THIRD QUARTERLY REPORT

ON

"SPECTRORADIOMETRIC CALIBRATION OF THE THEMATIC MAPPER AND MULTISPECTRAL SCANNER SYSTEM"

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NASA/Goddard Space Flight Center
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James M. Palmer, Co-Investigator

Philip N. Slater, Principal Investigator

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

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Introduction

This is the third quarterly report on contract NAS5-27382 entitled, "Spectroradiometric Calibration of the Thematic Mapper and the Multispectral Scanner System." In this report, we describe a) the results we obtained from our TM calibration on January 3, 1983, b) the results of a moments analysis to determine the equivalent bandpasses, effective central wavelengths and normalized responses of the TM and MSS spectral bands, c) the calibration of the $BaSO_4$ plate used at White Sands and d) our future plans.

Results of the first TM calibration attempt

In this section we present the results obtained for the absolute calibration of TM bands 2, 3, and 4. The results are based on TM image data collected simultaneously with ground and atmospheric data at White Sands, New Mexico on January 3, 1983.

On that day, an 80 mm layer of snow covered our site. We determined the reflectance of the snow by using a Barnes radiometer with a $BaSO_4$ plate as a reference. Subsequent calibration of the plate allowed us to correct for its non-lambertian characteristics when solar-irradiated at a 60° zenith angle. These results are listed in Table 1.

Table 1. Snow reflectance values.

Band	Measured values	Reflectance of $BaSO_4$	Corrected values
1	0.961 ± 0.015	0.80 ± 0.017	0.769 ± 0.023
2	0.963 ± 0.014	0.79 ± 0.017	0.761 ± 0.023
3	0.957 ± 0.013	0.79 ± 0.017	0.756 ± 0.023
4	0.927 ± 0.011	0.79 ± 0.017	0.732 ± 0.022

Rayleigh spectral optical depths (τ_{Ray}) were determined for the effective center wavelengths of the TM bands (λ_c) from knowing that the barometric pressure was 889.5 mB. A solar radiometer using nine 10-nm bands in the visible and near ir was used to determine the total spectral optical depths, τ_T, at these 9 wavelengths. From these data the Mie and ozone optical depths (τ_{Mie} and τ_{oz}) were determined.

In bands 1, 2, and 3, the component of τ_T due to molecular absorption, τ_{abs}, is entirely due to ozone. Water vapor and CO_2 are present in addition to ozone in band 4. Their effects have been included in Table 2 which lists the values of the various atmospheric constituents in bands 1 through 4.

Table 2. Atmospheric values.

Band	λ_c(μm)	τ_T	τ_{Mie}	τ_{Ray}	τ_{abs}
1	0.485	0.2913	0.1475	0.1424	0.0014
2	0.57	0.2177	0.1382	0.0736	0.0059
3	0.66	0.1718	0.1282	0.0406	0.0030
4	0.84	0.1344	0.1099	0.0153	0.0092

Using the data in Table 2 as input to the radiative transfer code developed by B. M. Herman, the following quantities were calculated:

$E_{D,Dir}$: the direct solar irradiance at the ground = $\cos\theta_z \exp(-\tau_T \sec\theta_z)$

$E_{D,Dif}$: the diffuse solar irradiance at the ground

L_{Dir}: the direct radiance at the TM due to $E_{D,Dir} + E_{D,Dif}$

L_P: the path radiance at the TM = $L_T - (E_{D,Dir} + E_{D,Dif}) \frac{\rho}{\pi} \exp(-\tau_T \sec 5°)$

L_T: the total radiance at the TM

Table 3. Irradiances and radiances (normalized to unity solar exoatmospheric irradiance).

Band	Solar Zenith Angle	$E_{D,Dir}$	$E_{D,Dif}$	L_{Dir}	L_P	L_T
1	55°	0.345	0.185	0.097	0.033	0.1301
	65°	0.212	0.152	0.067	0.025	0.092
2	55°	0.392	0.145	0.105	0.024	0.129
	65°	0.253	0.122	0.043	0.019	0.092
3	55°	0.425	0.122	0.111	0.019	0.130
	65°	0.282	0.104	0.078	0.015	0.093
4	55°	0.454	0.095	0.112	0.014	0.126
	65°	0.308	0.082	0.079	0.011	0.090

Using the equivalent passband technique of Palmer and Tomasko[1] and the exoatmospheric solar spectral irradiance values of Labs and Neckel,[2] the values for the exoatmospheric irradiances within the TM passbands ($Ex\Delta\lambda$), were calculated for the earth-sun distance on January 3. The required values of L_T for the solar zenith angle of 60° were found by interpolating between the 55° and 65° data from Table 3. These, when multiplied by their corresponding $Ex\Delta\lambda$ values, gave the radiances in mW/cm^2-sr in the TM passbands listed in Table 4.

Table 4. Exoatmospheric irradiances and the radiances at the TM in the TM passbands.

Band	Equivalent bandwidth in μm	$E \times \Delta\lambda$ mW/cm²	L_T mW/cm²-sr
1	0.0712	12.2	1.36
2	0.0884	13.8	1.52
3	0.0773	10.7	1.19
4	0.1345	13.7	1.47

By identifying our site on the CCT-B image, we determined which detectors scanned the area and how many samples each collected. Detectors 1, 2, 3, 15 and 16 collected 5, 3, 1, 2, and 4 samples respectively. We found the average digital count for each detector, then calculated the average detector spectral radiance using offset and gain values reported by Barker et al.[3] These spectral radiances were multiplied by the number of samples for each detector. The resultant products were added and then divided by the total number of samples, 15. Thus we derived a value for the average spectral radiance of our site as measured by the TM, proportionally weighted according to the number of samples per detector.

