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Setting standards for European ultraviolet spectroradiometers

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Setting standards for European ultraviolet spectroradiometers

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FOREWORD

Stratospheric ozone depletion due to the anthropogenic emissions of chlorofluorocarbons and other ozone-depleting chemicals to the stratosphere causes the increase of a biologically important part of the solar ultraviolet (UV-B) radiation reaching the earth's surface. This may constitute a great threat to the biosphere, because it can cause damaging effects to human beings and to ecosystems.

The European Commission through various research projects in the frame of its R&D Programmes STEP (1989-1992) and ENVIRONMENT (1991-1994) supports research activities on stratospheric ozone depletion and its major known consequence, the increase in the fluxes of UV-B radiation at the earth's surface. As part of the latter research, the STEP-CT900076 project entitled "Determination of standards of a UV-B monitoring network" aims at the improvement of measuring techniques and at the establishment of methods and criteria towards achieving reliable solar absolute UV measurements. Specifically, during the course of this project, three intercomparison campaigns were organised at Panorama (Thessaloniki), Greece in July 1991 and August 1992 and at Garmisch-Partenkirchen, Germany in July 1993. These intercomparisons of UV-B spectroradiometers aimed at assessing the compatibility among instruments and thus to the establishment of a network for measuring the UV-B field and its temporal and spatial variability in Europe.

This report follows two previous published reports (Air Pollution Research Reports 38 and 49) which described the first and the second intercomparisons respectively. The present report describes the third intercomparison at Garmisch-Partenkirchen and presents the final results of the three-year STEP project which are largely based on these intercomparisons. As a product of this investigation, the operational standards for a European network of ultraviolet spectroradiometers were determined.

The European Commission acknowledges gratefully the work of all scientists involved in the project, especially, Dr Ann Webb for the coordination, Prof Christos Zerefos and Dr Alkiviadis Bais for hosting the two intercomparisons at Panorama, Dr Gunther Seckmeyer for hosting the third intercomparison at Garmisch-Partenkirchen, as well as Drs Brian Gardiner and Peter Kirch for the editorial work in all three published reports.

Brussels, September 1994

H. Ott,
DG XII/D1

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Names of participants who attended the third intercomparison are underlined. Contact addresses are shown in Appendix G.

Introduction

Although the importance of ultraviolet radiation in the biosphere has been known to scientists for a long time, it is only in recent years that its deleterious effects have become the subject of widespread public interest and debate. Even in the scientific community, however, it is not always fully appreciated just how diverse the effects of ultraviolet radiation can be, nor how much they depend on the wavelength of the radiation.

Whether the effect is beneficial or detrimental, or more complex; whether it is in a plant or an animal, marine or terrestrial; whether it is an acute or a chronic effect, superficial or systemic; in fact, whatever its character, it will invariably be found to depend on wavelength. That is to say, a certain amount of ultraviolet radiation will not have the same effect at one wavelength as at another. This remains true no matter whether the amount is reckoned in terms of energy or the number of photons. It would be a straightforward matter if all ultraviolet effects had the *same* spectral dependence, but this is decidedly not the case. In fact, each effect has its own characteristic spectral response. For a particular effect of ultraviolet radiation on an organism, the spectral dependence can be represented as a function of wavelength which is known as the action spectrum for that effect. Action spectra are typically steep functions of wavelength. It follows that assessment of ultraviolet effects requires spectrally-resolved data on the incident radiation flux.

This flux is determined by a number of factors, including the extraterrestrial solar spectrum, the elevation of the Sun above the horizon, barometric pressure, atmospheric ozone, air pollution (in the form of suspended particles), clouds, and surface albedo. The ultraviolet irradiance which results from these influences is itself a steep function of wavelength in the region of interest, but whereas most action spectra decline as the wavelength increases, the incident radiation becomes more intense. The product of the spectral irradiance and the action spectrum is therefore even more wavelength-dependent than either alone. It is this product which determines the biological effect on the organism. Consequently, when evaluating the influence of variations in atmospheric parameters, it is necessary to perform the assessment at each individual wavelength. This applies equally to theoretical and experimental investigations.

Spectral measurements are therefore required as a basis for calculation, particularly in the light of public concern over the future state of the ozone layer. If the consequences of ozone depletion are to be predicted and assessed, the relationship between solar ultraviolet irradiance and its controlling factors must first be firmly established. This will only be possible if the spectral irradiance measurements are made to a consistently high standard, using accurately calibrated spectroradiometers under carefully controlled observing conditions, with stable and reliable operating procedures.

This document constitutes the Final Report of a three-year investigation to determine the operational standards that would be required in a European network of ultraviolet spectroradiometers. The study was carried out at the behest of the European Commission in response to the need for reliable and accurate measurements of solar ultraviolet irradiance when evaluating and predicting the consequences of atmospheric ozone depletion. During the course of the project three intercomparison campaigns were carried out at annual intervals in order to bring together a wide range of ultraviolet spectroradiometers for assessment of their specifications, operating procedures and performance.

The final results of the investigation are largely based on the third of these intercomparisons, which therefore forms the core of this report. A full account of this campaign is followed by a detailed discussion of the factors which have been found to be important for the successful measurement of ultraviolet irradiance, and the criteria which have to be met in order to ensure reliable and consistent results. The conclusions and recommendations at the end of the report are based on the lessons learned in all three intercomparisons and in subsidiary experiments, and also on experience gained during measurements at the home sites of the participants.

The principal aim of the investigation was to find out the best way to make reliable and accurate spectral measurements of the ultraviolet radiation incident on the Earth's surface, by using a number of independent instruments, comparing their results, and attempting to understand, explain, and resolve their differences. On the basis of simultaneous intercomparison measurements by a series of spectroradiometers, it was planned to improve the techniques and examine the results achieved by the improvements, to specify the instrumental characteristics and procedures necessary to obtain reliable results, and to recommend possible steps to be taken for future development of the systems.

From the start, the hallmark of the project was the broad diversity of the spectroradiometers. An initial grouping of four scanning instruments was formed in 1991, of which two were single and two double monochromators, one of each pair being commercially available while the other was built by its operators. The diffusers, bandwidths and spectral ranges were all very different. A fifth instrument, with a diode-array detector and integrating sphere, was then at the design stage. Two more instruments joined the team before the first scheduled campaign, and by the time the third annual intercomparison had taken place there were 12 very disparate instruments in the group, not counting visitors from other continents.

In addition to laboratory measurements of spectral irradiance standard lamps, both at the intercomparisons and at the home institutes, a prototype Transportable Lamp System (TLS) was designed and constructed in order to monitor the stability of the absolute irradiance calibration of the spectroradiometers over a period of time. Improvements were made to the output aperture and lamp mountings after operational tests during the second intercomparison, and the TLS was again measured by several of the instruments which took part in the third campaign. The TLS was subsequently sent round a selection of the participating institutes to evaluate its performance in its operational role.

The results of the first two intercomparisons were reported in earlier publications. The first was in the nature of an exploratory investigation, as very little previous work had been done to intercompare instruments of radically different design side by side in the field. The main result of the first campaign was that relative spectral irradiance could be achieved by several instruments with a good degree of agreement (except at the very shortest wavelengths where the ultraviolet intensity is at its weakest), whereas absolute agreement was elusive. Moreover, the results of lamp calibrations indoors did not provide a reliable guide to the absolute calibration when viewing the Sun and the sky. Much of this was probably due to deficiencies in the lamp room; the success of the second intercomparison was partly due to the improved control of lamp current, geometry, and stray light during calibration scans.

In the second campaign, a much better standard of agreement was achieved by a small group of instruments both in the lamp room and on the roof. With these core instruments, the outstanding problems were clearly identifiable as stray light at short wavelengths, cosine response, and the individual slit functions. The other instruments did not generally meet an adequate standard for participation in an international network, partly owing to deficiencies in their technical specifications, but also owing to shortcomings in their calibration and characterisation procedures.

With this result in mind, the third intercomparison had a twofold aim: firstly to improve the quality, reliability, and accuracy of the measurements made by the core instruments, and secondly to provide a platform and comparative standard against which other candidate instruments could be assessed. In the report which follows, it will be seen that the third campaign broke new ground in the investigation of the core instruments, measured the improvements achieved in the others, and examined several new instruments of widely varying design which had not previously taken part in the project.

Terminology

The principal requirement during this project was the measurement of the *global solar spectral irradiance*, that is to say the amount of energy arriving per second on unit area of a horizontal surface, per unit of wavelength interval, from all parts of the sky above the horizontal, including the disc of the Sun itself.

To measure global solar irradiance the instruments are aligned with the optical axis of the inlet window pointing towards the zenith. Ideally, a point source at a fixed distance from the spectrometer should produce a signal proportional to the cosine of the zenith angle of the source. This is accomplished either by viewing the sky through a translucent *diffuser* plate, manufactured from teflon or quartz, or by accepting incident radiation into a hollow *integrating sphere*. In practice it is difficult to achieve a perfect *cosine response*, especially at large zenith angles.

The wavelength resolution of these spectrometers is of the order of 1 nm. If the *slit function* (the instrumental response to a monochromatic spectral line) is accurately known, its full width at half maximum (FWHM) is a useful indicator of the *bandwidth* (see Appendix D). At any one moment, a scanning spectrometer should record radiation in a wavelength range covering no more than two or three times that bandwidth. Radiation which reaches the detector from outside this region is called *stray light*: near-field stray light if it comes from wavelengths which are removed from the centre of the slit function by no more than about four times the FWHM, and which follow the nominal wavelength setting of the spectrometer as the diffraction gratings are turned; far-field stray light if it comes from more distant wavelengths.

The participating teams and their instruments will be referred to throughout this report by the abbreviations ATI, ATW, BE, DEG, DEH, DEK, DEM, FR, GB, GR, NLK, NLR, NLRD, NLRE, and NO, as follows:

ATI	Austria - Innsbruck	Institut für Medizinische Physik
ATW	Austria - Vienna	Universität für Bodenkultur
BE	Belgium	Institut d'Aéronomie Spatiale de Belgique
DEG	Germany - Garmisch-Partenkirchen	Institut für Atmosphärische Umweltforschung
DEH	Germany - Hohenpeissenberg	Deutscher Wetterdienst
DEK	Germany - Karlsruhe	Botanisches Institut der Universität Karlsruhe
FR	France	University of Lille
GB	Great Britain	University of Reading
GR	Greece	University of Thessaloniki
NLK	Netherlands - KNMI	Royal Netherlands Meteorological Institute
NLR	Netherlands - RIVM	National Institute of Public Health
NO	Norway	University of Tromsø

In selecting the above abbreviations we have adopted the two-letter ISO country codes.

The DEM instrument was rented from GSF, Munich, and operated by the DEG team. The NLR team operated the NLRD and NLRE instruments.

Where the results from a group of instruments are averaged, the group mean will be denoted by one of the following labels: MB (BE, DEM, and NLRD); MC (ATI, GB, and GR); MD (ATI, DEM, GB, and GR); MF (all the MB and MC instruments together); MX (the six MF instruments together with DEK, NLK, NLRE, and NO).

Third Intercomparison

Introduction

The Third European Intercomparison of Ultraviolet Spectroradiometers took place at the Fraunhofer Institute for Atmospheric Environmental Research in Garmisch-Partenkirchen in July 1993. Ten independent teams took part throughout the campaign, submitting data from eleven spectroradiometers. Three additional spectroradiometers were deployed on an experimental basis, and two more were operated during part of the campaign by visiting teams. Various non-spectral instruments were also tested. Four of the eleven participating spectroradiometers were new to the group, and only one of the former participants had dropped out. With scientists from Norway in the north to Greece in the south, the gamut of European experience was in the melting-pot.

Having arranged a sturdy platform on the roof for the instruments and a well-appointed calibration room in the basement for the laboratory measurements, our hosts also provided alpine scenery in the background and Bavarian hospitality in the foreground to ensure the continuation of the spirit of European scientific co-operation which we have successfully established and maintained throughout these campaigns.

Site

Observations were made from an existing platform mounted on the roof of the Fraunhofer Institute for Atmospheric Environmental Research, 3 km south-west of Garmisch-Partenkirchen, Germany, at latitude 47° 29' N, longitude 11° 04' E, and at an altitude of 730 m above sea level. Although the horizon was mountainous in most directions, the mountains were far away and therefore presented the same silhouette to all the instruments. A bigger problem for the intercomparison work was obstacles on the platform itself, mainly fixed instrument cabins and the head of the access stair, but also to some extent the various mounting brackets and poles of the instruments. With so many instruments in operation, it was also difficult to control the flow of personnel to and from the roof. For the most part, the platform was kept clear during scans, but there were a few occasions when a shadow was cast on an instrument. Even on a platform measuring 10 m by 11 m there was barely enough room to place all the instruments so that their operators would not get in each other's way. Fortunately, two of the spectroradiometers were fixed in their trailer which was stationed at a convenient spot in the grounds of the institute.

The main operations room for the intercomparison was in the attic immediately below the platform, and offered ample space for the computing and control equipment for all the instruments on the roof. Cable runs were up to 30 m long, but this did not present any insuperable problems.

Instruments

Several of the instruments in this campaign were completely new additions to the group, and most of the others had undergone modifications or improvements since the last intercomparison. The specifications of all the instruments will be found in Appendix D, with additional technical and operational details in Appendix C. We review here some recent innovations and significant features.

The ATI instrument (labelled AI in previous reports) has been fitted with a new optical head and diffuser, but still retains the optical fibre which has proved so beneficial in the past. In place of the earlier linear gantry, the new head contains a rotating mechanism which offers up the diffuser, the direct lens, and the zenith aperture in turn to the fibre.

In order to reduce the width of the near-field shoulders in the slit function, the centre slit of the spectrometer has been made rather narrower. However, the temperature dependence of the absolute calibration appears to have worsened, presumably because the instrument is now more susceptible to slight misalignment of the slits. It may therefore be expedient to revert to the wider centre slit. Additional magnetic shielding has been provided for the photomultiplier. A pyranometer is now directly connected to the control system, recording global solar irradiance at ten-second intervals throughout each spectral scan. Broadband turbidity measurements are made with an actinometer.

The ATW instrument (labelled AW in previous reports) was not present at the third intercomparison.

The BE instrument (previously labelled B) contains two spectroradiometers in a weatherproof housing: one to measure global solar irradiance and the other to record radiation from the zenith sky. A new diffuser has been installed in the global instrument, in order to provide an improved cosine response.

During the campaign, the DEH team visited the intercomparison site and briefly operated a standard Brewer ozone spectrophotometer with a single monochromator.

The DEK instrument gave us our first opportunity to test an Optronic model 752 spectroradiometer. Instead of a diffuser, this instrument has an integrating sphere which is protected from the weather by a quartz dome. As a commercially-available product it has been configured as a turnkey laboratory bench instrument rather than as a spectroradiometric research tool, and will have to be reprogrammed in order to allow the flexibility required for intercomparison work. For example, it was not easy to alter the scanning rate or the wavelength step, and the results of a mercury lamp scan could not be stored for subsequent inspection. Some customised software development will probably overcome these problems. An enclosed housing has been built for the optical head, in order to provide a temperature-stabilised environment, and the photomultiplier is cooled by a small Peltier unit.

Results from the DEM instrument (labelled D in the previous report) were corrected for the cosine error of the diffuser before being submitted. The correction involves assumptions about the partitioning of the global irradiance between direct and diffuse radiation and about the angular distribution of the diffuse radiation which will be discussed later.

The most compact spectroradiometer in this campaign was the FR instrument, based on a Jobin-Yvon spectrometer. This was a new, home-built instrument, which had not previously attended an intercomparison.

The GB instrument is one of an identical pair, the other having been deployed in the second intercomparison. The only recent changes were in the refrigerator system and in the layout of the fibre. Previously, the fibre was loosely coiled on top of the spectrometer, but it has now been straightened out, and is supported inside a vertical metal tube. The refrigerator system is now fully enclosed and stabilised to 16° ± 1° C.

In the first and second intercomparisons, the GR instrument was a Brewer spectroradiometer with the traditional single monochromator. For this third campaign, however, a new GR Brewer was introduced which is fitted with a double monochromator consisting of two of the standard single monochromators in tandem. The output beam from the first is diverted into the second by two 45° plane mirrors, the rotating slit mask being placed between these mirrors rather than after the second monochromator. This instrument should therefore be less susceptible to stray light than the standard instrument. The spectral range has also been extended up to 365 nm.

The instrument operated by the NLK team was based on the same spectrometer as in the second intercomparison (where it was labelled NL), but on this occasion a new diode array had to be installed at short notice before the measurements began, the original having being irreparably damaged when the tripod was accidentally toppled. A fresh calibration was therefore necessary, using the NLK team's lamp in the calibration room.

The instruments which were operated by the NLR team from a trailer in the grounds of the host institute were both new to the intercomparisons. The Dilor spectrometer, NLRD, a double monochromator with a fine spectral resolution, was fixed in the trailer and could not easily be moved. Consequently, it did not take part in the lamp scans in the calibration room. The EG&G diode-array instrument, NLRE, is a single monochromator with a 1024-element detector. Both instruments have integrating spheres as receivers. The normal procedure was to record a spectrum with the NLRE instrument immediately before and after the NLRD spectral scan. A pyranometer was operated in conjunction with the spectroradiometers.

The NO instrument (labelled N in previous reports) is now mounted on a specially-constructed tripod. A new diffuser has been fitted, and the photomultiplier has been replaced.

Observation schedule

Two new features were introduced in the measurement protocol for this intercomparison. On previous occasions, data had been exchanged freely between the participants throughout the campaign, in the hope that anomalies in the instruments would quickly come to light. This proved to be invaluable, as it allowed on-the-spot investigations of instrumental problems. Free exchange of data does, however, detract from the independence of the operators, as it is not clear afterwards whether the performance of an individual instrument could still have been achieved in the absence of the others. To avoid this, the present campaign was designed with a blindness rule: no exchange of data was to be allowed until the end of the scheduled measurements on the roof. In the event, the roof measurements were made before the lamp scans, in order to profit from favourable weather, so the blindness rule was in two parts: no exchange of daylight data was allowed until the roof measurements were finished, and no exchange of lamp data was allowed until the end of the campaign. The blindness rule was policed to the extent that participants were occasionally criticised if their conversation included remarks that might be construed as a breach of the rule. With most of the participants working in the same room while making simultaneous measurements, a more formal blindness protocol would have been difficult to achieve.

The second innovation was the synchronised scan. This arose from previous experience in cloudy weather, with the irradiance changing significantly from minute to minute. Most of the instruments take several minutes to complete a spectral scan but do not normally proceed through the spectrum at the same rate. To ensure exact compatibility of recorded spectra, a synchronised scan was specified to start at 280 nm on the nominal time (usually an exact hour or half-hour UT), and to proceed in steps of 0.5 nm every 3 seconds. The rate was chosen to allow everyone to take part, although some were forced for technical reasons to make steps of 1 nm every 6 seconds in order to keep up. There was no objection to an instrument starting at a different wavelength, for example 290 nm, provided it joined the scheme at the appropriate moment. These synchronised scans did not normally proceed beyond 420 nm, even for those instruments that had sufficient range, as the duration was already 14 minutes at 420 nm. The diode-array instruments (NLK and NLRE) could not conform, as they record the whole spectral range at once: NLK therefore made its measurement after 4 minutes, when the scanning instruments had reached 320 nm, while NLRE recorded a spectrum before and after the synchronised scan. One or two of the scanning spectrometers were not easily reprogrammed, but all except DEK eventually succumbed to their operators' desires.

Although synchronised observations were designed in order to cope with cloud, they were also used for most of the clear sky scans in this campaign. At other times, the traditional freestyle observations were made (synchronised at about 308 nm), in order to allow each instrument to profit from its own capabilities in spectral range, wavelength step, and scanning speed. Some instruments adjust their integration time at each wavelength in order to achieve an adequate signal without wasting time, an advantage which is lost in the synchronised scans. Nevertheless, in retrospect, it would probably have been better to make all the intercomparison observations in synchronised mode, as there is less room for uncertainty in interpreting them afterwards. In particular, the changing elevation of the Sun does not introduce any error in synchronised comparisons.

Having arrived on 19 July 1993 in continuous rain, the teams set up their instruments on 20 July, and carried out a laboratory comparison of the ammeters used for measuring lamp currents. The following day was used for individual instrument calibrations and operational tests. Preliminary outdoor measurements began in poor weather on 22 July. Two full days of daylight scans were successfully obtained during a spell of dry weather on 23 and 24 July, but rain on 25 July brought the outdoor campaign to an end. By this time, some instruments had already begun the indoor programme of measurements, using the TLS and the facilities in the lamp calibration room. These measurements continued throughout the following three days, and were finally completed early on 29 July. The instruments were packed and crated on 30 July, and most of the teams departed on 31 July 1993.

Throughout this report, observation times will be given in UT. It may help the reader to know that the Sun reached its maximum altitude at about 1120 UT each day.

Calibration room

Each spectroradiometer derives its absolute spectral irradiance scale from a calibrated irradiance standard, usually a 1000 W FEL or DXW tungsten-halogen lamp whose certificate depends, directly or indirectly, on one of the major national standards laboratories. The calibration is then maintained and renewed by periodic checks on subsidiary transfer lamps. These calibrations are invariably performed with the beam normal to the spectroradiometer's receiving surface, which may be a diffuser or the entrance aperture of an integrating sphere. In order to evaluate the irradiance calibrations, therefore, we exposed each instrument in turn to the beam from a single standard lamp, with the receiver normal to the beam and at the distance specified for the lamp. The instrument then performed its own independent measurement of the spectral irradiance of the lamp, and the result was subsequently compared with the lamp certificate. For this purpose, the host institute provided a fully-equipped calibration room and a certificated 1000 W lamp.

The facilities in the calibration room surpassed those of the two previous campaigns, both in the elimination of stray light and in the monitoring of the lamp current. Two adjacent dark rooms were provided: one for the 1000 W lamp and the other for the instrument, with a small aperture in the connecting wall for the light beam to pass through. Both rooms were lined with black cloth to absorb unwanted stray light. An adjustable gantry in the lamp room carried three lamp holders, each of which could be aligned in turn with the aperture in the wall. A helium-neon laser was used to obtain a repeatable alignment of the instrument diffuser in the beam of the standard lamp. In all cases the lamp was mounted with the filament axis vertical and the calibrated beam horizontal: consequently some spectroradiometers had to be turned on one side to allow the diffuser to view the beam. Only those instruments with either an integrating sphere or a fibre-optic input could be operated in an upright position while measuring the horizontal beam from the lamp.

The constant-current power supply was computer-controlled, its output current being monitored to an accuracy of 0.01% by measuring the voltage across a standard 0.1 ohm precision resistor in series with the lamp. The voltage across the lamp itself was also monitored by means of a separate pair of wires connected directly to the lamp holder. Three displays were shown simultaneously on the computer screen, two monitoring the lamp current and voltage since the start of the experiment, while the other showed the voltage at the power supply. This proved to be a most informative display, as it revealed small changes in the lamp voltage at constant current. While the lamp current was maintained within about 0.002% of its nominal value of 8.000 A, the voltage across the lamp could show many fluctuations of the order of 0.02% during a typical experiment lasting an hour or so. Some lamps were more prone to these fluctuations than others, so that it was possible to choose a lamp which had a more stable behaviour, in the hope of obtaining more consistent results. Nevertheless, on a few occasions during the campaign, larger steps in voltage were observed, for no apparent reason, even on a lamp which was otherwise well-behaved. These larger steps were usually (but not always) negative and up to 0.2% in size, i.e. a voltage drop of about 200 mV. A digital luxmeter, operating independently of the irradiance equipment, always recorded a corresponding drop in the output of the lamp when a large voltage drop was observed, and the difference in the spectral output of the lamp will be seen below in the discussion of the ATI lamp scans.

These variations in lamp output are generally smaller than the other uncertainties encountered in the overall calibration of a spectroradiometer, but they provide a useful guide to the condition of a lamp and the performance that can be expected from it.

Accurate measurement of the lamp current is critical in this type of work. Errors in excess of 0.02% are to be avoided if possible, as the output of a tungsten lamp at 300 nm is very sensitive to small changes in current. A comparison of the various meters which the participants had brought to the field site showed that the only satisfactory method was to measure the voltage across a precision resistor in series with the lamp. A suitable resistor will be certified to an accuracy of better than 0.01%. When compared with the precision resistor method, the other meters, mostly hand-held portable multimeters, had errors ranging from 0.1% to 0.6%. The BE and DEG precision resistor systems agreed with each other to 0.01%.

The principal irradiance standard throughout this campaign was lamp BN-9101-133, a 1000 W FEL lamp with a calibration certificate from PTB (Physikalisch-Technische Bundesanstalt, Germany). It will be referred to in this report simply as lamp BN-133. This type of lamp is operated at a distance of 700 mm from the diffuser of the instrument under test, measured to a specified fiducial surface on the lamp mount. The distance to the lamp filament is therefore slightly greater, about 720 mm. Lamp F-302, supplied by Optronic Laboratories with a calibration traceable to NIST (National Institute of Standards and Technology) and operated at a distance of 500 mm, was used as an independent verification of the output from lamp BN-133. The standard current for these lamps is 8.0 A.

Lamp scans

The purpose of the lamp scans in the calibration room is to discover whether the absolute calibrations of the various instruments are in agreement with each other. These are the calibrations which were in operational use when the instruments were deployed on the roof. In some cases they are exactly the same calibrations which were in use at the home stations before the instruments travelled to the intercomparison. In other cases they were determined or verified on arrival at the intercomparison site by means of transfer lamp standards which embodied the home calibration: this is generally preferable, as most instruments are liable to change their calibration during transport. We shall describe the results from each instrument in turn.

ATI

Two successive spectral scans of lamp BN-133 by the ATI instrument gave virtually identical results. The first scan of the pair is shown in Figure 1 together with the irradiance values given in the lamp certificate. The ratio of ATI to BN-133 is shown in Figure 2 for both scans. It can be seen that the ATI/BN-133 ratio lay between 1.00 and 1.02 in the UVA and visible regions of the spectrum, and between 1.02 and 1.05 in the UVB. After the first pair of scans, the lamp voltage fell suddenly by 200 mV. The resulting fall of about 0.8% in the irradiance recorded by the ATI instrument (Figure 3) can be seen by comparing the ratios from the second pair of scans (Figure 4) with those from the first pair. This drop in output clearly demonstrates the advantage of monitoring the voltage across the lamp, and the necessity of maintaining a family of lamps in each laboratory. One might ask why the lamp voltage is not given with the certificate.

Despite the change in the lamp voltage, the four successive scans showed a consistent pattern. Even the fine detail, for example the feature at 386 nm, is repeatable. The features seen in this pattern are not found with the other instruments, and must therefore lie in the ATI instrument itself. In fact, each instrument exhibits a pattern of its own, which represents the discrepancies which have arisen between the original scan of the home calibration lamp and the present measurement of lamp BN-133. In a few cases these features arise from anomalies in the output of the calibration lamps, or in the calibration procedures, but mostly they are attributable to variations in the sensitivity of the photomultiplier, or in the mechanism that links the movement of the gratings, or in the linearity of the amplifier.

The overall level of agreement between the ATI calibration and the BN-133 certificate is very satisfactory, as the typical difference of 1% in the UVA and visible regions is comparable with the inherent uncertainties in the lamp itself. The larger discrepancy in the UVB results may be partly attributable to the ATI ammeter which had been used in the home calibration. As the ammeter was reading high, the home calibration lamp would have been dimmer than normal, forcing the instrument to report too high an irradiance.

In order to verify the reliability of the spectral output of lamp BN-133 in the calibration room, we also performed three scans of lamp F-302 by the ATI instrument. A typical scan is shown in Figure 5, with the corresponding ATI/F-302 ratio in Figure 6. It can be seen that the results from lamp F-302 lay within 2% or 3% of those from lamp BN-133 throughout the wavelength range measured. The three scans of lamp F-302 were virtually identical to each other, and it is noticeable that they displayed the same spectral structure as in the BN-133 scans, showing that these features do not arise in the lamps.

BE

A series of five scans of lamp BN-133 by the BE instrument gave consistent results. Typical examples are shown in Figure 7. The BE/BN-133 ratios were flat in the visible region but rather erratic in the ultraviolet (Figure 8), particularly at the shortest wavelengths.

DEH

The DEH instrument did not take part in the lamp scans.

DEK

The DEK/BN-133 ratio was close to unity at 600 nm, falling off to below 0.9 in the UVB region (Figures 9 and 10). Three consecutive scans gave consistent results.

DEM

The irradiance standard throughout these measurements, lamp BN-133, is one of a set of PTB-certificated lamps operated by the DEG team, but it nevertheless provides an independent check on the DEM instrument, which depends for its usual calibration on a 100 W lamp with a certificate from NPL. Figures 11 and 12 show that the agreement between DEM and lamp BN-133 was better than about 2% at wavelengths above 310 nm, while the instrument was higher than the lamp by between 1% and 5% at the shortest wavelengths.

FR

The FR scans were repeatable to within a few per cent, displaying a systematic wavelength-dependent ratio with the BN-133 certificate, lying between 1.5 and 2.5 throughout the spectral range of the instrument (Figures 13 and 14). This instrument had not previously taken part in an intercomparison, and was clearly operating with only a provisional calibration. The repeatability of the scans suggests that good results should be obtained once a definitive absolute irradiance calibration is available.

GB

Three successive scans of lamp BN-133 by the GB instrument agreed well with each other. The first scan is shown in Figure 15. Between 310 and 370 nm the GB/BN-133 ratio is about 0.96, rising to near unity at wavelengths shorter than 300 nm (Figure 16). In the visible region the ratio falls to about 0.9. The home calibration of the GB transfer lamp was performed in two parts, with a discontinuity in the overlap region between 380 and 400 nm. The wavelength dependence of the GB/BN-133 ratio is not found in the other instruments, and is therefore a characteristic of the GB calibration. As with the ATI instrument, some of the fine detail in the ratios is also repeatable.

GR

As the GR instrument is not designed to operate while lying on its side, it proved impossible to obtain reliable lamp scans in the calibration room using the horizontal beam from lamp BN-133.

NLK

In the data as originally submitted, the NLK lamp scan fell short of the certificated irradiance by an amount which was largely independent of wavelength, suggesting an over-correction for stray light. It turned out that the procedure used in the daylight scans, in which the signal from the first 20 diodes is assumed to be due to stray light, had been applied to the lamp scans. However, the ultraviolet output from the lamp at 290 nm is by no means negligible, and cannot be attributed to stray light. The corrected data are shown in Figure 17. Above 300 nm, the corrected NLK/BN-133 ratio is up to 10% high (Figure 18).

NLRD

No NLRD scans of lamp BN-133 were possible, as the Dilor instrument was fixed in the NLR trailer and could not, therefore, be transported into the calibration room.

NLRE

The ratio of NLRE to BN-133 was 0.97 with a slight wavelength-dependent variation of about 1% or 2%. The lowest ratios, around 0.95, were recorded at the shortest wavelengths (Figures 19 and 20), but were obscured by noise, owing to the difficulty of recording an adequate signal simultaneously across the whole wavelength range.

NO

Scans of lamp BN-133 performed by the NO instrument yielded a ratio of 1.05 for NO/BN-133 (Figures 21 and 22), and remained within about 2% of that value throughout the wavelength range of the instrument, which extends up to 600 nm.

Transportable Lamp System

In order to provide a means of monitoring the stability of spectral irradiance calibrations at the home sites during the period between successive intercomparison campaigns, the Transportable Lamp System (TLS) was conceived, designed, and built by the BE team. The TLS is a portable unit with five 200 W lamps in a rotating carousel. Each lamp can be selected in turn to give a steady and repeatable beam of light at the exit port in the base of the unit. The diameter of the exit port can be varied from 5 mm to 25 mm to suit the requirements of individual spectroradiometers. During the third intercomparison, ten of the available instruments tested the TLS by measuring its spectral output.

Successive scans gave results in good agreement with each other, provided that the spectroradiometer and the TLS were not moved. However, some variations were seen in scans made on separate days on the same instrument. The largest differences were encountered when comparing measurements made indoors and outdoors. These may be partly due to the effects of varying ventilation on the output of the lamps. The different instruments showed some consistency in the measured ratios for the various TLS lamps, but there remain some unexplained anomalies.

A full account of the TLS, including its technical description and all the results obtained to date, will be found in a report prepared by Didier Gillotay of the BE team, entitled *The Transportable Lamp System, a Relative Reference for the Future.* The implications of these results will be explored further in the Discussion section below.

Slit function measurements

Ideally, a scanning spectroradiometer should measure only one monochromatic wavelength at a time. In practice, even the best spectrometers allow a narrow band of wavelengths to reach the detector. The width of this band is typically of the order of a nanometre, but the wavelengths at the edge of the band are much less likely to reach the detector than those at the centre. Each spectrometer has a characteristic function which represents the probability that photons of a particular wavelength will get through the exit slit, relative to those of a nominal wavelength. The wings of this slit function represent extraneous wavelengths which the spectrometer has failed to exclude. During a scan, the nominal wavelength advances step by step through the spectrum, taking the slit function with it. A small part of the function, representing background stray light unconnected with the movement of the gratings, is found at virtually all wavelengths and will not move with the scan. In some circumstances this background can be important, for example when stray visible light obscures the weak signal at the very shortest ultraviolet settings, but for the moment we shall confine our attention to the part of the function which moves with the nominal wavelength.

In most spectrometers, the slit function does not change much for a moderate change in nominal wavelength. Consequently, it is possible to determine the shape of the function by sampling it at one actual wavelength as the nominal wavelength steps past it. To achieve this, we illuminate the diffuser of the spectrometer with a narrow spectral line from a discharge lamp or laser. When the nominal wavelength is, say, 3 nm *higher* than the laser line, we assume that the result applies to any radiation whose actual wavelength is 3 nm *lower* than the nominal wavelength. Note that if the slit function is now graphed with incident wavelength as the abscissa, relative to the nominal wavelength labelled zero (Figures 23 to 31), the graph will be a mirror image of the experimental scan in which nominal wavelength was the abscissa and the incident wavelength was constant. Before this can be accepted as a determination of the slit function, however, it must be truncated to remove any other spectral lines and background noise from the lamp or laser.

Several of the instruments performed scans on a mercury discharge lamp, with the results shown in Figures 23 to 31. Also included are some scans performed at the home institutes on HeCd (325 nm) and HeNe (633 nm) lasers. The strength of the 254 nm mercury line makes it very useful, whereas multiple spectral lines such as the mercury complex at 313 nm are confusing. Determination of the far wings of the slit function requires a particularly pure radiation source, for which a HeCd laser is more suitable than a mercury lamp.

The scans shown in Figures 23 to 31 were typically performed at intervals of 0.1 nm or less, and have been arbitrarily normalised to unity at the nominal wavelength. It can be seen that the shape of a slit function does not generally change much with wavelength, although the width may vary. The ATI and DEM slit functions can be obtained to better than three orders of magnitude below the maximum by truncating the 254 nm scans at +3.0 nm and −3.0 nm, whereas the other mercury lines offered only two orders of magnitude. The asymmetric shape of the wider GB slit function is consistently found at three widely separated wavelengths. Unlike the other instruments, the NLK diode-array appears to have quite different slit functions at 297 and 404 nm. The advantage of the HeCd laser can be seen in the NLRD slit function which has been determined to better than four orders of magnitude at 325 nm.

When performing irradiance calibration measurements in the lamp room, the slit function plays only a secondary role, as the output of the lamp varies smoothly and gently with wavelength. On the roof, however, the slit function controls the amplitude of the fluctuations in the measured irradiance as the instrument scans the maxima and minima of the Fraunhofer structure in the solar spectrum. Consequently, the ratio of simultaneous spectra from two instruments exhibits a structure which embodies both slit functions. To reconcile results from different instruments, therefore, their slit functions must be known.

Cosine measurements

Many of the participants had laboratory facilities at their home institutes to enable them to measure the cosine response of their instruments. For the benefit of those who did not, a turntable was made available in the lamp room. By placing the instrument on its side and adjusting its position to make the centre of the receiving surface coineide with the rotational axis of the turntable, the operator could turn the instrument so as to view the lamp horizontally at any desired angle of incidence, while keeping the distance constant. Most teams determined their cosine responses at home, using a variety of similar procedures. For an instrument such as GR, which cannot be operated while it is lying on its side, the lamp must be moved while the instrument remains stationary. Whatever the method, there are several possible sources of error, mostly arising from uncertainty in the relative alignment and orientation of the instrument and the lamp.

Cosine responses for the ATI, BE, DEH, DEM, FR, GR, NLK, and NLRD instruments are shown in Figures 32 to 39. These are all up-to-date measurements on the instruments as they were deployed in the third campaign. The GB response was measured on the other instrument of the GB pair and was shown in the report of the second intercomparison. Cosine responses are not yet available for the DEK, NLRE, and NO instruments.

These experiments are very time consuming, so it is rare to have much accumulated evidence of repeatability over a long period. Where spectral scans have been made, the wavelength dependence has generally turned out to be comparatively small. However, the azimuthal variations can be significant, and are seldom determined. It is desirable to explore the angular response over the whole of the hemisphere viewed by the receiving surface, but most measurements consist only of a cosine determination in one azimuthal plane. The relationship between the orientation of the instrument in the laboratory and its alignment on the roof is also important but has generally received insufficient attention. Each instrument should have a fiducial reflecting plate which can be aligned with a laser in the laboratory and with a spirit level on the roof, or some equivalent arrangement, in order to define the nominal axis of the receiving surface. Inscribed lines on the plate can then be used as co-ordinate axes to define the centre of the receiver and the nominal zero azimuth.

Daylight scans

The most critical test of the spectroradiometers was in the measurement of global solar irradiance on the roof. Simultaneous spectral scans were carried out by all available instruments during a short period of favourable weather. On the first dry day of observations (23 July 1993) cloud persisted throughout the hours of daylight. We were then very fortunate to have one complete day of virtually clear blue skies (24 July 1993) which provided an ideal opportunity to compare the instruments over a wide range of solar zenith angle. All the instruments were fully operational at 0400 UT, and followed a schedule of half-hourly observations until 1730 UT.

In the assessment which follows, it should be remembered that all the instruments were obliged to operate independently, using their own calibrations. No results were exchanged between the teams until after all the daylight data had been submitted.

In describing and evaluating the measurement ratios and discrepancies between the instruments, we have ignored the characteristic spectral fluctuations which are due to the interaction of the solar Fraunhofer structure with the slit functions. These fluctuations are largely independent of the solar zenith angle and will be discussed separately below.

When examining simultaneous measurements from such a wide range of disparate instruments, it is inevitable that considerable variation will be found in the results. Figure 41 shows the spread of measurements recorded by ten spectroradiometers with the Sun high in the sky. A comparison of the results at different solar zenith angles can be seen on a logarithmic scale in Figure 42. At first sight, these measurements may seem somewhat chaotic. Fortunately, however, several instruments were in much closer agreement than the rest. To demonstrate this, we form the mean of the ten spectra in Figure 41 (denoted by MX) and relate each individual result to this mean. These ratios are shown in Figures 43 and 44 for the clear-sky case of 24 July 1993. (We also show the result for the DEH instrument, which was excluded from the mean on account of its limited wavelength range.) The corresponding ratios for the cloudy case (23 July 1993) are shown in Figures 45 and 46. In each case, MX denotes the mean of the ten spectra recorded on the occasion in question.

There is a broad similarity between the results on the two days, although the relative positions of some instruments changed from one day to the next. It can be seen that the relationships between the instruments in Figures 43 and 45 are largely independent of wavelength. Some of these instruments also maintained close agreement over a wide range of solar zenith angle. In particular, ATI, GB, and GR lay within about 7% of each other throughout both days, and about 4% from 0730 to 1530 UT. This level of agreement may hide a degree of similarity in the cosine responses of these three instruments. However, there will be a tacit presumption that any departure of 10% or more from these instruments constitutes an error, unless it is attributable to cosine response. By the same token, it will be assumed that a large diurnal discrepancy which is not symmetrical about local apparent noon cannot be caused by the angular response of the ATI, GB, and GR instruments, especially as two of these instruments rotated in azimuth with the Sun. This point will be discussed further in the section on diurnal variation.

Reference

In order to examine the daylight scans of the individual instruments in detail, some means must be found of comparing one instrument with another, as there is no absolute standard against which to make a comparison. The most convenient way to make comparisons among a large number of instruments is to establish some kind of common reference, with which each of the instruments can be compared. The common reference can be a single instrument or a combination of instruments.

In the reports of the previous two campaigns, we compared each instrument in turn with the ATI spectroradiometer, choosing it largely on the basis of its operating characteristics and its general performance and availability. As these considerations are no less favourable on this occasion, we have again adopted the ATI instrument as a convenient working reference. It is at once an honour and an embarrassment for the ATI team to have their instrument singled out in this way. On the one hand it seems to suggest that they have somehow been judged the best, but on the other hand it exposes any little flaw in their instrument to the unremitting scrutiny of all the others. Indeed, the ATI team have themselves expressed misgivings about being put under the spotlight in this way, and it may seem invidious to choose them again. We therefore owe them some explanation, in the course of which we shall attempt to specify the factors which must be taken into consideration when choosing a reference.

It might be thought that the best solution would be simply to take the average of all the instruments, but it turns out not to be so. There are comparatively few occasions on which *all* the instruments were available. If an instrument misses an observation, that observation time is bound to be absent from the chronological sequence for the mean of any group which includes that instrument. In any ratio to that mean, the corresponding observations from the other instruments are therefore suppressed and lost to view, whether they are in the group or not.

If the results from the various instruments were more or less normally distributed, and it were merely a matter of spotting one or two rogues among an otherwise normally-distributed population of instruments, then there might be some merit in taking the mean of all the instruments present at each observing time, even if it were not always the same group. But this is most certainly not the case. The distribution is very far from being normal, so that the absence of a single instrument can significantly alter the mean, thereby making it useless as a uniform reference. If the reference is to be used for the purpose of detecting and interpreting systematic anomalies in the individual instruments, it must not itself be unduly anomalous in its inherent characteristics. It is therefore an advantage to use the same group of instruments throughout, choosing those which are most often available and have few if any anomalous features in their recorded spectra.

In order to retain as much as possible of the information in the original measurements, it is advisable to include in the reference only those instruments which made measurements at the most widely-used set of wavelengths. In the present campaign, most of the instruments measured at intervals of 0.5 nm from 290 nm or less to 400 nm or more. To include in the mean those instruments which only made measurements at steps of 1.0 nm would be to throw away half the data of the other instruments, not only those in the mean but all the rest as well, as an instrument can only be compared with a reference at the wavelengths which are present in the reference. For the same reason, an instrument with a restricted wavelength range should not be included in the reference.

In practice, these strictures have a somewhat bistable effect on the formulation of the reference. If a large number of instruments are suitable for inclusion, then the disturbing influence of each is relatively small, and can be tolerated. But if few instruments are suitable, then any anomalous behaviour or systematic error in any one of them, such as a marked azimuthal response or calibration drift, has a significant effect whenever the reference is used, and has to be taken into account when interpreting the comparison of any instrument with the reference. In this case, the natural solution is to use as few instruments as possible in the reference, so that the comparison is as simple and clear as possible. If one instrument can be found that meets the requirements of availability and wavelength discrimination, with little or no anomalous behaviour, then it is likely to make a good reference for the campaign. The introduction of a second or third instrument into the reference merely reduces the number of occasions on which it can be used and the wavelengths at which it applies, and introduces more anomalous features to complicate the interpretation of any comparison with the other instruments.

Of the twelve instruments which took part in the present intercomparison, several were unsuitable either because they missed too many observations or because they exhibited gross systematic errors or anomalous behaviour. Of the rest, some were excluded on account of their limited spectral coverage or susceptibility to stray light at short wavelengths, or because they were not able to make fully synchronised observations. Only two instruments remained, one of which, GB, was then eliminated on the basis of its rather broad slit function. The last, ATI, was therefore chosen as the working reference, not because it was a far superior instrument but because it fulfilled the requirements for a reference by virtue of its availability, wavelength resolution and range, stray light rejection, and generally satisfactory performance both in the lamp room and on the roof. Additional advantages of the ATI instrument were its rotating optical head and fibre-optic input, which should help to reduce azimuthal effects, especially in clear skies.

In other parts of this report we have made use of reference means consisting of 3, 4, 6, and 10 instruments where appropriate, but for the present purpose we have used a single instrument for the sake of clarity and convenience. It does not follow that a single instrument, let alone the same instrument, will necessarily make the best reference in any future intercomparison campaigns: it all depends on the availability, characteristics, and performance of the participating spectroradiometers.

In the present intercomparison, it is important to remember that when comparing an instrument with the ATI reference by examining the ratio of their recorded spectra, the characteristics of both instruments will be present in the ratio. Any systematic error or anomalous behaviour in the ATI instrument must therefore be taken into account when interpreting the ratios.

For the benefit of those who find the use of a single-instrument reference somewhat arbitrary, we reiterate here the caveat which circumscribes our use of this method of analysis:

The ATI instrument is an arbitrary reference, selected for convenience. There is no implication that it is to be regarded as a standard: in the absence of ATI, another instrument would have served as a convenient reference instead. The ATI instrument was chosen to serve as a reference on this occasion simply because it was present at all the relevant observation times, recorded spectra at steps of 0.5 nm over the full wavelength range with good stray light rejection, and gave satisfactory and consistent results both in the lamp room and on the roof.

We now examine the results of each instrument in turn, looking first at the spectra recorded on 24 July 1993, the day of clear blue skies.

ATI

In the comparisons which follow, it will be seen that the ATI spectroradiometer performed very favourably with respect to the other instruments. Two possible weaknesses may, however, be noted at this stage. Firstly, the cosine response of the ATI diffuser and fore-optics, like those of many other instruments, is far from ideal. Secondly, in comparison with the GB and GR instruments, ATI showed a variation of about 4% during the morning (0400 to 1130 UT). The ATI optical head is rotated in azimuth to follow that of the Sun, as is the GR instrument itself. The small errors in levelling of these instruments are not sufficient to account for the 4% morning variation, and any stray reflections of sunlight from metalwork on the roof should have affected ATI and GR to much the same extent, as they were close together on the platform, whereas the GB instrument was further away. It seems likely, therefore, that the ATI instrument sensitivity drifted during the course of the morning by about 4%, possibly as a result of the temperature sensitivity which was introduced when the centre slit was made narrower.

BE

The BE scans which were originally labelled 0615 UT to 0930 UT on 24 July 1993 have been re-labelled 0600 UT to 0915 UT following a 15-minute timing error which was reported by the BE team after their daylight measurements had been submitted. The corrected times have been used throughout this report.

The BE instrument was in excellent agreement with ATI, GB, and GR near local noon (Figure 47) throughout its spectral range, but the ATI/BE ratio showed a strong diurnal variation, from 1.13 at 0700 UT to 0.90 at 1600 UT at 355 nm (Figure 48). In the visible region, the diurnal effect was weaker, with ATI/BE ratios of 1.12 and 0.94 at 415 nm. If these diurnal variations are too large to be accounted for by errors in levelling, they must be attributed either to temporal drift in sensitivity or to an azimuthal effect in the fore-optics of the spectrometer. The measured cosine response of the BE instrument was particularly promising (Figure 33), but it was only measured in one plane. The position of the BE instrument on the observation platform gave it an unobstructed view in the direction of the Sun at all times of the day.

DEH

The DEH instrument successfully records the spectrum between 290 nm and 320 nm when the Sun is high in the sky (Figure 49). At wavelengths longer than 300 nm, the ATI/DEH ratios increase slightly with wavelength, especially at high solar zenith angles (Figure 50). Between 305 nm and 315 nm, the ratios fall from about 1.15 to 1.05 during the course of the day. However, at wavelengths shorter than 300 nm, the ATI/DEH ratios are anomalously low when the Sun is low in the sky, which suggests that part of the signal in the DEH instrument is attributable to stray light from longer wavelengths. The spectral structure of the DEH measurements shows that the DEH slit function must be rather similar to that of the GR instrument.

DEK

Until 0700 UT on 24 July 1993, the ATI/DEK ratios are in the range 1.2 to 1.3 at 400 nm, and fall off towards shorter wavelengths (Figure 52, 0700 UT). From 0730 UT onwards, the ratios are much less dependent on wavelength in the UVA, falling off in the UVB, and to a lesser extent in the visible (Figure 52, 1130 UT). The lower ATI/DEK ratios in the UVB may be partly due to an error in the DEK wavelength calibration which can be seen in Figure 51. The ATI/DEK ratio in the UVA was steady at around 1.01 from 0800 UT to 1000 UT, but subsequently fluctuated between 1.10 and 0.93 (Figure 52, 1330 UT), possibly owing to an azimuth effect in the integrating sphere.

DEM

The ATI/DEM ratio is typically 0.92 (Figure 53) at wavelengths above 325 nm, but rather less at shorter wavelengths. Throughout the day, the ATI/DEM ratio at 312 nm is about 5% lower than at 333 nm (Figure 54). It will be shown later that these low ratios can be explained by a 0.3 nm difference in the wavelength calibrations of the ATI and DEM instruments. A progressive diurnal variation can also be seen in Figure 54. For example, the ATI/DEM ratio at 350 nm falls steadily from 0.97 at 0530 UT to 0.83 at 1700 UT. These discrepancies must be partly due to the fact that the DEM results have already been corrected for the cosine response of the DEM diffuser, whereas the ATI spectra are shown exactly as recorded. However, the diurnal variation cannot be explained in this way. Some 4% might be attributed to the implied morning variation of the ATI instrument described earlier, but there remains another 10% to be accounted for. Unless the sensitivity of the instrument drifts with time, a diurnal variation of this sort must arise either from an azimuthal effect in the spectrometer and its diffuser, from inadequate levelling of the diffuser relative to the local vertical, or from a difference in the radiation field viewed by the two instruments from their respective positions on the platform. This question will be discussed in more detail below. We note here that diffuser alignment alone is insufficient to account for the observed diurnal variations, as it would give rise to a more marked dependence on wavelength.

