4 shows the ratio of 2DVD-derived precipitation rates (for the said event, with three curves showing the results from applying the mentioned methods (a) through (c)) to the tipping bucket measured rate. It is seen that - for this event - method (c) performs best, though the red line still differs from the ideally constant ratio 1. Seen over a larger number of events, performance generally increases from (a) to (c). Results shown here are to be taken as preliminary samples, additional, more detailed work on this topic is underway.

4 Drop canting angle determination

Artificially generated water drops were subjected to falling, from a 35 m high tower, into the capture area of the 2DVD. The purpose was to identify the presence and significance of drop canting and oscillation effects introduced by micro-turbulences in otherwise stagnant air (the experiment was conducted during apparently calm conditions). In addition, it was to show that the 2DVD is capable of reliably measuring such parameters. In order to introduce an artificial mean canting angle, the 2DVD's sensor unit was tilted by (nominally) 0, 2 and/or 5 degrees (see Table 1) into the main directions (i.e. parallel to one, orthogonal to the other camera), letting expect that canting angle distributions derived from the two line-scan camera images (front view = A, side view = B) should have their means at just the negative angle. Table 1 presents sample results of this experiment, for three tilt angle pairs. It is seen that drop canting angle (or instrument's tilt angle) variations as small as 5 degrees, maybe even smaller, can reliably be identified. Taking the small errors obtained for the tilt angle pair ($-5°$, $-5°$), and in contrast the rather large errors for the other two cases, one may expect that there was additional external aerodynamic influence present for the latter ones. Therefore a series of such measurements is planned to be conducted under even better controlled and monitored conditions. This should deliver additional arguments for using the 2DVD as reference instrument for polarimetric radar data inversion and interpretation.



(a)

(b)

Fig. 6. Drop size distribution plus sample raindrop (6.16 mm in diameter), measured in Graz, Austria on 7 August 2002, 11:33–11:53, with an average rainrate of 52 mm/hr for these 20 minutes. Canting angles of the raindrop indicated.

5 Selected results obtained in different climates

2DVD units have been employed in a number of campaigns in different climates. Already in 1995 one 2DVD was operated by the Papua New-Guinea University of Technology, with the main purpose of verifying the instrument's capability of dealing with the large number of drops in tropical rainfall. The 2DVD-measured drop size distribution (DSD) of one event selected from this 6 months lasting experiment is shown in Figs. 5a and 5b. Figure 5a presents rainfall rate R vs. time, from 9:00 to 11:00 on 21 June 1995, integration period 30 seconds, with peak values exceeding 40 mm/hr. For the most intense part of this event, from 09:25 to 10:05, Fig. 5b shows the drop size distribution (DSD), together with the exponential DSD model by Marshall and Palmer (1948), with $N_o = 8000$/m3mm and a specific $D_o = 1.781$ mm. It is evident, that the measured distribution has, compared to the model, a lack of larger drops, which is of significance when converting radar reflectivity Z into rainfall rate R (underestimation of R).

Figures 5a and 5b (as well as Figs. 6 and 7) are actually sub-windows of the 2DVD's presentation surface which is on-line accessible by the user, during operational measurements. Data archiving is done in the background, undisturbed by any viewing or analysis actions. Results from a very recent summertime event in Graz / Austria are shown in Figs. 6a and b. It was an intense rain event in the first half of August 2002, when many places of Central Europe were stroken by severe floods. Figure 6a shows the dropsize distribution for 11:33–11:53, 7 August 2002, with an average rainrate of 52 mm/hr for these 20 minutes. Peak rainrates came up to more than 100 mm/hr. As with many convectice events in the Alpine mountain range, big drops of 6 mm and more were observed, Fig. 6b giving a sample.

Finally Figs. 7a and 7b show a moderate mid-latitude event recorded in Graz, Austria on 25 September 2001, from 19:00 to 21:00. Again Fig. 7a presents rainfall rate vs. time, indicating a peak value around 37 mm/hr. The red curve represents 2DVD data, while the blue curve stands for values measured by a co-sited tipping bucket rain gauge. The two lines do not differ much, they are nearly identical. The drop size distribution in Fig. 7b, covering the time interval 19:41 to 19:49, now matches quite well with a Marshall-Palmer distribution, in this case having $D_o = 1.694$ mm, shown as a yellow line. The first-glance impression that there again is a lack of large drops cannot be held upright when considering the excess densities at 4.65 mm and 5.45 mm diameter, which are compensating the "hole" between 4.7 mm and 5.4 mm. Here the limit of statistical significance has been reached, due to the limited observation time (8 minutes).

