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Supporting Research

April 22, 1981

PERFORMANCE COMPARISON FOR BARNES MODEL 12-1000, EXOTECH MODEL 100, AND IDEAS INC. BIOMETER MARK II

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16. Abstract

As an adjunct to acceptance testing of the prototype of the Barnes Model 12-1000 it was decided to include testing of the Exotech Model 100A. The Model 100A was known to be linear instrument having excellent temperature stability and optical characteristics; therefore; it was felt that inclusion of this unit would serve more as a test of the procedures used than as a test of the Model 100A.

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PERFORMANCE COMPARISON FOR
Barnes Model 12-1000, Exotech Model 100, and
Ideas Inc. Biometer Mark II.

I. Introduction.

As an adjunct to acceptance testing of the prototype of the Barnes Model 12-1000 it was decided to include testing of the Exotech Model 100A. The Model 100A was known to be linear instrument having excellent temperature stability and optical characteristics; therefore, it was felt that inclusion of this unit would serve more as a test of the procedures used than as a test of the Model 100A.

In the summer of 1980, a Biometer was loaned to Jon Ranson, a new graduate student at LARS, by C.J. Tucker of GSC. Since we were planning to use a Model 100A to measure the angular reflectance properties of a soybean field, we investigated the Biometer to determine if it would be suitable for inclusion in this experiment. It was quickly determined that the 1.55-1.75 (Lead Sulfide) channel was not stable enough to make accurate measurements. However, it was felt that the Thematic Mapper Band channels 0.63-0.69 and 0.76-0.90 would be desirable to include in the study so we investigated the field of view of these channels in order that they might be modified to 10^{o} (half power - full angle) field of view which was required for this study. It was found that, although the first-cut design of the field of view was for a 24^{o} (limit of response-full angle) and 16^{o} (half power-full angle) response, the unit showed response to 80^{o} full angle. It was also determined that, due to the large detectors used in the Biometer it would be difficult to quickly design a small, simple modification which would correct the field of view to a sharp 10^{o} (half-power - full angle); therefore, it was decided not to use the unit until a well defined field of view could be established. The wisdom of this action was later underscored by the receipt of an article (for review) by a USDA author who concluded that, based on measurements by a Biometer, the reflectance of a 0.406 m x 0.457 m gray panel was dependent on the reflectance of the adjacent vicinity when viewed from a distance of 0.51 meters with the "24^{o}" field of view.

During the summer of 1980 a number of USDA and university researchers asked me if the data from the 1.55-1.75 channel of the Biometer was useful and I replied that, in my opinion, it was not. Since a number of other competent researchers were questioning the performance of the Biometer Mark II it was decided to include the Biometer in the acceptance testing procedures used for the Barnes Model 12-1000. I was later contacted by C.J. Tucker and W. Jones of GSC who assured me that the unit was, in fact, stable and Mr. Jones described why, in his opinion, the design was stable and how the field of view was being corrected. (See conclusions).

II. Tests and Results

The tests and results reported here do not represent all the tests run on the Model 12-1000 prototype. Only tests of radiometry in the measurement of agricultural subjects in a field environment are reported.

Since it was known that the Model 100A is a high performance instrument, it was used to check the stability of the lamps used for the linearity and stability tests and to estimate the limit of uncertainty associated with these tests.

A. System Stability.

When exposed to a step change at its input transducer, a system should reach a meaningful, stable response within a useful time interval.

1. The instruments were first tested for stable operation by exposing each channel of each instrument to a source of diffuse radiance of sufficient extent to completely fill its field of view and of sufficient intensity to obtain a mid-scale reading on each channel. Then a black panel was used to completely block the radiance. Following this the dark level of each channel was monitored on a printing 4½ digit volt meter (Biometer readings were taken from the LCD display on the Biometer). The Model 100A and Model 12-1000 responses showed no instability in settling to the dark level. The silicon detector channels (0.63-0.69, 0.76-0.90) on the Biometer Mark II showed only slight settling instability which was difficult to measure with the LCD display. However, the lead sulfide detector channel on the Biometer (1.55-1.75) seemed to require a long time to settle and seemed to never stop drifting. Similar results were obtained when the blocking panel was removed exposing the units to the source of radiance.

2. A more sophisticated version of (1.) above was performed using the instrument dark levels, a 17% diffuse reflector and a "100"% reflector in sunlight with similar results. The lead sulfide channel of the Biometer Mark II was unstable.

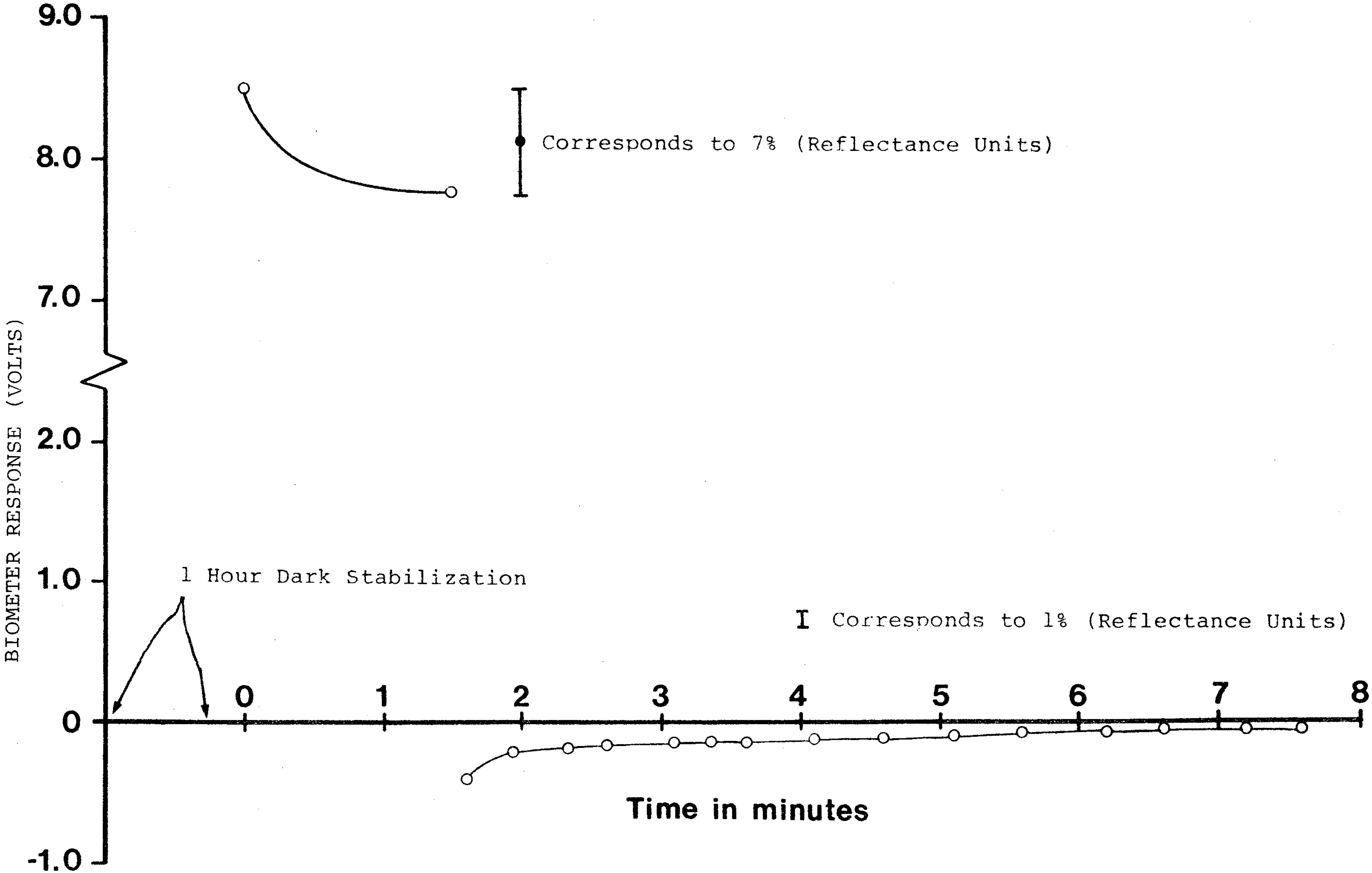
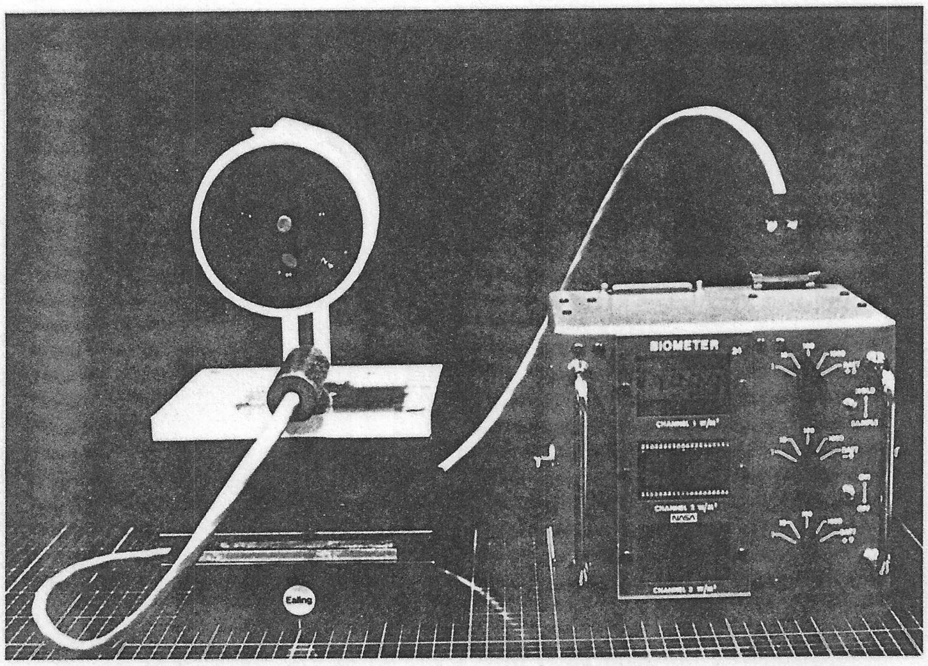