The cause of the general 8% difference between the results of the ATI and DEM instruments, even with the Sun high in the sky, at wavelengths longer than 330 nm, is not fully understood. It did not appear in the lamp room, but did turn up in subsequent scans of a 100 W lamp by the ATI and DEM instruments. The ATI cosine correction, which is not included in the ratio, may be sufficient to account for part of it, but any error attributable to the ATI ammeter calibration would tend to widen the gap rather than narrow it. It is therefore possible that the good agreement achieved by the ATI and DEM instruments in the lamp room at wavelengths longer than 330 nm was not a reliable guide to the ratio of their irradiance calibrations on the roof. The residual discrepancy is about 4% to 8%.

FR

The FR instrument followed the spectral structure of the solar irradiance faithfully (Figure 55), but recorded too high a value at all wavelengths. The ATI/FR ratio was generally in the range 0.6 to 0.7 (Figure 56) during most of the day. Some of this discrepancy is accounted for by the anomalous absolute calibration of the FR instrument as seen in the lamp room (Figure 13). A residual reading at wavelengths between 280 nm and 300 nm suggests that stray light, dark current, or some other constant offset was not fully removed. A wavelength shift of up to 3 nm was present in the first few observations in the early morning.

GB

In the spectral region from 315 to 355 nm, the ATI and GB instruments are in good agreement (Figure 57), the ATI/GB ratio declining from 1.06 to 1.02 in the course of the morning and remaining at 1.02 for the rest of the day (Figure 58). Between 355 and 385 nm, the ATI/GB ratio is generally about 1% higher. The oscillations in the ratio follow from the wider bandwidth of the GB spectrometer, as can be seen in the spectral structure of the scans in Figure 57. At wavelengths shorter than 315 nm, the ATI/GB ratio becomes progressively smaller, again as a consequence of the GB bandwidth.

GR

At wavelengths shorter than 325 nm, the ATI/GR ratio was steady at about 1.04 from 0700 to 1500 UT (Figures 59 and 60). At longer wavelengths, it was about 2% less. In the first hours of daylight ATI/GR was 1.06 throughout the spectral range of the GR instrument, whereas in the evening it fell to unity at 1800 UT. Above 325 nm, therefore, the ATI, GB, and GR instruments lay within 2% of each other throughout the afternoon and evening.

It is remarkable that the GB and GR spectroradiometers, having travelled to a blind trial from opposite sides of Europe, were generally within 2% or 3% of each other in the UVA throughout the day, despite their very different designs and the great disparity in their bandwidths. This was one of the most encouraging results of the campaign and a considerable improvement on the earlier intercomparisons.

NLK

The ATI/NLK ratios fall into three distinct wavelength regions. The band from 323 to 343 nm is generally much more consistent than the rest of the spectrum, with ATI/NLK ratios around unity in the middle of the day, and higher values in the morning (1.06 at 0700 UT). The afternoon ratio is rather lower (0.95 at 1600 UT). A more significant diurnal asymmetry is found at all other wavelengths (Figure 62). At 313 nm, the ATI/NLK ratio falls from 1.32 at 0700 UT to 1.15 at 1600 UT, whereas at 367 nm it falls from 0.97 to 0.80 in the same period. At these wavelengths, the ATI and NLK slit functions produce stationary points in the ATI/NLK ratio, from which the diurnal variation can be easily determined. The instantaneous NLK measurement was made when the scanning instruments had reached 320 nm in their synchronised scans, leaving a time difference of one minute for every 10 nm before and after 320 nm. However, the diurnal variation in the ATI/NLK ratio at the longer wavelengths is only partially explained by this time difference, while the variation at 313 nm is scarcely affected. In a single monochromator, the shortest wavelengths are usually the most difficult to measure, on account of stray light. In the NLK instrument, the longest wavelengths are also difficult, as they are weakened by the filter which serves to absorb most of the visible component of the incident radiation. Nevertheless, between 0900 UT and 1330 UT, the ATI and NLK instruments are in very good agreement at medium and high wavelengths in the NLK spectral range (Figure 61).

NLRD

The ATI/NLRD ratios are fairly flat when the Sun is low in the sky, around 1.2 in the UVA at 0430 UT, and 1.05 at 1800 UT. However, in the middle of the day, according to the original data submitted during the intercomparison, there is a considerable wavelength dependence of the ATI/NLRD ratios, with a minimum of 1.0 near 345 nm and values approaching 1.5 at both ends of the wavelength range (Figure 64). At the shorter wavelengths, the cause of this variation is not known. However, the high ATI/NLRD ratios at the longest wavelengths have been traced to the dead time of the counting system, for which an additional correction has now been calculated by the NLR team. The revised data are shown in Figures 65 and 66, where a considerable improvement can be seen in the ATI/NLRD ratios. The dead-time correction has not, however, removed the diurnal variation in the ATI/NLRD ratios. The corrected data will be used throughout the remainder of this report.

NLRE

As the NLRE (diode-array) instrument recorded a complete spectrum before and after each synchronised scan, the ATI/NLRE ratio for a particular wavelength has to be estimated by interpolating between the two spectra according to the time at which the scanning instruments reached the wavelength in question. At 1130 UT, however, the elevation of the Sun did not change significantly during the scan and it is sufficient to look at the first NLRE spectrum. It can be seen that the NLRE instrument faithfully reproduces the spectral structure of the ultraviolet irradiance (Figure 67), but the absolute calibration varies with wavelength. The ATI/NLRE ratio is invariably highest in the UVB near 310 nm, where the NLRE instrument usually records less than half of the available radiation (Figure 68). This may be due to an error in the subtraction of the dark current when measuring stray light with the yellow filter, as described in Appendix C. Taking into account the timing of the spectra, the form of the ATI/NLRE ratio remains fairly constant throughout the day.

NO

Finally, we come to the NO instrument, whose behaviour is perhaps the most tantalising of all. This instrument has been present at each of the three intercomparisons, and has performed better on each successive occasion. It now faithfully records the structure of the incident spectrum from below 300 nm in the ultraviolet to 600 nm in the visible, with a finer spectral resolution than most of the other instruments (Figure 69). The ATI/NO ratio is spectrally flat throughout the ultraviolet spectrum (Figure 70), and the diurnal variation is small. In fact the ATI/NO ratio in the UVA lies within 5% of its mean value from 0630 UT to 1530 UT. Unfortunately, this mean ratio is 1.245. In other words, the NO instrument appears to record only 80% of the irradiance when on the roof. By contrast, in the calibration room it records 5% more than is shown on the lamp certificate, with a spectral variation of only about 3%. The cause of the difference in calibration between lamp and sky has not been easy to discover. In a double monochromator it might have been attributed to a misalignment of the gratings, but the NO instrument has only one grating. The spectral and temporal stability of the ATI/NO ratio indicates that only one relatively simple factor is to blame. Recent investigations suggest that it could be the result of turning the instrument on its side to make the lamp measurement, although the spectrometer is ruggedly built and does not appear to move internally when tilted. If this question could be resolved, the NO instrument would be one of the better instruments in the group, as its spectral range and slit function are both excellent. At the shortest wavelengths, where single monochromators do not generally perform well, the NO instrument is free of significant stray light down to 303 nm with the Sun high in the sky (Figures 70 and 125).

Cloudy day

The results obtained in the cloudy conditions of 23 July 1993 agreed broadly with those described above for the clear-sky case, although there were some fluctuations in the ratios due to the presence of broken cloud, especially between 1000 and 1130 UT. Apart from these fluctuations, the ATI, GB, and GR instruments were within about 4% of each other throughout the day in the wavelength range from 315 to 355 nm. The ATI/DEM ratios were more consistent on the cloudy day, lying between 0.86 and 0.91 for most of the day. The absence of a diurnal trend in these ratios is encouraging, as it shows that the irradiance calibrations of the ATI and DEM instruments could maintain a stable relationship in the absence of bright sunshine.

The NLRD instrument displayed the same behaviour on both days, giving similar results to ATI at UVA wavelengths, but progressively higher values of the ATI/NLRD ratio with decreasing wavelength in the UVB region. The ATI/NLRD ratios in the UVA were mostly in the range 0.92 to 1.00 on the cloudy day. The NO instrument maintained a consistent relationship with ATI throughout the cloudy day, giving ATI/NO ratios in the range 1.20 to 1.25, similar to those obtained in clear skies. Although the readings of the FR instrument were too high, the ratio ATI/FR was fairly constant throughout the cloudy day, typically in the range 0.55 to 0.61 at 340 nm. On both days, the BE instrument showed a marked diurnal variation: the ATI/BE ratios declined from 1.2 in the morning of the cloudy day to 0.88 in the late afternoon.

Diurnal variations

Although most biologically-active ultraviolet radiation is received when the Sun is fairly high in the sky, it is of interest to know how faithfully the instruments responded to the lower fluxes at the beginning and end of the day. In winter and at high latitudes the solar elevation is low even at midday. In order to minimise the confusing effect of the individual slit functions, we have chosen two wavelengths, 313 nm in the UVB and 333 nm in the UVA, where the Fraunhofer structure allows a short respite from the large fluctuations normally encountered in the spectral ratios from a pair of instruments. These wavelengths are also in a region of the spectrum where most of the instruments are performing at their best.

In order to provide a uniform reference against which to assess the diurnal variations, we have formed the mean of a group of spectroradiometers. To facilitate subsequent discussion of the effect of applying a cosine correction, we have included in this reference mean only those spectroradiometers for which a measured cosine response was available. All the instruments in the group made measurements at half-hourly intervals over a range of solar zenith angles in the morning and afternoon of both days, although not all the instruments were present at every observation time. The reference mean (denoted here by MF) consists of six instruments, namely ATI, BE, DEM, GB, GR, and NLRD. Figures 71 and 72 show the behaviour of each of these instruments relative to their mean at 313 nm and 333 nm for the clear-sky case of 24 July 1993.

It can be seen that the instruments fall into two distinct groups. The ATI, GB, and GR instruments agree closely throughout the day, showing a tendency to fall from morning to afternoon relative to the MF mean, while the BE, DEM, and NLRD instruments form a more incoherent grouping which tends to rise relative to the MF mean, although the NLRD instrument falls in the afternoon. The reason for these disparities will be dealt with in the Discussion section below. For the moment, however, there is no way of knowing for certain which of the two groups is closer to the correct diurnal variation. It will therefore be instructive to consider them separately, if only to show how the interpretation of the results is affected by the choice of reference.

We begin by examining the ratios of the ATI, GB, and GR instruments to their mean, which will be denoted by MC. These ratios are shown in Figures 73 to 78 as a function of solar zenith angle. (The morning has the longer tail on 24 July 1993.) It can be seen that the GR instrument adheres closely to the mean throughout the day, while the ATI and GB instruments show small diurnal variations, ATI being higher in the morning and GB in the afternoon. Figures 79 to 84 show the corresponding set of ratios for the BE, DEM, and NLRD instruments relative to their mean, which is designated MB. These graphs show the MB instruments in the best possible light, but they also demonstrate some interesting points about the art of choosing reference means and presenting ratios based on them.

The first point is that there are more observations available for MC than for MB or MF. If an instrument misses an observation, that observation time is bound to be absent from any mean which includes that instrument. The second point is that the anomalous behaviour of the BE instrument (in the first few observations in the morning) has affected all the MB ratios. Relative to an average of three instruments, the magnitude of such an anomaly is reduced by one third in the anomalous instrument, and appears with a magnitude of one third in the other two. (In Figures 79 to 84 we have used the BE data after correction for the BE timing error.) Lastly, comparison of these graphs with the corresponding curves in Figures 71 and 72 shows how the choice of reference mean can influence the picture.

The remaining instruments have been compared with the group mean to which they most closely relate. The NLRE/MB ratios (Figures 85 and 86) show a tendency to increase with solar zenith angle, in contrast to the behaviour of the sister instrument NLRD. The diurnal variation of the other diode-array instrument, NLK, is well-behaved in relation to MB (Figures 87 and 88), despite a shadow which is cast on the diffuser by the surrounding metal ring at solar zenith angles greater than about 60°. The DEK results (Figures 89 and 90) clearly suggest an anomalous cosine response. The shape of this anomaly is not dependent on the choice of reference mean, although it is much better determined in relation to MC, as there are more than twice as many points available. This is one of the most intriguing results of the intercomparison campaign, as it could not have been obtained without the presence of at least two other spectroradiometers. The DEK instrument was fitted with an integrating sphere under a weatherproof quartz dome; the question therefore arises whether the anomaly was an artefact of the experimental conditions on the platform or an inherent characteristic of the instrument. Finally, the NO spectroradiometer shows a flat response relative to the MC instruments, with some diurnal asymmetry at the higher solar zenith angles (Figures 91 and 92).

The relationship between the two groups of instruments can be seen in the MB/MC ratios (Figures 93 and 94), which reflect the diurnal trends seen in Figures 71 and 72 for the clear-sky case of 24 July 1993.

The behaviour of the six MF instruments on the cloudy day (23 July 1993) was rather different. Only the three MC instruments showed a consistent diurnal variation (Figures 95 and 96) throughout the day. In order to obviate the effects of cloud variability, the scanning spectrometers adopted a synchronised schedule in which all the instruments observed the same wavelength simultaneously, advancing by 0.5 nm every three seconds. However, the various instruments were not always in perfect synchronism, this being the first occasion on which such a scheme had been attempted. Some awkward adjustments had to be made to cope with pre-scan operations, variable integration times, slow scanning speeds, drifting computer clocks, and inflexible software. Consequently, large fluctuations can be found in the spectral ratio between two instruments during periods of patchy cloud. This is particularly noticeable in the morning around 1000 to 1100 UT.

Apart from these fluctuations the diurnal behaviour of most instruments was rather better on the cloudy day, with less tendency to show a systematic dependence on solar zenith angle. This is only to be expected, as the instrumental cosine and azimuth responses will be less critical in the absence of bright sunshine. The ATI, GB, and GR instruments maintained a consistent relationship at 313 nm and 333 nm on 23 July 1993, in relative diurnal variation and absolute spectral irradiance (Figures 97 to 102). Of the other instruments in the MF group (Figures 103 to 108), only BE showed any systematic difference between morning and afternoon. (Note that the afternoon has the longer tail on 23 July 1993.) The large diurnal asymmetry in BE (Figures 103 and 104) suggests a marked drift in sensitivity between 1000 and 1300 UT on 23 July 1993 rather than a cosine or azimuth effect, as the cloud cover reached 7 oktas on several occasions in the morning and in the afternoon.

In assessing the above results, it should be remembered that none of the operators (except DEM) made any correction for the cosine error of their receivers. Some of the dependence on solar zenith angle will therefore be attributable to the cosine errors of the individual instruments. However, variations which are not simply a function of solar zenith angle, such as diurnal asymmetry, must have some other cause. The most probable explanations are (a) temporal drift in instrumental sensitivity, (b) extraneous hardware falling in the field of view of the instrument, and (c) azimuthal dependence of the instrument response, which may arise either in the spectrometer itself or through misalignment of the receiving surface. It is nearly impossible to assign causes without more detailed measurements and comparisons, but it is useful to differentiate the instruments according to their external azimuthal attributes.

Generally speaking, azimuthal variations should not occur in those instruments which use an optical fibre or rotate with the Sun. The individual strands of the optical fibre serve to twist the azimuth at random, so that the radiation entering the spectrometer should carry no information about the original azimuth, unless the diffuser itself has an azimuthal asymmetry or tilt. This applies to the ATI, DEM, and GB instruments. Where the optical head is rotated in azimuth to follow the Sun, as in the ATI and GR instruments, any azimuthal effect in the system will be minimised and there should be little or no systematic diurnal asymmetry in clear skies, provided the rotational axis is vertical.

Cosine correction

Only the DEM results were corrected for the cosine error of the diffuser before being submitted, and it is therefore of interest to know how the intercomparison results would be affected if a similar correction were to be applied to the other instruments. In order to achieve this the DEG team, who operated the DEM instrument, undertook to compute cosine correction factors for the other instruments by applying their usual algorithm to the measured cosine response of each instrument in turn. We have applied these correction factors to the original measurements, and have repeated the diurnal variation analysis on the revised spectra.

Before considering the outcome, it is perhaps worth remarking that this is not intended to be a comprehensive treatment of the cosine problem: rather it is an attempt to gauge the magnitude of the effect in relation to the observed differences between the instruments, in order to judge its importance. The calculation of the correction factor for each instrument depends not only on the measured cosine response for the instrument but also on an estimate of the proportion of diffuse radiation in the global flux and an assumption about the angular distribution of that diffuse radiation. In the algorithm used by the DEG team, the diffuse radiation is assumed to be isotropic, and the diffuse/global ratio is estimated from an empirical radiation model as a function of the wavelength and the solar zenith angle. The correction factor for the direct radiation is then taken from the measured cosine response curve, while the factor for diffuse radiation is calculated once for each instrument on the basis of the isotropic assumption. This assumption, the diffuse/global ratio, and the measured cosine response are all open to question. Moreover, the azimuth response has been left out of account, the GB cosine response is from a sister instrument, and the diffuse correction which had already been adopted for the DEM instrument was 5% less than for isotropic radiation, in order to improve the agreement of the measurements with the empirical model. For these reasons, the cosine correction factors should be regarded merely as an indication of the magnitude of the effect.

It can be seen in Figures 109 and 110 that the application of the cosine correction has greatly improved the agreement between the instruments on the afternoon of 24 July 1993 while making it rather worse in the morning. The main reason for the improvement in the afternoon is that the members of the MC group (ATI, GB, and GR) now coincide with the BE and DEM instruments. The BE instrument needed only a very small correction as its cosine response is rather flat (Figure 33), while the DEM data already included the cosine correction and therefore did not change. (Note that MF in Figures 109 and 110 refers to the mean of the cosine-corrected data for the six MF instruments.) The improved agreement in the afternoon was therefore obtained by applying quite large corrections to the MC instruments. Consequently, the morning ratios are spread over a wide range, and the distinction between the MB and MC groups is rather more obvious than before. The output of the three MC instruments decreases during the course of the morning, while that of the three MB instruments increases.

Taken separately, therefore, the two groups show very little systematic diurnal variation. Figures 111 to 122 show that the behaviour of the individual instruments relative to their group mean is much the same as before: the cosine correction has made only a small difference. However, the two groups are now in much better agreement in the afternoon, as can be seen by comparing Figures 123 and 124 with Figures 93 and 94. After correction for the cosine effect, the MB/MC ratio is much nearer unity in the afternoon. On the face of it, therefore, the cosine correction would appear to have been worth while, if only a convincing explanation could be found for the discrepancy between the instruments in the morning. This is not to say that the particular algorithm used here is the right one, only that some overall improvement in consistency was obtained in the afternoon of one day by attempting to calculate and remove the differences in the cosine effects of the various instruments.

Discussion

In assessing the results of these investigations it is important to bear in mind the primary purpose of an intercomparison campaign: it is to improve the quality of the measurements made by the individual instruments at their home sites, by revealing discrepancies between the instruments, and examining their causes with a view to reducing or eliminating them. It is not enough merely to determine the sign and the size of a discrepancy. If its cause is not understood, there can be no guarantee that its effect will remain the same at the home site in the months to come. Indeed some of the instrumental errors are the result of changes during the journey to the intercomparison and are not relevant to the home site at all.

The side-by-side simultaneous comparisons on the roof provide the most stringent test of an instrument's capabilities. Every aspect of its performance is tested: the accuracy and stability of its absolute spectral irradiance calibration, the cosine and azimuth response of its input optics, the slit function, stray light, and dark current, the alignment and orientation of the receiving surface, the temperature dependence of the spectrometer, and the timing and other data-logging functions of the computer. It is therefore gratifying to report that considerable progress has been made in the sky scans since the first faltering steps at the start of the project. Those instruments which were previously unable to obtain any satisfactory spectral measurements of global irradiance are now giving stable and spectrally consistent results, while those instruments which showed discrepancies of 10% to 20% at low solar zenith angles in the first campaign are now in agreement at the 5% to 10% level.

New instruments have also joined the group in the meantime, and are already producing well-calibrated spectra in agreement with the others. On the other hand, it is salutary to observe that several instruments made completely erroneous measurements when they first joined the group, despite careful prior attempts at laboratory calibrations. Participation in the intercomparisons was therefore an essential prerequisite for obtaining reliable results.

The sky scans are the most revealing of all the measurements, as they show the final performance of the instrument with all factors in operation, but to gain insight into the nature and causes of discrepancies between instruments it is necessary to examine those measurements which treat an individual process in isolation.

Lamp calibrations

The most convincing evidence of progress has come from the lamp scans. In the first intercomparison, discrepancies of 20% were found, not only between lamps but between scans of the same lamp on separate days and between lamp ratios on separate days. These errors, which were probably due to fluctuations in the lamp current and scattered light in the calibration room, have now been eliminated. In the third intercomparison, the darkroom was particularly well-equipped and instrumented, with the result that several instruments were able to demonstrate agreement with the PTB calibration certificate of a 1000 W lamp to within 5% in the range 310 to 340 nm.

During the course of the project, several processes have been identified as factors contributing to the residual differences between the measured spectra and the lamp certificates. The first of these is often neglected: the measurement of the lamp current during the absolute irradiance calibration governs the accuracy of all subsequent spectral measurements. Most ammeters are simply not accurate enough, nor are the small shunts which are supplied as plug-in modules for voltmeters. The only satisfactory method is to measure the voltage across a precision standard resistor in series with the lamp. A suitable resistor, typically 0.1 ohm, will have a certificate showing the absolute resistance to six significant figures at a standard temperature, together with the temperature coefficient. At the third intercomparison, those systems which used a precision resistor agreed to within 1 mA in 8 A, whereas the other meters showed discrepancies of several parts per thousand.

The next source of error lies in the progressive deterioration of the calibration lamp. It is usually assumed that the lamp calibration will remain stable during the first 50 hours of operation after the certified calibration. However, careful monitoring of lamp current and voltage, as carried out during the third intercomparison, shows that these lamps can exhibit sudden unpredictable changes in their characteristics, superimposed on a slow long-term drift. Fortunately, the consequent changes in radiative output are small, typically 1% or less, but it is prudent to monitor them in order to judge the condition of each lamp in use, and it is essential to maintain a family of lamps in each laboratory.

Elaborate precautions were taken to eliminate scattered light during the lamp scans in the third intercomparison. The lamp and the instrument were in separate rooms, on opposite sides of a partition, with only a small aperture to allow the calibrated beam to pass from one room to the other. Black cloth was deployed in order to absorb stray photons, and the walls of the rooms were also black. The facilities had been designed by the DEG team specifically for spectral lamp measurements of this sort, and were therefore ideally suited to their purpose. Nevertheless, some of the discrepancies between the lamp scans may be attributable to scattered light in the laboratories of the home institutes where the instruments received their original absolute irradiance calibrations. Not all the operators have a suitable darkroom in which to perform the calibrations and other laboratory measurements. Other things being equal, scattered light in the home laboratory will tend to yield low readings in the intercomparison darkroom.

In all three intercomparisons, the lamp scans were performed using a 1 kW lamp with a vertical filament and a horizontal calibrated beam. Each instrument was therefore turned on its side in order to view the lamp. For some instruments this presents no difficulty, as the rigidity of the spectrometer allows it to operate in either orientation. But some instruments are built to operate only in the upright position, and do not give satisfactory results when tilted. This effect may be so marked as to make measurement of the horizontal-beam lamp impossible, as with the GR instrument, but in less severe cases it may produce a plausible but erroneous result. Some of the discrepancies in the lamp scans may therefore be due to this effect.

Finally, when assessing the lamp scans it is important to remember that the journey to the intercomparison site can alter the absolute calibration of an instrument, both in wavelength and in irradiance, as a result of mechanical shocks received in transit. These calibrations must therefore be verified or renewed on arrival at the intercomparison meeting. The absolute wavelength calibration can be obtained from a mercury discharge lamp or by making use of the Fraunhofer structure in the solar spectrum, but the irradiance calibration will depend on the output of one or more transfer lamps which accompany each instrument.

Some operators are understandably reluctant to transport their principal standard lamps away from their home institutes, and could not in any case expect to reproduce at the intercomparison site the conditions under which they would have performed a full irradiance calibration at home. The transfer lamp unit is therefore likely to be a portable system mounted on the instrument itself, with no calibration certificate from a national standards laboratory. It derives its calibration from scans made at the home institute, prior to departure, using the instrument calibration derived from the operator's principal certificated standard lamp.

The lamp scans at an intercomparison meeting are therefore performed in less than ideal circumstances: the instruments may not be at their best, and their irradiance calibrations may not be as reliable as they would have been in regular operation at home. Nevertheless, the lamp scans in the third intercomparison show that it is possible to achieve results within 3% of the calibration certificate of an independent lamp in the ultraviolet region. With careful attention to the sources of error described above, it should be possible in the future to bring all of the instruments up to this standard of absolute irradiance calibration at wavelengths longer than 300 nm, and to within 5% between 280 nm and 300 nm. However, it should be noted that successive scans by the same instrument on two well-maintained standard lamps can differ by 2% to 3%. Such discrepancies can probably only be resolved, if at all, by careful laboratory investigation of a family of lamps of different types over a period of many months.

Transportable Lamp System

The results obtained by the Transportable Lamp System (TLS) during the third intercomparison campaign showed that repeatable spectral measurements could be obtained on the output of the unit, provided that adequate steps were taken to ensure precise repositioning of the TLS on each occasion. It is therefore important that the operators of each individual spectroradiometer should design and construct a well-adapted rigid interface to fit between the TLS and their instrument. Repeatable results will only be obtained if the beam geometry is identical on every occasion, where the light passes from the TLS exit aperture to the spectroradiometer input optics.

After the third intercomparison, fresh lamps were installed in the TLS and it was transported to the sites of the GB, FR, and NLR teams, returning to the BE institute in Brussels for checking. Results from these experiments were very encouraging. The TLS survived the journeys unscathed, and gave consistent and repeatable results in most cases. Successive scans were within a few parts per thousand at wavelengths longer than 300 nm on the GB instrument. However, a difference of some 6% between different days on the NLRD instrument shows that accurate positioning can be critical. A full discussion of the TLS results will be found in the report entitled *The Transportable Lamp System, a Relative Reference for the Future* prepared by Didier Gillotay and published by the BE team in Brussels.

Stray light and sensitivity

At the shortest ultraviolet wavelengths, all spectroradiometers run into difficulties. The logarithmic graphs in Figures 125 to 128 show how the various instruments respond to the dearth of photons at wavelengths shorter than 300 nm when the Sun is high in the sky. Broadly speaking, the same behaviour is encountered as the solar zenith angle increases, but at progressively longer wavelengths. At the shortest wavelength settings in a single monochromator, the faint ultraviolet radiation is overwhelmed by visible light which has been scattered in unorthodox directions by the optical components of the spectrometer, including the grating itself. The result is a false signal which is roughly constant with wavelength, giving a clear indication of the lower wavelength limit of reliable ultraviolet data. This can be seen in the NO spectrum in Figure 125. The other single monochromators attempt to subtract the stray light from the recorded spectrum, either by assuming that the signal at the shortest wavelengths is wholly due to stray light and subtracting that signal throughout the spectrum, or by making a separate measurement with a filter which only passes the stray light. Using the first of these methods, the NLK instrument obtains ultraviolet data down to 295 nm at low solar zenith angles (Figure 128). The NLRE instrument is not designed to operate below 300 nm, as that region is covered by NLRD.

Stray light is much less of a problem in the double monochromators. In some cases it is below the level of detection, being surpassed by the signal due to background noise in the amplifier and fluctuations in the dark current of the photomultiplier. All the double monochromators can record ultraviolet irradiances down to about 10^{-6} W m^{-2} nm^{-1} at low solar zenith angles, so that their lower wavelength limit for reliable data is generally between 289 and 291 nm. This wavelength limit is much the same for the instruments which show a residual signal at the shortest wavelengths (ATI, DEK, DEM, NLRD) and those that do not (GB, GR), except for BE, in which the signal falls off below 295 nm (Figures 125 to 128).

To ensure that stray light is kept to a minimum, it is best not to expose the spectrometer to dust and other extraneous deposits which might accumulate on the optical surfaces. The diffraction gratings are particularly vulnerable, as they are virtually impossible to clean. For instruments which are capable of measuring down to 290 nm when the Sun is high in the sky, a worthwhile improvement in sensitivity could only be achieved by radical alterations to the instrumental specifications and techniques: for example, spectral filters to remove stray light, cooled detectors to reduce the dark current, and long integration times in photon counting mode with discrimination against cosmic rays.

Wavelength shifts

The fundamental wavelength calibration of each spectrometer is inherent in the construction of the instrument itself, and generally requires only a small correction, usually a constant offset, in order to achieve a wavelength accuracy of around 0.1 to 0.3 nm in the better instruments. Operationally, this offset is determined either by scanning a mercury discharge lamp or by making use of the Fraunhofer lines in the solar spectrum. However, for accurate work, a wavelength-dependent correction may be required. The most critical region is the steep slope of the incident spectral irradiance at wavelengths shorter than 320 nm. As the slit function is also critical in this region, it is only worth while improving the wavelength calibration if a correction for the effect of the slit function is made in tandem.

Slit function

It has been noticeable in each intercomparison that the irradiance ratio between two instruments shows a consistent spectral pattern irrespective of the solar zenith angle and the state of the sky. This pattern is largely a manifestation of the interaction between the slit functions of the two instruments. It should therefore be possible to account for it in terms of the measured slit functions and thereby arrive at a reconciliation of the two instruments which is independent of their bandwidths.

If the spectral distribution of radiation across the wavelength interval covered by the slit function were proportional to the corresponding distribution in the lamp calibration (for each instrument) then the instruments would agree, and their irradiance ratio would be spectrally flat. But this is clearly not the case. The aim is therefore to calculate the actual distribution across the slit function of the radiation incident at the Earth's surface. To do this, we make use of a radiative transfer model as an intermediary between the two instruments. It is not necessary for this purpose that the model should provide an accurate representation of the whole spectrum at once: only that it should represent the relative spectral distribution across the slit function in use, a band of no more than 6 nm in the present instance. Factors which change only slowly with wavelength are therefore of no consequence here. The absorption due to ozone is, however, important in the UVB region of the spectrum, as it changes rapidly with wavelength. For the present case, we have used 280 m-atm-cm as the total ozone value, which gives good agreement both with the global irradiance spectra and with total ozone determinations performed by the GR Brewer spectrometer.

We have truncated the slit functions shown in Figures 23 to 31 (at −1.8 to +4.2 nm for GB, −0.7 to +0.8 nm for GR, and −3.0 to +3.0 nm for ATI and DEM), and convolved them with the model irradiance to simulate the spectral structure obtained by each instrument during a scan. The ratio of these simulations for a pair of instruments represents the ideal ratio of their recorded spectra which would be obtained if the instruments were perfectly calibrated. Figure 129 shows the calculated ATI/GR ratio for 1130 UT on 24 July 1993. The structure in this ratio spectrum can be compared directly with the observed ratio in Figure 130.

It is clear from this comparison that many of the features in Figure 130 arise from the interaction of the instrumental slit functions. An additional contribution to the variance in the observed ratios can be expected if there are any wavelength shifts in the two instruments. These can be corrected by shifting the observed spectra to minimise the amplitude of the fluctuations in the ratio of observed to simulated spectra. The ratio of observed ATI/GR to calculated ATI/GR then gives an estimate of the factor which remains between the two instruments after the effect of the slit functions has been removed. This is shown in Figure 131 where it can be seen that much of the variance in Figure 130 has now been accounted for. The corresponding ratios for ATI/DEM and ATI/GB are given in Figures 132 and 133, while the GB/GR ratio is shown in Figure 134. The wavelength of the structure in these ratios is commensurate with the bandwidth of the narrower slit function, suggesting that a further reduction in the amplitude of the residuals could be obtained by further development of the method.

The improvement in the ratios is particularly noticeable at the shortest wavelengths, where both the wavelength shifts and the effect of the slit functions are important. The wavelength corrections used in the above calculations were −0.1 nm for ATI and GR, +0.2 nm for DEM, and −0.2 nm for GB. The spectral flatness of the ratios in Figures 131 to 134 is chiefly due to the wavelength correction, whereas the reduction in the amplitude of the spectral structure is achieved by taking the slit functions into account.

Diurnal variation

It is one thing to get the instruments to agree with each other when the Sun is high in the sky, and quite another to sustain this agreement throughout the course of the day. Most spectroradiometers have a satisfactory cosine response at small solar zenith angles, but become progressively worse as the zenith angle increases. Azimuthal variations are also generally more pronounced at large solar zenith angles. Even if two instruments have identical angular response functions, their absolute spectral irradiance calibrations may drift apart during the day. One or other of these effects may play a significant role in explaining the observed differences between the various instruments in their measurements of diurnal variation.

To minimise errors due to the cosine and azimuth effects it is important that the receiving surface is correctly aligned, with its nominal axis pointing to the zenith. Subsequent assessment and correction of the cosine and azimuth errors are made easier if the alignment is monitored with respect to fiducial lines and surfaces on the receiving head which can be related to the nominal directions used during the laboratory measurement of the cosine and azimuth responses. Correct alignment of the receiving heads can be difficult to achieve on an intercomparison platform where the mountings are necessarily makeshift and temporary. The interpretation of discrepancies between instruments is often hampered by uncertainties of this sort. The contrast between the diurnal behaviour of the instruments in the MB group and those in the MC group shows that the explanations are not straightforward.

Some uncertainty must also be ascribed to the relative positions of the instruments on the platform. If all the spectroradiometers had exactly the same field of view, their discrepancies would be due solely to the performance of the instruments themselves. When there are obstructions present, it is tempting to attribute some of the variation in the results to their influence.

In the first two intercomparisons, there were no significant obstructions on the platform, other than people coming and going to attend to their instruments. But in the third campaign, one corner of the platform was occupied by instrument cabins over two metres in height, which came within the field of view of several of the spectroradiometers. Some of the instruments had their diffusers raised up, in order to minimise the effect of the obstructions. One diffuser was on the roof of a cabin, and two other instruments were not on the platform at all. The remaining spectroradiometers were placed as far away as practicable on the other two sides of the 10-metre-square platform. As seen from these instruments the cabins occupied only a small proportion of the sky, at low elevation. Some crude tests with a sheet of dark cloth held in front of the white cabins produced no significant change in the irradiance measured by one instrument in the late afternoon. It is therefore quite possible that the obstructions made no significant difference to the results. Nevertheless, the worry remains that some of the discrepancies between the instruments may have been due to reflection of sunlight in the morning, or obscuration of skylight in the afternoon, particularly as the MC instruments and those with similar diurnal variations occupied positions on the platform which formed a loosely contiguous group, whereas the MB instruments did not.

There is no way of knowing in retrospect how much the diurnal variations were influenced by the obstructions, if at all, just as there is no way of knowing whether the alignment of the diffusers played any significant role. These uncertainties raise an important point about the aims of intercomparisons and the way they are conducted. The purpose of an intercomparison is not only to demonstrate the extent to which the instruments agree, but also to enable us to identify with certainty the source of the error when they do not. The second of these aims is much more elusive than the first, but arguably more important. Without clear information on the causes of the discrepancies it is impossible to give reliable guidance for improvement.

There are therefore some implications here for the conduct of future intercomparisons. Firstly, the platform should be free of nearby obstructions to the extent that all the instruments see virtually the same field. Distant hills are not a problem, but local buildings and hardware should not extend above the receiving surfaces of the instruments. Secondly, the alignment of the diffusers (and integrating spheres) should be more closely monitored during the intercomparison, using the fiducial lines and surfaces defined in the laboratory determinations of cosine and azimuth responses. Thirdly, if possible, additional experiments should be designed with a view to separating the sources of error, especially receiver alignment, cosine and azimuth response, temperature coefficient of sensitivity, and temporal drift of the irradiance calibration. These could include frequent transfer lamp measurements during the course of a day, and experiments involving rotation or tilt of the instrument receivers.

Cosine correction

Even on an ideal platform, with perfect alignment and no azimuth response, all the instruments are still expected to display a cosine effect due to the imperfect cosine response of their receivers. To assess the effectiveness of the cosine correction in improving the accuracy of the instruments in optimum conditions, we have compared the results obtained at 1130 UT on 24 July 1993 before and after the application of the cosine correction. The aim here is to observe the effect of the cosine correction on the whole of the spectrum recorded at one observation time, whereas the previous analysis examined selected wavelengths during the course of the day.

The effect of the slit function was removed using the technique described earlier. Only scanning instruments were considered, therefore, as the slit function of a diode-array spectrometer is rather different in nature.

For this exercise, the results have been referred to an average of several instruments for which cosine responses were available. Of the instruments which made an observation at 1130 UT, six were suitable for the purpose. (DEH was not included in the average on account of its limited wavelength range.) In relation to the mean of these six instruments, BE was rather high, and NLRD rather low, at the shortest wavelengths, so the mean of the other four instruments (ATI, DEM, GB, and GR) was used for the subsequent calculations. This mean is denoted by MD. The results are shown in Figures 135 to 138. For the four MD instruments, the application of the cosine correction appears to have the effect of improving the consistency of the results slightly. Nevertheless, discrepancies of the order of 10% remain between the instruments in the MD group even after correction for the cosine effect. These may be due either to systematic differences in the absolute irradiance calibrations, or to the errors inherent in the calculation of the cosine corrections. At the longer wavelengths in Figure 136 the agreement is rather better, the MD instruments being generally within about 5% of their mean.

Ancillary measurements

Several operators have installed a pyranometer to make broadband measurements of the solar irradiance at intervals of a minute or less during a scan of the spectroradiometer. This provides a check on variations due to changing cloud cover. Some actinometric determinations of aerosol optical depth are also made. However, many of the teams have been slow to attend to ancillary measurements, particularly the horizon profiles of the home sites, which are not yet generally available. Information on the cloud regime and surface albedo are also lacking. Future interpretation of spectra recorded at the home institutes may depend critically on the availability of ancillary data on the atmospheric and other conditions which prevailed when the observations were made.

Competence

Reliable spectral measurements of the solar ultraviolet irradiance depend not only on satisfactory instrumentation, but also on the general level of competence displayed by the individual operators. During this project, considerable progress has been made in standards of competence, stimulated largely by the desire to achieve better results at the next intercomparison. The consistency of lamp calibration tests has improved, more attention is paid to scattered light in the laboratory, and new equipment has been introduced to make more accurate measurements of lamp current. Most operators have now measured the angular response and slit function of their instruments, and further experiments are planned to explore and extend the laboratory characterisation of a group of spectroradiometers.

However, there is still plenty of room for improvement in competence. Several instruments have systematic errors in absolute spectral irradiance calibration which can certainly be removed by good laboratory work. Procedures can also be tightened to ensure that fewer observations are lost for minor reasons during intercomparisons, and further software development can improve the facility for making synchronised observations in sunny and cloudy conditions, which is itself an advance on the methods used during the earlier campaigns. The standard of data documentation, file handling, and computer organisation has continually improved throughout the project, in line with the general progress in operational and instrumental competence.

Conclusions and Recommendations

The most important conclusion to emerge from this project is that participation in an intercomparison is a powerful stimulation for improvement in the specification and operation of a spectroradiometer. It need not be in a grand campaign with ten or more instruments, invaluable though these are. Even a small meeting with two, three, or four instruments can be just as informative, as it gives more opportunity for exploratory investigation and control. Those instruments which were present at all three major intercomparisons (ATI, BE, GB, GR, and NO) have all made improvements in their instruments and their procedures in response to the results obtained. Of the instruments which took part in the most recent campaign, the best are in agreement with each other to within about 10% when the Sun is high in the sky (Figure 136). These results were achieved in a blind test by instruments of independent design, using calibrations based on spectral irradiance lamps held at their home institutes.

All the spectroradiometers which took part in the campaign demonstrated their ability to make detailed spectrally resolved measurements of global solar ultraviolet irradiance on an absolute scale. These instruments have no difficulty in reproducing the spectral structure of the incident radiation in accordance with their individual slit functions, and agree in that respect over the whole of their operating wavelength range. Where they differ, the disparity is generally a systematic ratio which varies smoothly with wavelength. The source of these systematic differences is elusive, but is expected to be a combination of calibration error and drift, angular response, and the effects of stray light. For the double monochromators, stray light is not a serious problem. However, calibration drift and angular response are together responsible for significant discrepancies between some of the instruments during the course of the day. These are exemplified in Figures 71 and 72.

It is clear from the intercomparison results that some of the instruments displayed systematic errors in excess of 15%, even with the Sun high in the sky. These may be due in part to the unfamiliar operating conditions of an intercomparison site, but they will nevertheless have to be resolved before the instruments in question can be regarded as suitable for deployment in an international network. However, none of the instruments suffered from insuperable or intractable problems. All of them have the potential to reach the standards of the best instruments. The aim of the following recommendations is therefore twofold: to enable the best instruments to consolidate and improve their demonstrated capacity to produce consistent results; and to enable the remaining instruments to identify and eliminate the sources of error which currently prevent them from realising their full potential.

Specifications of instruments

To operate successfully in an international network, a spectroradiometer must satisfy certain minimum requirements. The spectral resolution of the spectrometer should be of the order of 1 nm or better, to enable adequate control of the wavelength calibration and to provide adequate information in the spectral region where the irradiance is a steep function of wavelength. In particular, the FWHM of the slit function should ideally be 1 nm or less, and the near-field wings of the slit function should be no worse than those shown for the ATI instrument in Figure 23. For more detailed investigation of the region below 300 nm, a slit function with a FWHM of 0.5 nm or less is an advantage, provided that the wavelength calibration is accurate to 0.1 nm in this region. In general, the wavelength calibration should be stable to 0.2 nm or better between successive measurements of the mercury discharge lamp. It is a relatively simple matter to correct a small wavelength error after the event, provided it is uniform over the spectral range of the instrument. Ideally, therefore, the error in the wavelength calibration should not differ by more than 0.1 nm from one part of the spectrum to another.

The spectral range of the instrument should include the interval from 290 nm to 360 nm in order to reveal the extent of stray-light contamination, and to allow adequate intercomparison with other instruments. Those instruments which are capable of measuring the output of a tungsten lamp down to 250 nm are better able to give a more convincing demonstration of the stability and accuracy of their absolute irradiance calibration at short wavelengths, while those with a spectral range extending to 500 nm or more can provide more detailed information on the spectral dependence of the optical depth of the atmosphere. For simultaneous intercomparisons of scanning spectroradiometers, a useful working range is 280 nm to 420 nm.

Every instrument must be able to make measurements at steps of 0.5 nm in nominal wavelength throughout its spectral range, in order to provide adequate detail for intercomparison work and wavelength calibration. To enable synchronised scans, each instrument should be provided with a special operating mode in which the scan is made in steps of 0.5 nm, each step to take an integral number of seconds in the range 1 to 3. Additional options should be made available according to the capabilities of the instrument. In this mode, the starting time, starting wavelength, wavelength step, and time step are to be specified for each scan, shortly before it commences, in accordance with the synchronisation protocol of the intercomparison. For this purpose, it must be possible to synchronise the clock of each instrument to the nearest second of Universal Time at the start of the day's operations, and to maintain such synchronisation by periodic checks or corrections during the day. For normal operations other than synchronised scans, the instrument clocks should always be accurate to within 10 seconds of Universal Time.

The absolute irradiance calibration of the instrument should not be expected to drift by more than 2% in the course of a day, nor between successive spectral irradiance calibrations with its working standard lamp. For most instruments, this means that the high voltage to the photomultiplier must be carefully controlled to within one volt or better, and that some temperature stabilisation is required for the spectrometer itself and for the analogue electronics.

The cosine and azimuth response of the receiving surface is a significant source of error in most instruments. For many practical purposes the error may not be important, but an inadequate cosine response is a perennial source of uncertainty. The interpretation of intercomparison results would be a great deal easier if the instruments had satisfactory angular responses, as any discrepancies could then more confidently be attributed to other causes. In this respect, a receiver with a cosine error of 5% or less at a zenith angle of 60°, and 10% at 75°, can be regarded as far superior to one with errors three times as great, provided that the same cosine accuracy can be obtained at all azimuths. A significant azimuthal variation (more than 2% at 60°, or 4% at 75°) is to be avoided if at all possible, as it is generally impracticable to make a subsequent correction for it.

Since many of the present instruments do not meet these standards, some improvement in the design of the diffusers is desirable. Instruments whose receivers rotate in azimuth with the Sun are already protected to some extent against azimuthal errors. For all other instruments, the use of a fibre-optic cable is recommended as a means of minimising the effect of azimuthal variations in the receiver response. For instruments with neither a fibre-optic cable nor a rotating receiver, a full laboratory measurement of the azimuth response is essential. The search for azimuthal variations is particularly important in the case of instruments with integrating spheres, as the exit port is generally not directly below the entrance port but in the side of the sphere at a fixed azimuth relative to the instrument casing.

The effect of stray light should be determined at the shortest wavelengths, for example by extending the spectral range down to 280 nm. With the Sun high in the sky, the error due to stray light should not exceed 10^{-6} W m^{-2} nm^{-1} for a double monochromator or 10^{-4} W m^{-2} nm^{-1} for a single monochromator. Other residual errors, such as the effect of amplifier noise and uncertainty in the elimination of the dark current, should also be estimated, and should not give rise to an error greater than 10^{-6} W m^{-2} nm^{-1} in the measured irradiance at the shortest detectable wavelengths.

Procedures for calibrations

In order to ensure that its absolute irradiance calibrations are reliable and repeatable, each station should maintain a family of calibration lamps in such a way that variations in the output of one lamp can be detected by comparison with the others. Some of these lamps will have calibration certificates from national standards laboratories, while others will have obtained their calibration via the operator's own spectroradiometer. Some of these transfer standard lamps and their ancillary equipment will be portable so that they can conveniently be used to calibrate the instrument in the field and at instrument intercomparisons. The certificated lamps should be used very seldom, so as to preserve their original calibration, but the spectroradiometer should be exposed to the other lamps at frequent intervals, with the aim of ensuring that when the instrument is behaving normally the operator is confident of the accuracy of the absolute irradiance calibration to better than 3% at 400 nm and better than 5% at 300 nm, relative to the calibration which would have been obtained in the laboratory with a newly-calibrated lamp.

The success of this operational calibration scheme must be put to the test from time to time in side-by-side intercomparisons with other spectroradiometers, and by making use of the Transportable Lamp System on its circuit of the participating institutes.

For those instruments which can only be calibrated in the upright position, a method must be developed which will allow the absolute irradiance scale embodied in a certificated lamp with a horizontal beam to be transferred to a lamp with a vertical beam. The most promising solution to this problem is to use a spectroradiometer with a fibre-optic input cable on a computer-controlled altazimuth mount.

During the working life of each lamp, its condition should be monitored by continually measuring the voltage dropped across it at its standard current. The lamp current itself should be determined by measuring the voltage across a precision resistor in series with the lamp. Some independent check on the accuracy of the voltmeter is desirable.

Every effort should be made to minimise the influence of scattered light in the laboratory during lamp measurements at the home institutes, and some exploratory investigations should be carried out to determine the main sources of scattered light and their relative significance.

For each spectroradiometer, a determination of the slit function is required at intervals of 0.1 nm or less in wavelength. The shape of the slit function should be determined at several wavelengths throughout the spectral range of the instrument, using selected lines from a mercury or similar discharge lamp. If possible, at least one determination should be made using an ultraviolet laser, in order to explore the wings of the slit function, which give rise to near-field stray light.

A system must be developed to enable repeatable and accurate determination of the cosine and azimuth response of an instrument, preferably in its upright position. The measurements must be made at several wavelengths, but it is more important to be sure that the angular responses of the input optics are reliably characterised in the laboratory to the extent that the cosine and azimuth functions can be confidently invoked when the instrument is deployed on the roof. The measurement system must therefore ensure that repeatable results are obtained when the instrument is removed and replaced, and that the orientation of the receiving surface can be reliably transferred from the laboratory to the roof. Moreover, the errors in the measurement system must be explored by varying the experimental arrangements in order to discover which aspects of the system are the most critical.

Site criteria and operations

At the home institutes, spectral irradiance calibrations must be performed at frequent intervals, in order to ensure that significant changes in the sensitivity of the spectroradiometer are detected promptly. One calibration per month may be sufficient for an instrument which is demonstrably stable, otherwise once per week is advisable. Most instruments are sensitive to temperature. Some form of temperature-stabilised environment is therefore recommended for the spectrometer, unless it can be shown experimentally that the relevant temperature coefficients are negligible.

The correct orientation of the receiving surface should be specified with respect to inscribed fiducial lines and reference surfaces on the optical head and on the site observing platform or mounting. The nominal axis of the receiving surface, as used in the laboratory cosine response measurement, must be set vertical, and the nominal zero azimuth line must be oriented on a known bearing relative to geographic north.

The observing site itself should be free of nearby obstructions which might obscure a significant part of the sky as seen by the instrument, or reflect extraneous light on to its receiving surface. Each site operator should prepare a description and a diagram of the horizon as viewed by the instrument, showing the elevation and azimuth of all obstructions which mask the sky. A description of the surrounding terrain should also be prepared, so that the surface albedo can be estimated out to a distance of, say, 15 km from the station.

Occasional visits by independent observers or instruments are to be encouraged, in order to provide fresh insight into the operational procedures at the station.

Finally, the use of Universal Time is recommended wherever possible, in order to facilitate international comparisons, ensure compatibility with other international geophysical operations, and reduce the risk of confusion.

