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CONTENTS

CALIBRATION AND INTERCOMPARISON OF THE GATE C-BAND RADARS

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ABSTRACT. The field portions of a major experiment within the Global Atmospheric Research Program (GARP), the GARP Atlantic Tropical Experiment (GATE), were conducted from June through September 1974. A central objective of GATE was to establish a high quality data base for studying the interactions between the large scale circulations and the smaller scale weather systems over the tropical Atlantic Ocean. Better understanding of these interactions is needed to improve the parameterization of convection in the numerical weather prediction models.

A significant ingredient of the data base is accurate quantitative rainfall estimates covering the primary ship array; for example, such estimates are required to assess the precipitation component of the atmospheric water and energy budgets. Digital data from four C-band shipboard radars, supplemented with shipboard rain-gage data, formed the primary sources of information for deriving the rainfall estimates.

Since the success of water and energy budget studies depends on accurate precipitation estimates, which, in turn, directly depend on the accuracy of the overall calibrations of the C-band radars, a multifaceted approach for calibrating and intercomparing the data from the four C-band systems was taken. Comprehensive calibration and intercomparison of the GATE radars were particularly important since many of the subassemblies were built specifically for GATE, which precluded a lengthy record of calibration characteristics prior to GATE. Steps were taken to provide for (1) accurate calibration of the radar hardware; (2) adequate pre-GATE testing of the radar systems; (3) consistency, in the mean, between the reflectivity fields from the

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individual radars, based on various intercomparison techniques; (4) assessment and removal of systematic biases; (5) verification of estimated systematic biases based on "ground-truth" comparisons with the shipboard rain gages; and (6) assessment of probable accuracies of the final rainfall estimates.

To identify and assess the magnitudes of any systematic biases between sensors the hardware aspects of the overall calibration problem were first considered; included were system characteristics, system tests, hardware calibration procedures (for the receiver/digital-processor and the total system gain), and analysis of the hardware calibration data. Next, reflectivity data from the radar systems were intercompared to evaluate the consistency in relative calibrations between radars. Although comparisons were made between "collocated" radars while they were briefly together during official intercomparison periods, most of the comparisons were made while the ships were on station and separated by approximately 165 km. The on-station comparisons were made using reflectivity data from overlap regions, usually located between the radar sites. Because the data being compared were sometimes located at different ranges, and because the range effects could vary from radar to radar, the range performance characteristics of the four C-band radars were examined. Also, the effects of atmospheric and rainfall attenuation on range performance were evaluated.

The radar-to-gage "ground-truth" comparisons were first done on an individual radar basis using selected gages within the field of view of a radar. Based on the results from these comparisons, those from the radar-to-radar intercomparisons, and on the excellent stability of the hardware calibrations, systematic biases were estimated for the radars. The validation of these bias estimates was accomplished by comparing the final merged radar-rainfall estimates with the rain-gage data from all ship stations. Finally, still using the shipboard gages as "ground truth," expected accuracies of the radar estimates for several space and time scales were assessed.

1. INTRODUCTION

The field portions of a major experiment within the Global Atmospheric Research Program (GARP), the GARP Atlantic Tropical Experiment (GATE), were conducted from June through September 1974. The fundamental objectives of GATE have been discussed elsewhere; for example, see Kuettner et al. (1974) and Austin (1975). Briefly stated, the central objective was to provide a basis for developing methods to determine the interactions between the large scale circulations and the smaller scale weather systems over the tropical Atlantic Ocean. Parameterization models of tropical convection, which realistically account for control by, and feedback to the synoptic scale, must be developed by carefully considering such scale interactions. If these interactions can be clearly defined based on GATE data, the accuracy of global numerical prediction can be improved.

Analysis and validation of the GATE data sets fell under the auspices of five major subprograms that divide GATE according to major disciplines (Kuettner et al., 1974). The radar analyses were an integral part of the Convection Subprogram (Betts, 1974; Betts and Rodenhuis, 1975; Hudlow, 1975).

