ESTIMACIÓN DE DATOS TROPICALES FALTANTES DE CANTIDAD DE LLUVIA USANDO DATOS SATELITALES AJUSTADOS

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RESUMEN

Un procedimiento actualizado para estimar datos faltantes de cantidad de lluvia mensual y anual de estaciones tropicales fue diseñado y validado. Para las estimaciones, el procedimiento incluye el ajuste de los continuos datos mensuales provenientes de la Misión Tropical de Medición de Lluvia (TRMM) con los discontinuos datos mensuales de la estación en consideración por medio de transferencia de parámetros estadísticos. El procedimiento fue aplicado experimentalmente a los 216 datos mensuales en mm medidos con pluviómetro Hellman en la estación Karimao (Período 1998-2015), localizada a 12 km al SE de Caracas (Venezuela) cerca del embalse La Pereza dentro del área de estudio *Caracas.* Los datos TRMM usados abarcan 216 valores originales obtenidos para el área de Caracas (1998-2015) mediante la página web de Internet *Giovann*i, mantenida por NASA en los Estados Unidos de América, con mínima resolución de 120 km^2. Los datos originales TRMM tienen un sobre estimado de 30 %. Durante la validación, se simuló una muestra aleatoria de 42 datos faltantes que permitió calcular un error grande no aceptable de ±40 % en los datos ajustados TRMM, pero los datos anuales provenientes de los 216 datos mensuales ajustados presentaron error pequeño de ±11 % aceptable. Finalmente, aunque se obtuvo buen resultado con el nivel de trabajo anual, se recomienda el uso cuidadoso de datos satelitales para llenar los datos faltantes de pluviometría en áreas tropicales. El satélite TRMM ha sido substituido.

Palabras clave: lluvia, faltantes, estimación, tropical, TRMM

ESTIMATION OF MISSING TROPICAL RAINFALL GAUGE DATA BY USING ADJUSTED SATELLITE DATA

ABSTRACT

A *state-of-the-art* procedure aimed to estimate the frequent gaps of missed monthly and annual rainfall data items of tropical stations was designed and tested. For the gaps assessments the procedure included the adjustment by using a statistical parametric transference of the nearly continuous satellite monthly rainfall registers coming from the Tropical Rainfall Measuring Mission (TRMM) with the available discontinuous monthly rainfall data items of the station under consideration. The procedure was experimentally applied to the 216 monthly rain gauge values in mm measured with *Hellman* pluviometer from the station Karimao (Period 1998-2015) located at 12 km to the SE of Caracas (Venezuela), in the study area of Caracas near La Pereza reservoir. The TRMM data included 216 monthly original values in mm (1998-2015) downloaded for this area from the Internet web page Giovanni maintained by NASA in the United States of America with minimum resolution of 120 km^2. The original TRMM data have an overestimation of 30 %. After the adjustment of the original monthly TRMM data, the analysis of a random sample of 42 missing data gaps was simulated and this helped to calculate a large non-acceptable error of ±40 % but the annual values obtained with the whole TRMM monthly adjusted values produced a small acceptable error of ±11 %. Finally, even though a good result was obtained for the annual level, the recommendation is a careful use of satellite data to fill rain gauge data gaps in tropical areas. The original TRMM satellite was substituted.

Keywords: rainfall, gaps, estimation, tropical, TRMM

INTRODUCTION

From the clouds, under special conditions, water drops can precipitate reaching the ground which is called *rainfall*. In fixed specific locations named *stations* specialists install small instruments called rain gauges or pluviometers in order to measure the rainfall in liter per square meter or millimeter (mm). In each station, the received rainfall data is accumulated daily in a never-end fashion. For a given station the daily values of a specific month of a given year are accumulated to provide a single amount (P, mm) named monthly precipitation. For example, the 31 daily rainfalls accumulated during March 2015 in the location *Caracas-Alta Florida* gave for that specific month a monthly P=6 mm rounded to the integer. Monthly values are used to form a matrix of data running over a specific period or lapse of years. A scheme for the small frequently used *Hellman* pluviometer is depicted in figure 1.

