Preliminary Calibration of GRAMS Instrument System Against BORCAL Data

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Abstract

Preliminary calibration of whole-sky irradiance for the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site Ground Radiation Measurement System (GRAMS) and GRAMSCAL instruments were carried out relative to Broadband Outdoor Radiometer CALibration (BORCAL) data. Three one-month periods, two with eight days and one with nine days of about 1.5% absolute accuracy BORCAL data are available for comparison under relatively clear-sky conditions. GRAMS data is at hand for all three of these periods and GRAMSCAL data is available for two of them. Simple calibration functions are obtained that yield irradiance accurate to 5% or better for both instruments as long as the sun is higher than 10 to 20 degrees above the horizon. The calibration functions seem to be very stable over the 13-month period for which data has been collected and, therefore, presumably for longer.

Introduction

There are two GRAMS-type instruments located at the SGP CART site central facility in north central Oklahoma: one is called GRAMS and the other GRAMSCAL. The two instruments were made by Valero's (Valero et al. 1982, 1997) group at Scripps Institution of Oceanography and are identical insofar as possible. GRAMSCAL is located atop the calibration trailer, perhaps 4 meters higher than GRAMS at about 150 meters horizontal separation. GRAMSCAL should suffer less interference from objects on the near horizon (people, buildings) than does GRAMS, and when sky conditions are highly structured, as with scattered clouds drifting by, GRAMSCAL should be expected to lead or lag GRAMS by as much as 10 or 20 seconds, depending on wind speed and direction.

The effort described here compares both GRAMS and GRAMSCAL voltage output to BORCAL (Nelson et al. 1998) measurements of 'global' irradiance at the CART site. Global irradiance is defined as the sum of diffuse irradiance (measured) and direct irradiance (measured) multiplied by the cosine of the (calculated) solar zenith angle.

For this comparison to be useful, the so-called 'dark current,' which is actually a 'dark voltage,' must be subtracted from GRAMS and GRAMSCAL readings before the comparison. Therefore, dark voltage must be determined as a precondition to BORCAL comparison.

BORCAL Data

These data are measured under the aegis of Tom Stoffel of the National Renewable Energy Laboratory (NREL). Briefly, reduced measured quantities are direct solar flux and diffuse solar irradiance without filter, that is, with an effective filter function of unity over the entire solar spectrum. Total solar irradiance, called 'global' irradiance in the BORCAL data, is obtained by multiplying solar direct flux by the calculated cosine of the solar zenith angle and adding it to measured diffuse irradiance.

Dan Nelson of the CART site guided us to Steve Wilcox of NREL, who kindly furnished us with BORCAL data from three campaigns: 1) 9702, containing data taken during September 1997; 2) 9801, with data taken during May 1998; and 3) 9802, with data taken from mid-July 1998 to mid-August 1998. These approximate one-month periods provide good coverage of summer to early fall months. Winter coverage is lacking.

GRAMS Dark Voltage

GRAMS data on hand for this rather quick study is for the month of September in 1997, and for the months of May, June, July, August, and September in 1998. More could be obtained and, if done, should eliminate or quantify the above caveat about seasonal cycles in dark voltage.

Figure 1 is a typical example of GRAMS data from which pre-dawn dark voltage is determined.

This plot resulted from our automatic dark voltage algorithm. The red data points (there is no line connecting data points—there are simply a lot of data points) are ones the algorithm has accepted for processing. Their average is 3.62 microvolts. The straight blue line is a linear fit through the red points; if it is too steep, the algorithm rejects the data. The algorithm tested for correct date after creating this figure; after such testing the horizontal axis had 24 hours subtracted and the date was increased by one day. Thus, our algorithm records average dark voltage as being centered at time 10.6 hours on May 1, 1998, rather than at 34.6 hours on April 30, 1998, as the a0 data has it. One may note that the approximate 20-minute quasi-periodic oscillation frequently seen in GRAMS data can be discerned in the red portion. An oscillation of about 0.2 μV amplitude and one-minute quasi-period is also present but indiscernible at the figure's time resolution.

Some data doesn't look as nice as that in Figure 1. Figure 2 shows another example, which may have produced a somewhat high estimate of dark voltage at 3.08 μV. The curve in Figure 2 will begin rising steeply toward its noontime value of about 250 microvolts by hour 13 (37 on the figure). It is highly unlikely that the average value could fall as low as 3.0 microvolts if data in the hour remaining were included. An error of less than 3% in a value that itself affects the maximum value of solar irradiance by only 1.2% seems acceptable.

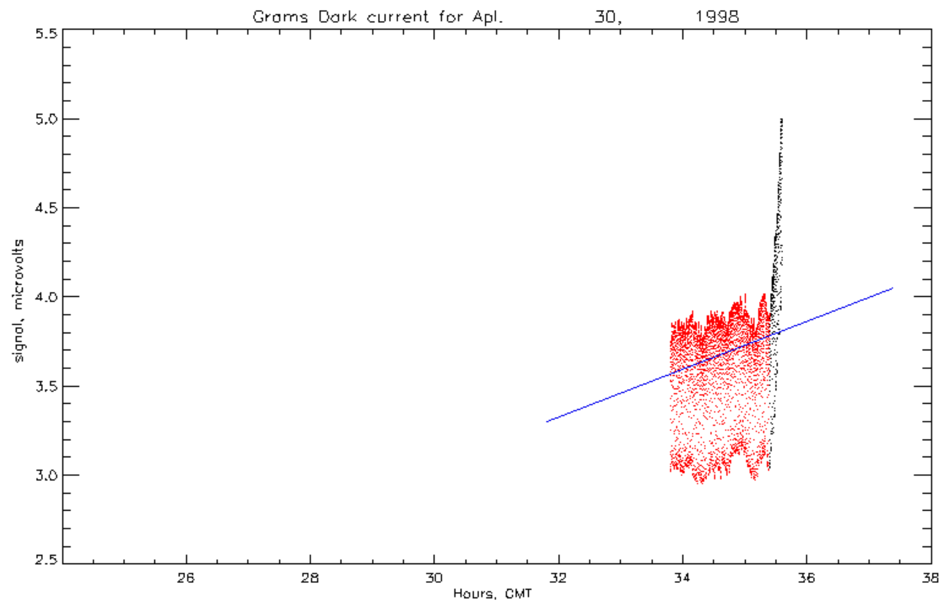

Figure 1. GRAMS data for dark voltage determination on May 1, 1998. Red points were used in the calculation, the blue line is a linear fit through red data points. Black data points to the right of the red ones were rejected as being influenced by twilight. Data near Greenwich Mean Time (GMT) hour 24 of April 30, to the left in the figure, was probably in the file, but our algorithm found that data cut off too soon to be useful in calculating a dark voltage and eliminated it from consideration, and from plotting.

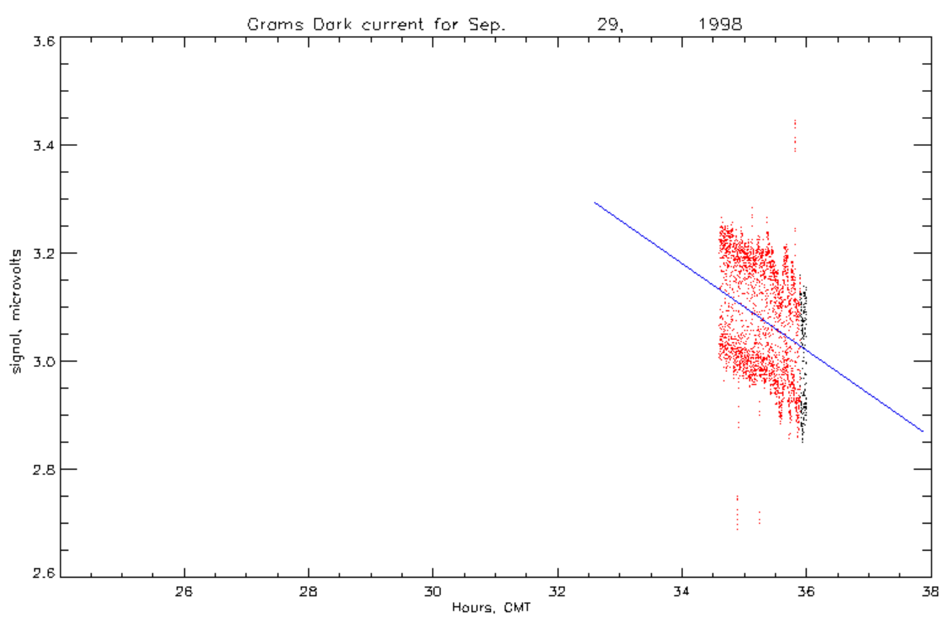

Figure 2. GRAMS dark voltage data for September 30, 1998.

Figure 3 shows all the dark voltage data currently in hand for GRAMS. It is in every case pre-dawn. There is no midday or post sunset data in the set. It looks as if a seasonal cycle with amplitude of about 0.5 μV may be present, as well as a small linear increase of about 0.5 μV/year.

The extreme low value at about day 490 occurs on May 4, 1998. It appears to be real, as shown in detail in Figure 4. The readings are low but the data look perfectly good. Compare to May 2 and May 3 in Figures 5 and 6.

The two highest values, which occur around day 500 (one shown in detail in Figure 7), on the other hand, may be due to crudeness in our algorithm. The daytime signal came on smoothly enough that part of it got included in the dark voltage. If the higher red points were excluded, the effect would be less than a 10% lowering of the average dark voltage, which would affect midday signal by only about 0.01%.

For comparison to Figure 3, we include Figure 8 showing GRAMS dark voltages wherein this author looked at each day's plot, such as those shown above and manually instructed the computer to accept or reject data. In case of acceptance, the author chose times to begin and end calculation of dark voltage average. The major difference that strikes the eye, other than a different presentation, is that the computer algorithm shown in Figure 3 rejected the second low value of dark voltage, whereas the human accepted it. The calculations of Figure 8, those influenced directly by a human, were done before the automatic algorithm was developed. The good agreement between the two methods adds credence to both.

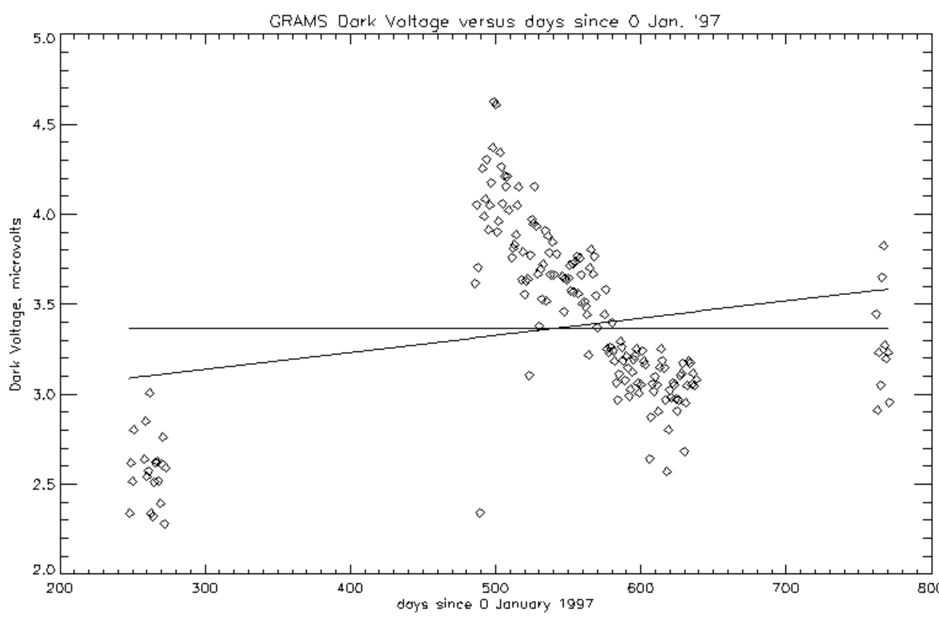

Figure 3. GRAMS dark voltage. Dark voltage for data spanning 13 months is shown. A fully automated algorithm determined all dark voltages. The horizontal line is the average and the line sloping at about 0.3 μV per year is a linear fit to the data.