Ancillary measurements

In addition to broadband pyranometry, which provides a useful indication of variations in cloud cover, some measurements of atmospheric optical depth as a function of wavelength are a valuable adjunct to global spectral irradiance data. These can be provided either by making spectral scans of the direct solar beam, or by conventional actinometry using a filter instrument. A full record should also be maintained at each site of any available information regarding the state of the atmosphere, such as meteorological and ozone data, together with estimates of, and a diary of changes in, the surface albedo of the surrounding terrain.

Competence

It is not enough to have a high-quality instrument making accurate measurements: it is also necessary to demonstrate convincingly that the results are good. This requires not only the usual calibration work and laboratory measurements but also a certain level of stability in the instrument and its performance, and in the operators and procedures.

Without this stability there is no guarantee that the results will continue to be reliable in the months and years to come: the quality cannot be predicted with confidence.

The determination of the slit function, angular response, and other instrumental parameters should not therefore be regarded as a task to be performed once only, but should be repeated at intervals in order to demonstrate the reproducibility and reliability of the results, and to record any actual changes, especially as a consequence of deliberate adjustments to the optical and mechanical alignment, or the introduction or replacement of critical components. The wavelength and irradiance calibrations should be performed on a regular and frequent schedule, sufficient to ensure that any unexpected steps or drifts are found promptly, otherwise substantial periods of solar irradiance data are liable to be lost.

With competent operations, there will seldom be any need to revise the recorded spectral irradiances, and any revised files will be clearly distinguished from the originals. Documentation and file handling are crucial aspects of competence. The competent operator will ensure that appropriate particulars such as the date, time (preferably Universal Time), location, calibration provenance, observational conditions, version date, rate of scan, instrument settings, and diagnostic readings such as EHT voltage, are correctly recorded in the file with the spectral measurements. The data will generally be free of mistakes, anomalous formats, and contradictory or suspect information, so that when these occur they will usually turn out to be the fault of the recipient rather than the instrument operator.

An operator who produces consistent results by using a stable instrument and competent procedures has certainly succeeded in providing internal evidence for the validity of the spectral measurements. But without independent proof it is impossible to judge whether the data are accurate and reliable. It is quite possible for an instrument to appear to work correctly while actually giving erroneous and unreliable results. It is therefore essential to make side-by-side comparisons, either with an instrument of proven reliability or by direct intercomparison with a number of other instruments in an international campaign.

The onus is on the operator not only to check the overall performance of the instrument and the success of the procedures, and to devise adequate means of quality assurance, but also to initiate and execute the necessary changes in order to attain better standards.

Intercomparisons do not of themselves solve problems or improve results. They merely demonstrate the level of success achieved and indicate promising directions for future progress.

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Appendices

A. Meteorological Data

B. Ozone Data

C. Operational Notes

D. Table of Instrument Specifications

E. Site Information

F. Publications

G. Contact Addresses

Appendix A. Meteorological Data

European Intercomparison of Ultraviolet Spectroradiometers
Garmisch-Partenkirchen, Germany, 19-31 July 1993

Visual observations of cloud cover and rain were recorded by B.G. Gardiner and P.J. Kirsch. A dash in the last column indicates that no observation was made. Instrumental data, which are half-hour means ending at the time shown, were kindly supplied by the Fraunhofer-Institut für Atmosphärische Umweltforschung.

Date	Time UT	Temp. °C	Dew pt. °C	Vap.press. mbar	RH %	Press. mbar	Cloud oktas
Jul 22	0700	11.5	10.2	12.5	92	937.5	7 Sc, 8 As
	0730	11.7	9.9	12.2	89	937.8	7 Sc, 8 As, rain
	0800	11.3	10.1	12.4	93	938.2	7 Sc, 8 As, rain
	0830	11.1	10.0	12.3	93	938.3	7 Sc, 8 As, rain
	0900	11.6	9.6	12.0	88	938.2	7 Sc, 8 As
	0930	11.7	9.3	11.7	85	938.4	7 Sc, 8 As, rain
	1000	10.9	9.2	11.6	89	938.6	-
	1030	11.2	9.3	11.7	88	938.6	-
	1100	11.7	9.7	12.0	88	938.7	-
	1130	11.7	9.8	12.2	88	938.8	-
	1200	12.1	10.1	12.4	88	938.7	-
	1230	13.0	10.5	12.7	85	938.4	-
	1300	13.1	9.4	11.8	78	938.4	-
	1330	13.2	9.1	11.6	76	938.3	-
	1400	13.6	8.7	11.3	72	938.2	-
	1430	14.8	8.9	11.4	68	937.9	-
	1500	13.9	8.8	11.3	71	938.3	-
	1530	13.2	10.3	12.5	83	938.6	-
	1600	13.4	10.1	12.4	81	938.7	-
	1630	12.9	9.3	11.8	79	939.0	-
	1700	12.4	8.5	11.1	77	939.2	-
	1730	12.4	9.3	11.7	81	939.2	-
	1800	12.5	9.3	11.7	81	939.3	-
Jul 23	0800	13.2	8.8	11.4	75	941.0	7 Sc
	0830	13.3	8.3	11.0	72	941.0	7 Sc
	0900	13.5	8.5	11.1	72	941.1	7 Sc, tr Ac
	0930	14.6	8.5	11.1	67	940.9	6 Sc
	1000	16.6	7.2	10.2	54	940.6	5 Sc
	1030	17.4	5.7	9.2	46	940.3	6 Sc
	1100	18.1	5.6	9.1	44	940.0	5 Sc
	1130	18.8	5.6	9.1	42	939.7	6 Sc
	1200	19.0	5.7	9.2	42	939.7	5 Sc
	1230	17.9	5.9	9.3	45	939.5	4 Sc, tr Ci
	1300	18.0	6.1	9.4	46	939.2	4 Sc, 2 Ci
	1330	18.4	6.7	9.9	47	939.1	2 Sc, 3 Ci
	1400	18.8	7.1	10.1	47	938.9	2 Sc, 2 Ci
	1430	18.8	7.1	10.1	47	938.8	2 Sc, 1 Ci, 2 Cs
	1500	19.1	7.4	10.3	47	938.8	3 Sc, 2 Ac, 1 Ci, 2 Cs
	1530	19.0	7.3	10.3	47	938.7	2 Sc, 5 Ac, tr Ci, 2 Cs
	1600	18.8	7.4	10.3	48	938.7	2 Sc, 7 Ac, 2 Cs
	1630	19.0	7.8	10.6	48	938.8	2 Sc, 2 Ac, 3 Cs
	1700	18.4	7.8	10.6	50	938.8	2 Sc, 1 Ac, 4 Cs
	1730	17.7	7.9	10.7	53	938.9	-
	1800	17.4	8.0	10.7	54	938.9	2 Sc, 1 Ac

Date	Time UT	Temp. °C	Dew pt. °C	Vap.press. mbar	RH %	Press. mbar	Cloud oktas
Jul 24	0400	9.0	8.5	11.1	97	938.6	tr Ac
	0430	8.3	7.9	10.7	97	938.7	tr Ac
	0500	9.2	8.8	11.3	98	938.7	tr Ac
	0530	10.6	10.1	12.4	97	938.5	tr Ac
	0600	12.0	10.4	12.6	90	938.4	tr Ac
	0630	13.4	10.8	13.0	84	938.4	tr Cu
	0700	14.6	10.7	12.8	77	938.3	tr Cu
	0730	16.2	10.2	12.5	68	937.9	tr Cu
	0800	17.8	9.7	12.0	59	937.5	tr Cu
	0830	18.7	9.5	11.9	55	937.2	tr Cu
	0900	19.2	9.1	11.5	52	936.9	tr Cu
	0930	19.5	9.4	11.8	52	936.7	tr Cu
	1000	19.8	9.7	12.1	52	936.3	tr Cu
	1030	20.4	10.2	12.5	52	935.7	tr Cu
	1100	20.9	10.6	12.8	52	935.4	tr Cu
	1130	21.2	11.1	13.3	53	935.2	tr Cu
	1200	21.5	11.8	13.9	54	934.9	tr Cu
	1230	21.9	12.0	14.1	53	934.6	tr Cu
	1300	22.3	12.5	14.5	54	934.2	tr Cu
	1330	22.6	12.7	14.7	53	933.8	tr Cu
	1400	22.8	13.1	15.1	54	933.5	tr Cu
	1430	23.0	13.3	15.3	55	933.3	tr Cu
	1500	22.9	13.1	15.1	54	933.0	tr Cu
	1530	23.1	13.1	15.1	53	932.6	tr Cu, tr Ci
	1600	22.9	13.2	15.2	54	932.2	tr Cu, tr Ci
	1630	22.9	13.2	15.2	55	932.0	tr Cu, tr Ci
	1700	22.6	13.1	15.1	55	931.8	tr Sc, tr Ci
	1730	22.3	12.9	14.9	55	931.7	tr Sc, tr Ci
	1800	21.8	12.5	14.5	55	931.6	tr Sc, tr Ac, 3 Ci
Jul 25	0400	13.4	12.4	14.4	94	927.1	2 Sc, 3 Ac, 2 Ci
	0430	13.0	11.8	13.9	93	927.1	2 Sc, 3 Ac
	0500	13.2	12.1	14.2	93	927.1	4 Sc, 6 Ac
	0530	14.5	13.0	15.0	91	927.5	4 Sc, 6 Ac
	0600	15.7	13.5	15.5	87	927.9	4 Sc, 7 Ac
	0630	16.5	13.9	15.9	84	928.0	-
	0700	17.6	14.5	16.5	82	928.1	-
	0730	17.7	14.5	16.6	82	927.8	-
	0800	17.9	15.1	17.2	84	927.3	6 Ac, 8 As
	0830	18.4	15.7	17.9	84	927.2	3 Sc, 5 Ac, 7 As, rain
	0900	18.8	15.5	17.6	81	927.1	4 Sc, 5 Ac, 4 As
	0930	19.5	15.8	18.0	79	926.9	3 Sc, 5 Ac, 4 As
	1000	20.0	15.1	17.2	73	927.0	tr Sc, 6 Ac, 8 As
	1030	20.4	14.8	16.8	70	927.0	8 Ns, rain
	1100	20.3	15.2	17.3	73	927.4	rain
	1130	20.1	14.9	17.0	72	927.3	no rain
	1200	20.7	14.5	16.5	68	927.1	2 Sc, 3 Ac
	1230	21.7	14.4	16.4	63	926.9	5 Sc, 3 Ac
	1300	21.5	13.2	15.2	59	926.7	7 Sc, 2 Ac, 6 As
	1330	20.1	12.8	14.8	63	926.7	7 Sc, 8 As, rain
	1400	18.8	12.7	14.7	68	927.3	rain shower
	1430	16.2	13.0	15.1	82	928.3	-
	1500	15.7	13.9	15.9	89	928.5	-
	1530	16.2	14.7	16.8	91	928.7	6 Sc, 8 As, rain

Appendix B. Ozone Data

In addition to global ultraviolet irradiance measurements, the GR Brewer spectrophotometer made regular determinations of the total atmospheric content of ozone and sulphur dioxide, the results of which are shown in the following table.

Day of July 1993	Total ozone (m-atm-cm)	SO_2 column (m-atm-cm)
20	---	---
21	333.1 ± 5.3	0.0 ± 0.1
22	---	---
23	300.3 ± 2.6	0.0 ± 0.9
24	291.2 ± 5.3	0.0 ± 0.6
25	---	---
26	325.7 ± 8.8	0.0 ± 0.4
27	313.9 ± 1.9	0.0 ± 0.4
28	---	---
29	292.6 ± 3.4	0.0 ± 0.8
30	293.0 ± 10.3	0.1 ± 1.5

Appendix C. Operational Notes

The following sections have been compiled from verbal and written accounts supplied by the individual participating teams. They describe the special characteristics of each instrument and its performance, together with procedural details and improvements. The operational specifications of all twelve instruments will be found in Appendix D below.

ATI

The Bentham DM150 double monochromator (focal length 150 mm in each half) is operated within the range 280 nm to 500 nm using a grating of 2400 lines/mm. To avoid backlash, scans ascend from 275 nm. The entrance and exit slits are 0.61 mm wide. The centre slit is normally 10 mm wide, but was temporarily set at 5 mm during the third intercomparison. A baffle has been installed in order to reduce far-field stray light, particularly during measurements of direct solar radiation. The spectrometer is enclosed in a refrigerator system to keep its temperature in the range 15° C to 25° C. Additional magnetic shielding has been provided for the photomultiplier. Its high voltage is controlled to 0.1 V by computer. Integration time is automatically adjusted, in the range 10 ms to 2 s, according to the ratio of the signal to the dark current. A correction is applied to ensure linearity across the current amplifier stages.

A fibre-optic cable, specially adapted by Bentham, leads from a 5 mm diameter inlet circle to a rectangular outlet matched to the entrance slit of the spectrometer. Three optical inputs can be presented in turn to the fibre inlet, by rotating a turret under computer control. Global irradiance is measured by means of a 1 mm thick diffuser, cut from a plane sheet of teflon. Observations of direct sunlight, with a field of view of about 1.2° in diameter, are made using a mechanical pointing system with two microstep stepping motors and a small telescope with a quartz lens. Zenith observations can also be recorded with a field of view of about 8°. In addition to the spectroradiometer measurements, an actinometer is operated in cloudless conditions, and a pyranometer records global solar irradiance at intervals of 10 seconds during each spectral scan.

A 1000 W tungsten lamp with a PTB certificate is used to calibrate the spectroradiometer at a distance of 700 mm, with the diffuser in place and the lamp beam horizontal. During field campaigns, the instrument is recalibrated with a 100 W lamp mounted close to the diffuser. Wavelength calibration is achieved by comparison with the solar Fraunhofer features between 340 nm and 350 nm, using the SUSIM spectrum.

BE

The BE instrument has been constructed to hold two spectroradiometers which are identical except for their input optics. In one, the field of view is restricted to a cone around the zenith, with an angular diameter of about 15°. The second spectroradiometer has been modified to enable it to view the whole hemisphere of the sky, in order to record global solar irradiance. Both machines are contained in a single weatherproof housing.

Scanning is achieved by a micrometric screw and stepper motor, the rotation of the gratings being coupled by an invar lever system. A beam splitter directs 50% of the beam to a single photodiode (EG&G UV 444b), while the remainder goes to the photomultiplier. A neutral density filter is available in front of the entrance slit, and a second filter in front of the photomultiplier eliminates higher orders of diffraction and prevents saturation. The photomultiplier is not cooled, and is operated in photon-counting mode at a voltage of 825 V in the ultraviolet and 750 V in the visible, with a short overlap in mid-scan. The microprocessor controller autoranges the output of a bank of 14-bit counters after integration of the signal over 0.2 seconds. Optical paths in the spectrometer are comprehensively baffled in order to reduce stray light to below the limit of detectability. The entrance and exit slits are 0.1 mm wide, and the centre slit 0.25 mm. Linear dispersion is 4 nm/mm, and the full spectral range available is from 166 to 700 nm. The bandwidth (FWHM) has been measured at a number of wavelengths, by mercury lamp and by helium-neon laser, and has been found to be about 0.5 nm throughout the spectral range. The cosine response of the global irradiance spectroradiometer was obtained by using a teflon diffuser with a thickness of 3.5 mm. The wavelength scale is controlled with reference to a mercury lamp and the solar Fraunhofer structure. Irradiance calibrations were performed with a NIST-traceable 1000 W quartz-halogen lamp at a distance of 500 mm. The BE instrument can be left to record spectra automatically.

DEH

The DEH instrument, a Brewer ozone spectrophotometer with a single monochromator, measures global spectral ultraviolet irradiance together with determinations of the total atmospheric content of ozone and sulphur dioxide. The instrument is fitted with a teflon diffuser protected by a quartz dome. The ultraviolet spectrum was scanned from 290 to 320 nm in steps of 0.5 nm by rotation of the grating, using the second of the six available exit slits. Wavelength calibration is by mercury lamp. The Brewer is weatherproof and can be left to run automatically.

DEK

The Optronic model 752 spectroradiometer is equipped with an integrating sphere which is protected from the weather by a quartz dome. The temperature of the optical head is stabilised at 21° ± 1° C. The photomultiplier operates in current mode at a voltage of 648.2 V. It is protected by a magnetic shield, and cooled by a small Peltier unit. The dark current is 3 ± 1 pA, while the signal at 400 nm is typically about 10 μA at high Sun elevations. All three slits are 0.125 mm wide, the dispersion at the exit slit being 8 nm/mm. Wavelength calibration is obtained by mercury lamp. Unlike the earlier 742 model, the 752 instrument uses an auto-ranging linear amplifier. The absolute irradiance scale is based on a 1000 W lamp supplied by Optronic Laboratories and traceable to NIST. A 200 W transfer lamp and a small 5 W lamp are used for field calibrations. Various scanning modes are available, offering a choice of integration time at each wavelength. However, it was not possible to set an arbitrary scanning speed for the purposes of making synchronised scans.

DEM

A Bentham DM300 double monochromator was operated with the input beam chopped at 272 Hz by a rotating sector wheel, in order to increase the signal-to-noise ratio. The output of the phase-locked amplifier was monitored to ensure optimum consistency during the measurements. At any one wavelength, the shortest integration time was 0.2 s, and the longest 3 s. Stray light is below the noise level. A single quartz plate diffuser was used. The instrument can be operated with or without a quartz optical fibre between the diffuser and the entrance slit of the spectroradiometer. A new fibre has recently been installed, as the old one had some broken strands. With the fibre in use the instrument is weatherproof, although the signal-to-noise ratio is reduced by a factor of about 100. No significant asymmetry was found in the cosine response.

The spectral irradiance calibration of the DEM instrument is derived from a 100 W lamp at 350 mm from the diffuser. It has been found that the inverse square law can be used to obtain the lamp calibration from its NPL certificate which refers to a distance of 500 mm, provided that the distances are measured to the pins of the lamp. In order to ensure steady operating conditions, the spectroradiometer and its ancillary equipment are housed in an air-conditioned cabin, providing temperature stabilisation to within 0.5° C. The consequence of this design is that the cabin is rather heavy and bulky. An uninterruptible power supply is available to keep the instrument running during power cuts. The weight of the spectroradiometer equipment is about 300 kg. The total cargo weight including the cabin, packing crates and ancillary equipment amounts to 1100 kg. A pyranometer and an illuminometer are operated as integral parts of the observing system.

FR

A compact instrument based on a Jobin-Yvon DH10 spectrometer was operated with a grating of 1200 lines/mm. The entrance and exit slits are 0.25 mm wide, with a centre slit of 0.5 mm. The Hamamatsu 1P28 photomultiplier was run at 900 V. The dark current was not subtracted from the measurements, but it is intended to subtract it in future campaigns. A mercury lamp was used for wavelength determination, and the original irradiance calibration was performed in Brussels by the BE team, using a NIST-traceable 1000 W lamp. No secondary lamp was used in the July 1993 campaign. This instrument had not attended any previous intercomparisons, and was effectively undergoing its first operational trials. The original irradiance calibration clearly did not apply to the data recorded during the intercomparison, possibly because of changes in the heights of the entrance and exit slits, both of which were adjustable. The spectroradiometer is not temperature-stabilised. A quartz diffuser was used.

GB

The Optronic 742 spectroradiometer (one of two identical instruments) was operated with a quartz optical fibre (1 m x 4 mm diameter) between the entrance slit of the monochromator and a teflon diffuser by Bentham. This new diffuser is in place of the Optronic teflon diffuser which would otherwise sit directly over the entrance slit. The optical fibre is held straight and vertical, supported in a metal tube. In order to stabilise its radiometric sensitivity, the spectrometer (including the photomultiplier) is placed inside a refrigerated chamber, which is fully enclosed and temperature-regulated to 16° ± 1° C. A thermistor has been mounted in the base of the optical head, next to the photomultiplier, and the internal temperature of the instrument is recorded at the time of each scan. The widths of the entrance, centre, and exit slits are 0.25, 0.5, and 0.25 mm respectively.

The absolute irradiance calibration is obtained from a 1000 W FEL lamp supplied by Optronic, and traceable to NIST. The instrument is calibrated during intercomparison campaigns by means of a 200 W transfer standard tungsten-halogen lamp at a distance of 130 mm from the diffuser in an enclosed housing. An additional small unit containing a 5 W tungsten lamp and a mercury wavelength standard are also used in the field to monitor the calibrations.

Dark current and stray light are automatically offset immediately prior to each scan by subtracting the signal at a wavelength of 260 nm. Wavelength alignment is checked and corrected if necessary before each hourly scan by comparison with the Fraunhofer lines of the Sun, to a resolution of 0.1 nm. A photodiode (peak sensitivity 560 nm) has been installed online to monitor the broadband irradiance throughout each scan as a guide to variability in cloud cover. The instrument can be run unattended according to a pre-programmed schedule, provided that the weather is dry.

GR

The GR instrument, a Mk III Brewer ozone spectrophotometer incorporating a double monochromator, measures global spectral ultraviolet irradiance, together with determinations of the total atmospheric content of ozone and sulphur dioxide. Optically, it consists of two identical Mk II Brewer monochromators in tandem, with the rotating slit mask acting as the centre slit of the double monochromator. The two holographic plane gratings have 3600 lines per mm and operate in first order. Stray light is greatly reduced in the double Brewer, and no attempt is made to subtract it from the reported spectra. The photomultiplier is operated in photon counting mode at 1550 V. The wavelength range of this instrument has been extended up to 365 nm. A mercury lamp wavelength calibration is performed before each spectral scan. The primary irradiance calibration is derived from the vertical beam of an overhead 1000 W DXW lamp at a distance of 500 mm, and the field calibration is obtained by one of five 50 W transfer standards at 50 mm from the teflon diffuser, which is protected by a quartz dome. The instrument rotates about a vertical axis so that the nominal zero azimuth of the diffuser is always facing the Sun. The Brewer can be left unattended to complete a programmed sequence of observations, and is housed in a weatherproof casing.

NLK

By using a diode array as detector, the NLK spectrometer obviates the need for a scanning mechanism and gathers the whole spectrum at once. It is therefore unaffected by short-term variations in cloud cover. In any case, a spectrum can be gathered in a few seconds, whereas the other instruments take minutes. However, like most diode-array spectrometers, it is limited to a single monochromator, and requires a filter in order to exclude most of the unwanted visible light.

The NLK instrument is based on a crossed Czerny-Turner spectrometer, the Jarrell Ash MonoSpec 18, with a 1200 lines/mm grating operating in first order to give a dispersion of 4.5 nm/mm. The detector is a Reticon 1024-element EG&G type M1453A silicon photodiode array behind a fused silica face plate. The array measures 25 mm by 2.5 mm and is Peltier-cooled to 5° C. The sensitivity is uniform across the detector to within ±5%. During the July 1993 campaign the diode array unit was destroyed when the instrument tripod was accidentally knocked over, but a new unit was quickly obtained from a local supplier, and the NLK instrument was recalibrated on its own lamp at the intercomparison site. Wavelength calibration is performed by a mercury lamp. The irradiance standard is an Oriel 1000 W FEL lamp operated at 7.9 A and 500 mm distance, with a certificate traceable to NIST.

Global spectral irradiance in the range 290 to 415 nm is recorded during an integration period of 3 s when the sky is clear, and 18 s when cloudy. Incoming radiation is gathered by a teflon diffuser. Despite the use of a filter with a cut-off in the region of 400 nm, a significant quantity of stray light is detected. The first 20 diodes at the short-wavelength end are assumed to be recording only stray light, and their average signal is therefore subtracted from the whole array.

NLR

The NLR team operated two spectroradiometers: the NLRD scanning instrument, which is designed to obtain reliable results at UVB wavelengths, and the NLRE diode-array instrument, which covers the UVA range. In each instrument, the incoming radiation is gathered by an integrating sphere of diameter 100 mm, with an entrance port of diameter 25 mm, and an exit port of diameter 12.5 mm. The spheres are coated internally with Spectralon, and each has a small quartz dome to protect it from the weather. In each instrument, two mirrors and two lenses are used to form an image of the exit port of the sphere at the entrance slit of the spectrometer.

The spectral irradiance calibrations are obtained with a 1000 W FEL lamp supplied by Optronic Laboratories and traceable to NIST. The lamp is used at a distance of 500 mm, but with the filament horizontal and the beam vertical. The instruments are mounted in a temperature-stabilised (18° ± 1° C) mobile container, from which extraneous light is excluded. Spectrally-integrated global solar irradiance is recorded by a Kipp & Zonen CM21 pyranometer.

NLRD

The NLRD instrument is a Dilor XY double monochromator with plane gratings of 2400 lines/mm, dispersion of 0.375 nm/mm, and slit widths of 0.80, 0.96, and 0.80 mm. A measurement of the slit function, using the 325 nm line from a HeCd laser, showed the full width to be 0.35 nm at half maximum and 1.37 nm at 10^{-4} of maximum. The photomultiplier operates at room temperature in photon counting mode at 2000 ± 1 V. Integration time varies from 1.5 s at 280 nm to 0.1 s at 400 nm. Stray light is less than the dark current. Wavelength calibration is obtained by mercury lamp. The specified wavelength accuracy is 0.03 nm, with a specified repeatability of 0.001 nm. Following the July 1993 campaign, a correction was introduced in order to take account of the 0.13 µs dead time of the counting system.

NLRE

The NLRE diode-array spectrograph combines the EG&G model M1235 instrument with a Reticon 1024-element EG&G type M1453A diode-array detector, Peltier-cooled to −5° C. The spectrometer is a single monochromator with a slit width of 25 µm and a grating of 600 lines/mm. Spectral resolution is 0.15 nm per pixel. Wavelength calibration is performed by mercury lamp and verified by the solar Fraunhofer structure. The specified wavelength accuracy is 0.4 nm, with a specified repeatability of 0.1 nm. The dark current is determined by means of a manual shutter. Stray light is measured before each spectrum is recorded, by inserting a yellow filter which excludes the ultraviolet and blue light. The resulting signal is subtracted, diode by diode, from the subsequent spectral measurement. Below about 305 to 310 nm, stray light generally precludes reliable measurements. At 450 nm, the stray light signal is typically about 5% of the recorded counts when the Sun is high in the sky.

NO

The NO instrument is based on a Jobin-Yvon HR320 Czerny-Turner single monochromator with a plane holographic grating measuring 58 by 58 mm. The 1P28 photomultiplier is operated in photon counting mode. With a 100 ms integration time, a scan from 290 to 600 nm in steps of 0.1 nm takes 6.5 minutes. The diffuser is a flat teflon plate, and the outermost element is a quartz dome of diameter 50 mm. The instrument is contained in a weatherproof case mounted on a sturdy tripod, and can be left operating unattended for prolonged periods.

The irradiance calibration is derived from a NIST-traceable 1000 W FEL tungsten lamp supplied by Eppley Laboratories. Determinations of the dark current are made during the calibration procedure, although the dark current and stray light are not removed from the recorded sky spectra. The principal advantages of this instrument are its speed, its narrow bandwidth, and its all-weather automatic capability.

Appendix D. Table of Instrument Specifications

	ATI	BE	DEH	DEK	DEM	FR
Spectrometer type	Bentham DM150	JY DH10	Brewer MK II	Optronic 752	Bentham DM300	JY DH10
Focal length/mm	150	100	160	90	300	100
Gratings	two	two	one	two	two	two
plane/concave	plane	conc	plane	conc	plane	conc
holographic	yes	yes	yes	yes	yes	yes
lines/mm	2400	1200	1800	1200	2400	1200
Bandwidth (FWHM)/nm	0.9	0.5	0.6	1.0	1.0	1.2
Step/nm						
usual	0.5	0.32	0.5	1.0	0.5	0.5
finest	0.04	0.08	0.1	0.03	0.015	0.05
Usual range/nm						
from	280	212	290	290	285	280
to	500	683	320	710	410	550
Direction of scan	up	up	up	up	up	up
Scan duration/s	120	270	180	235	210	300
Diffuser	teflon	teflon	teflon	integ. sphere	quartz	quartz
Detector type	PM EMI 9250Q	PM Hamam. R292	PM EMI 9789QA	PM S-20	PM EMI 9250Q	PM Hamam. 1P28
Weatherproof	no	yes	yes	no	yes	no
Automatic	yes	yes	yes	yes	yes	yes
Temperature stabilised optics	yes	no	no	yes	yes	no
Dark current removed	yes	yes	yes	no	yes	no
Stray light removed	no	yes	yes	no	no	no
Radiation standard	PTB	NIST	NIST	NIST	NPL	NIST
Main lamp/W	1000	1000	1000	1000	100	1000
Secondary lamp/W	100	200	50	200		

NIST National Institute of Standards and Technology
NPL National Physical Laboratory
PTB Physikalisch-Technische Bundesanstalt

Appendix D. Table of Instrument Specifications (continued)

	GB	GR	NLK	NLRD	NLRE	NO
Spectrometer type	Optronic 742	Brewer MK III	EG&G M1229	Dilor XY	EG&G M1235	JY HR320
Focal length/mm	100	160	156	500	280	320
Gratings	two	two	one	two	one	one
plane/concave	conc	plane	plane	plane	plane	plane
holographic	yes	yes		yes	yes	yes
lines/mm	1200	3600	1200	2400	600	1200
Bandwidth (FWHM)/nm	1.6	0.6	1.0	0.35	0.32	0.35
Step/nm						
usual	1.0	0.5	0.135	0.4	0.15	0.1
finest	0.1	0.1	0.135	0.002	0.15	0.01
Usual range/nm						
from	280	285	288	285	300	290
to	500	365	416	360	450	600
Direction of scan	up	up	---	up	---	up
Scan duration/s	275	396	3	480	0.99	390
Diffuser	teflon	teflon	teflon	integ. sphere	integ. sphere	teflon
Detector type	PM S-20	PM EMI 9789QA	diode array M1453A	PM EMI 9883QB	diode array M1453A	PM Hamam. 1P28
Weatherproof	no	yes	no	yes	yes	yes
Automatic	yes	yes	no	yes	yes	yes
Temperature stabilised optics	yes	no	no	yes	yes	no
Dark current removed	yes	yes	yes	yes	yes	no
Stray light removed	yes	no	yes	no	yes	no
Radiation standard	NIST	NIST	NIST	NIST	NIST	NIST
Main lamp/W	1000	1000	1000	1000	1000	1000
Secondary lamp/W	200	50	200		200	

NIST National Institute of Standards and Technology

Appendix E. Site Information

The aim of this project was not to set up a network of ultraviolet observing sites, but to determine the standards which would have to be met by the instruments in any network which might be set up in the future. Nevertheless, it was foreseen at the outset that the participating institutes would already constitute an embryonic network of stations, and that there might be some merit in recording data from these stations for future reference in any comparative study of the ultraviolet radiation regime in different parts of Europe.

Having performed three spectroradiometer intercomparisons and analysed their results, it is now clear that direct comparison of spectral measurements from different sites, and even from different periods at the same site, is much more problematical than was originally anticipated. However, it is also clear that a future European network is likely to consist of stations and instruments rather like those that have taken part in this project, and that progress towards a viable and self-consistent network will be made not by abandoning these stations and setting up a chain of different instruments at other sites, but by improving the standards of performance of the instruments and operators at the existing sites. With this in mind, it is perhaps of some use to enumerate these stations and their characteristics, as a preliminary indication of their variety and their suitability as sites for future network operations.

In the course of developing their instrumental and calibration facilities, many of the participants have made numerous measurements at their home sites over a period of some years. Some of the instruments were not designed or intended for routine atmospheric monitoring, but as experimental platforms to be developed for particular applications or investigations. In those cases, the field measurements have been sporadic and inhomogeneous. Others have made more regular measurements as part of a routine monitoring programme, while progressively improving their operational and calibration procedures. A future network based on these stations will probably retain this diversity, and indeed it ought to, as some questions are best resolved by climatological techniques while others can only be approached by designing and implementing specific programmes of investigation.

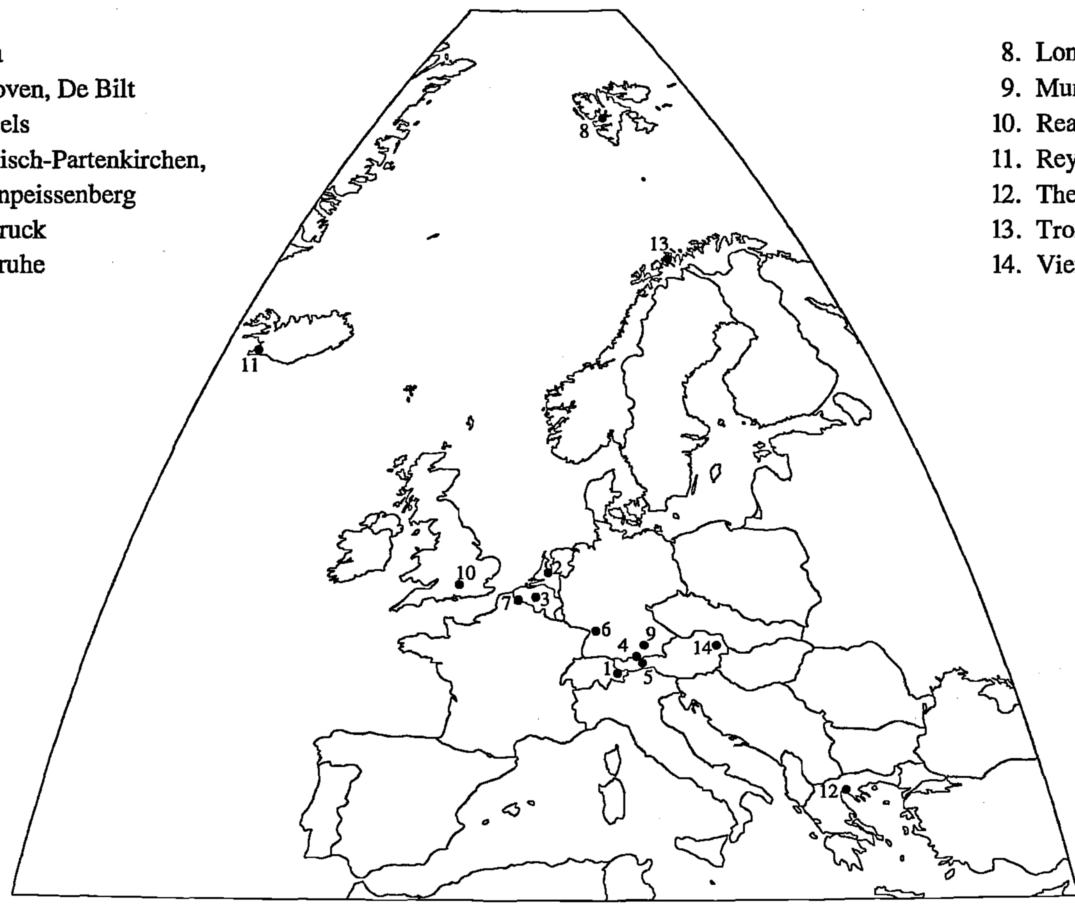
The sites themselves are also diverse, ranging from those which lie in the heart of the city to outlying coastal or island stations and isolated mountain summits. Some instruments have been operated at field stations remote from the permanent home site. The range of latitude and longitude is extensive, as can be seen in the accompanying map.

In the following pages, the latitude, longitude, and altitude of the instrument are given for each site, together with a description of the exact location. Note that the site codes are liable to change in the future, particularly if new stations are added. They are provided here to help the reader to associate the home sites with the instruments which participated in the intercomparison campaigns.

The text at the heading *Outlook* describes the field of view as seen by the instrument, and the extent to which the horizon is obscured, whereas *Surroundings* describes the terrain within a radius of about 10 km, with regard to its influence on the effective wide-area surface albedo.

Compatibility and comparability of the results from these disparate stations in the future will depend principally on the efforts of the operators to build verification, redundancy, repeatability, and procedural discipline into everyday operations at the observing site and calibration practices in the laboratory, and on successful performance in the intercomparison programme.

CEC Project : STEP 0076
Ultraviolet Spectral Measurement Sites



1. Arosa
2. Bilthoven, De Bilt
3. Brussels
4. Garmisch-Partenkirchen, Hohenpeissenberg
5. Innsbruck
6. Karlsruhe
7. Lille
8. Longyearbyen
9. Munich
10. Reading
11. Reykjavik
12. Thessaloniki
13. Tromsø
14. Vienna

Locality	Latitude	Longitude	Altitude	
Innsbruck	47° 16' N	11° 23' E	577 m	ATI

Instrument Site	Country
Department of Meteorology, University of Innsbruck	Austria

Controlling Institute: Institute for Medical Physics, University of Innsbruck.
Description of Site: On the roof of the Department of Meteorology in the University of Innsbruck.
Outlook: The skyline is about 15° to 20° above the horizontal plane in the northern quadrant, about 10° in the southern quadrant, and about 5° to 10° in the eastern and western quadrants. Detailed measurements of the skyline are available.
Surroundings: There is a park for about 500 m around the site, with houses and streets beyond.
Instrument: Spectral irradiance measurements are made with the Bentham DM150 spectroradiometer (labelled ATI in the intercomparison report), fitted with a quartz fibre. The instrument is temperature stabilised to about ± 3° C.
Measurement Periods: Measurements were carried out on selected days in 1993: Jan 4 and 18, Apr 14, 20, and 21, and Jun 8 to 11.
Schedule: Pairs of direct and global solar irradiance scans were scheduled at intervals of about 5° in solar elevation.
Operational Conditions: Automated measurements were performed if the sky was clear or if there were only a few clouds far away from the Sun.
Spectral Range and Duration of Scan: The spectrum was scanned from 290 nm to 500 nm at intervals of 0.5 nm, the duration of each scan being between 100 and 200 seconds.
Calibration Methods: In the laboratory, a 1000 W DXW lamp, calibrated by PTB, is used as the principal irradiance standard, with another 1000 W DXW lamp as subsidiary standard. Irradiance calibrations are made before and after each campaign. These laboratory measurements are made with a horizontal calibrated beam. In the field, a 100 W lamp with a vertical beam is used to monitor the stability of the instrument's irradiance calibration. Wavelength calibration is achieved by comparison with the solar Fraunhofer structure before each scan.
Ancillary Data: A pyranometer records the global solar irradiance during each scan. Actinometric measurements are also made from time to time.
Field Stations: Spectral measurements were also carried out in 1993 at three field stations remote from the home site in Innsbruck. In March, a field campaign was conducted at the Lichtklimatisches Observatorium in Arosa (46° 47' N, 9° 41' E, 1840 m). This station has forest and houses within a radius of 5 km, and alpine pasture beyond. Measurements were made from Jun 21 to Jul 3 at the Auroral Observatory in Tromsø (see separate site description), and a short campaign was carried out on the summit of the Wank Mountain (47° 31' N, 11° 09' E, 1780 m) from Aug 1 to 4, after the intercomparison at Garmisch-Partenkirchen.
Additional Remarks: The ATI instrument was developed for experimental purposes, and is therefore not deployed in routine monitoring. The spectroradiometer system is subjected to a programme of continual improvement between field measurement campaigns such as those mentioned above, which were supported by the CEC project STEP-0076, and occasional deployments at the Innsbruck site.

Locality	Latitude	Longitude	Altitude	
Vienna	48° 14' N	16° 20' E	200 m	ATW

Instrument Site	Country
Institut für Meteorologie und Physik, BOKU	Austria

Controlling Institute: Institut für Meteorologie und Physik, Universität für Bodenkultur, Vienna.
Description of Site: On a platform attached to the roof of the institute.
Outlook: There is an extensive view over the roofs of Vienna.
Surroundings: The institute lies in a built-up area with some parkland nearby.
Instrument: A Jobin-Yvon HD10 spectrometer was operated with two concave gratings of 1200 lines per mm, an integrating sphere, and a Hamamatsu R928 photomultiplier. The bandwidth of the instrument was 1.4 nm.
Measurement Periods: No regular measurements have been made at the home site, but a series of measurements was carried out in autumn 1992 at three field stations in Bavaria.
Schedule: Global and diffuse irradiance scans were performed at intervals of 5° in solar elevation, starting at 20°.
Operational Conditions: The instrument was operated manually.
Spectral Range and Duration of Scan: The spectrum was scanned from 280 nm to 400 nm with a step of 0.2 nm and a scan duration of 7 minutes.
Calibration Methods: A mercury lamp was used for wavelength calibration and for the determination of the instrumental slit function. The spectral irradiance calibration was obtained from a NIST-traceable FEL lamp. A subsidiary lamp was used to check the irradiance calibration after each scan.
Ancillary Data: Meteorological data and global solar irradiance were recorded.
Field Stations: The instrument was taken in turn to three field stations: Zugspitze (47° 25' N, 10° 59' E, 2961 m), Wank (47° 31' N, 11° 09' E, 1780 m), and Unterammergau (47° 37' N, 11° 03' E, 900 m). The Zugspitze and Wank sites are on mountain summits, while the Unterammergau site is in a rural area.
Additional Remarks: The above measurements were carried out in order to study the effect of altitude on the results. It is planned to deploy a Bentham spectroradiometer at a station outside Vienna, and at the Sonnblick field observatory.

Locality	Latitude	Longitude	Altitude	
Brussels	50° 48' N	4° 21' E	120 m	BE

Instrument Site	Country
Institut d'Aéronomie Spatiale de Belgique, Uccle	Belgium

Controlling Institute: Institut d'Aéronomie Spatiale de Belgique, Uccle, Brussels.
Description of Site: Top of the main IASB building, on a roof area of 20 m^2.
Outlook: Trees and buildings rising to an elevation of 10° in the SW quadrant.
Surroundings: Institute buildings lie within 300 m. Beyond that is a residential area, with a forest at a distance of 2 km to the south.
Instruments: Two Jobin-Yvon HD10 spectroradiometers are operated in a single weatherproof case. One (labelled BE in the intercomparison report) measures global irradiance, while the other measures the diffuse radiation from around the zenith direction with a field of view of ± 5°. Since 1985 these instruments have operated with a new scanning mechanism, a new grating support, and internal baffling to reduce the effect of scattered light within the instrument. The weatherproof case was introduced in 1992, together with a new design of entrance optics using a teflon diffuser. Temperature stabilisation was added in 1994.
Measurement Periods: A continuous measurement programme has been in operation since 26 Mar 1993. Measurements were made on an occasional basis between 1980 and 1993.
Schedule: Spectral scans are made at intervals of 15 minutes from dawn to dusk.
Operational Conditions: The instrument operates automatically in all weather conditions.
Spectral Range and Duration of Scan: The spectrum is scanned from 210 nm to 680 nm at intervals of 0.3 nm, the duration of each scan being 400 seconds.
Calibration Methods: Wavelength calibration and slit function measurements are performed with low-pressure mercury and hollow-cathode lamps. The principal irradiance standard is based on NIST-certificated 1000 W FEL lamps. Five 200 W quartz lamps are used as a subsidiary standard. Absolute spectral irradiance calibrations are performed 4 times a year with the 1000 W certificated lamps, supplemented by relative calibrations once per month using the 200 W lamps. The angular response of the instrument is determined with a 1000 W FEL lamp on a rotating plate.
Ancillary Data: Meteorological data are recorded four times per day: pressure, temperature, dew point, wind speed and direction, cloud amount and type. One or two measurements of total ozone are made each day, with a profile twice a week. Pyranometric measurements of solar radiation are made every 10 seconds.
Additional Remarks: A third instrument of the same type measuring the direct solar irradiance will be installed on a solar pointing system in the near future. It is also planned to install UVA and UVB meters early in 1995.

Locality Garmisch-Partenkirchen	Latitude 47° 29' N	Longitude 11° 04' E	Altitude 730 m	DEG

Instrument Site	Country
Institute for Atmospheric Environmental Research	Germany

Controlling Institute: Fraunhofer-Institut für Atmosphärische Umweltforschung (IFU), Garmisch-Partenkirchen.
Description of Site: North-west corner of the roof platform on the IFU building (since the start of measurements at IFU in April 1993). The platform is 10 m square.
Outlook: There are no local obstructions above the horizon. However, the site is surrounded by mountains, rising to an elevation of 20° in the north and 15° in the south. To the east and west the skyline is generally 5° to 10° above the horizon.
Surroundings: The instrument is located on the roof of the detached institute building, which is surrounded by meadows and woodland. The outskirts of the town of Garmisch-Partenkirchen lie 500 m to the north-east. The distance to the mountains is 1 to 2 km to the south, 2 km to the north-west, and 5 km to the east. The major part of the mountains is covered with forest.
Instrument: Global and direct irradiance measurements are made with a Bentham DM300 spectroradiometer. All measurements are carried out with the instrument temperature stabilised at 20° ± 0.5° C.
Measurement Periods: Measurements were made at this site for four weeks in the autumn of 1990, and for the period 27 Apr to 3 Aug 1993. A continuous programme of measurements began on 1 Apr 1994.
Schedule: Scans are performed every 6 to 10 minutes from dawn to dusk. In the more recent measurements, direct and global scans alternate, unless the Sun is obscured by clouds.
Operational Conditions: The instrument runs unattended under automatic operation in clear and cloudy conditions.
Spectral Range and Duration of Scan: The spectrum is scanned from 285 nm to 410 nm with a scan duration of 4 to 10 minutes. The earliest measurements were made with a bandwidth of 1 nm and a wavelength step of 1 nm. A smaller step of 0.5 nm was introduced in the range 290 nm to 310 nm. In the most recent measurements, the nominal bandwidth and the step are both 0.5 nm.
Calibration Methods: Wavelength calibration is obtained with a low-pressure pen-ray mercury lamp. In the laboratory the spectral irradiance standard is a 1000 W FEL lamp with a PTB certificate, calibrated with the beam horizontal. A smaller 100 W NPL-certificated lamp is used in the field. Calibrations have been performed at least once per week using a 100 W lamp in a specially designed housing without moving the instrument. The angular response of the detector has been measured in the institute's calibration room, and also by commercial consultants PRC Krochmann. The slit function has been measured at the 254 nm mercury line.
Ancillary Data: Meteorological parameters are recorded (pressure, temperature, dew point, wind speed & direction, visibility, sunshine duration), and a number of radiometric instruments are deployed (pyranometer, illuminometer, broadband UVB meter, multi-filter shadowband radiometer, and a pyrheliometer mounted on a sun tracker). Several LIDAR systems are in use, and trace gas measurements are made at ground level and on the nearby Wank Mountain (1780 m above sea level), including ozone, sulphur dioxide and nitrogen dioxide.

Locality	Latitude	Longitude	Altitude	
Hohenpeißenberg	47° 48' N	11° 01' E	989 m	DEH

Instrument Site	Country
Meteorological Observatory Hohenpeißenberg	Germany

Controlling Institute: Deutscher Wetterdienst, Meteorologisches Observatorium Hohenpeißenberg.
Description of Site: Since May 1993, on the southernmost edge of the roof platform. Previously on the southward-facing balcony of the observation tower.
Outlook: At the new location the field of view is clear except for a 10 m steel anemometer mast at a distance of 2 m to the north-west, and the 25 m observation tower at about 50 m to the north-west. At the previous location, the 7th floor and radome covered about 20% of the horizon in the northern sector. There is a church about 300 m away to the south-east.
Surroundings: The site is on the summit of an isolated mountain.
Instrument: Global spectral ultraviolet irradiance is measured by a Brewer single-monochromator spectroradiometer, with a holographic grating of 1800 lines per mm. There have been no significant changes to the instrument.
Measurement Periods: Sporadic measurements have been made since 1985. A regular programme began in January 1990.
Schedule: Measurements are made at half-hour intervals from dawn to dusk.
Operational Conditions: The instrument runs unattended, making automatic observations during all weather conditions.
Spectral Range and Duration of Scan: The spectrum is scanned from 290 nm to 320 nm (325 nm if required) with a wavelength step of 0.5 nm. The duration of a scan is about 7 minutes.
Calibration Methods: In the early years, calibrations were made with 100 W mercury lamps, calibrated by the manufacturer. The irradiance calibration is now obtained from a 1000 W FEL lamp, calibrated with a PTB-certificated standard. The calibration is performed with a horizontal beam by turning the Brewer on its side. At present the absolute irradiance calibration is carried out once a year. It is planned to increase this to twice a year, with a monthly check of the calibration stability. The cosine response has been determined for a point source. It is planned to improve the applied correction, which does not at present separate direct and diffuse radiation.
Ancillary Data: A complete set of meteorological measurements is recorded, including radiation, ozone (total and vertical profile) and aerosol measurements. Additional trace gases will be measured in the future.
Additional Remarks: The Brewer instrument is mainly used for total ozone measurements, with the ultraviolet spectroradiometric measurements as an additional programme.

Locality	Latitude	Longitude	Altitude	
Karlsruhe	49° 01' N	8° 25' E	116 m	DEK

Instrument Site	Country
Chemistry Building, University of Karlsruhe	Germany

Controlling Institute: Botanisches Institut der Universität Karlsruhe.
Description of Site: In the centre of the 300 m^2 roof area of the Chemistry building, on the university campus.
Outlook: The site is at the highest point of the university campus. There are no obstructions to the field of view by other buildings or equipment on the roof.
Surroundings: Forest extends to a distance of about 40 km to the north. The city of Karlsruhe lies to the west, south, and east at a distance of 2 to 3 km.
Instrument: Spectral irradiance is measured with an Optronic 752 spectroradiometer (labelled DEK in the intercomparison report) to which an optical fibre input has now been fitted.
Measurement Periods: In 1993 and 1994, measurements were made on most days from April to September. Occasional measurements were also made between October 1993 and April 1994.
Schedule: Scans were made at intervals of 15 minutes from dawn to dusk.
Operational Conditions: Measurements were made on clear and cloudy days, but not during precipitation.
Spectral Range and Duration of Scan: The spectrum was scanned from 290 nm to 700 nm in steps of 1 nm. The duration of a scan depends on the signal-to-noise ratio, varying from 15 minutes at sunrise and sunset down to 5 minutes at the highest solar elevation.
Calibration Methods: The wavelength calibration is checked every day with a 5 W fluorescent lamp. The spectral irradiance calibration is based on 1000 W FEL and 200 W DXW lamps with a horizontal calibrated beam. The calibration of the 1000 W lamp is NIST-traceable. The 200 W calibration is carried out every two months. A calibration check with a 5 W transportable lamp is performed every day.
Ancillary Data: Pressure and temperature are recorded, and a quantum sensor provides a measurement of photosynthetically-active radiation in the visible region of the spectrum.