The final step in the calculation was to multiply the average spectral radiance at the TM by the equivalent passband to determine the radiance within each TM band (Table 4). These values are compared in Tables 5, 6 and 7.

Table 5. Calculation of radiance in TM band 2 from preflight calibration data[3] and comparison with inflight White Sands data.

Detector	Average Count	Average Spectral Radiance	Gain	Offset
3	139.0	17.04	8.014	2.41
2	143.7	17.42	8.117	2.33
1	146.2	17.52	8.174	2.99
16	141.5	17.43	7.979	2.43
15	147.5	17.71	8.195	2.83

Weighted average = 17.47 mW cm^{-2} sr^{-1} μm^{-1}
Equivalent band radiance from weighted average = 1.537 mW cm^{-2} sr^{-1}
Equivalent band radiance from Table 4 = 1.52 mW cm^{-2} sr^{-1}
Agreement = -1.0% and +2.5% with reference to preflight calibration and December 8, 1982 inflight data[4] respectively.

Table 6. Calculation of radiance in TM band 3 from preflight calibration data[3] and comparison with inflight White Sands data.

Detector	Average Count	Average Spectral Radiance	Gain	Offset
3	165.0	15.40	10.590	1.89
2	169.7	15.86	10.602	1.57
1	171.6	15.73	10.777	2.13
16	167.8	15.85	10.484	1.63
15	172.5	15.88	10.769	1.53

Weighted average = 15.78 mW cm^{-2} sr^{-1} μm^{-1}
Equivalent band radiance from weighted average = 1.215 mW cm^{-2} sr^{-1}
Equivalent band radiance from Table 4 = 1.19 mW cm^{-2} sr^{-1}
Agreement = -1.8% and 3.0% with reference to preflight and December 8, 1982 inflight data[4] respectively.

Table 7. Calculation of radiance in TM band 4 from preflight calibration data[3] and comparison with inflight White Sands data.

Detector	Average Count	Average Spectral Radiance	Gain	Offset
3	133.0	11.89	11.019	1.96
2	132.0	12.02	10.817	1.94
1	134.2	12.00	10.972	2.53
16	132.0	12.01	10.828	2.00
15	131.5	12.05	10.771	1.69

Weighted average = 12.01 $mWcm^{-2}\ sr^{-1}\ \mu m^{-1}$
Equivalent band radiance from weighted average = 1.609 $mWcm^{-2}\ sr^{-1}$
Equivalent band radiance from Table 4 = 1.47 $mWcm^{-2}\ sr^{-1}$
Agreement = -8.5% and -5.6% with reference to preflight and December 8, 1982 inflight data[4] respectively.

Comments

The experimental results presented in this section represent our only opportunity so far to conduct an inflight absolute calibration of the TM. The main purpose of the January 3, 1983 experiment, however, was to familiarize ourselves with the scientific and logistic problems involved and to gain some field experience to guide us in the design and development of improved measurement techniques and field equipment. It is encouraging that we were able, two months into the contract, using quickly assembled equipment and little prior experience, to obtain results for bands 2, 3, and 4 that fall between 1% and 8.5% of the NASA/SBRC values.

Other comments are briefly as follows:

1. The estimated uncertainty for our results of January 3, 1983 is ±5%. The estimated uncertainty for the preflight absolute calibration of the TM is ±6%.

2. Because of the limitations of the instruments used on January 3, τ_{abs} in band 4 due to water vapor and CO_2 could not be measured. Instead, the LOWTRAN code was used to compute the water vapor and CO_2 transmittances across band 4 at 5 cm^{-1} intervals. The water vapor transmittance was scaled, to account for the 44% relative humidity measured at White Sands on January 3, then averaged to find $\tau_{H_2O+CO_2}$. Finally, the measured value of τ_{oz} = 0.0003 was added to provide τ_{abs}. The effect of an error in this estimate can be judged by noting that the inclusion of water vapor and CO_2 lowered the predicted radiance level at the TM by only 2%.

3. Band 1 saturated over the snow field at White Sands. NASA'S data indicate that a saturation level of 255 counts corresponds to a radiance at the sensor of 1.14 $mWcm^{-2}sr^{-1}$ in TM band 1. Our estimate is that the snowfield provided a radiance level of 1.36 $mWcm^{-2}sr^{-1}$ at the sensor.

4. We made no attempt to collect atmospheric data for calibrating band 6.

5. The field equipment used on January 3, 1983 is incapable of measuring solar irradiance in bands 5 and 7. Even if the

appropriate data had been available, the low snow reflectance of about 0.09 and 0.04 in bands 5 and 7 respectively would have adversely affected the calibration accuracy. Fortunately, White Sands, New Mexico is not often snow covered and the gypsum surface has a reflectance between 3 and 5 times the reflectance of snow in these bands, depending on whether the gypsum is damp or dry.

6. In reducing our data, we initially incorrectly assumed that published data for TM saturation levels were derived by integrating the spectral responses of the bands. This incorrect assumption can lead to errors as large as 20%. In Table 8 we list the weighted central wavelengths of the first four TM bands, their nominal halfwidths (as commonly reported in the literature), the accurate halfwidths (1/2 power points from Santa Barbara Research Center transmittance data), equivalent halfwidth (used here), and normalized filter response, unweighted by solar irradiance data.

Table 8. Bandwidths for the first four TM bands.