More details of tropical rain gauging may be seen in Hidalgo and Hidalgo (2006). Some P (mm) values in most tropical stations are missing in an unfortunate issue called in this paper *gap of monthly data*. This problem constitutes the main restriction in the rainfall research applied to the management of water reservoirs fed by rivers. Any solution to fill the gaps of this issue is of course welcome. Table 1 illustrates the occurrence of such gaps as well as accumulated values embracing more than one month of the station *La Pereza Reservoir* near *Caracas.* (Coordinates: 1200 masl; 10.4427°N & 66.7392°W). Means and standard deviations (Std) of *La Pereza* are incomplete due to data gaps. In table 1 missed data are also indicated with a trace (-) and accumulated values are marked with asterisks (* and **). Annual total in table 1 is 978 mm obtained as the sum of the 12 monthly means.

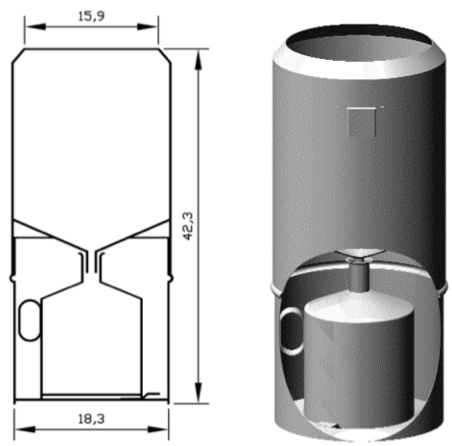

Figure 1. *Scheme of a Hellman rain gauge. Values are given in cm. The mouth Circular diameter is 15.9577 cm. (Source: Proper design)*

Table 1. Available monthly rain gauge data of *La Pereza Reservoir* station in mm (1970-1983)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1970	-	-	-	-	-	-	-	-	-	50	36	105
1971	20	13	9	56	42	95	148	129	101	136	47	79
1972	96	13	7	40	267	112	138	114	64	99	60	29
1973	9	5	8	77	32	41	40	140	134	101	153	64
1974	45	12	6	7	39	30	100	157	102	-	-	-
1976	-	-	-	-	-	-	-	-	16	81	58	19
1977	-	5	5	4	70	145	*	279**	102	-	-	-
1978	7	2	6	91	35	137	*	304**	30	120	74	115
1979	14	2	75	121	112	353	188	184	150	74	134	122
1980	35	12	7	28	96	130	180	198	142	34	120	31
1981	10	113	23	240	140	231	155	179	152	84	19	56
1982	51	26	12	87	*	439**	120	51	121	80	66	52
1983	70	8	3	40	173	171	120	98	47	-	-	-
Mean	34	22	19	63	102	153	126	145	103	84	67	60
Std	27	32	23	62	74	107	44	48	49	28	43	34

Special symbols are explained in the text.
Source: INAMEH web page (see References).

Some missed data items of the station *El Dorado* (Venezuela) were filled by Hidalgo and others (2014) with locally adjusted satellite data from the Tropical Rainfall Measuring Mission (TRMM) but there were no details about this way of solution. That is why we undertook in detail this kind of solution which included TRMM satellite data. Sensor TMI on the satellite of that mission (see figure 2) passively received the microwave energy emerging from clusters of rain drops to convert this energy into rainfall intensity *R* in mm/h. Data of *R* was available every 3 hours at a standard geographical 120 km^2 resolution. Rainfall in mm was obtained by multiplying *R* (mm/h) intensity by the elapsed time. Bibliographical research did not give information on rainfall data gaps in the area of *Caracas* (Venezuela), the study area. However, the recently obtained local rainfall data files did have data gaps. The procedure we designed allowed us to complete our research, to fill those data gaps by quantifying the errors in mm and also in percentage. Objective and Methodology related to this procedure are given below.

