Inter-comparison of Raingauges on Rainfall Amount and Intensity Measurements in a Tropical Environment

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Abstract

The Hong Kong Observatory (HKO) has been carrying out a field inter-comparison of various automatic raingauges since 2011 with a view to identifying raingauges that can meet WMO's ±5% accuracy requirement in measuring rainfall amount and are robust enough to be deployed in a tropical environment. The inter-comparison was conducted at HKO's meteorological stations at King's Park (KP) (WMO Station No. 45004) and Hong Kong International Airport (HKIA) (WMO Station No. 45007) in Hong Kong. Preliminary results of the inter-comparison conducted in 2011 and 2012 were presented at TECO-2012.

The inter-comparison continued in 2013 with the introduction of two 0.1-mm resolution Pluvio-OTT weighing gauges, the type of which outperformed others in WMO's field inter-comparison held between October 2007 and April 2009. The performances of 14 raingauges, comprising 5 different measurement methods, viz. drop-counting, weighing, tipping bucket without correction, tipping bucket with software correction and tipping bucket with extra pulse correction, were evaluated. The focus of the inter-comparison in 2013 was to study the performance of these raingauges in rainfall intensity measurement, especially during heavy rain situations. During this period, different high rainfall intensity episodes with five consecutive 1-minute rainfall intensity exceeding 10 mm/hr, 30 mm/hr, 50 mm/hr, 70 mm/hr and 100 mm/hr were selected for analysis. Among these rain episodes, the maximum 1-minute rainfall intensity as high as around 130 mm/hr was recorded by the OTT raingauges.

This paper serves to conclude the 3-year (2011–2013) inter-comparison exercise for rainfall amount measurements as well as to provide preliminary 1-year (2013) comparison results on rainfall intensity measurements.

1. Introduction

The Hong Kong Observatory (HKO) has been conducting field inter-comparison of automatic raingauges at its meteorological stations at King's Park (KP) and Hong Kong International Airport (HKIA) in Hong Kong since 2011. The objective of the comparison exercises is to identify which types of 0.1-mm resolution raingauges can meet the WMO's ±5% accuracy requirement in measuring rainfall amount and are robust enough to be deployed in the field in tropics. Preliminary results of the inter-comparison conducted in 2011 and 2012 were presented at TECO-2012 (Tam et.al 2012).

The inter-comparison continued in 2013 with the introduction of two 0.1-mm resolution Pluvio-OTT[1] weighing gauges at the KP test site to serve as the reference raingauges for benchmarking the performances of other raingauges in rainfall intensity measurements.

In a tropical environment like Hong Kong where rainfall intensity can exceed 300 mm/hr in the rainy season, the inter-comparison at KP and HKIA provides a good opportunity to evaluate quantitatively the performances of various raingauges in both rainfall amount and intensity measurements. The latter, in particular, has become more important as improvements of rainfall intensity measurements could provide valuable information for consideration of rainstorm warnings to help mitigating the impact of severe weather events.

[1] *During the WMO laboratory inter-comparison of rainfall intensity gauges held between September 2004 and September 2005, the Pluvio-OTT weighing gauge has shown excellent accuracy in constant flow conditions with relative error less than ±2% in the calibration range of 2 - 1,200 mm/hr (Lanza et. al, 2006). It also outperformed other raingauges during the WMO's field inter-comparison of rainfall intensity gauges held between October 2007 and April 2009 in Vigna di Valle, Italy (Vuerich et. al, 2009).*

2. Procedures and Methods

2.1 Selection of instruments and inter-comparison sites

A total of 14 raingauges comprising 5 different measurement methods, viz. drop-counting, weighing, tipping bucket without correction, tipping bucket with software correction and tipping bucket with extra pulse correction, have been chosen for the comparison. Details of the raingauge types installed at KP and HKIA for the inter-comparison are shown in Tables 1 and 2 respectively, and the corresponding photos of the equipment set up at these two test sites are shown in Figures 1 and 2 respectively. HKO's manned meteorological stations at KP and HKIA with good exposure were chosen as the field inter-comparison sites. The design and rationale of the equipment layout at KP and HKIA are described in Tam et. al (2012).

2.2 Instrument calibration

All raingauges have been calibrated in-house before deployment to the field. Detailed procedures for carrying out in-house calibration of the raingauges, the calibration results of each type of raingauge and the method used to conduct on-site calibration checks of the raingauges installed at the two test beds have been summarized in Tam et. al (2012).

The two Pluvio-OTT weighing gauges were also calibrated in-house before installing at the KP test site in June 2013 and they both showed good accuracy (Figure 3). For rainfall amount, the measurement uncertainties can meet the WMO's ±5% accuracy requirement in the whole calibration range from around 30 mm/hr to 400 mm/hr. For rainfall intensity, it can also meet the WMO's ±2% accuracy requirement for flow rate exceeding 10 mm/hr. It is thus considered suitable to deploy the two Pluvio-OTT weighing gauges as reference rainfall intensity gauges for benchmarking the performances of other raingauges at the KP test site.

3. Results

At KP, a total of 142 rain episodes (defined as 24-hr rainfall ≥ 10 mm recorded by one of the two manual raingauges [Manual (A) raingauge as shown in Figure 1] at KP) were recorded from 1 April 2011 to 30 October 2013[2]. Similarly at HKIA, 127 rain episodes (defined as 24-hr rainfall ≥ 10 mm recorded by the manual raingauge at HKIA) occurred from 19 March 2011 to 31 December 2013.

[2] *The raingauges were removed from the KP test site for re-calibration in the laboratory in November 2013.*

3.1 24-hr total rainfall

The performance of raingauges at KP is summarized in Table 3 and Figure 4, while the results at HKIA are shown in Table 4 and Figure 5. The root mean square errors (RMSE), mean percentage differences and standard deviations of percentage errors were all calculated with reference to the manual raingauges at the two sites.

At KP, it was observed that:

i) Apart from ETG, all raingauges had mean percentage differences less than 5% and met the WMO accuracy requirement, except for the Logotronic raingauges (Logotronic (A) and Logotronic (B)) which had a mean percentage difference exceeding 5% for 24-hr rainfall ≥ 50 mm. The mean percentage differences for ETG were greater than 5% for all rain episodes.

ii) The mean percentage differences of the Casella 0.5-mm resolution raingauges were 2.8%, indicating an accuracy that could meet WMO's requirement despite having a coarser resolution.

iii) The mean percentage differences of the two Logotronic raingauges (4.5% and 4.8%) were larger than the two SL3-1 raingauges (3.1% and 2.6%). The corresponding RMSE for the two Logotronic raingauges (2.6 mm and 3.6 mm) were also larger than the two SL3-1 raingauges (1.8 mm and 1.7 mm). This seemed to suggest slightly better performance of SL3-1.

iv) The mean percentage differences of the ETG raingauge was 5.8%, the largest among all raingauges at the site. Differences for all three rainfall sub-categories also exceeded 5%. The performance of ETG was less satisfactory than the other raingauges. More importantly, the electronic device of the raingauge for carrying out software correction malfunctioned in November 2011 and it could not be resumed to normal operation. The ETG raingauge was withdrawn from the KP test site afterwards.

v) Discounting the Casella raingauge, the mean percentage differences differed by less than 1% for the same model of raingauges. Since the 24-hr rainfall recorded by the two manual gauges only differed by a maximum of 2.0 mm during the whole test period, the spatial variability of rainfall recorded by the raingauges at KP was thus very small during the period.