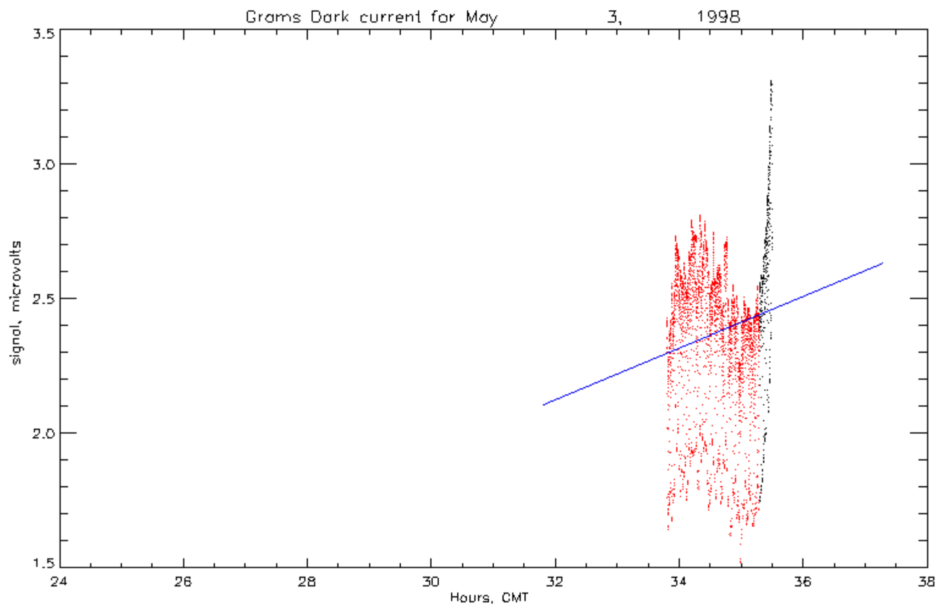

Figure 4. Dark voltage for May 4, 1998. Data is substantially lower than preceding or following days, but appears normal. Mean is 2.34 μV.

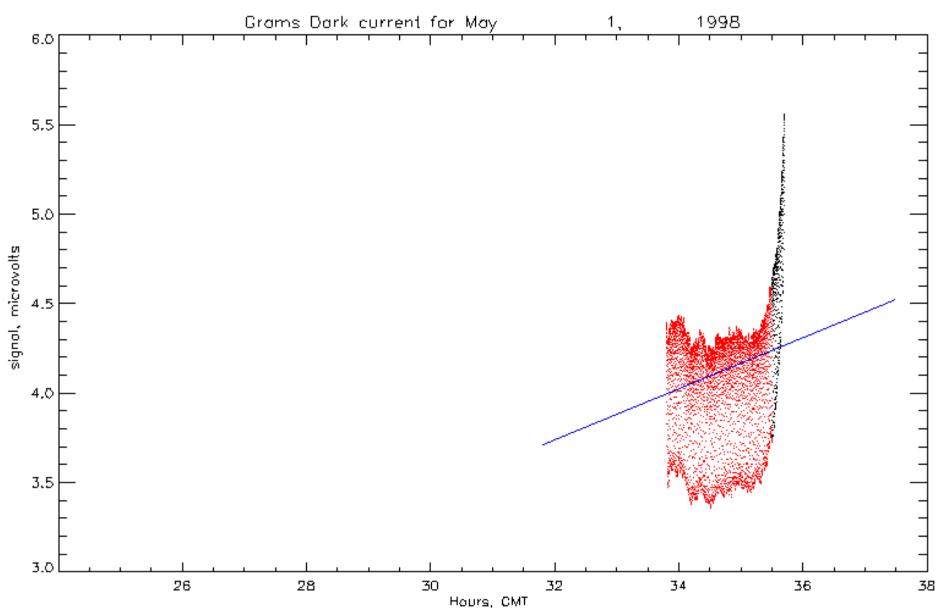

Figure 5. GRAMS dark voltage data of May 2, 1998. Data is a little smoother than was that of May 4, but not unusually so. Mean dark voltage is 4.05 μV.

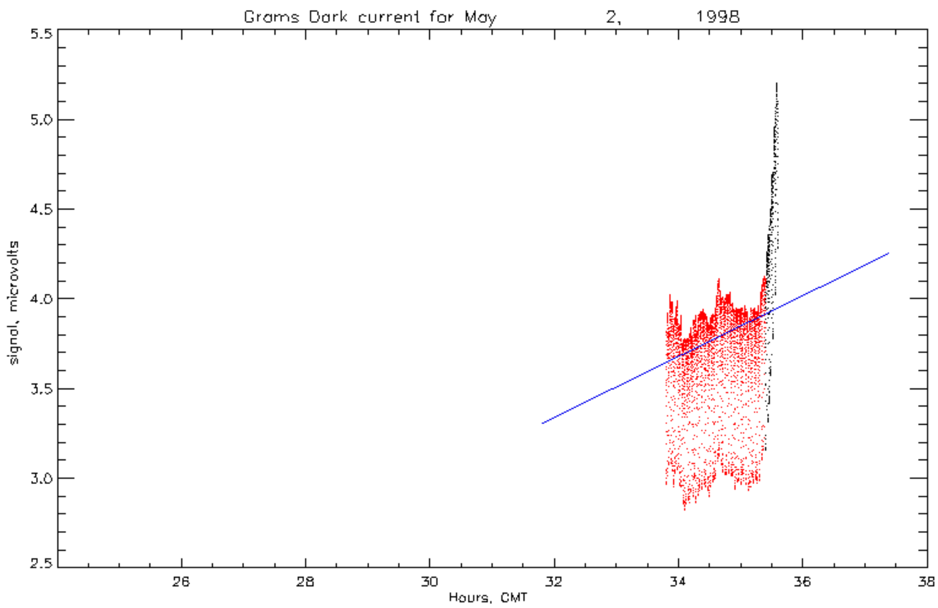

Figure 6. GRAMS dark voltage for May 3, 1998. Average of the red points is 3.71 μV.

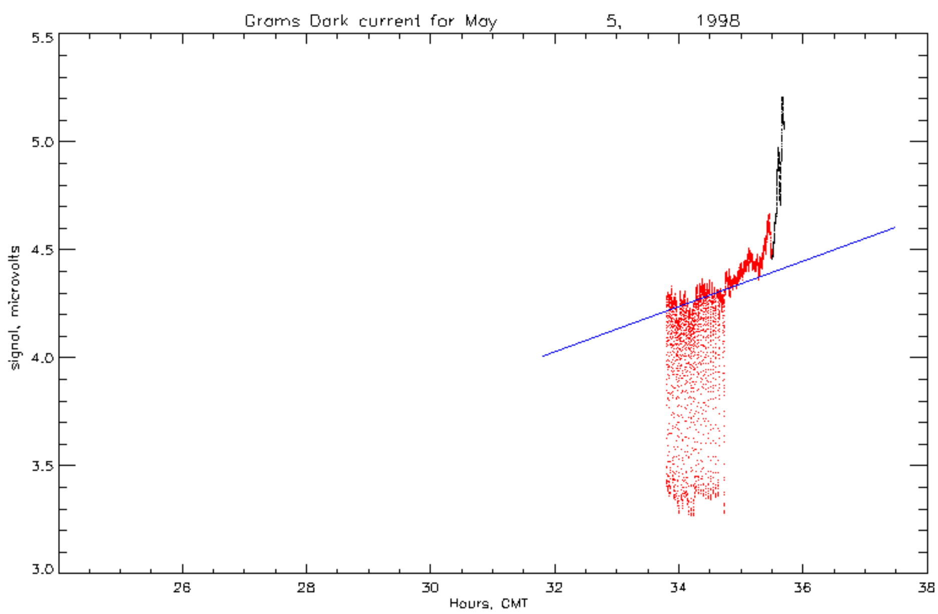

Figure 7. GRAMS dark voltage data for May 6, 1998. Possibly polluted slightly by pre-dawn twilight, at a value of 4.25-microvolts.

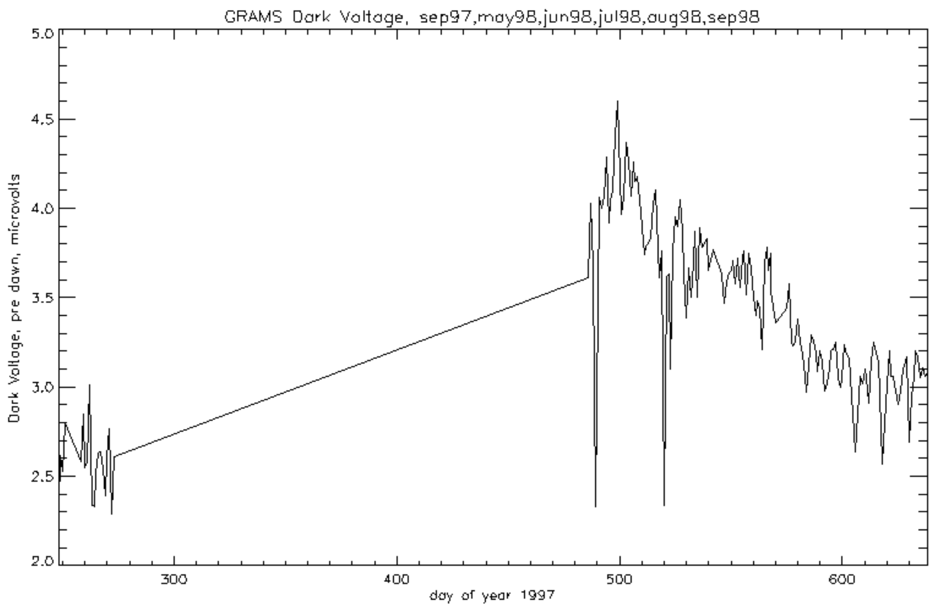

Figure 8. GRAMS dark voltage determined by man-machine interactively. This set of dark voltages is very similar to those of Figure 3, which was done entirely by computer.

Value of Dark Voltage to be Used for GRAMS in the Following Analysis

My conclusion is that, for the present, a constant value of 3.4 μV is an adequate value of dark voltage for GRAMS. The largest error this value makes, in comparison to any value in the data set represented by Figure 3 is about 30%. For a noontime clear reading of 250 μV, this amounts to an introduced error of 0.4% ($0.3 \times 3.4/250$), approaching 1% for low sun angles, far less than the 5% accuracy believable for the instrument.

GRAMSCAL Dark Voltage

Figure 9 shows values of GRAMSCAL dark voltage produced by the same algorithm that produced Figure 3 for GRAMS, without adjustment. GRAMSCAL has an order of magnitude higher dark voltage than does GRAMS. It also appears less reliable than GRAMS; that is, more data gaps indicating non-operation appear in the archived data. A similar pattern to that of Figure 3 appears in Figure 9. One could interpret the figure as indicating a linear rise of about 0.5 μV per year and an annual oscillation with similar amplitude. But note that this rise and amplitude oscillation are, in this case, superimposed on an average dark voltage of 22.81 μV, indicated by the horizontal line in Figure 9. The absolute magnitude of annual variation, if it is even real, appears to be independent of its base value. If one subtracted 20 μV from all entries, the figure would show variation comparable to but even less than Figure 3 for GRAMS. Possibly the lessor variation is simply due to fewer data points.

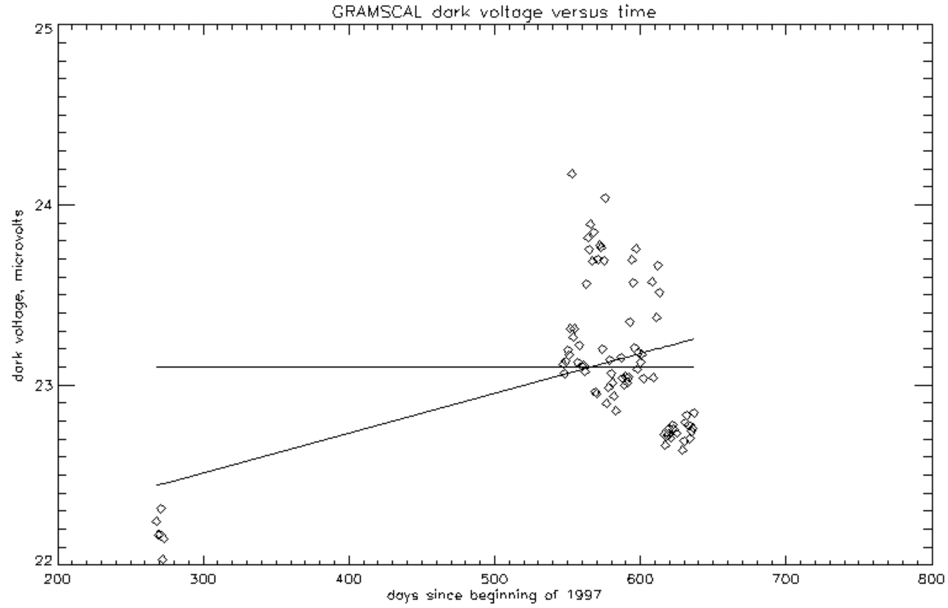

Figure 9. Dark voltage for GRAMSCAL. The same algorithm that generated data for Figure 3 generated this figure. It includes data from September 1997 and July, August, and September 1998.

