N93-26483

A Comparative Assessment of R. M. Young and Tipping Bucket Rain Gauges

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1.0 Introduction

Rain rates as derived from standard tipping bucket rain gauges have variable integration times corresponding to the interval between bucket tips. For example, the integration time for the Weathertronics [1985] rain gauge (described in Section 2) is given by

$$\Delta T = \frac{15.24}{R} \qquad \text{(min)} \tag{1}$$

where R is the rain rate expressed in mm/h and ΔT is the time between tips expressed in minutes. It is apparent that a rain rate of 1 mm/h has an integration time in excess of 15 minutes. Rain rates larger than 15.24 mm/h will have integration times smaller than 1 minute. The integration time is dictated by the time it takes to fill a small tipping bucket where each tip gives rise to 0.254 mm of rainfall. Hence, a uniform rain rate of 1 mm/h over a 15 minute period will give rise to the same rain rate as 0 mm/h rainfall over the first 14 minutes and 15 mm/h between 14 to 15 minutes from the reference tip. Hence, the rain intensity fluctuations may not be captured with the tipping bucket rain gauge for highly variable rates encompassing lower and higher values over a given integration time.

Where rain gauges are used with path attenuation models operating at 20 GHz to 30 GHz, improved measurement resolution at the smaller rain rates may be a requirement. Assuming a uniform rain rate along a slant path, the attenuation at 30 GHz for a Marshall-Palmer drop size distribution is given by [Olsen et al., 1978],

$$A = a\,R^{b}\,\ell = 0.186\,R^{1.043}\,\ell \qquad \text{(dB)} \tag{2}$$

where ℓ is the slant path length along which the effective rain rate R is assumed uniform. For example, given a rain height of 4 km, a path elevation angle of 45°, and a uniform rain along the path of 1 mm/h, the attenuation is 1.1 dB. At 2 mm/h and 5 mm/h, it is 2.2 dB and 5.7 dB, respectively. Where design fade margins are low, an accurate knowledge of the rain rate distributions at the lower rain rates is therefore important. The standard tipping bucket rain gauge may not meet this requirement because its operations entails large integration times at the smaller rain rates.

The R. M. Young capacitive rain gauge [1990] operates on an entirely different principal and allows shorter and uniform integration intervals for the determination of rain rate. The objectives of this effort is to provide an assessment of the features of the R. M. Young capacitive gauge and to compare these features with those of the standard tipping bucket rain gauge. As part of this assessment, we have examined a number of rain rate–time series derived from measurements with approximately co-located gauges (2.5 inches edge to edge) at the NASA Wallops Flight Facility, Wallops Island, Virginia.

2.0 Tipping Bucket Rain Gauge

2.1 Operation

A schematic representation of the tipping bucket rain gauge is given in Figure 1 and a listing of the specifications is given in Table 1. Water flows down the funnel assembly shown in Figure 1 (item 4) and into the tipping bucket assembly (item 5). The tipping bucket assembly consists of two capture volumes separated by a partition. When one capture volume fills to an equivalent rainfall of 0.254 mm, the assembly tips and discharges the water. After tipping, the other end of the tipping bucket assembly (second capture volume) is now in position to receive the water flow through the funnel assembly. Each time a tip occurs, there is a momentary closure of a mercury switch (switch closure time ≈ 100 milliseconds). The switch closure causes a voltage level change which is monitored by a connecting PC. Whenever such a voltage level change is noted, the PC records the corresponding clock time. In this way, the tipping times are continuously monitored. Equation (1) gives the corresponding rain rate for the time between tips given given by ΔT (in minutes).

2.2 Calibration and Accuracy of Measurement

Considerable experience exists with this type of gauge as 10 systems were employed in the Mid-Atlantic coast of the United States over a period exceeding five years [Goldhirsh, 1990; Goldhirsh et al., 1992]. The manufacturer stated uncertainty is 0.5% at 12.7 mm/h. Calibrations were performed with this type of gauge by directing water down the funnel assembly at an approximate constant rate of 12–15 mm/h over a period of approximately one hour. Since each tip represents 0.254 mm of rainfall, the number of tips times 0.254 should correspond to the total known rainfall poured through the funnel. More water than is calibrated is normally required to tip the bucket because of mechanical friction in the bearings resulting in rainfall errors. Care must therefore be taken in properly lubricating the bearings (e.g., every six months). In addition, the bucket stops (denoted by item 8 in Figure 1) should be adjusted to maintain a proper balance of the tipping bucket assembly, since these stops may shift or wear over a period of time.

Repeated calibrations over a period of five years corresponding to the network of 10 gauges have demonstrated errors of less than 5% after six months in the field and less than 2% after calibration. A source of errors associated with tipping bucket rain gauges is the spillover effect at high rain rates (e.g., above 100 mm/h). At rain rates above 100 mm/h, the time between tips is approximately smaller than 9 seconds, and significant amounts of rain water may overfill the bucket volumes.

The following criteria should also be followed in properly siting rain gauges: [1] Possible updrafts will prevent drops from falling at their terminal velocities. The assumption that rain drops fall at their terminal velocity must be valid in order to obtain an accurate measure of rain rate. It is therefore important to place the gauge near the ground and in a protected area where updrafts are generally small. [2] Care must also be exercised in not placing the gauge near any tall structure which blocks the flow of rain or causes possible spillover effects of rain water into the gauge.