Locality	Latitude	Longitude	Altitude	DEM
Munich	48° 13' N	11° 35' E	500 m	

Instrument Site	Country
GSF, Neuherberg	Germany

Controlling Institute: Fraunhofer-Institut für Atmosphärische Umweltforschung (IFU), Garmisch-Partenkirchen.
Description of Site: On the roof of the BIOP institute building on the GSF campus.
Outlook: There were no obstructions on the roof itself, and nearby buildings obscured less than 5° of the sky above the horizon.
Surroundings: The instrument was located on the roof of the detached institute building, which is at the end of a track and surrounded by meadows and woodland. The city of Munich begins at a distance of 2 km to the south.
Instrument: Spectral irradiance measurements were made with a Bentham DM300 spectroradiometer. There was no temperature stabilisation in 1986 and 1987, but all measurements from 1988 onwards were carried out with the instrument temperature stabilised at 20° ± 0.5° C.
Measurement Periods: Sporadic measurements were made in 1986 and 1987, mainly near noon. More regular measurements were carried out for a three-week period in summer 1988, six weeks in late spring 1989, and four weeks in summer 1990. A period of only a few days in 1991 (Jul 28 to Aug 2) was followed by a longer programme in 1992 (Apr 21 to Aug 4).
Schedule: Scans were recorded at intervals of 5 to 10 minutes from dawn to dusk.
Operational Conditions: The instrument ran unattended under automatic operation in clear and cloudy conditions.
Spectral Range and Duration of Scan: The spectrum was scanned from 285 nm to 410 nm with a scan duration of 5 minutes. From 1986 to 1990 the measurements were made with a bandwidth of 2.5 nm and a wavelength step of 1 nm below 320 nm and 2.5 nm above. In 1991 and 1992, the bandwidth and the step were both 1 nm.
Calibration Methods: Wavelength calibration was obtained with a low-pressure pen-ray mercury lamp. The spectral irradiance standard was a 100 W lamp with a certificate from NPL. During measurement periods, calibrations were performed about once per week using a 100 W lamp in a specially designed housing without moving the instrument. The angular response of the detector was measured by commercial consultants PRC Krochmann. The slit function was measured mainly at the 254 nm mercury line.
Field Stations: In autumn 1989, spectral irradiance measurements were carried out on the Wank Mountain, (47° 31' N, 11° 09' E, 1780 m).

Locality	Latitude	Longitude	Altitude	FR
Lille	50° 37' N	3° 10' E	40 m	

Instrument Site	Country
Building P5, Cité Scientifique, Villeneuve d'Ascq	France

Controlling Institute: Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille.
Description of Site: The site is located on the campus of the Université des Sciences et Technologies de Lille, Cité Scientifique, Villeneuve d'Ascq. The spectroradiometer is placed centrally on the roof of the Physics building P5, where about 30 m^2 of roof area is available.
Outlook: The skyline is generally below 5° elevation, with only the occasional obstruction in the range 5° to 10°.
Surroundings: There are some lawns and woods between the university buildings, which lie within 800 m of the site. Beyond that is agricultural land at a distance of 1 km to the east, while the city suburbs lie at about the same distance to the north and west.
Instrument: A Jobin-Yvon DH10 spectrometer (labelled FR in the intercomparison report) is operated with a quartz diffuser to measure global spectral irradiance.
Measurement Periods: So far only some tentative measurements have been made, in April and May 1994, on clear and cloudy days.
Operational Conditions: The instrument operates automatically, but measurements are not made during precipitation.
Spectral Range and Duration of Scan: The spectrum is scanned from 280 nm to 500 nm in steps of 0.5 nm. The duration of a scan is 200 s.
Calibration Methods: Wavelength calibration has been obtained with reference to the Fraunhofer lines in the solar ultraviolet spectrum. Spectral irradiance calibrations have previously been made at IASB, Brussels. However, it is planned to make these calibrations on site in the near future by installing a certificated standard lamp. The IASB calibrations were made with 1000 W and 200 W lamps.
Ancillary Data: Atmospheric optical depth is measured with a photometer.

Locality	Latitude	Longitude	Altitude	
Reading	51° 26' N	0° 56' W	68 m	GB

Instrument Site	Country
Department of Meteorology, University of Reading	United Kingdom

Controlling Institute: Department of Meteorology, University of Reading.
Description of Site: Before Dec 1992: At the centre of the north edge of the roof of K spur, on the Meteorology building. After Dec 1992: In the engineering shed on the meteorological site, in the north-east corner of the compound, with the diffuser mounted above the apex of the roof. The two sites are about 250 m apart.
Outlook: Current site: The nearest buildings are about 100 m to the NNE (8.2 m high), 75 m to the south (14.3 m high), and 95 m to the east (3 m high). There is a tennis court to the north, and a 10 m anemometer tower 30 m to the east.
Surroundings: The campus of parkland and university buildings extends for 0.25 km to the N and E, 0.5 km to the S and 1 km to the W. It is surrounded by residential areas. Reading lies 3 km to the NW. The nearest open land is 2 km to the N, 3 km to the S and E, and 8 km to the W, a mixture of farmland, villages, woodland and water.
Instruments: Two Optronic 742 spectroradiometers have been used to measure global solar irradiance. Before Dec 1992, the instrument was placed outside only while measuring. There was no rigorous temperature control. After Dec 1992, the optics head was in a temperature-stabilised cabinet and was fitted with an optical fibre and external diffuser. The instrument was permanently mounted at the observing site.
Measurement Periods: (a) From August 1989 to December 1992.
(b) From December 1992 to the present (except January 1993, July 1993, and occasional breaks of some days or weeks).
Schedule: Before December 1992, measurements were made on an occasional basis. After December 1992, measurements were made hourly from sunrise to sunset.
Operational Conditions: Before December 1992, the instrument was operated in manual or semi-automatic mode, predominantly in clear conditions. After December 1992, measurements were made automatically in all conditions.
Spectral Range and Duration of Scan: Before Dec 1992, the spectral range was 280 nm to 400 nm in steps of 1 nm, with a scan duration of 4 minutes. After Dec 1992, it was 280 nm to 500 nm at 2 seconds per 1 nm step, scan duration 7.5 minutes.
Calibration Methods: Wavelength calibration is obtained by mercury lamp. Since July 1992, Fraunhofer lines have also been used to check the alignment before each scan. Before 1992, the irradiance calibration was checked twice a year at consultants Glen Spectra. A 5 W tungsten lamp monitored the stability to within about 4%. Since 1992, the calibration has been based on a NIST-traceable 1000 W FEL lamp with a horizontal calibrated beam. A subsidiary 1000 W lamp is kept as a working standard. Field calibrations are performed every one or two weeks, using one of several 200 W transfer lamps which are operated with a vertical beam. Slit functions have been determined with a HeCd laser and a mercury lamp. After the 1993 intercomparison, the instruments were adjusted to give more symmetric slit functions. Cosine response is measured on a turntable, using a laser with a beam expander and spatial filter.
Ancillary Data: A photodiode is used to monitor the stability of visible radiation during each scan. Pyranometers record hourly averages of global and diffuse irradiance. A broadband erythemal UV detector was installed in January 1994. Standard meteorological parameters are also available on site.
Additional Remarks: No distinction is made between data from the instruments which have been in use since 1991. They have virtually identical characteristics, and have been calibrated by the same standard lamps. Before Dec 1992, the instruments were not fully temperature-regulated, and were not routinely calibrated and deployed. Data prior to Dec 1992 are therefore sporadic and less accurate than subsequent data.

Locality	Latitude	Longitude	Altitude	
Thessaloniki	40° 37' N	22° 58' E	60 m	GR

Instrument Site	Country
Physics Department, University of Thessaloniki	Greece

Controlling Institute: Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki.
Description of Site: Both spectroradiometers are located on the south part of the Physics building roof. The roof has an area of about 100 m^2 covered with asphalt.
Outlook: The sky is partly obscured by the wall of a building which extends to the north of the input optics of both instruments. The wall has an area of 15 m^2 and is 50% cream-coloured PVC and 50% glass. From the point of view of the single-monochromator Brewer, the wall is 3 m away and rises to 2 m above the horizon. For the double Brewer it is 5 m away and 2.5 m above the horizon.
Surroundings: Within a radius of about 500 m the area is covered by concrete buildings (50%), grass (30%), and trees (20%). Beyond that, within a distance of 10 km, the southern sector is covered by sea water, the northern sector by pine forest, and the eastern and western sectors by city buildings, 90% of which have concrete roofs.
Instruments: Two Brewer spectrophotometers have been operated: one with a single monochromator (MK II) and one with a double monochromator (MK III). No significant modifications have been made to these instruments.
Measurement Periods: Measurements have been carried out with the single Brewer on a regular basis since October 1989. The double Brewer has been operated for intermittent periods of one to four months at a time since May 1993.
Schedule: At the start of the programme the single Brewer recorded one global irradiance scan at local noon. The frequency of observations was progressively increased in 1990 to five per day. Since September 1992, global scans have been performed at intervals of about 5° in solar elevation from sunrise to sunset. Direct solar irradiance is also recorded several times per day. A similar schedule has been operated on the double Brewer, with direct scans since February 1994.
Operational Conditions: The instruments run unattended, making automatic observations during all weather conditions.
Spectral Range and Duration of Scan: The single Brewer scans the ultraviolet spectrum from 290 nm to 330 nm in steps of 0.5 nm, with a scan duration of 160 s. The double Brewer scans from 287.5 nm to 366.0 nm, also in 0.5 nm steps, and takes 450 s for each scan.
Calibration Methods: The wavelength calibration is based on an internal mercury lamp. The spectral irradiance calibration is obtained from a 1000 W DXW lamp with a vertical beam; one such lamp has a NIST-traceable calibration, and three others are working standards. The stability of the instrument calibration is monitored by means of five 50 W lamps, used about once per two weeks. The 1000 W working standards are measured every two months and the principal 1000 W standard every six months.
Ancillary Data: In addition to the spectral ultraviolet measurements, the two Brewer instruments also measure the total column of ozone and sulphur dioxide. Pyranometer data, broadband erythemal UV dose (global and diffuse) and UVA pyranometer data are all recorded every minute together with the standard deviation of the instantaneous measurements taken within the one-minute interval. The detailed pyranometer measurements are used to reject those spectral scans that are obtained during rapidly changing atmospheric conditions (e.g. fast-moving broken clouds). Cloud cover information and meteorological data are available from the local meteorological office.
Field Stations: Spectral measurements have also been carried out in Reykjavik (64° 08' N, 21° 54' W) in collaboration with Icelandic colleagues.

Locality	Latitude	Longitude	Altitude	
De Bilt	52° 06' N	5° 11' E	17 m	NLK

Instrument Site	Country
Royal Netherlands Meteorological Institute	Netherlands

Controlling Institute: Royal Netherlands Meteorological Institute (KNMI), De Bilt.
Description of Site: The instruments are mounted on top of a container on the roof at the southern end of a four-storey building at KNMI.
Outlook: The horizon is almost clear, except for a satellite dish on the adjacent roof at very low elevation to the north-west, a tall brick tower to the north, on top of which is a precipitation radar, and a few isolated antenna masts.
Surroundings: Apart from a few houses close by, the institute is surrounded by parkland with trees, meadow, and gardens. The city of Utrecht lies in the western and southern quadrants at a distance of about 5 km. To the north is the town of Bilthoven at about 1 km. In the north-east quadrant the land is forested. The town of Zeist is at a distance of 5 km to the south-east, with forest beyond.
Instruments: Two ultraviolet spectroradiometers are in use: the EG&G diode-array spectrograph (labelled NLK in the intercomparison report) and a double-monochromator Brewer spectrophotometer. The diode-array spectrograph is an experimental instrument, which will shortly be improved by the introduction of temperature stabilisation. The double Brewer is identical to the one deployed by the GR team in Thessaloniki.
Measurement Periods: Experimental measurements started in 1993 with the diode-array spectrograph but were not performed on a regular basis. A routine monitoring programme began in January 1994, based on the Brewer instrument.
Schedule: Global spectral irradiance is recorded at intervals of 5° in solar elevation from sunrise to sunset.
Operational Conditions: Measurements are performed automatically under all weather conditions.
Spectral Range and Duration of Scan: The Brewer scans the spectrum from 286.5 nm to 364.5 nm in steps of 0.5 nm, with a scan duration of about 8 minutes. The diode-array instrument covers the range from about 290 nm to 420 nm with an array of 1024 diodes. Integration times are typically between 0.3 seconds and 6 seconds.
Calibration Methods: For the diode-array spectrograph, the wavelength calibration is obtained from a low-pressure mercury lamp. Spectral irradiance is calibrated using two 1000 W FEL NIST-traceable standard lamps with a horizontal beam, and one 200 W transfer standard. The Brewer is calibrated in wavelength using the internal mercury lamp, supplemented by scans on an external mercury lamp. To date, the spectral irradiance calibration for the Brewer has been obtained from the manufacturers. The stability of the calibration is routinely checked every two weeks with 50 W lamps. A calibration facility is under construction at KNMI, to be based on 1000 W DXW lamps with a vertical beam. A 1000 W calibration will be performed every two months. This facility will also be suitable for cosine response measurements. At present, these are performed on a rotating table, with the lamp in a fixed position. Slit functions have been determined with a mercury lamp.
Ancillary Data: Meteorological data are recorded routinely (including pressure, temperature, humidity, cloud cover, sunshine duration, and a weekly ozone ascent). Additional radiation instruments include pyranometers for global and diffuse irradiance, a pyrheliometer, and narrowband ultraviolet meters for global and direct radiation at 306 nm (4 nm FWHM) and 367 nm (10 nm FWHM).

Locality	Latitude	Longitude	Altitude	NLR
Bilthoven	52° 07' N	5° 11' E	0 m	

Instrument Site	Country
Nat. Inst. of Public Health & Environmental Protection	Netherlands

Controlling Institute: National Institute of Public Health and Environmental Protection (RIVM), Bilthoven.
Description of Site: The instrument truck is located on a small square surrounded by grass, at a distance of about 50 m to the east of the nearest institute buildings.
Outlook: In most directions there are trees rising to between 5° and 15° above the horizon. One tree reaches 19°. The institute buildings do not exceed 10°.
Surroundings: The institute buildings lie within 500 m. Beyond that, the city of Utrecht and its suburbs extend to the south and south-west. In the north-east quadrant the land is forested. The town of Zeist is at a distance of 5 km to the south-east, with forest beyond. To the west is motorway.
Instruments: Two instruments are in use: a scanning spectroradiometer and a diode-array spectrograph. The DILOR XY-50 spectroradiometer is a double monochromator with 9883QB photomultiplier operated in photon counting mode. The EG&G model 1235 spectrograph is combined with a 1453A diode-array detector and 1471A detector interface. Each instrument has an integrating sphere, with lenses and mirrors to couple light into the monochromator.
Measurement Periods: Measurements began in April 1993 on an irregular basis, with varying time intervals and wavelength ranges. Since February 1994, monitoring has been carried out according to a fixed protocol, interrupted only for calibrations of the system and intercomparisons.
Schedule: Global solar irradiance is measured every 12 minutes from sunrise to sunset.
Operational Conditions: The instruments run unattended under automatic operation.
Spectral Range and Duration of Scan: The spectroradiometer scans from 285 nm to 355 nm in steps of 0.5 nm, with a scan duration of 9 minutes. The spectrograph covers the range 300 nm to 450 nm in steps of 0.15 nm with a measurement duration of 2.1 seconds. The spectrograph makes a measurement at every step of the spectroradiometer, averaging the results and presenting the statistical variations at selected wavelengths.
Calibration Methods: The wavelength calibration is performed using a low-pressure mercury lamp. The wavelength setting is checked after each scan using the Fraunhofer structure in the solar spectrum. The spectral irradiance calibration is performed with a 1000 W DXW lamp with a certificate traceable to NIST. The lamp is used with the beam vertical. Absolute spectral irradiance calibrations are not performed regularly. The calibration is checked daily with a secondary standard consisting of a 200 W lamp in a housing. When changes in the recorded signal of this lamp are found the system is recalibrated against the 1000 W DXW lamp. The slit function is determined with the 325 nm line of a HeCd laser.
Ancillary Data: A pyranometer and an ultraviolet broadband meter are operated. LIDAR measurements of aerosol and ozone profiles are made on the site.

Locality	Latitude	Longitude	Altitude	
Tromsø	69° 40' N	18° 56' E	100 m	NO

Instrument Site	Country
Auroral Observatory, University of Tromsø	Norway

Controlling Institute: Auroral Observatory, University of Tromsø.
Description of Site: The instrument is on a wooden platform at the north end of the roof of the main building of the Auroral Observatory.
Outlook: There is no obstruction from surrounding buildings. The high mountains in the distance extend only a few degrees above the horizon.
Surroundings: Institute buildings lie within 100 m to 300 m to the north-east of the main building. There is a small lake 200 m to 500 m to the south, and then the outskirts of the city of Tromsø. Sea areas are found on all sides at a distance of 1 km to 5 km, with mountains beyond.
Instrument: A Jobin-Yvon HR320 single monochromator has been operated with a teflon diffuser which has a thickness of 3.2 mm. For recent measurements, a JY optical fibre input has been fitted. Temperature stabilisation has been introduced for the diffuser, optical fibre, monochromator, preamplifier and high voltage power supply. The photomultiplier is cooled.
Measurement Periods: Measurements have been carried out sporadically during the continual development of the spectrometer system since the inception of the project in 1991. A regular programme of measurements was carried out from January to April 1992 in Tromsø, and from 20 to 28 July 1992 at the field station on Spitzbergen.
Schedule: One global irradiance scan is made every 15 minutes from dawn to dusk. In the period of the midnight Sun, measurements are made 24 hours a day.
Operational Conditions: Measurements are made under automatic operation on clear and cloudy days and in all weather conditions.
Spectral Range and Duration of Scan: In earlier periods the spectrum was scanned from 290 nm to 600 nm in steps of 0.1 nm with a scan duration of 7 minutes. Recent measurements have covered the range 280 nm to 600 nm with a 0.5 nm step and a duration of 5 to 10 minutes.
Calibration Methods: The wavelength calibration is obtained initially by mercury lamp, and subsequently checked by the use of solar Fraunhofer lines. The spectral irradiance calibration is based on a 1000 W FEL lamp from Eppley, together with a subsidiary DXW lamp. Both lamps are traceable to NIST and are used with the beam horizontal. An absolute irradiance calibration was done before every major measuring period, but otherwise not more than twice a year. The slit function of the instrument has been determined using a mercury lamp at 296.7 nm and a HeNe laser at 632.8 nm.
Ancillary Data: Meteorological data are available from nearby weather stations both in Tromsø and on Spitzbergen.
Field Stations: A field station has been maintained at Longyearbyen on Spitzbergen (78° N, 16° E). From time to time the Tromsø instrument has been transported to Spitzbergen for periods of measurement when the Sun is above the horizon.

Appendix F. Publications

The following list contains a selection of relevant publications produced by the participants in the project in recent years.

Ambach, W. and Blumthaler, M. 1993. Biological effectiveness of solar UV radiation in humans. *Experientia, 49* (9), 747-753.

Bais, A.F. and Blumthaler, M. 1994. A small scale intercomparison of UV spectroradiometers. *Proc. European Symposium on Effects of Environmental UV Radiation, 27-29 October 1993, Munich,* (in press).

Bais, A.F. and Zerefos, C.S. 1993. The effect of changes in ozone on solar UV-B radiation at Reykjavik. In: Stamnes, K.H. (Ed.). Atmospheric radiation, pp. 263-267. *Proc. SPIE, 2049.*

Bais, A.F., Zerefos, C.S., Meleti, C., Ziomas, I.C. and Tourpali, K. 1993. Spectral measurements of solar UVB radiation and its relations to total ozone, SO_2, and clouds. *Journal of Geophysical Research, 98* (D3), 5199-5204.

Bais, A.F., Zerefos, C.S. and Tourpali, K. 1993. Solar UV-B measurements at high latitudes with a double monochromator Brewer spectrophotometer. *NATO Advanced Research Workshop on Atmospheric Studies by Optical Methods, 14-18 September 1993, Apatity, Russia.*

Bais, A.F., Zerefos, C.S., Meleti, C., Ziomas, I.C., Tourpali, K., Karaouza, V. and Balis, D. 1994. Variability of solar UV-B radiation at high and middle latitudes during EASOE 1991/92. *Geophysical Research Letters, 21* (13), 1403-1406.

Blumthaler, M. 1993. Solar UV measurements. In: Tevini, M. (Ed.). *UV-B radiation and ozone depletion,* pp. 71-94. CRC Press, Inc., Boca Raton.

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Blumthaler, M., Salzgeber, M. and Ambach, W. 1994. Ozone and ultraviolet-B irradiances: experimental determination of the radiation amplification factor. *Photochemistry and Photobiology,* (in press).

Blumthaler, M., Webb, A.R., Seckmeyer, G., Bais, A.F., Huber, M. and Mayer, B. 1994. Simultaneous spectroradiometry: a study of solar UV irradiance at two altitudes. *Geophysical Research Letters,* (in press).

Dirmhirn, I., Sreedharan, C.R. and Venugopal, G. 1993. Spectral ultraviolet radiation instrument and preliminary measurements in mountainous terrain. *Theoretical and Applied Climatology, 46* (4), 219-228.

Forster, P.M., Shine, K.P. and Webb, A.R. 1993. Comparison of radiation schemes for calculating UV radiation. In: Stamnes, K.H. (Ed.). Atmospheric radiation, pp. 129-138. *Proc. SPIE, 2049.*

Gardiner, B.G. and Kirsch, P.J. 1992. European intercomparison of ultraviolet spectrometers, Panorama, Greece, 3-12 July 1991. *Air Pollution Research Report 38.* Commission of the European Communities, Brussels, ISBN 2 87263 067 8, 70 pp.

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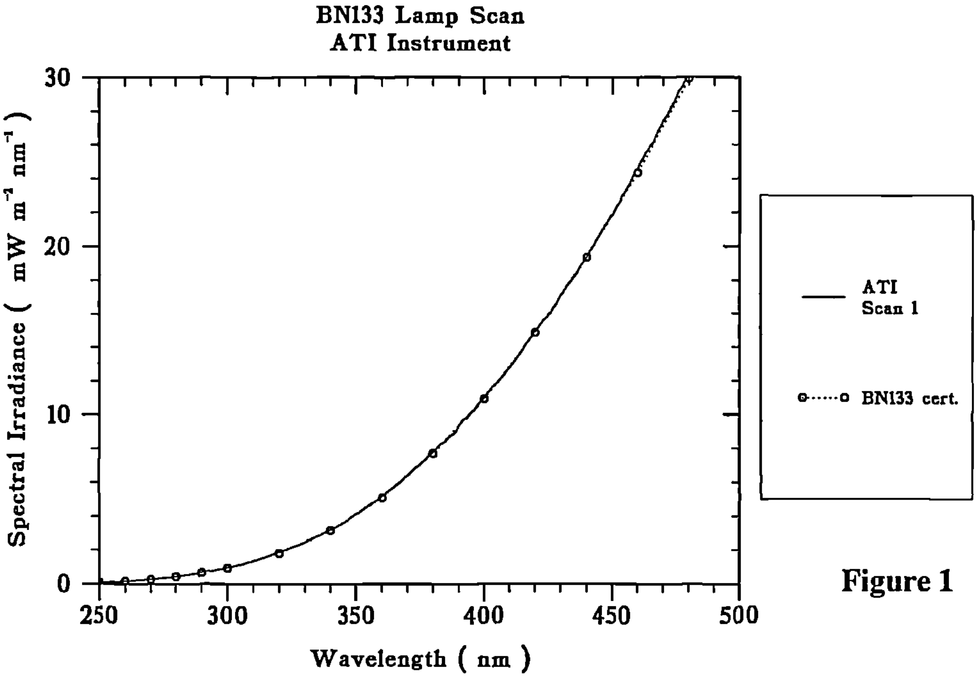

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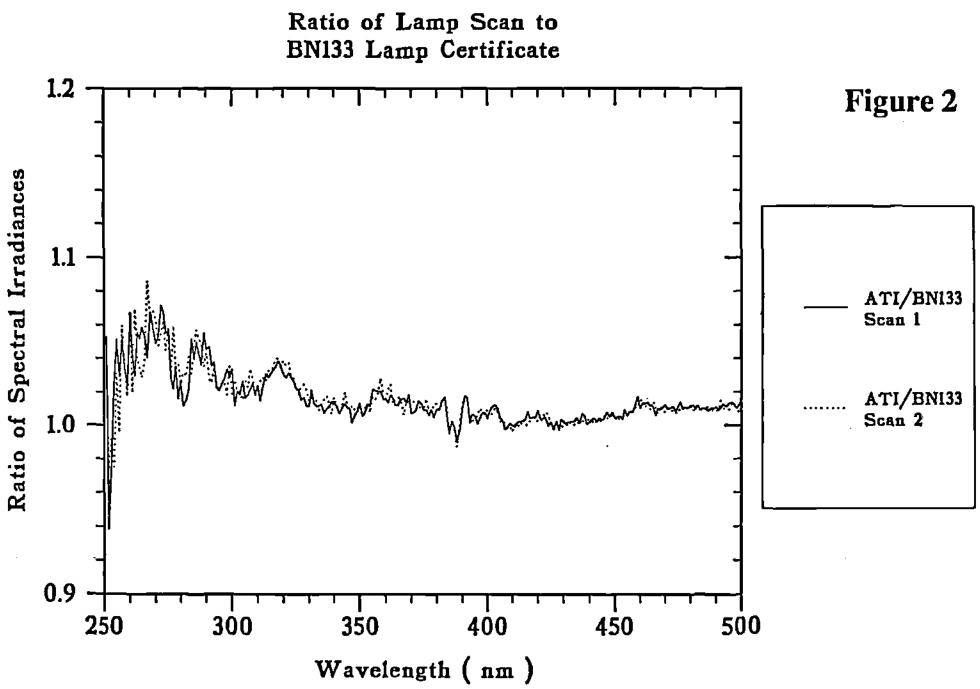

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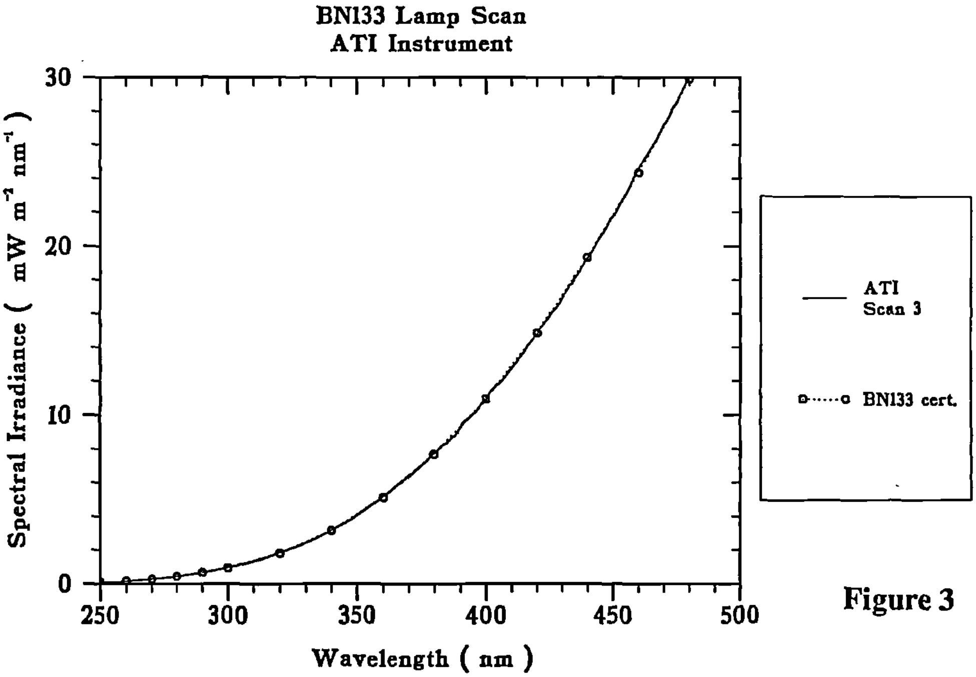

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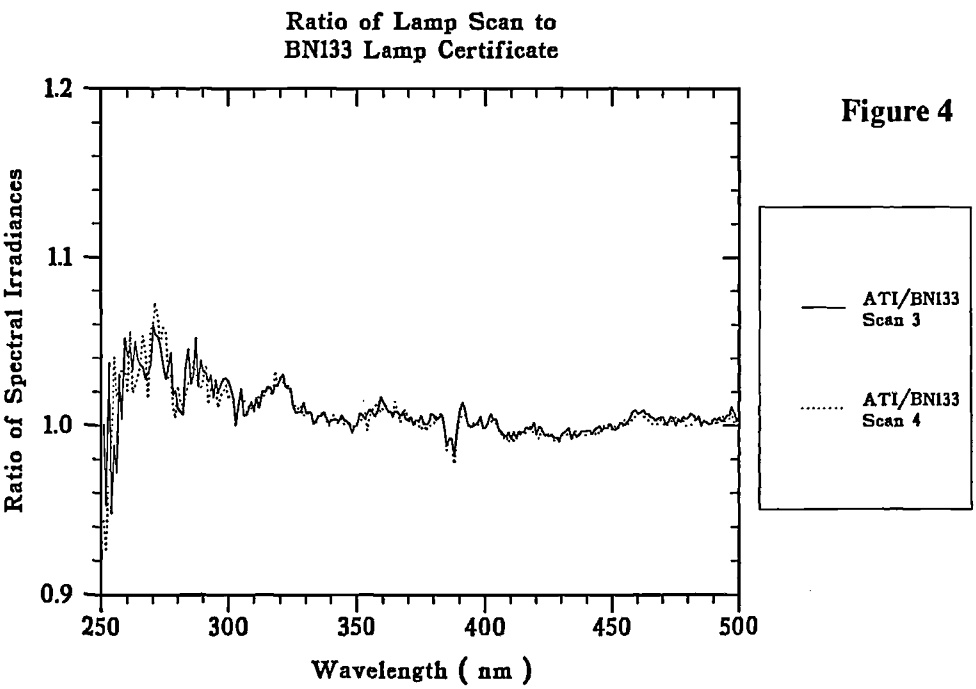

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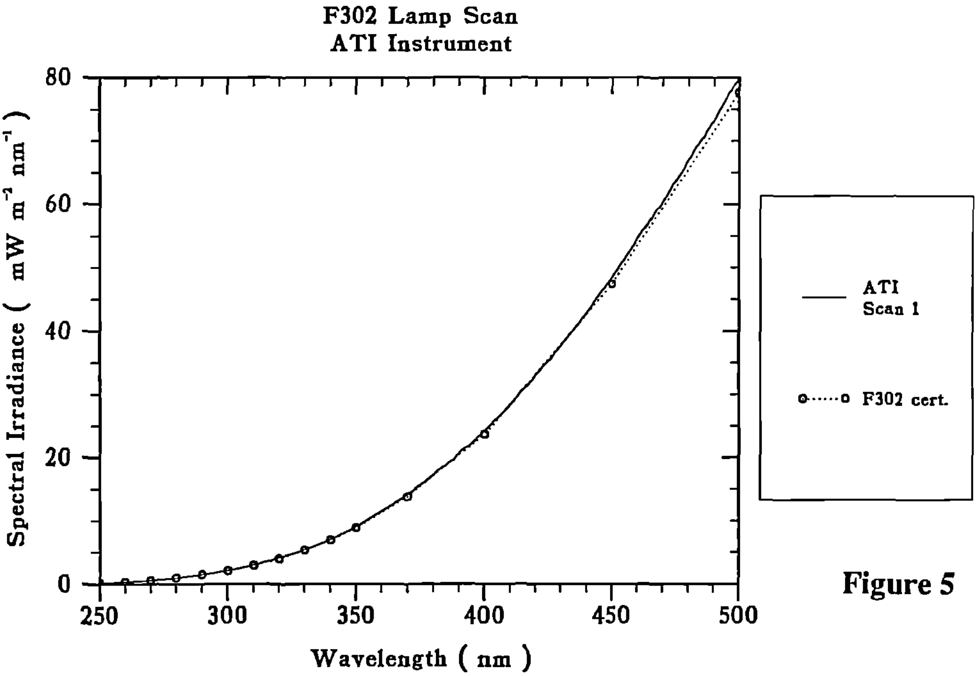

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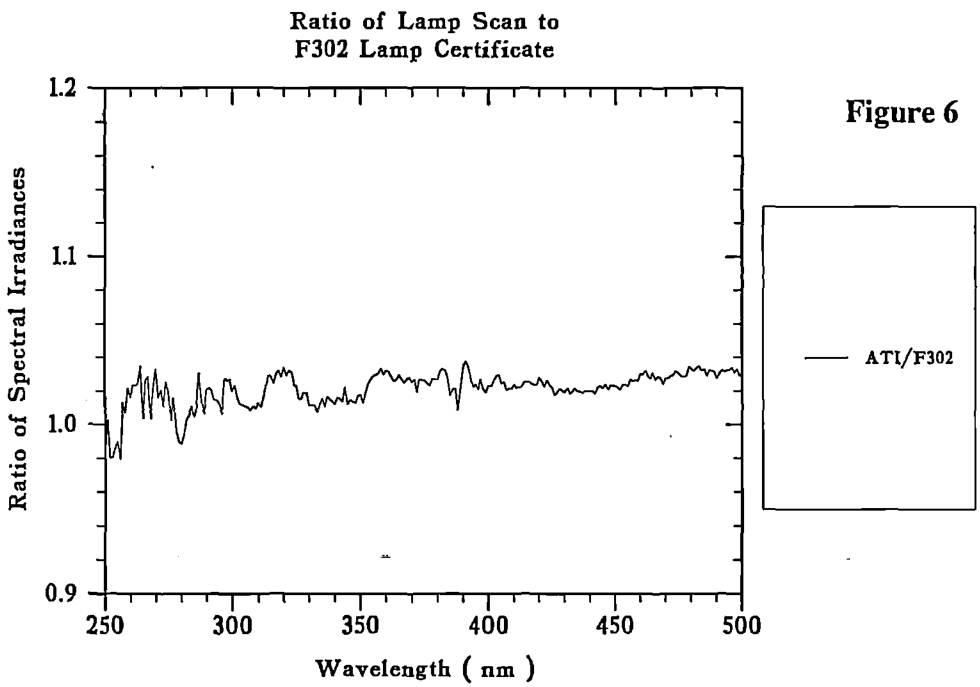

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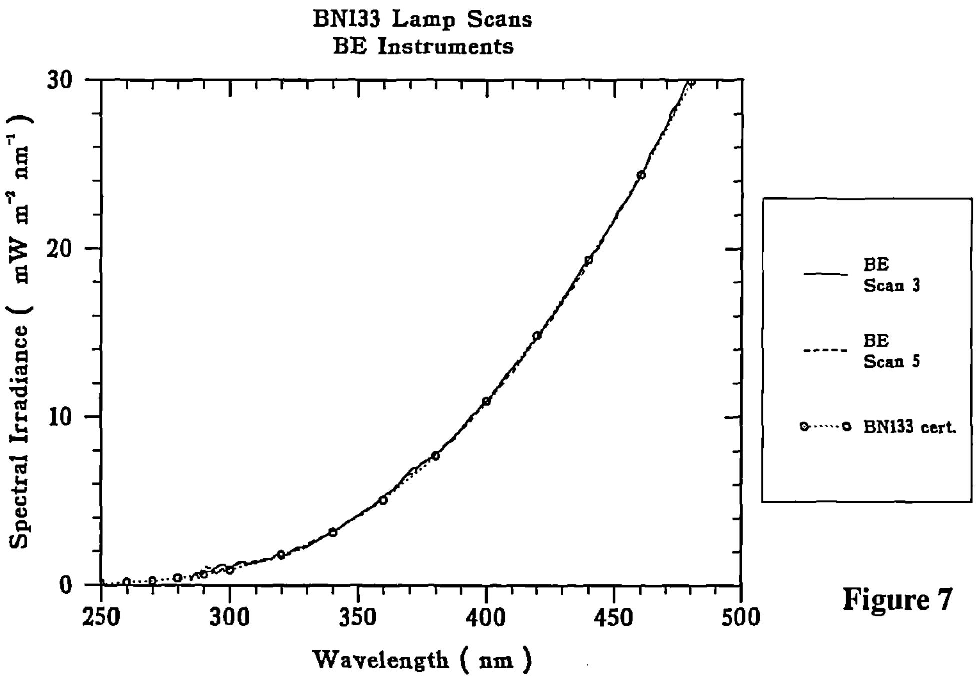

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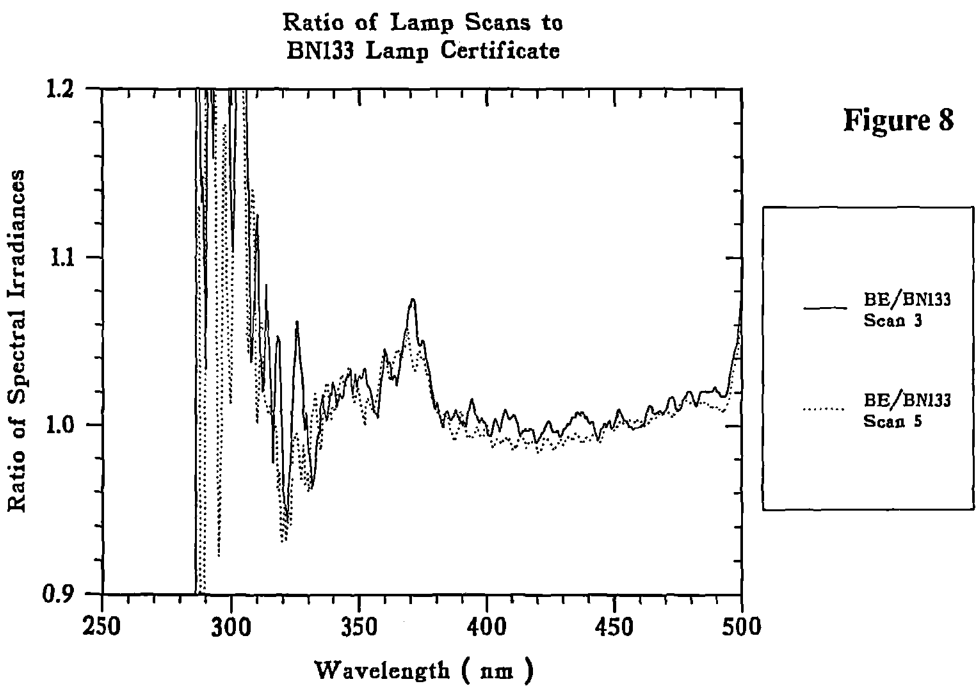

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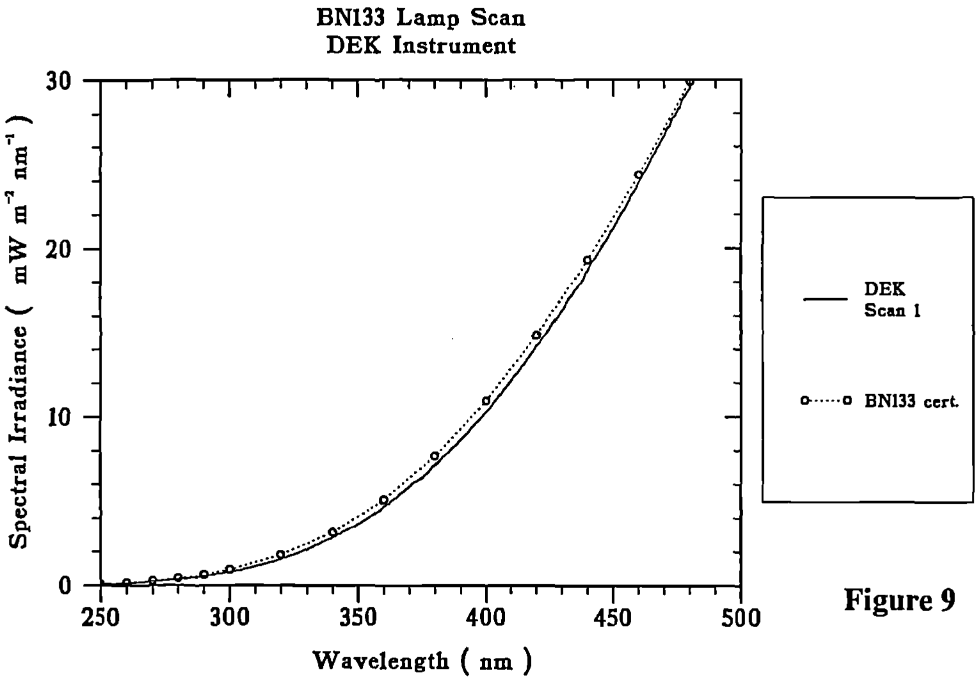

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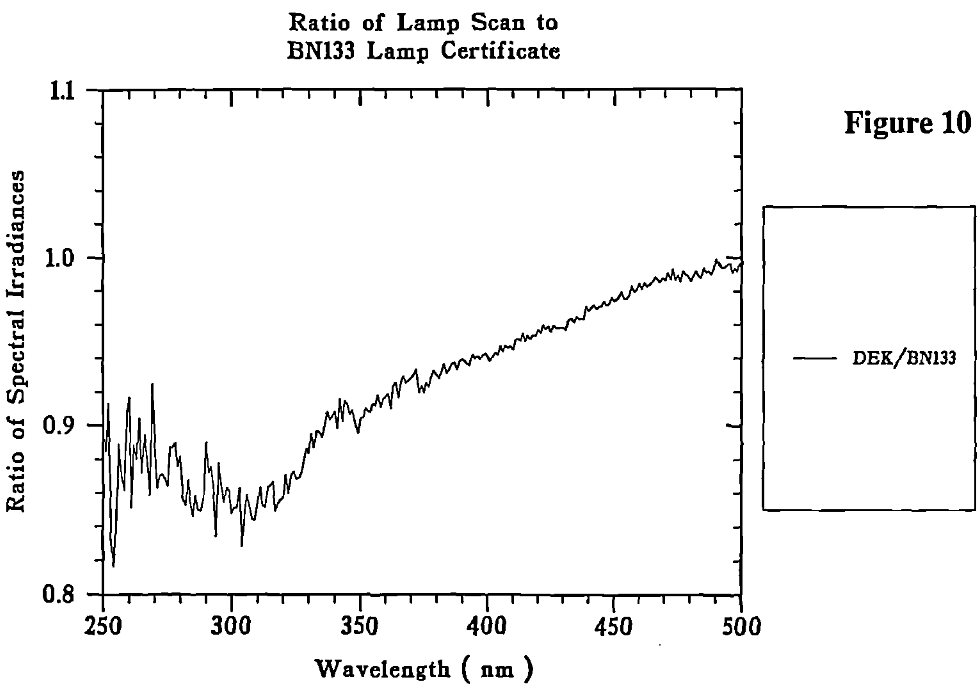

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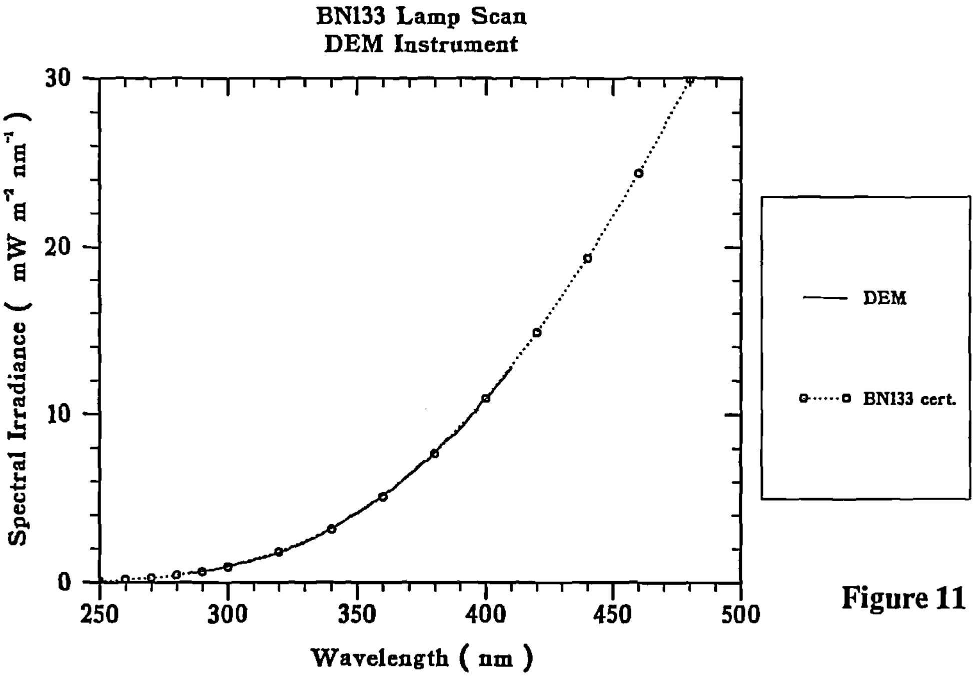

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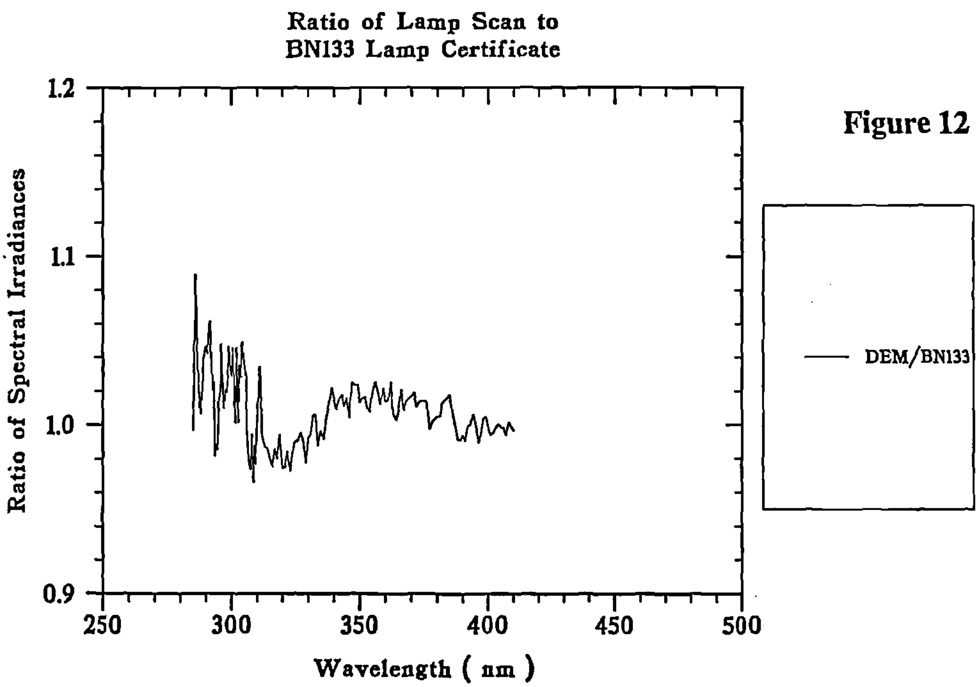

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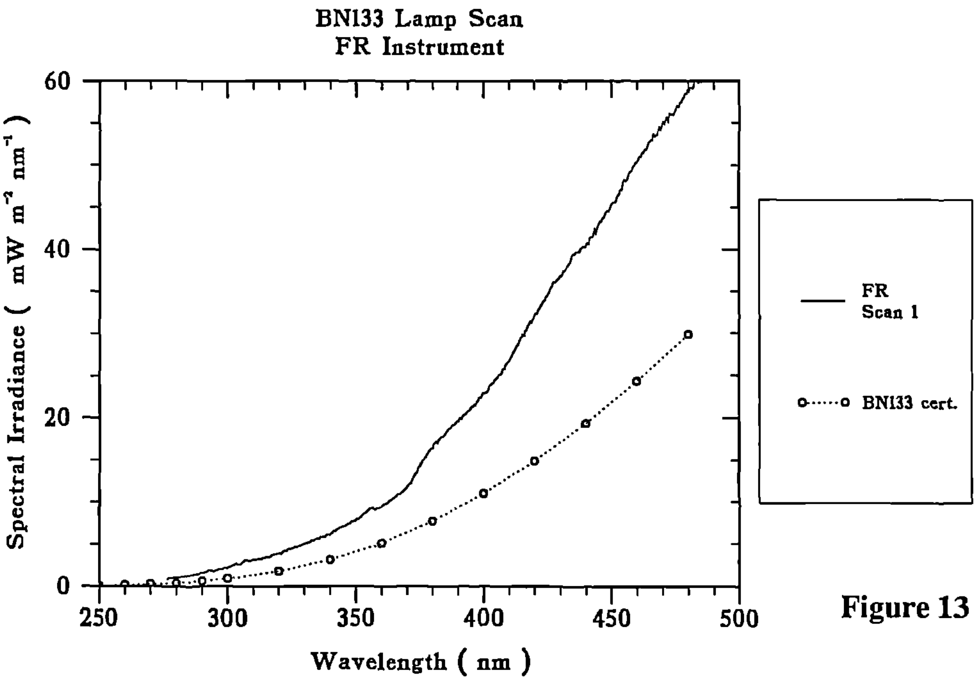