Figure 1. Stability test results for Biometer Mark II.

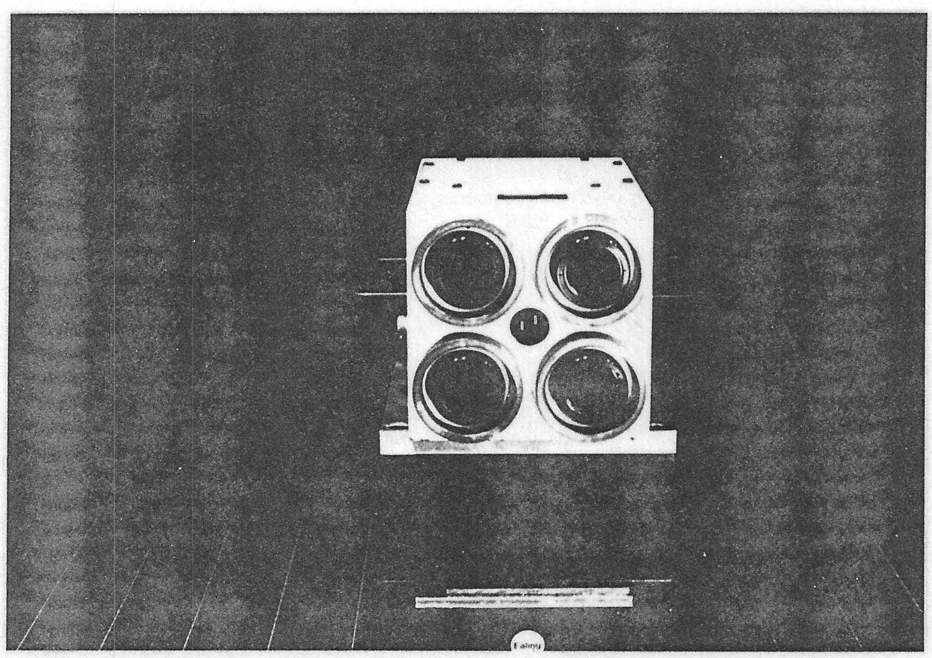
3. In order to quantify the instability in the lead sulfide channel, the field of view of the channel was filled with a large diffuse source of radiance having an intensity equal to a 70% reflector in sunlight. The unit was then blocked so as to read the dark level response for one hour. While the unit was still drifting, (as evidenced on the x1 scale) it was assumed that the drift was not related to the instability but, rather, reflected the component of 1/f noise which is an inevitable result of the signal processing design. Following this hour of stabilization the response was set to 0.000 and the panel was removed exposing the unit to the source of radiance. The initial response was recorded and the change in response in 10 second intervals was observed until 1 minute and 30 seconds had elapsed. At this time the change in a 10 second interval was less than 0.08 or 1% of the reading of 7.75. See Figure 1.

Then the dark cover was reinstalled and the dark level readings were monitored at approximately 30 second intervals for six minutes. The results of this test are shown in Figure 1. The unit required 3 minutes for the dark levels to settle to within 1% reflectance units of zero.

A similar test was run with an intensity equivalent to that of a 12% reflector in sunlight. The dark level was initially 0.5% (reflectance units) from 0, an error of 5% of value for the 12% reflector. One minute and 30 seconds were required for the unit to settle to an error of 1% of value for the 12% reflector. (See Conclusions).

