LOCKHEED ELECTRONICS COMPANY, INC.
HOUSTON AEROSPACE SYSTEMS DIVISION
16811 EL CAMINO REAL • HOUSTON, TEXAS 77058 • TELEPHONE (AREA CODE 713) 488-0080

Ref: 642-1257
Job Order No. 73-213
Contract NAS 9-12200
NASA CR-
140238

Technical Memorandum

Data Processing Improvements for the Skylab S-191 EREP Spectrometer

By

Charles E. Campbell

Approved: J. J. Carney
J. J. Carney, Supervisor (Acting)
Sensor Performance Evaluation Section

Distribution:

JSC/T. L. Barnett
L. F. Childs
A. L. Grandfield
W. E. Hensley
R. D. Juday
A. E. Potter

LEC/O. N. Brandt
J. J. Carney
J. E. Davis
E. L. Downs
C. L. Hughes
R. E. Tokerud
Technical Library (2)
REDAF (3)
Job Order File

June 1974 LEC-3580

IMPROVEMENT OF THE DATA PROCESSING FOR THE S-191 SPECTROMETER

The S-191 represents a considerable advance over previous radiometers. For example, the responsivity around 0.8 micron has a repeatability (inverse of deviation) when averaged over the scans of one autocal which is one fifth the repeatability with which the Bureau of Standards calibrates its in-house secondary standards.

Nevertheless there is a tendency to expect the performance to far exceed that of previous field instruments, in particular to expect Bureau of Standards accuracy for a field instrument. Certainly at this point the instrument is pushing the state-of-the-art for field instruments and further improvement in accuracy is a development or perhaps even a research problem.

Past claims for the performance of field radiometers, regardless of the customer or manufacturer, have generally been greatly exaggerated. Moreover, almost all spectral field measurements in the literature have either not involved an attempt at accurate calibration or the data is given in photometric units.

Also, the Bureau of Standards has not confirmed Boltzmann's law within 1 percent or Planck's Law within 5 percent. The calibration of spectral radiance sources in the visible for industry by the Bureau involves an absolute error usually given in the literature as 5 percent.

The repeatability of optical radiance measurements is usually considerably better.

In general with optical instruments, accurate measurements can be made only when the instrument and errors are thoroughly understood and corrections are made for the errors.

It is the purpose of this discussion to review the data processing problems which have been found in the old version of the production data, their diagnosis, and, to the extent practical, the corrective measures initiated.

This information has been taken into account in developing the new version of the processing. Emphasis here is to describe the work of LEC, although it is impossible to separate the work of LEC and NASA in some cases. However, improvements made by NASA alone are omitted.

The data referred to is that of SL-2 and SL-3. Items investigated as follows:

1. The radiance outputs of the production data were found to be low in the visible and near infrared (IR) by a factor of exactly ten. The use of the raw data and autocals had given the correct values. Obviously a decimal point error had been made, probably the result of a mixup in units. The problem was fixed by changing the input responsivities by a factor of ten. This was merely a card input change.

2. The production lunar data on SL-2 had indicated scan times less than the actual 0.93 second, usually 0.01 second. Occasionally this anomaly occurred for other situations. The production data radiances were erroneous. However, the raw visible and near IR data were correct.

   The positive thermal channel was used for sync. For the lunar data on SL-2 the reference was set too low for the hot lunar surface, causing the positive thermal IR output count to saturate, although the detector had not saturated. The result was that a continuous sync for scan start was indicated. In addition, if a spurious spike occurred, the resulting spurious sync caused the start of another indicated scan.

   The solution requires that the filter position voltage V4 be within certain values simultaneously with the maximum count on the positive IR channel. This solution would be expected to eliminate most of the spurious syncs.

3. In the lead sulfide spectral region the output radiance was zero between 1.00 and 1.38 microns.

   At first it was believed that the factor of ten error had caused the output value to go below threshold so that zero was printed out. However, this problem was also noticed for the high radiance values during autocals. Thus something was wrong with the program.

FOD has stated that the error in the program has been found and eliminated.

4. The lead sulfide (near infrared) data above 1.38 microns was useless because of the apparent variation of the responsivity from one autocal to the next.

   The cause of this difficulty was that the table in the Calibration Handbook had been incorporated into the production program with an error caused by switching indices.