TM Band	Weighted Central λ_c μm	Nominal Halfwidth	Accurate Halfwidth	Equivalent Halfwidth	Normalized Response
1	0.4855	0.07	0.066	0.0712	0.8473
2	0.5706	0.08	0.081	0.0884	0.8305
3	0.6587	0.06	0.069	0.0773	0.8669
4	0.8361	0.14	0.129	0.1345	0.9305

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7. The January 3, 1983 experiment gave us several ideas on how to improve our measurement techniques. For example, we have since designed and built a cart for moving either the Barnes spectroradiometer or a new instrument under development, over the reference site. Together with the acquisition of low altitude imagery, this will allow us to make more accurate reflectance maps of the site. We have designed and built a new dual-radiometer system for accurately determining the non-lambertian characteristics of our reference reflectance panels. Finally, we have started the construction of two spectropolarimeters that will be accurately calibrated in an absolute sense using self-calibrated detectors. These spectropolarimeters will be used for more accurately measuring ground reflectances and atmospheric characteristics. They will also be used to check the results of the radiative transfer program at ground and aircraft altitudes.

With these improvements, we hope to achieve our goal of an uncertainty of inflight absolute radiometric calibration of less than ±3%.

Effective bandwidths for the Landsat-4 Multispectral Scanner and Thematic Mapper

Relative spectral responsivities for the Multispectral Scanner System (MSS) and the Thematic Mapper (TM) subsystems of Landsat-4 have been obtained from NASA (Markham and Barker, 1983; Hughes Aircraft Company, unpublished reports, 1981). These data, provided in tabular form were analyzed using a recently described normalization technique (Palmer and Tomasko, 1980) that yields an effective center wavelength, band pass and equivalent squareband responsivity which has been demonstrated to give accurate results for continuous sources. Each of the 24 detectors of the flight (F) and protoflight (PF) MSS instruments has been analyzed and means and standard deviations have been computed for each channel. Comparisons are shown between the previously published bandwidths and center wavelengths and those derived here. For the TM sensor, the same parameters have been obtained and comparisons are made with the conventional bandwidth determination. In addition, plots of spectral responsivity indicating the calculated parameters are presented for each sensor. Since data from a typical band 6 thermal detector was presented at various temperatures, several temperature coefficients have been derived.

The results of the moments bandwidth normalization method as applied to the MSS and TM scanners are compared with previously derived values. Table 9 shows the analysis of the MSS protoflight instrument. Each detector was individually analyzed and means and standard

Table 9. Moments spectral analysis - MSS protoflight instrument.

Band	Chan	Moments analysis R	λ_1	λ_2	$\Delta\lambda$	λ_c	NASA data[6] λ_c	$\Delta\lambda$
1	1	91.14	493.3	610.0	116.7	551.7	551	110
	2	91.84	493.2	609.4	116.2	551.3	550.5	109
	3	90.05	492.7	609.6	116.9	551.1	550.5	109
	4	89.52	491.3	608.4	117.1	549.8	549.5	109
	5	89.81	491.0	607.8	116.8	549.4	549	108
	6	90.84	492.3	609.6	117.6	551.1	550	110
	MEAN	90.53	492.3	609.2	116.9	550.7	550.1	109.2
	ST DV	.82	.70	.97	.45	.88	.85	.69
2	7	88.09	598.8	709.1	110.3	653.9	655.5	105
	8	91.50	599.6	698.5	98.9	649.1	649	94
	9	91.37	600.9	698.3	97.4	649.6	649	92
	10	90.18	600.1	699.3	99.2	649.7	650	94
	11	93.26	601.7	700.1	98.4	650.9	651	94
	12	90.40	599.5	697.3	97.8	648.4	648.5	93
	MEAN	90.80	600.1	700.4	100.3	650.3	650.5	95.3
	ST DV	1.57	1.02	3.98	4.48	1.94	2.35	4.38
3	13	84.32	694.8	812.2	117.4	753.5	756.5	113
	14	85.46	695.9	811.1	115.2	753.5	756	110
	15	85.08	695.9	814.8	118.9	755.4	757.5	113
	16	87.32	697.5	813.6	116.1	755.5	757.5	111
	17	84.60	695.5	813.2	117.7	754.3	757	112
	18	80.82	694.5	811.3	116.8	752.9	756.5	111
	MEAN	84.60	695.7	812.7	117.0	754.2	756.8	111.7
	ST DV	1.95	1.02	1.06	1.18	0.87	0.25	1.10
4	19	81.30	791.9	1067.6	275.7	929.8	916.5	217
	20	76.83	788.3	1051.7	263.4	920.0	907.5	199
	21	82.95	794.3	1078.2	283.9	936.3	928.5	241
	22	78.83	789.9	1053.5	263.6	921.7	909.5	205
	23	78.25	789.6	1066.0	276.4	927.8	916	218
	24	80.37	790.0	1060.0	270.0	925.0	912.5	211
	MEAN	79.76	790.7	1062.8	272.1	926.8	915.1	215.2
	ST DV	2.03	1.85	9.0	7.3	5.4	6.8	13.3

deviations were then determined for each band. The column headings are R for the equivalent squareband responsivity, λ_1 and λ_2 respectively for the short- and long- wavelength bandpass limits, $\Delta\lambda$ for the bandpass and λ_c for the effective wavelength (centroid). The right hand columns are the center wavelength (calculated as the arithmetic mean of the 50% band limits) and the bandpass as published by Markham and Barker (1983). The 48 plots needed to visualize these data are given in the paper by Markham and Barker and need not be duplicated here. Table 10 gives the same results for the MSS flight instrument.

Comparison of the results shown in Tables 9 and 10 show that the effective wavelength is the same for the two analysis methods within ±0.3% for the first three bands and about 1% for band 4. The effective bandpasses are somewhat different with the moments analysis giving wider bandpasses than the 50% points. The ratio of the bandpasses (50% moments) is typically 0.95 ± 0.02 for the first three bands and 0.8 ± 0.025 for band 4. Further comparisons can be readily made using the tables.