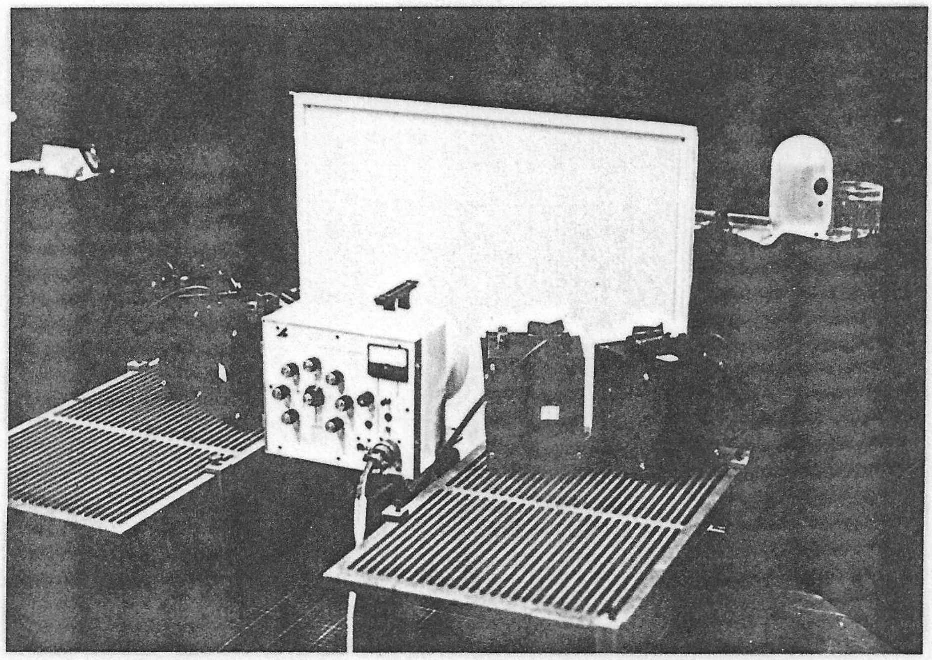


(a) Biometer MarkII SN:24

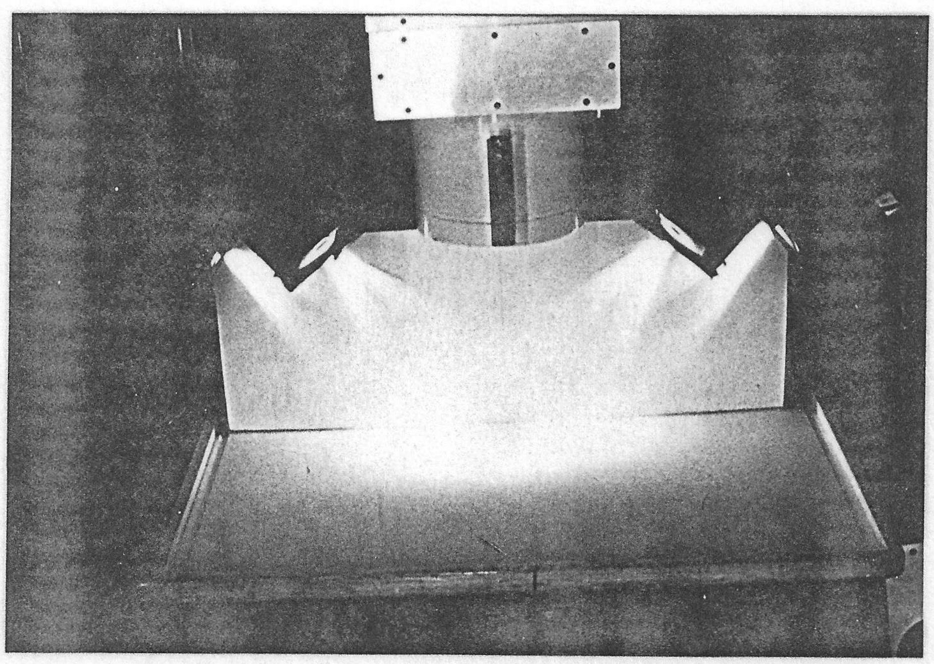


(b) Model 100A SN:3431

Figure 2. Biometer and Model 100A shown with mounting stands on optical table.



(a)



(b)

Figure 3. Model 12-1000 prototype shown with mounting bracket on optical table. (a) Rear view of linearity set-up showing four sources and reflectance surface. (b) Above view of linearity set-up showing cones of light from four sources projected onto cardboard alignment fixture.

B. Linearity (at 25 C)

To measure a radiance or reflectance with simplicity and accuracy, it is important that the sensor respond linearly to input radiant power over the range of input power for which it will be used.

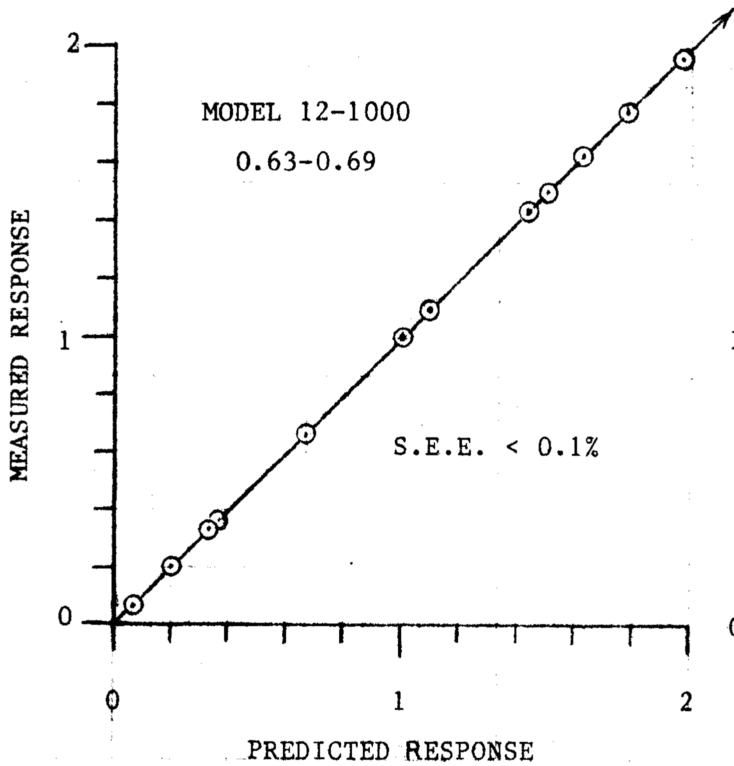
1. The instruments were tested for linear response using a sum-of-sources technique. This technique involved aiming four sources of irradiance at a diffuse white surface to simultaneously provide a view-filling source of radiance for each channel of the radiometer under test. Then the response, v_i, to the radiance, L_i, of each source was determined by blocking the other three sources. Next, the eleven possible sums of radiances were produced by systematically blocking combinations of sources. A regression of the eleven responses to sums of radiances to the corresponding sums of responses was used to determine a standard error of estimate. The standard error of estimate, normalized to the response of the instrument to a 100% diffuse reflector normal to the sun on a clear day near noon, was taken to be a useful measure of the linearity. The voltage responses of the Biometer Mark II were read from its LCD displays. The voltage responses of the Model 12-1000 and the Model 100A were measured with a 40,000 count printing voltmeter. (See Figures 2 and 3)

2. The Model 100A was the first unit tested for linearity and the linearity was found to be better than 0.1% for the x 1 range which is usually used in the field. One aspect of this test which went unnoticed was that about three hours time was allowed for the lamps and their power supply to stablize. Several attempts were required to learn this lesson. The initial tests of the Model 12-1000 were aimed at the low-level performance of the precision rectifiers. These tests indicated systematic non-linearities on the order of 0.2% of full scale. A bread board circuit for the precision rectifier was modified to eliminate this non-linearity and the modification was agreed to by the vendor.

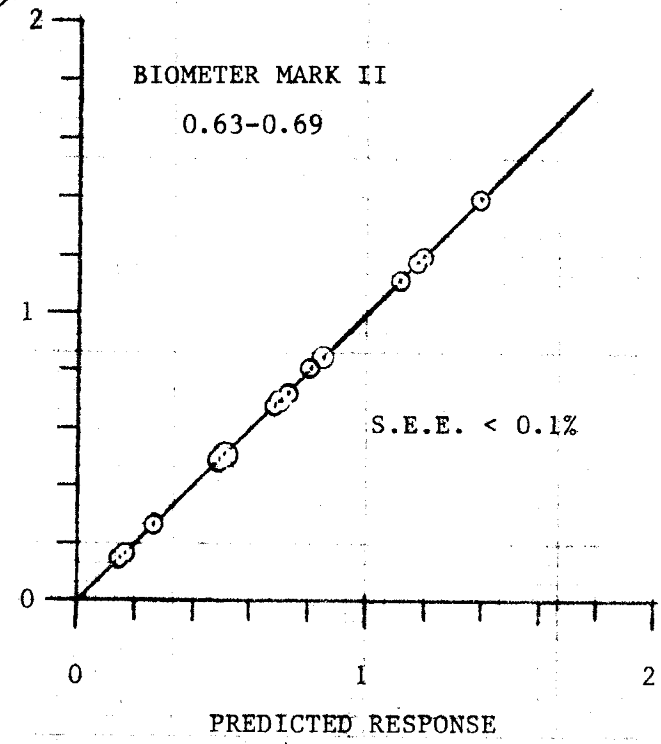
3. Results:

a. Silicon Channels. The standard error of estimate for regression of the response of the sums against the sums of reponses was less than 0.1% when normalized to the Nominal Maximum In-Band Radiance (NMIBR) for all channels having silicon detectors. This is shown in Figure 4. In addition, the Model 100A and the Model 12-100 were tested to about 2.5 times the NMIBR using the sums of sources technique. The Biometer Mark II was tested to about 4 and 1.5 NMIBR In channels 1 and 2 respectively using Neutral Density filters. No non-linearity was noted.