3.0 The R. M. Young Gage Capacitive Gauge

3.1 Operation and Specifications

A schematic of the Young precipitation gauge is depicted in Figure 2 and the specifications are summarized in Table 2. This device, which has no moving parts, is based on capacitive changes within a vertical tube internal to the gauge (item B; Figure 2). The gauge's operating temperatures range between −20°C to +50°C and employs a 20 W/28 V heater/thermostat assembly. The heater serve the purpose of preventing freezing of water in the tube (item B) and catchment assembly (item A) when ambient temperatures fall below 0°C. The tube capacitance is part of a circuit which generates a DC voltage between 0 to 5 V. This voltage is monitored in real time by a PC which converts the voltage to a machine unit in the range between 0 to 2048. For the system described here, the value of the voltage (expressed in machine units) is sampled and stored in the computer in 5 second intervals. The tube fills to an equivalent rainfall of 50 mm (5 VDC or 2048 machine units), whereupon it automatically self siphons (item C).

The rain rate may be calculated by taking the voltage difference (or equivalent machine unit difference) over a period of time called the "integration" or "resolution" interval. Based on the above description, it may be demonstrated that the rain rate is given by

$$R = \frac{87.8904\ (\Delta \mathrm{MU})}{\Delta \mathrm{T}} \qquad (\mathrm{mm/h}) \tag{3}$$

where ΔT is the sampling time interval (expressed in seconds) and ΔMU is the increase in machine units over the interval ΔT.

Although, the data acquisition circuitry employed with this system samples the voltage at five second intervals, other sampling times may be used (e.g., 1 s). The rain rate (3) may be applied to any integer value of these samples. For example, assuming a data acquisition sampling time of 5 s, and taking the difference of every 12th, results in an integration time $\Delta T = 60$ s in (3). Selection of the integration time may easily be accomplished with software.

3.2 Calibration and Accuracy

The criteria for siting the Young gauge are the same as mentioned for the tipping bucket case. The major calibration issue with regard to the Young gauge deals with the stability of the output voltage linearity and the level of system noise. The output voltage slope should be

1 V per 10 mm of rainfall. The manufacturer stated unsmoothed electronic noise associated with the system is ± 200 mV or ± 2 mm of the actual rainfall. This system noise may be mitigated by proper averaging and smoothing as exemplified in Section 4. The calibrated rainfall was derived by pouring known water volumes through the catchment assembly (item A in Figure 2) and noting the corresponding values of machine units MU employing the expression

$$\mathrm{RFC} = \left(\frac{50}{2048}\right) \mathrm{MU} \qquad (\mathrm{mm}) \tag{4}$$

where each value of machine units MU (per calibration) was obtained by averaging over a 25 second interval. The calibrated levels over a weekly interval showed the peak rainfall difference between the data points and the calculated linear relation to be less than 0.5 mm and the peak RMS about the average values to be less than 0.1 mm. It is apparent from the calibration measurements to date that the linearity is quite good and the longer term stability in the calibration is excellent.

After a rainfall of 50 mm, the Young gauge automatically self siphons (item C; Figure 2). Since it takes approximately 24 seconds to undergo this operation, this measurement time is lost. This may not be too difficult a constraint since an average rain rate of 25 mm/h will only result in 24 seconds of lost measurement time every 2 hours. After each rain day, it is suggested that water be added to the tube such that it self siphons and is prepared for the next rain event with near zero volume.

4.0 Comparison of Rain Rate Events Derived with Young and Tipping Bucket Gauges

In this section we compare rain rate time–series for the Young and tipping bucket rain gauges for a one hour example rain event during February 15, 1992. Other comparisons, which have been made during the remainder of the rain period and for rain events during March 26, and April 22, 1992, showed generally similar results.

4.1 Young One Minute Average Versus Tipping Bucket Values

In Figure 3 is shown a one hour rain event over the local time interval 15:00–16:00. The curve represented by the solid line with unshaded dots corresponds to the tipping bucket rain gauge levels, and the dashed curve with shaded dots represent the rain rates derived from the Young gauge using an integration time of 1 minute. Both curves generally track each other quite well, where below 15 mm/h the Young gauge values generally fluctuate about the lines connecting the tipping bucket levels. Above 15 mm/h, the tipping bucket gauge has a smaller than one minute integration time and is capable of capturing the higher rain intensities between 15.2 h and 15.3 h. In Table 3 are given the overall rainfalls in mm for the tipping bucket and the Young one minute average cases. The rainfalls are given by the respective areas under the rain rate curves. The right hand column in Table 3 represents the percent difference of rainfall relative to the tipping bucket values. The tipping bucket rain gauge levels is shown to overestimate the Young one minute integration time rainfall by approximately 3% which is within the accuracy of both gauges. We note that between the interval 15.6 h to 16.0 h, the Young rain rate levels fluctuate between 0 mm and 5 mm, whereas the tipping bucket gauge values are approximately constant between 2–3 mm/h. The Young fluctuations may, in part, be caused by noise in the electronics. As a further demonstration of the relative measurements at the higher rain intensities, Figure 4 shows a focused view over the period 15–15.4 h.