Table 11 shows the moments spectral analysis as applied to the TM instrument flown on Landsat-4. Thermal band 6 is treated separately and data are available for three temperatures. Here the 50% bandwidth points were determined by linear interpolation of the relative spectral responsivity tables in the vicinity of the 50% response points. The bandwidth $\Delta\lambda$ is the difference between the 50% points. The effective wavelength λ_c is midway between the 50% points. Figure 1 shows the relative spectral responsivities for bands 1-5 and 7 with the equivalent

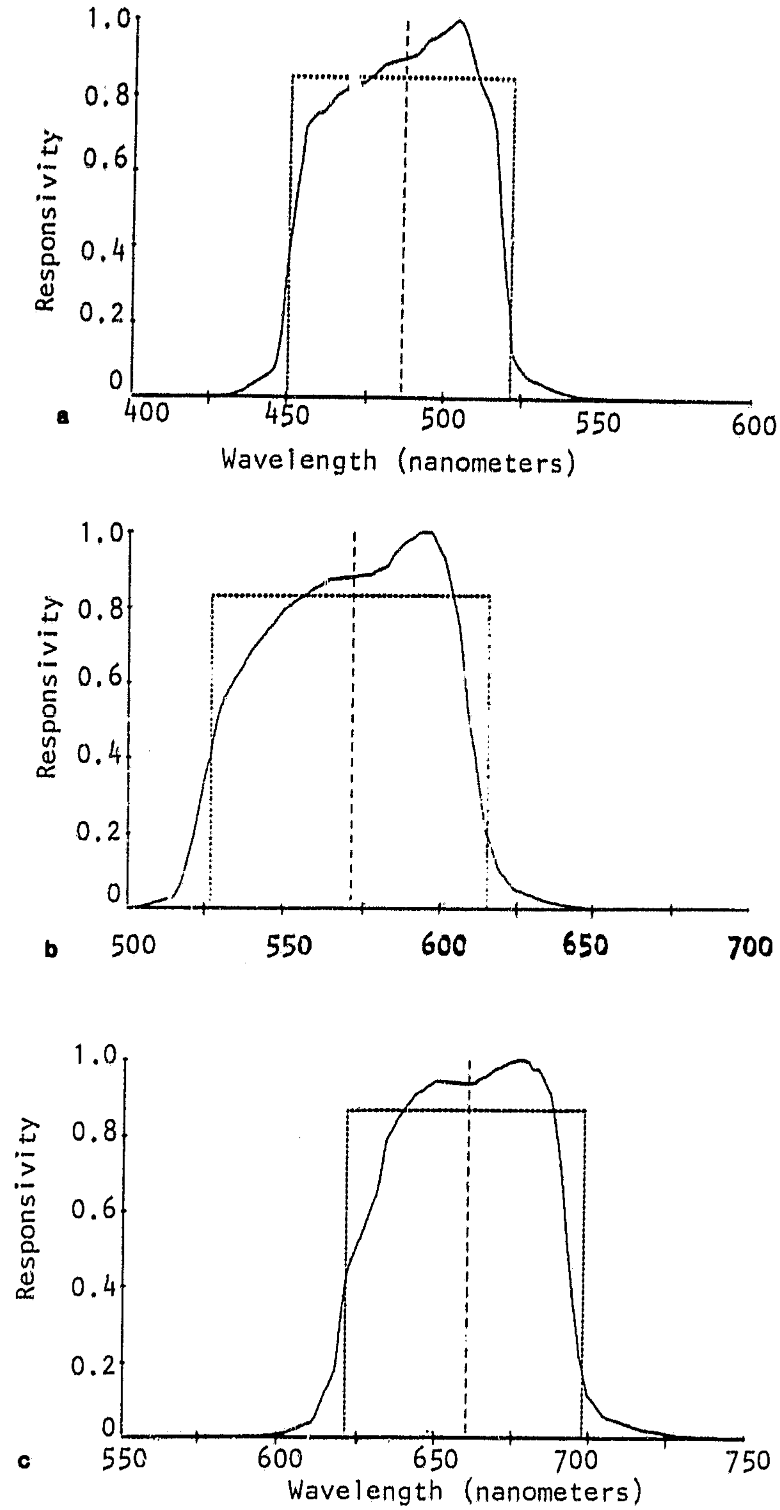

Figure 1. a) TM band 1; b) TM band 2; c) TM band 3.