Shipboard meteorological radar measurements during GATE were taken with a total of four C-band and four X-band systems. Figure 1 shows the deployment and approximate coverage of the radars for Phase I of GATE. Table 1 gives the countries, ships, and the principal organizations involved in taking GATE radar measurements.

Refined quantitative precipitation estimates covering an area somewhat larger than the B-scale hexagonal array shown in figure 1 have been derived at the Center for Experiment Design and Data Analysis (CEDDA)[2] as a major task within the Convection Subprogram. C-band radar data, supplemented with shipboard rain-gage data, formed the primary data base for deriving the rainfall estimates. Because of the large attenuations that occur with high rainfall rates in the X-band and because the B-scale array was adequately covered by C-band radars, X-band data were not used at CEDDA in the derivation of the comprehensive series of precipitation maps covering the three GATE field Phases. However, the X-band data are being used by other Convection Subprogram scientists for detailed case studies of individual echoes or ensembles of echoes and their life histories. Photographs from the X-band radars also were included for the GATE International Meteorological Radar Atlas (Arkell and Hudlow, 1977), which contains 3-hourly mosaics of the radar photographs from the C- and X-band radars for 24 days of GATE.

Since the success of the B-scale water and energy budget studies depends on accurate B-scale precipitation estimates, which in turn directly depend upon the accuracy of the calibration of the C-band radars, a multifaceted approach for calibrating and intercomparing the data from the four C-band systems was taken. The calibrations also affect the quality of the three-dimensional distributions of hydrometeor content derived from the GATE radar data. Comprehensive calibration and intercomparison of the GATE radars were particularly important since many of the subassemblies were built specifically for GATE, which precluded acquiring a lengthy record of calibration characteristics prior to GATE.

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[2] Now the Center for Environmental Assessment Services (CEAS).