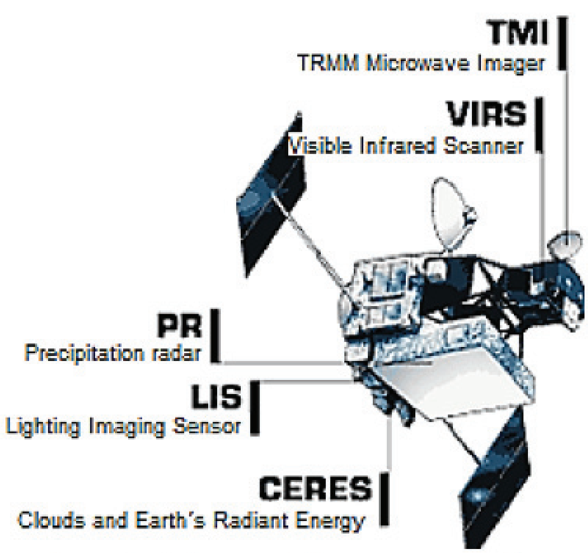

Figure 2. *Scheme of the TRMM satellite. The sensor TMI is the source of rainfall data used in this paper. (Source: NASA web page, see References)*

OBJECTIVE AND METHODOLOGY

The objective is to design and test a *state of the art* procedure aimed to fill gaps of missing monthly and annual precipitation data; in this paper, the *state of the art* means the use of rainfall data measured from the outer space by satellite. The methodology has the following steps: (1) to design a routine for estimations, (2) to select a conventional station in the area of *Caracas* (the study area) with minimum gaps for numerical experiments and later to collect the monthly data as well as to calculate annual data, (3) to review satellite rainfall sources in the Internet and select a source for tropical rainfall data, (4) to collect monthly satellite rainfall data for the study area and calculate annual values from that selected source, (5) to apply the routine, and finally (6) to calculate errors and extract conclusions. The Internet is a public global information interchange system used nowadays (April 2017) on the telephones lines among computers.

RESULTS

Routine for estimation

The routine for the estimation of multiple rainfall gaps in the monthly and annual register of a station under study needs an auxiliary data set with few data gaps considered conceptually similar, equivalent or homologues to the station under study. This auxiliary data set could come from a station in a neighborhood near the station, however, most of the time this kind of data set also has too many gaps. Thus, data sets coming from satellite operations with none or few gaps is the best option nowadays. For a specific area, the satellite rainfall data seem to be equivalent to that of the ground station but there are differences among means and standard deviations of the monthly and annual time series; thus satellite data is suitable to be adjusted with parameters coming from the station under study in a fashion named transference of parameters or parametric transference. The routine must be applied 12 times at monthly level (one for each monthly series from January to December). The annual adjusted value for a specific year is the sum of the 12 monthly rainfall of this year. The monthly routine adjustment formula is

$$z=[(y-m)/d]\cdot D+M \qquad (1)$$

where *z* is an adjusted TRMM single value for a specific month and year, *y* is an original TRMM single value for that month and year, *m* and *d* are available mean and standard deviation respectfully of the original TRMM data from which comes *y* for the specific month, *M* and *D* are mean and standard deviation respectfully for the station under consideration for the specific month. Those six items are in mm of rainfall. The four statistical parameters *m*, *d*, *M* and *D* are calculated as soon as possible for each month. Thus it must be four parameters for each month for a total of 48 parameters for a procedure application from January to December. After the *z* calculation of all missed values of the station under consideration, it will be necessary to obtain the estimation error without monthly discrimination. Estimations with an error in the order of ±10% or better can be accepted but in the order of ±30% or worst a rejection of estimation is required. A recalculation of z can be done after the actualization of M and D with gaps filled with a new routine application.

Data sources

Two well-known sources of tropical rainfall data for the area under study are (November 2016): the Instituto Nacional de Meteorología e Hidrología (INAMEH) web page of the Venezuelan government (see References) and the web page *Giovanni* in Acker & Leptoukh (2007) maintained by the National Aeronautics and Space Administration (NASA) of the United States of America (see References). *Giovanni* allows users to download tropical rainfall data from the TRMM algorithm. In INAMEH page monthly data of the study area but with gaps were obtained. Thus the station *Karimao* near the station *La Pereza Reservoir* with no gaps from 1997 to 2016 was selected. The location of *Karimao* is depicted in figure 3 as a point inside a rectangle. Figure 3 covers the whole study area to the south of the Caribbean Sea. Table 2 shows monthly and annual data in mm for *Karimao* station. From *Giovanni* monthly data for ranges 10.4° N to 10.5° N and 66.7° W to 66.8° W shown in table 3 were obtained; the annual values were calculated by a sum. Table 2 is a mixture of data from the neighbor stations S-157 and S-177 located both in the *Karimao* suburb. Figure 4 shows the sector of *Karimao* mountains in which S-157 and S-177 are located. Rough coordinates of *Karimao* are: 900 masl, 10.46°N and 66.72°W.