At HKIA, some notable points were:

i) The mean percentage differences of Ogawa A, Ogawa B, Ogawa C and Logotronic raingauges were 4.9%, 4.6%, 4.9% and 7.1% respectively. All could meet the WMO's ±5% accuracy requirement except for the Logotronic raingauge. The Ogawa B raingauge failed to operate in August 2012 due to problems with its electronics and it was then taken out of the comparison site.

ii) SL3-1 performed not as good as the two sets of SL3-1 at the KP test site and the mean percentage difference was 5.9%. However, after relocating the manual raingauge closer to other raingauges in 2012 and fine-tuning the tipping mechanism of the SL3-1 raingauge, the recent results from 23 November 2012 to 31 December 2013 showed improvements and the mean percentage difference dropped to 4.9% for all rainfall events ≥ 10 mm, meeting the WMO's ±5% accuracy requirement.

iii) The mean percentage differences of Meteoservis raingauge were less than 5% in all rainfall categories, meeting the WMO's ±5% accuracy requirement. However, it malfunctioned in December 2012 and could not be resumed operation. The raingauge was subsequently removed from the HKIA test site.

3.2 Rainfall intensity

A comparison of the 1-minute mean and 5-minute mean rainfall intensity recorded by the raingauges at King's Park between 4 June 2013 and 30 October 2013 was conducted using the two OTT as the reference raingauges. During this nearly 5-month period, the two OTT gauges recorded the highest 1-minute mean rainfall intensity of around 130 mm/hr on 11 June 2013.

Different rainfall intensity episodes (defined based on five consecutive 1-minute mean rainfall intensity from the averages of the two OTT reference raingauges exceeding 10 mm/hr, 30 mm/hr, 50 mm/hr, 70 mm/hr and 100 mm/hr respectively) have been selected for comparison. The results are shown in Tables 5 and 6 respectively. Except for the two OTT raingauges which have direct rainfall intensity output, rainfall intensity for all other gauges were derived from multiplying the 1-minute total rainfall by 60. Hence, for tip resolution of 0.1 mm and 0.5 mm, the resolution of rainfall intensity will be 6 mm/hr and 30 mm/hr respectively over a period of 1 minute (Lanza et. al, 2006).

From the results in Tables 5 and 6, it can be observed that:

i) Due to the high natural variability of rainfall intensity, the RMSE and mean percentage differences associated with 1-minute mean rainfall intensity were a lot higher than those of the 5-minute mean rainfall intensity. This was consistent with the findings in Vuerich et al. (2009).

ii) For 5-minute mean rainfall intensity, the RMSE and mean percentage differences of the two SL3-1 raingauges were < 5 mm/hr for intensity ≤ 100 mm/hr, and < 5% for intensity > 100 mm/hr (except for SL3-1 (B) for intensity > 30 mm/hr with RMSE of 5.1 mm/hr, slightly exceeding the WMO's requirement of 5 mm/hr). The results showed that the performance of SL3-1 was the best among other raingauges in the comparison. This suggested that 5-minute mean rainfall intensity measured by SL3-1 would possibly be able to meet WMO's accuracy requirement in rainfall intensity measurements.

3.3 Rainfall intensity derived from successive rainfall tips

In 2014, a software program for acquiring rainfall data from the raingauges at KP was implemented to enable recording of the occurrence time of individual rainfall tips. Hence, the time difference of successive rainfall tips can be used to derive the short-term or near instantaneous rainfall intensity. The 1-minute mean rainfall intensity was then obtained by taking the average of rainfall intensity derived from successive rainfall tips over a 1-minute interval.

There are thus two different methods to calculate the 1-minute mean rainfall intensity.

One is based on 1-minute total rainfall x 60 (Section 3.2), while another is based on the average of rainfall intensity derived from successive rainfall tips over a 1-minute interval. A calibration test was conducted using the SL3-1 raingauge (the best performer in rainfall intensity measurements as mentioned in Section 3.2) to identify which of these two methods would be more appropriate. The test range was from around 6 mm/hr to 400 mm/hr. The results (Table 7) showed that the former method performed better.

3.4 Rainfall intensity recorded during intense rainstorms in 2014

The raingauges at KP recorded rainfall intensity associated with two intense rainstorms that occurred on two separate occasions in 2014. The opportunity is taken to compare the rainfall intensity values calculated by the two different methods as mentioned in Section 3.3 above and the intensity recorded by the two OTT reference gauges.

The first rainstorm occurred on the night of 30 March 2014 and hails were reported during the event. Figures 6 and 7 show the time series of rainfall intensities as recorded by the raingauges at KP calculated based on 1-minute total rainfall x 60 in Figure 6 and successive rainfall tips in Figure 7 respectively. (The rainfall intensity of the 0.5-mm Casella raingauge is not plotted as its resolution is too coarse). Peak intensities and times of occurrence recorded by the raingauges are summarized in Table 8.

The peak intensities recorded by the gauges were generally comparable. The rainfall intensity calculated based on 1-minute total rainfall x 60 agreed well with the intensity measured by the two reference OTT gauges while that based on the 1-minute average of rainfall intensity derived from successive rainfall tips was relatively higher. Furthermore, times of peak intensity registered by the SL3-1, Logotronic and OTT raingauges were mostly at 20:32 HKT for the 1st peak and 21:34 – 21:35 HKT for the 2nd peak. The OTT raingauges showed no noticeable time delay in detecting the peak intensity although weighing gauges were usually subject to some delay in response due to the time required for the raingauge's microprocessor in deriving the rainfall intensity (Lanza et. al, 2006).

The second rainstorm occurred on the night of 8 May 2014. Time series of rainfall intensities calculated based on 1-minute total rainfall x 60 and 1-minute average of rainfall intensity derived from successive rainfall tips are shown in Figures 8 and 9 respectively. Peak intensities and times of occurrence recorded by the raingauges are summarized in Table 9.

Similar to the feature observed in the 1st rainstorm, rainfall intensity calculated based on 1-minute total rainfall x 60 compared well with the intensity of the two OTT gauges. That based on 1-minute average of rainfall intensity derived from successive rainfall tips was on the high side.

4. Discussion

Considering the overall nearly 3-year results from the two inter-comparison sites at KP and HKIA and the operational experience gained in the comparison exercise, the SL3-1 raingauge seems to have better performance in the measurement of 24-hr total rainfall and in terms of robustness in the field environment.

As mentioned in Tam et al. (2012), Logotronic malfunctioned more frequently due to its smaller orifice size and hence suffering from blockage problem due to trapping of leaves or bird's droppings. For the Ogawa raingauge, it was limited by its larger percentage difference (>5%) for rainfall intensities exceeding 100 mm/hr (Chan and Yeung, 2004). The performance of ETG was also less satisfactory with comparatively higher mean percentage difference (5.8%), RMSE (2.6 mm) and standard deviation of percentage error (±4.6%). All Ogawa, Logotronic, ETG and Meteoservis raingauges were equipped with electronic devices which were subject to the impact of lightning and prone to failure. Both the Ogawa and Meteoservis raingauges required considerable amount of maintenance works.

The two Pluvio-OTT weighing gauges showed good accuracy when undergoing in-house calibration with uncertainties meeting the WMO's ±5% and ±2% requirements for rainfall amount and intensity measurements respectively. Using the two OTT as reference gauges, field results at KP indicated that 5-minute mean rainfall intensity measured by SL3-1 had a RMSE less than or close to 5 mm/hr and mean percentage difference smaller than or slightly above 5%, suggesting the possibility of meeting WMO's 5mm/hr and ±5% requirement.

Regarding derivation of rainfall intensity, both in-house calibration and field measurement results at KP suggested that rainfall intensity calculated based on 1-minute total rainfall x 60 was more appropriate than that based on 1-minute average of rainfall intensity derived from successive rainfall tips.