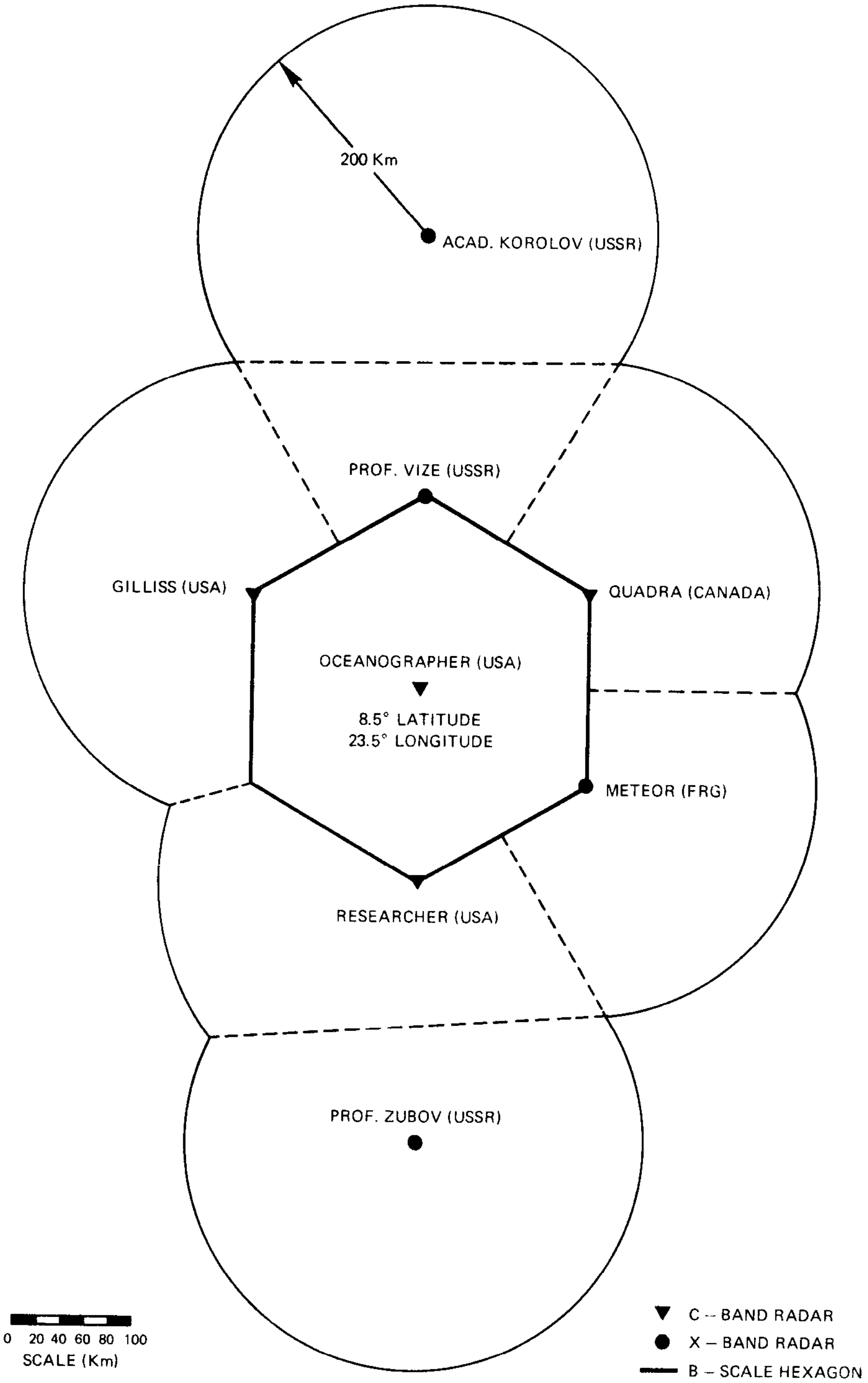

Figure 1.--The GATE B-scale array and radar network showing the deployment of C-band and X-band radars during Phase I, and the maximum coverage included in the pictorial atlas (Arkell and Hudlow, 1977). The quantitative coverage is considerably less.

Table 1.--Countries, ships, and organizations involved in taking GATE radar measurements

Country	Ship(s)	Organization(s)
Canada	Quadra	McGill Weather Radar Observatory and the Physics Department, McGill University, Montreal.
Federal Republic of Germany (FRG)	Meteor Planet	Institute for the Physics of the Atmosphere, DFVLR, Oberpfaffenhofen. Meteorological Institute at the University of Bonn.
Union of Soviet Socialist Republics (USSR)	Acad. Korolov Prof. Vize Prof. Zubov	Hydrometeorological Service (Moscow and Leningrad). Central Aerological Observatory, Moscow. Arctic and Antarctic Research Institute, Leningrad.
United States of America (USA)	Gilliss Oceanographer Researcher	Center for Experiment Design and Data Analysis, NOAA, Washington, D.C. Department of Atmospheric Sciences, University of Washington, Seattle, Wash. Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass. Department of Physics, University of Puerto Rico, San Juan.

Two basic plateaus were reached in the calibration and intercomparison efforts at CEDDA. The first was late in the summer of 1975 when the transfer coefficients in the edit-preprocess computer program were "frozen," and production processing was begun in September 1975 on the data sets from the Oceanographer and Researcher radars. The evaluation and validation of all hardware calibration data were complete by then, and selected intercomparisons of reflectivity fields in regions of overlap between the two radars verified that the equivalent reflectivity factors[3] generally agreed to within 2 to 3 dB. One subroutine in the preprocess

[3] The terms reflectivity factor and reflectivity are used interchangeably in this report.

program transformed the digital machine numbers to reflectivities (dBZ's), which were output to tape for archiving.

In addition to the calibration and intercomparison studies performed at CEDDA prior to September 1975, for the two National Oceanic and Atmospheric Administration (NOAA) radars (Oceanographer and Researcher), similar studies that included the Quadra and Gilliss radars were carried out in parallel at McGill University and the Massachusetts Institute of Technology (MIT). Data from the Gilliss radar also were archived as reflectivities, while the Quadra data were archived as coded values that can be transformed to reflectivities.