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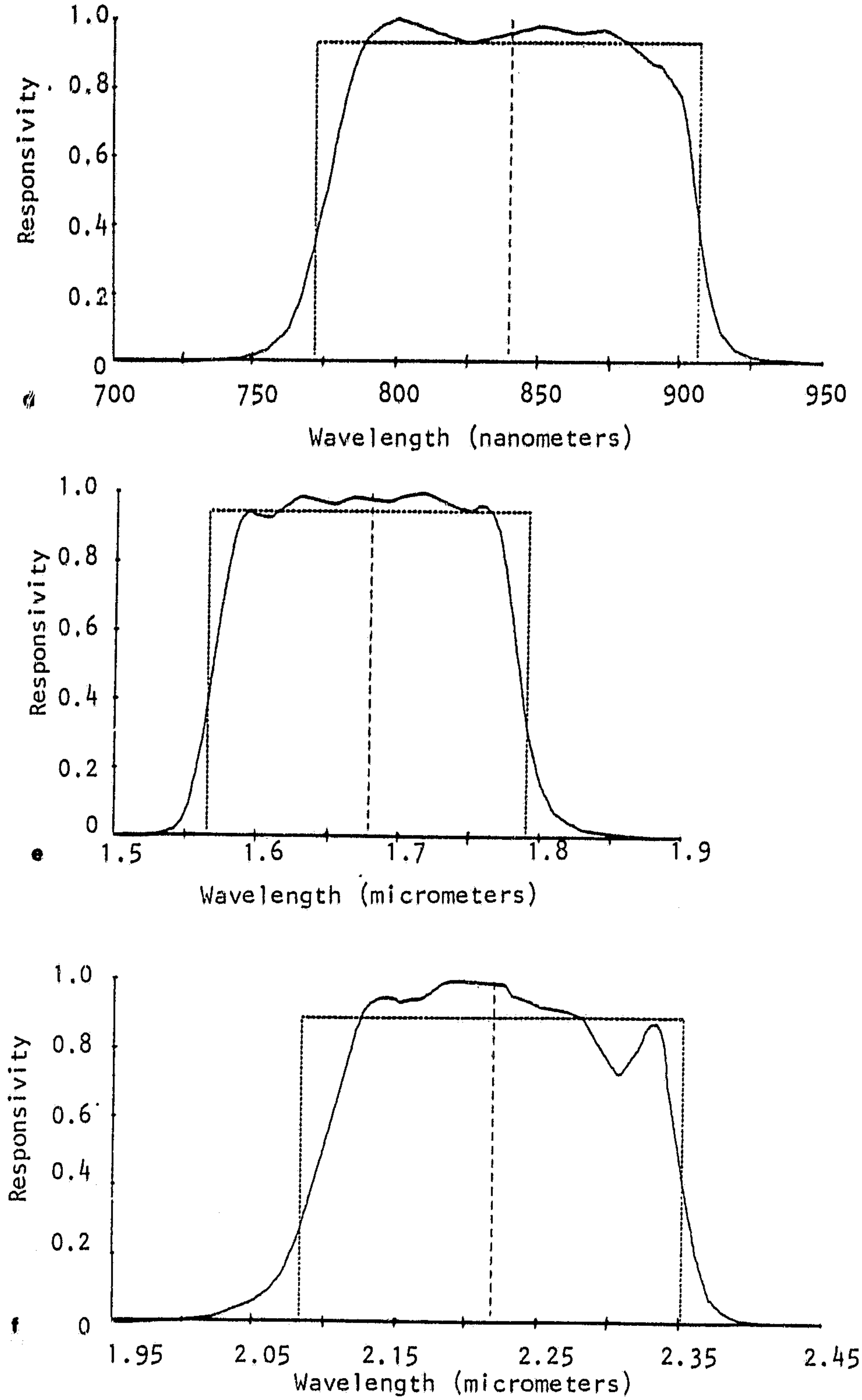

Figure 1. (continued) d) TM band 4, e) TM band 5, f) TM band 7.

Table 10. Moments spectral analysis - MSS flight instrument.

		Moments analysis				NASA data[6]		
Band	Chan	R	λ_1	λ_2	$\Delta\lambda$	λ_c	λ_c	$\Delta\lambda$
1	1	92.04	495.7	611.7	116.0	553.7	552	110
	2	90.50	496.9	612.1	115.2	554.5	552.5	109
	3	91.04	493.7	609.3	115.6	551.5	551	110
	4	91.22	492.8	608.8	116.0	550.8	551	110
	5	91.14	494.9	611.3	116.4	553.1	552	110
	6	92.01	495.0	611.0	116.0	553.0	552.5	111
	MEAN	91.18	494.9	610.7	116.0	552.8	551.8	110.0
	ST DV	.55	1.35	1.17	.37	1.36	.85	.58
2	7	91.27	601.1	699.8	98.7	650.5	650	94
	8	91.00	601.0	698.6	97.6	649.8	649.5	93
	9	89.61	599.9	698.3	98.4	649.1	650	94
	10	89.93	599.3	697.3	98.0	648.3	649	94
	11	91.32	600.6	699.1	98.5	649.8	650	94
	12	91.83	600.7	699.6	98.9	650.2	650	94
	MEAN	91.14	600.7	698.8	98.4	649.8	649.8	93.8
	ST DV	.81	.75	.71	.44	.77	.42	.37
3	13	85.98	699.3	815.1	115.8	757.2	759	110
	14	85.50	698.4	814.4	116.0	756.4	759	110
	15	85.92	698.3	813.7	115.4	756.0	759	110
	16	84.44	699.4	815.1	115.7	757.2	759	110
	17	84.43	698.5	814.4	115.9	756.5	759	110
	18	85.41	698.4	815.1	116.7	756.7	759	110
	MEAN	85.46	698.5	814.7	115.9	756.7	759	110
	ST DV	.63	.61	.25	.41	.41	0	0
4	19	82.06	793.3	1066.0	272.7	921.6	919.5	221
	20	84.53	796.0	1075.8	279.8	935.9	928.5	239
	21	85.06	796.4	1075.9	279.5	936.2	928	238
	22	77.61	790.3	1059.5	269.2	924.9	912	206
	23	80.98	792.5	1068.6	276.1	930.6	922	226
	24	83.14	794.2	1069.9	275.7	932.0	924.5	231
	MEAN	82.60	793.7	1069.3	275.9	931.3	922.4	226.8
	ST DV	2.48	1.9	5.8	3.7	3.7	5.7	11.2

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Table 11. Moments spectral analysis - Thematic Mapper.

Band	Moments analysis					50% BW analysis	
	R	λ_1	λ_2	$\Delta\lambda$	λ_c	λ_c	$\Delta\lambda$
1	84.75	450.3	521.8	71.5	486.1	484.9	66.1
2	83.07	526.9	615.6	88.7	571.2	569.1	80.6
3	86.73	621.3	698.4	77.1	659.8	658.7	68.7
4	93.05	771.9	906.8	134.9	839.3	840.6	129.1
5	94.65	1564	1791	227	1678	1676	216.9
7	89.17	2082	2351	269	2217	2272	250.2
6-1	75.00	10.29	11.93	1.637	11.11	11.01	1.179
6-2	74.73	10.29	11.97	1.680	11.13	11.03	1.220
6-3	75.89	10.29	11.94	1.653	11.12	11.04	1.243
6-4	77.92	10.32	11.99	1.676	11.15	11.08	1.317
6-90K	83.97	10.35	12.12	1.766	11.23	11.18	1.517
6-105K	66.69	10.22	11.79	1.566	11.01	10.87	0.915

squareband response and effective wavelength shown. Figure 2 is for detectors 1-4 of band 6 at 95K along with a typical band 6 detector at temperatures of 90 and 105K.