5. Conclusion

Field inter-comparison of automatic raingauges based on five different measurement methods was conducted at KP and HKIA in March 2011 - 31 December 2013 to assess their accuracy in measuring rainfall amount against WMO's ±5% requirement. During the comparison periods, 142 and 127 rain episodes were recorded at KP and HKIA respectively. SL3-1 outperformed the other raingauges in the comparison in terms of reliability and measurement accuracy. It was also more robust in operation and required less maintenance effort. As such, SL3-1 is potentially the best option in measuring rainfall amount with 0.1-mm resolution in a tropical climate like Hong Kong.

In-house calibration from around 30 mm/hr to 400 mm/hr showed good accuracy of the two Pluvio-OTT weighing gauges in both rainfall amount and rainfall intensity measurements. Based on field measurements at KP during the two rainstorms on 30 March 2014 and 8 May 2014 respectively, no noticeable time delay was observed for the two OTT raingauges in detecting the peak rainfall intensity.

With OTT serving as reference gauges, 5-minute mean rainfall intensity measured by SL3-1 had lower RMSE (around 5 mm/hr or less) and mean percentage difference (less than 5%) than those of Logotronic and Casella, and the accuracy was good enough to possibly meet WMO's requirement. In addition to using OTT, SL3-1 may be an alternative choice for measuring rainfall intensity. More rainfall intensity data will be collected for further evaluation in this aspect.

6. Acknowledgements

The authors would like to thank their colleagues Mr. Y.H. Wong for helping to conduct the inter-comparison of raingauges at Hong Kong International Airport and preparing the necessary data for analysis. The authors would also like to thank Mr. K.C. Tsui for his invaluable advice and comments.

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Table 1 Types of raingauges installed at the King's Park (KP) Meteorological Station for the field inter-comparison

Raingauge	Measuring principle /data correction algorithm	Resolution (mm)	Maximum rainfall intensity declared (mm/hr)
Logotronic MRF-C	Tipping bucket (with extra pulse correction)	0.1	200
Shanghai SL3-1	Two layers of tipping buckets	0.1	240
ETG – R102 (ETG)	Tipping bucket (with software correction)	0.2*	300
Ordinary 203-mm raingauge	Manual (serves as benchmark)	0.1	---
Pluvio-OTT	Weighing	0.1	1,800
Casella 100573E	Tipping bucket (no correction)	0.5	300

*Recommended in Lanza et. al (2006).

Table 2 Types of raingauges installed at the Hong Kong International Airport (HKIA) Meteorological Station for the field inter-comparison

Raingauge	Measuring principle /data correction algorithm	Resolution (mm)	Maximum rainfall intensity declared (mm/hr)
Ogawa	Drop-counting	0.1	200
Logotronic MRF-C	Tipping bucket (with extra pulse correction)	0.1	200
Shanghai SL3-1	Two layers of tipping bucket	0.1	240
Meteoservis	Weighing	0.1	400
Ordinary 160-mm raingauge	Manual (serves as benchmark)	0.1	---

Table 3 Summary of rainfall comparison results at the King's Park Meteorological Station. (1 April 2011 – 30 October 2013)

Rainfall event	Type of raingauges[2]								
	Casella (0.5 mm)	SL3-1 (A) (0.1 mm)	SL3-1 (B) (0.1 mm)	Logotronic (A) (0.1 mm)	Logotronic (B) (0.1 mm)	OTT (A) (0.1 mm)	OTT (B) (0.1 mm)	ETG (0.2 mm)	Manual (A)
No. of rain episodes All (≥10mm)	**140**[3]	**134**[3]	**140**[3]	**136**[3]	**106**[3]	**38**[4]	**38**[4]	**33**[5]	**142**
Root Mean Square Error[1] (mm)	1.9	1.8	1.7	2.6	3.6	2.6	2.5	2.6	
Mean absolute percentage difference[1]	2.8%	3.1%	2.6%	4.5%	4.8%	3.4%	3.3%	5.8%	
No. of rain episodes ≥10mm and <25mm	**65**	**62**	**65**	**61**	**54**	**15**	**15**	**16**	**67**
Root Mean Square Error[1] (mm)	0.9	0.9	0.8	1.3	1.2	1.4	1.4	1.1	
Mean absolute percentage difference[1]	3.2%	3.6%	2.7%	4.8%	4.8%	4.2%	4.5%	5.4%	
No. of rain episodes ≥ 25mm and <50mm	**40**	**37**	**40**	**40**	**30**	**11**	**11**	**6**	**40**
Root Mean Square Error[1] (mm)	1.4	1.5	1.2	1.6	2.0	1.6	1.4	2.5	
Mean absolute percentage difference[1]	2.3%	2.9%	2.3%	3.6%	3.8%	2.2%	1.7%	7.9%	
No. of rain episodes ≥50mm	**35**	**35**	**35**	**35**	**22**	**12**	**12**	**11**	**35**
Root Mean Square Error[1] (mm)	3.4	2.8	2.9	4.6	7.4	4.0	3.9	3.9	
Mean absolute percentage difference[1]	2.7%	2.6%	2.7%	5.2%	5.9%	3.5%	3.4%	5.2%	

Note: (1) Reference was made to Manual (A) rain gauge at the King's Park Meteorological Station in compiling the root mean square errors and the mean absolute percentage differences.

(2) Locations of the raingauges in the test bed are shown in Figure 1.

(3) Fewer no. of rain episodes was due to maintenance of the raingauges.

(4) Fewer no. of rain episodes as the two OTT raingauges only started operation on 4 June 2013.

(5) The ETG raingauge malfunctioned in November 2011 and was withdrawn from the comparison site.

(6) Mean absolute percentage difference less than 5% are highlighted in yellow.

Table 4 Summary of rainfall comparison results at the Hong Kong International Airport (HKIA) Meteorological Station. (19 March 2011 – 31 December 2013)

Rainfall event	Type of raingauge[2]						
	Ogawa A (0.1 mm)	Ogawa B (0.1 mm)	Ogawa C (0.1 mm)	Logotronic (0.1 mm)	Meteoservis (0.1 mm)	SL3-1 (0.1 mm)	Manual
No. of rain episodes All (≥10mm)	**118**[3]	**57**[4]	**121**[3]	**126**[3]	**67**[4]	**123**[3]	**127**
Root Mean Square Error[1] (mm)	4.1	2.4	2.4	2.5	3.7	3.4	
Mean absolute percentage difference[1]	4.9%	4.6%	4.9%	7.1%	3.5%	5.9%	
No. of rain episodes (≥10mm and <25mm)	**66**	**28**	**67**	**71**	**36**	**70**	**72**
Root Mean Square Error[1] (mm)	1.0	1.0	1.1	1.5	0.7	1.2	
Mean absolute percentage difference[1]	4.8%	5.3%	5.4%	8.6%	3.6%	6.8%	
No. of rain episodes (≥25mm and <50mm)	**27**	**14**	**28**	**29**	**16**	**27**	**29**
Root Mean Square Error[1] (mm)	2.4	2.0	1.9	2.2	0.8	2.4	
Mean absolute percentage difference[1]	5.0%	4.4%	4.3%	6.0%	2.4%	5.2%	
No. of rain episodes (≥50mm)	**25**	**15**	**26**	**26**	**15**	**26**	**26**
Root Mean Square Error[1] (mm)	8.4	4.1	4.3	4.4	7.7	6.6	
Mean absolute percentage difference[1]	5.2%	3.7%	4.3%	4.2%	4.4%	4.3%	

Note: (1) Reference was made to the manual rain gauge at the HKIA Meteorological Station in compiling the root mean square errors and the mean absolute percentage differences.

(2) Locations of the raingauges in the test bed are shown in Figure 2.

(3) Fewer no. of rain episodes was due to maintenance of the raingauges.

(4) The Ogawa B and Meteoservis raingauges malfunctioned in August 2012 and December 2012 respectively and they were withdrawn from the comparison site.

(5) Mean absolute percentage difference less than 5% are highlighted in yellow.