The second plateau in the calibration and intercomparison analyses at CEDDA was reached in April 1977. At that time the following additional studies had been completed:

1. Analysis of the GATE drop-size data by scientists at MIT, the University of Toronto, and NOAA's National Hurricane and Experimental Meteorology Laboratory (NHEML), culminating in a proposed reflectivity versus rainfall-rate relationship for GATE. Subsequent analyses by Cunning and Sax (1977) and Austin and Geotis (1979) resulted in somewhat conflicting relationships that will be discussed in section 3.3.

2. Evaluation of signal degradation with range for the four C-band radars.

3. Comparison of rainfall estimates from measurements taken with the radars when they were collocated during special intercomparison periods.

4. Comparison of Phase III reflectivity and volumetric water distributions from the four radars, and comparison of preliminary Phase III mean rainfall rates from the radars with those from selected shipboard gages.

5. Comparison of the final radar rainfall estimates from the individual radars with the shipboard rain gages.

Some of the initial intercomparison studies at CEDDA included data from the two NOAA radars only, since data from the Gilliss and Quadra were not available until after the archival processing had been completed at MIT and McGill University. However, the MIT and McGill groups became involved in their parallel efforts as early as May 1975 when they visually compared their data with hardcopy printouts of selected intercomparison data from the NOAA radars made available to them at that time. The variety of CEDDA intercomparison analyses, many of which included all four C-band radars, complemented by the MIT and McGill studies, form a definitive evaluation of the calibrations for all four C-band radars.

From the results presented in subsequent sections of this report, it was concluded that any significant systematic biases[4] in the radar estimates had been identified, and the final processing for the B-scale precipitation maps was begun in May 1977. These final estimates were based on data merged from two or more radars. As a final verification of the precipitation estimates, comparisons between the merged radar estimates and rain-gage catches on the various ships in the B-scale for daily and Phase totals were made.

2. GATE RADAR SYSTEMS AND SAMPLING

2.1 C-Band Radar Systems

Table 2 summarizes the technical characteristics and specifications of the four GATE C-band radars. All four systems were equipped with a digital video integrator and processor (DVIP). Basically, the DVIP's averaged the output video from the radar receivers over polar data bins of pre-defined sizes and recorded the numerical values on magnetic tape. The DVIP units for the Quadra and the NOAA radars were identical in design, while the Gilliss unit included a programmable integrator that provided, for example, greater flexibility in the selection of data resolutions or bin sizes (Silver and Geotis, 1976). The size of the polar bins used for recording the GATE data were 2° x 2 km for the NOAA radars, 1° x 1 km for the Quadra radar, and they varied from 1° x 0.25 km at close ranges to 1° x 1 km at far ranges for the Gilliss radar.

The block diagram shown in figure 2 illustrates the total Oceanographer radar system and the interfacing of the various components and subassemblies. The configurations of the Researcher and Quadra radar systems were very similar to the Oceanographer's, but the Gilliss system included a dedicated minicomputer that facilitated antenna control, data collection commands, and data handling (Silver and Geotis, 1976).

As mentioned above, the DVIP units for the two NOAA radars and the Quadra were identical in design. The theory for this design was based on research carried out at NOAA's Severe Storms Laboratory (Sirmans and Doviak, 1973). The DVIP's were very similar to the operational units undergoing implementation by the National Weather Service (Shreeve, 1974). The data bin averages are derived from equally weighted range samples and exponentially weighted

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[4] A principal objective of this report is to identify systematic biases, sometimes simply referred to as biases, which we define as the mean difference between the overall calibration of two sensors [between radars and/or between radar(s) and rain gage(s)], as determined from comparative analyses using a large data sample [e.g. one Phase of data (≃ 20 days)]. The biases might result from systematic hardware calibration errors and/or from errors in the transfer equations, including differences caused by the use of erroneous mean coefficients in the reflectivity-rainfall relationship. Although range effects are considered in chapter 7, the systematic biases, as defined for this report, are not range-dependent.