4.2 Young Variable Integration Rain Rates Versus Tipping Bucket Values

To improve upon the resolution at the higher rain rates and to mitigate the noise effects at the lower precipitation values, a processing code was developed for the Young data having the following algorithm:

$R < 5$ mm/h	Integration time is 2 minutes
$5 \leq R \leq 15$ mm/h	Integration time is 1 minute
$R > 15$ mm/h	Integration time is 30 seconds

The computer code containing the above algorithm initially interrogates the one minute integration rain rates before changing the time resolution. The rain rates derived with the above algorithm is referred to as the "variable integration time" or "variable resolution time" case. In Figure 5 we compare the variable resolution time and tipping bucket rain rate cases. It is apparent, that the peak values above 15 mm/h are better characterized (between 15.2 h and 15.3 h) and the rain rate fluctuations smaller than 5 mm/h are less noisy than the one minute integration case. Figure 6 shows a focused view of the rain event in the interval 15–15.4 h which exhibits generally higher values than those derived from the tipping bucket case. The overall rainfall for the variable integration time Young case exceeds the tipping bucket levels by approximately 2% which is again within the tolerances of both systems.

4.3 Young Variable Integration Rain Rates Versus One Minute Average

In Figure 7 we compare the variable resolution rain rates with the one minute averages, where both are derived from the Young data. Above 15 mm/h, the variable resolution rates are noted to contain more structure. The two rainfalls are in agreement with one another to within approximately ± 3%.

5.0 Summary and Conclusions

The tipping bucket and Young gauge rain rates have been noted to track each other relatively well for all rain rate–time series examined. The comparative rainfalls over the one hour period also generally agreed relatively well with one another to within the combined measurement uncertainties for each gauge. For the three rain days hitherto considered, the average percent difference in rainfall relative to the tipping bucket case was approximately 3% and 6% for the variable and one minute integration rates, respectively.

A major advantage of the R. M. Young capacitive gauge is that the desired integration time may be programmed into the system through appropriate software. The rain rates derived using the capacitive gauge is obtained by differencing voltages which are proportional to the depth in which water fills a tube. If the rain rate is low and a short sampling period is selected, the noise in the electronics may vary more than the voltage change due to the small capacity difference, and a noisy signal will result. Hence, one should select a long enough integration time such that the electronic noise, when converted to rainfall, is small relative to the difference rainfall measurement. Ideally, a variable sampling time should be programmed into the system to mitigate the effects of noise at the lower rain rates and to capture the rain rates peaks at the high rain intensities. A two minute sampling time in the rain rate interval between 1 mm/h and 5 mm/h has been found to give relatively good results although one minute may be acceptable. Other averaging methods for mitigating the electronic noise should be explored. In Table 4 are listed the advantages and disadvantages of the R. M. Young capacitive gauge system. A possible disadvantage of this system is that after the tube has filled to a capacity of 50 mm of rainfall, it automatically discharges, resulting in approximately 25 seconds of lost measurement time.

The tipping bucket rain gauge, on the other hand, is a simpler device to interface with a computer system since only the tipping times need to be recorded. The times between tips are variable with excessively long intervals at the smaller rain rates. For example, it takes approximately 15 minutes to record a uniform rain rate of 1 mm/h. The large integration times at the smaller rain rates results in the inability to capture variabilities in rain intensities; a condition which may be important for slant path attenuation modeling. The tipping bucket gauge has also moving parts which must be periodically serviced. In Table 5 are summarized advantages and disadvantages of this system.

Both the tipping bucket and capacitive gauge appears to have the same level of uncertainty in measuring rainfall which is less than 5%.

6.0 Acknowledgements

Many thanks to Norris Beasley, Site Manager of the SPANDAR radar facility at the NASA Wallops Flight Facility for his assistance and cooperation. This work was supported by the NASA Propagation Program directed by the Office of Commercial Programs under Contract N0039-91-C-0001.

7.0 References

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Goldhirsh, J., V. Krichevsky, and N. E. Gebo, "Rain Rate Statistics and Modeled Slant Path Fade Distributions at 20 GHz and 30 GHz Derived from a Rain Gauge Network in the Mid-Atlantic Coast of the United States over a Five Year Period," *APL/JHU Technical Report S1R92U-006*, March 1992.

Olsen, R. L., D. V. Rogers, and D. Hodge, "The aR^b Relation in the Calculation of Rain Attenuation," *IEEE Trans. Antennas and Propagation*, Vol.26, No. 2, pp. 318–329, 1978.

Weathertronics, "Manual for Tipping Bucket Rain Gage: Model 6010," *Manual PN 6010-01*, WEATHERtronics Division, Qualimetrics Inc., Sacramento, CA, March 1983.

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Table 1: Parameters for WEATHERtronics [1983] tipping bucket rain gauge.

Parameter	Value
Manufacturer	Qualimetrics, Inc., 277 Del Monte Street, West Sacramento, CA 95651, (916) 271-2660
Model #	6010
Capture Diameter	20.32 cm
esolution	0.254 mm/tip
Measured Rainfall Accuracy (mm)	< 5 % at 12.5 mm/h
Switch Closure Time	100 msec
Weight	8 lbs.
Gauge Length	19 inches
Collecting Orifice Height Above Ground	3.75 ft.

Table 2: Parameters for R. M. Young [1990] capacitive gauge.

Parameter	Value
Manufacturer	R. M. Young, 2801 Aero-Park Drive, Tranverse City, MI, 49684, (616) 946 3980
Model #	50202
Capture Diameter	11.28 cm
Output Voltage	0–5 VDC
Voltage/rainfall	100 mV/mm
Point Sampling Accuracy	±2 mm
Weight	5.6 lbs.
Gauge Length	26 inches
Collecting Orifice Height Above Ground	3.75 ft.
Discharge Rainfall Range	50 mm
Discharge Time	24 s

Table 3: Comparative rainfalls for indicated events and integration times.