Table 5 Summary of 1-minute mean rainfall intensity comparison results at King's Park (4 June 2013 – 30 October 2013)

Rainfall event	Type of raingauge					
	Casella	SL3-1 (A)	SL3-1 (B)	Logotronic (A)	Logotronic (B)	Mean of OTT(A) and OTT(B)
No. of rain episodes[1] >10 mm/hr	166	166	166	166	105[3]	166
Root Mean Square Error[2] (mm/hr)	17.7	12.4	12.4	13.0	12.0	
Mean absolute percentage difference[2]	59.3%	29.5%	28.1%	29.6%	28.4%	
No. of rain episodes[1] >30 mm/hr	58	58	58	58	33	58
Root Mean Square Error[2] (mm/hr)	19.5	14.9	15.1	15.5	14.1	
Mean absolute percentage difference[2]	27.2%	18.7%	18.7%	19.5%	17.7%	
No. of rain episodes[1] >50 mm/hr	26	26	26	26	15	26
Root Mean Square Error[2] (mm/hr)	20.6	15.8	16.5	17.0	15.3	
Mean absolute percentage difference[2]	19.9%	14.2%	15.0%	15.8%	14.2%	
No. of rain episodes[1] >70 mm/hr	7	7	7	7	3	7
Root Mean Square Error[2] (mm/hr)	20.5	15.8	16.7	16.7	12.7	
Mean absolute percentage difference[2]	17.6%	11.9%	12.9%	13.3%	9.2%	
No. of rain episodes[1] >100 mm/hr	2	2	2	2	2	2
Root Mean Square Error[2] (mm/hr)	12.7	8.9	11.2	11.2	13.3	
Mean absolute percentage difference[2]	8.5%	5.3%	6.6%	7.0%	7.8%	

Note: (1) Rain episodes are defined as 5-consective 1-minute mean rainfall intensity from the averages of OTT (A) and OTT (B) reference raingauges exceeding 10 mm/hr, 30 mm/hr, 50 mm/hr, 70 mm/hr and 100 mm/hr respectively.

(2) Reference was made to the 1-minute mean rainfall intensity recorded by the two Pluvio-OTT raingauges.

(3) Fewer no. of rain episodes as the Logotronic (B) raingauge malfunctioned since 23 August 2013.

(4) WMO's achievable measurement uncertainty for rainfall intensity measurement in field environment is 5 mm/hr or 5% above 100 mm/hr.

Table 6 Summary of 5-minute mean rainfall intensity comparison results at King's Park (4 June 2013 – 30 October 2013)

Rainfall event	Type of raingauge					
	Casella	SL3-1 (A)	SL3-1 (B)	Logotronic (A)	Logotronic (B)	Mean of OTT (A) and OTT (B)
No. of rain episodes[1] >10 mm/hr	166	166	166	166	105[3]	166
Root Mean Square Error[2] (mm/hr)	5.3	4.4	4.5	4.9	5.6	
Mean absolute percentage difference[2]	11.3%	8.2%	8.2%	9.3%	10.7%	
No. of rain episodes[1] >30 mm/hr	58	58	58	58	33	58
Root Mean Square Error[2] (mm/hr)	5.9	4.9	5.1	5.5	7.3	
Mean absolute percentage difference[2]	7.2%	5.7%	5.9%	7.0%	9.1%	
No. of rain episodes[1] >50 mm/hr	26	26	26	26	15	26
Root Mean Square Error[2] (mm/hr)	6.2	4.5	4.5	5.9	7.6	
Mean absolute percentage difference[2]	5.9%	4.2%	4.2%	6.0%	7.8%	
No. of rain episodes[1] >70 mm/hr	7	7	7	7	3	7
Root Mean Square Error[2] (mm/hr)	6.6	4.8	4.3	6.4	7.3	
Mean absolute percentage difference[2]	5.1%	3.9%	3.4%	5.3%	5.4%	
No. of rain episodes[1] >100 mm/hr	2	2	2	2	2	2
Root Mean Square Error[2] (mm/hr)	3.2	2.7	2.9	6.5	5.9	
Mean absolute percentage difference[2]	2.2%	1.9%	2.2%	5.2%	4.5%	

Note: (1) Rain episodes are defined as 5-consective 1-minute mean rainfall intensity from the averages of OTT (A) and OTT (B) reference raingauges exceeding 10 mm/hr, 30 mm/hr, 50 mm/hr, 70 mm/hr and 100 mm/hr respectively.

(2) Reference was made to the 5-minute mean rainfall intensity recorded by the two Pluvio-OTT raingauges.

(3) Fewer no. of rain episodes as the Logotronic (B) raingauge malfunctioned since 23 August 2013.

(4) WMO's achievable measurement uncertainty for rainfall intensity measurement in field environment is 5 mm/hr or 5% above 100 mm/hr.

(5) Root Mean Square Error less than 5 mm/hr or percentage differences less than 5% are highlighted in yellow.

Table 7 Evaluation of SL3-1 raingauge on rainfall intensity measurements using different methods to calculate the 1-minute mean rainfall intensity

Method to calculate rainfall intensity	Reference 1-minute mean rainfall intensity calculated based on the change of water weight (mm/hr)							
	6.5	13.3	26.2	65.3	132.0	197.7	267.2	411.3
1-minute mean rainfall intensity calculated based on 1-minute total rainfall x 60 (mm/hr)	6.3	13.2	25.3	63.5	131.5	199.2	271.5	384.0
Mean percentage difference[1]	-3.1%	-0.8%	-3.4%	-2.8%	-0.4%	0.8%	1.6%	-6.6%
1-minute mean rainfall intensity calculated based on the average of rainfall intensity derived from successive rainfall tips over a 1-minute interval (mm/hr)	6.5	14.5	26.6	73.1	142.3	206.2	274.3	384.4
Mean percentage difference[1]	0.0%	9.0%	1.5%	11.9%	7.8%	4.3%	2.7%	-6.5%

Note: (1) Reference was made to the 1-minute mean rainfall intensity calculated based on the change of water weight.

(2) WMO's achievable measurement uncertainty for rainfall intensity measurement under laboratory conditions is 5% above 2 mm/hr and 2% above 10 mm/hr.

(3) Percentage errors meeting WMO requirement are highlighted in yellow.

Table 8 Peak rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site during the intense rainstorm on the night of 30 March 2014.

Time hh:mm	**1-minute mean rainfall intensity (mm/hr)**							
Rain episode 1	OTT (A)	OTT (B)	SL3-1(A)		SL3-1(B)		Logotronic (A)	
			Method 1[1]	Method 2[2]	Method 1[1]	Method 2[2]	Method 1[1]	Method 2[2]
20:31	102.0	105.2	114	138.4	108	126.4	102	158.9
20:32	133.5	147.4	144	190.4	150	170.3	150	203.9
20:33	133.7	131.3	138	158.1	132	144.5	132	173.1
20:34	129.2	137.3	126	161.2	126	149.7	126	167.2
Rain episode 2								
21:32	111.4	104.3	108	132.3	102	127.6	114	161.4
21:33	130.1	137.2	138	162.6	144	159.9	138	190.7
21:34	150.2	145.5	138	159.2	150	170.6	150	193.9
21:35	147.7	146.9	138	164.8	150	171.4	NA	NA
21:36	126.7	130.1	144	171.0	132	144.5	138	189.2
21:37	108.5	109.2	108	139.4	102	125.8	108	130.0
21:38	102.2	102.1	102	126.2	102	108.7	102	155.8

Note: (1) 1-minute mean rainfall intensity based on 1-minute total rainfall x 60.
(2) 1-minute mean rainfall intensity based on the average of rainfall intensity derived from successive rainfall tips over a 1-minute interval.
(3) For each rain episode, the peak rainfall intensity measured by individual raingauge is highlighted in yellow.