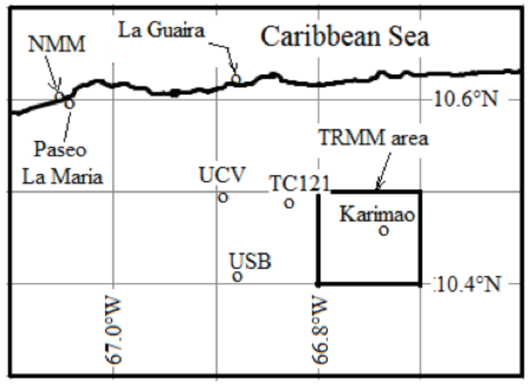

Figure 3. *Location of Karimao station and TRMM perception area. The TRMM/TRMI perception area is 0.1°x0.1° near 11x11 km2 or 121 km2. Some references points were included. (Source; proper design)*

Figure 4. *View of the Karimao sector in which rainfall measurements were made. (Source: Proper photograph)*

Table 2. Monthly and annual rain gauge data of *Karimao* station in mm (1998-2015)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1998	0	0	132	13	132	217	145	120	141	126	66	64	1156
1999	3	1	7	254	16	68	64	173	153	107	96	186	1126
2000	33	11	98	22	33	113	115	115	97	83	142	46	908
2001	0	7	0	21	66	90	140	133	78	171	91	123	919
2002	10	10	28	85	135	102	118	169	127	71	47	23	924
2003	6	20	1	59	38	120	199	86	168	136	96	64	994
2004	7	16	11	52	172	105	140	49	164	176	161	41	1094
2005	88	120	1	51	233	198	158	104	71	63	126	70	1283
2006	53	75	30	5	177	115	123	129	78	110	44	29	968
2007	10	2	46	55	33	254	102	183	94	41	85	103	1007
2008	16	6	0	89	114	125	96	63	32	185	123	52	903
2009	10	41	20	15	50	14	81	127	33	44	27	25	490
2010	49	0	4	116	140	169	138	114	182	130	273	77	1590
2011	24	95	7	73	230	192	128	59	130	35	149	139	1260
2012	26	7	48	175	109	105	106	272	84	57	36	42	1351
2013	7	1	3	117	157	130	67	90	195	85	113	44	1008
2014	13	1	1	14	27	128	71	201	99	189	77	21	841
2015	39	13	10	11	64	86	63	11	35	77	73	34	507
Mean	22	24	25	68	107	129	114	122	109	105	101	65	1019
Std	23	36	37	65	70	58	37	62	51	51	58	45	
Mean(&)	24	28	26	64	110	136	115	126	115	106	97	65	
Std (&)	25	38	39	65	71	63	30	67	57	54	67	47	

Hellman pluviometer is used.
The 42 shaded values were selected with a random sampling.
Symbol (&) means the exclusion of the 42 point of the random sample.
The column of Total is the sum of the twelve monthly values for the year with no gaps.