   This problem has been corrected.

5. When a channel saturates (count reaches 1023) the radiance is printed out as zero. This is the same as if the radiance were too low for the value to be measured. This ambiguity caused difficulty at first in diagnosing problems, but the ambiguity was soon resolved either from the context or by examining the raw (count) data.

   It was recommended that when saturation occurs that all nine's be printed or a number so high it is physically impossible. However, this recommendation had been made before and it was stated that excessive changing of the program would be required.

   The PI's have been notified of this ambiguity and the problem is inconsequential.

6. Different values of output radiance appeared in the three silicon detector columns. It had been assumed that the responsivities of the less sensitive channels were exactly 1/10 and 1/100 the responsivities of the most sensitive channel and that the biases were known exactly. These assumptions were not precisely correct.

   The correct responsivities and the biases have been calculated and implemented for the purpose of giving the same radiance at all levels of radiance (except for digitizing noise).

7. The output of all three silicon channels is presented. The channel to select is the most sensitive which is not saturated. A3 is the most sensitive channel, next A5 and last A2. Ideally this decision would have been made by the computer and only one channel printed out at a time. This would have saved paper and filing space.

   No error is involved and it is unlikely that this will be changed.

8. The data was duplicated where filters overlapped and two different radiances were printed out at the same wavelength.

   These duplications have been eliminated by selecting, where duplication occurred, the data with the least systematic and/or random errors.

9. The data is not in order. The tabulations of radiances for one scan are located in two different places in a data book. For the first part of SL-2 they were located in different volumes. Also in each location different wavelength regions are not in order with respect to wavelength, but rather in the order in which the data is recorded.

The reason that the data for a single scan is located in two places is because the system was designed before the data processing requirements were completely determined. More wavelengths were selected than originally planned so a two-pass system was used.

This problem is merely a small inconvenience to the users and a large change in the data processing would be necessary to eliminate the problem.

10. It is believed that the accuracy with which the reflectances of the dichroic beamsplitter and external mirrors is known is insufficient, causing some errors in the calculations. Those reflectances have been adjusted in attempts to eliminate these errors empirically. However, the error due to off-band radiation has prevented this. It may be feasible to adjust these reflectances empirically after a method has been determined for reducing the error caused by off-band radiation.

11. The most important source of random noise was not caused by the variation of the signal, but rather

the fluctuation in indicated wavelength. The ramp voltage V4, which gives the orientation of the circularly variable filter, and therefore the wavelength of the instantaneous output signal, did not always go to the same value. Also digitizing noise due to the size of the increments caused a voltage error. In addition, random noise may have been present.

See appendix A for a description.

A new algorithm has been provided by NASA for determining the wavelength which should greatly reduce digitizing errors. The error is expected to be less than the inherent fluctuations in the reflectance of the ground within the field of view.

12. The most serious radiometric error is caused by the off-band radiation. This effect was recognized only after data processing errors described previously had been diagnosed.

This effect is caused by radiation far from the wavelength interval detected being transmitted by the filter. The effect is worst at wavelengths where the detector is least sensitive and the radiation level the lowest, either during data taking and/or calibration. Because of this effect errors exist in the following wavelength regions 0.4 to 0.5, 1.0 to 1.1, 2.0 to 2.5, 6.0 to 8.0 and above 14 microns with the errors being serious at 0.4 to 0.45 micron, 6 to 7 and above 15 microns.

Work is being done on methods of reducing this error but it is difficult. Certainly considerable computer time will be required to correct this error.

See appendix B for a description.

13. In addition, it should be noted that other sources of error exist in the infrared, although they are much smaller than the off-band radiation error. It has been observed that most of the largest time dependent deviations in responsivity are associated with the most extreme temperatures or temperature gradients within the instrument. The uncertainty in temperatures of the external mirrors as well as the time lag of temperature of the dichroic and small uncertainties in the emissivities of internal sources probably contribute errors.

    By selecting responsivities obtained from the auto-cals associated with the particular pass for which the data is used, the errors due to internal temperature effects can probably be reduced to a negligible value.

14. The SL-2 and SL-3 data contained only the intermediate (meaning temporary) radiance calibrations. Rough comparison with lunar data in the literature indicates that the output values in the silicon channels are high by 48 percent. The calibration data obtained at Cape Kennedy will be used in later data.