Table 9 Peak rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site during the intense rainstorm on the night of 8 May 2014.

Time hh:mm	**1-minute mean rainfall intensity (mm/hr)**							
Rain episode 1	OTT (A)	OTT (B)	SL3-1(A)		SL3-1(B)		Logotronic (A)	
			Method 1[1]	Method 2[2]	Method 1[1]	Method 2[2]	Method 1[1]	Method 2[2]
22:17	150.0	150.1	150	165.8	150	152.7	156	194.7
22:18	160.5	155.8	156	176.3	156	157.2	150	198.3
22:19	157.7	155.8	150	179.4	168	162.6	No data	
22:20	168.0	161.9	174	187.9	162	165.3	162	202.8
22:21	158.1	156.3	162	184.9	162	160.6	150	199.2
22:22	135.8	139.1	132	153.7	138	143.4	144	189.2
Rain episode 2								
22:34	132.9	134.1	132	151.8	144	141.9	138	170.5
22:35	159.7	150.8	162	180.2	162	162.7	156	200.7
22:36	160.4	162.6	168	185.9	168	166.1	162	199.3
22:37	150.1	146.1	144	161.4	156	159.9	150	196.3
22:38	78.8	80.2	72	119.2	84	98.9	72	121.2

Note: (1) 1-minute mean rainfall intensity based on 1-minute total rainfall x 60.
(2) 1-minute mean rainfall intensity based on the average of rainfall intensity derived from successive rainfall tips over a 1-minute interval.
(3) For each rain episode, the peak rainfall intensity measured by individual raingauge is highlighted in yellow.

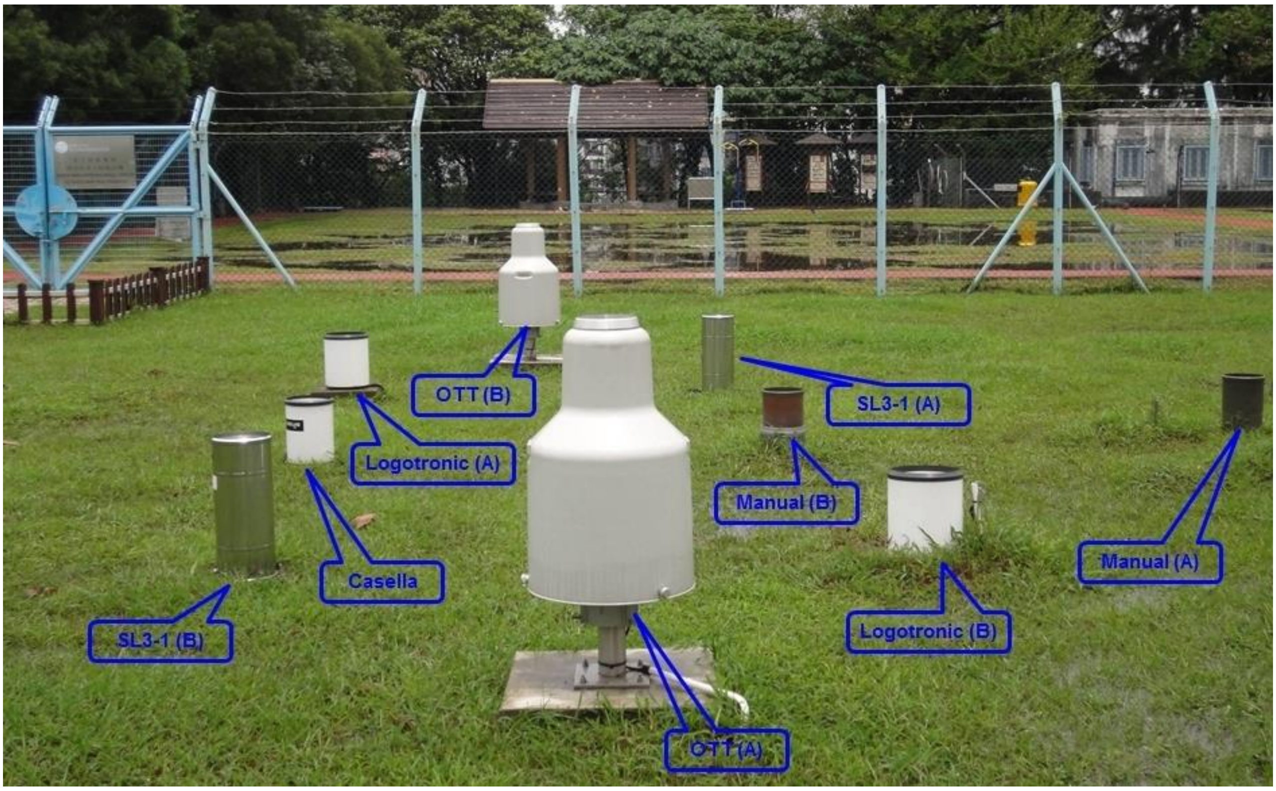

Figure 1 **Locations of raingauges at the King's Park Meteorological Station test bed (The location of OTT (B) raingauge was originally occupied by the ETG raingauge which malfunctioned in November 2011 and was removed from the test site).**

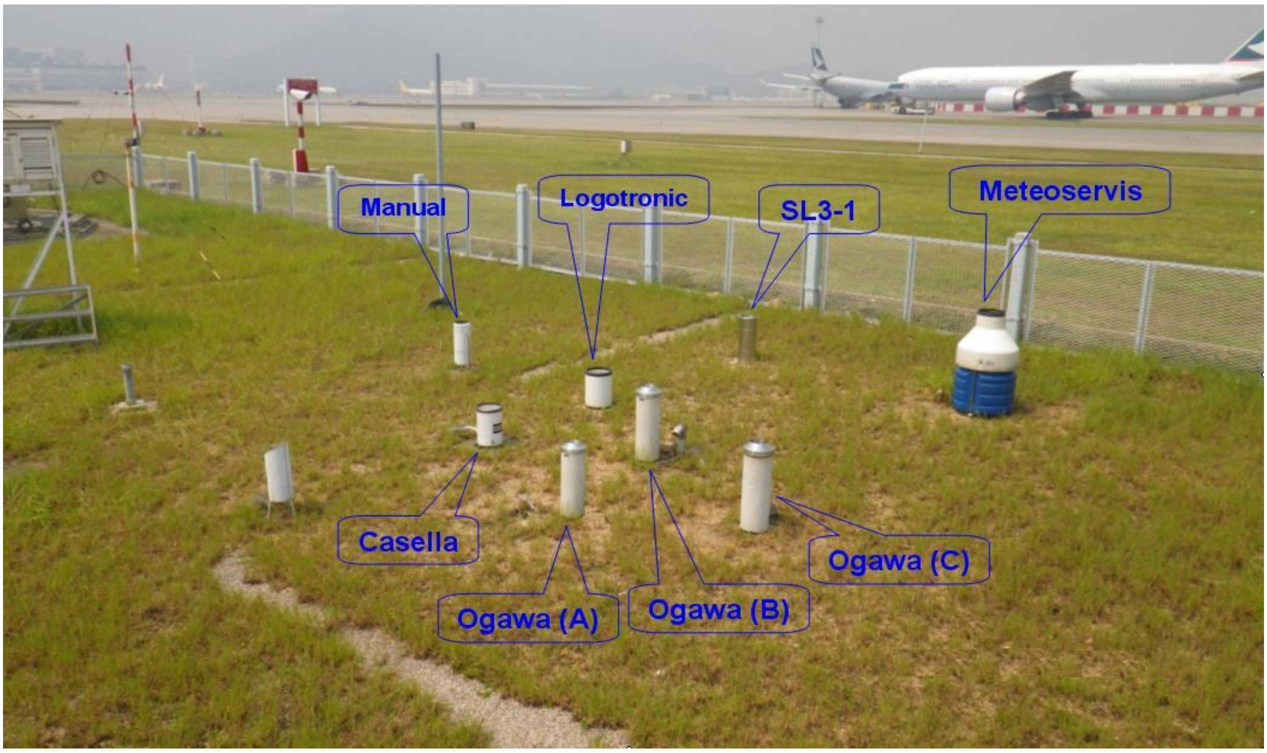

Figure 2 **Locations of raingauges at the Hong Kong International Airport Meteorological Station test bed.**