Two illustrative plots of GRAMSCAL dark voltage are shown in Figures 10 and 11. They show that the absolute variation in dark signal also appears to be independent of the magnitude of dark voltage. The spread in GRAMSCAL dark voltage readings is, if anything, less than those for GRAMS, despite the GRAMSCAL dark voltage being almost an order of magnitude larger than that of GRAMS.

Our algorithm climbs higher on the dawn slope than was the case for GRAMS data. This is because the algorithm uses a test on fractional rise rather than on absolute change to cut off the averaging process. Despite the poor appearance, the error introduced is not large and we have not adjusted the algorithm.

Value of Dark Voltage to be Used for GRAMSCAL in Following Analysis

Based on the similar reasoning as for the case of GRAMS, we choose to use 22.82 μV as the dark voltage for GRAMSCAL. The error introduced by using this constant is so small as not to be worth fixing, at least not until more definitive evidence is obtained.

BORCAL-GRAMS Comparison

Figures 12 and 13 show satisfying examples of BORCAL-GRAMS comparison. Figure 12 is one of the best data comparisons from BORCAL series 9702. Not shown is an equally good data comparison taken the following day, September 30, 1997. The figure is a good one for comparison because both curves are smooth, almost continuously overlapping, and give nearly complete coverage from about 1.5 hours after sunrise (about 8:00 a.m. local sun time) to an hour or so before sunset (about 5:00 p.m.).

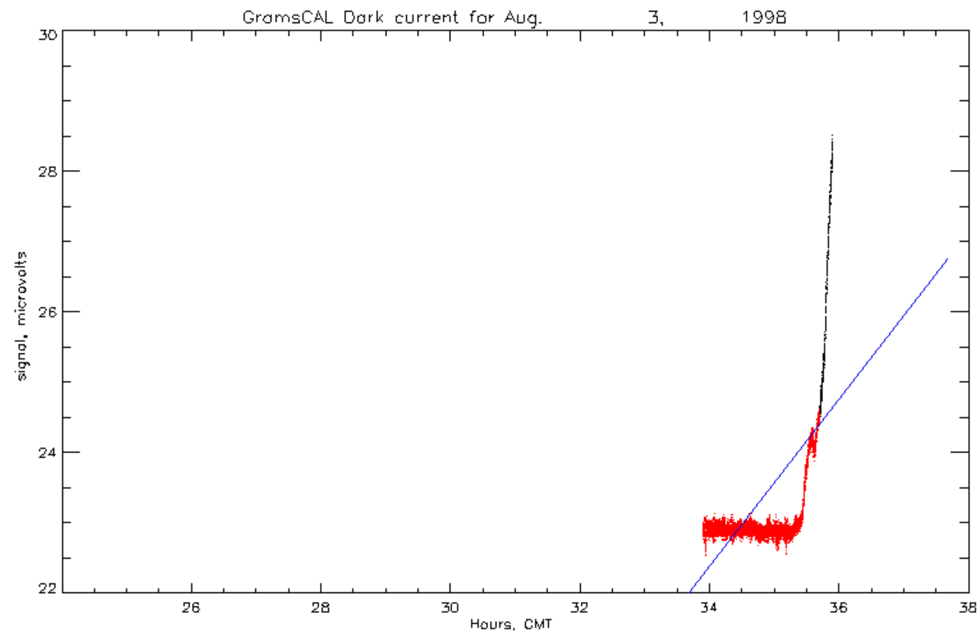

Figure 10. GRAMSCAL data for pre-dawn August 4, 1998, dark voltage.

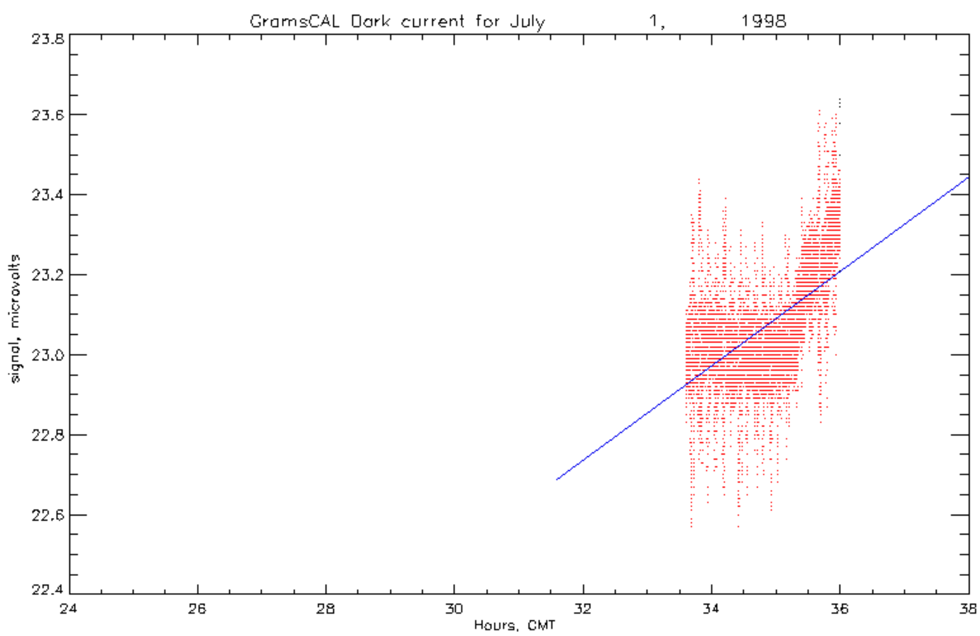

Figure 11. GRAMSCAL dark voltage data for July 2, 1998.

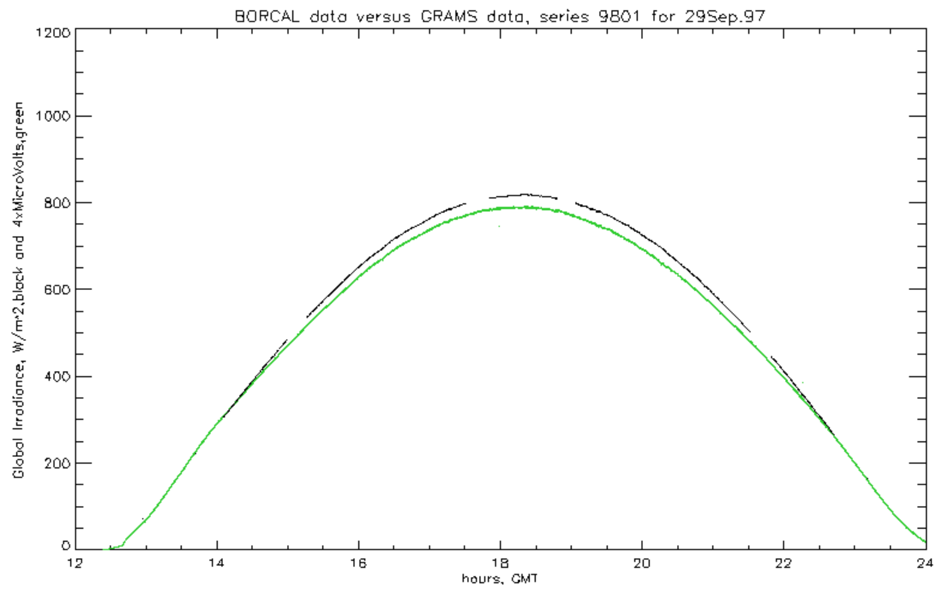

Figure 12. BORCAL and GRAMS data compared for September 29, 1997. One-minute averages of BORCAL global irradiance in W/m^2, accurate to 1.5% absolute, are plotted in black versus GMT for the pristine clear day of September 29, 1997, at the SGP CART central site. Also shown is GRAMS data, in microvolts, plotted in green versus GMT. GRAMS and BORCAL are approximately collocated. For convenience in comparison, the GRAMS values have been multiplied by a factor of 4. Lines connect no data points; the appearance of lines indicates that data points are closely spaced and smooth.

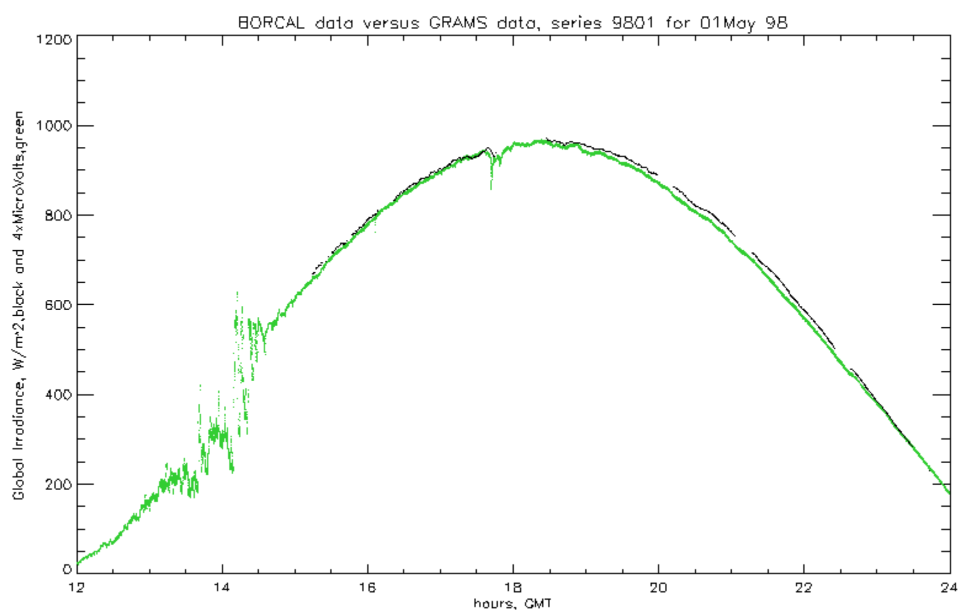

Figure 13. BORCAL and GRAMS data compared for May 1, 1998.

Figure 13 shows what is easily the best day for comparison from BORCAL series 9801, May 1, 1998, the very first day of the series. It is not as smooth as Figure 12, but this is not all bad; at least we see that many irregularities of the data match, showing the instruments to be highly correlated as expected. The data is not as good as that of Figure 12, because it isn't as smooth, continuous, or complete, beginning a little after 10:00 a.m. local sun time and ending a little before 5:30 p.m.

The best day of BORCAL series 9802 for comparison is shown in Figure 14. It is July 15, 1998, and one can see it is far from ideal in any respect. Nevertheless, because of weather and equipment outages, it's the best there is.

One of many frustrating comparisons is shown in Figure 15. This is for August 17, 1998, the last day of the series, BORCAL 9802. There are perhaps two minutes of overlap in the whole day, BORCAL data beginning just before GRAMS data ends.

BORCAL-GRAMS Calibration

The approach taken in calibration was the simplest that held promise of utility. We took one of the two best days on the basis of comparison, instrumental operating time overlap, smooth data and extent of temporal coverage. We choose September 29, 1997, rather than September 30, 1997, because September 29, 1997, was an even more pristine day. A simple calibration factor, C, was found that can be multiplied times GRAMS data to obtain a match with BORCAL accurate to better than 2% over the available range of data for that day. This function is

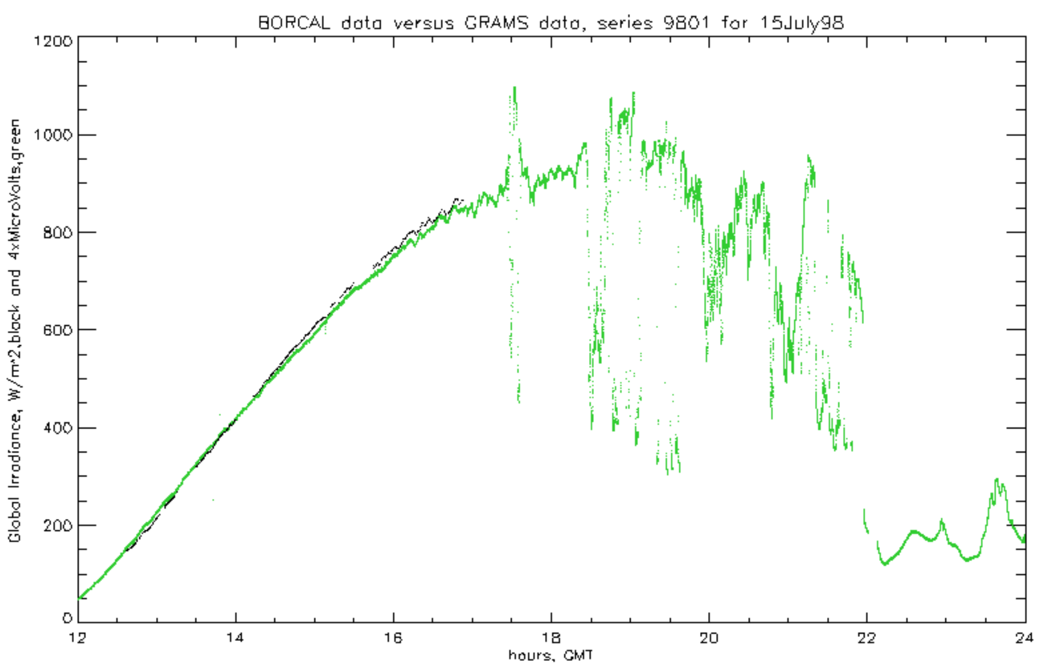

Figure 14. BORCAL and GRAMS data compared for July 15, 1998.