APPENDIX A

RADIANCE ERROR CAUSED BY ERROR IN WAVELENGTH

APPENDIX A

RADIANCE ERROR CAUSED BY ERROR IN WAVELENGTH

The responsivity curve of silicon rises steeply, reaches a peak and then drops sharply at the long wavelength end of its sensitivity. A small error in wavelength in the steep parts of the curve introduces a significant error, whereas a comparable error in wavelength near the peak introduces little error. It was also noticed that there was a statistical tendency for the tabulated radiances for an individual scan in the visible and near IR to be high at short wavelengths and low at long wavelengths or vice versa.

In the second column of table 1 is the ratio of noise-to-signal based upon ground tests. The noise equivalent radiance of the Calibration Test Report of the manufacturer was divided by the radiance values used at that time. In the third column is the ratio of fluctuation among autocals to the radiance used in the interim calibrations. For each autocal the signal had been averaged over seven scans (each point of which was averaged over five data points) thus the random noise due to the detector and amplifiers should have been greatly reduced. Yet the fluctuation or "noise" between autocals was much greater than the noise during the ground tests.

It should be noted that the responsivity deviations for the visible in column 3 are mostly within ±2 percent and this is less than the absolute error in calibration. The long term stability in the visible is surprisingly good.

TABLE 1

Wavelength	Noise at Signal Calibration (one point)	Measured Noise to Signal (average 5 points)	% Change Per Micron	Wavelength Error	Voltage Error
.4	2.8×10^{-2}	1.98×10^{-2}	3440	.00058	.0017
.5	0.37	1.73	825	.00210	.0063
.6	0.094	1.17	663	.00175	.0052
.7	0.038	.456	500	.00091	.0027
.8	0.034	.568	278	.00200	.0032
.9	0.32	1.74	762	.00280	.0042
1.0	0.60	2.64	1320	.00200	.0030
1.1	0.53	6.52	2680	.00243	.0037

Actually, the noise from individual scans was much greater. Averaging scans over one autocal greatly reduced the noise, probably even more than would be expected from random statistics.

This effect also occurs in the thermal infrared, but the smaller variation in responsivity with wavelength greatly reduces this effect.

The characteristics of the measured fluctuation during flight autocals was qualitatively like a wavelength shift rather than appearing like a responsivity change because there was a tendency for the responsivity to be high at short wavelengths and low at long wavelengths or vice versa.

The absolute values of the slope of the responsivity curve for the A2 channel was measured and given in column four expressed in units of percent change in responsivity per micron.

The measured noise was divided by the responsivity change per micron to give the wavelength error necessary to cause the measured noise. The calibration graphs of A4, (wavelength position), giving the wavelength versus voltage relations, were used to calculate the voltage error which would cause this wavelength fluctuation. Except for the shortest wavelengths, the voltage error necessary to produce this noise is about 3 or 4 millivolts.

One count on the A4 voltage is 4 millivolts. Thus the error amounts to one count. Also it was previously noted in paragraph 5.2 of the SL-2 Sensor Performance Report that there was an average shift in wavelength of corresponding to 3.68 millivolts, although the fluctuation was not measured. As previously mentioned, the deviations of individual scans was much greater than the deviations of the averages over the seven scans of an autocal.

Table 2 gives the ratio of the average production radiances on the autocals to the original input values. These ratios are identical to the ratios of the average responsivities during SL-2 and SL-3 to the average responsivities obtained from ground tests.

Again, it appears that the variations from unity are caused by a systematic wavelength shift rather than any change in the signal channels. There appeared to be no change between SL-2 and SL-3, but more autocals need to be measured.

The cause of this effect is the variation in ramp voltage giving the wavelength. This is obvious from the variation in the peak value found in the raw data.

TABLE 2

Wavelength	Ratio of Average Measured Responsivity During Flight to Responsivity from Ground Test Data and Used in Production Processing
.4	1.030
.5	0.989
.6	1.013
.7	.998
.8	.997
.9	.996
1.0	.992
1.1	.952

APPENDIX B

OFF-BAND RADIATION OF THE S-191 SPECTROMETER

APPENDIX B

OFF-BAND RADIATION OF THE S191 SPECTROMETER

INTRODUCTION

Strong evidence now exists that the most important source of error in the S-191 is off-band radiation, i.e., radiation which is detected, but which is far from the wavelength which is expected to be detected by the sensor at that particular time. This error is high at wavelengths where the responsivity of the instrument and the signal strength are low and small at wavelengths where both responsivity and signal strength are high.