**The manual raingauge was relocated closer to the other raingauges in 2012 and the new location of the manual raingauge is shown.*

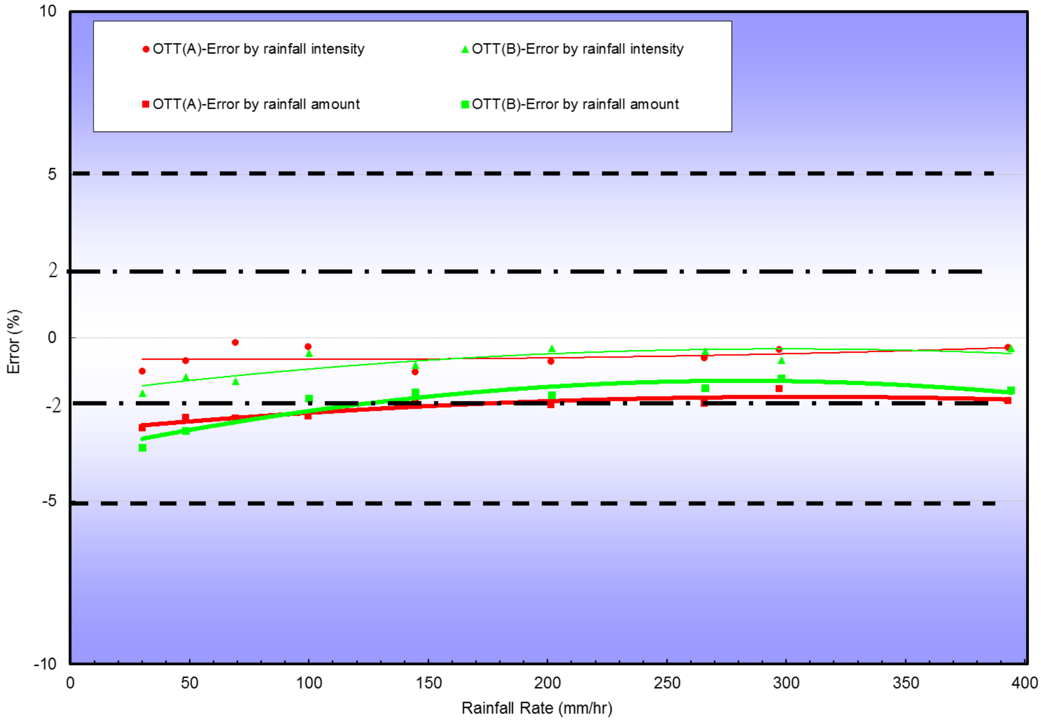

Figure 3 Error curves (compared with WMO's ±2% and ±5% uncertainty limits for rainfall intensity and rainfall amount accuracy requirements respectively) obtained in the laboratory under different simulated rainfall rates for the two Pluvio-OTT weighing gauges before deployment to the King's Park site (second order polynomial functions are used for curve fitting).

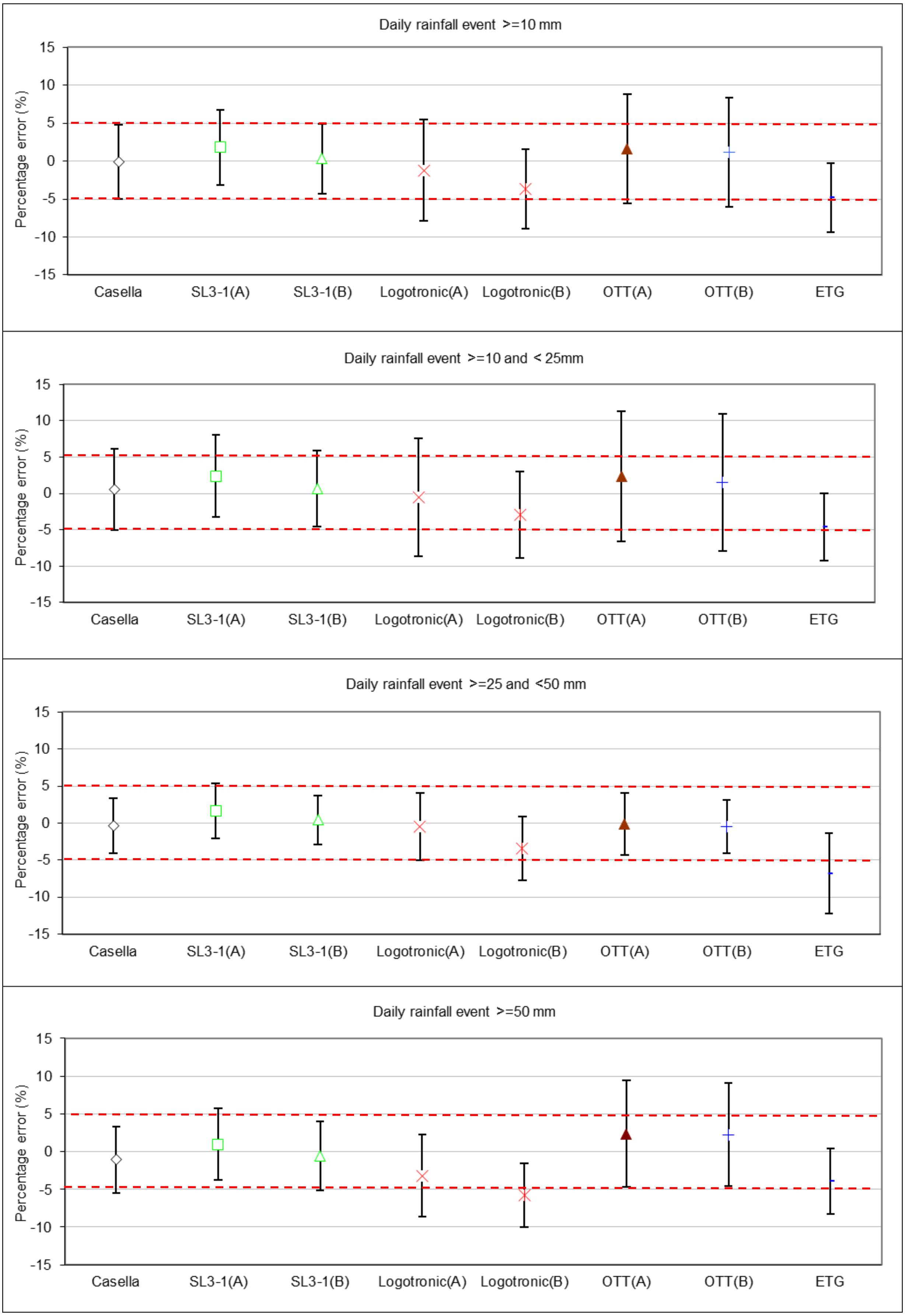

Figure 4 Mean percentage errors of various raingauges (compared to manual gauge (A)) at the King's Park site. Vertical bar denotes ±1 standard deviation.