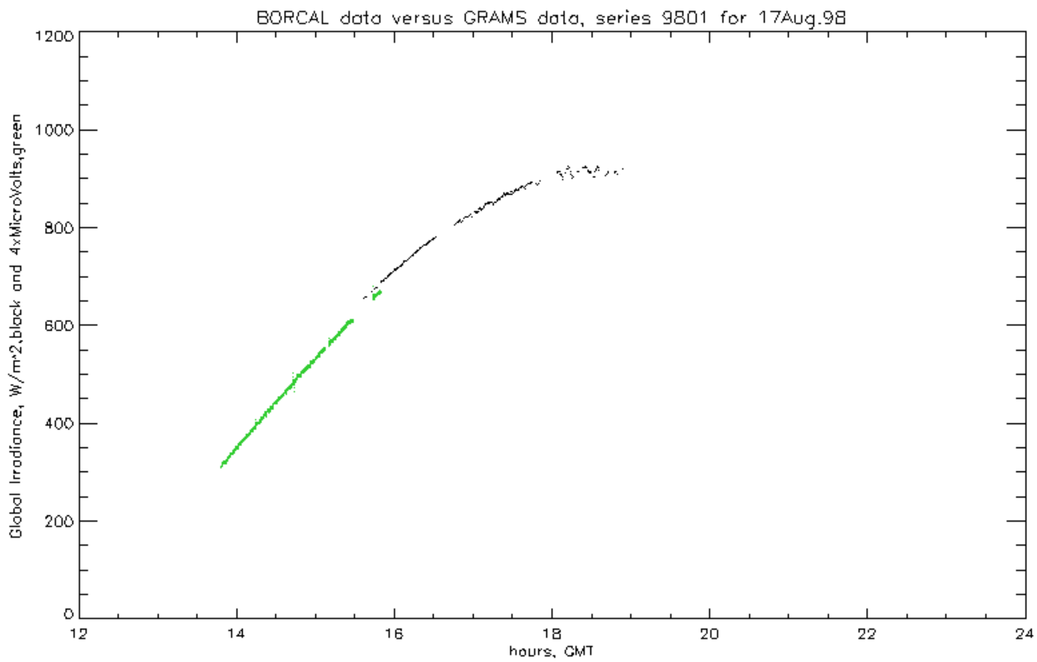

Figure 15. BORCAL and GRAMS data compared for August 17, 1998.

$$C = 3.9441 + 0.0108175h - 0.015(m - 2.1) - 0.12\exp - {}^{(m-1.29)}\!\!\diagup_{0.3}$$

where h is hours, GMT, and m is atmospheric path, in air masses (straight up is 1.0).

It is important to note that the above calibration factor was obtained by eyeball fitting, using functions that seemed to the author to be promising. It seems likely that a more thorough treatment could produce a more reliable form for C.

This same calibration function was then tried against BORCAL-GRAMS data from all series and, surprisingly, was found to yield less than a 5% discrepancy for every ten-minute average reading of all BORCAL series. Accuracy of 5% seems sufficiently good calibration. The following curves (Figures 16 through 28) show comparisons, using the value of C above, for a sample of BORCAL days where at least one ten-minute period has overlap (not necessarily ten minutes of overlap) with GRAMS data. The sample includes the entire spread of comparison, from best to worst.

BORCAL-GRAMSCAL Comparison

A calibration factor similar to that for GRAMS, independent of calendar time, was developed for GRAMSCAL. Again the date September 29, 1997, was chosen, it having the best overlap for the largest fraction of a day with smooth data, and it being the clearest day with data. The formula for the calibration factor has a simpler form than was the case for GRAMS. For GRAMSCAL it is

$$C = 4.167 + 0.0276h - 0.268m$$

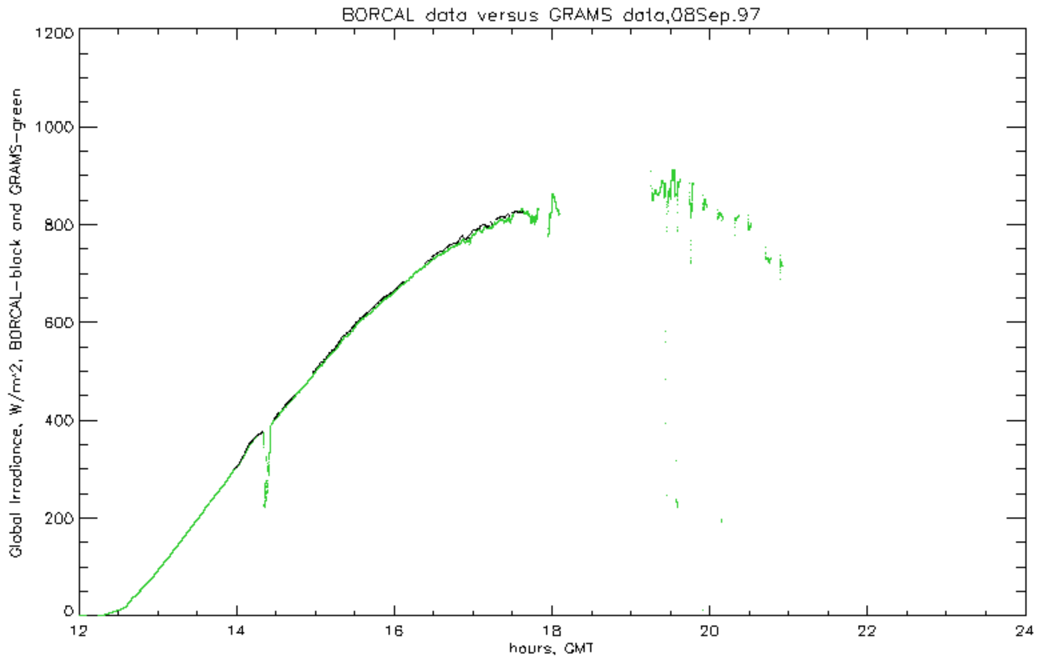

Figure 16. Calibrated GRAMS versus BORCAL for September 8, 1997.

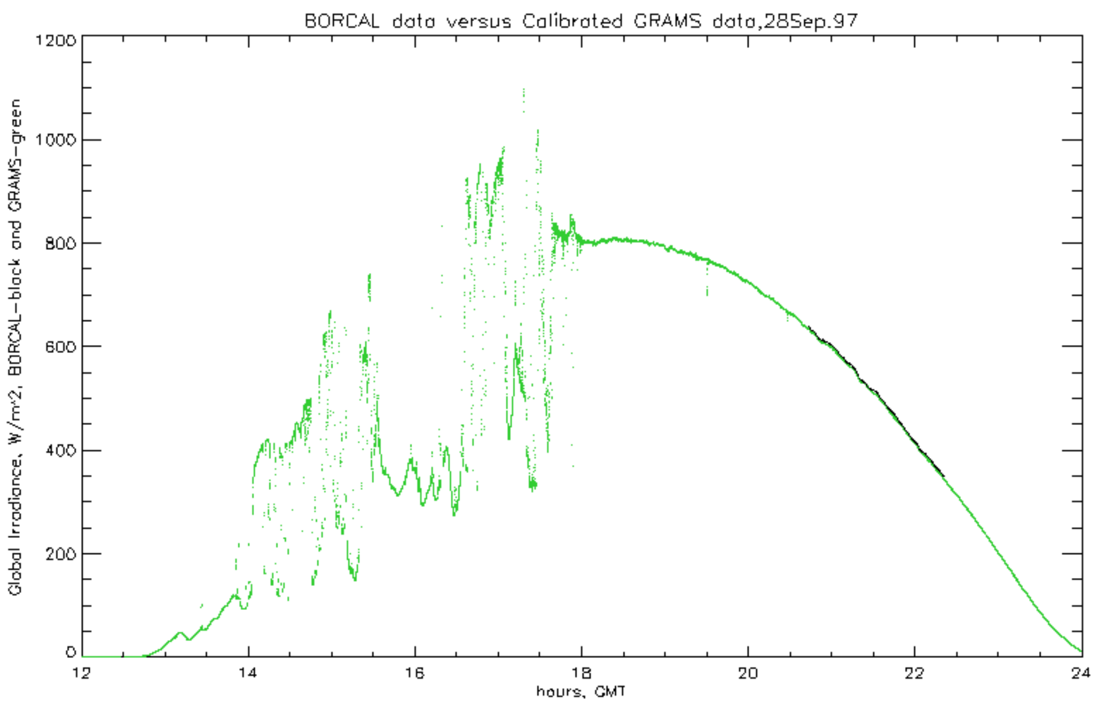

Figure 17. Calibrated GRAMS versus BORCAL data for September 28, 1997.

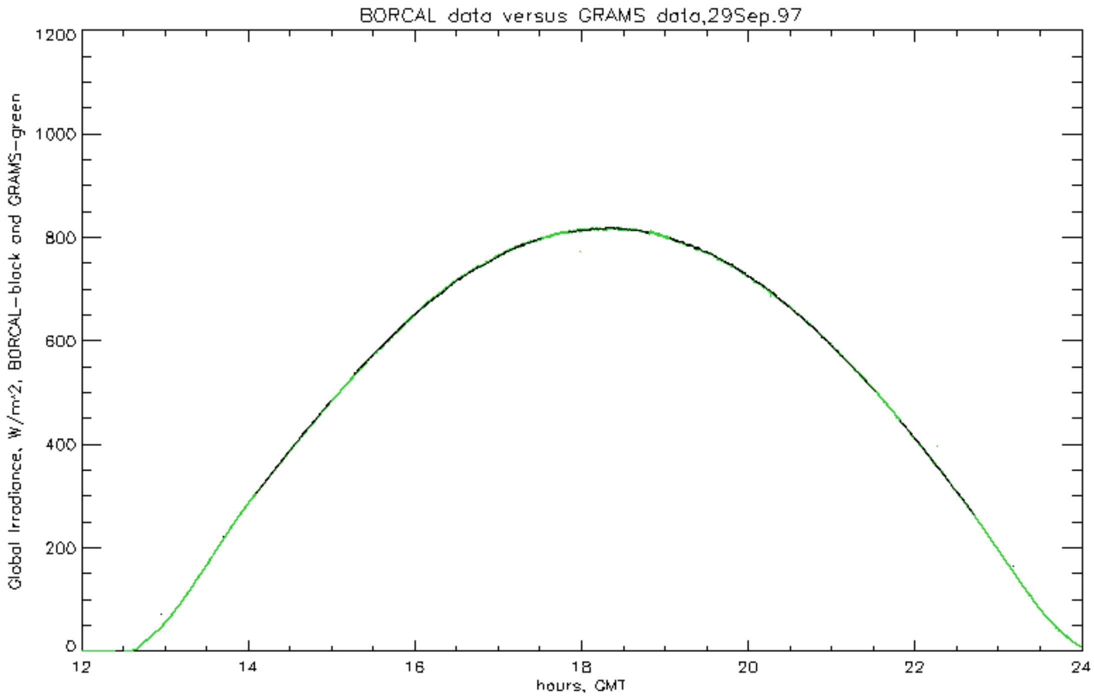

Figure 18. Calibrated GRAMS versus BORCAL data for September 29, 1997.