This problem is so severe that calibration at wavelengths near the ends of the wavelength range can not be made until this problem is solved.

The error due to off-band radiation is much greater than the error due to variations in computed wavelength caused by the drift of the wavelength indicating voltage V4. The latter has been considerably reduced by an algorithm developed by NASA.

The objective here is to document how the problem was detected. A more rigorous analysis including equations for the correction will come in a later report.

SHORT WAVELENGTH RADIATION

The short wavelength region will be discussed first because it is simpler and the effect was first observed in this region.

Quick Look raw data on SL-2 for the moon was used to calculate the lunar radiance. No absolute lunar radiance data for comparison was available, but McCord's data which gave the relative radiance as a function of wavelength was normalized so the S-191 and McCord's data agreed at 0.5 micron.

The agreement was good from 0.5 micron to the longest wavelength for McCord's data. However, below 0.5 micron the indicated S-191 radiance dropped rapidly. At 0.4 micron it was low by 80 percent, or 1/5 of McCord's radiance.

When the PHO-TR524 production radiance data was examined the result was the same, showing that a mathematical error was not involved. Moreover the calculated lunar reflectance was too low to be physically realistic.

The first conclusion was that an absorbing material with a short wavelength cut-off had become deposited on the external mirrors.

As a check, a comparison was made with a quick calculation from the OMC (on-module-calibrator) data which was obtained during the calibration at Cape Kennedy. A similar calculation to that above, but using the OMC data, gave a radiance 40 percent low at 0.4 micron in comparison with McCord's data. Thus the problem was present before flight.

Because these discrepancies appeared to be very large only at the short wavelength limit of the system, obviously the most likely cause was the leakage of off-band radiation at wavelengths where the silicon detector was most sensitive at the same time the low sensitive spectral region around 0.4 micron was being recorded.

The interim input responsivities in the region 0.4 to 0.5 were examined. Below 0.5 the responsivities dropped, a minimum was reached and the responsivities increased sharply as 0.4 micron was approached. This was unacceptable because the responsivity of the silicon detector was decreasing throughout this range. It appeared that when the data for the interim calibration was obtained, off-band radiation was dominating.

The amount of off-band radiation would be expected to vary with the spectral distribution of the source and experimental conditions. This doubtless accounted for the 80 percent error at 0.4 micron with an ordinary tungsten lamp and the 40 percent error with the quartz-iodide lamp of the OMC mentioned above.

The specification was that the transmittance of the filter for off-band radiation was less than 0.1 percent and therefore one might expect the effect would be negligible. Thus it was necessary to calculate the expected error due to off-band radiation to determine the effect.

A rough calculation of the ratio of off-band radiance to in-band radiance was made.

The formula is

$$\frac{N_f}{N_i} = \frac{C_i C \int R(\lambda) T(\lambda) N(\lambda) d\lambda}{C_i C R_i(\lambda) T_i(\lambda) N_i (\Delta\lambda)_i}$$

The i refers to the in-band radiation, i.e., the quantity which is desired to be measured. Initially i was 0.4 micron, which is the worst case. $T(\lambda)$ is the transmittance of the filter. The integral is taken only over wavelengths not including $\lambda = i$ or the significant portion of the tail of the band. N_i is the true value of radiance which it is desired to measure. N_f is the erroneous contribution to N_i which is caused by the off-band radiation. $N(\lambda)$ is the actual spectral radiance, $R(\lambda)$ the spectral responsivity, C the factor for converting voltage to counts and C_i the conversion factor for converting counts to radiance at $\lambda \backsim i$. The subscript i requires that $\lambda = i$ approximately when applied to functions of wavelength. $(\Delta\lambda)_i$ is the effective bandwidth at the wavelength monitored, i.e., for which λ is approximately i.

The following values were selected for determining the off-band radiation at 0.4 micron.

$T(\lambda) = 0.001$, which was the upper limit for the specification. (Experimental data obtained later from the manufacturer indicated that $T(\lambda)$ could be approximated by a constant.)