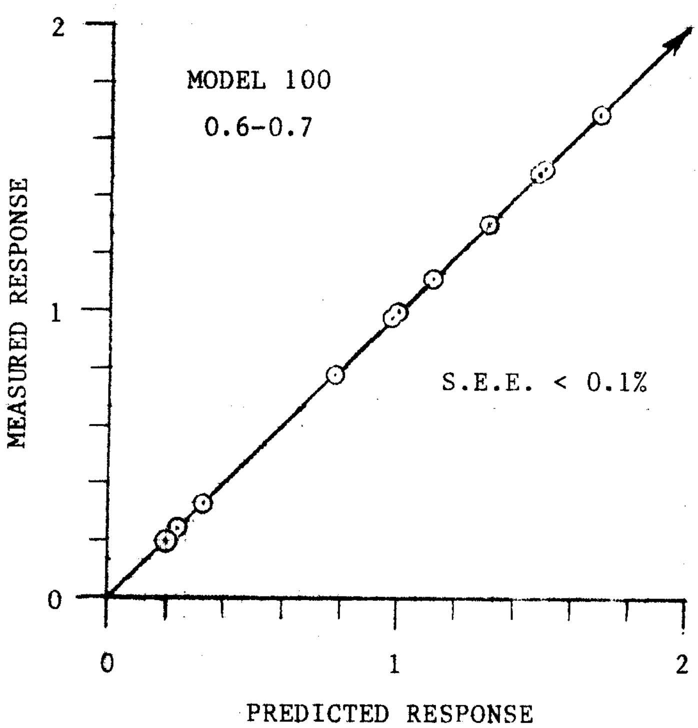
b. Lead Sulfide Channels. The standard error of estimate for regression of the response of the sums against the sums of responses was less than 0.1% for radiances less than about 1.5 NMIBR for the Model 12-1000. See Figure 5 (a). In addition, the Model 12-1000 sensors were tested to about 2.5 NMIBR with S.E.E. values less than 1.5% NMIBR for the regression over the entire range. The Biometer Mark II was tested using the sum of sources technique from 0 to 0.7 NMIBR with a standard error of estimate of 1% NMIBR. An alternative test using neutral density filters (precision perforated nickel) was used whereby the silicon channels (already proven linear) were used to measure the transmittance of the screens and the result compared with the measurement by the lead sulfide channel. This technique yielded a S.E.E. of 0.4% up to about 0.75 NMIBR and revealed a non-linearity near 1.0 NMIBR. See Figure 5 (b). It is felt that the high S.E.E. of channel 3 of the Biometer is due to settling phenomena, rather than a fundamental non-linearity. However, repeat tests indicated a non-linearity in channel 3 of the Biometer somewhere near 1.0 NMIBR.



(a)



(b)



(c)

Figure 4. Results of linearity test for silicon detectors. Responses normalized to "Nominal Maximum In-Band Radiance" (clear day -- near noon -- earth surface) for a painted barium sulfate reflectance standard pointed at sun."

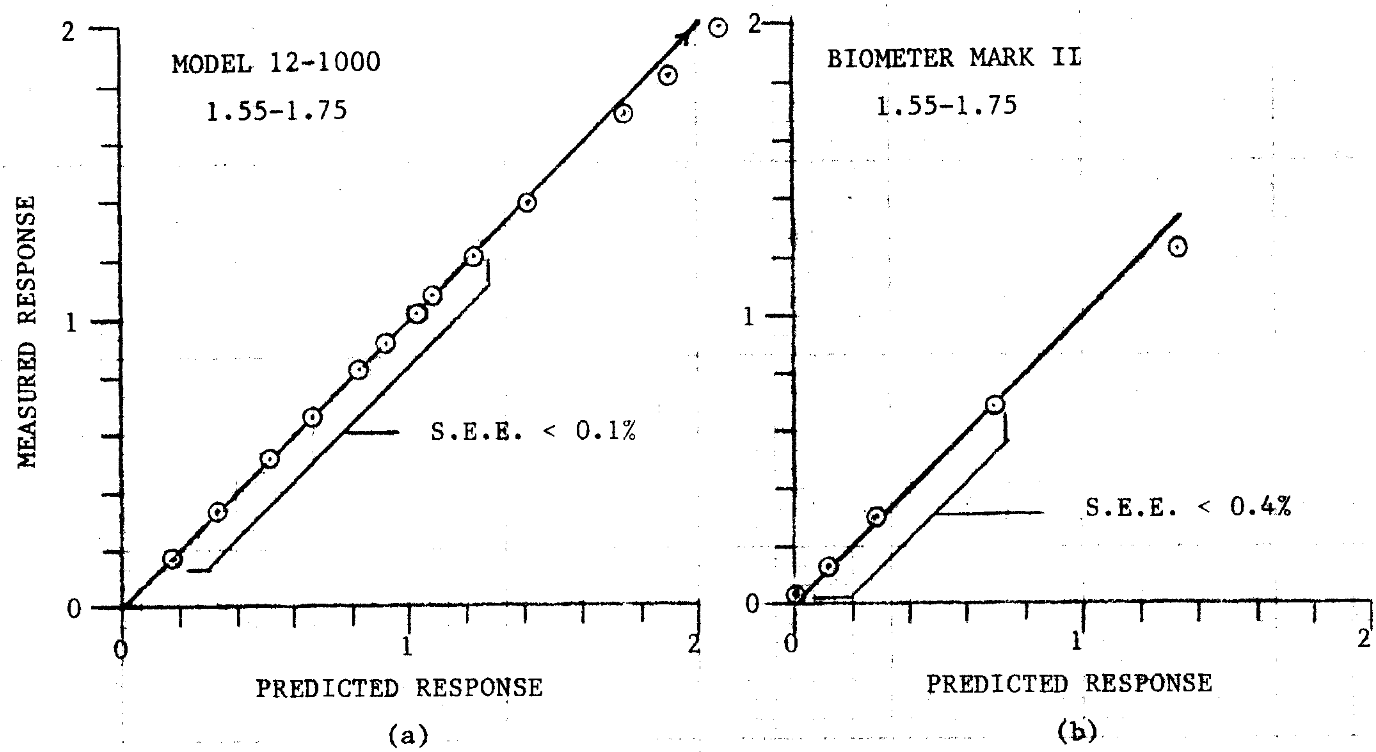


Figure 5. Results of linearity test for lead sulfide detectors. Responses normalized to "Nominal Maximum In-Band Radiance" (clear day--near noon--earth surface) for a painted barium sulfate reference standard pointed at sun.

C. Temperature Stability

Following a step change in its environmental temperature, a system should perform in one of the following ways:

(i) not change its characteristics significantly during an appropriate time interval

(ii) change its characterists in a moderate, predictable manner which can be measured and, if necessary, compensated.

To typify reasonably severe field conditions the design of the Model 12-1000 was aimed at the following condition:

" Detector temperature shall be monitored; and analog compensation shall be used to limit the relative limit of uncertainity ((maximum franctional error)) in reflectance measurement to 1% (0.4μm to 1μm) and 2% (1μm to 2.5μm) for a 5 celsius degree step in temperature imposed for 20 minutes (20 H_z filter)." filter)."

Based on 10 years of experience with field operations and 5 years of experience with helicopter operations it was felt that this condition would be more than adequate. Furthermore, if accuracies of more than 2% of value were required the measured detector termperature could be used to compensate for changes in responsivity of the detectors.

1. The Model 12-100 and Biometer Mark II were tested by enclosing them with a cardboard chamber while mounted securely on an optical table. The front of the chamber was filled with a cover which, when removed, exposed each channel of the radiometer to a view-filling source of stable radiance. See Figure 6. Attached to the rear of the cardboard chamber was an environmental chamber which contained two blowers which circulated heated or cooled air at a rate of about 40 c.f.m around the mounted instrument. Two thermometers were used to monitor the air temperature of the blown and "stagnant" air in the cardboard chamber. Dry nitrogen was used to lower the dew point to prevent condensation during the tests at temperatures lower than 20 c.