Table 2.--Radar characteristics and specifications

Characteristics	Oceanographer	Researcher	Gilliss	Quadra
Wavelength	5.3 cm	5.3 cm	5.3 cm	5.3 cm
Peak power transmitted	215 kW	225 kW	250 kW	1000 kW
Pulse length	0.57 km	0.60 km	0.60 km	0.30 km
Minimum detectable signal	-100 dBm	-100 dBm	-100 dBm	-90 dBm
Antenna gain (referenced to directional coupler)	39.9 dB	35.0 dB	39.0 dB	43.5 dB
Pulse repetition frequency	259 Hz	250 Hz	250 Hz	320 Hz
Polarization	Horizontal	Horizontal	Horizontal	Vertical
Beam width	1.5°	2.0°	1.5°	1.0°
Base elevation tilt-angle	0.6°	0.5°	0.5°	0.6°
Radome	Yes	No	Yes	Yes

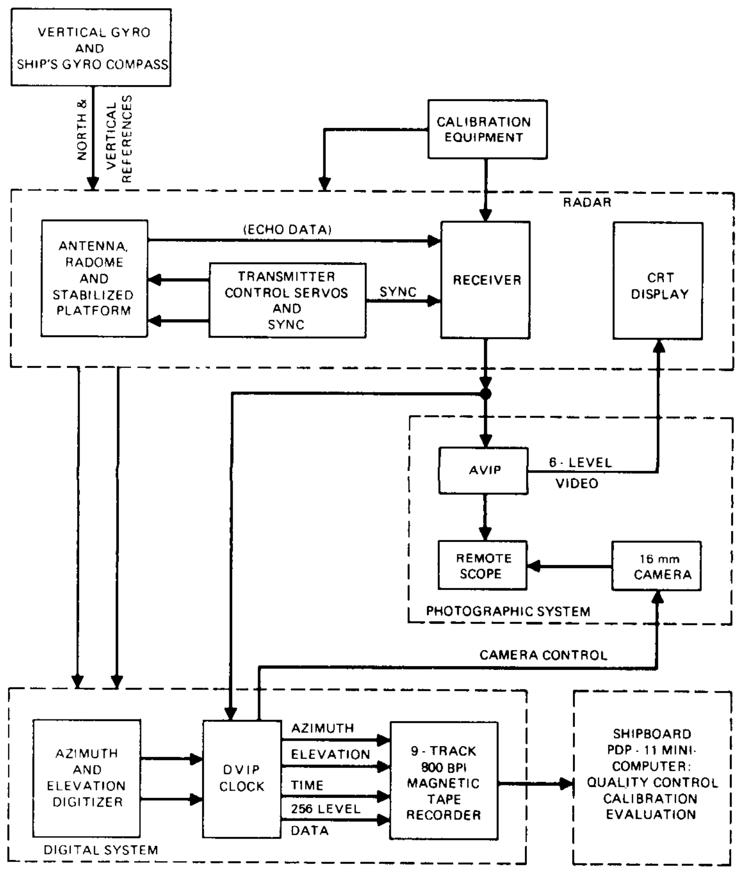

Figure 2.--Radar system on the Oceanographer.

pulse-to-pulse (azimuthal) information. The weight given to successive pulses follows an exponential decay in the direction of the older pulses (Shreeve, 1974). With the time constant scaling factor and antenna rotation speeds used with these three GATE radars, decay to e^{-1} occurred in approximately 0.33° of antenna rotation.

Instead of continuous integration with exponential time weighting, as for the NOAA DVIP, a rectangular window was applied with the Gilliss programmable processor, and an integration cycle corresponding to 1° of antenna rotation was used. Both integrators reduced the standard deviation of pulse-to-pulse fluctuations from a precipitation echo to less than 1 dB. Differences in integrator accuracies affecting the intensity estimates, and their spatial resolution, are not explicitly considered in the calibration and intercomparison analyses that follow. However, the NOAA integrator and the one designed at MIT apparently give comparable precision when hydrologic estimates are derived for the scales considered in this study as is demonstrated by the overall agreement from the various intercomparisons.