Table 3. Original monthly and annual satellite data from TRMM in mm (1998-2015)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1998	39	37	65	62	172	202	186	148	123	115	124	100	1373
1999	54	46	25	129	63	127	199	185	200	181	156	253	1620
2000	99	54	55	24	77	116	189	123	156	132	202	66	1291
2001	44	31	18	15	77	122	156	151	109	165	150	122	1159
2002	49	28	21	82	124	135	136	121	143	111	96	66	1114
2003	36	22	17	81	81	141	242	131	95	186	132	73	1239
2004	52	26	15	61	203	169	153	111	146	118	176	77	1308
2005	83	244	13	73	169	234	203	205	89	128	206	90	1738
2006	108	67	24	20	175	168	138	201	139	153	132	83	1408
2007	38	30	56	39	68	189	121	284	144	164	120	232	1485
2008	46	31	12	83	82	129	213	132	106	201	213	87	1336
2009	45	49	27	19	68	73	135	142	134	64	97	79	932
2010	37	35	30	98	147	208	205	155	229	153	348	153	1799
2011	72	71	34	86	201	155	165	163	120	106	160	162	1495
2012	66	34	56	111	132	127	131	218	132	177	97	120	1402
2013	41	35	26	87	119	114	105	142	160	138	101	97	1164
2014	49	27	18	50	76	129	129	202	151	124	106	87	1148
2015	72	36	30	26	88	59	105	121	119	126	85	51	918
Mean	57	50	30	64	118	144	162	163	139	141	150	111	1329
Std	22	50	17	34	49	45	40	45	35	34	64	56	244

The column of Total is the sum of the twelve monthly values for the year.
Satellite TRMM scanning area: 10.4°N to 10.5°N and 66.7°W to 66.8°W.
The location of that area is depicted as the small rectangle inside Figure 3.

The combined operation of these two stations assures the existence of no data gaps in registers. At the end of tables 2 and 3 are the means and standard deviations (std) for each month column in mm. A rainfall TRMM +30.4% overestimation is notable by comparing the conventional annual total of 1019 mm of table 2 for *Karimao* against 1329 mm of table 3 provided by the TRMM algorithm. Table 1 permitted to calculate a mean annual total of near 980 mm close to that of *Karimao* given a rough confirmation to the overestimation; thereafter an adjusting procedure must be undertaken over the TRMM original monthly values.

Estimation of data

The whole table 3 was converted into table 4 which contains satellite adjusted or estimated data with the help of the formula (1) and the 12 means and 12 standards deviations at the bottom of table 2 and similar parameters at the bottom of table 3. Each value in table 4 must be very similar to its homologue in table 2 but this must be tested. To do testing, in table 2, 42 simulated missing values at random against their homologues of table 4 were marked.

Table 4. Adjusted TRMM data with *Karimao* statistics in mm

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1998	2	18	109	60	189	217	134	104	89	64	70	56	1111
1999	20	25	14	188	29	111	143	159	216	168	104	184	1362
2000	73	31	84	0	49	95	135	65	144	90	152	27	946
2001	8	14	0	0	50	105	111	108	67	143	97	74	775
2002	15	11	5	98	119	123	95	63	122	58	41	27	778
2003	0	7	0	98	56	131	176	78	43	176	79	33	876
2004	18	9	0	59	234	171	109	48	127	69	124	37	1005
2005	54	174	0	92	184	262	146	189	34	85	156	47	1415
2006	83	41	11	0	193	168	97	183	116	125	78	42	1137
2007	2	12	88	16	37	198	84	308	124	142	67	166	1243
2008	11	13	0	101	57	115	154	79	62	200	163	45	1000
2009	9	27	18	0	37	36	95	94	108	-17	42	38	487
2010	1	17	26	128	151	225	148	115	264	125	305	99	1602
2011	41	44	34	106	231	151	117	126	85	50	108	107	1200
2012	34	16	86	154	131	111	92	209	105	163	41	73	1214
2013	5	16	16	108	111	93	72	94	150	100	43	53	865
2014	14	10	0	32	48	114	90	185	135	78	51	45	810
2015	41	17	26	0	66	16	72	63	83	81	29	15	508
Mean	24	28	28	69	110	136	115	126	115	106	97	65	1019
Std	25	38	36	59	71	63	30	67	57	54	67	47	298

The column of Total is the sum of the twelve monthly values for the year with no gaps.
Marked items define positions of the simulated gaps.
Scanning area coverage is similar to that of Table 2.