$T_i(\lambda) = 1$, assuming, $T(\lambda)$ was normalized to be unity at the peak of the band.

$(\Delta\lambda)_i = 0.004$ for 1 percent resolution, where $\Delta\lambda$ is taken as the interval between the 50 percent points.

The counts selected were from an autocal, $CR_i(\lambda)N_i = 14$ at 0.4 micron.

The bias had been subtracted from all the counts.

The values for $CR(\lambda)N(\lambda)$ are:

λ	Count
0.40	14
0.45	47
0.50	202
0.55	447
0.60	958
0.65	1680
0.70	2600
0.75	2900
0.80	3200
0.85	2865
0.90	2530
0.95	1750
1.00	970
1.05	555
1.10	141
1.15	76
1.20	11

The most sensitive silicon channel was used. When the channel saturated, the output of the next most sensitive channel, with a responsivity lower by a factor of 10, was multiplied by 10.

The increments of wavelength between points are .05. Because of the large uncertainty in $T(\lambda)$, probably 25 percent or 50 percent, simple addition for the numerical integration was performed. The sum of the numbers in the column was 20946 and when multiplied by .05 gave 1047 for the integral.

It should be noted that an approximate method of calculating the integral, by multiplying half the peak by the off-band width gave approximately the same answer. The peak 3200 divided by 2 and then multiplied by 0.80 gave 1440, which is probably close enough for estimating the error, considering the uncertainties in $T(\lambda)$ and band shape which gives $(\Delta\lambda)_i$.

The ratio of error due to off-band radiation to the in-band radiation was

$$\frac{N_f}{N_i} = \frac{0.001 \times 1047}{14 \times .004} = 18.7$$

At 0.45 micron the corresponding figure is 5.0 and at 0.50 micron the corresponding figure is 1.0.

The number 18.7 at 0.40 micron is considerably greater than the factor of 5 found from the lunar data. Therefore, the manufacturer of the filter was contacted. It was learned that although the specification for transmittance of off-band radiation was 0.001, that the actual transmittance was approximately 0.0001. This would give a ratio for off-band radiation error to in-band radiation of 1.87 at 0.40 micron, 0.5 at 0.45 micron and 0.1 at 0.50 micron.

A more relevant quantity is the ratio of indicated to actual radiance, which is the $(N_f + N_i)/N_i$. This would be 2.87 at 0.40 micron, 1.5 at 0.45 micron and 1.1 at o.5 micron.

Another consideration is that the tail of the band at longer wavelengths than the 50 percent point which is used to approximate the long wavelength edge of the band. In this case where the count on the autocal increases extremely rapidly with wavelength, the tail probably contributes considerable to the signal. This would add to the above error, giving an error factor greater than 2.87 at 0.4 micron.

Thus the calculated error is the same order of magnitude as the factor of 5 estimated from using the intermediate radiance parameters or the factor of 1.67 using the OMC calibration data, where each was compared with the lunar data.

The reason for the large response to off-band radiation is that tungsten radiation peaks at around one micron, the responsivity of silicon peaks at around 0.7 and both are weak below 0.5 micron. This effect is severe during calibration when tungsten radiation is used, but much less at 0.4 micron during data taking when reflected solar radiation is being detected.

A definition of responsivity is

$$R = \frac{V}{N}$$

where V is the output voltage (count or response) and N is the spectral radiance which is sensed. This is the equation which was used in PHO-TR524. (This definition of responsivity involves integrated quantities and therefore differs from $R(\lambda)$ used previously.)

The purpose of using the equation here is to show directly what the effect of off-band radiation is on the PHO-TR524 data and not to show how to correct for it. The method of correction is being developed now and will come in another report. It is merely the objective here to show historically how the conclusions were reached that off-band radiation was a problem.

If the philosophy is followed that the responsivity is the ratio of output voltage to input radiance, then it is necessary to include the off-band terms.

$$R = \frac{V_i + V_f}{N_i + \int T(\lambda) R(\lambda) N(\lambda) d\lambda}$$

where V_f is the voltage contributed by the off-band radiation and the integral is the total off-band radiance which is transmitted by the filter. Let the integral be called N_t.

Obviously this equation is useless for data calculations; it is merely used here to illustrate the point.