As with the MSS data, there is little difference between the methods with regard to effective wavelength and the moments method again gives wider bandpasses. Band 6 also shows some strong temperature dependences. The temperature coefficients derived from this limited data set are shown in Table 12 with units in micrometers per Kelvin (except R).

Table 12. Temperature coefficients.

PARAMETER	TEMPCO (μm/K)
R (responsivity	-1.12
λ_1 (short wavelength	-0.0086
λ_2 (long wavelength	-0.021
$\Delta\lambda$ (bandpass)	-0.013
λ_C (centroid)	-0.014

Reflectance measurement of the $BaSO_4$ plate

The reflectance of the 1.2 x 1.2 m (4 x 4 ft) $BaSO_4$ reference panel was measured using the set-up illustrated in Figure 3:

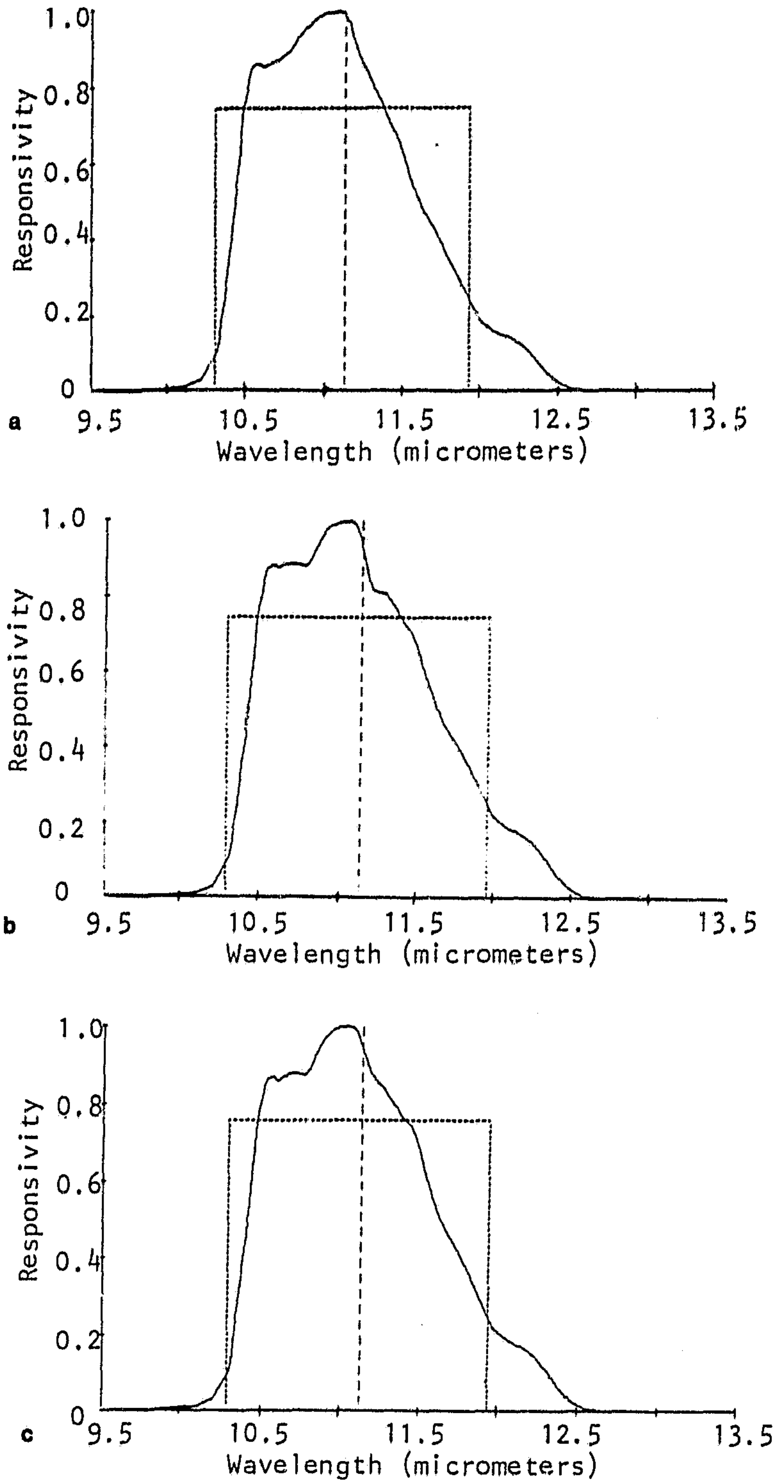

Figure 2. a) TM band 6-1, b) TM band 6-2, c) TM band 6-3.