Event Date	Start Time (h)	End Time (h)	Integration Type	Rainfall (mm)	Rainfall Percent Difference
2/15/92	15	16	Young: 1 minute	7.55	−3.2
			Young: Variable	7.98	+2.3
			Tipping Bucket	7.80	
3/26/92	14	15	Young: 1 minute	8.21	−13.1
			Young: Variable	8.90	−5.8
			Tipping Bucket	9.45	
4/22/92	4.5	5.5	Young: 1 minute	10.60	−2.3
			Young: Variable	10.62	−2.1
			Tipping Bucket	10.85	

Table 4: Advantages and disadvantages of R. M. Young gauge.

	Advantages	**Disadvantages**
1.	Integration times are selectable.	Automatic siphoning causes lost measurement time of approximately 24 seconds after 50 mm of rainfall.
2.	Integration time may be made fixed or variable depending on rain rate.	Noise in electronics corresponding to an equivalent ± 2 mm of rainfall must be mitigated by averaging or extending integration times.
3.	Integration times of 1–2 minutes possible for rain rates between 1 and 5 mm/h.	
4.	No moving parts.	
5.	Calibration is linear and stable over weekly periods.	

Table 5: Advantages and disadvantages of tipping bucket gauge.

	Advantages	Disadvantages
1.	Simple output (switch closure)	Integration times are variable.
2.	Shorter integration times automatically capture higher rain rates.	Smaller rain rates correspond to large integration times.
3.	Proven capability in the field.	Moving parts require servicing at 6 month intervals.
4.		Friction effects may cause inaccuracies.
5.		Spillover effects at high rain rates cause inaccuracies.

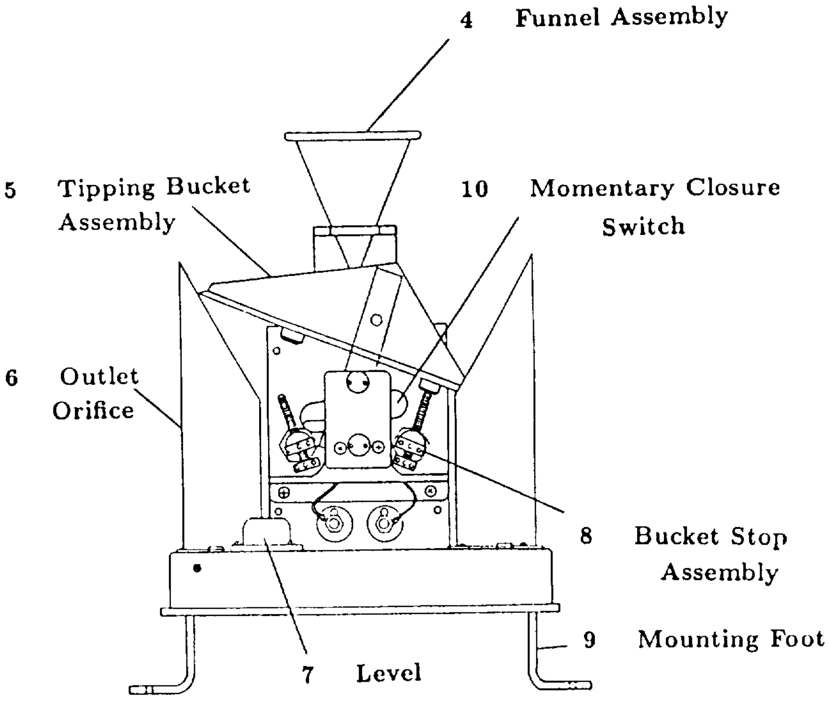

Figure 1: Schematic of Weathertronics [1983] tipping bucket rain gauge.

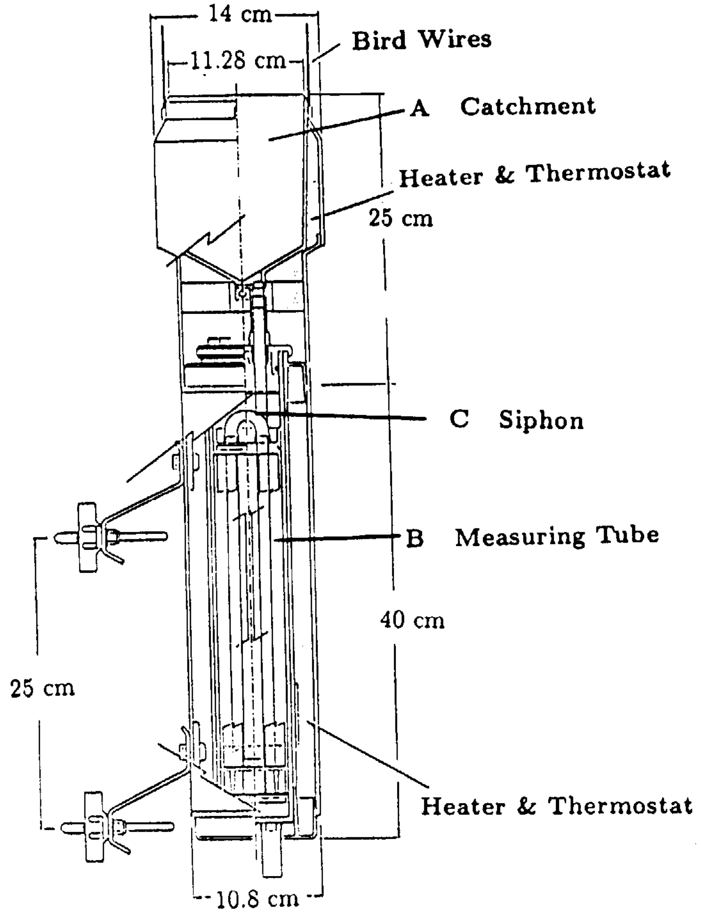

Figure 2: Schematic of R. M. Young [1990] capacitive rain gauge.