2.2 Radar Data Collection and Treatment

Except for scheduled and unscheduled maintenance and calibration periods, the GATE radar installations were normally operated 24 hr a day during all three Phases of GATE. Antenna-tilt sequences consisting of 360° scans at a series of antenna elevation angles were collected nominally every 15 min with the Gilliss, Oceanographer, and Researcher radars and every 5 min with the Quadra radar. Also, higher frequency observations were collected with all radars during special intercomparison periods.

The intercomparison analyses presented in the following sections are based on low-altitude digital data from the various radars. For several of the analyses, sea clutter was eliminated by using data from the 2° or 4° tilt scan at close ranges, instead of from the base-tilt scan, which was nominally collected at 0.5°. Elimination of sea clutter was essential for the collocated radar/rain-gage comparisons presented in section 11.4.

Most of the data analyses have been done using Cartesian data arrays obtained by rectifying the polar reflectivity fields. One exception was the use of polar coordinate data for range-dependent comparisons of special measurements from the C-band radars when they were collocated (ch. 8). The range-dependent evaluations presented in chapter 7 for the two NOAA radars, which were derived from the Cartesian data, were compared with those derived directly from the polar coordinate data. These comparisons showed no significant differences.

The size of the Cartesian data bins (4 km x 4 km) was standardized for all radars; albeit, the polar to Cartesian rectification algorithms used at CEDDA, MIT, and McGill to transform the NOAA, Gilliss, and Quadra data, respectively, differed in some of the details. Identification of biases originating from these differences has not been explicitly considered as part of the intercomparison studies. The overall consistency in the results from the various intercomparison analyses seems to show that any biases originating from differences between the polar to Cartesian rectification algorithms are generally small. Pragmatically, if general agreement is achieved among all radars in the overlap regions and between individual radars and the shipboard rain gages, then the possibility that compensating biases still exist is of secondary importance.

3. BASIC EQUATIONS

3.1 Radar Equations

The average power, $\overline{P}_r$, received at the radar antenna from a volume of hydrometeor particles uniformly filling a nonattenuated circular radar beam is given by (Probert-Jones, 1962):

$$\overline{P}_r = [(\frac{\pi^3}{710})(\frac{P_t G^2 h \theta^2}{\lambda^2})][|K|^2 \frac{Z_e}{r^2}] , \qquad (1)$$

where P_t is the peak transmitted power, G is the antenna gain, h is the pulse width (distance units), θ is the beam width, λ is the wavelength, Z_e is the equivalent reflectivity factor, r is the slant range to the target, and

$$K = (m^2 - 1)/(m^2 + 2) ,$$

where m is the complex index of refraction of the hydrometeors.

For example, substituting the values for the *Oceanographer*'s radar characteristics given in table 2 into eq. (1), solving for Z_e, and expressing the resultant relationship in decibels gives

$$Z_e^* = \overline{P}_r^* + 20 \log (r) + 70.0 \quad , \qquad (2)$$

where

$$Z_e^* \equiv 10 \log (Z_e) \ ,$$

and

$$\overline{P}_r^* \equiv 10 \log (\overline{P}_r) \ ,$$

where the units of Z_e and $\overline{P}_r$ are mm^6/m^3 and mW, respectively. The units for r in eq. (2) are km.