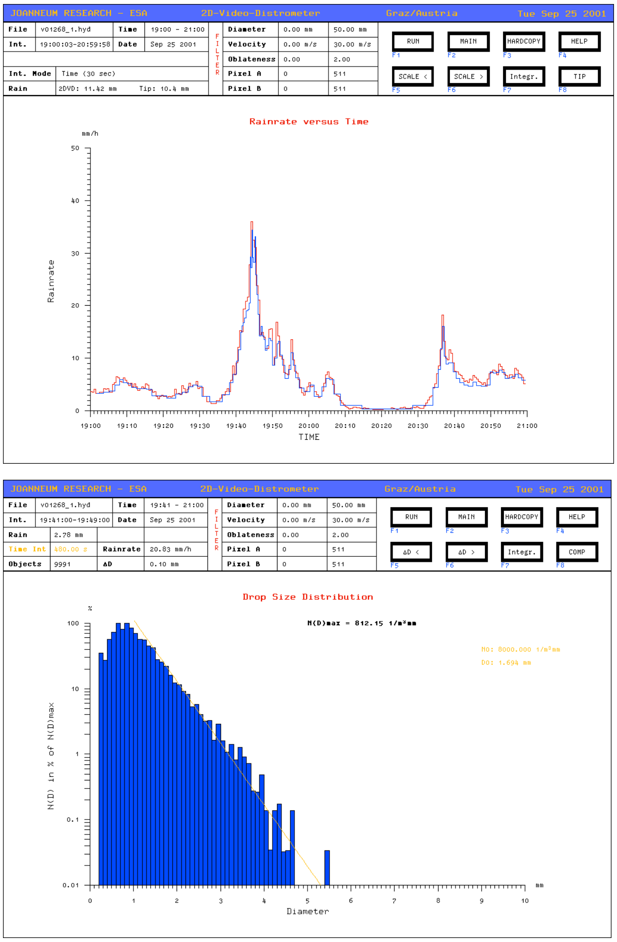


Fig. 7. Rainrate vs. time (19:00–21:00) and drop size distribution (19:41–19:49) for moderate mid-latitude event, recorded in Graz, Austria on 25 September 2001. Red curve represents 2DVD-measured rainfall rate, blue curve gives tipping bucket raingauge.

6 Validation of weather radar measurements

The sample events shown in Figs. 5 to 7 clearly indicate the need for retrieving ancillary information when operating weather radars for quantitative applications (e.g. flood monitoring, water management, electromagnetic wave propagation studies). They also indicate that the 2DVD is a well suited instrument for this purpose, especially when going into polarimetric radar measurements where particle shapes and spatial alignment/orientation characteristics are of significance. 2DVD data are stored and available to the user in real time (actually with a small delay of less than one minute). So in real time the information to determine precipitation's phase state (rain, sleet, hail, etc.) is available, with the details for size distribution and shape information included. Figures 8 and 9 show Z-R pairs, derived from 2DVD measurements for the rain recorded in Graz / Austria on 7 August 2002 (cf. Fig. 6) and in Lae / Papua New Guinea on 21 June 1995 (cf. Fig. 5). The blue dots represent the Z-R pairs derived from 2DVD measurements for