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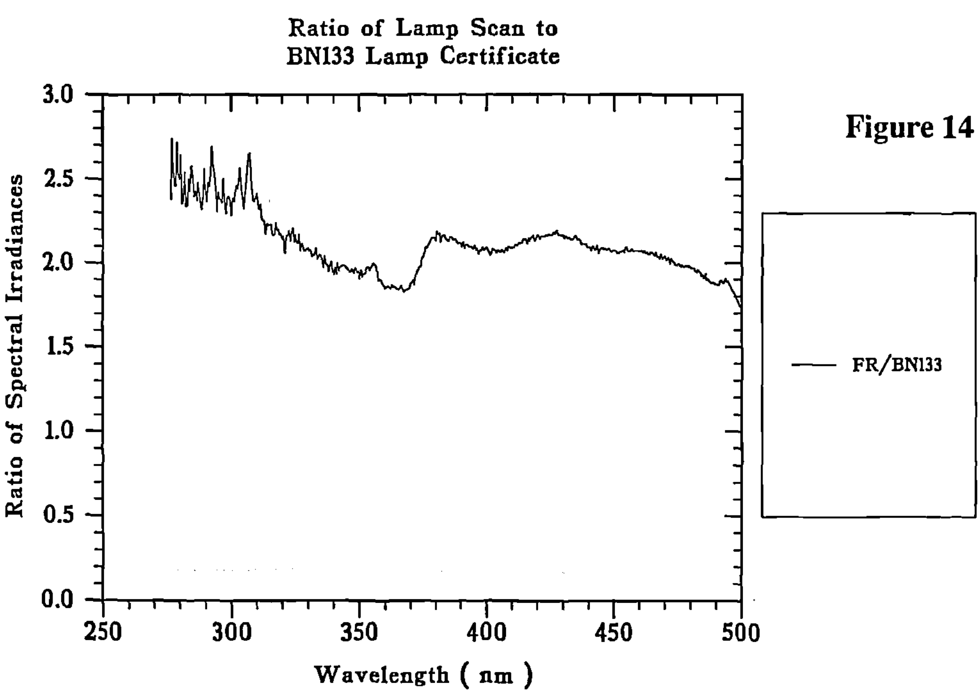

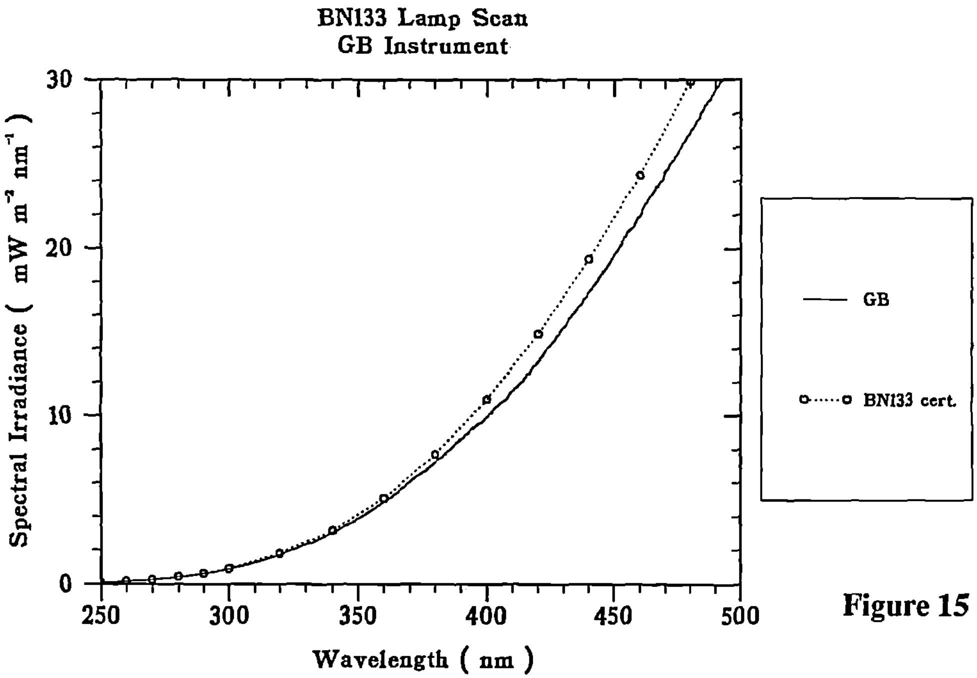

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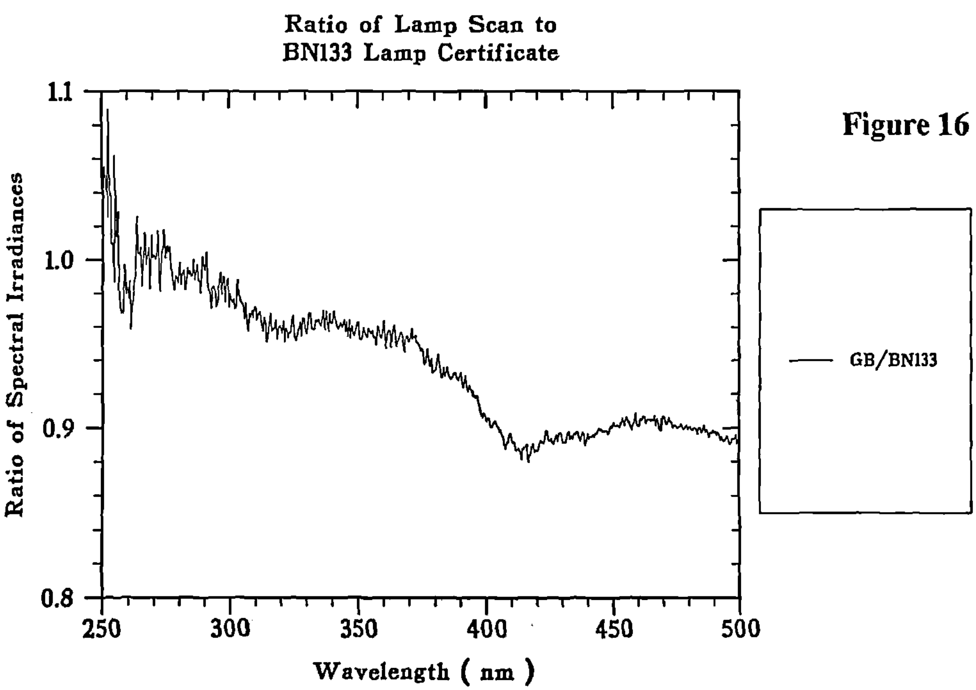

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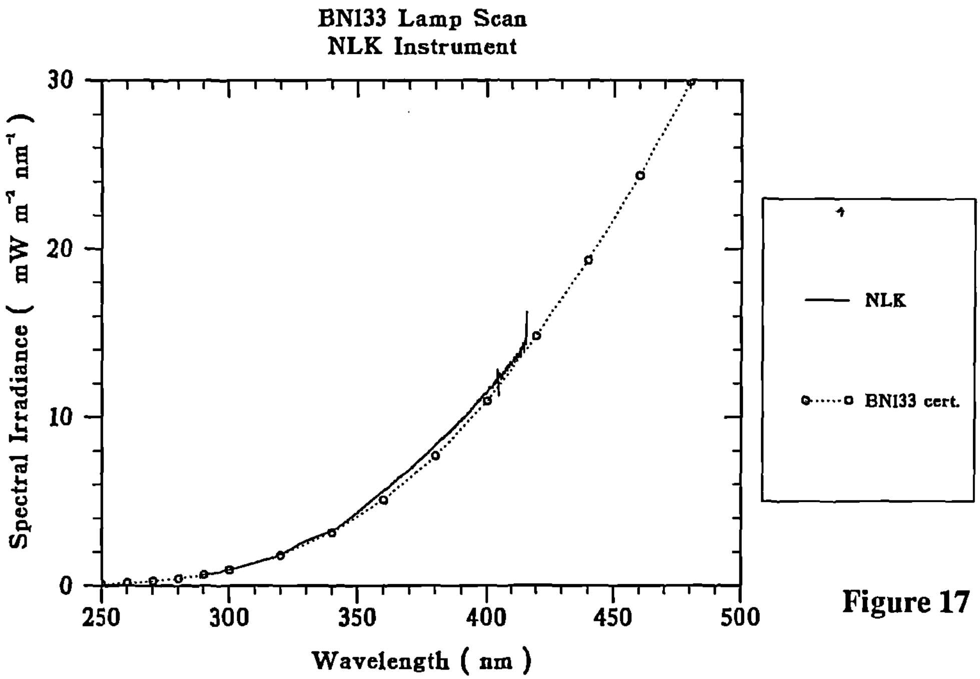

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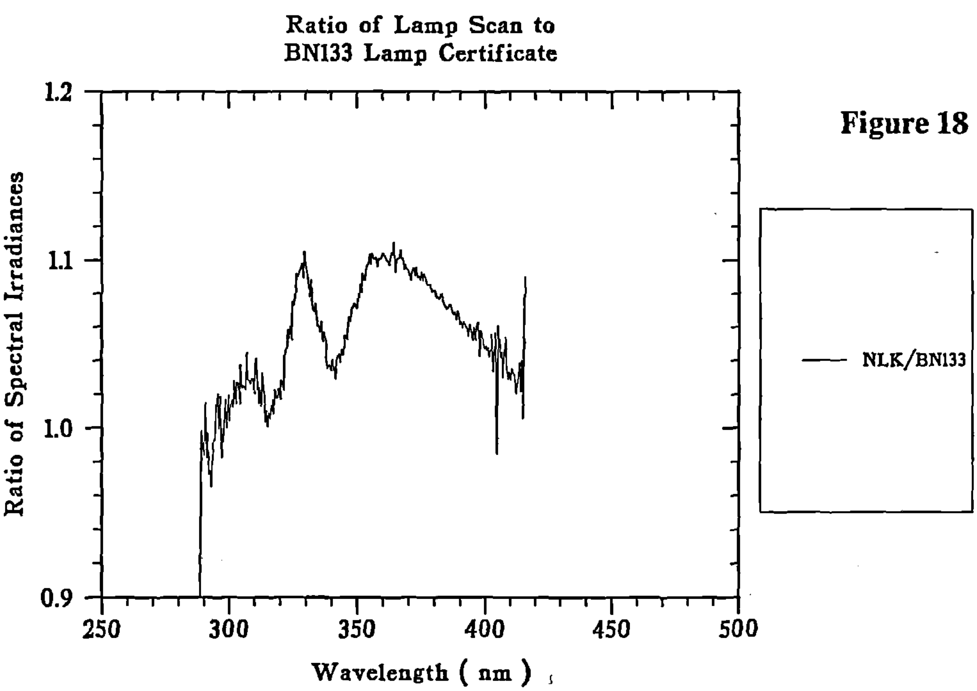

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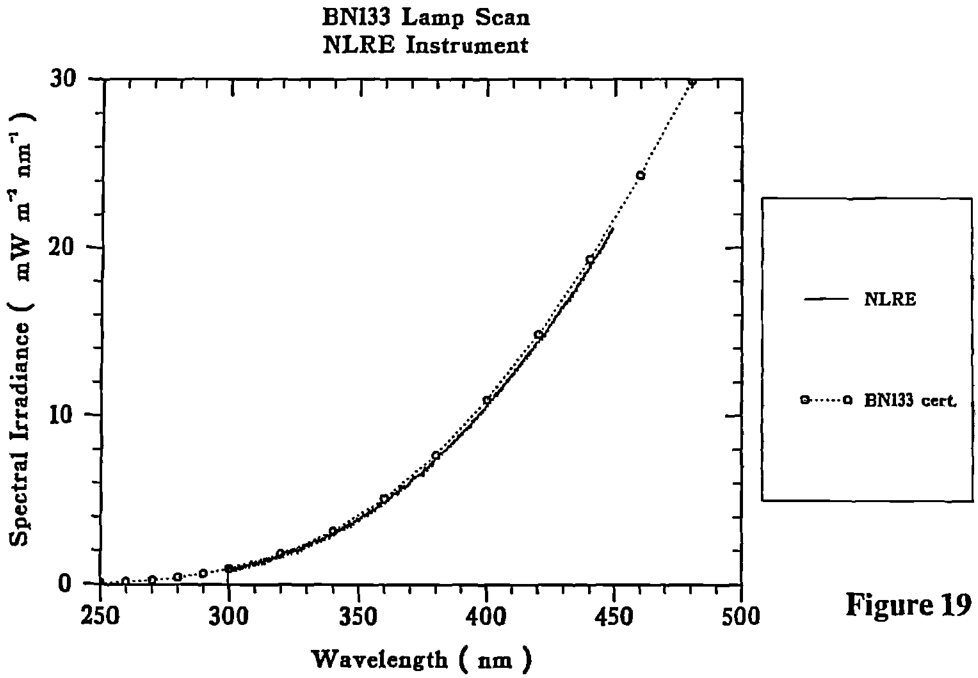

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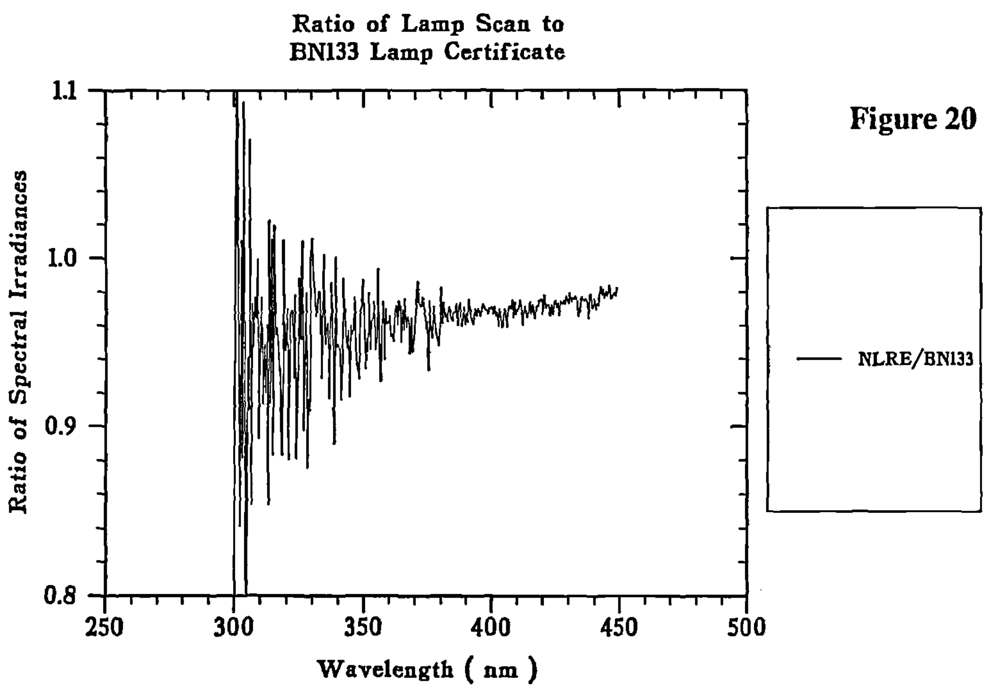

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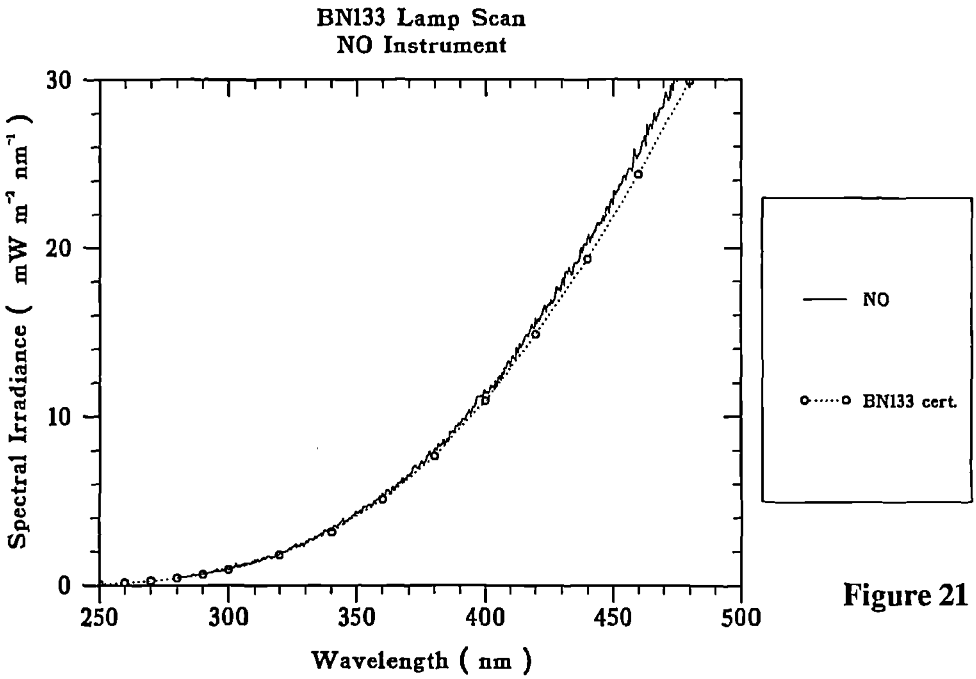

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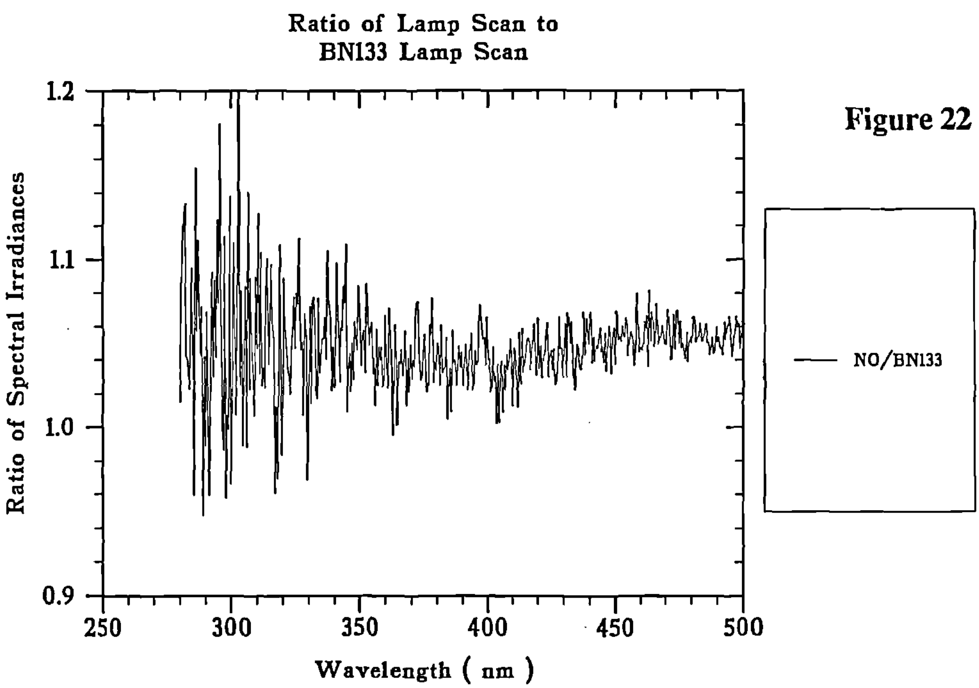

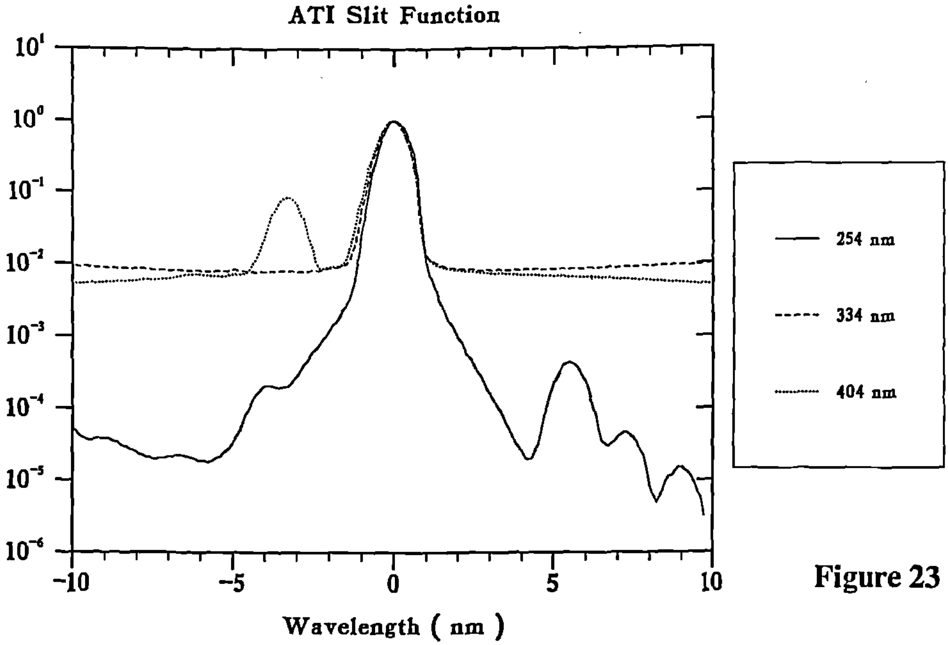

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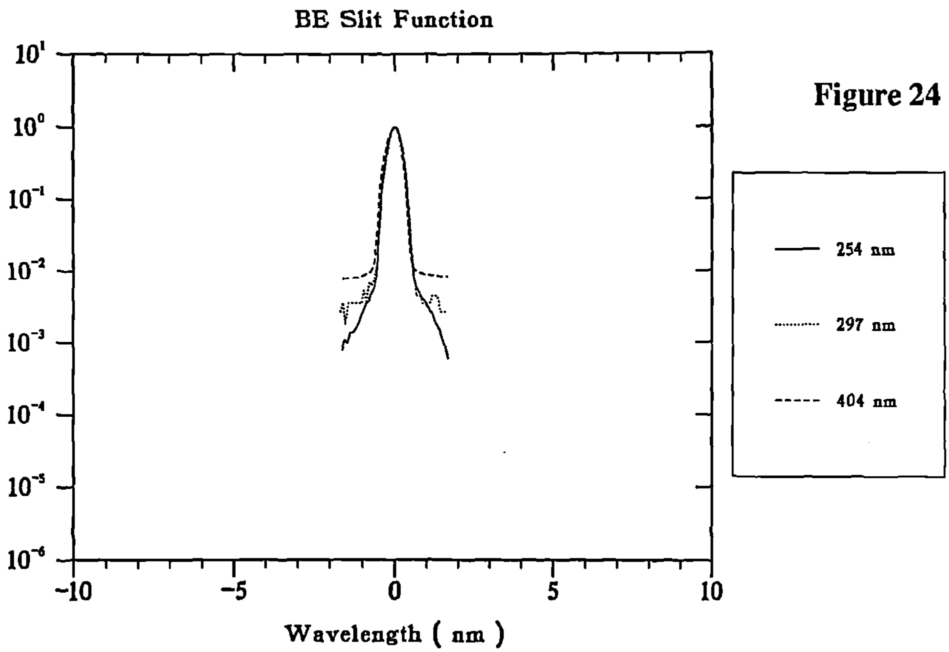

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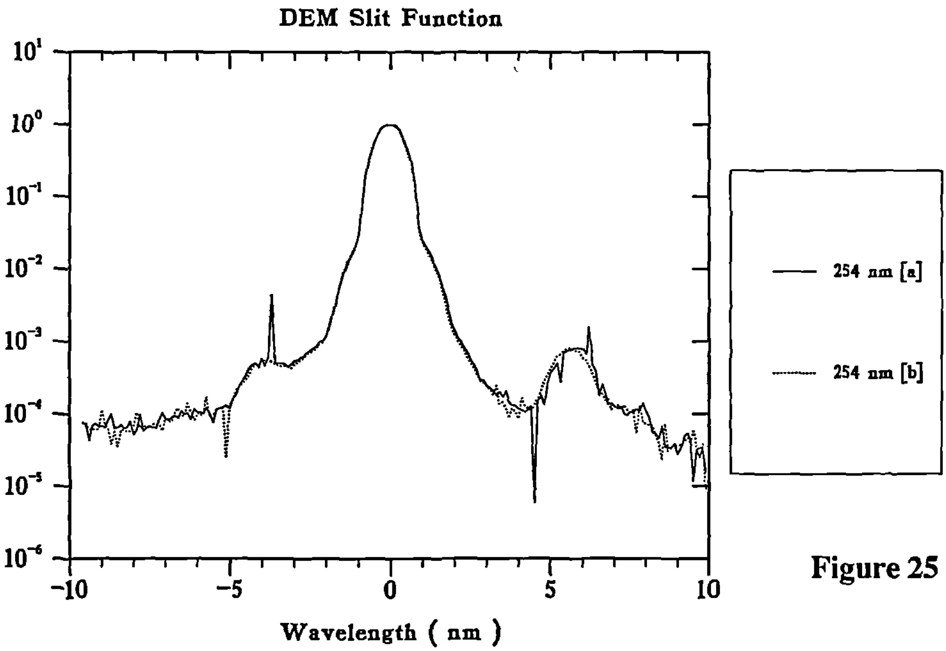

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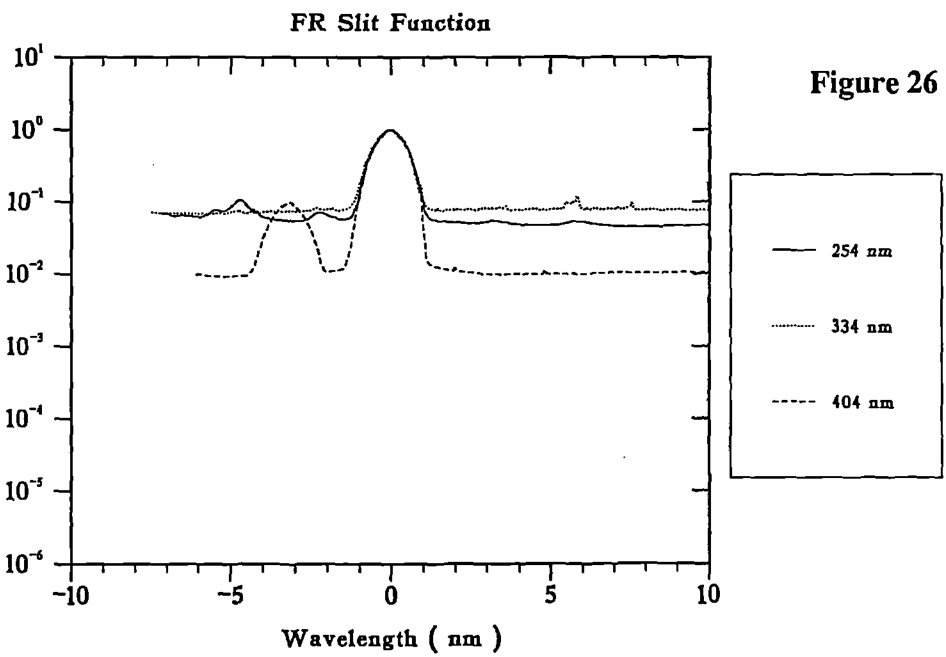

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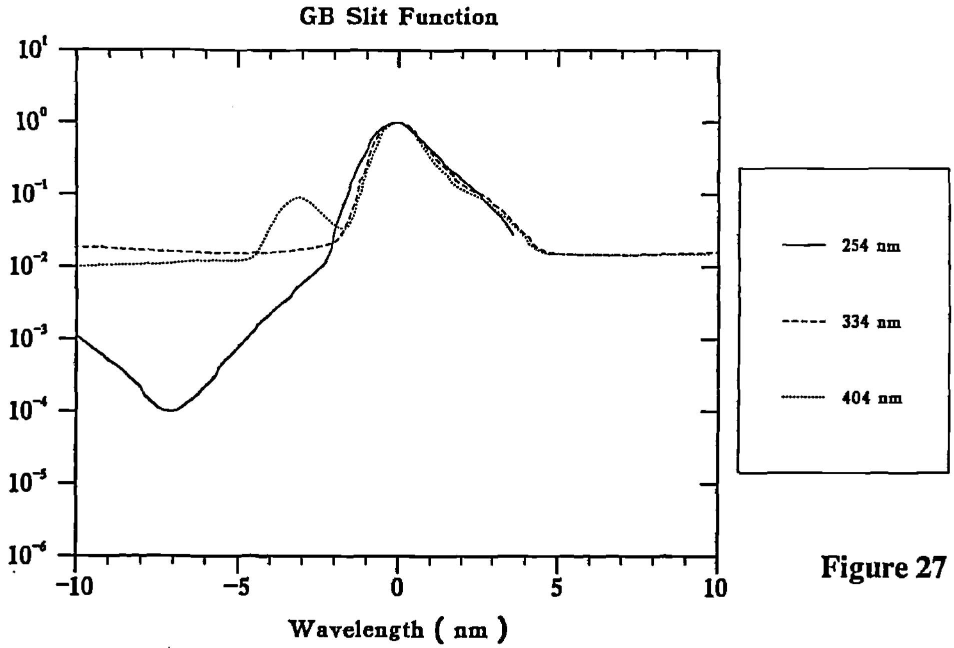

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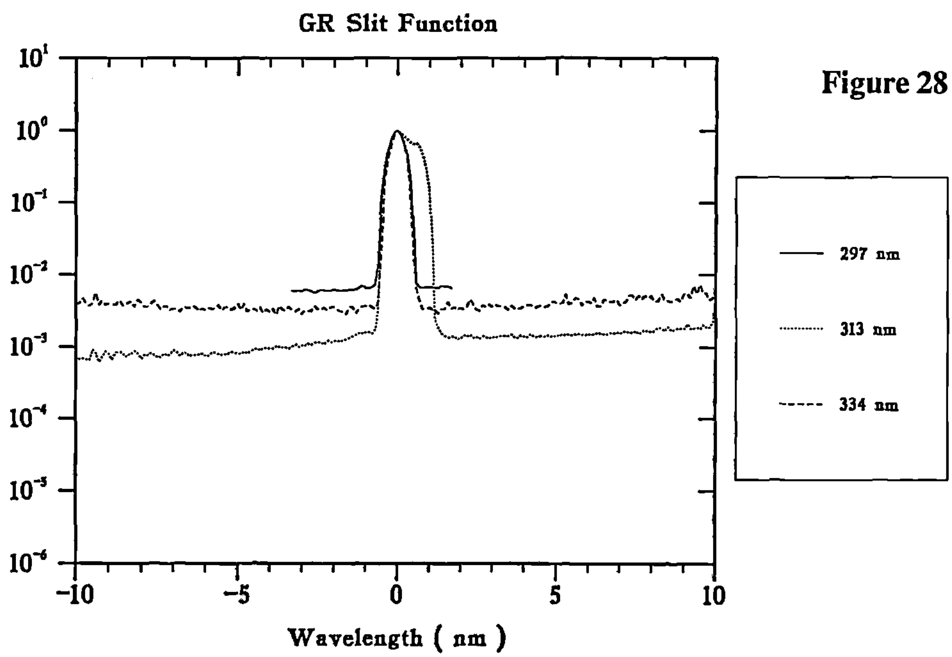

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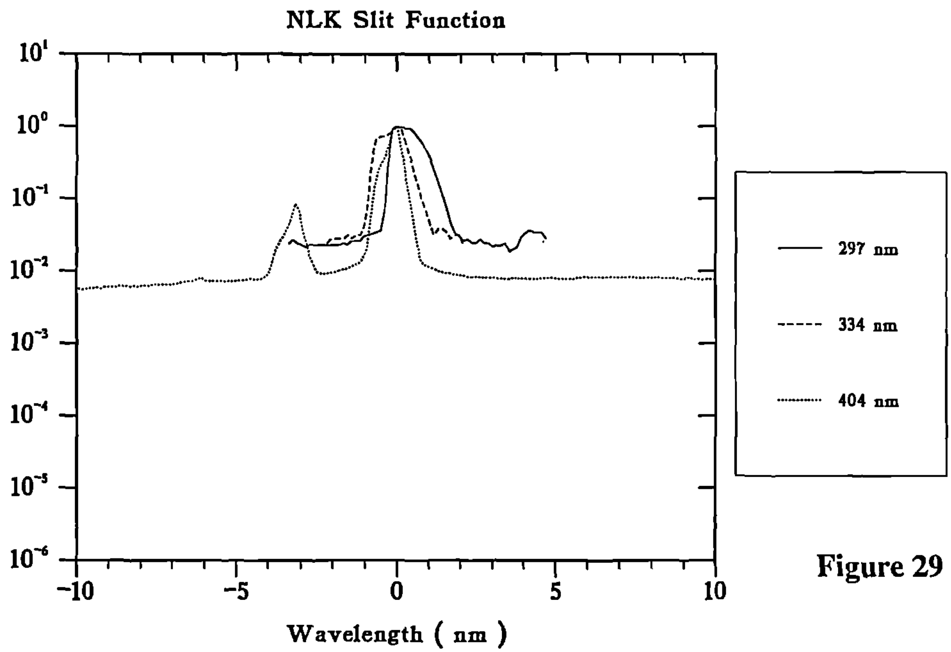

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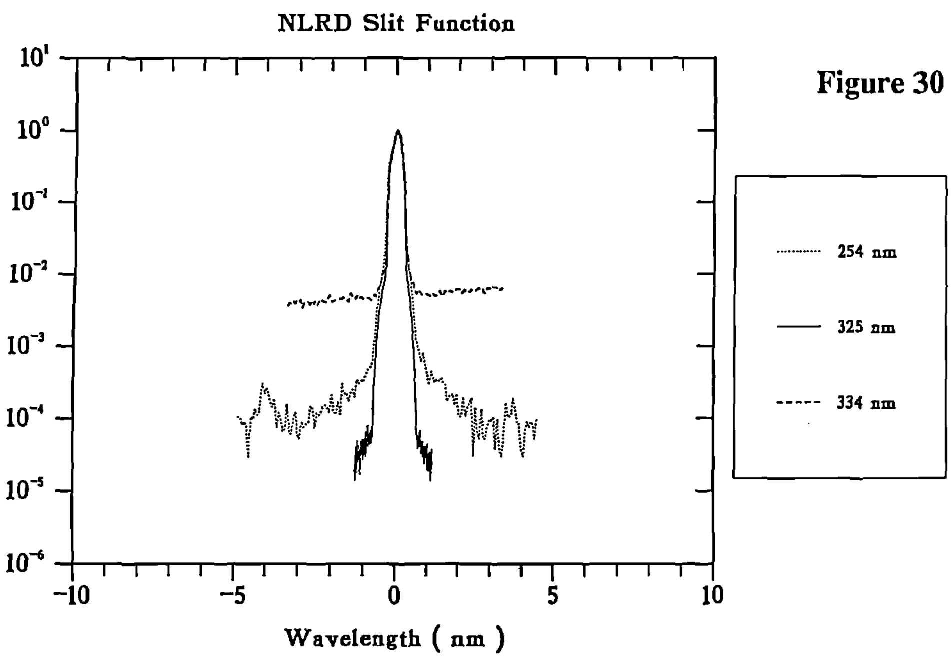

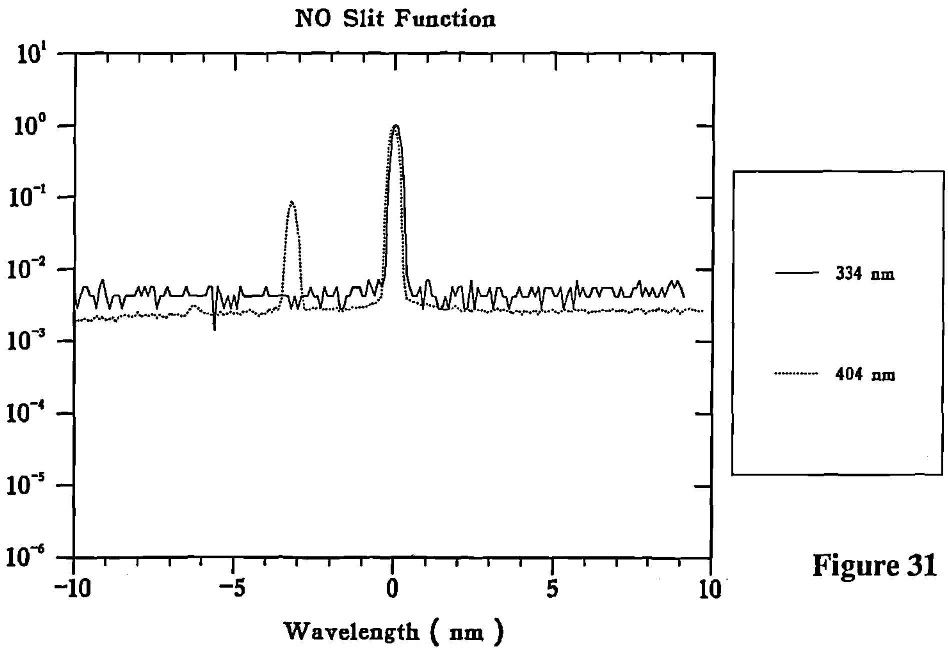

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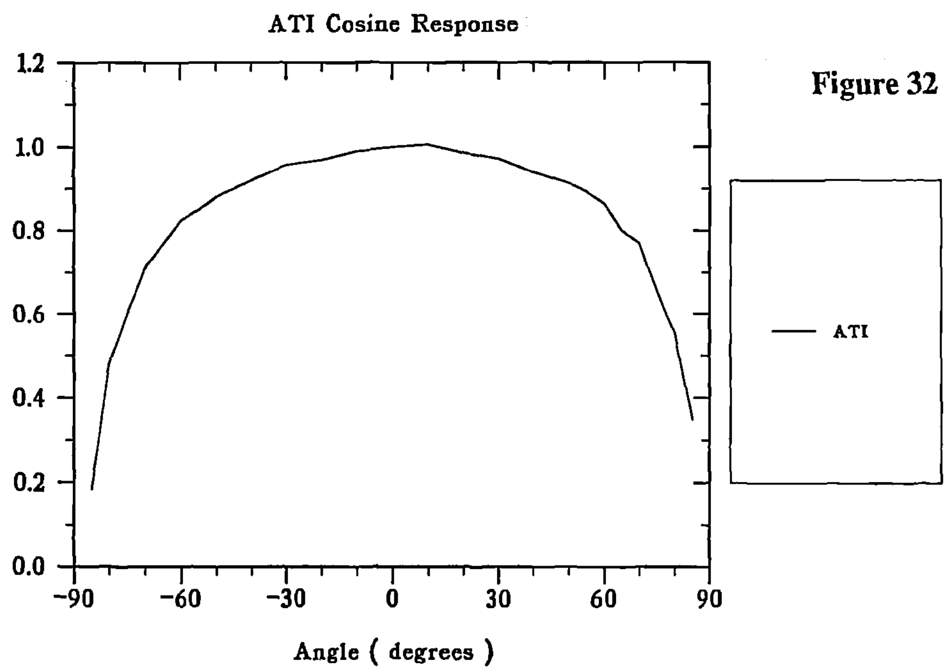

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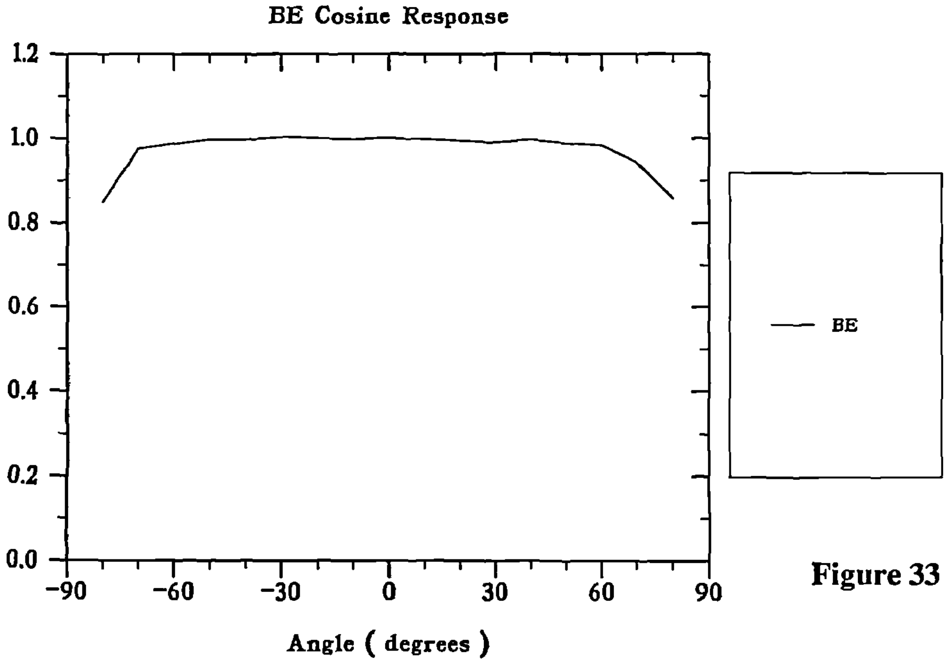

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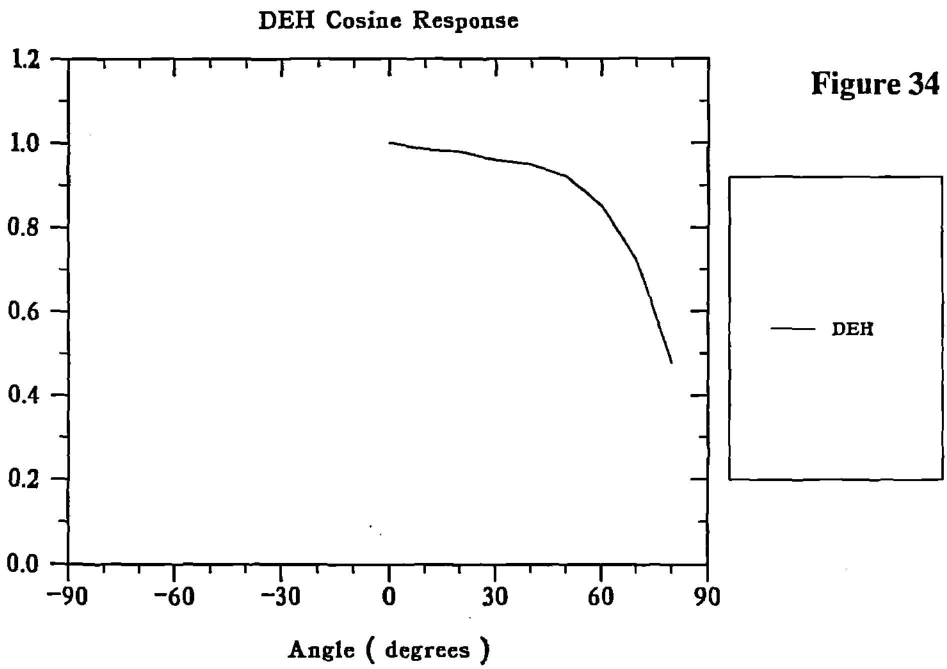

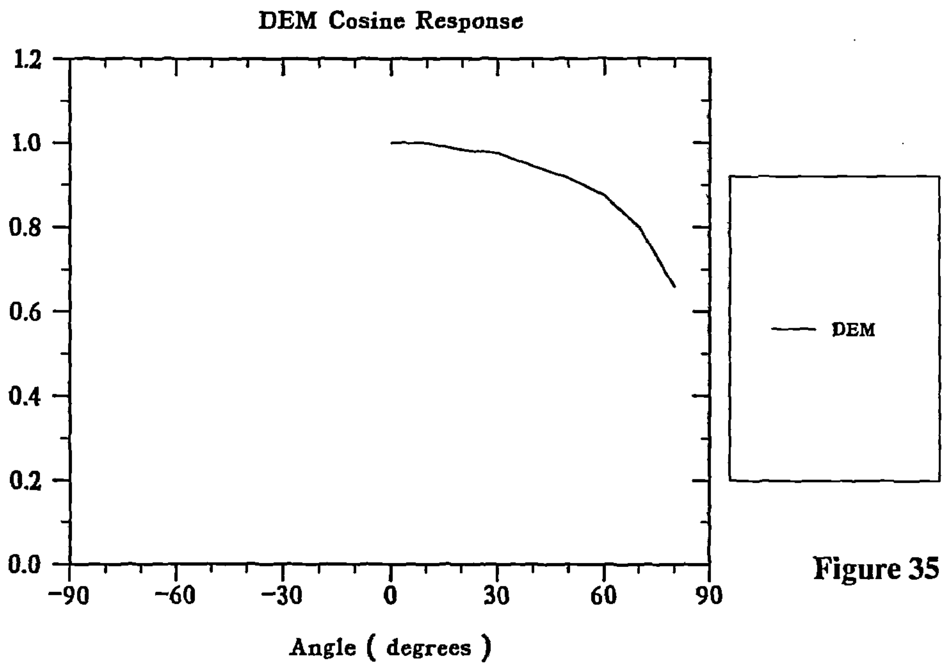

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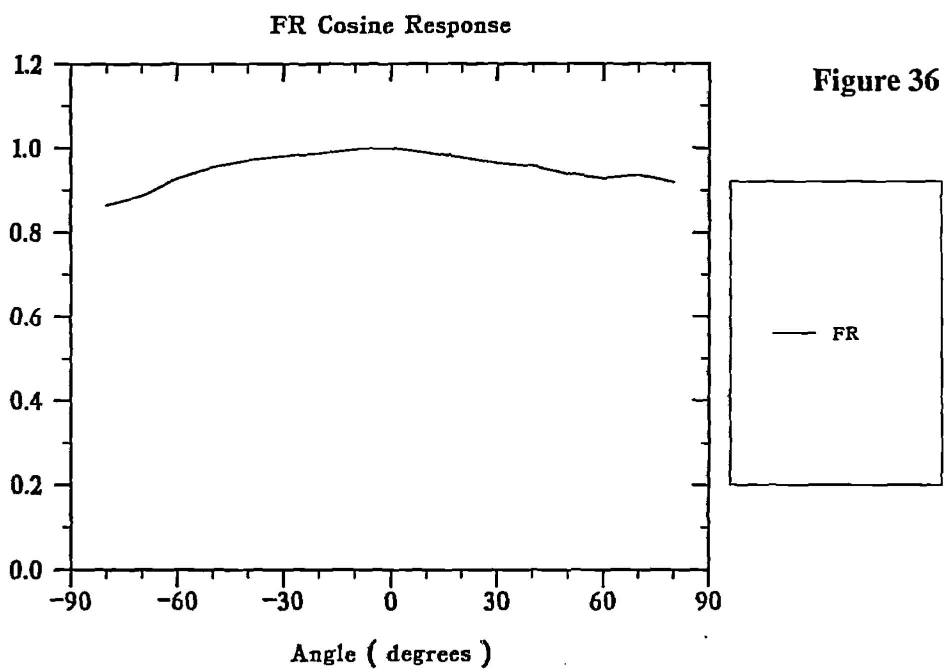

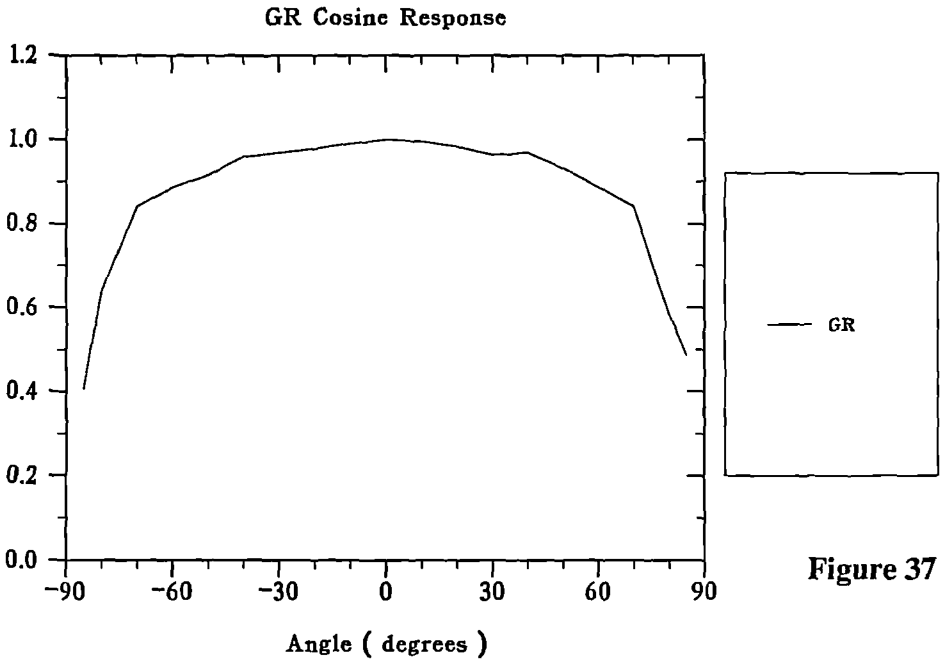

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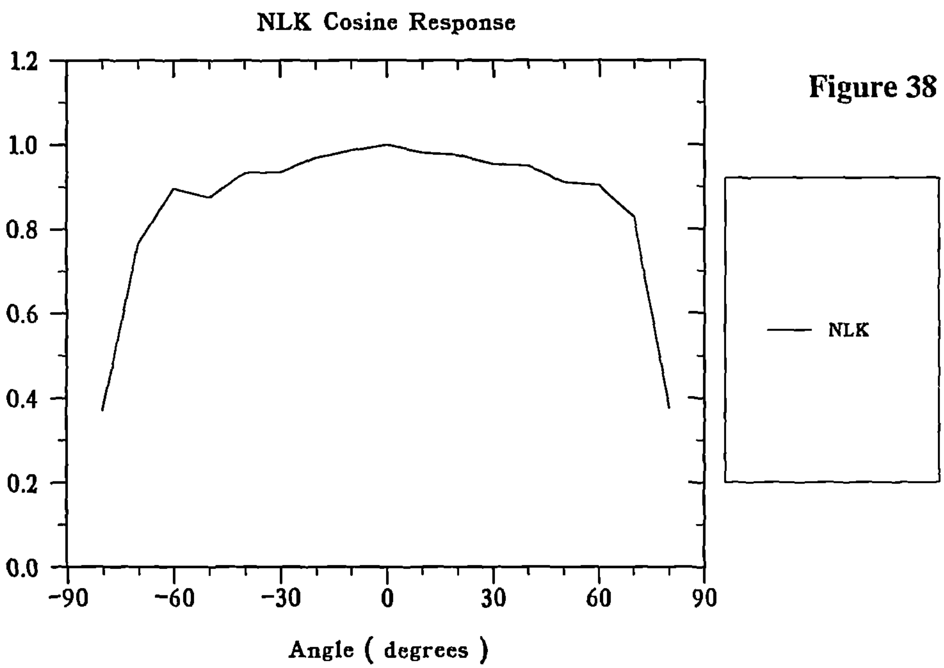