With a logarithmic receiver, the DVIP gives $\overline{\log P_r}$ and not $\log \overline{P}_r$. The bias given by $\log \overline{P}_r - \overline{\log P_r}$ is approximately +2.5 dB (Marshall and Hitschfeld, 1953). Another bias results from the analog-to-digital (A/D) conversion. In the A/D converters of the NOAA DVIP's, the digital values for the instantaneous analog voltages are truncated at 6 bits. A 64-dB dynamic range gives 1-dB class intervals, and the truncation, therefore, causes a 0.5-dB bias (half of the class interval). To account for these biases when using eq. (2), 2.5 dB + 0.5 dB = 3.0 dB should be added to the right-hand side of the expression. Thus, the *Oceanographer*'s radar equation becomes

$$Z_e^* = \overline{P}_r^* + 20 \log (r) + 73.0 \ . \qquad (3)$$

Equations analogous to (3) for the other three C-band radars will not be presented here, but they were derived in an analogous manner using the radar characteristics given in table 2 by Hudlow (1976), Austin (1976), and Catalfamo (1978) for the *Researcher*, *Gilliss*, and *Quadra*, respectively.

3.2 Analysis of Variance of Transmitter Outputs and Digitizer Input-Output Transfer Functions

"Bench" calibrations of the NOAA radar were made every few days. They consisted of injecting a range of test signals from a C-band signal generator into the directional coupler and recording the outputs from the digital processor. The output power from the radar transmitter and the noise (threshold) level of the receiver/processor were also continually monitored. Similar calibrations of the *Gilliss* and *Quadra* radars were made at approximately the same intervals.

The output powers from the NOAA radar transmitters were never observed to fluctuate by more than 5 percent from the values given in table 2. All calibration runs from the individual radars exhibited excellent internal consistency and system stability. As an example of the precision that can be achieved with modern solid-state radar components, figure 3 summarizes the results from the 12 *Oceanographer* bench calibrations made during GATE