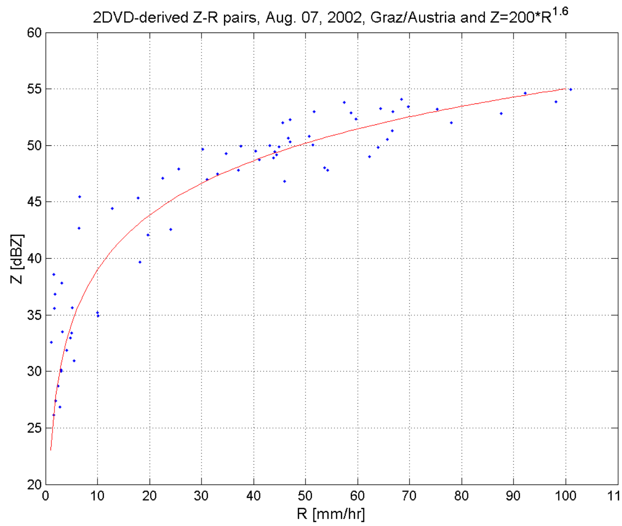


Fig. 8. $Z-R$ pairs (blue dots) derived from 2DVD measurements in Graz, Austria, 7 August 2002. Red line denotes $Z = 200 \cdot R^{1.6}$.

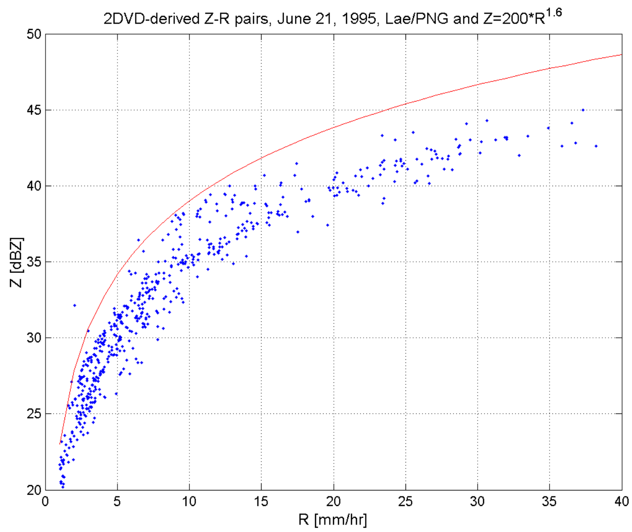


Fig. 9. $Z-R$ pairs (blue dots) derived from 2DVD measurements in Lae, Papua New Guinea, 21 June 1995. Red line denotes $Z = 200 \cdot R^{1.6}$.

30 seconds integration intervals, the red line gives the standard relationship $Z = 200 \cdot R^{1.6}$. It is clearly visible, that the intense mid-latitude summertime rain event (Fig. 8) follows $Z = 200 \cdot R^{1.6}$ rather well, whereas application of this formula for the tropical rain event (Fig. 9) would result in considerable errors of a Z-derived rainrate. Such point monitoring information may very well be applied to improve the radar-derived rainfall parameters. Using data from the Graz / Hilmwarte research weather radar (Randeu et al., 1991) it was shown by Schönhuber (1998), that radar-derived prediction of propagation parameters for a satellite slantpath showed better results, taking into account the point monitoring information given by the 2DVD. Improvements were obtained for single parameter radar modelling ($Z-R$ con-

versions) and for dual polarisation parameter modelling as well. Beyond work performed in Graz / Austria a number of relevant research groups are using 2DVD units and data, and carried out respective studies, refer to, for example, Barthazy (1998), Hubbert et al. (1997), Ibrahim et al. (1998), Kruger and Krajewski (2002), Schuur et al. (2001a, b), and Tokay et al. (1999, 2001).

7 Summary and conclusion

In the last decades intense work has been done to study rainfall characteristics, for purposes of remote sensing, telecommunications, and others more. Whereas widely tested models exist for certain precipitation types, e.g. for widespread rain in moderate climate regions, the dynamic behaviour of convective and/or mixed phase precipitation events still reveals some open questions. Climatic dependencies are further to be investigated as well. Multiparameter polarimetric radars are a suitable tool for enhanced observations. The 2D-Video-Distrometer (2DVD) provides imaging ground validation data, giving comprehensive information on precipitation parameters, on individual particles and precipitation bulk parameters (rainrate, size distribution, etc.). Included is size and shape of particles, estimates for snowflakes' water equivalent may be obtained and information on raindrop orientation angles. 2DVD data are a point monitoring information given in real time. Weather radar data interpretation could be improved, integrating 2DVD information into the analysis algorithms. A number of relevant research groups carry out 2DVD measurements and / or use such data.

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