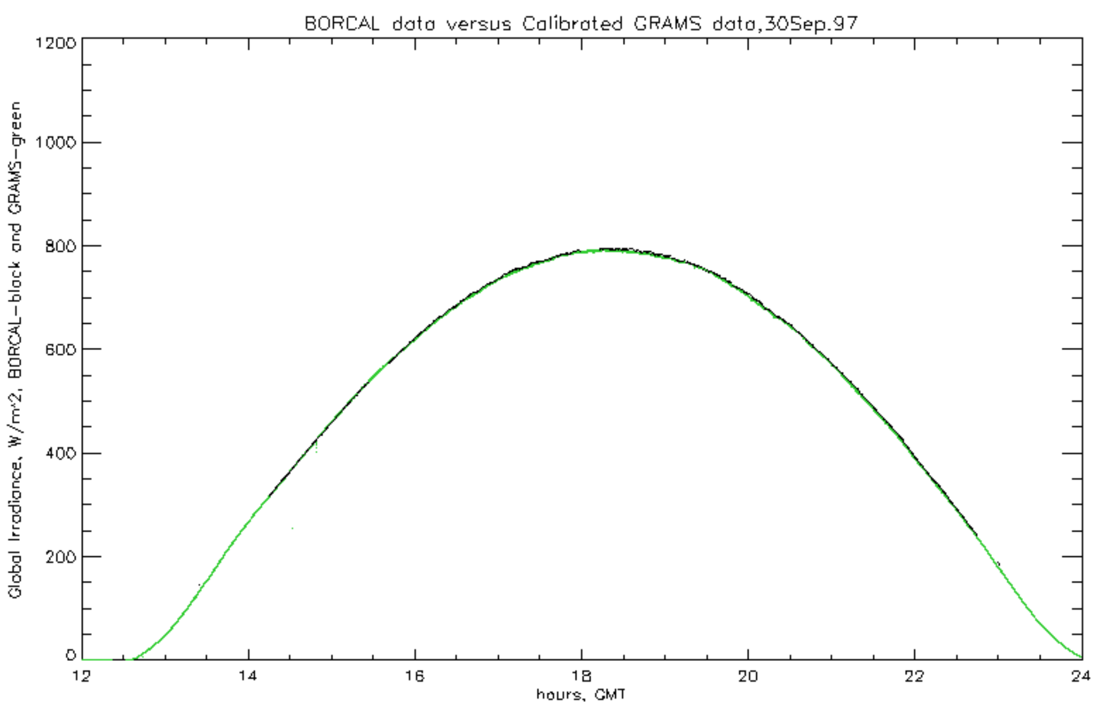

Figure 19. Calibrated GRAMS versus BORCAL data for September 30, 1997.

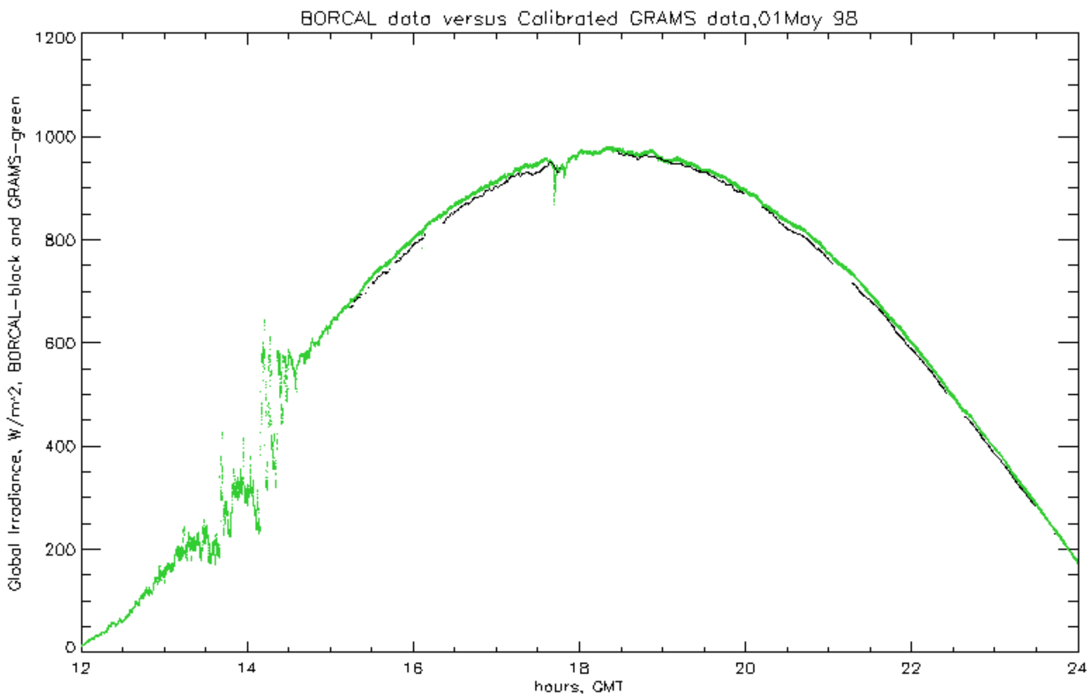

Figure 20. Calibrated GRAMS versus BORCAL data for May 1, 1998.

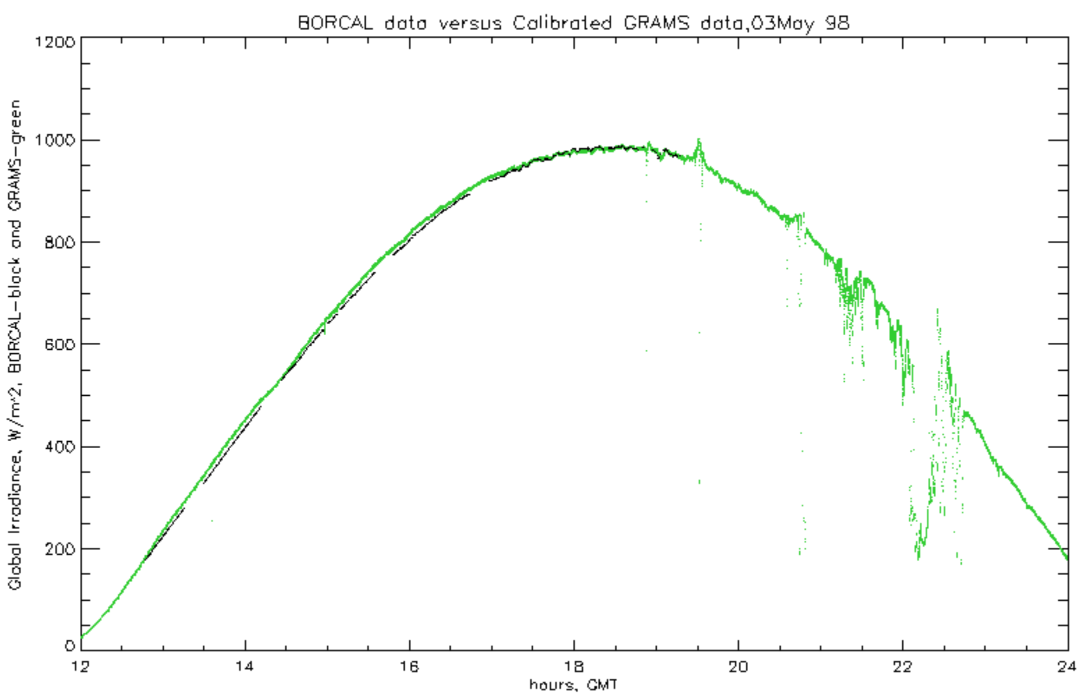

Figure 21. Calibrated GRAMS versus BORCAL data for May 3, 1998.

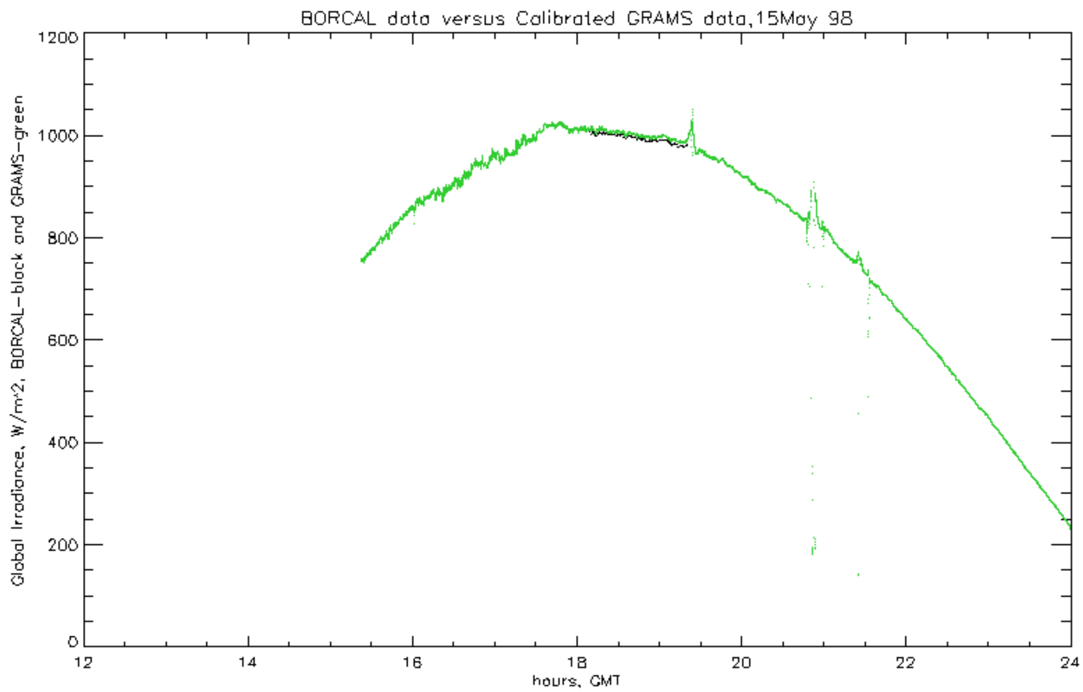

Figure 22. Calibrated GRAMS versus BORCAL data for May 15, 1998.

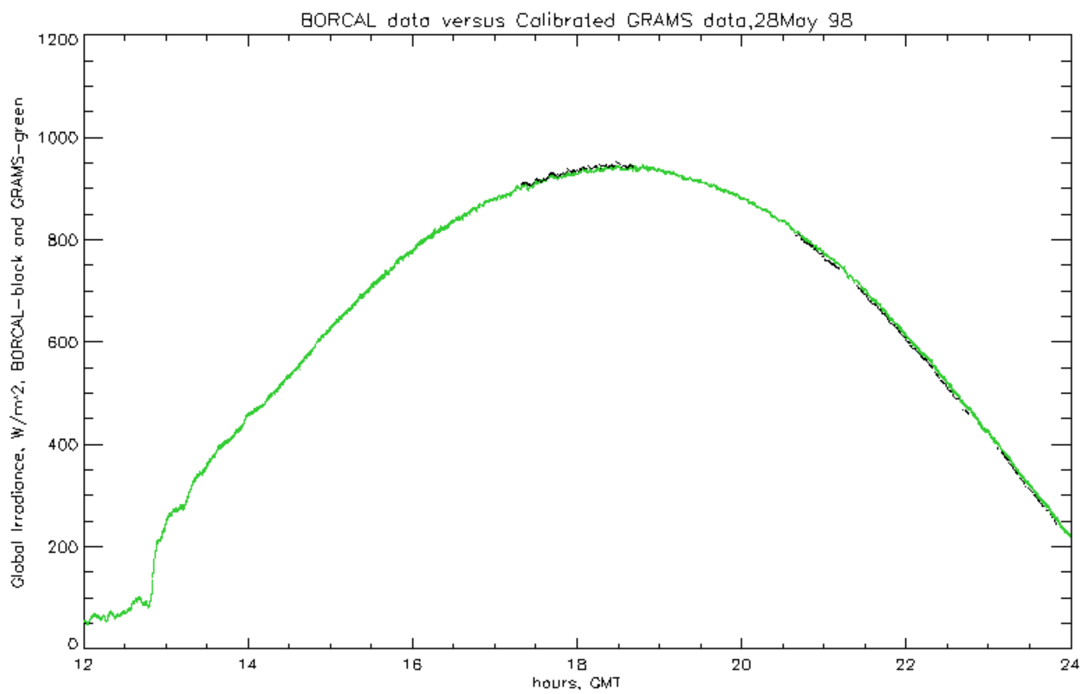

Figure 23. Calibrated GRAMS versus BORCAL data for May 28, 1998.