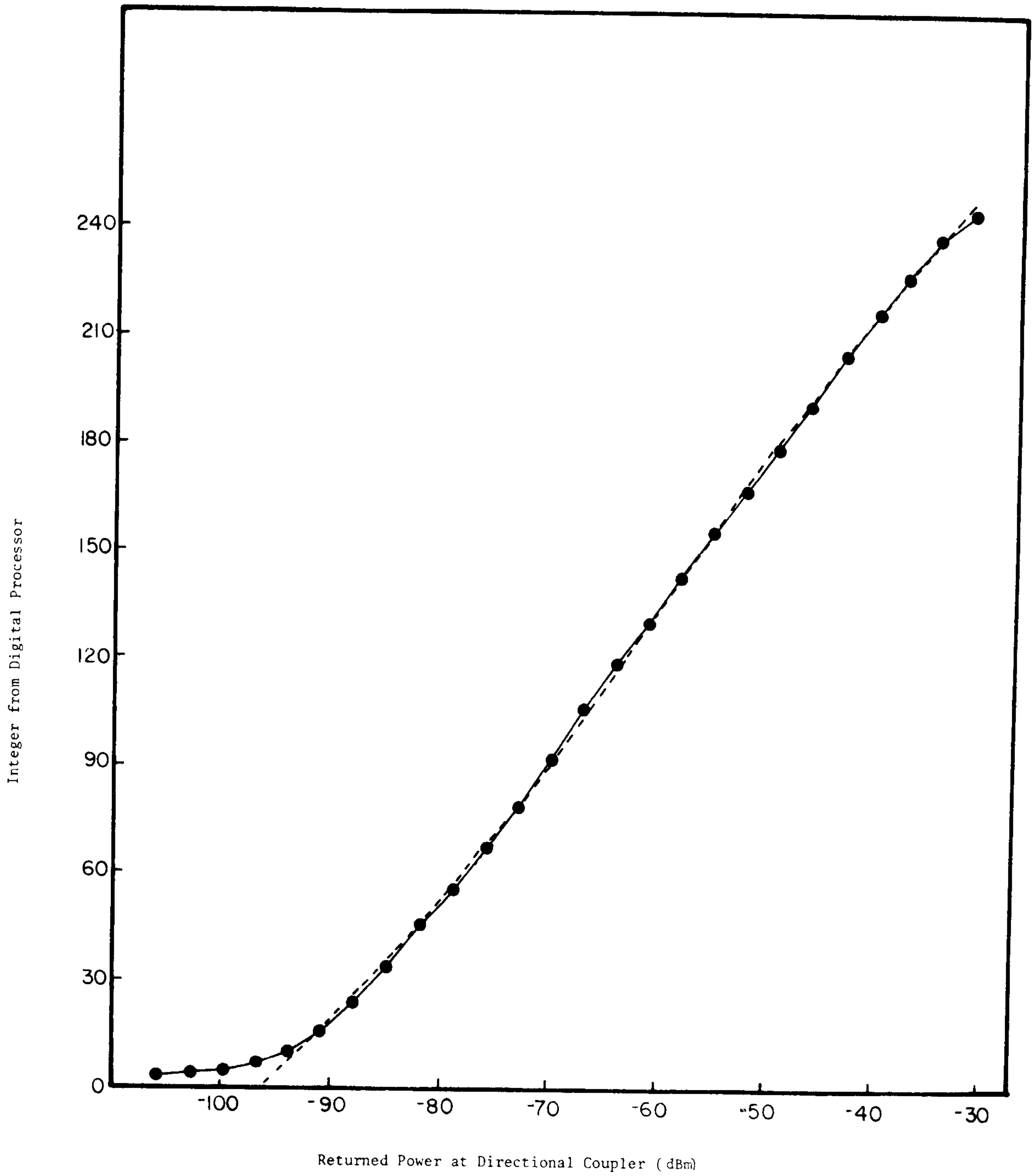

Figure 3.--The mean (solid) and least-squares (dashed) fits to the data from all Oceanographer "bench" calibrations.

and illustrates the good stability of the digital processor, which also reflects the stable characteristics of the radar receiver. The dashed curve is the least-squares fit of a third-degree polynomial to all individual data points from the 12 bench calibrations (258 points). Each calibration run consisted of points that spanned the dynamic range of the receiver/processor in 3-dB increments. However, the lower 4 points were deleted from the 12 sets of calibration data before the least-squares fit was made. The solid curve depicts the mean of the 12 sets of calibration data.

Before the 12 Oceanographer calibration runs were lumped into one group, they were kept separate for the three GATE Phases, and a least-squares fit for each Phase was obtained. The additional variance explained by the Phase subgroupings was insignificant when compared with the $\pm$ 1-dB possible error in the input calibration signals from the generator. Therefore, the Oceanographer data for all periods were processed using the third-degree polynomial curve shown in figure 3. The accompanying mathematical expression is

$$\overline{P}_r^* = -96.28 + 0.35\,D - 8.66 \times 10^{-4}\,D^2 + 2.10 \times 10^{-6}\,D^3 , \qquad (4)$$

where D is an integer (0-255) from the digital processor, and $\overline{P}_r^*$ is the corresponding return power. The correlation coefficient for the least-squares fit, eq. (4), is 0.999, and the standard error of estimate is 0.74 dB.

Analysis of the variance of the input-output response curves for the Researcher's radar receiver/processor was performed in an identical manner to that described above for the Oceanographer. Again, the stability of the Researcher's system was found to be good, although the standard error of estimate ($\approx$ 1.0 dB) was somewhat larger than for the Oceanographer curve. Also, because of a change in the alinement of the Researcher DVIP between Phases I and II, it was necessary to apply two calibration curves: one for Phase I and another for Phases II and III (Hudlow, 1976). Calibration curves analogous to the one for the Oceanographer (fig. 3) also were determined for the Quadra and Gilliss at McGill University and MIT, respectively, where the reflectivity measurements from these two radars were processed (Catalfamo, 1978; Austin, 1976).

3.3 Reflectivity-Rainfall Relationships

The first step in converting radar reflectivity measurements into rainfall rate estimates usually consists of using an empirical relationship that relates the reflectivity factor to rainfall rate. The equation normally takes the form of the following logarithmic function:

$$Z = A\,R^B , \qquad (5)$$

or

$$\log (Z) = \log (A) + B \log (R) , \qquad (6)$$

where Z is the reflectivity factor in mm^6/m^3, R is the rainfall rate in mm/hr, and A and B are regression coefficients. A and B are usually determined from