$V_i + V_f$ is the measured voltage, so the numerator is fixed. However, for production processing only N_i is used to calculate the responsivity

$$R = \frac{V_i + V_f}{N_i}$$

If V_f is significant, or as at 0.4 micron quite large, then the responsivity so calculated is too large. It was shown earlier that V_f could be much larger than V_i at 0.4 micron.

When obtaining data, the responsivity equation is used in the inverse form. The quantity to be calculated is now N_i

$$N_i = \frac{V_i + V_f - RN_t}{R}$$

Reflected solar radiation is strong at 0.4 to 0.6 and relatively weak at longer wavelengths compared to tungsten radiation. V_f and N_t are relatively much smaller, thus as an approximation we may neglect $(V_f - RN_t)$ in order to qualitatively determine the effect.

Because R is too large, the calculated N_i is too low, in agreement with the lunar data.

A similar type of problem would occur at the other end of the spectral sensitivity curve of the silicon channel at 1.0 to 1.2 microns, but the effect would be smaller because of the high in-band spectral radiance during calibration. Similarly the lead sulfide data would have a problem at both ends of its spectral responsivity curve, but to a lesser degree because of the spectral distribution of tungsten radiation.

For comparing two sources with the same spectral distribution the off-band radiation would cause no relative error.

THERMAL RADIATION

The same problem occurs in the infrared (IR), but the situation is more complicated because the reference, against which the radiation is chopped, is non-zero and corrections must be made for the emission from the dichroic and external mirrors.

Several anomalous effects were noted at the short wavelength end of the spectral range, namely at 6 to 8 microns. In particular, deep space had a "measured" radiance which was negative and the moon had an anomalously high radiance.

Attempts were made to adjust various parameters, especially the reflectance of the dichroic beamsplitter, the emissivity of the reference, and the external mirror temperatures. However, it was found that the anomalous effects were relatively insensitive to reasonable changes in these parameters.

For example, in order to eliminate the negative radiance for deep space at 6 microns by adjusting the reflectance of the dichroic beamsplitter, it was necessary to make the reflectance greater than unity. This implies (a) a very large error in the original measurement of reflectance, (b) a physically impossible reflectance, and (c) a negative emissivity.

Moreover, the uncertainty in the mirror temperature for deep space did not cause the apparent negative radiance of deep space at 6 to 8 microns, because at 10 microns the apparent radiance was positive.

The inability to eliminate the anomalies at 6 to 8 microns with reasonable changes in parameters indicated there was something wrong with the assumptions used in deriving the equations.

Extensive manipulations of the equations, including putting all the equations into a computer program so that the effects of various changes in assumptions could be determined quickly, indicated that a radiative bias probably existed and was dependent upon reference temperature, dichroic temperature and wavelength. It appeared that the only logical explanation was the presence of off-band radiation, similar to that which occurs in the visible.

A rough calculation of the ratio of error to in-band radiation (N_f/N_i) was made in the infrared at 6 microns, similar to that made for the short wavelength region. The result was a 10 percent error.

This 10 percent effect of off-band radiation at 6 microns is roughly comparable to the observed anomalies. At longer wavelengths where the system was more sensitive, with radiation up to 14 or 15 microns the effect would be considerably less. Above 15 microns the system response is less and the off-band radiation is again important.

Again, the approach will be historical, to show in a semi-quantitative manner what the problem was with the production processing.

The equation for the responsivity which is being used is

$$R(\lambda) = \frac{\bar{V}_i(\lambda)}{LWLI_{ci}(\lambda) - I_r(\lambda)}$$

$I_r(\lambda)$ is the radiance from the reference which is chopped against. $LWLI_{ci}$ is the thermal infrared (LWL means long wavelength in contrast to the visible) radiance entering the chopper, such as the signal. For the case of deep space the radiance comes from the external mirrors and dichroic beam-splitter. $\bar{V}_i(\lambda)$ is the output voltage as averaged over several data points.

For short wavelengths, 6 to 8 microns, on deep space data the calculated responsivity is negative. The numerator is negative and the denominator positive. Because the numerator is the measured voltage, the problem must be in the denominator.

Note that the denominator has a low value and is the difference between two large quantities when the reference temperature and signal are within certain ranges. This is the case when the calculated responsivity is (anomalously) negative. Thus the denominator is very sensitive to small changes.