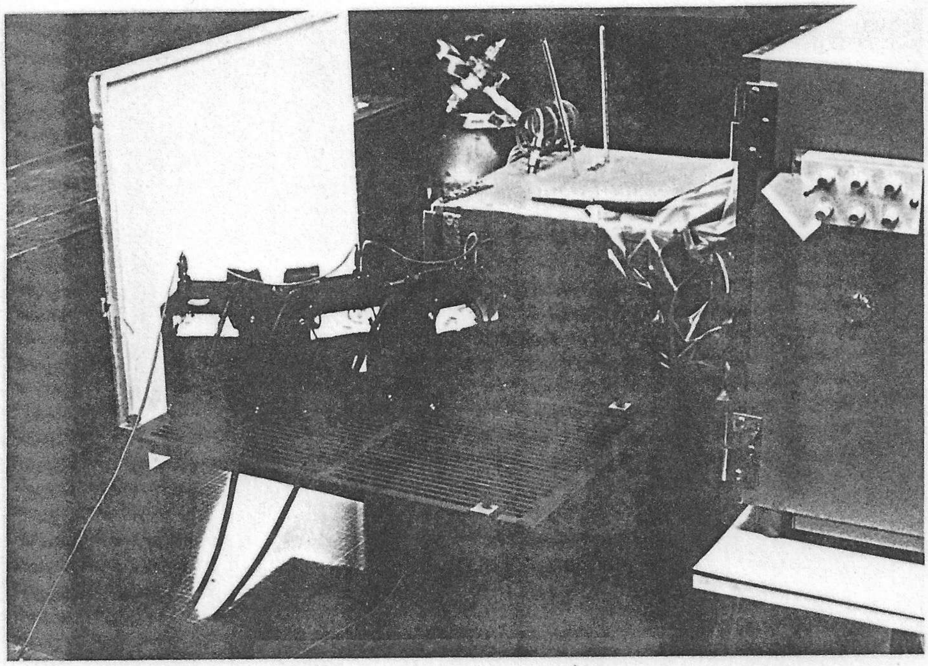


Figure 6. Temperature stability test set up. from left to right: diffuse reflector, lamps, cardboard chamber, and environmental chamber.

2. The detector, chopper, and body temperature sensors of the Model 12-1000 were calibrated from 0 to 55C by allowing the instrument (turned-off) to reach equilibrium at five temperatures and fitting the standard thermistor curve to the responses at each temperature. The instrument was only turned on briefly to obtain the readings; thus, the chopper motor and other sources of heat were not a factor in the readings. In the production models, temperature to voltage converters will be linear and calibrated to ± 0.1°C, which will eliminate the need for this step.

3. To obtain data for the 5°C steps in temperature, the Model 12-1000 was brought to equilibrium at 20 C prior to the introduction of air cooled to much less than 15 C. As the chamber cooled toward 15 C, the temperature of the air was warmed to slightly cooler than 15 C. The effect was a rapid step in air temperature which approximated a 5°C step. The instrument was continuously running and the response of each channel was measured with a 40,000 count printing voltmeter as the instrument cooled toward the new equilibrium temperature of 15 C. Similar procedures were used to produce +5°C temperature steps.

Similar procedures were used to produce the temperature steps used to test the Biometer Mark II. However, the electronics module of the Biometer was not placed in the chamber to allow for readings of the LCD display.

4. Results

a. The Model 12-1000 was tested for the temperature steps indicated in Table 1.

Table 1. Percent change in 20 minutes following 5°C step. Model 12-1000

	Prototype Channel Number						
Δ	1	2	3	4	5	6	7
ΔT, °C	0.45-0.52	0.52-0.6	0.63-0.69	0.76-0.90	1.55-1.75	1.15-1.30	2.08-2.35
20-15	+1.5	+1.2	+1.3	+1.0	+1.3	+2.0	+2.0
15-20	-1.0	-1.0	-1.0	-0.0	-0.2	-1.54	-0.9
20-25	-1.8	-1.5	-1.4	-1.4	-2.0	-2.7	-1.7
25-30	-1.6	-1.6	-1.2	-1.1	-2.0	-2.5	-2.0
30-35	-1.4	-1.5	-1.4	-1.2	-2.1	-2.6	-2.0
35-40	-1.1	-1.1	-1.0	-0.7	-1.8	-2.2	-1.9
40-35	+0.7	0.7	+0.8	+0.7	+1.3	+1.9	+1.4
35-30	+0.7	+0.9	+1.0	+0.8	+1.5	+1.9	+1.4

The data in Table 1 are not smooth and uniform due to a number of thermal factors which were operating within the instrument and the test set. The chopper motor tends to heat the unit faster when heating and retard cooling. As well, the temperature step required initial overdrive on the air temperature and this was done manually. However, the responses at equilibrium at 15°C and 40°C were used to compute equilibrium temperature coefficients for the silicon detectors and lead sulfide detectors of 0.6% and 0.87% per degree C. Since the temperature drive is 5°C and the time constant is nominally 20 minutes, the estimated maximums for the 5° step imposed for 20 minutes are 1.9% and 2.7% for silicon and lead sulfide, respectively. With the view that these are fractional errors and not reflectance units, that the typical time to calibration is about 10 minutes, and that the probability of a 5°C step in temperature is small, these performances are well suited to the vast majority of field measurement applications. Furthermore, the availability of the detector temperature signal allows the researcher to compensate for extreme situations.

As a result of this test the vendor is investigating a simplification of the circuitry which may improve the temperature stability of the silicon channels.

b. <u>The Biometer Mark II</u> was tested for temperature stability as indicated in Table 2.

Table 2. Percent change in indicated time interval following indicated step temperature change.

			Channel Number		
Ti-Tf C	ΔT °C	ΔT Min	1 0.52-0.60	2 0.63-0.69	3 1.55-1.75
14.4-19.4	5	13	<0.5%	-0.9%	- 7.9%
19.4-23.9	4.5	29	-0.8%	-0.8%	- 7.9%
31.7-36.7	5	18	<0.5%	+0.4%	-10.7%
33.3-38.3	5	18	<0.5%	+0.8%	- 5.9%

The direct coupled photovoltaic silicon PIN diodes in channels 1 and 2 performed as anticipated. The lead sulfide channel performance was systematic and not due to random drift. Depending on the temperature range, the coefficient seemed to be between 1.5 and 2% per celsius degree for complete "stabilization." Since the A/D converter has a variation of only 0.03% for a 5°C temperature change it is felt that the results would be essentially the same had the electronics module been included in the temperature controlled chamber.

c. <u>Model 100A</u>

The temperature coefficient for the silicon channels of the Model 100A is about 0.3%/C°. For a temperature drive of 5° and a time constant of 20 minutes, the estimated maximum percent change in 20 minutes is about 1%.

D. Noise and Quantization Errors

When an observation is made with an instrument, the random factors should be small, fairly well specified, and acknowledged.

1. The three instruments were examined for random phenomena during testing for linearity and in the field. Noise from the Model 12-1000 and Model 100A were examined on the oscilloscope to determine the character of the noise. It was determined that the noise in the Model 100A was mainly shot noise and 1/f noise and the noise in the Model 12-1000 was mainly demodulation residuals with added random noise of various types in nearly negligible amounts. The Model 100A was tested in sunlight for partition noise or other noise which might be a function of the input radiant intensity--none was found. It was inconvenient to test the noise of the Biometer Mark II as it was quantized. However, during the stability tests some 1/f type noise was noticed in channel 2. Furthermore, 1/f type noise is obviously present in the channel 3 of the Biometer as evidenced by the continual "drift" of that channel with and without signal.