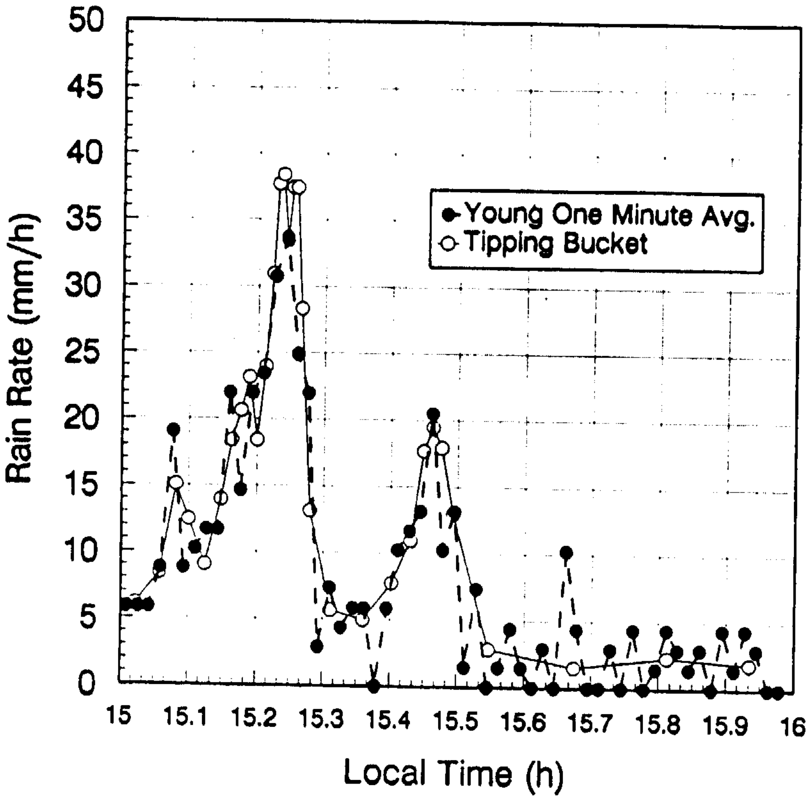

Figure 3: Rain rates for February 15, 1992 derived from tipping bucket and one minute integration time Young gauge.

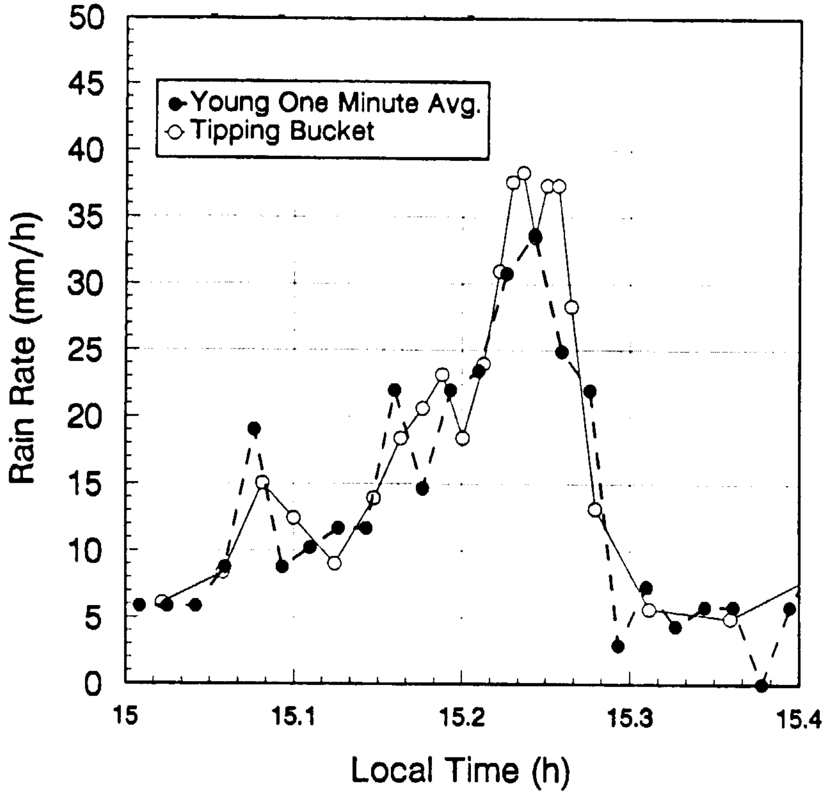

Figure 4: Focused Rain rates for February 15, 1992 derived from tipping bucket and one minute integration time Young gauge.