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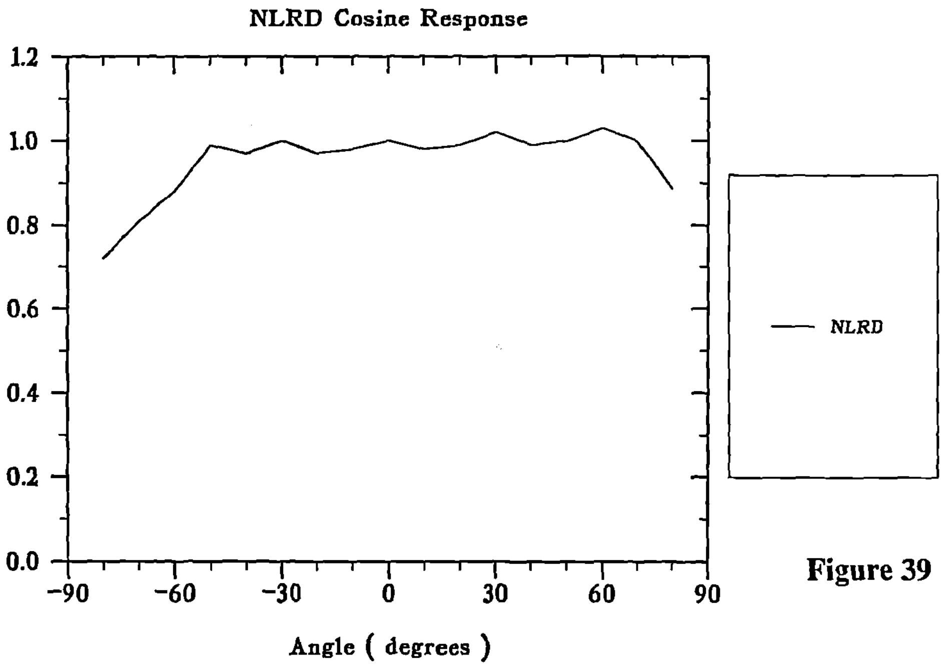

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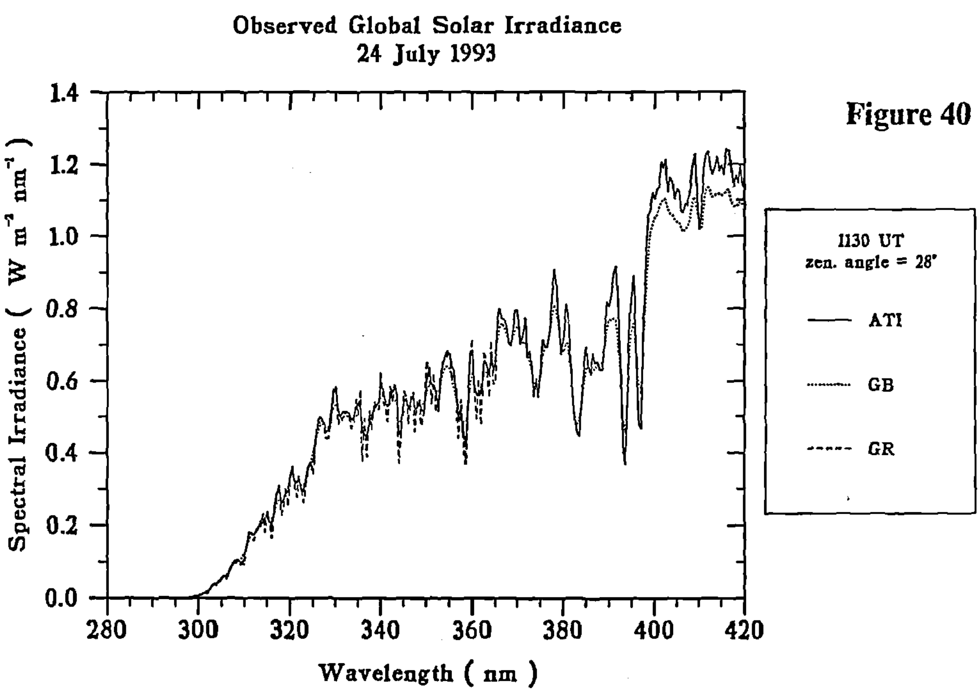

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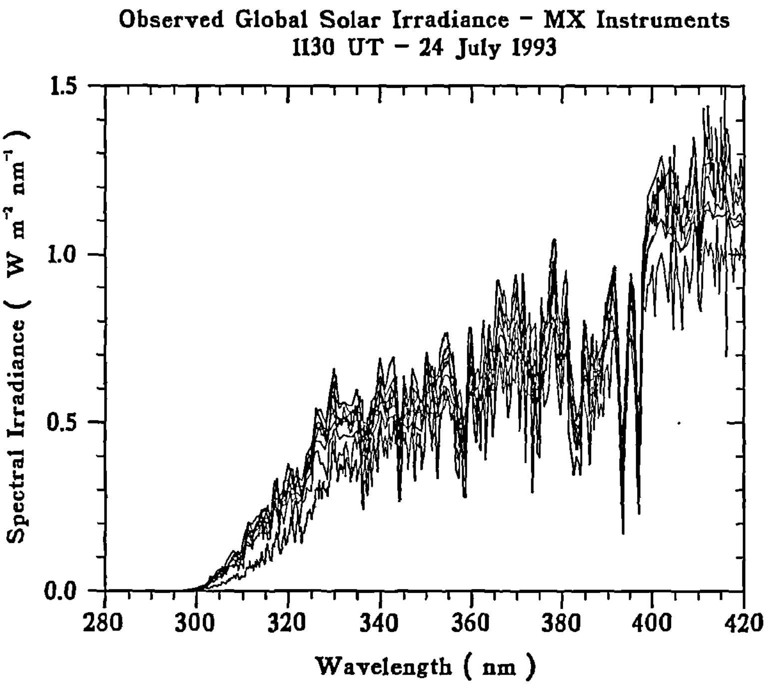

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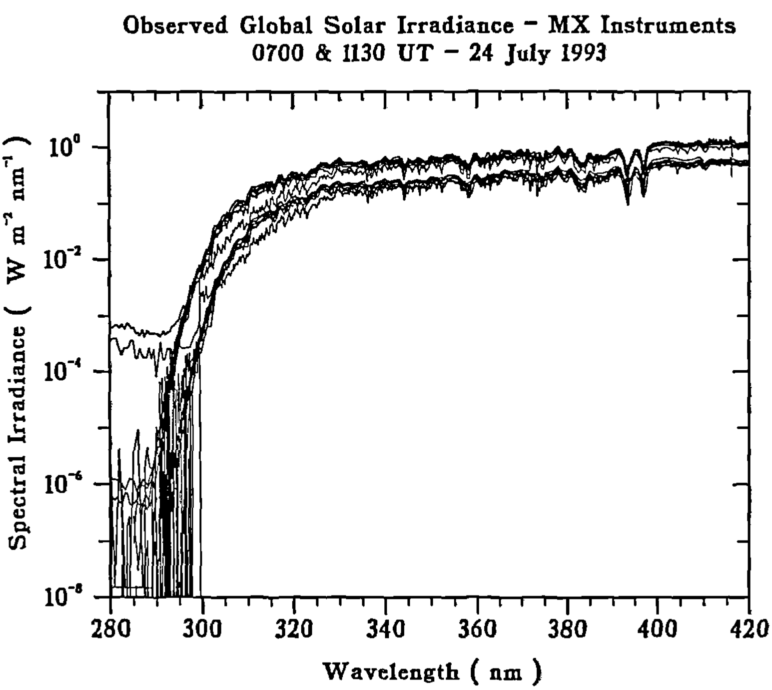

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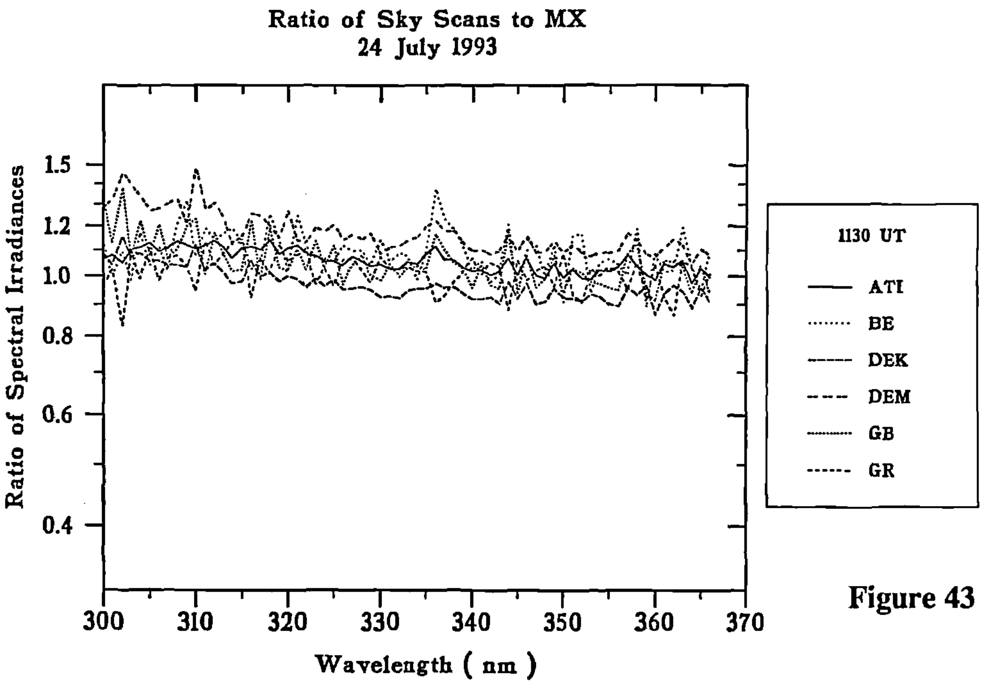

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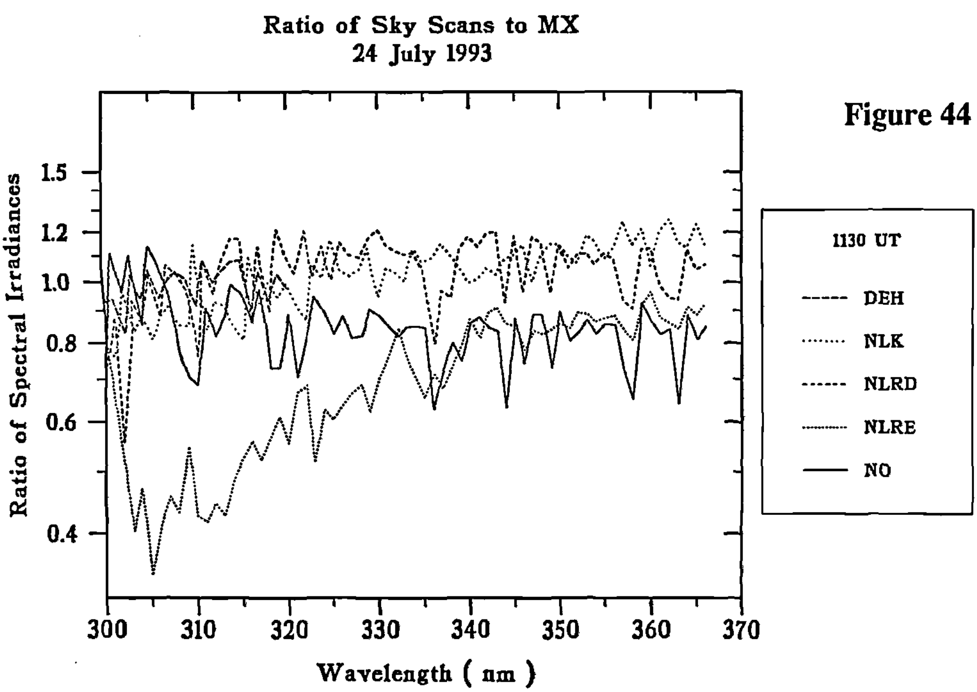

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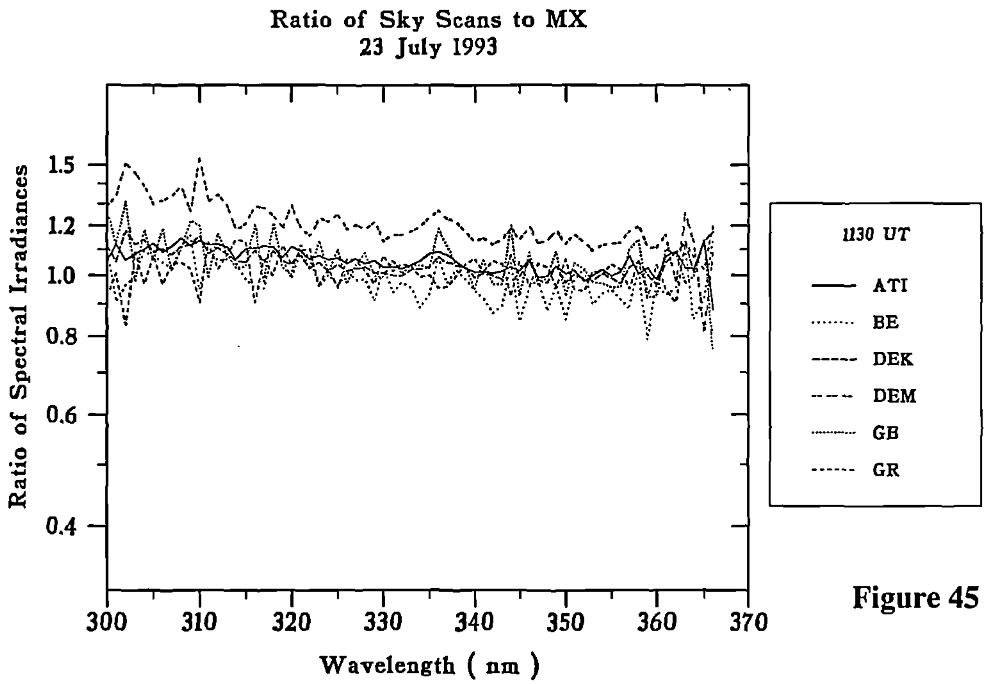

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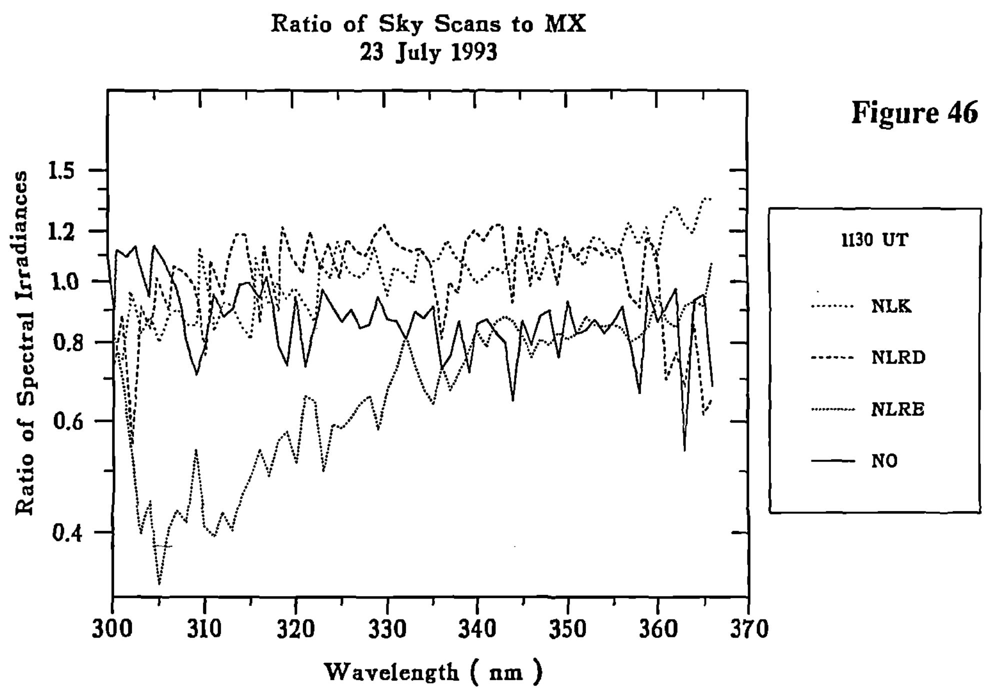

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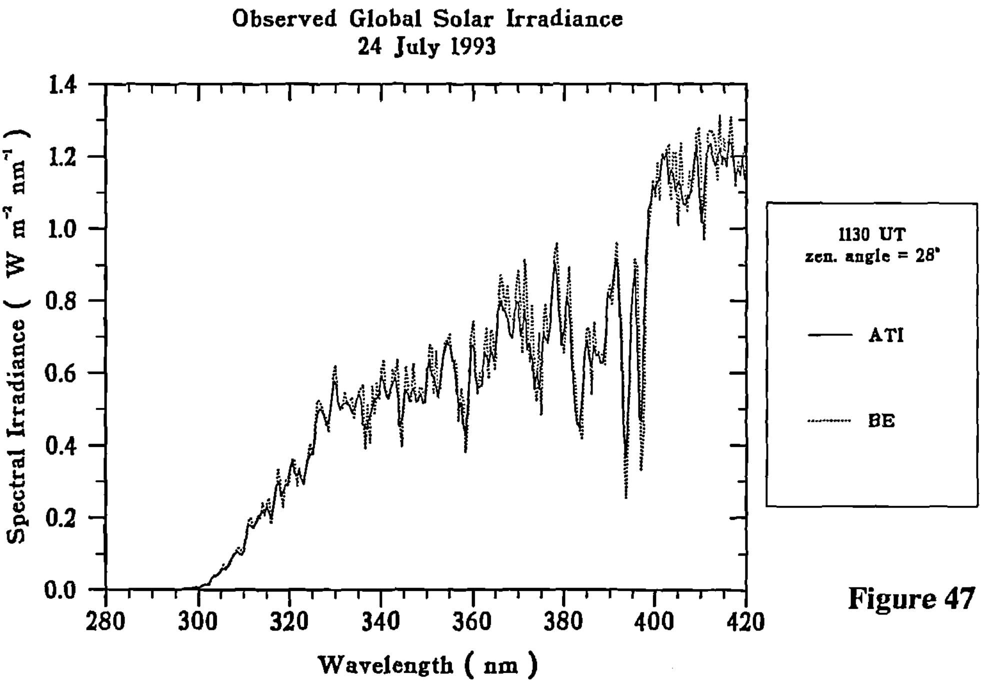

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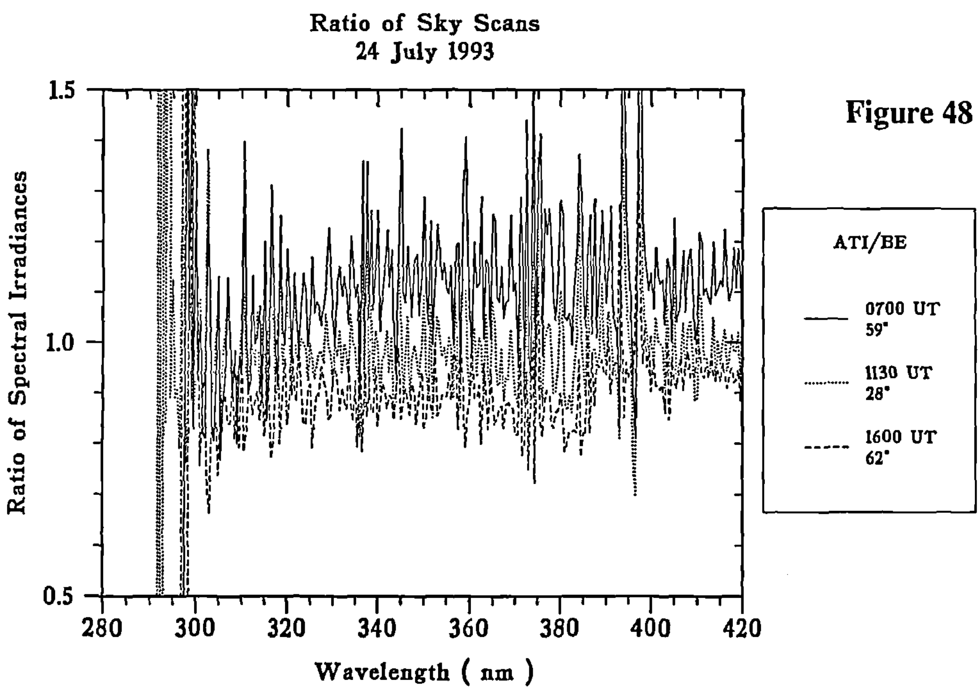

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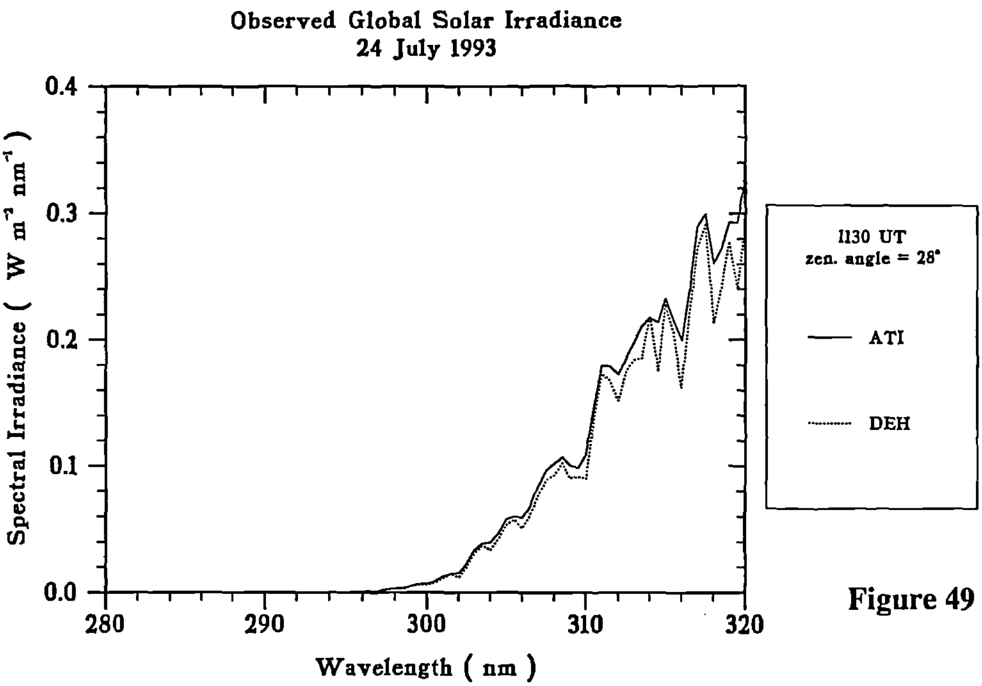

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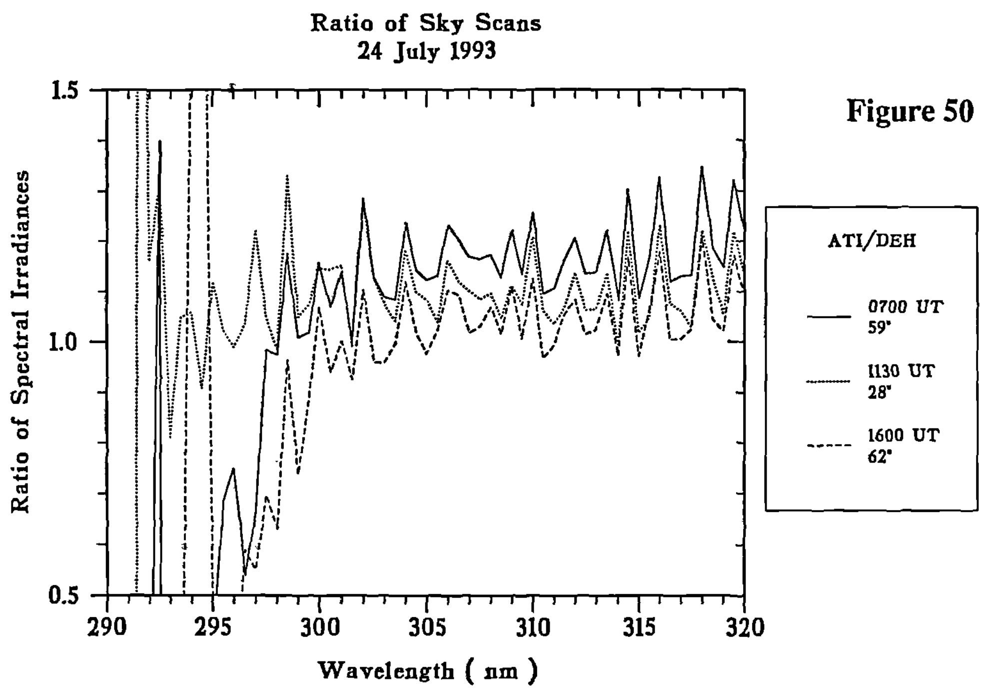

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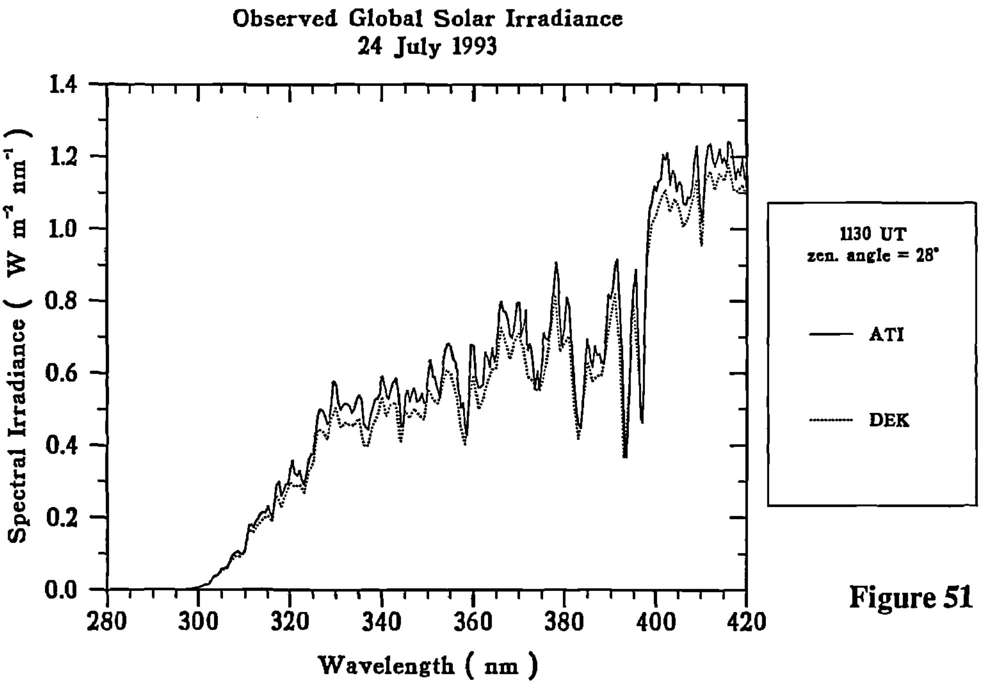

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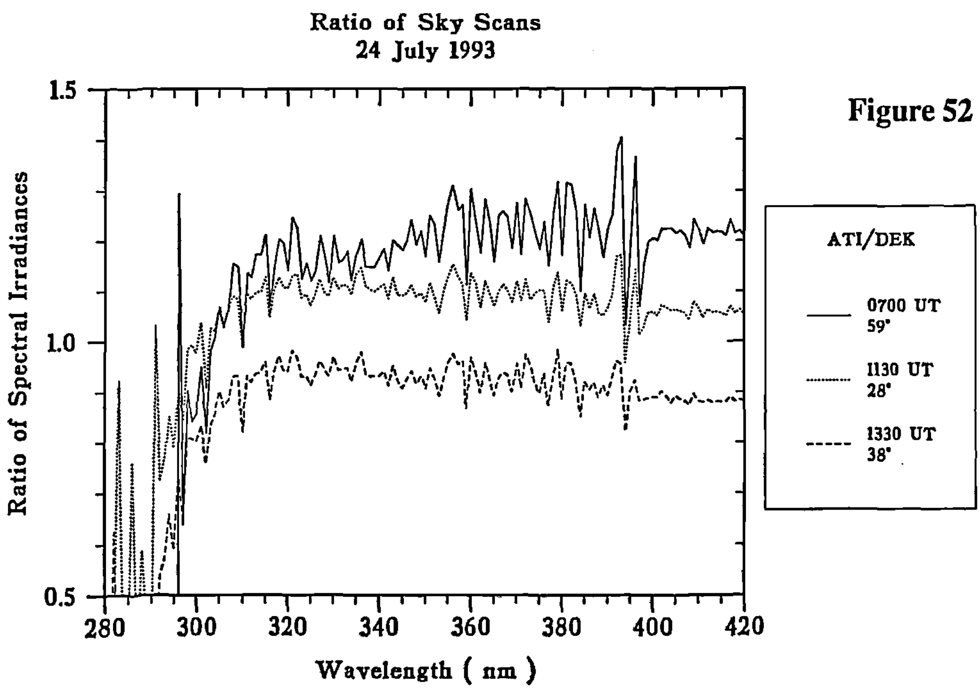

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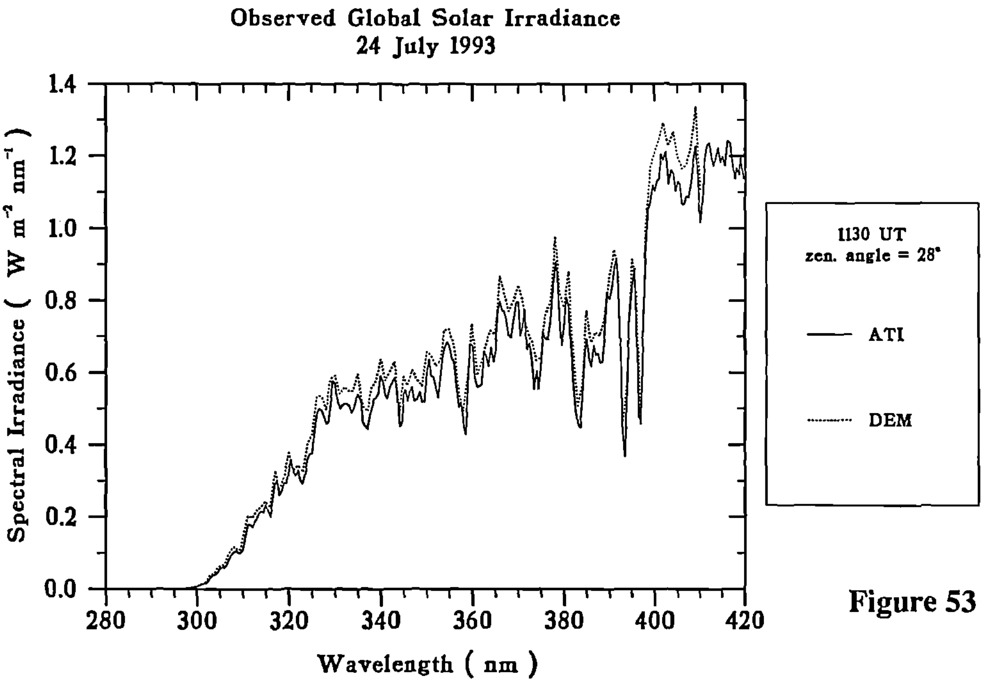
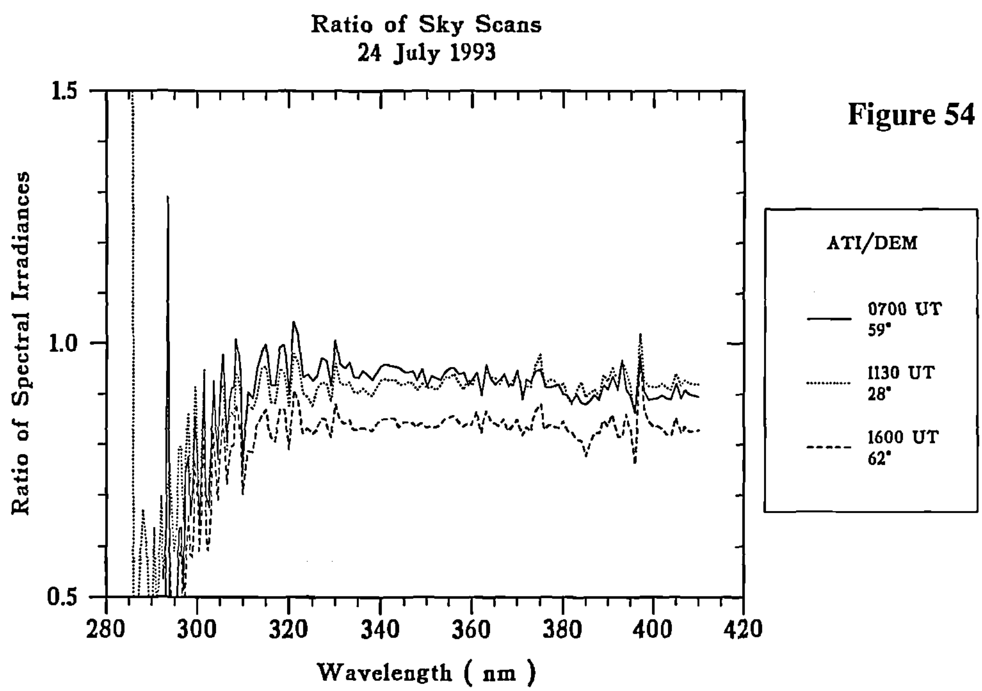
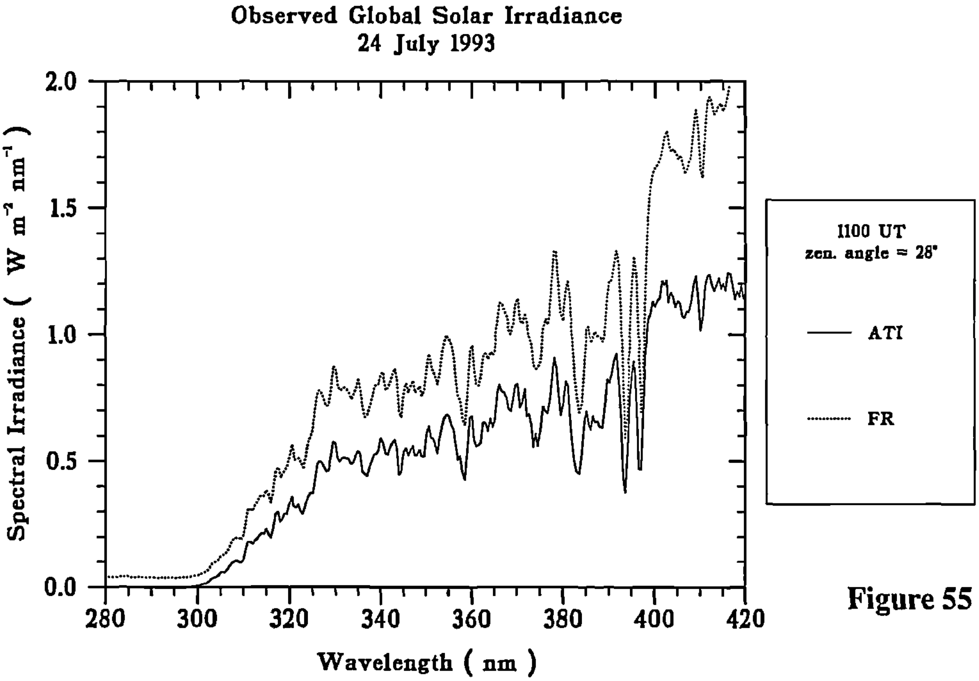


Figure 53

Figure 54





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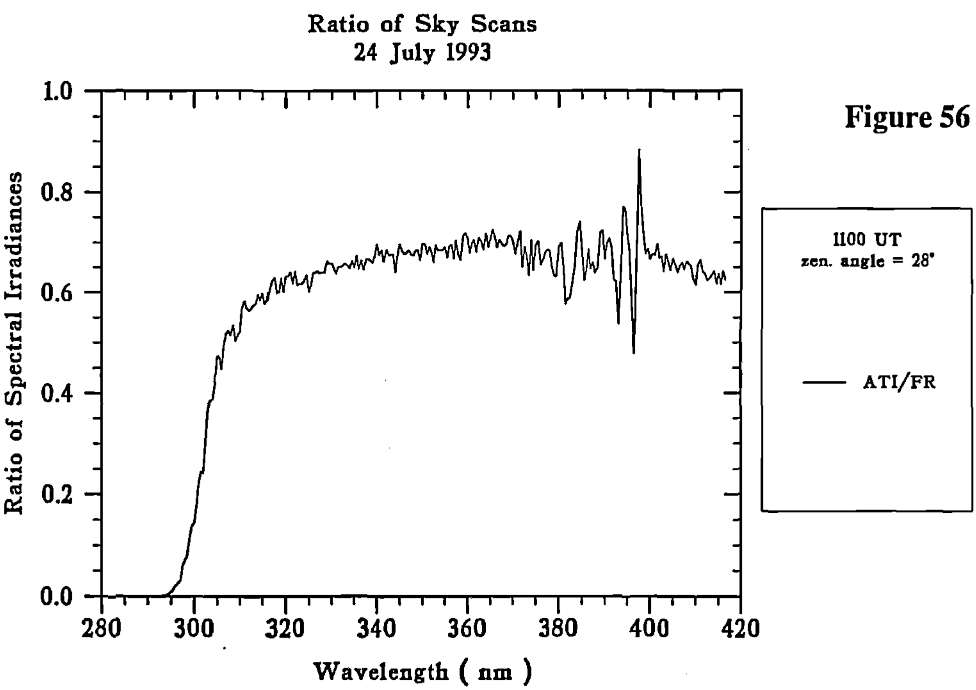

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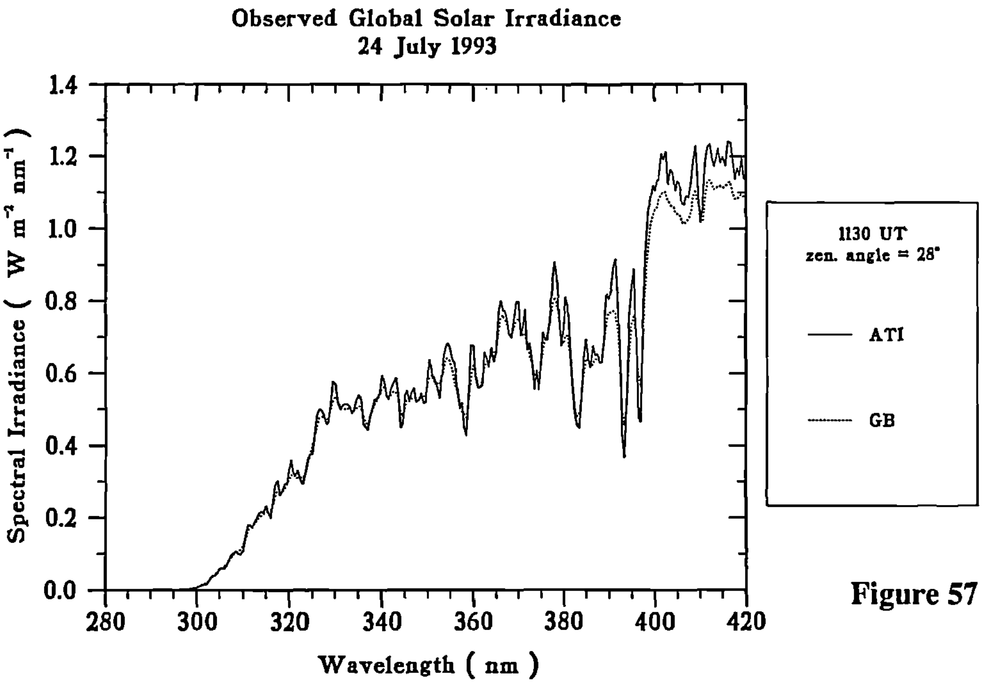

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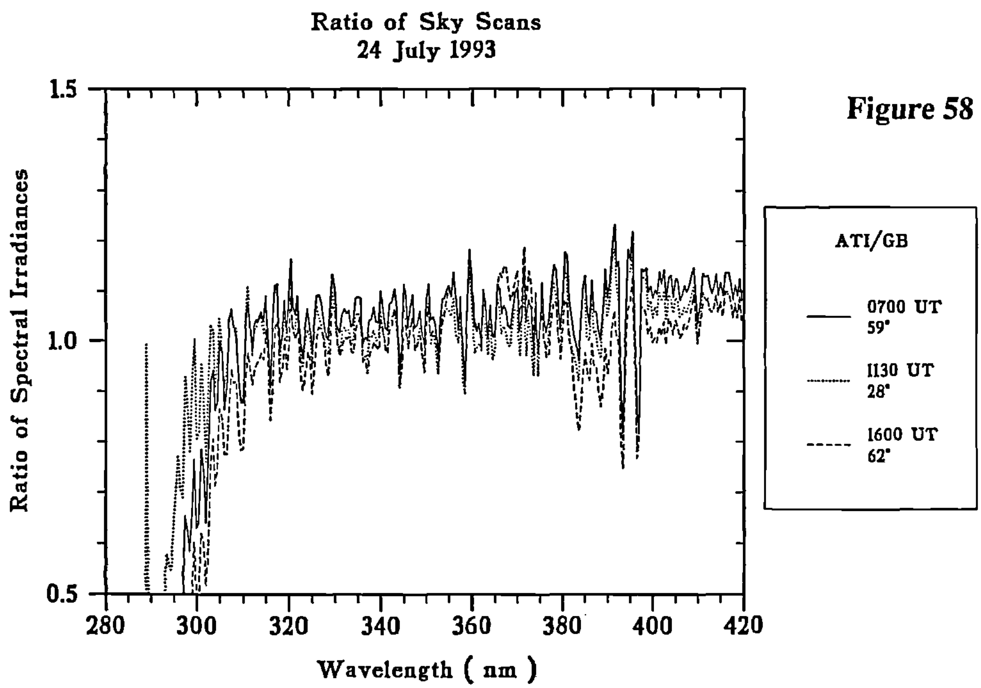

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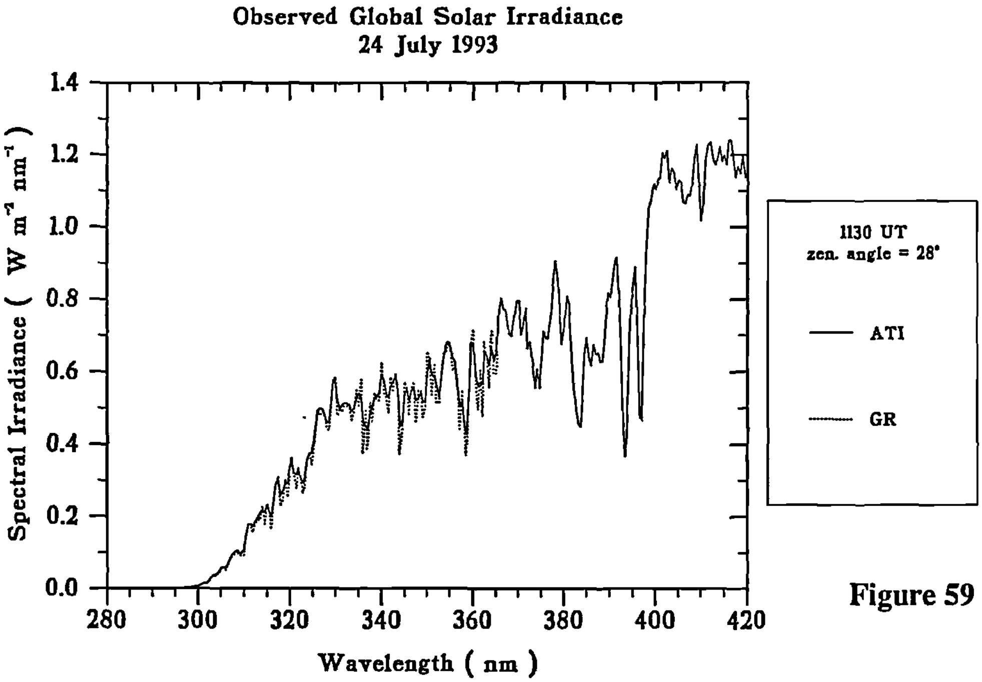

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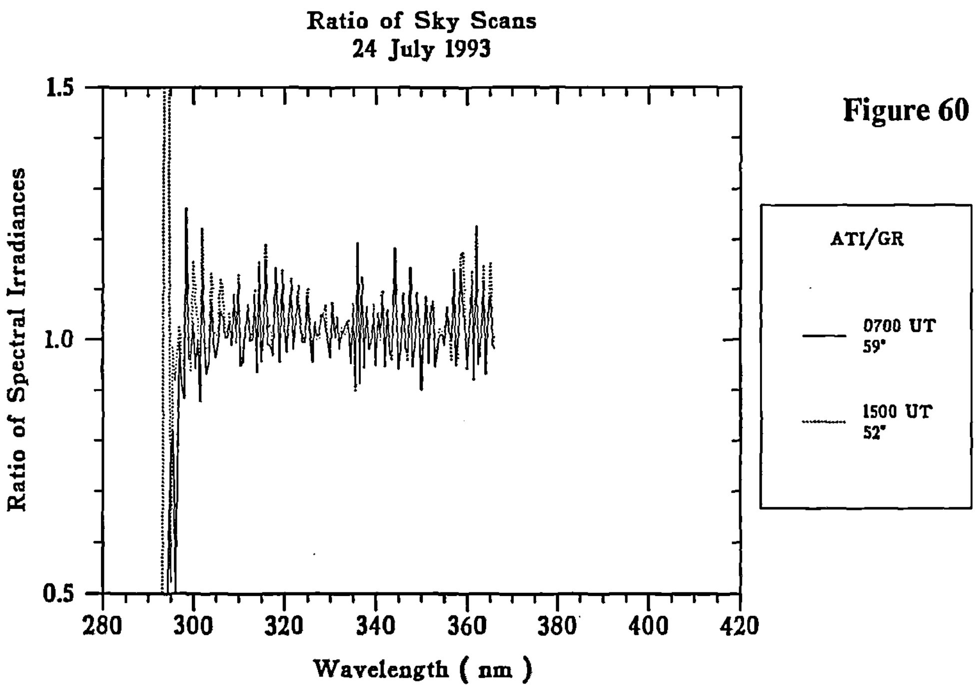

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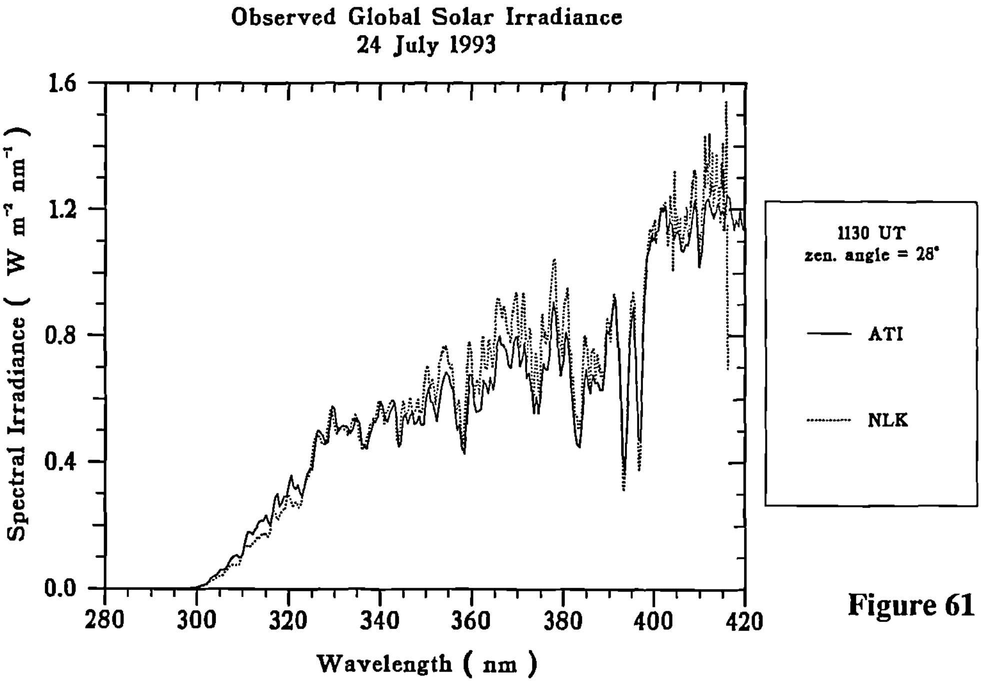