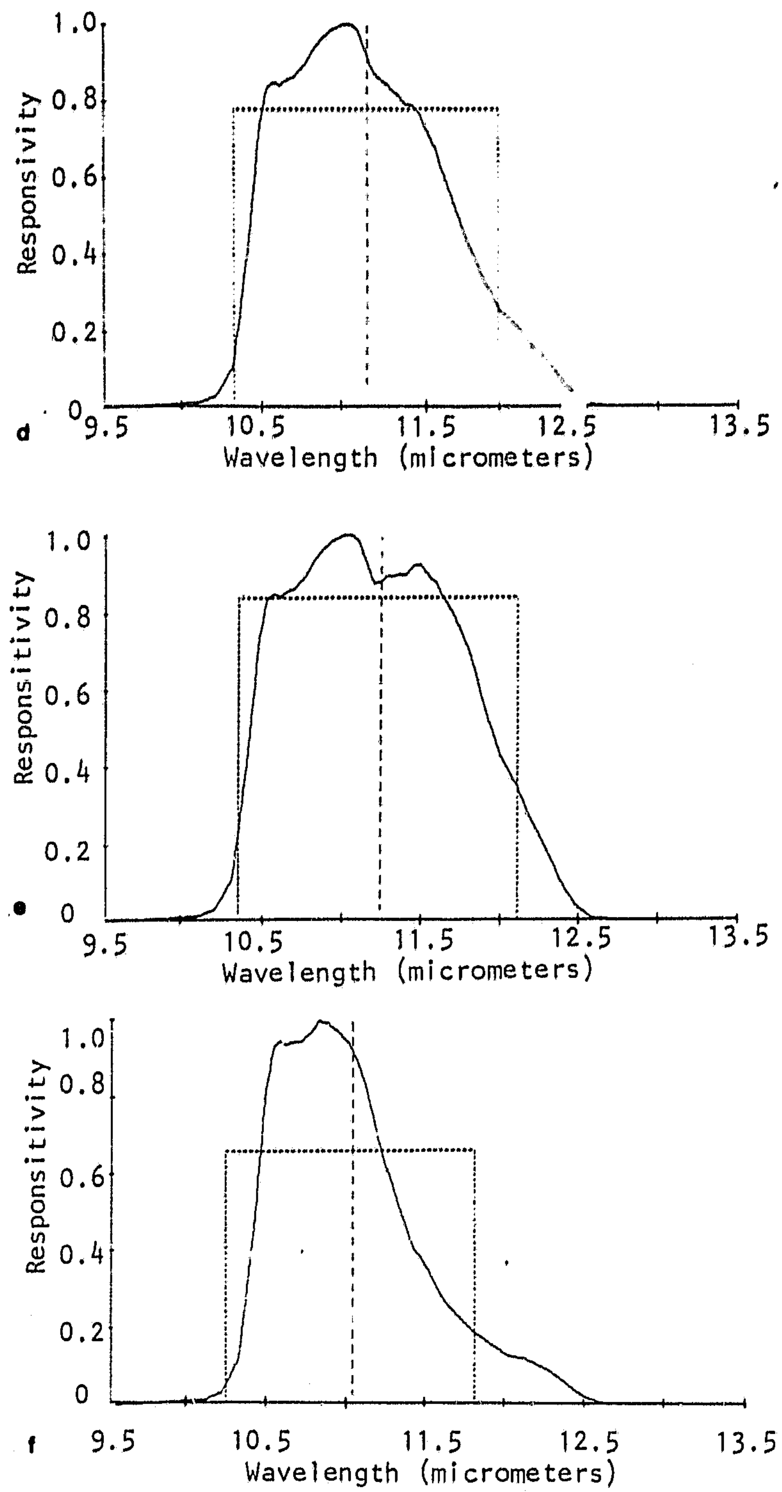

Figure 2. (continued) d) TM band 6-4, e) TM band 6 at 90° K, f) TM band 6 at 105° K.

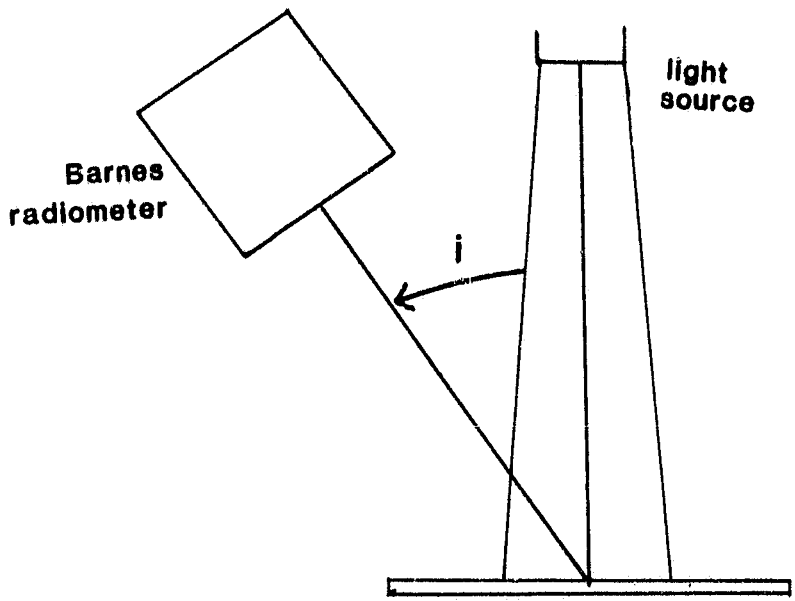

Figure 3. Layout of $BaSO_4$ calibration procedure.

The field of view of the Barnes radiometer was set to 1.0° by putting in the additional lens, and the radiometer was mounted on a movable arm. Due to physical limitations, the angle of observation, i, was only varied from 10° to 65°.

The light source vertically illuminated the panel. Figure 4 shows the irradiance uniformity on the panel. An absolute measurement was done at 15° comparing the $BaSO_4$ to a radiometrically calibrated Halon sample.