Monthly gaps

The 42 simulated monthly gaps marked in table 2 with the function integer of random between 0 and 1 plus 0.75 were contrasted against their TRMM homologues in table 4 as shown in figure 5. Note for this figure 5: (1) the software *Excel* of *Microsoft Corporation* was used for calculations and drawings, (2) the linear fitting model is $y=ax+b$, (3) the relative error (%) is calculated as 100 times the standard error of the adjusted TRMM values divided by the respective mean original value for *Karimao* station taken as true, (4) the *probability* was obtained with the function DIST.F(F,df2,df) of *Excel* software and (5) the line adjusted to the dispersion gives an estimation absolute error of ±32.4 mm over a true mean of 82 mm to obtain by division a relative error of ±39.6 % considered definitively large for the present climatic application. The monthly column of table 5 shows the outputs of the *Excel* software tool to study variance related to figure 5; the very low probability about $4x10^{-10}$ for F=67.6 indicates that the correlation is not due to random sampling.

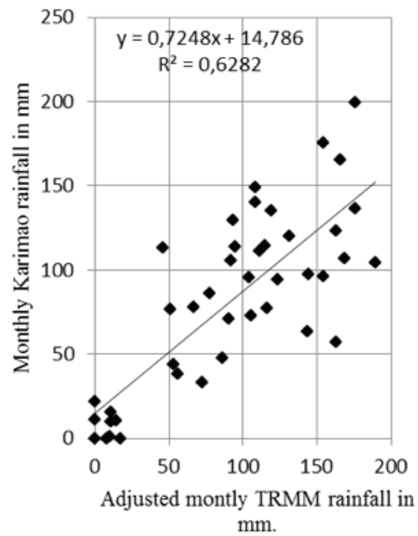

Figure 5. *Dispersion of the 42 randomsample points of monthly rainfall.*
The line gives a trend with an estimation error of ±32.4 mm over a true mean of 82.0 mm or 39.6%.
(Source: Proper calculations and design)

Table 5. Statistical summary related to Figures 5 and 6		
	Monthly sample (Figure 5)	Annual series (Figure 6)
Number of ítems (*n*)	42	18
Mean of adjusted TRMM in mm	92.65	1012.20
Mean of original *Karimao* in mm	81.9	1018.6
Slop value (*a*) in mm/mm	0.72	0.79
Intercept value (*b*) in mm	14.79	223.73
Error of *a* in mm	0.0882	0.0903
Error of *b* in mm	9.58	95.37
Correlation coefficient	0.63	0.83
Standard estimation error in mm	32.43	115.74
Relative estimation error in %	39.6	11.4
Ratio F of Snedecor	67.57	75.66
df	40	16
Ssrg square sum of regression	71051.8	1013434.4
Ssres square sum of residual	42059.4	214324.4
df2	1	1
Probability	3.9846E-10	1.8427E-07
Verification of probability	67.57	75.66
See additional details in the text.		

Annual estimations

To explore the agreement among the annual adjusted data of TRMM against the observed data at *Karimao,* the random sample was not used but the total values to the right of tables 2 and 4 were used to produce figure 6. The line adjusted to the dispersion gives an estimation absolute error of ±115.74 mm over a true mean of 1018.6 mm to obtain a relative error of ±11.4 %. The formula to convert annual adjusted TRMM rainfall into nearly *Karimao* rainfall is:

$$y = 0.7853 \cdot x + 223.73 \qquad (2)$$

where x is an annual adjusted TRMM total (mm) and y is an annual total as if they were measured in *Karimao* (mm). Formula (2) may be interpreted as the local adjusted TRMM annual calibration. The annual column of Table 5 presents the outputs of the *Excel* tool for the annual values of adjusted TRMM where the probability of F=75.7 is also very low, therefore the correlation is not due to a random occurrence.