2. Tests and Results

a. The Model 100A was monitored with a 40,000 count printing voltmeter during the linearity tests. Since the signal was constant and the unit was in equilibrium with the 35 C air, repeated measurements with the voltmeter were used to establish the standard deviation of the output signal. While the standard deviation was not constant it was nearly so. Typically it was between .0001 and .0002 volts rms. A value of 0.00015 will be used for σ in the next section.

b. The Model 12-1000 was also monitored during the linearity tests and it was noted that the noise was proportional to the input signal. It was determined that a limit of the standard deviation of this noise was about 0.08% of the channel response with the average of the standard deviations being about 0.04% for each channel.

c. The Biometer Mark II was monitored during the linearity tests but the digitization was the limiting factor in channels 1 and 2 and while the digitization is a factor in channel 3 it drifts with time. Thus, the quantization was considered. The limit of uncertainty for the AD2020 is 0.1% of value + 1 digit + 0.03% per degree C. The dynamic range for field measurement using the field of view defining aperture plate (which is extensively tested under laboratory and field conditions) and the recently released design for a

24° field of view cone are listed in Table 3.

Table 3. Nominal Maximum Response - Biometer

	Channel		
Aperture	1	2	3
Standard Plate	22.0	48.5	11.0
24° cone	44.0	86.3	13.5

The data for the standard plate was determined on a bright summer day in 1980. The data for the 24° cone was obtained by determining the ratio of the response of the instrument with the standard plate to the response with the cone (using the average of two Biometers) for a view filling diffuse reflector exposed to sunlight on a spring afternoon in 1981.

The data in Table 3 represents the maximum response of each channel to a 100% reflector on a clear day near noon. It can be seen that the worst single reading for this situation is in channel 3 where the quantization is 90 parts per thousand. In addition, a 6% reflector, read on the same scale, will yield the number 0.5, 0.6 or 0.7 if only quantization noise is condidered.

E. Maximum Fractional Error

When a measurement is made with an instrument, the fractional (or absolute) error should be of reasonable size, well specified, and acknowledged.

The maximum fractional error for the measure of a 10% reflector using the Model 100A, Model 12-1000, and the Mark II Biometer (with the widely used aperture plate) will be determined using the relationships given in Appendix D.

1. Since the purpose is to compare the performance of the instruments, procedural errors and errors in the calibration and use of the reflectance standard are not considered.

2. Calculations of Maximum Fractional Error for Measurement of a 10% Reflector when a 5°C step in ambient temperature is imposed for 20 minutes following calibration.

a. Model 12-1000 (Quantization: 1 bit = 0.00122 volts)

$$\frac{\Delta R_F}{R_F} = 2\sqrt{2}\,\delta + \frac{0.00122}{3}(11) + \frac{N_T}{T^*}$$

where S* is 3 volts. Then $N_S = 0$ because only thermal induced errors are considered and N_T represents the effect of changing temperature.

$$\frac{\Delta R_F}{R_F} = 2\sqrt{2}\,\delta + 0.0045 + \frac{Z \cdot T^*}{T^*}$$

where Z is the fractional change in response due to the temperature condition.

For the Silicon detectors:

$$\frac{\Delta R_F}{R_F} = 2\sqrt{2}(0.0004) + 0.0045 + 0.016 = 2.2\%$$

where δ is the normalized standard deviation discussed in D, above and 0.016 represents the maximum fractional change caused by the temperature condition and is taken from Table 1 (1 point excepted).

Similarly for the lead sulfide detectors: (Quantization: 1 bit = 0.00122 volts)

$$\frac{\Delta R_F}{R_F} = 2\sqrt{2}(0.0004) + 0.0045 + 0.26 = 3.2\%$$

b. Model 100A: (Quantization: 1 bit - 0.00122 volts)

$$\frac{\Delta R_F}{R_F} = \frac{3\sqrt{2}\,\sigma_{ns}\sqrt{122}}{3} + \frac{2(0.00122)}{3} + Z$$

$$= 11\sqrt{2}(0.00015) + 0.009 + 0.01 = 2.1\%$$

where Z is determined using 0.3%/C° for the Model 100A with a driving temperature difference of 5°C and a 20 minute time constant.

c. Biometer Mark II

$$\frac{\Delta R_F}{R_F} = \frac{2 \times 0.1\ (11)}{S^*} + Z = \frac{2.2}{S^*} + Z$$

$$\frac{\Delta R_F}{R_F} = \begin{matrix} 0.1 + 0.005 \\ 0.45 + 0.008 \\ 0.2 + 0.079 \end{matrix} = \begin{matrix} 10.5\% & \text{(Channel 1)} \\ 5.3\% & \text{(Channel 2)} \\ 27.9\% & \text{(Channel 3)} \end{matrix}$$

where σ ns is assumed to be negligible and (from Table 3) S* is the nominal maximum in band response for the reference panel. If a gain change is used to measure the reflector:

$$\frac{\Delta R_F}{R_F} = \frac{\Delta S^*}{\Delta T^*} \oplus \frac{\Delta T^*}{T^*}$$

$$= \frac{2\,dig + N_S}{S^*} + \frac{2\,dig + N_T}{T^*}$$

$$= \frac{2\ (0.1)}{S^*} + \frac{2\ (0.01)}{0.1\ S^*} + Z$$

$$= \frac{0.4}{S^*} + Z$$

$$\frac{\Delta R_F}{R_F} = \begin{matrix} 0.018 + 0.005 \\ 0.008 + 0.008 \\ 0.036 + 0.079 \end{matrix} = \begin{matrix} 2.3\% & \text{(Channel 1)} \\ 1.6\% & \text{(Channel 2)} \\ 11.5\% & \text{(Chanel 3)} \end{matrix}$$

F. Field of View

The source of radiance is extremely important in the measurement process. It is essential that the researcher know what his instrument is "seeing." Thus, a radiometer usually has a well defined field of view.

1. Using a point source transit technique the field of view of the instruments was determined for the fields of view. The results are given in Figure 7.

2. The Biometer had 0.2% response at ±44° off-axis when the aperture plate was used to determine the field of view and at +24 and -36 when the 15° cone was used.