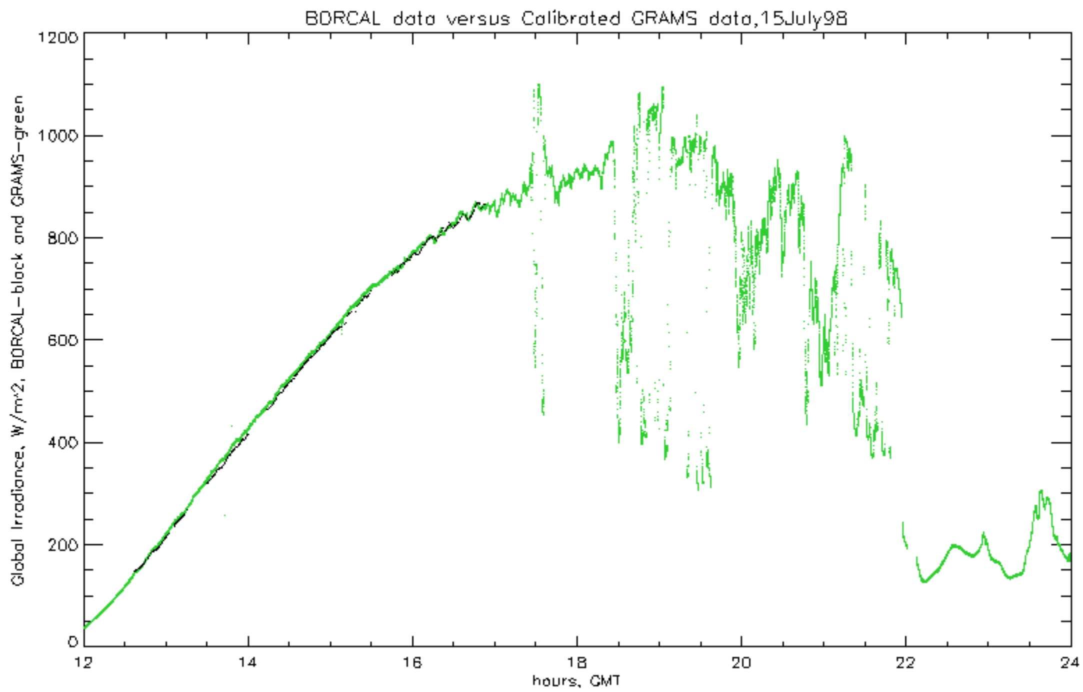

Figure 24. Calibrated GRAMS versus BORCAL data for July 15, 1998.

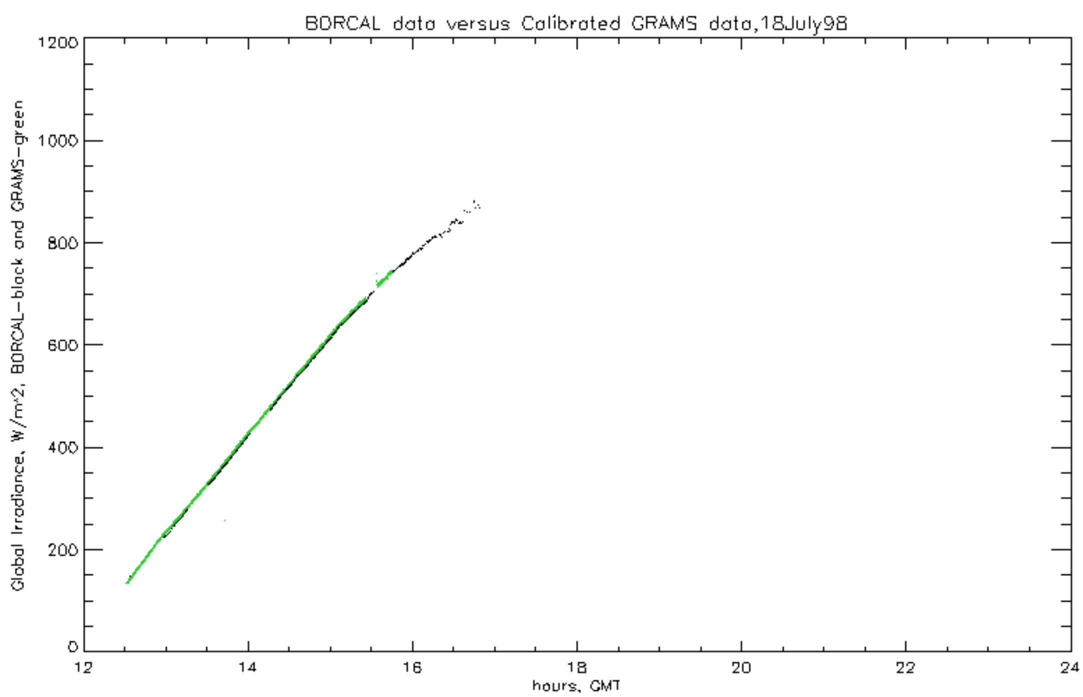

Figure 25. Calibrated GRAMS versus BORCAL data for July 18, 1998.

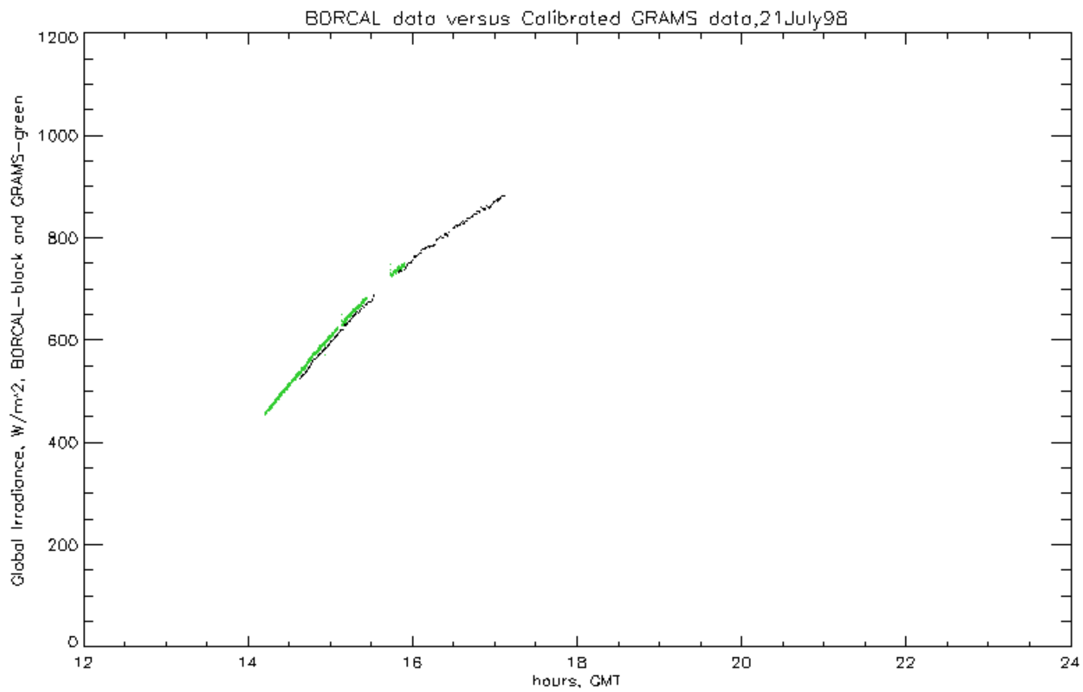

Figure 26. Calibrated GRAMS versus BORCAL data for July 30, 1998.

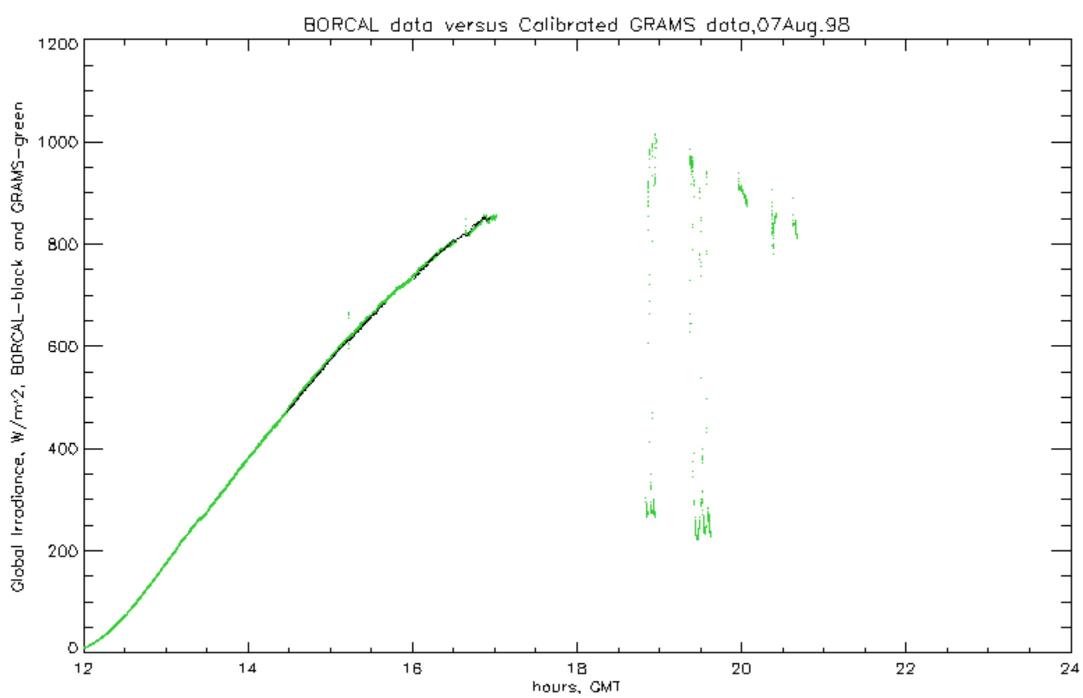

Figure 27. Calibrated GRAMS versus BORCAL data for August 7, 1998.

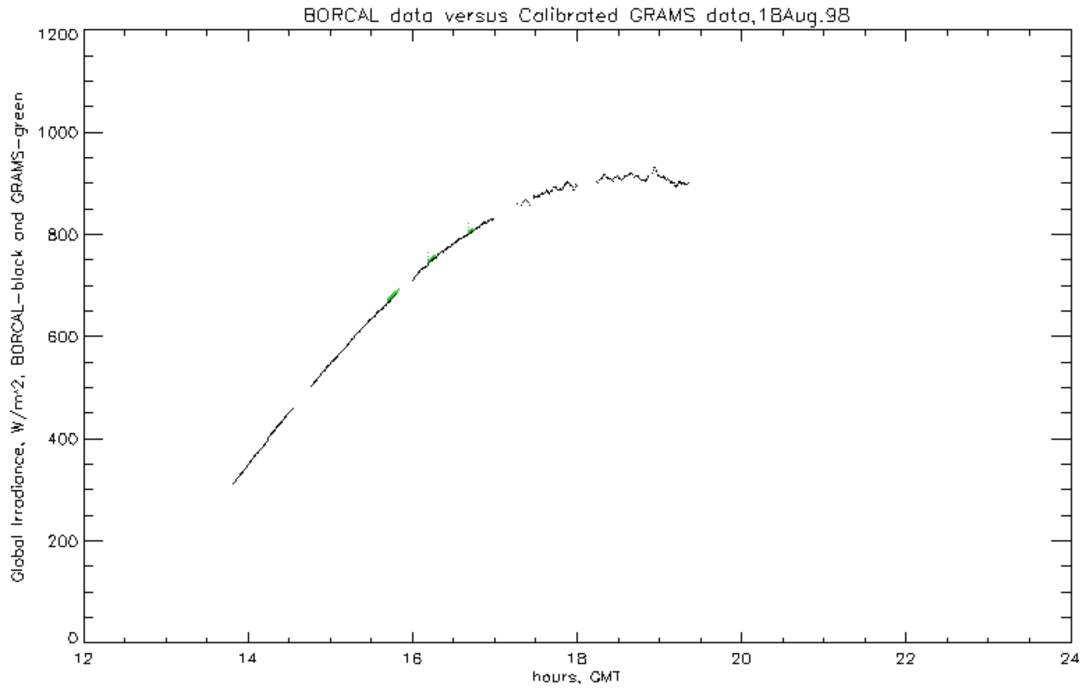

Figure 28. Calibrated GRAMS versus BORCAL data for August 18, 1998.

Again, h is hours; GMT, and m is atmospheric path, in air masses.

The following figures (Figures 29 through 37) show examples of comparison between GRAMSCAL and BORCAL. Again, the examples span the range from worst to best agreement. Agreement using this factor for all available data is within a little over 3%. Note that not as much GRAMSCAL data exists for September 1997 and none at all for May 1998. Further, no comparison is as precise as the September GRAMS data. This calibration factor, however, fits the data as least as well as instrumental accuracy seems to justify and has the advantage of simplicity and linearity. Which of the two forms will be more reliable remains to be seen.

Using the nominal BORCAL absolute accuracy of 1.5% and this calibration factor, one can hope to obtain measurements from GRAMSCAL with absolute accuracy of 5% or a little better. The adjective, ‘hope,’ was inserted into the last sentence because there is BORCAL data neither near winter solstice nor during periods of highly structured signal. Note however, that when the signal begins to develop structure on July 15 and 18 (Figures 32 and 33), the correlation between the two instruments is excellent and the calibration factor continues to yield agreement within 3% absolute.

The caveat that these calibration factors are the result of eyeball fitting bears repeating. A more thorough treatment could be expected to yield more accurate fits.