If this equation is made to include off-band radiation, it would read

$$R = \frac{\bar{V}_{i6} + \bar{V}_{if}}{(LWL_{ci6} - I_{r6}) + T(LWL_{cio} - I_{ro})}$$

where T is the fractional part of the off-band radiation transmitted. The two voltages in the numerator are the responses to the corresponding terms in the denominator.

For a cold reference, I_r at 6 microns is quite low because of the sharp, short wavelength drop-off in the Planck curve at 6 microns at low temperatures. The term $LWLI_{ci}$ at 6 microns is greater because the emission from the dichroic and external mirrors is at a higher temperature and the Planck curve is almost exponential with respect to temperature as well as wavelength at 6 microns. The right term in the denominator tends to be algebraically smaller than the left one because it comes from radiation at longer wavelengths, the major portion is at longer wavelengths than the peak of the Planck curve. In this spectral region the Planck radiation is much less sensitive to temperature and the ratio of LWL_{cio} to I_{ro} is less than for the left term. For the case of deep space, at 6 microns the left term is positive and the right term is negative. The corresponding voltages in the numerator have the corresponding signs.

For the case of deep space, each term in the denominator is very small because of the subtraction. The left term was calculated (in the production processing) to be positive, but the numerator was measured negative, giving a negative responsivity which is physically unrealistic (alternatively, if the responsivity were assumed to be positive, deep space appeared to have a negative radiance).

Because the left pair of terms is so small the right pair needed to have only small percentage difference to be negative and be greater in absolute value. In this case the whole denominator was negative. Thus the corresponding (right side) voltage term in the numerator was also negative and dominating.

In reality, if the whole denominator had been used, the negative denominator and numerator would have given a positive (although mixed) responsivity. However, only the positive left term in the denominator was used in the previous calculations, giving the wrong sign to the responsivity.

In cases other than deep space and where the left term of the denominator is not close to zero, there would still be significant errors by neglecting the off-band radiation at 6 to 8 microns.

However, around 10 microns the responsivity of the system for in-band radiation is greater than for the average wavelength, so the relative error is much smaller.

ADDITIONAL COMMENTS AND CONCLUSIONS

The above discussion shows that off-band radiation can explain the anomalous results. Moreover, no other explanation is satisfactory.

Also, off-band radiation could be transmitted, at least theoretically, by multiple reflections, as well as by the filter, if inadequate baffling precautions were taken in the construction of the spectrometer. However, it is understood that the baffling was well designed in the spectrometer.

A summary of the arguments for the off-band radiation as the primary source of error is given below, although not all have been discussed above. The off-band radiation explains the following:

1. The data is much more consistent at 8 to 14 microns than at 6 to 8 or 14 to 15-1/2, especially the constancy of responsivity using the autocals.

2. At 10 microns the radiance of the Monroe Reservoir as measured by ground truth and taking into account atmospheric effects by the Calfee-Pitts program agreed precisely with the measurement by the S-191. However, at longer and shorter wavelengths the S-191 gave a higher radiance and no modification of the Calfee-Pitts program could make them agree.

3. The intermediate responsivities for both the long wavelengths and short wavelengths used in the production data processing reach a minimum near the short wavelength end of the range and then go up as the end of the range is reached. This appears impossible because the detector responsivity is falling off; however, the response of the detector to off-band radiation during calibration could explain this.

4. The calculated responsivity has some non-linearity at 6 to 8 microns based upon autocal data.

5. The calculated radiance of deep space is very negative at 6 to 8 and around 15 microns and if deep space is assumed to have zero radiance, the calculated responsivity is negative. The explanation is that the ratio of off-band to in-band radiation changes with source temperature.

6. On other projects, high resolution interference filters have trouble with off-band radiation, even with blocking layers. In this case, even if the off-band radiation is within specs, the problem is explained.

7. Theoretically, if extreme care were not taken, some off-band radiation could be transmitted by multiple reflections in the spectrometer.

8. Actual numerical discrepancies were roughly comparable to the discrepancies calculated from rough off-band radiation effects calculations. (Lack of exact data prevents a precise comparison.)

9. Other explanations are inadequate, especially using constants considerably different from previously measured values, such as using a dichroic reflectance greater than unity. Because the off-band radiation effect varies with reference temperature, the measured responsivity is a function of reference temperature.

10. Different cal source and reference temperatures give different responsivities.