3. The Model 100A and Model 12-1000 have similar fields of view.

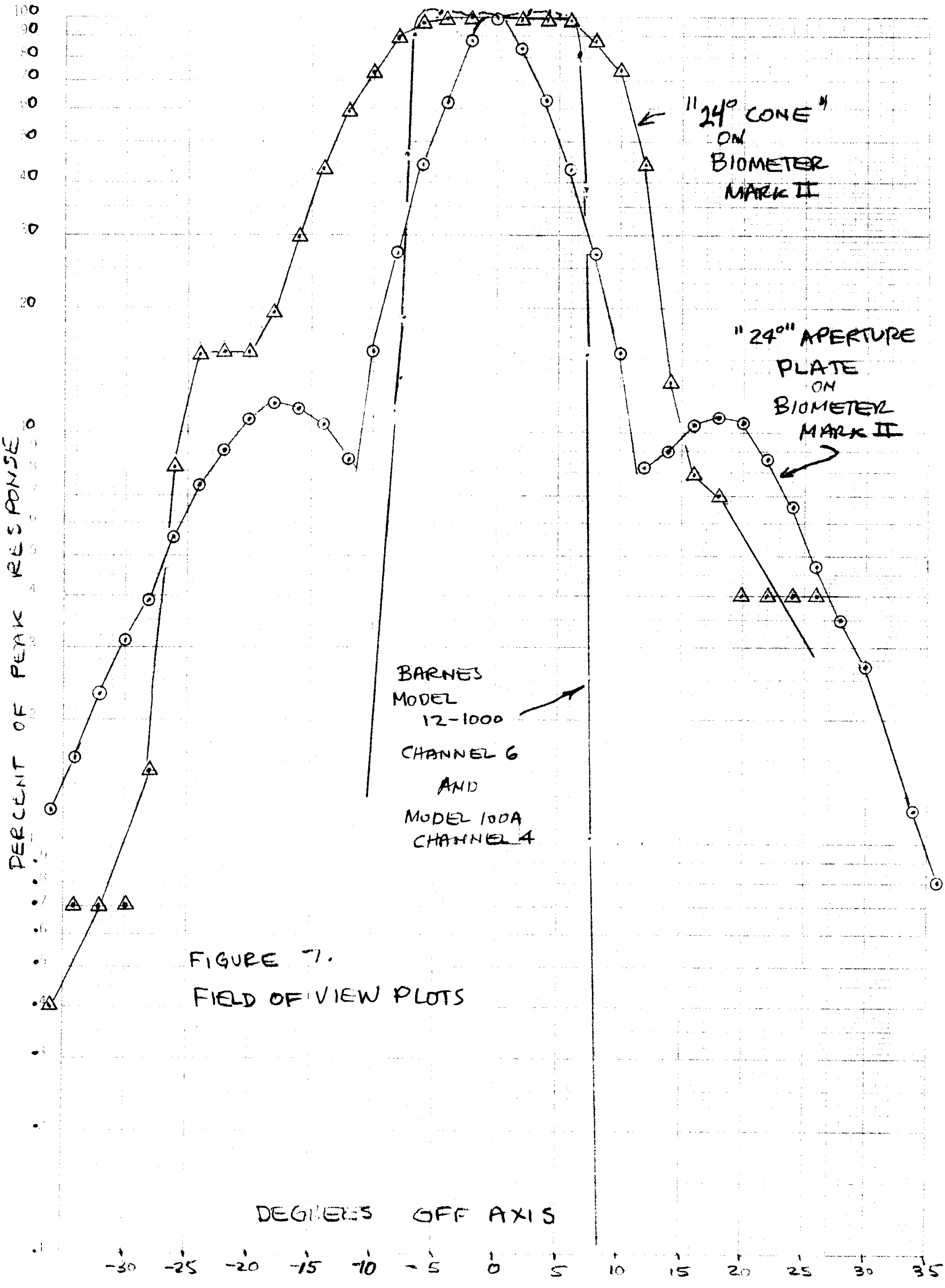


FIGURE 7.
FIELD OF VIEW PLOTS

III. Summary

A. All channels in all instruments, except channel 3 of the Biometer Mark II, were stable in response to input signals; linear; and adequately stable in response to temperature changes.

B. The Biometer Mark II is labelled with an inappropriate description of the units measured and the dynamic range is inappropriate for field measurements causing unnecessarily high fractional errors. The Biometer Mark II system is, then, quantization limited.

C. The dynamic range and noise performance of the Model 100A and Model 12-1000 are appropriate for remote sensing field research.

D. The field of view performance of the Model 100A and the Model 12-1000 are satisfactory. The Biometer Mark II has not, as yet, been satisfactorily equipped with an acceptable field of view determining device. Neither the widely used aperture plate nor the 24° cone are acceptable.

APPENDIX A

Why Use Maximum Uncertainties?

(i) They don't lie. An "rms" or "sigma" is frequently used to represent the variability of a reading of a variable having gaussian statistics. That is,

$$x = \bar{x} \pm \sigma$$

is used to express the variation of the variable, x. This is, of course, a lie. It is a lie for 1 out of every 3 readings of the variable, x.

(ii) All statistics are not gaussian. For example, if a variable is to be read one time on a volt meter (all error due to meter), it can, at best, be read to ±1 digit. Whatever, the statistics are, they are not gaussian.

(iii) Maximum uncertainties can be compared more fairly for systems having errors from several sources which have different statistics but which must be combined. For example,

$$\frac{\Delta S}{S} = \frac{\Delta x}{x} \oplus \frac{\Delta y}{y} \oplus \frac{\Delta z}{z}$$

describes the fractional uncertainty of a certain system. The question of how to add the errors arises immediately.
If y and z are gaussian random variables their terms may be added:

$$\frac{\Delta y}{y} \oplus \frac{\Delta z}{z} = \sqrt{\left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{\sigma_z}{z}\right)^2}$$

Next, if x is a voltmeter reading and Δx is ±1 digit of a voltmeter scale, then (assuming equally probable errors of +1, 0, and -1 digits)

$$\frac{\sigma_S}{S} = \sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{\sigma_z}{z}\right)^2}$$

where σ_x is $\sqrt{2}/3$ digits. But, if the system is quantization limited

($\sigma y/y$ and $\sigma z/z$ much less than one digit divided by x), then the statement

$$\frac{\Delta s}{s} \leq \frac{\sqrt{2}/3 \text{ digits}}{x}$$

is a lie 2 times out of 3! Furthermore, the limit of fractional uncertainty can not expressed as 3 x $\sigma s/s$ since, in this case, the effect of quantization will never be more than ±1 digit.

However, if the limit of fractional uncertainty is taken to be

$$\frac{\Delta s}{s} = \frac{1 \text{ digit}}{x} + 3\sqrt{\left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{\sigma_z}{z}\right)^2}$$

the value of $\Delta s/s$ will be exceeded on rare occasions, but a realistic limit will have been established. That limit can be compared to similarly obtained limits of error for other systems.

APPENDIX B

What is a Measurement

(i) Readings - a reading of a ruler can be estimated to a certain amount, Δx. A reading is the printed value recorded on a digital voltmeter or the written down version of a held value of the biometer. Associated with these readings is an uncertainty, Δx, such that:

$$x = \bar{x} \pm \Delta x$$

(ii) Observations - a reading on a ruler doesn't tell the length of the string! It takes two readings -- one at each end of the string. An observation, for our purposes is the response, x, of the radiometer to the target minus the response, x_o, of the radiometer to the dark level. Associated with each observation is an uncertainty such that

$$(x - x_o) = \overline{(x - x_o)} \pm \Delta(x - x_o)$$

(iii) Measurements - an observation obtained by reading the ruler at each end of the string provides a number for the length of the string. The correctness of that number depends on how well the ruler is made.

For our purposes, if a radiometer is calibrated to read out in Watts $\cdot$ M^{-2} $\cdot$ SR^{-1} (units of radiance), then it has been adjusted by some factor, k, so that if the true observation $(x-x_o)$ is known, then

$$\bar{L} = k\,\overline{(x - x_o)}$$

Then when a real measurement is made the reported radiance is

$$L = k\,(x - x_o)$$

and

$$\frac{\Delta L}{L} = \frac{\Delta k}{k} \oplus \frac{\Delta(x - x_o)}{x - x_o}$$

where Δk is the uncertainty in calibration and $\Delta(x-x_o)$ is the uncertainty in determining $(x-x_o)$. It will be seen in Appendix C that, even for this idyllic measurement, the fractional uncertainties add up to sizeable amounts.

APPENDIX C

Limit of Error Associated with Measuring Radiance

When measured in the field with one measurement,

$$L = k(x - x_o)$$

and

$$\frac{\Delta L}{L} = \frac{\Delta k}{k} \oplus \frac{\Delta(x-x_o)}{x-x_o}$$

The calibration constant k is determined in the laboratory:

$$k = \frac{L_{CAL}}{x-x_o},$$

When k is determined, the instrument is exposed to a view filling uniform radiance of known intensity, L_{cal}, and two readings must be made (the response to the radiance and the dark level). The instrument may be adjusted so that the difference is the "known" intensity. In this case

$$\frac{\Delta k}{k} = \frac{\Delta L_{CAL}}{L_{CAL}} \oplus \left[\frac{\Delta(x-x_o)}{x-x_o}\right]_{CAL}$$

Then the error associated with knowing the intensity of the radiance is $\Delta L/L_{cal}$ (usually about 10%) and the error associated with the measurement is represented by the other term. The combination represents the fractional uncertainty associated with the initial calibration. The measurement error in-the-field will be

$$\frac{\Delta L}{L} = \frac{\Delta L_{CAL}}{L_{CAL}} \oplus \left[\frac{\Delta(x-x_o)}{x-x_o}\right]_{CAL} \oplus \frac{\Delta(x-x_o)}{x-x_o}$$

where the first $\Delta(x-x_o)/(x-x_o)$ is inherited from the calibration process and the second is generated in the field measurement. Then let

$$v = x - x_o$$

$$\Delta v = \Delta x \oplus \Delta x_o$$

$$\Delta x = 3\sigma nx \oplus 1 \text{ digit} \oplus \text{systematic errors}$$

$$\Delta x_o = 3\sigma nxo \oplus 1 \text{ digit} \oplus \text{systematic errors}$$

Where σnx and σnxo are the variances of the noise for the measurement of x and x_o, respectively.