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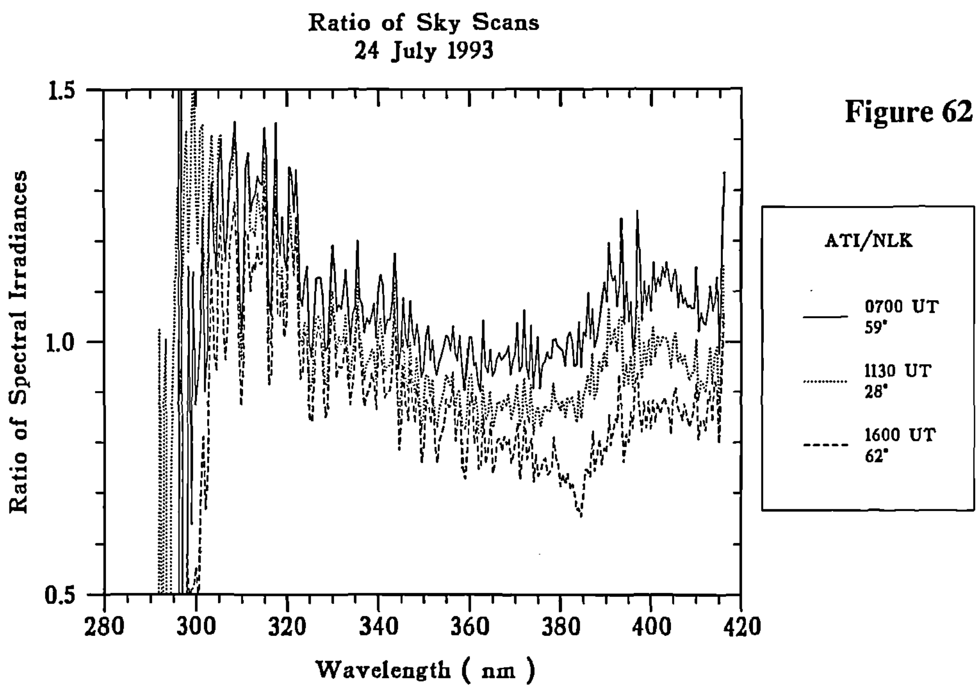

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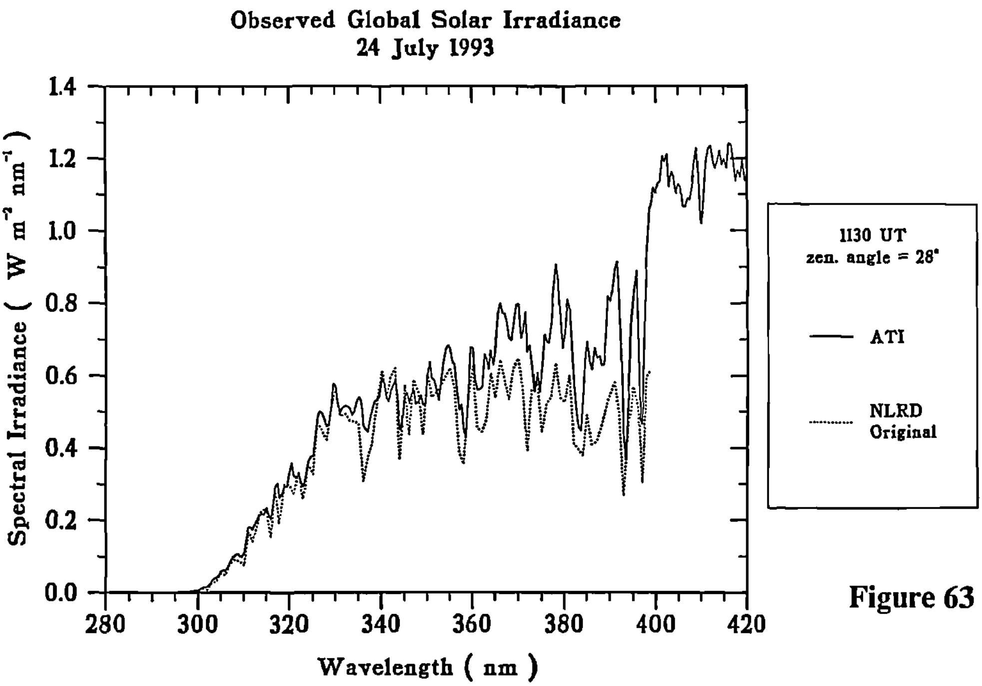

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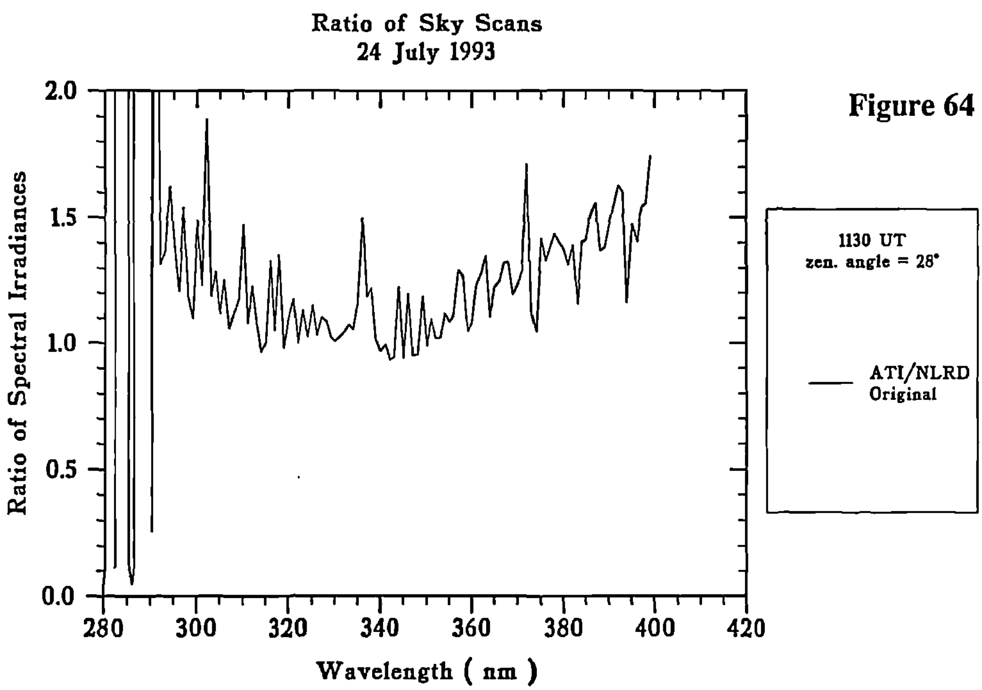

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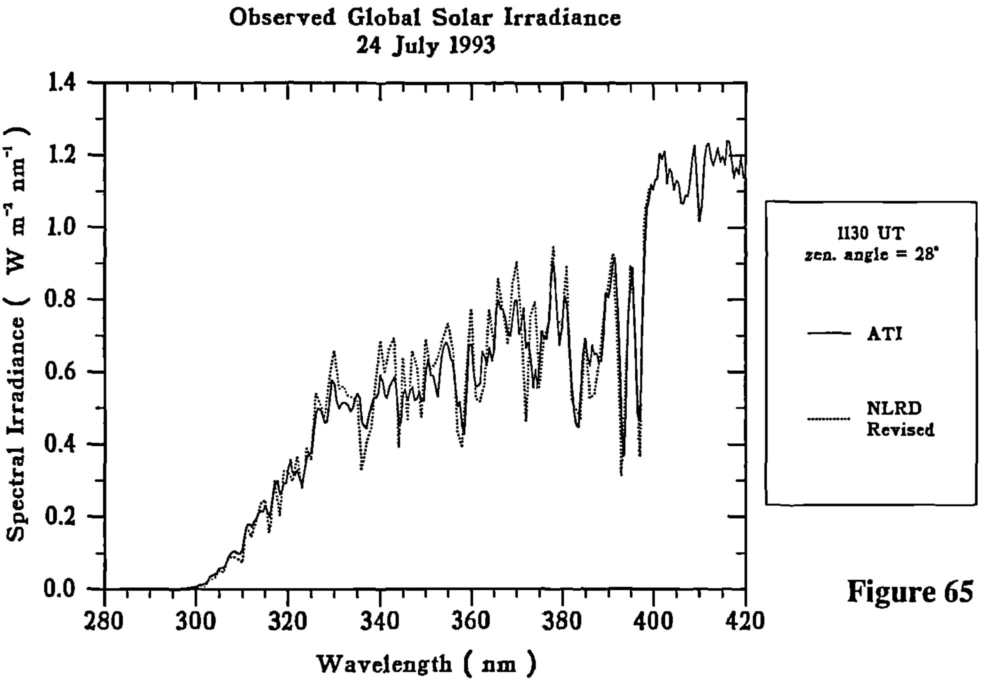

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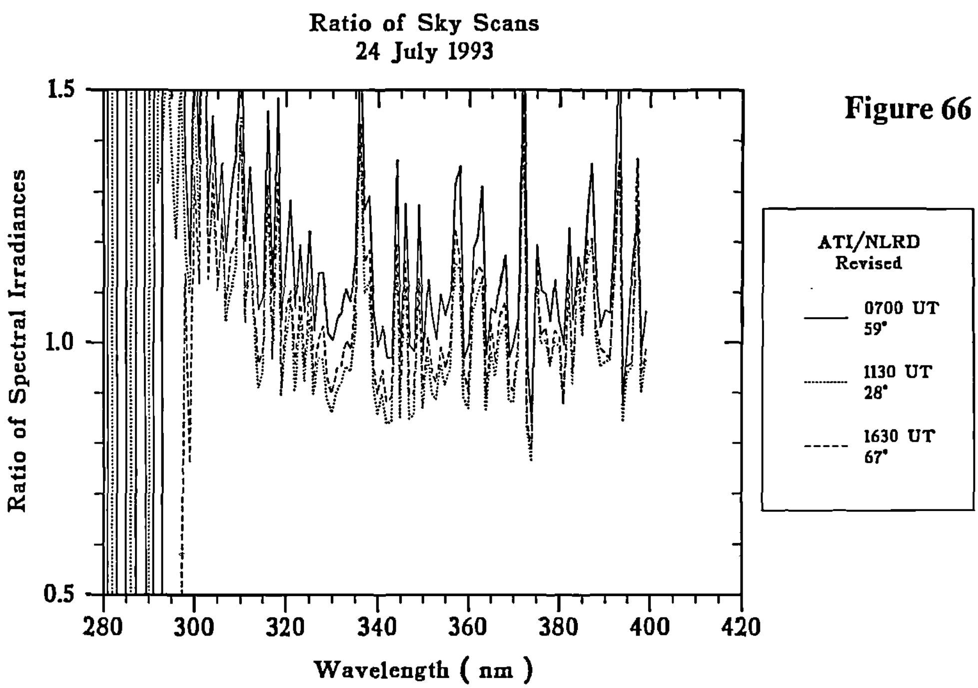

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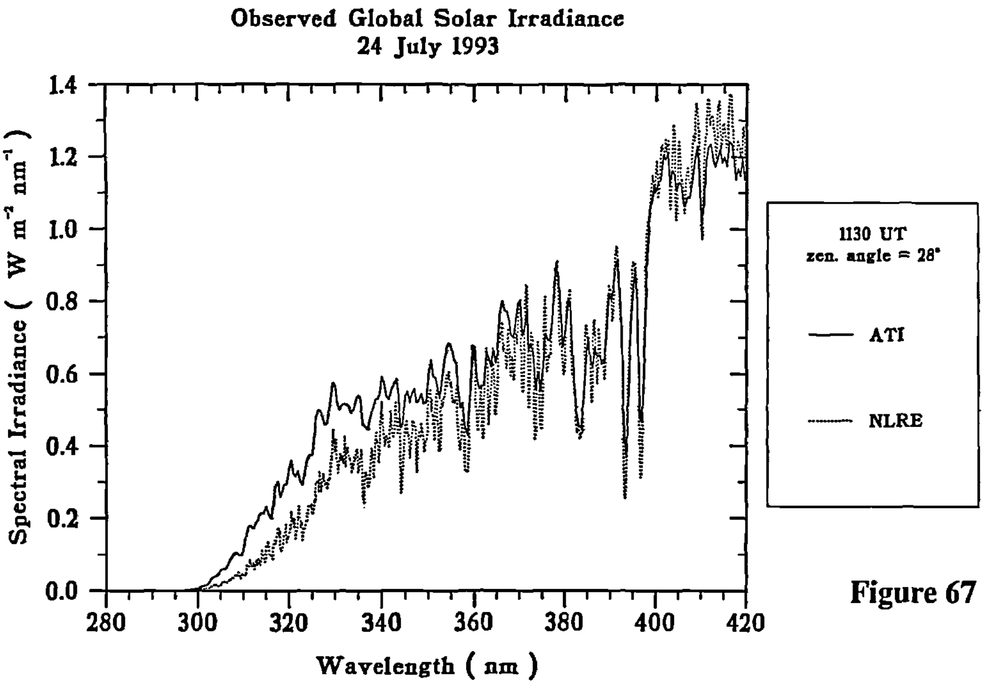

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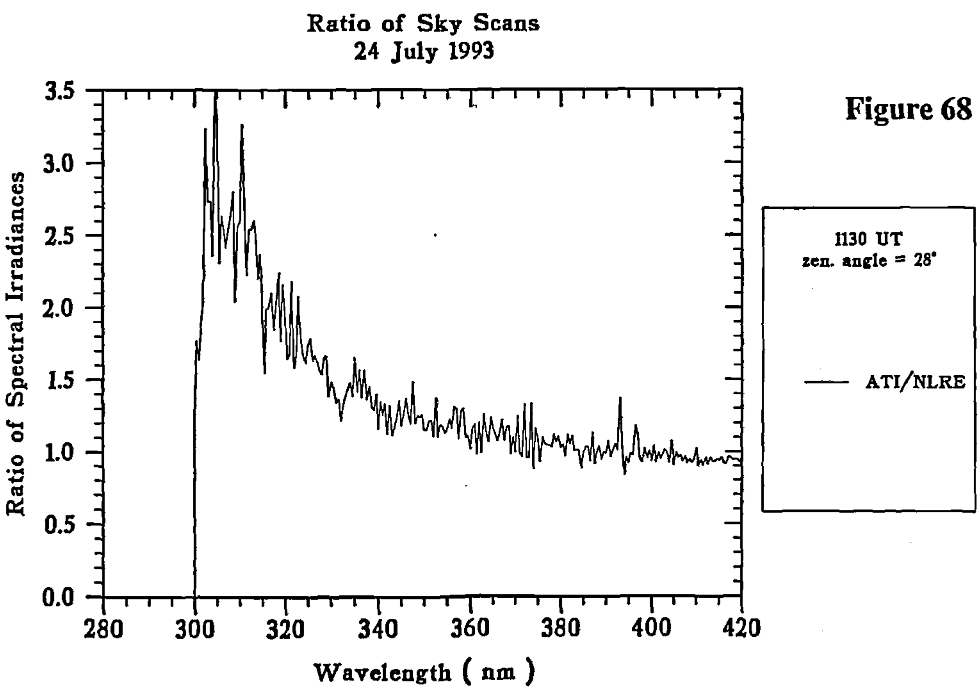

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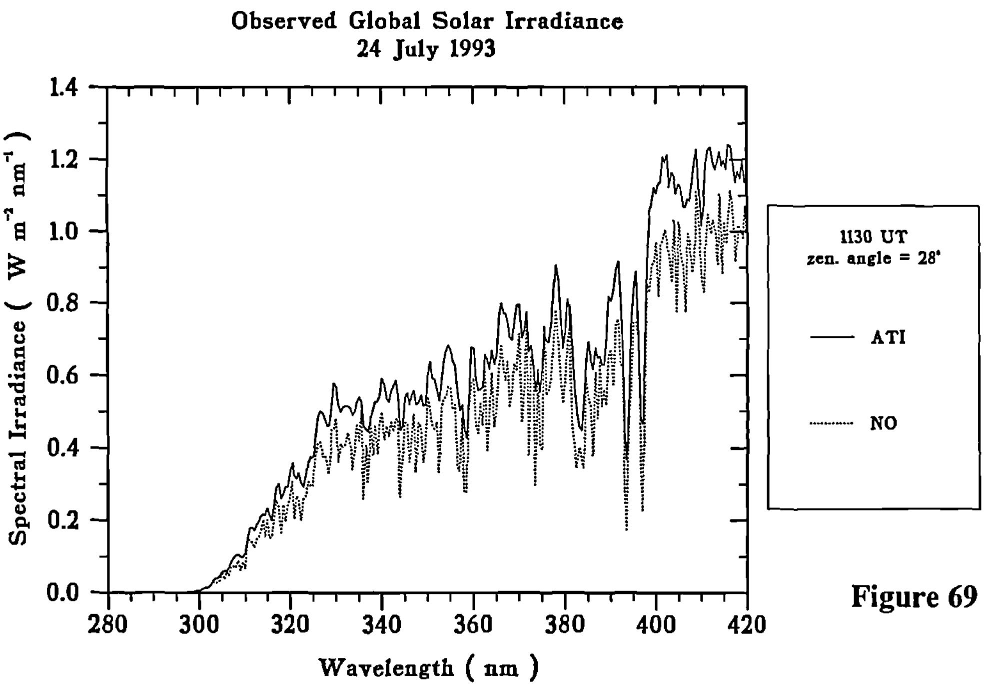

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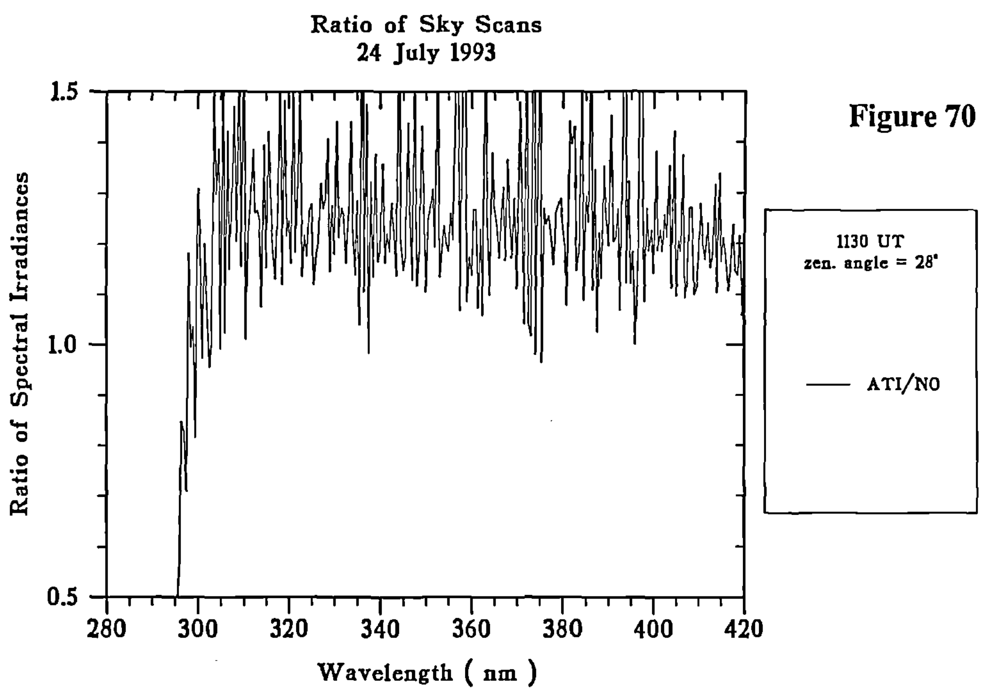

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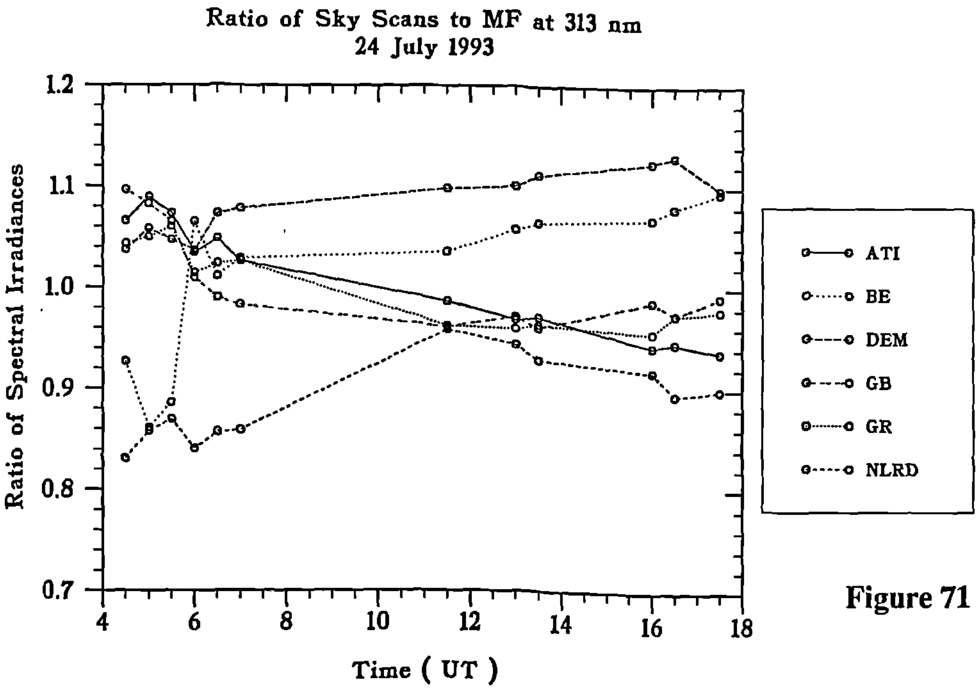
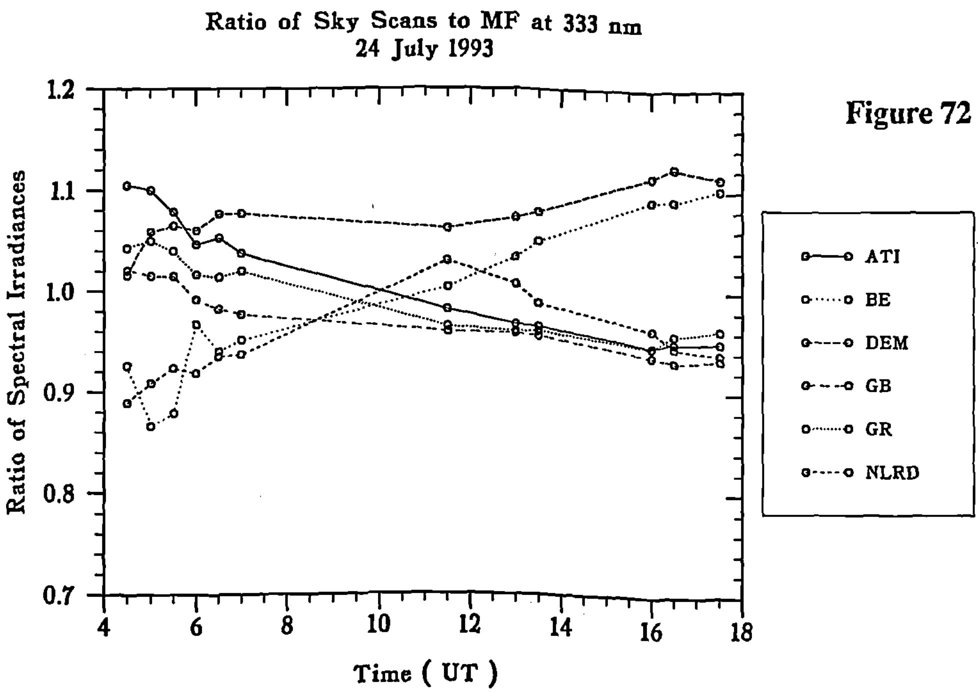
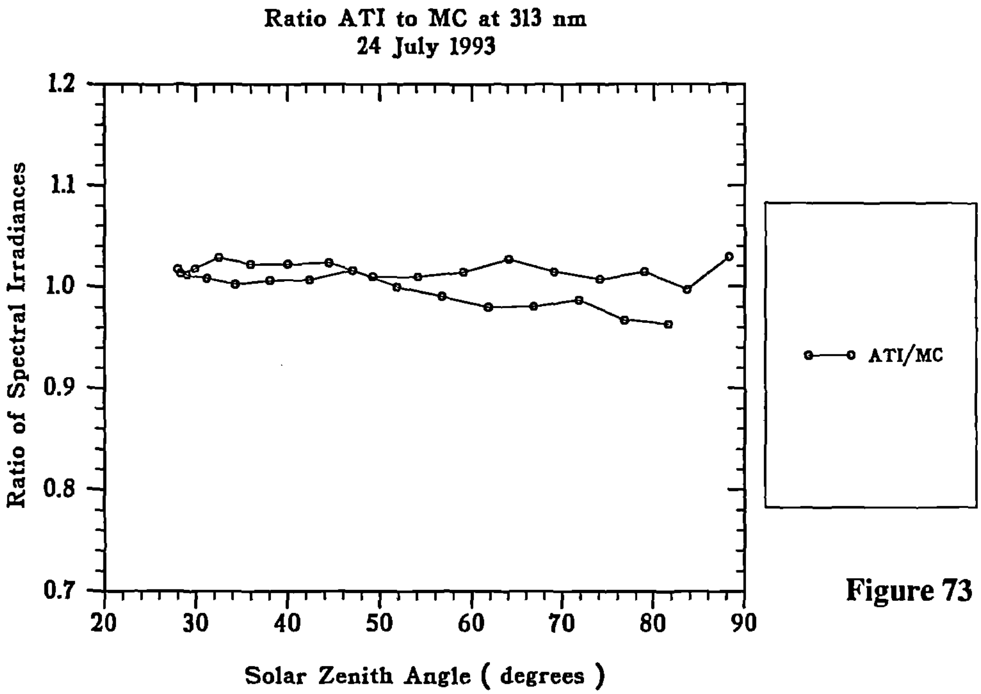


Figure 71

Figure 72





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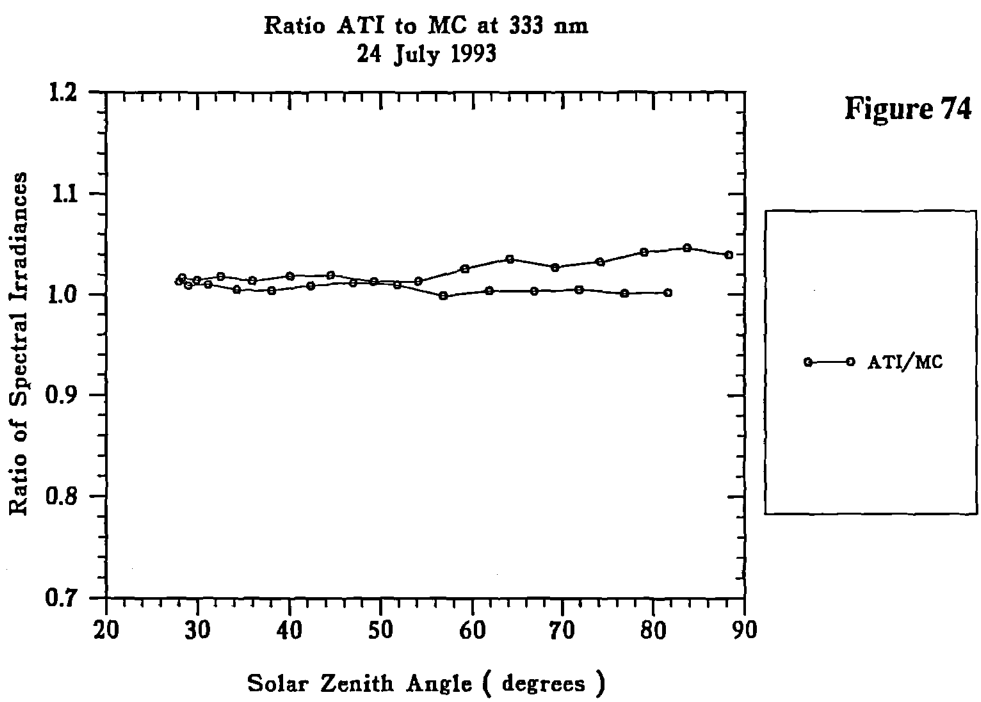

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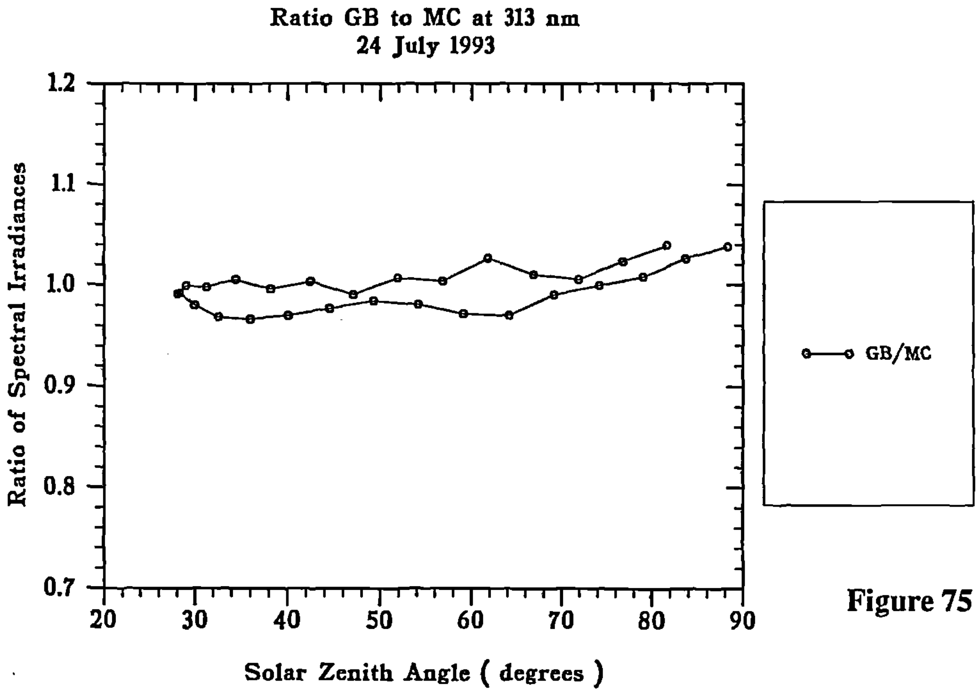

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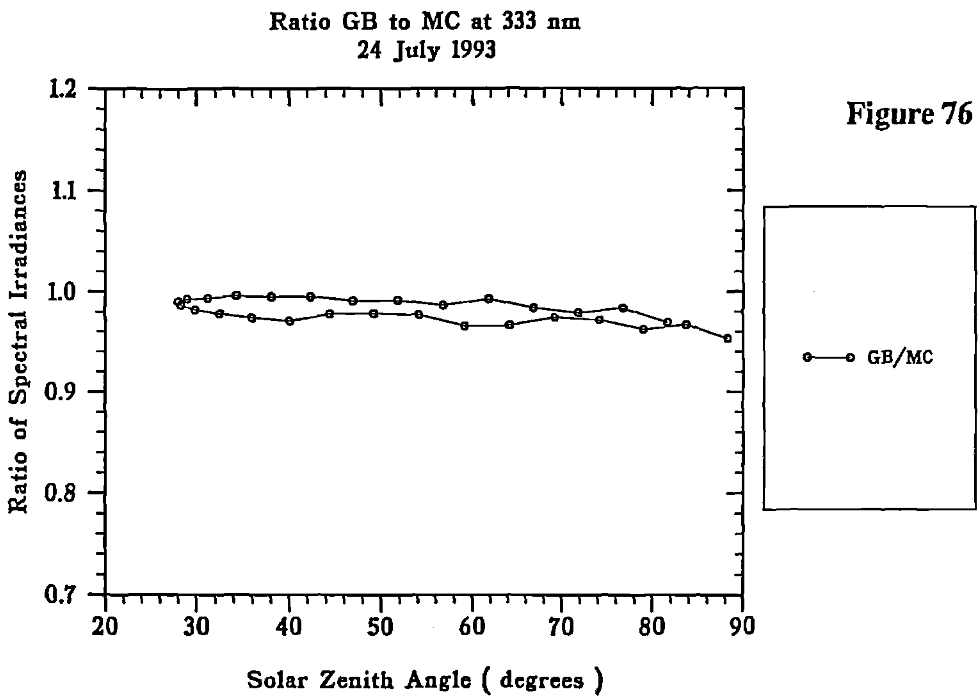

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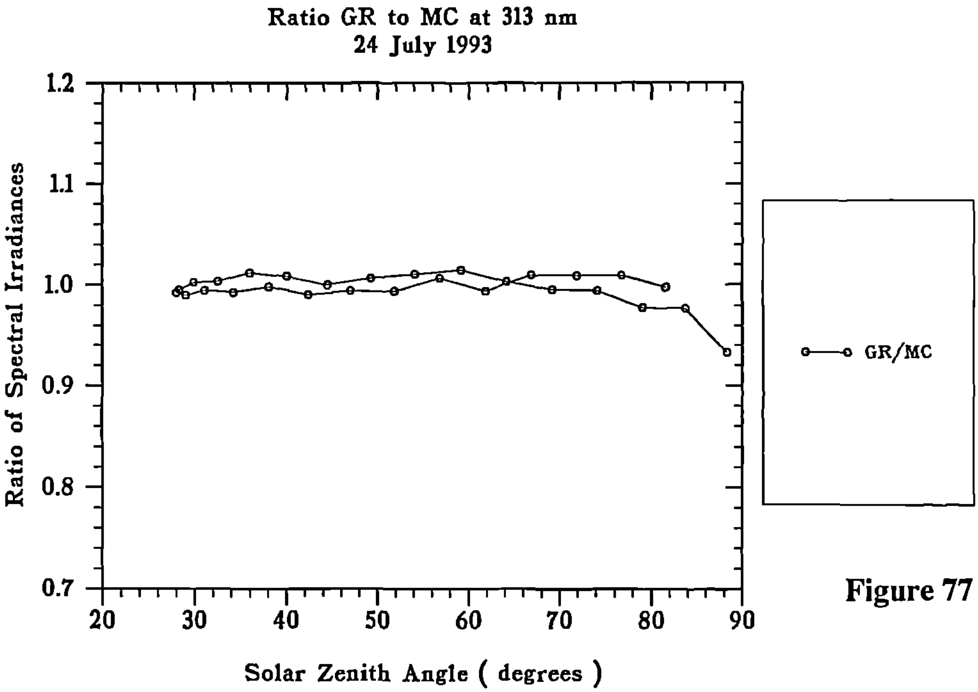
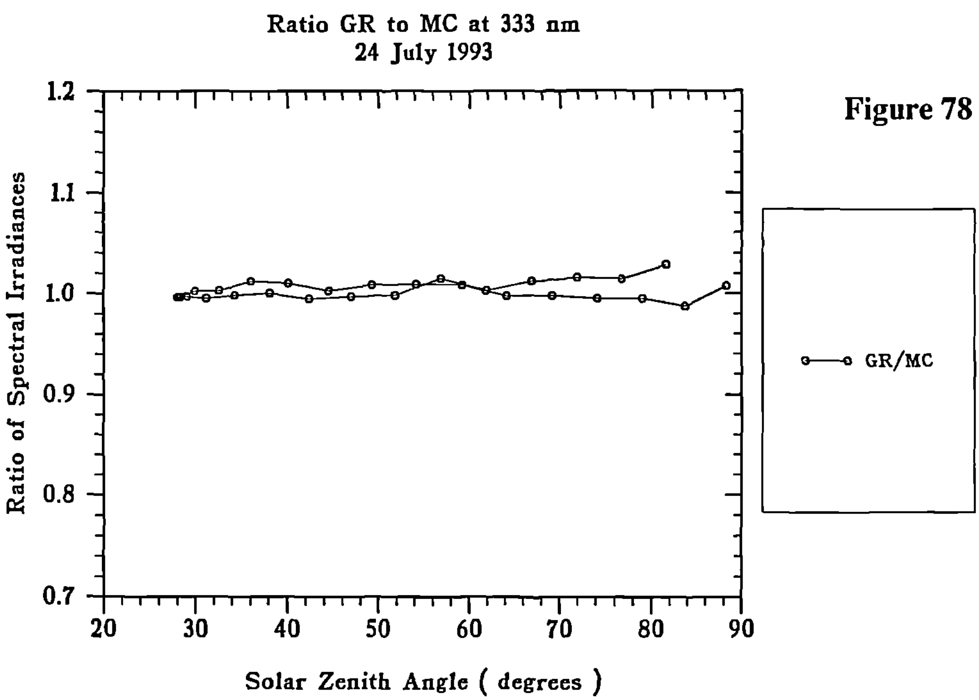
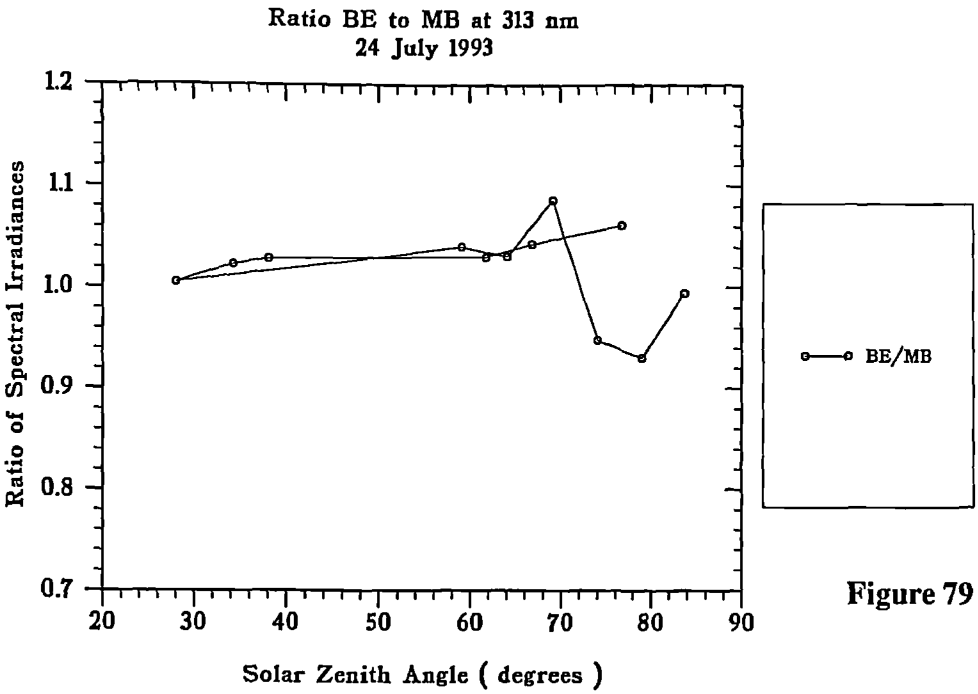


Figure 77

Figure 78





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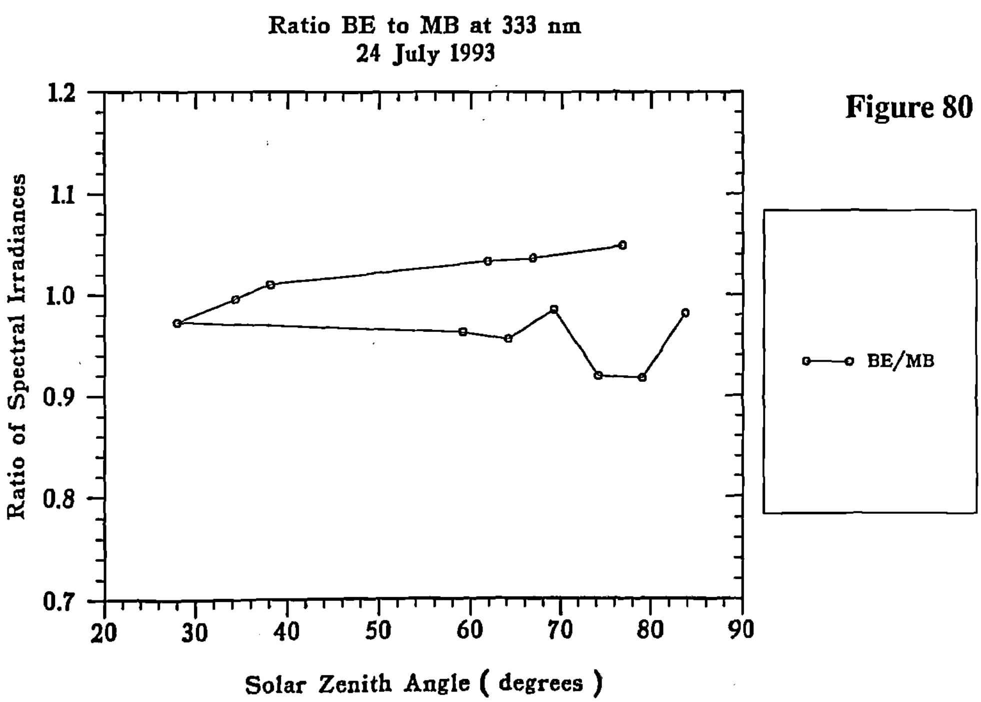

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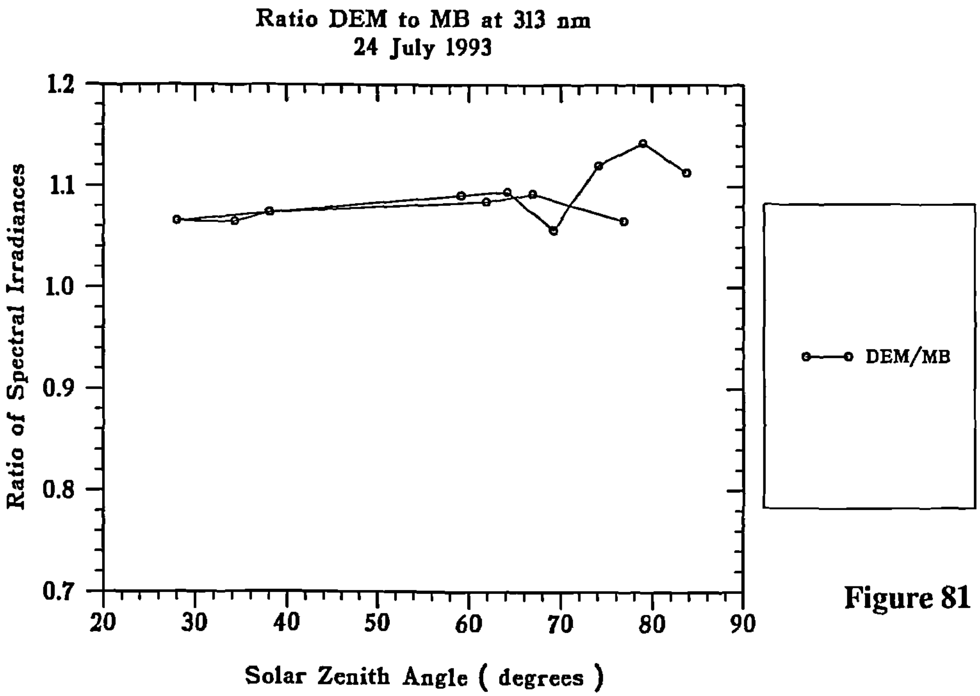

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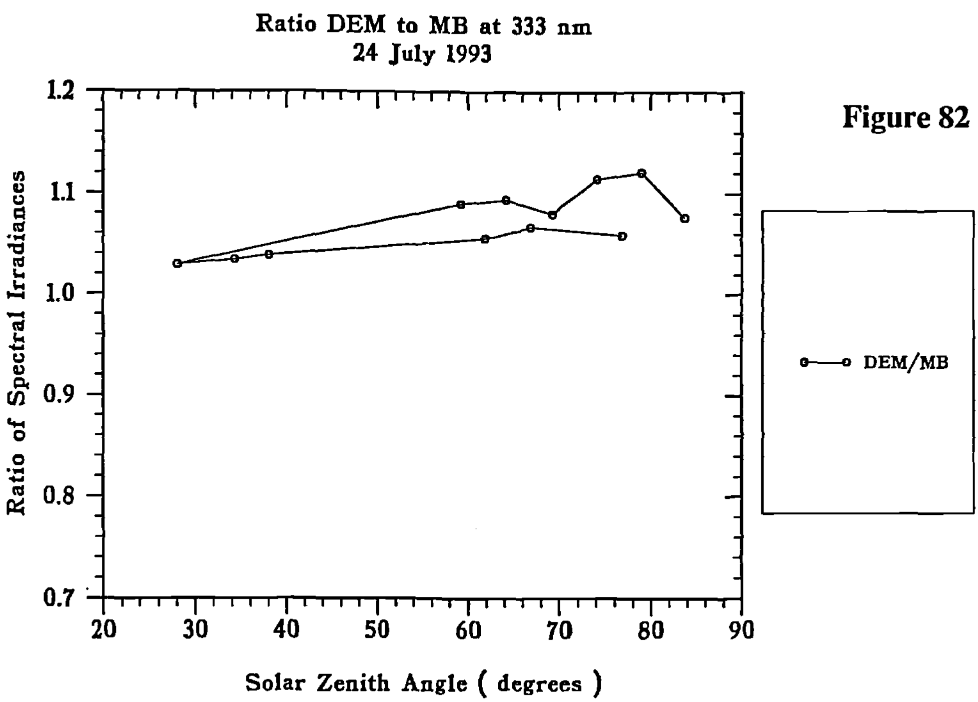


Figure 82

Ratio NLRD to MB at 313 nm
24 July 1993

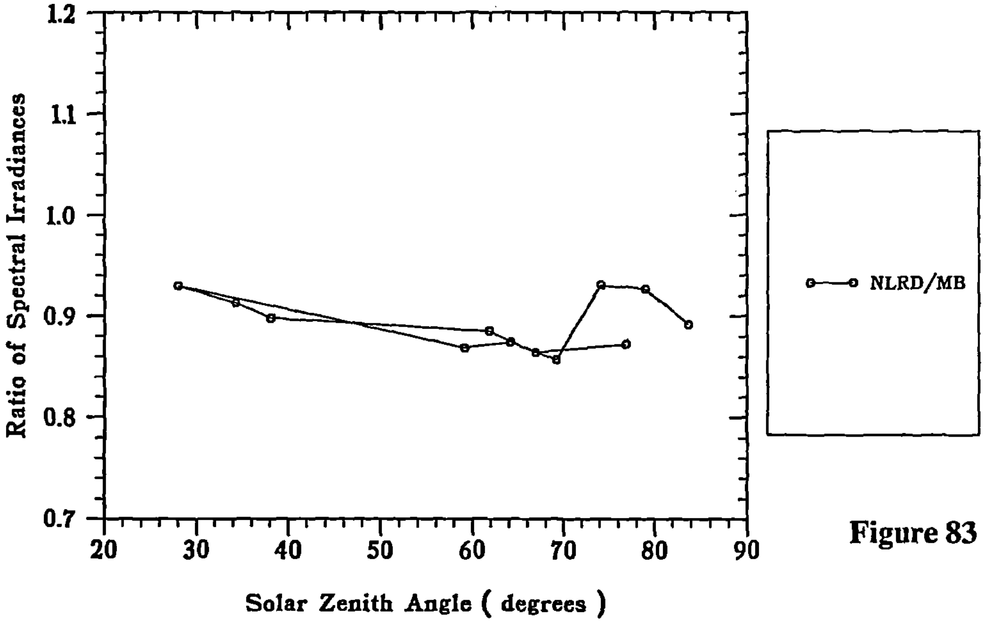
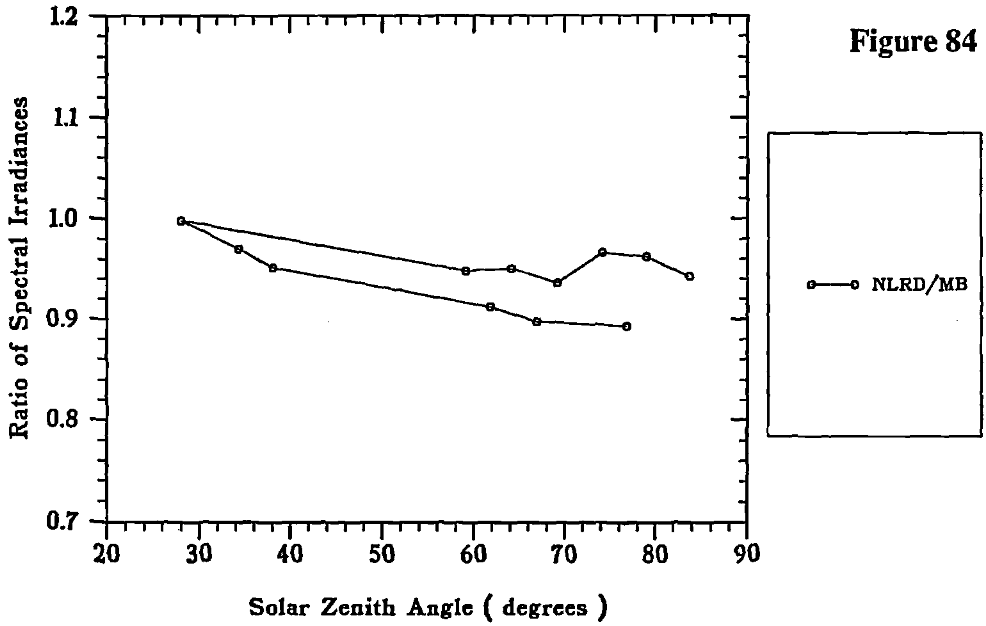