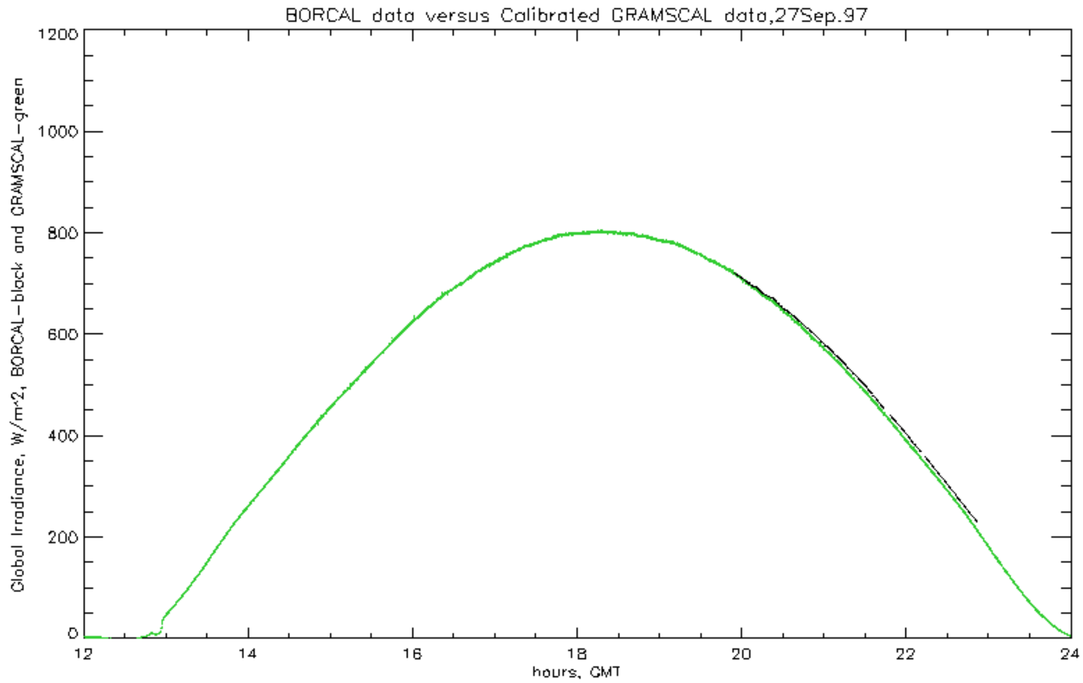

Figure 29. Calibrated GRAMSCAL versus BORCAL data for September 27, 1998.

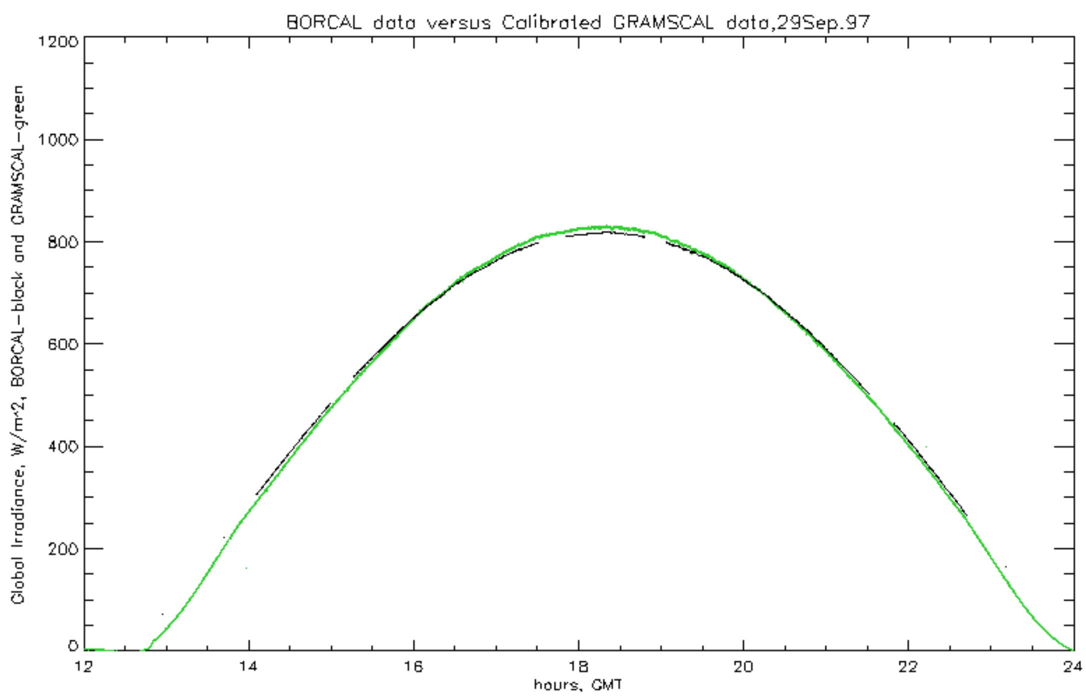

Figure 30. Calibrated GRAMSCAL versus BORCAL data for September 29, 1998.

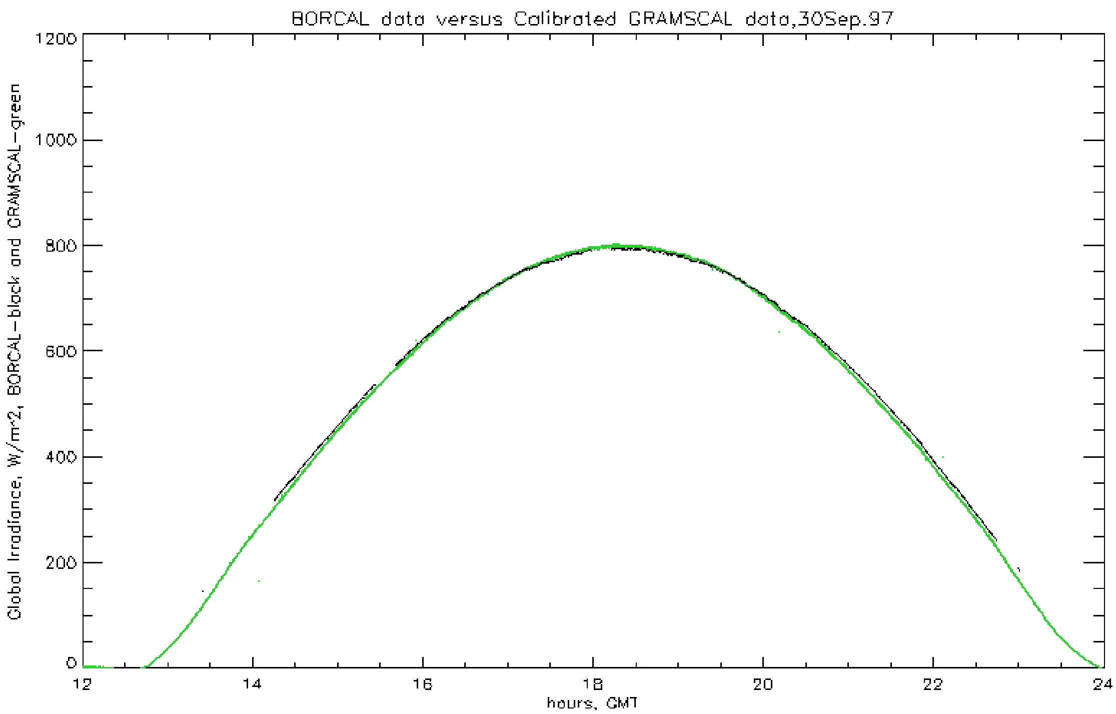

Figure 31. Calibrated GRAMSCAL versus BORCAL data for September 30, 1998.

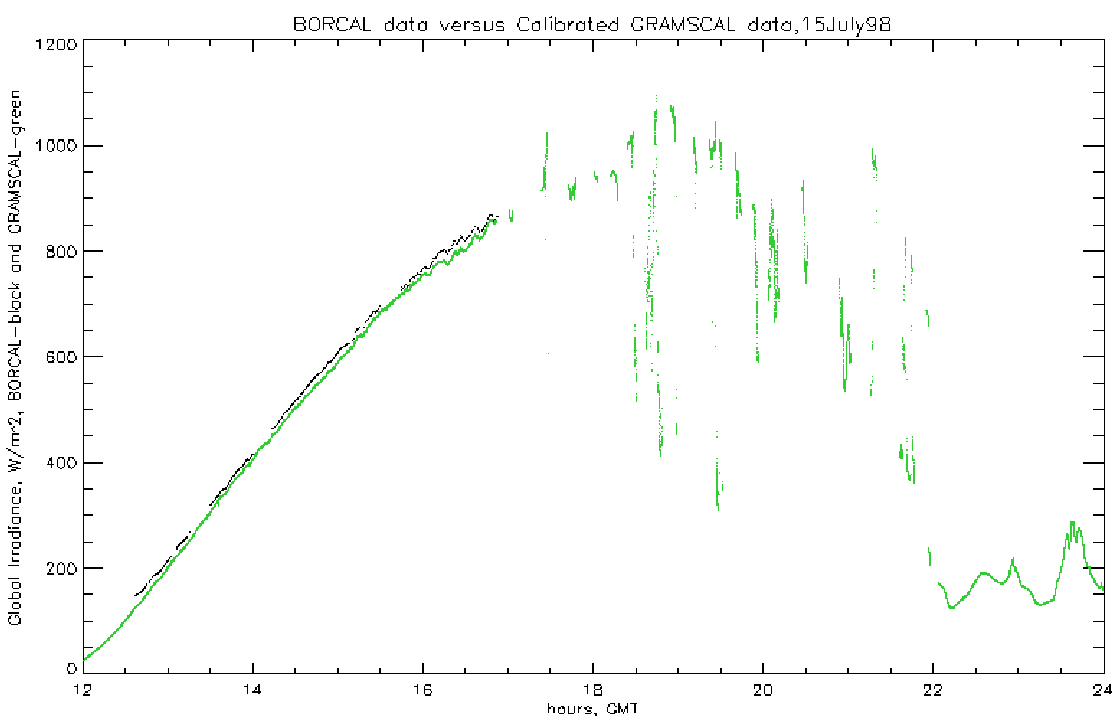

Figure 32. Calibrated GRAMSCAL versus BORCAL data for July 15, 1998.

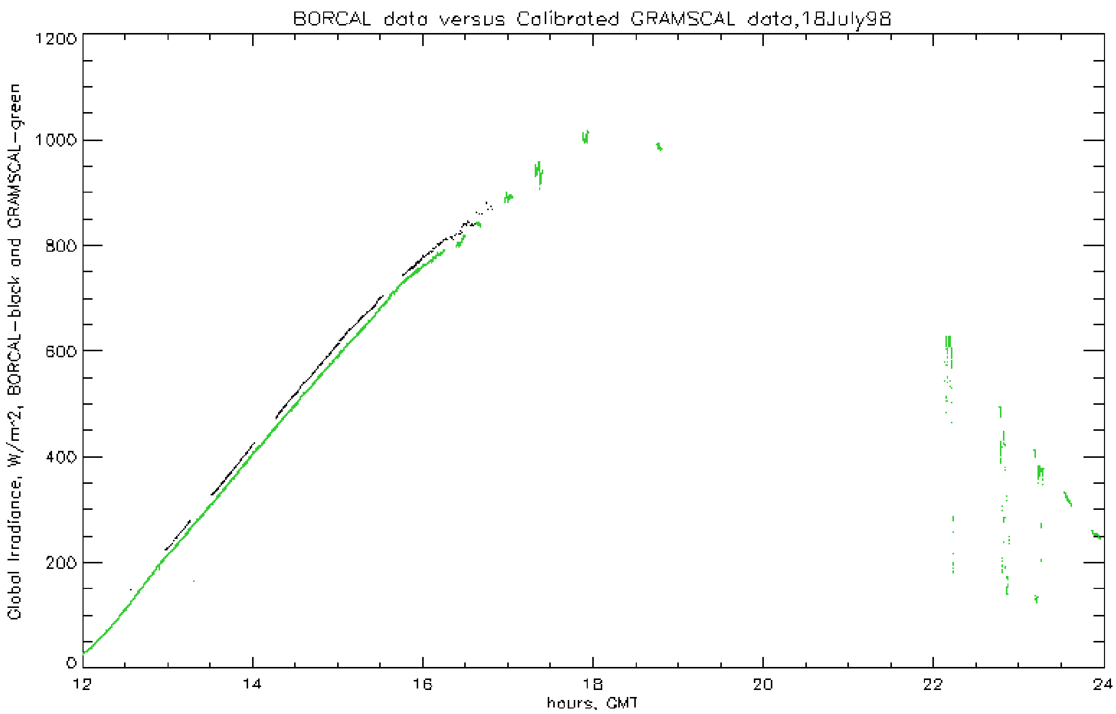

Figure 33. Calibrated GRAMSCAL versus BORCAL data for July 18, 1998.