For a d.c. coupled sensor, $3\ \sigma nx = 3\ \sigma nxo$ and the limit of Δv may be expressed:

$$\Delta v = \Delta(x-x_o) = 2 \text{ digit} + 3\sqrt{2}\ \sigma nx + \text{net systematic errors}$$

Then

$$\frac{\Delta L}{L} = \frac{\Delta L_{CAL}}{L_{CAL}} \oplus \left[\frac{2 \text{ dig.} + 3\sqrt{2}\ \sigma_{nx} + N_a}{x-x_o}\right]_{CAL} \oplus \left[\frac{2 \text{ dig.} + 3\sqrt{2}\ \sigma_{nx} + N_b}{x-x_o}\right]$$

where Na and Nb may be positive or negative net systematic errors at the time of calibration and field measurement, respectively. Now, while $\Delta L/L_{cal}$ may be typically 10%, it is not an instrument caused error and may be dropped from consideration when comparing instruments, but not when comparing systems.

The uncertainty can't be evaluated until the calibration response $(x-x_o)_{cal}$ and the field measurement response $(x-x_o)$ are known. However, for the best case (no random noise, no systematic noise, $(x-x_o)$ = full scale, volt meter accurate to ±1 digit):

$$\frac{\Delta L}{L} = \frac{\Delta L_{CAL}}{L_{CAL}} + \frac{4 \text{ least significant digits}}{\text{Full Scale digits}}.$$

It should be noted that one out of four measurements will have quantization derived errors of three or more digits.

For a chopper instrument, the rms value of the noise may be expressed as a fraction of the signal

$$\frac{\sigma_{nx}}{x} \approx \frac{\sigma_{n x_o}}{x_1} \approx \delta \approx \frac{\sqrt{2}}{2}\ \frac{N_x \text{ peak to peak}}{x}$$

where δ is nearly constant and Nx is the noise when the signal, x, is present (mainly demodulation residuals). The peak noise is $\sqrt{2}$ times the rms value. Then

$$\Delta x = (x-x_o)\ \sqrt{2}\ \delta \oplus 1 \text{ digit} \oplus \text{systematic errors}$$

$$\Delta x_o = (0)\ \sqrt{2}\ \delta \oplus 1 \text{ digit} \oplus \text{systematic errors}$$

and

$$\Delta(x-x_o) = (x-x_o)\ \sqrt{2}\ \delta \oplus 2 \text{ digits} \oplus \text{net systematic error}$$

and

$$\frac{\Delta L}{L} = \frac{\Delta L_{CAL}}{L_{CAL}} + 2\sqrt{2}\ \delta + \left(\frac{2 \text{ digits} + N_a}{x-x_o}\right)_{CAL} + \left(\frac{2 \text{ digits} + N_b}{x-x_o}\right)$$

represents the limit of uncertainty.

APPENDIX D

Limit of Error Associated with Measuring Reflectance Factor

The field measurement of reflectance factor, R_F is accomplished as follows:

$$R_F = \frac{T-D}{S-D} \times R_S$$

where T, S, and D are the responses of the radiometer to the reflecting target, the reflectance reference surface, and the dark level, respectively; and R_S is the reflectance factor of the reference surface. Then, to simplify:

$$R_F = \frac{T^*}{S^*} \times R_S$$

where T* = T−D and S* = S−D. Then it may be shown that

$$\Delta R_F = \frac{T^*}{S^*} \Delta R_S \oplus \frac{T^*}{S^*} R_S \frac{\Delta S^*}{S^*} \oplus R_S \frac{\Delta T^*}{S^*}$$

and

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_S}{R_S} \oplus \frac{\Delta S^*}{S^*} \oplus \frac{\Delta T^*}{T^*}$$

where $\Delta R_S/R_S$ stems from the uncertainty in the value for the measurement of reflectance factor for the reference surface.

<u>For a d.c. coupled sensors</u>

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_S}{R_S} \oplus \frac{\Delta S^*}{S^*} \oplus \frac{R_S}{R_F} \frac{\Delta T^*}{S^*}$$

Then, the contribution of this uncertainty for the reflectance panel may be dropped from consideration for comparison of instruments but not systems. Since the signal and dark noise, σns and σnd, are equal:

$$S^* = S - D$$

$$\Delta S^* = \Delta S \oplus \Delta D$$

$$\Delta S = 3\sigma ns \oplus 1 \text{ digit} \oplus \text{systematic error}$$

$$\Delta D = 3\sigma nd \oplus 1 \text{ digit} \oplus \text{systematic error}$$

$$\Delta S^* = 3\sqrt{2}\ \sigma ns + 2 \text{ digit} + \text{net systematic error } (N_s)$$

$$\Delta T^* = 3\sqrt{2}\ \sigma ns + 2 \text{ digit} + \text{net systematic error } (N_t)$$

where ΔS* and ΔT* are limits of uncertainty. Then the limit of fractional uncertainty for the d.c. coupled sensor is

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_s}{R_s} \oplus \frac{3\sqrt{2}\,\sigma_{ns} \oplus 2\text{ dig.} \oplus N_s}{S^*} \oplus \left[\frac{3\sqrt{2}\,\sigma_{ns} \oplus 2\text{ dig.} \oplus N_t}{S^*}\right]\left(\frac{R_s}{R_F}\right).$$

Then

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_s}{R_s} + \frac{3\sqrt{2}\,\sigma_{ns}\sqrt{1+\left(\frac{R_s}{R_F}\right)^2}}{S^*} + \frac{2\text{dig}\cdot\left(1+\frac{R_s}{R_F}\right)}{S^*} + \frac{N_s + N_t\left(\frac{R_s}{R_F}\right)}{S^*}$$

For a chopper instrument, the rms value of the noise may be expressed as a fraction of the signal

$$\frac{\sigma_{nx}}{x} \simeq \frac{\sigma_n x_o}{x_o} \simeq \delta \simeq \frac{\sqrt{2}}{2}\,\frac{N_x \text{ peak to peak}}{x}$$

where δ is nearly constant and N_x is the noise when the signal x is present (mainly demodulation residuals). The peak noise is $\sqrt{2}$ times the rms value. Then

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_s}{R_s} \oplus \frac{\Delta S^*}{S^*} \oplus \frac{\Delta T^*}{T^*}$$

and $\Delta S^* = \Delta S \oplus \Delta D$ where $\Delta D = 0$

$= \Delta S$

$= (S-D) \cdot \sqrt{2}\,\delta + 1$ digit + systematic errors (N_s)

$\Delta T^* = \Delta T + \Delta D$ where $\Delta D = 0$

$= \Delta T$

$= (T-D)\sqrt{2}\,\delta + 1$ digit + systematic errors (N_T)

Then, the limit of fractional uncertainty is

$$\frac{\Delta R_F}{R_F} = \frac{\Delta R_s}{R_s} + 2\sqrt{2}\,\delta + \frac{1\text{ dig}}{S^*}\left(1+\frac{R_s}{R_F}\right) + \frac{N_s}{S^*} + \frac{N_T}{T^*}$$

where N_S and N_T are net systematic errors.