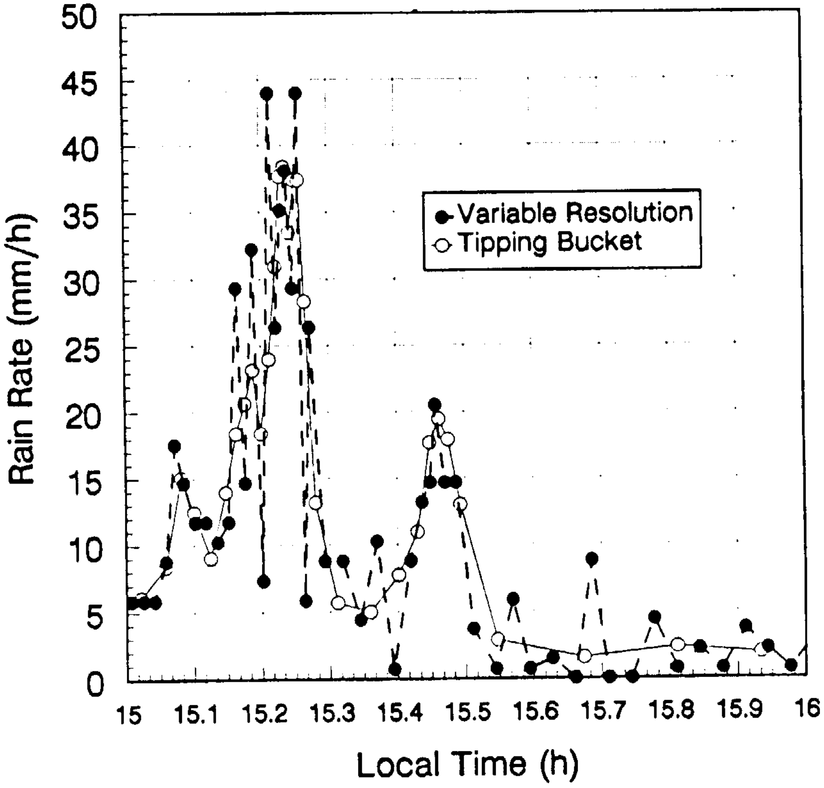

Figure 5: Rain rates for February 15, 1992 derived from tipping bucket and variable integration time Young gauge.

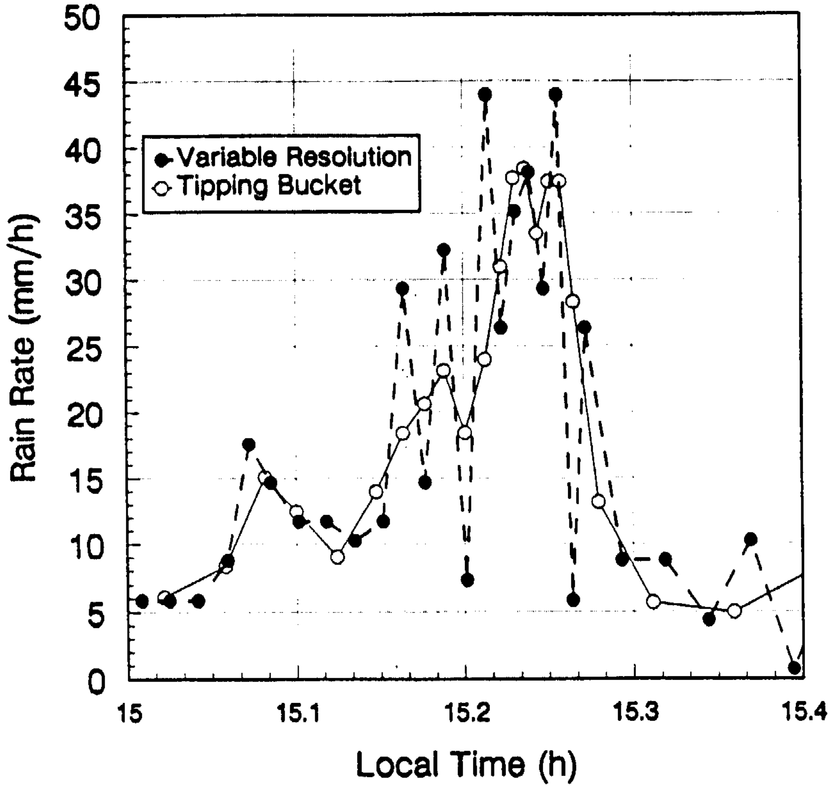

Figure 6: Focused Rain rates for February 15, 1992 derived from tipping bucket and variable integration time Young gauge.