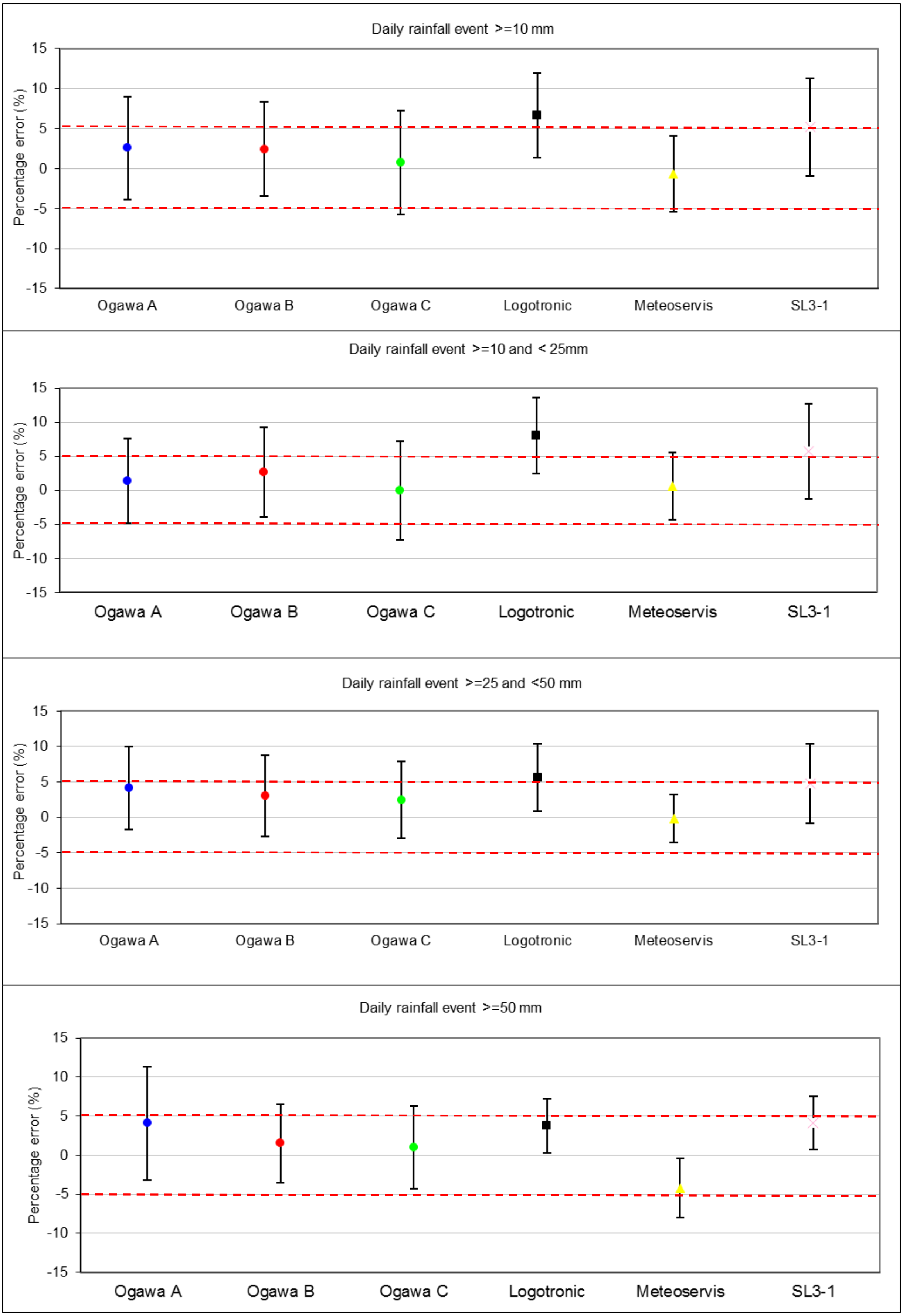

Figure 5 Mean percentage errors of various raingauges (compared to the manual gauge) at the Hong Kong International Airport site. Vertical bar denotes ±1 standard deviation.

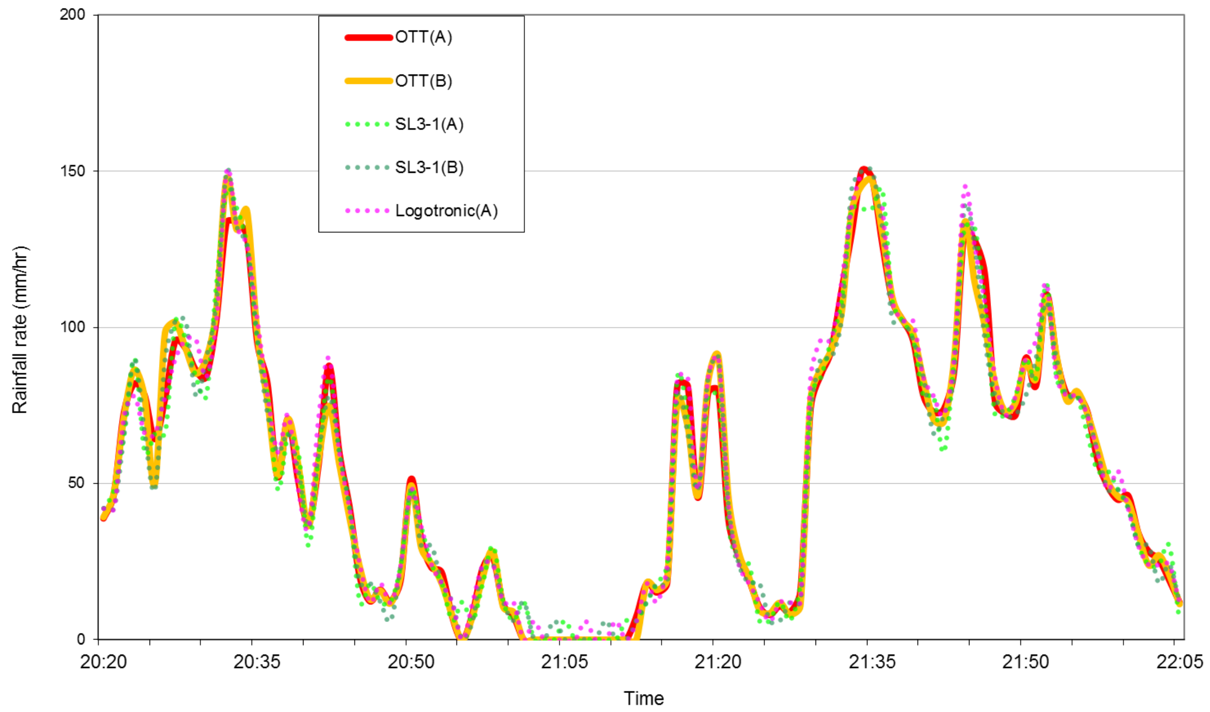

Figure 6 Time series of rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site on the night of 30 March 2014. The rainfall intensities were derived from 1-minute total rainfall x 60. (The Logotronic (B) raingauge was not included as it malfunctioned on 23 August 2013).