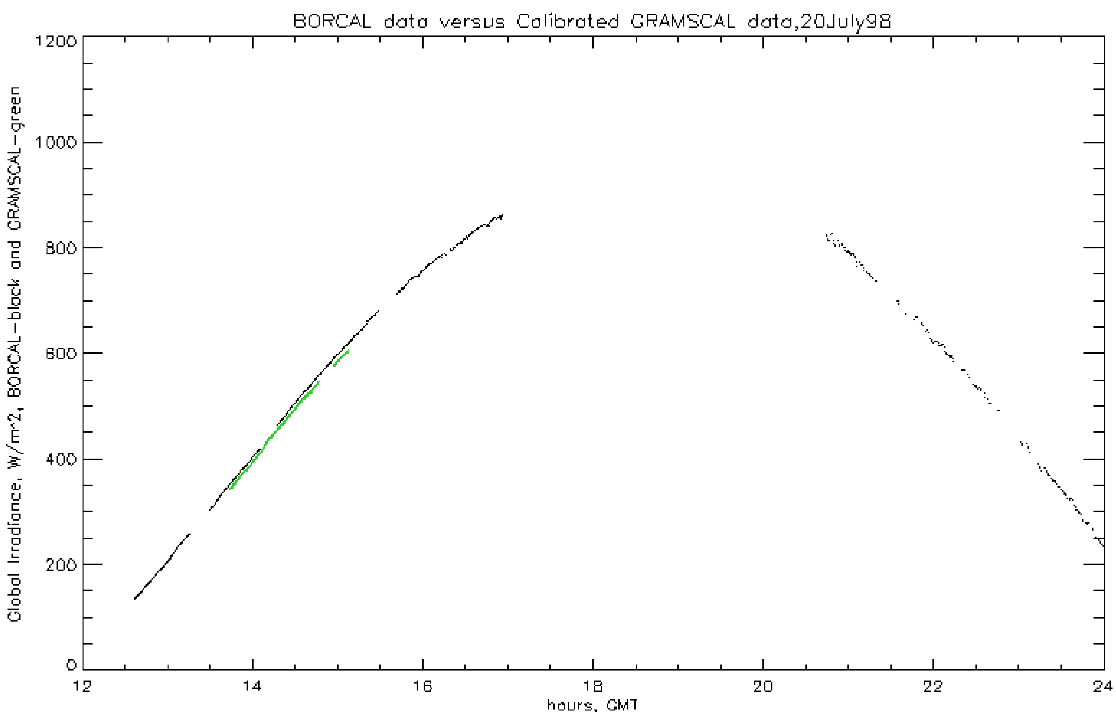

Figure 34. Calibrated GRAMSCAL versus BORCAL data for July 20, 1998.

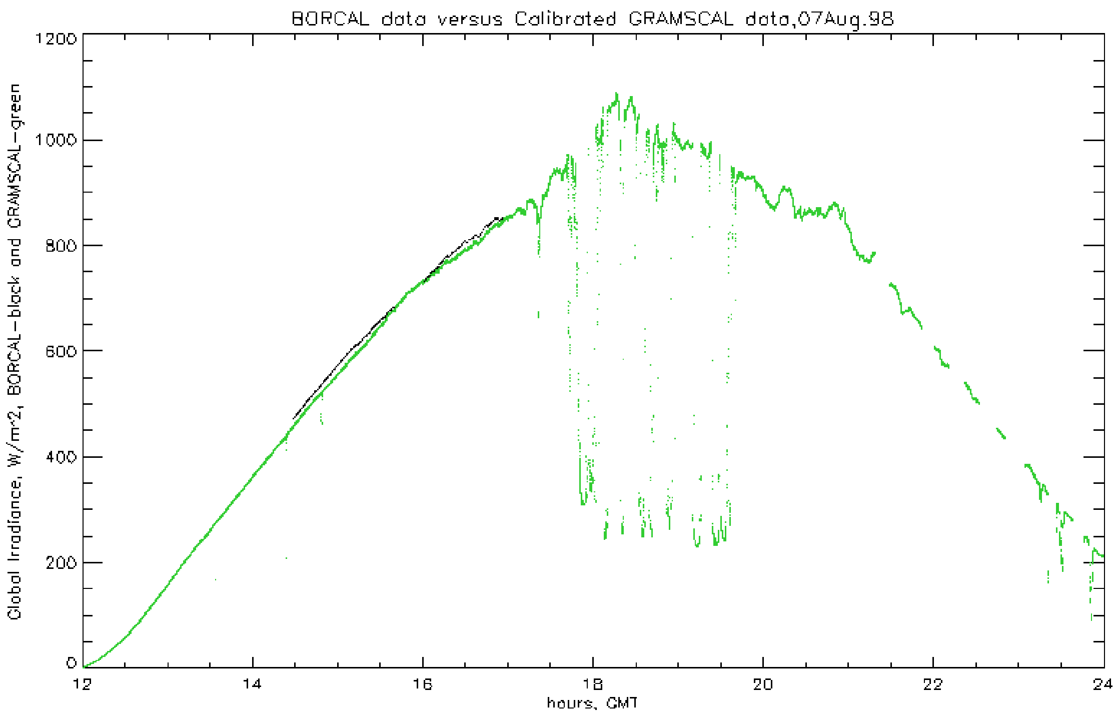

Figure 35. Calibrated GRAMSCAL versus BORCAL data for August 7, 1998.

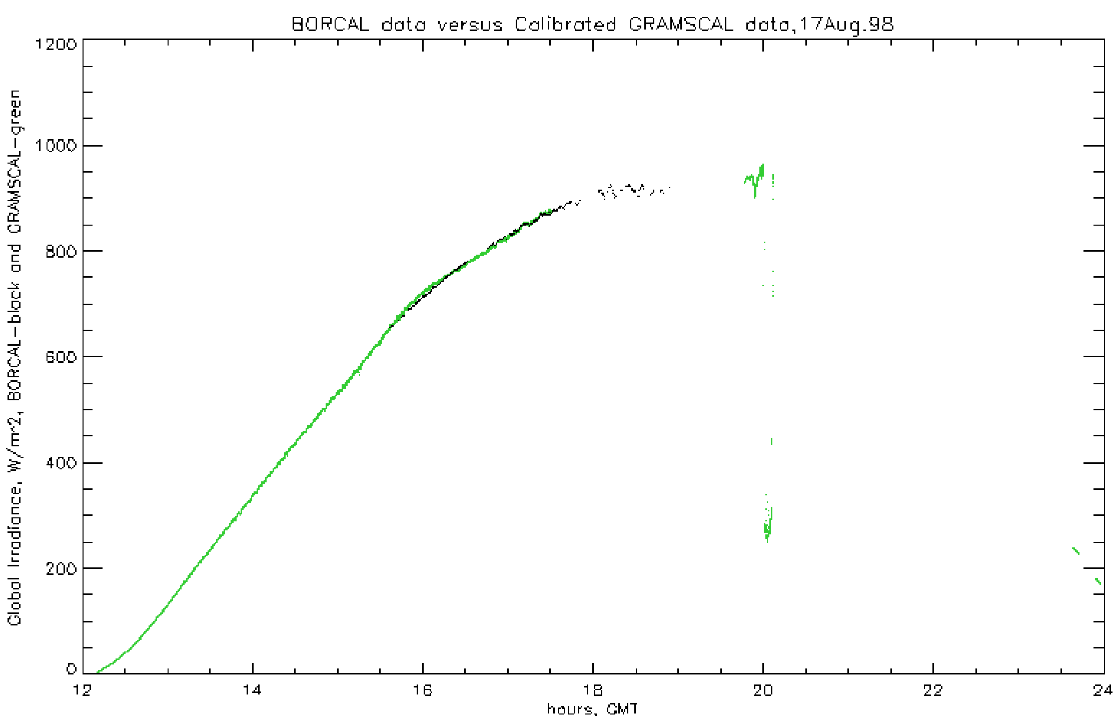

Figure 36. Calibrated GRAMSCAL versus BORCAL data for August 17, 1998.

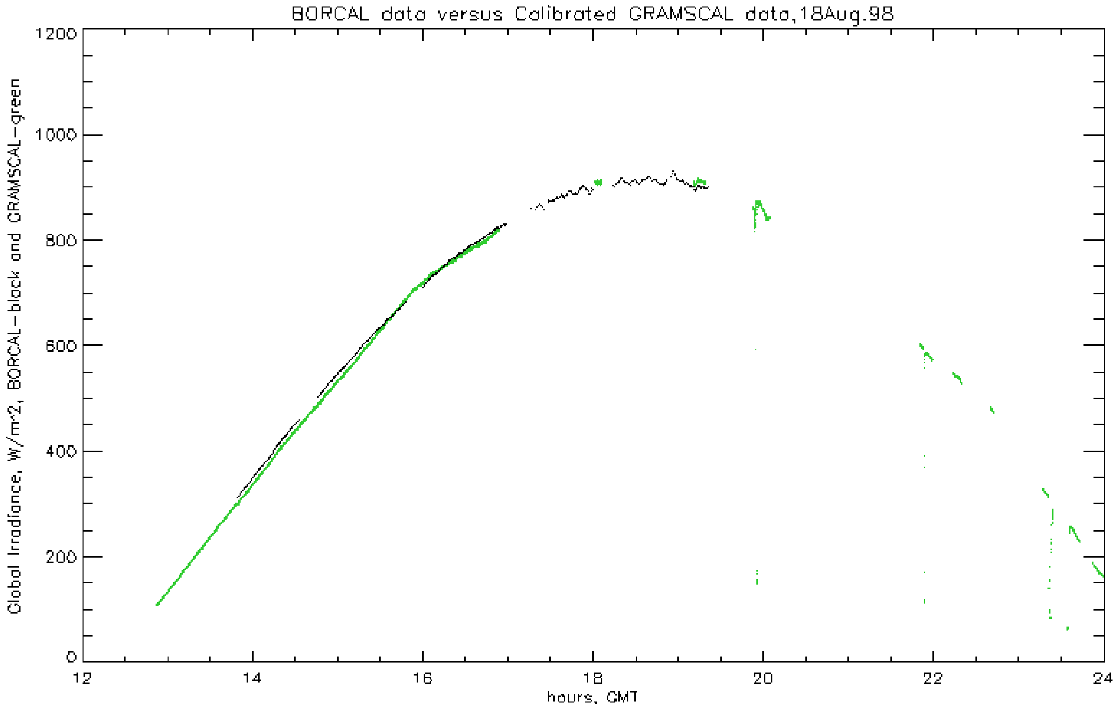

Figure 37. Calibrated GRAMSCAL versus BORCAL data for August 18, 1998.

Conclusions

The major conclusion is that both instruments appear to be sufficiently stable to yield about 5% accuracy in total irradiance if the sun is higher than, say, 10 or 20 degrees above the horizon and if the instruments are compared to measurements such as BORCAL sufficiently and frequently. A more elaborate calibration function that would work somewhat closer to the horizon might be determined by expending more effort. It is also possible that the overall accuracy might be improved to somewhat less than 5% by expending more effort.

Major caveats to the forgoing statement include the possibility of both daily and annual cycles in instrument dark voltage. It seems unlikely that any such cycles will cause the above-quoted error to increase greatly, but it can't be ruled out.

This caveat can be eliminated by three changes in operating procedure:

1. Run GRAMS and GRAMSCAL from two hours (rather than one) pre-sunrise to two hours post-sunrise.

2. Operate on sun-time or GMT rather than on a clock that changes twice a year between standard time and daylight savings time.

3. Cover each instrument within an hour or so of noon, long enough to get a stable reading, say, 20 minutes, and to be sure dark voltage isn't affected by some activity during the day. This might be done on an experimental basis, say for one week out of five for a year. If no significant effect is found, the procedure could be discontinued.

Another caveat stems from the fact for very good reasons BORCAL tends to be operated only during clear periods, but seemingly not all clear periods, during the course of a BORCAL campaign. Since afternoons are subject to local thermal clouds, scattered cloud conditions are common in the afternoon, particularly during clear weather and BORCAL data beyond local noon is not as well represented as during mid morning. On the other hand, GRAMS and GRAMSCAL, particularly GRAMSCAL during the period of concern, are down for various reasons at various times, sometimes frustratingly just when BORCAL is able to obtain unusually good data. Thus, the overlap of GRAMS and GRAMSCAL data with BORCAL is less than one might wish. More BORCAL or similar campaigns, hopefully some near winter solstice, can eliminate this caveat.

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