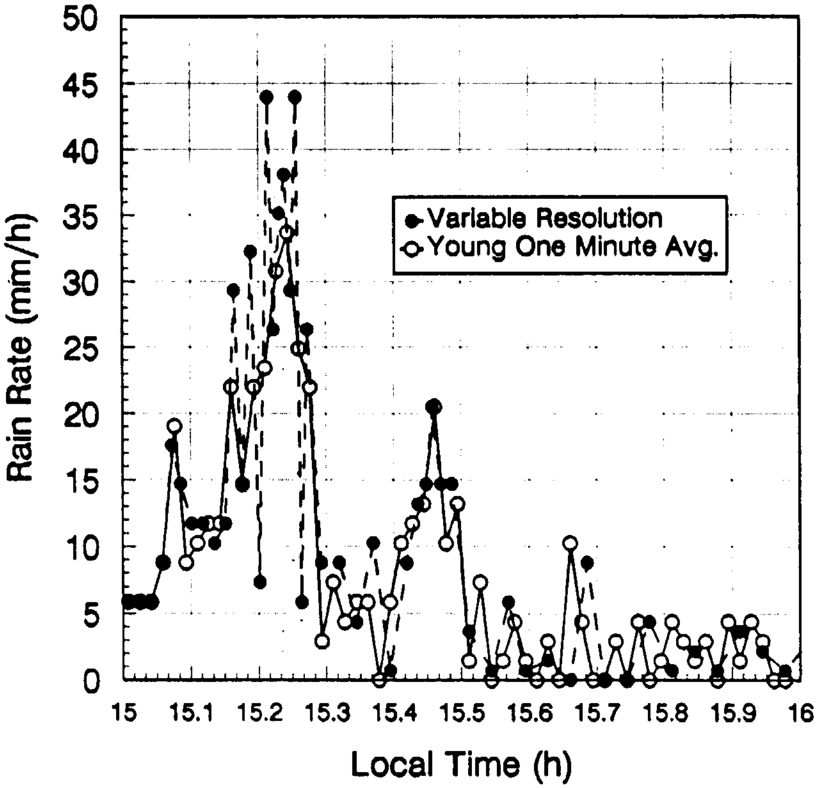

Figure 7: Rain rates for February 15, 1992 derived from one minute and variable integration times using the Young gauge.

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A PROGRESS REPORT

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HOUSTON, TEXAS, MAY 30, 1992

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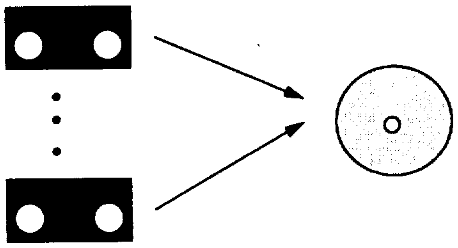
DATA COMPRESSION GOAL



1600 MB OF TOTAL DATA IN
4 MONTHS FROM 8 STATIONS

600 MB OF COMPRESSED DATA
ON CD-ROM FOR DISTRIBUTION

COMPRESSION TECHNIQUES

$$\text{COMPRESSION RATIO} = \frac{\text{ORIGINAL DATA SIZE}}{\text{COMPRESSED DATA SIZE}}$$

■ LOGICAL COMPRESSION	Utilize knowledge of data to reduce redundancy, e.g store one byte offset instead of two byte raw data.
■ PHYSICAL COMPRESSION	Use commercially available programs like PKZIP, ARC etc.

DATAFILE STRUCTURE

FILENAME FORMAT FOR HOURLY DATA FILES YYMMDDHH.S

S=1 .. 8 IS THE STATION IDENTIFICATION.

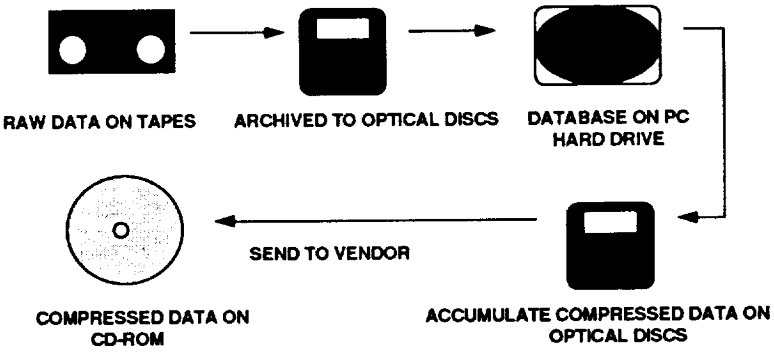
RAW DATA STRUCTURE		LOGICAL COMPRESSION
Time Stamp	4 Bytes	0 Bytes using filename
Beacon 20 GHz	2 Bytes	1 Byte using offsets
Beacon 27 GHz	2 Bytes	1 Byte using offsets
Radiometer 20 GHz	2 Bytes	1 Byte using offsets
Radiometer 27 GHz	2 Bytes	1 Byte using offsets
Environmental Data	2 Bytes	1 Byte using offsets
System Status Info.	2 Bytes	1 Byte using offsets
Total	16 Bytes	6 Bytes

COMPRESSION RATIOS

- MINIMUM REQUIRED C.R = $\frac{1600\ \text{MB}}{600\ \text{MB}}$ = 2.7
- ACHIEVABLE C.R = (LOGICAL C.R) X (PHYSICAL C.R)
  = (2.5) X (1.3)
  = 3.25
- GOAL OF DISTRIBUTING DATA EVERY 4 MONTHS ON CD-ROM IS ACHIEVABLE

DATA STORAGE MEDIA FLOW

(DISC MASTERING DONE BY VENDOR)