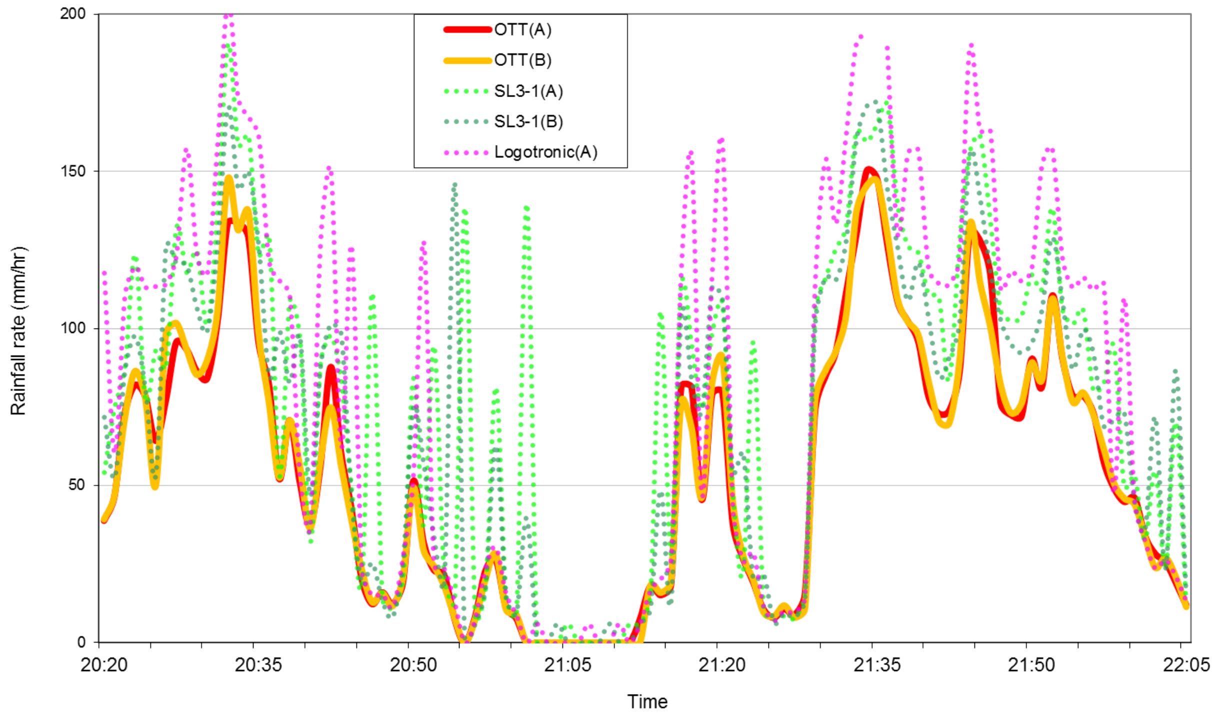

Figure 7 Time series of rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site on the night of 30 March 2014. The rainfall intensities were derived from the average of rainfall intensity calculated based on successive rainfall tips over a 1-minute interval.

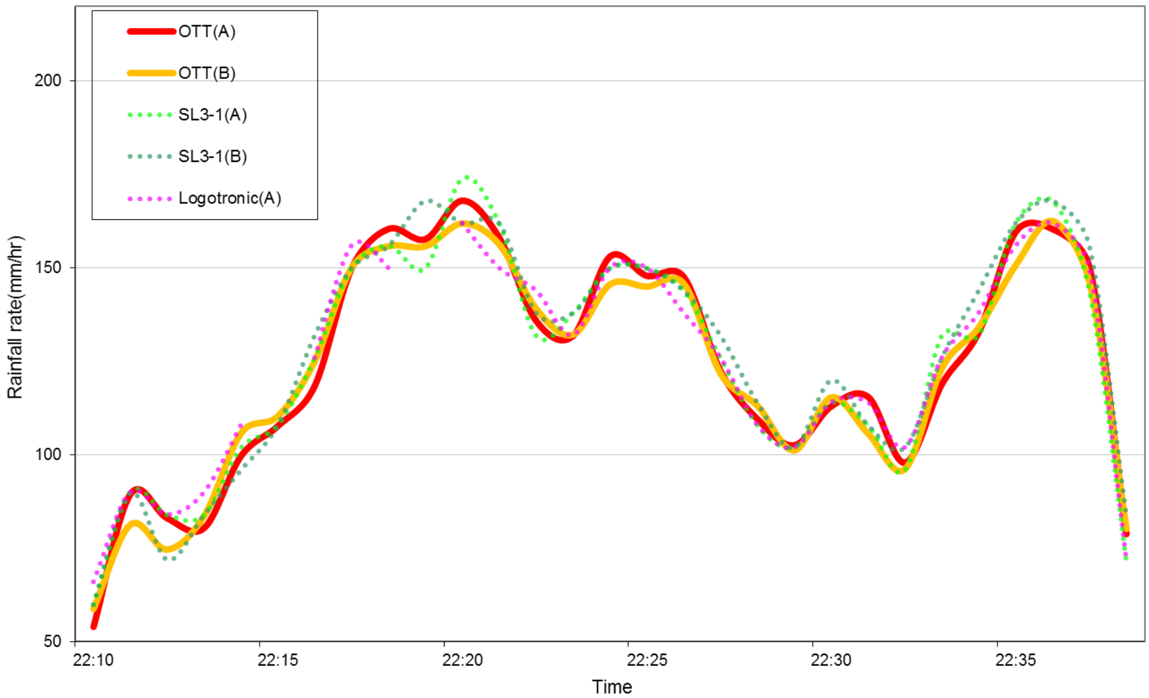

Figure 8 Time series of rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site on the night of 8 May 2014. The rainfall intensities were derived from 1-minute total rainfall x 60 (There were a few missing data from the Logotronic (A) raingauge).

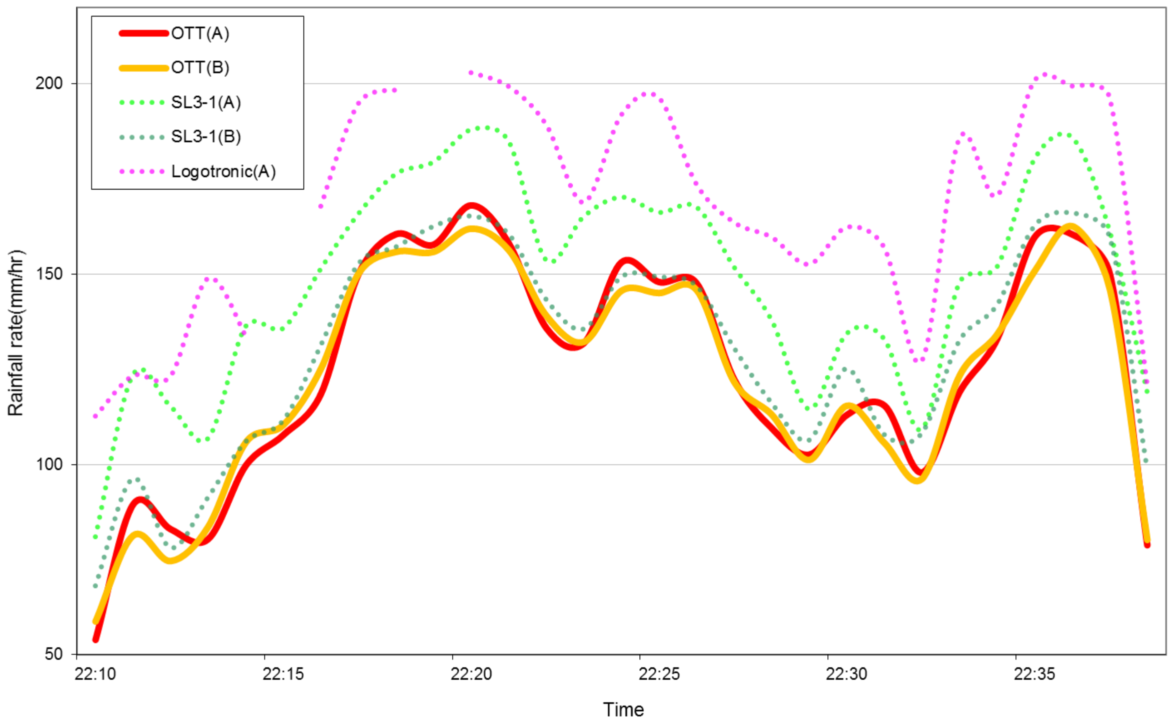

Figure 9 Time series of rainfall intensities recorded by various 0.1-mm resolution raingauges at the King's Park site on the night of 8 May 2014. The rainfall intensities were derived from the average of rainfall intensity calculated based on successive rainfall tips over a 1-minute interval.