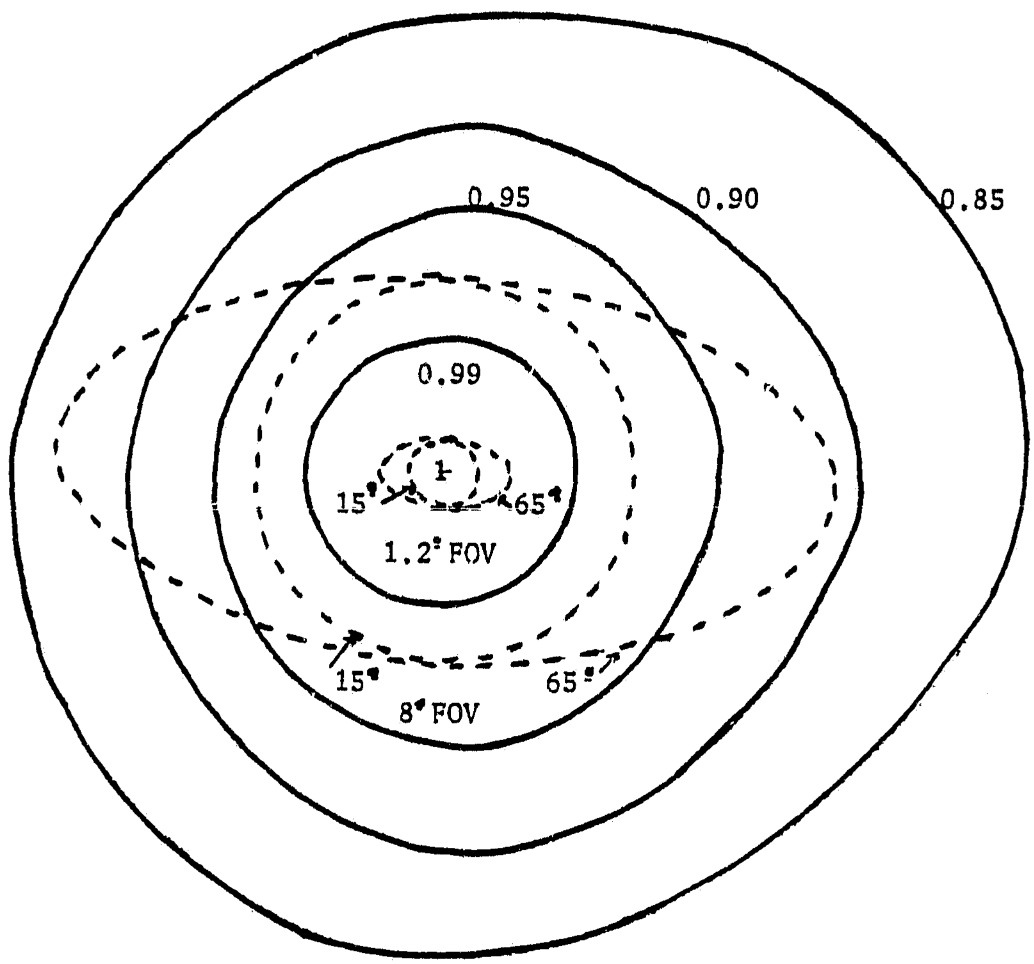

Figure 4. Contours of equal irradiances on the $BaSO_4$ panel compared to the projection of the Barnes fields of view of 1.2° and 8° at angles of view of 15° and 65°.

Table 13 gives the reflectance as a function of i obtained for 5 different positions on the plate according to the diagram in Figure 5.

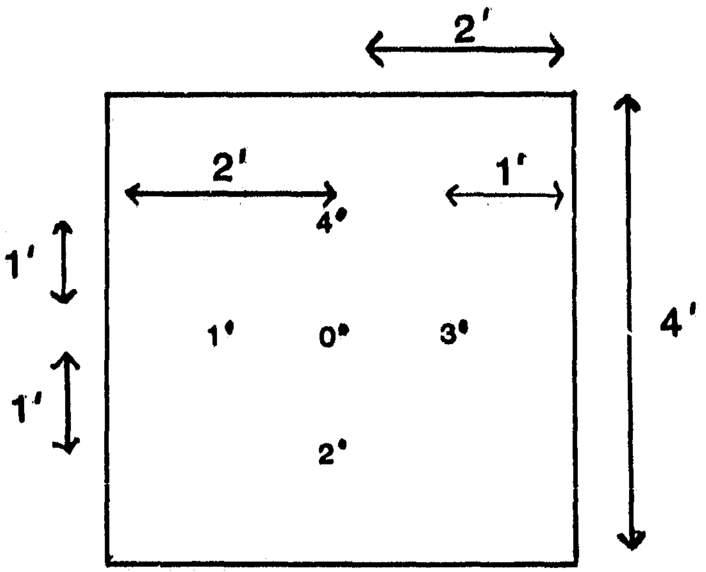

Figure 5. The locations of the five different positions on the plate.

Future plans

At present, two identical spectropolarimeters are under construction for use on this project to measure ground reflectances and atmospheric characteristics. A description of these instruments will be furnished in the next quarterly report.

We are presently planning an experiment at White Sands for later this year to field test the spectropolarimeters. We expect to fly one of the units in a helicopter to determine the radiance of the site through a 3 km atmospheric path and to have the other available for ground site and atmospheric measurements. With the instruments calibrated in an absolute sense, we will be able to check the accuracy

Table 13. Absolute reflectance values of 5 areas on the $BaSO_4$ reference panel in TM band 4 (0.76 - 0.90 μm).

	Position #				
i°	0	1	2	3	4
10	0.898	0.897	0.897	0.898	0.896
15	0.887	0.887	0.887	0.887	0.887
20	0.880	0.880	0.881	0.881	0.881
25	0.874	0.875	0.876	0.875	0.877
30	0.868	0.868	0.869	0.869	0.871
35	0.857	0.860	0.862	0.860	0.865
40	0.846	0.850	0.853	0.851	0.857
45	0.835	0.839	0.843	0.841	0.849
50	0.821	0.826	0.832	0.829	0.838
55	0.804	0.811	0.816	0.815	0.825
60	0.782	0.791	0.798	0.796	0.809
65	0.754	0.767	0.770	0.770	0.786

of the complete procedure we are pursuing in the TM calibration. The data obtained will be of great help in evaluating whether we can achieve the less than ±3% uncertainty in absolute calibration that we have set as a project goal.

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