RAW DATA ON TAPES

ARCHIVED TO OPTICAL DISCS

DATABASE ON PC HARD DRIVE

ACCUMULATE COMPRESSED DATA ON OPTICAL DISCS

SEND TO VENDOR

COMPRESSED DATA ON CD-ROM

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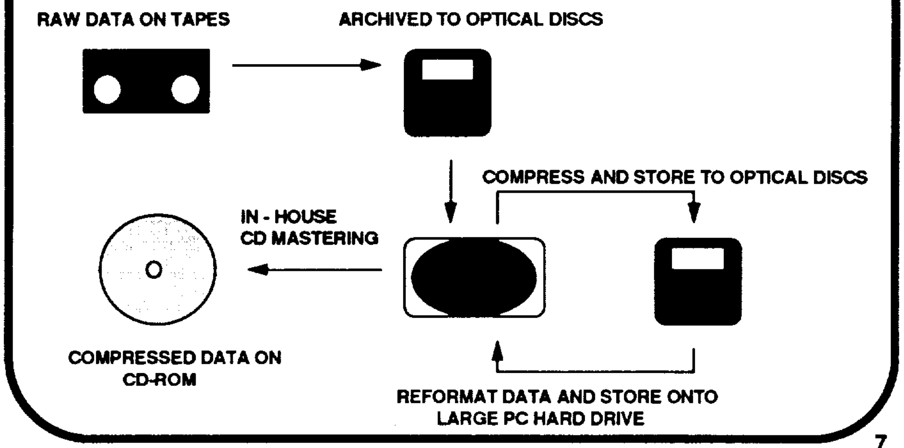
DATA STORAGE MEDIA FLOW

(DISC MASTERING DONE AT DATA CENTER)



RAW DATA ON TAPES

ARCHIVED TO OPTICAL DISCS

COMPRESS AND STORE TO OPTICAL DISCS

IN - HOUSE
CD MASTERING

COMPRESSED DATA ON
CD-ROM

REFORMAT DATA AND STORE ONTO
LARGE PC HARD DRIVE

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COST COMPARISON OF CD MASTERING

- CD MASTERING DONE BY A VENDOR
  COST = $1500 PER MASTER + $2 PER COPY
- CD MASTERING DONE AT DATA CENTER
  COST = $8000 (COST OF EQUIPMENT) + $20 PER COPY
- IN-HOUSE CD MASTERING AND PRODUCTION IS A PRICE-COMPETITIVE OPTION (BREAKEVEN IN 2 YEARS; 6 ISSUES)

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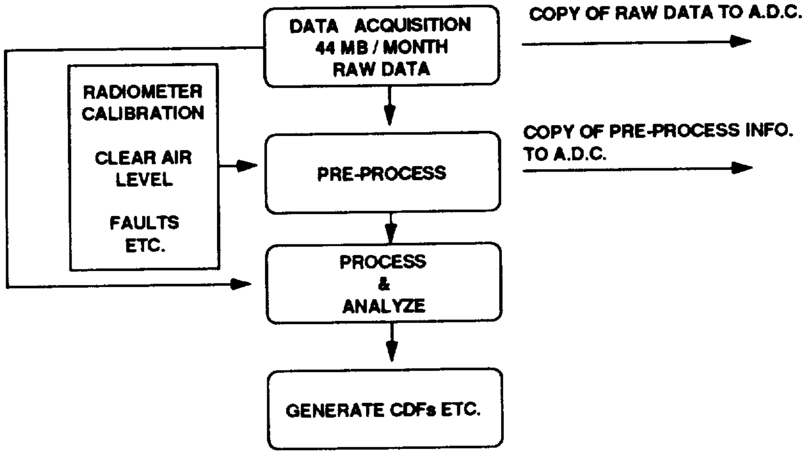
DATA FLOW FOR STATION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44 MB / MONTH
RAW DATA

COPY OF RAW DATA TO A.D.C.

RADIOMETER
CALIBRATION

CLEAR AIR
LEVEL

FAULTS
ETC.

PRE-PROCESS

COPY OF PRE-PROCESS INFO.
TO A.D.C.

PROCESS
&
ANALYZE

GENERATE CDFs ETC.

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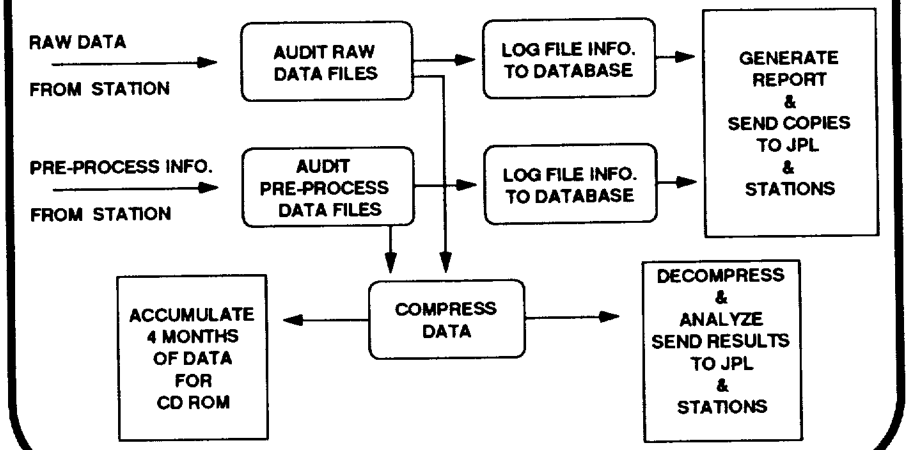
DATA FLOW FOR A.D.C.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FROM STATION

AUDIT RAW
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&
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TO JPL
&
STATIONS

PRE-PROCESS INFO.
FROM STATION

AUDIT
PRE-PROCESS
DATA FILES

LOG FILE INFO.
TO DATABASE

ACCUMULATE
4 MONTHS
OF DATA
FOR
CD ROM

COMPRESS
DATA

DECOMPRESS
&
ANALYZE
SEND RESULTS
TO JPL
&
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