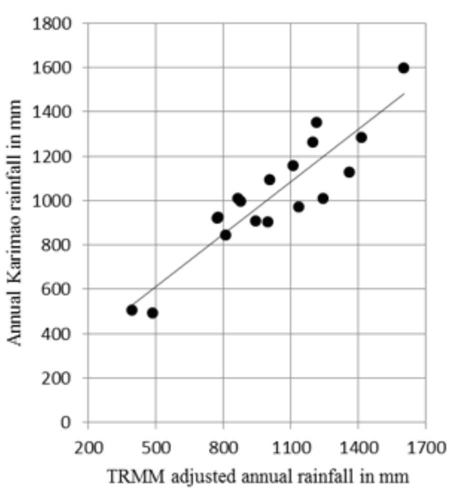

Figure 6. *Dispersion of 18 annual points of rainfall. (Source: Proper calculations and design with Excel)*

DISCUSSION AND RECOMMENDATIONS

The greater original monthly *P* (mm) obtained by satellite with respect to the homologue obtained in *Karimao* (see tables 2 and 3) is due to the large area of near 120 km^2 of TRMM contrasted with the very small 200 cm^2 mouth of the single *Hellman* rain gauge employed in *Karimao*. The probability *to see* rainfall for the TRMM or similar rainfall source is greater than that of catching rain by the pluviometer because in the tropics, rains are dispersed and in the study area the dispersed rains are very frequent even though during rainless periods. The differences are sometimes very large by the few daily passes of satellites over the same location; thus the satellite can detect the nucleuses of rainfall storms in the few passes overestimating the mean rain. After the adjustment of monthly TRMM values, biases above and below the *Karimao* standard were obtained. Then an explanation became necessary. An observation of some storms occurred in the area of *Karimao* permitted to know that some microburst remained stagnated over *Karimao* but with no rains in the main areas of *Caracas*. Thus it is difficult for the satellite sensor to detect this kind of rainfall, and in this case the TRMM values are underestimated. Of course this explanation resulted as a complement to the overestimation explanation given above. In the course of a year overestimations and underestimations must be canceled as indicated in low dispersion of figure 6. The paragraphs above contain the error due to satellite performances.

Operative problems arise from the time used to close the pluvial day; thus TRMM day runs from 00 to 24 UTC, but the *Karimao* pluvial day runs from 12 UTC of a day to 12 UTC of the next day, where UTC is Coordinated Universal Time maintained by the International Bureau of Weights and Measurements (BIPM, Paris), and conceptually referred to the geographic longitude 0°E/W. The hour 12 UTC is actually (16 Nov 2016) 08 am local time (LT) for Venezuela. By convention, in *Karimao*, the measured *P* is written for the measuring day in a book with paper and pencil, but the daily satellite data is assigned to the UTC day. Thus the *P* value given by TRMM is not exactly comparable with that measured in *Karimao*. The 08 LT for reading the *Hellman* pluviometer is the best in the tropics to avoid evaporation of the rainfalls received frequently in the last part of the afternoon and the night of the day before the reading, therefore it is not a good idea to change the 8 LT measuring time. There are neither errors nor missing data due to energy shortage or damage of batteries in *Karimao*, and thus Table 2 is true.

The large monthly ±39.6 % error is explained by the above mentioned causes. The minor 11.4 % error of annual estimation is explained including the very minimum daily registering error in only one day of every year, December 31, and the possible zero sum of satellite perception errors between rainless and rainy periods. The main recommendation for the monthly level is the gathering of TRMM data at a 3 hour basis and recalculation of daily values to compare with *Karimao* data, but this is a large task that goes beyond the limits of our research. In order to determine in which months and years the bias is very large a statistical study of residuals in the monthly linear fittings is needed, but this was not carried out in this research.

The successful annual adjustment of TRMM data can help engineers to fill gaps of monthly data by residuals specially when there is only one missing month during a specific year. The *granular theory* used in geology and oil industries that has been recommended to solve the problem of very large areal difference between the rain gauge mouth and the satellite scanning area will be undertaken later. The main achievement is the successful adjustment of annual rainfall data obtained from the TRMM algorithm for *Karimao* location. Thus, annual estimations were accepted as true to fill gaps. Finally a cautionary use of satellite data to fill missing rainfall data gaps in areas of tropical mountains like *Caracas is recommended.*

Finally, it is convenient to note for future developments: (1) that other non TRMM monthly rain fall satellite estimations have been available via Internet since 1994 (see Hidalgo, 1994) and (2) that the Global Precipitation Measurement Mission (GPMM) announced by Hou et al.,2014 needs to be evaluated.

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