Figure 83

Ratio NLRD to MB at 333 nm
24 July 1993

Figure 84



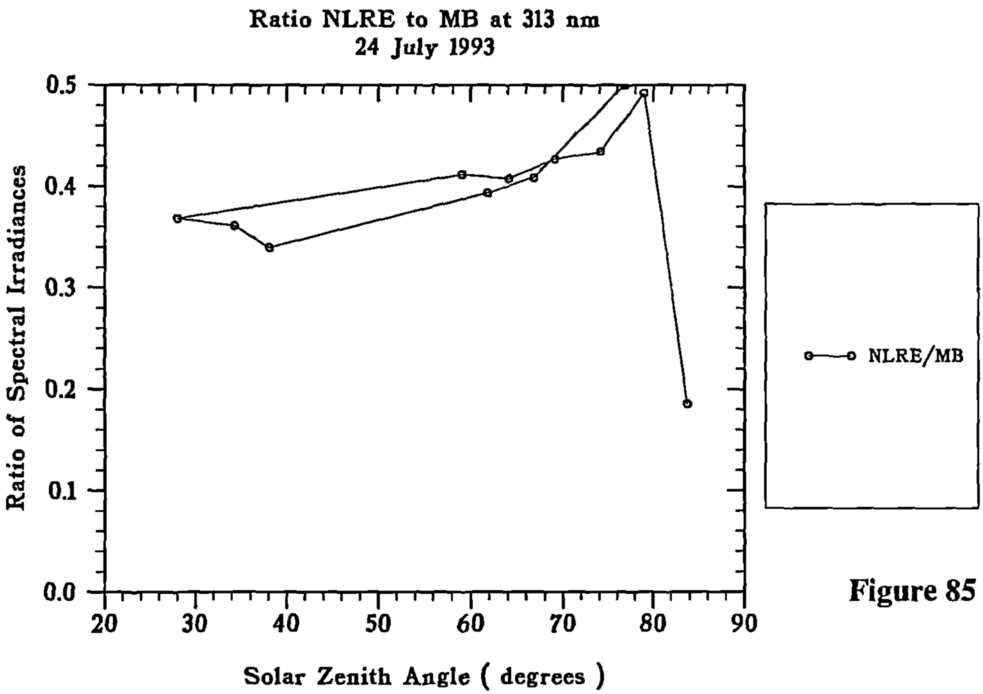
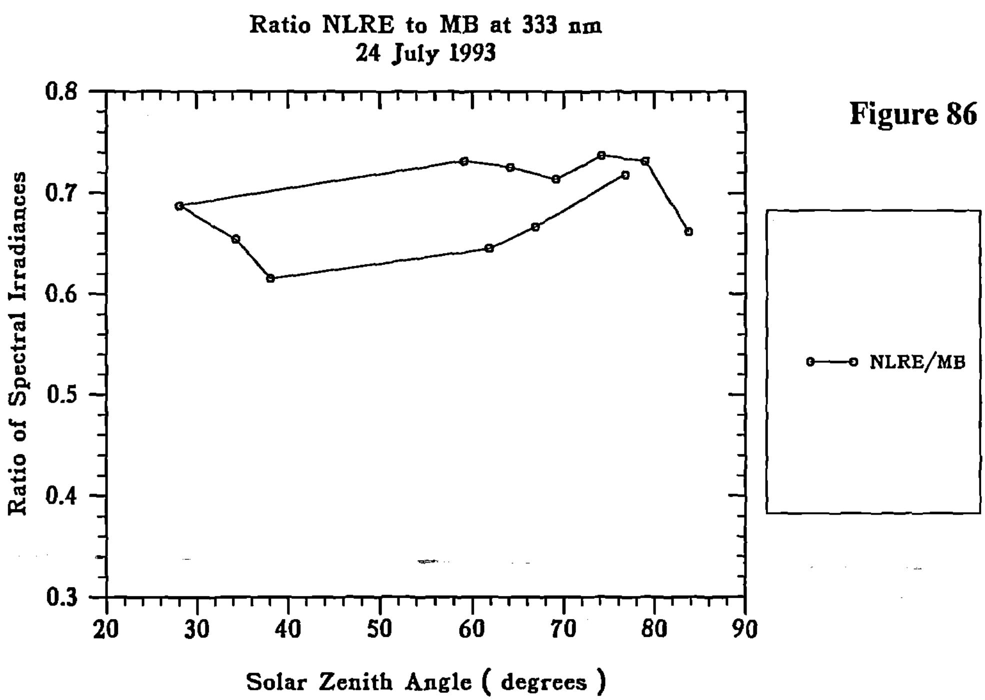


Figure 85



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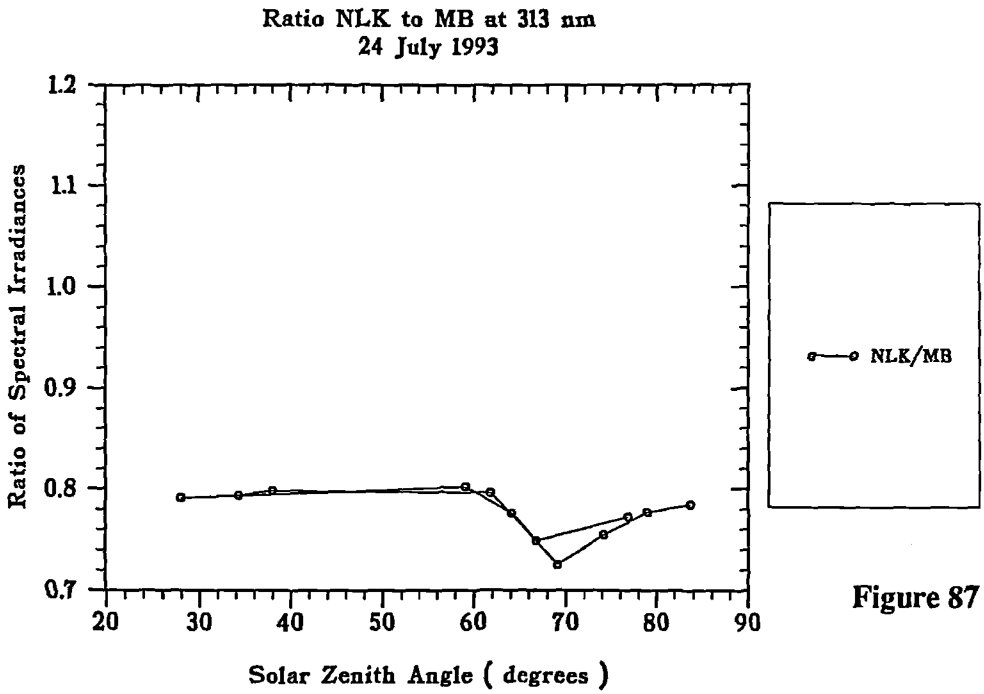

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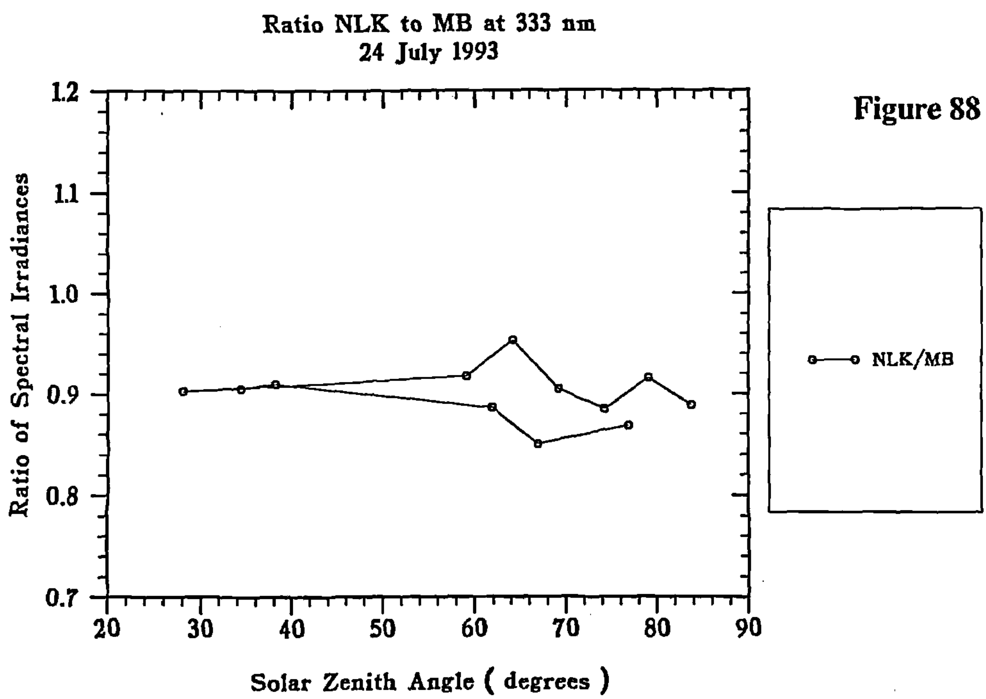

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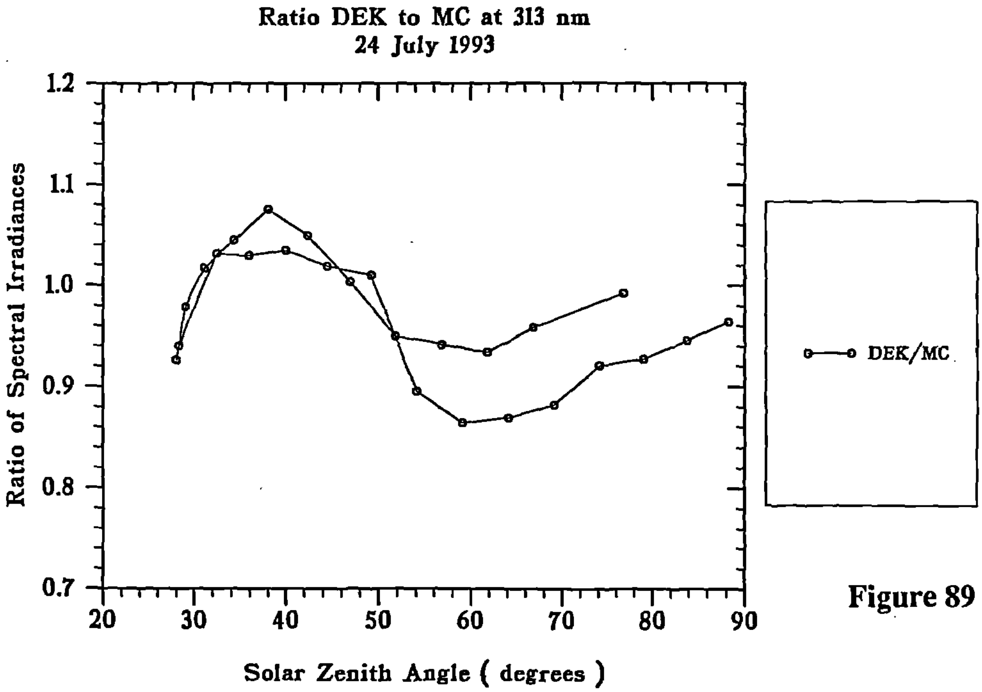

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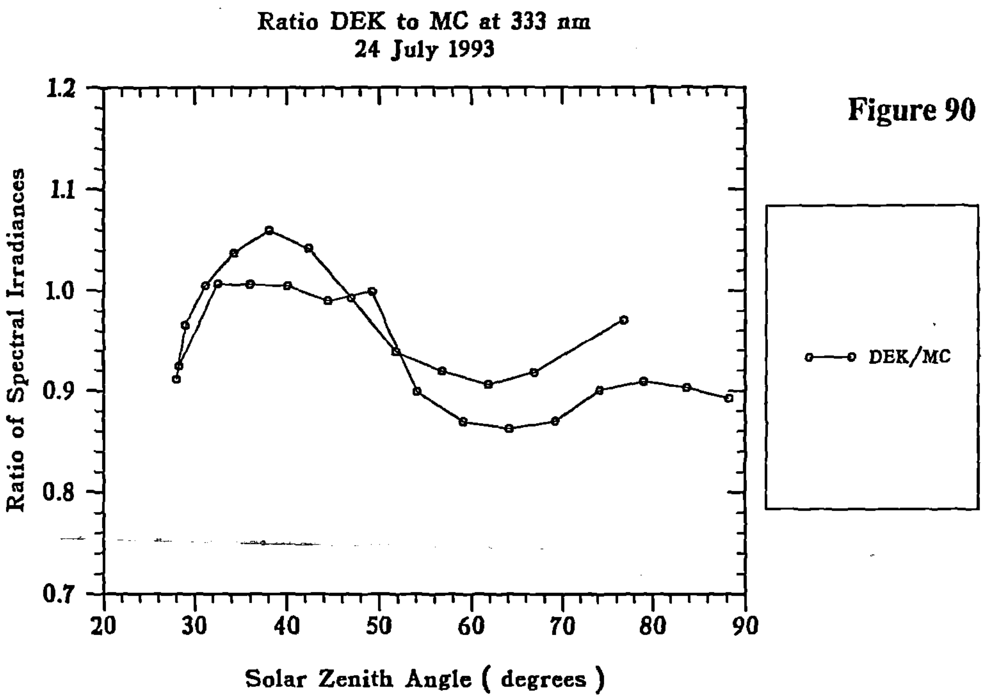

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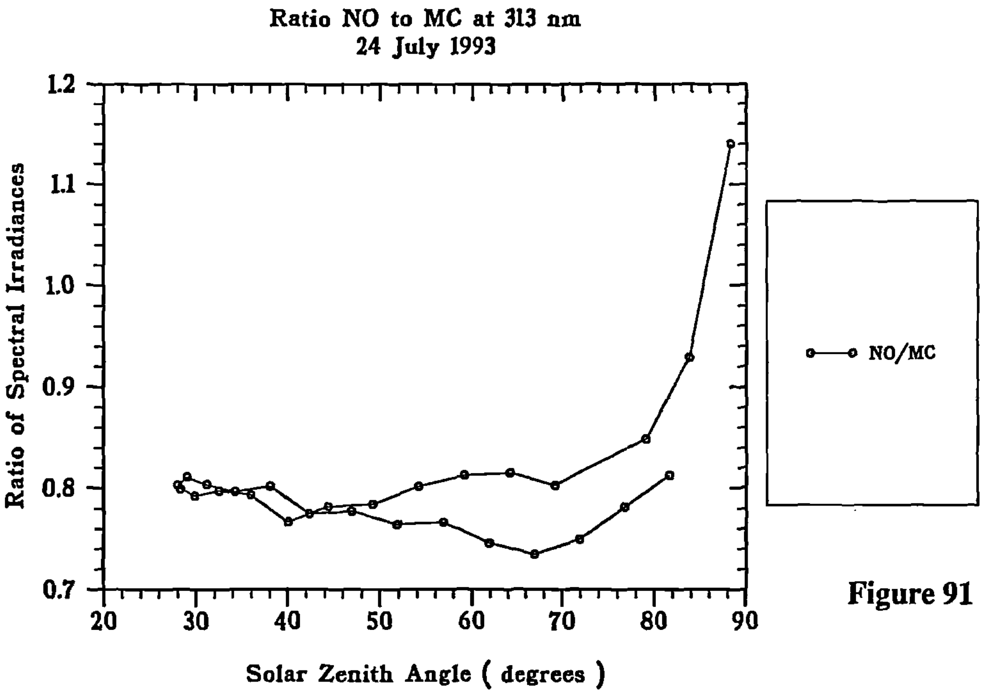

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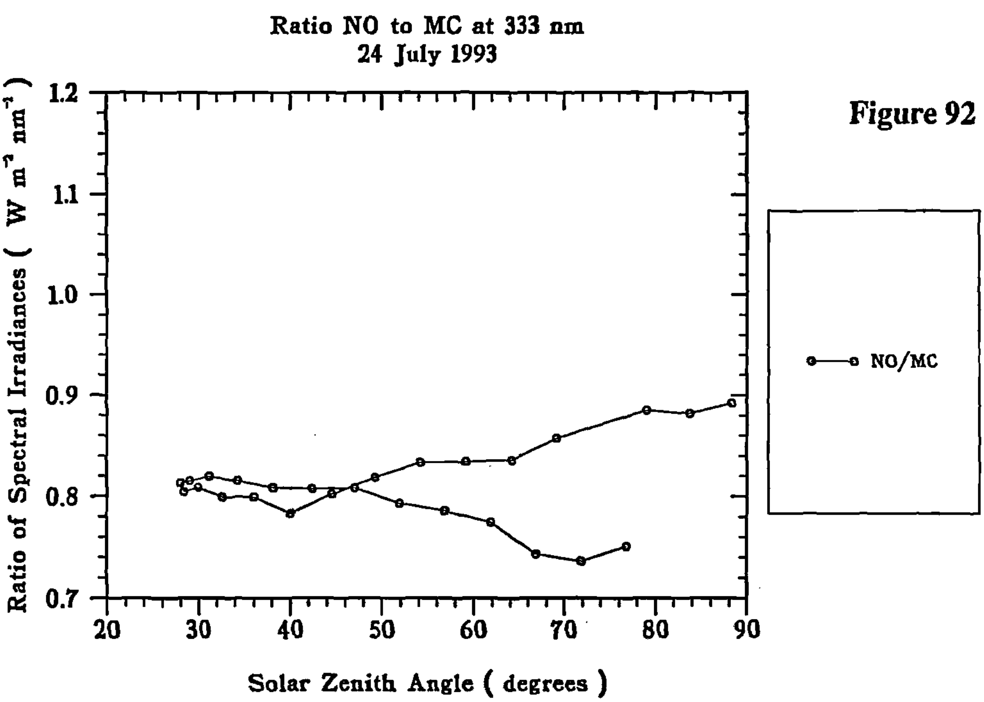

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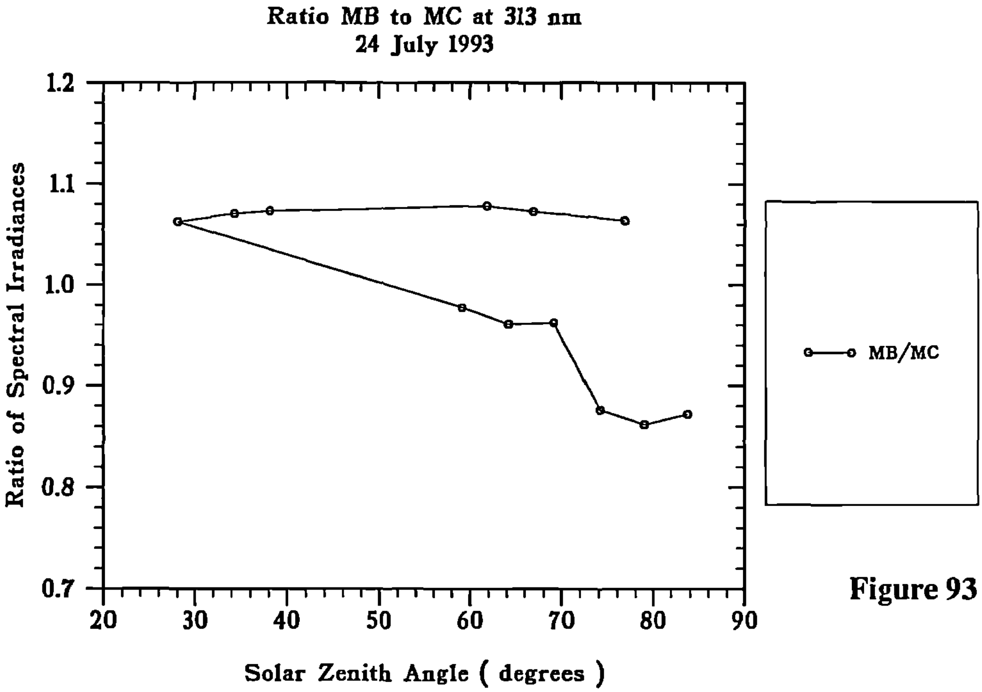

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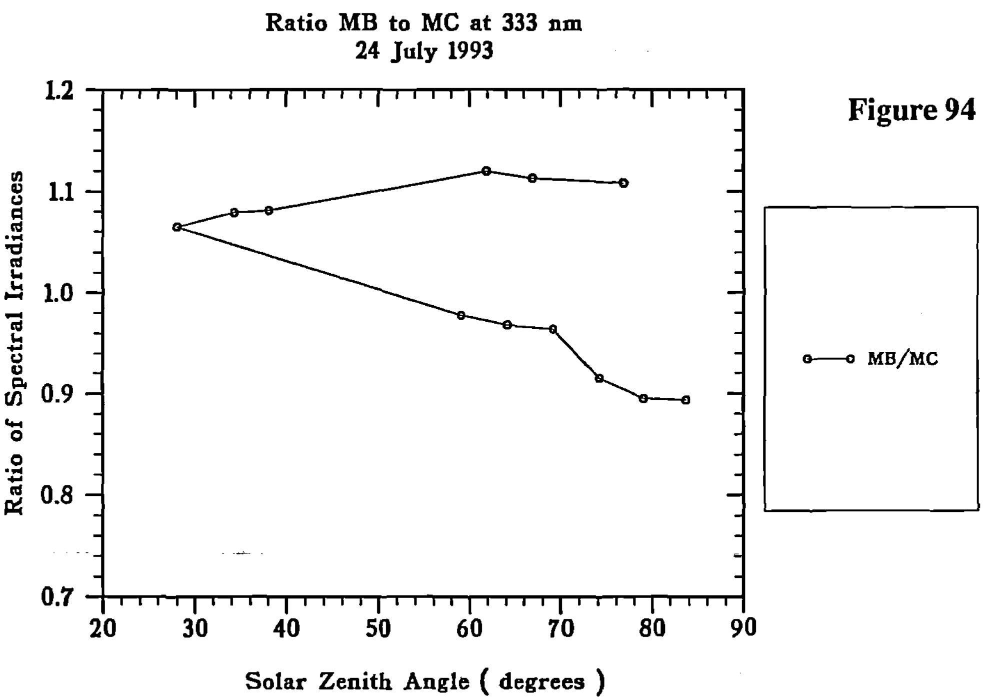

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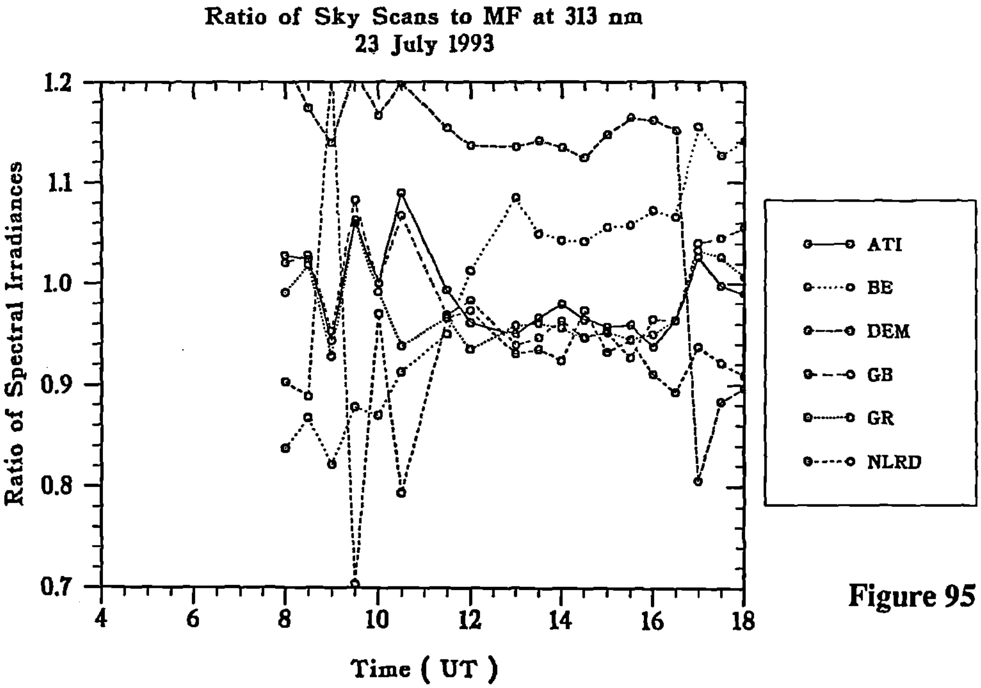

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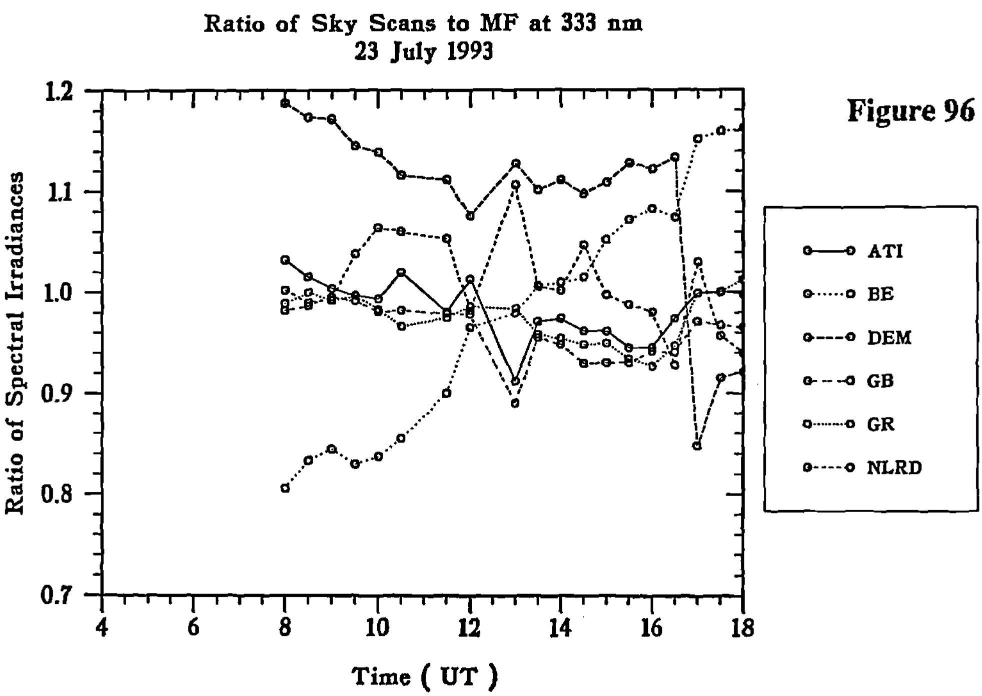

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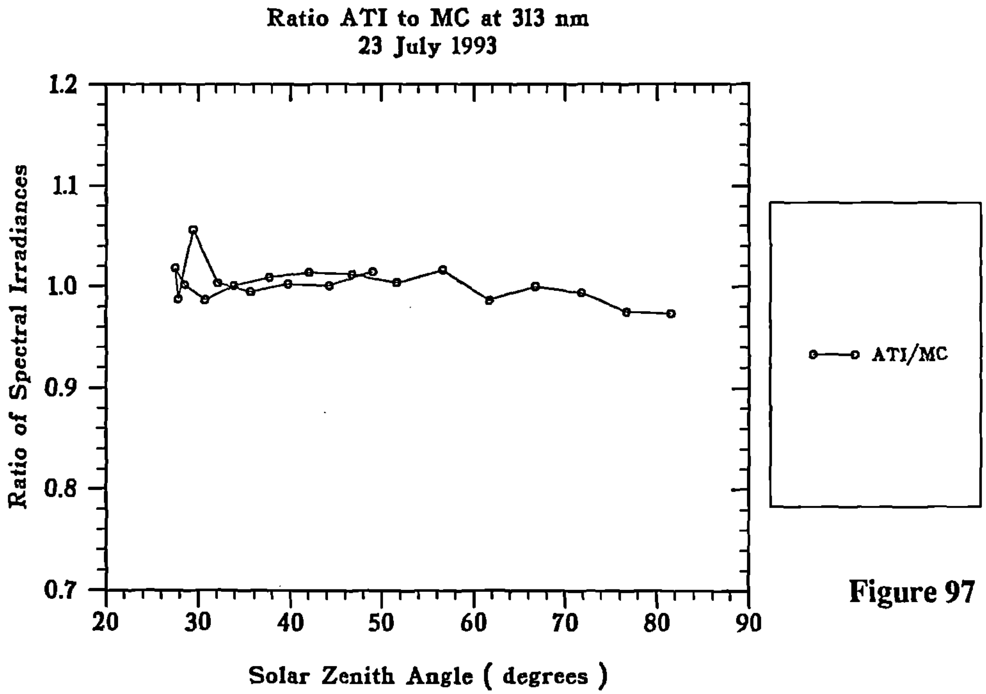

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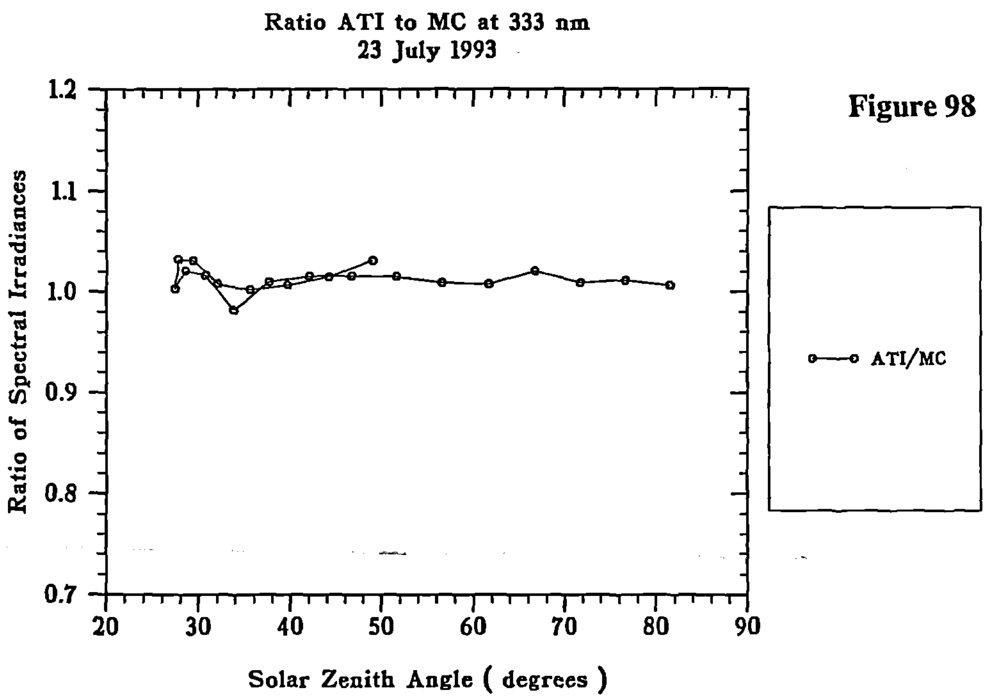


Figure 98

Ratio GB to MC at 313 nm
23 July 1993

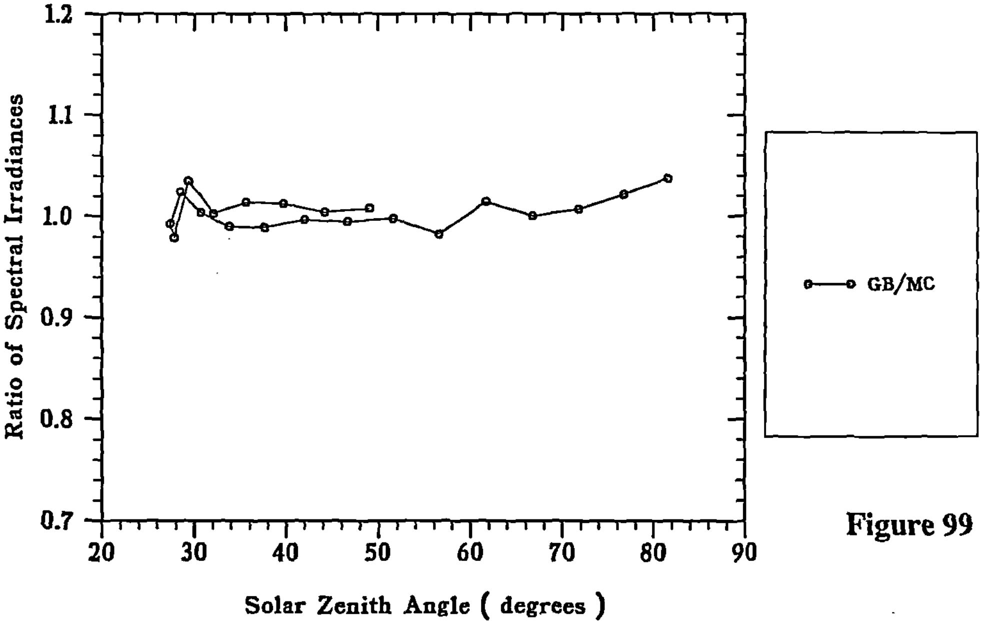


Figure 99

Ratio GB to MC at 333 nm
23 July 1993

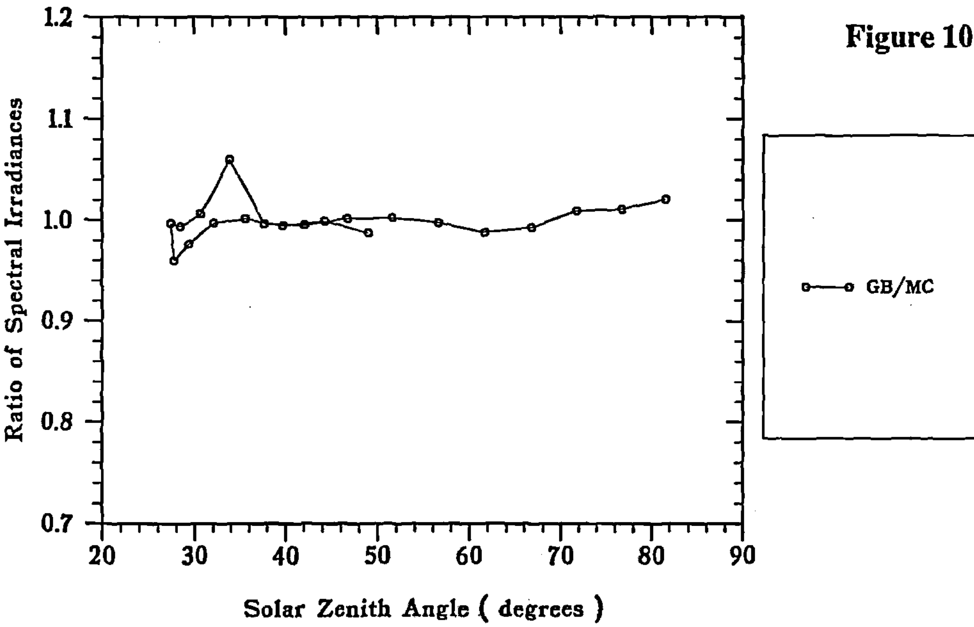


Figure 100

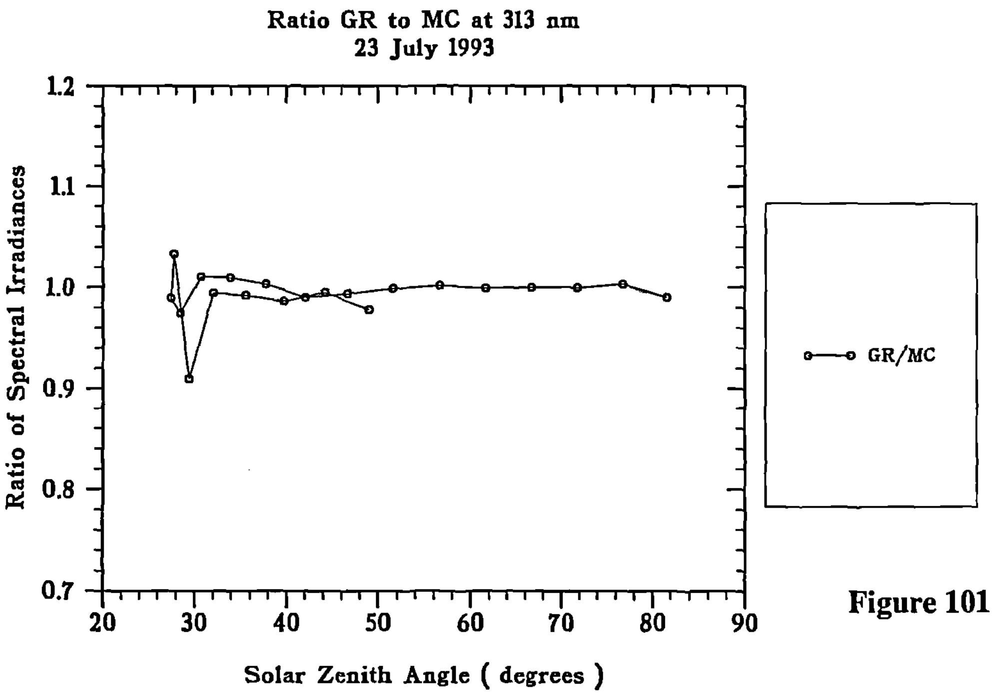


Figure 101

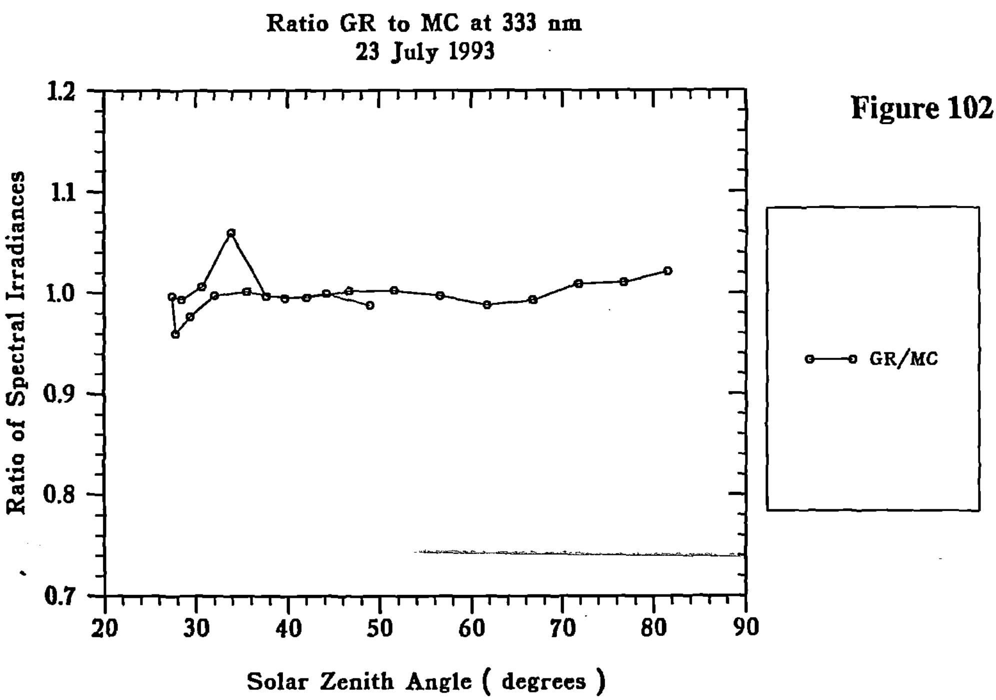


Figure 102

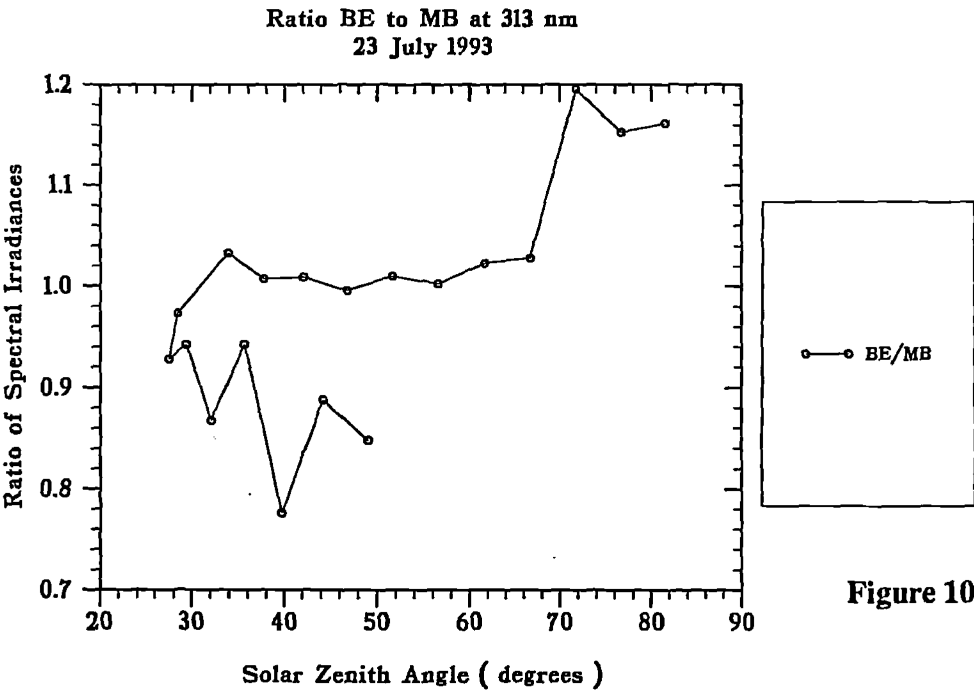
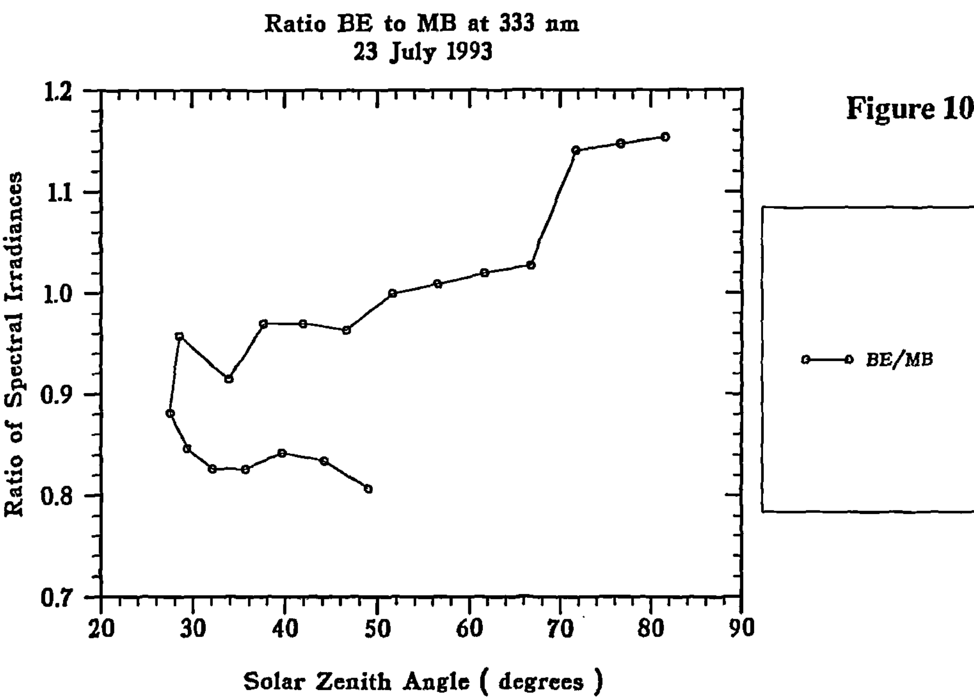


Figure 103

Figure 104



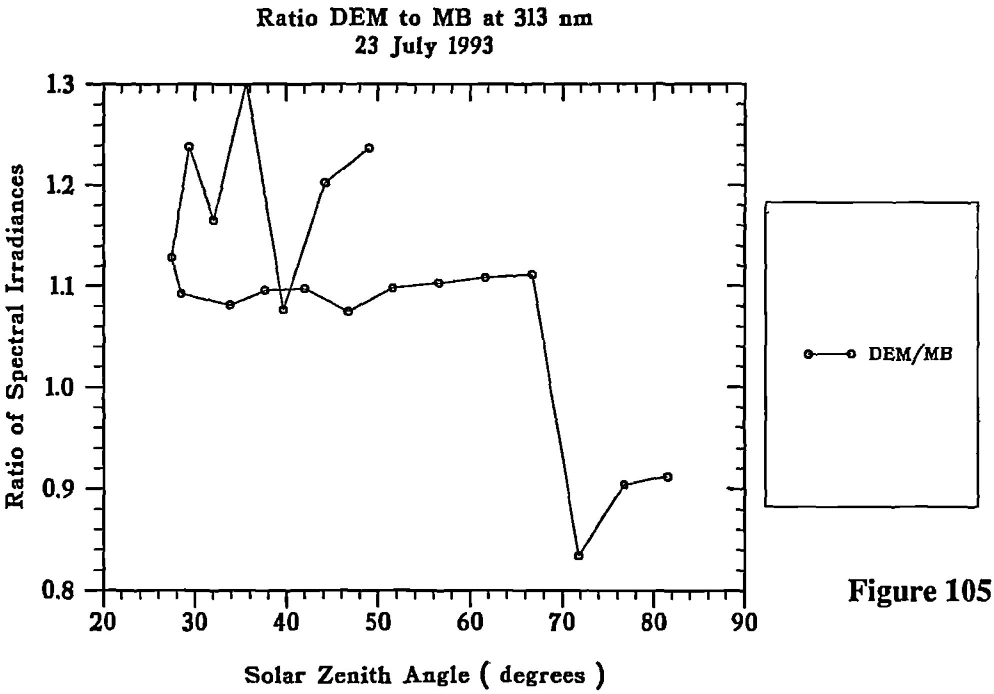


Figure 105

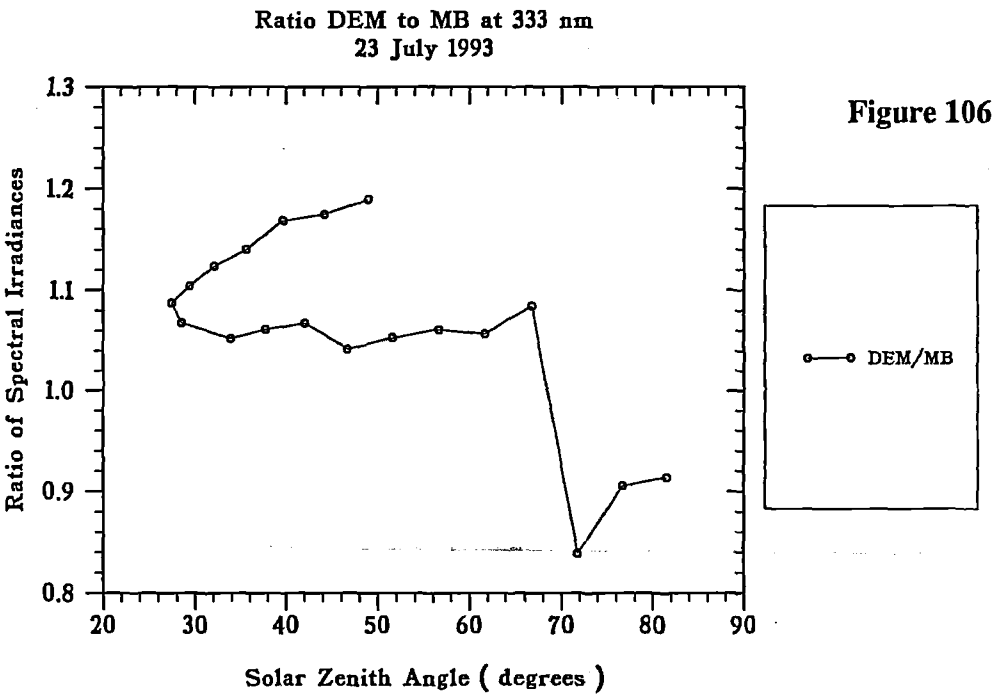
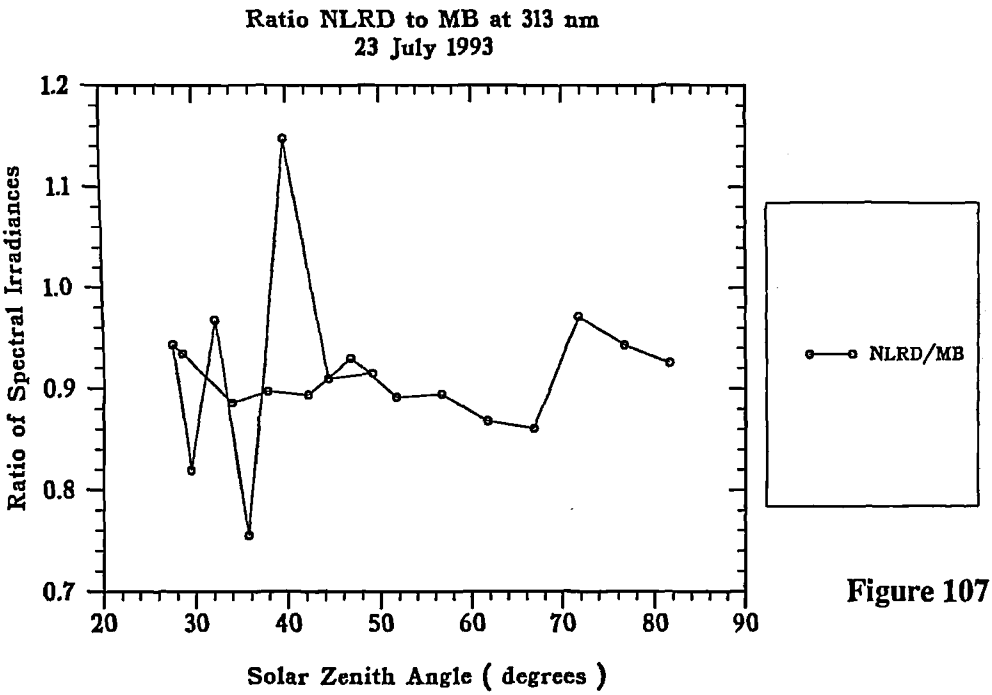


Figure 106



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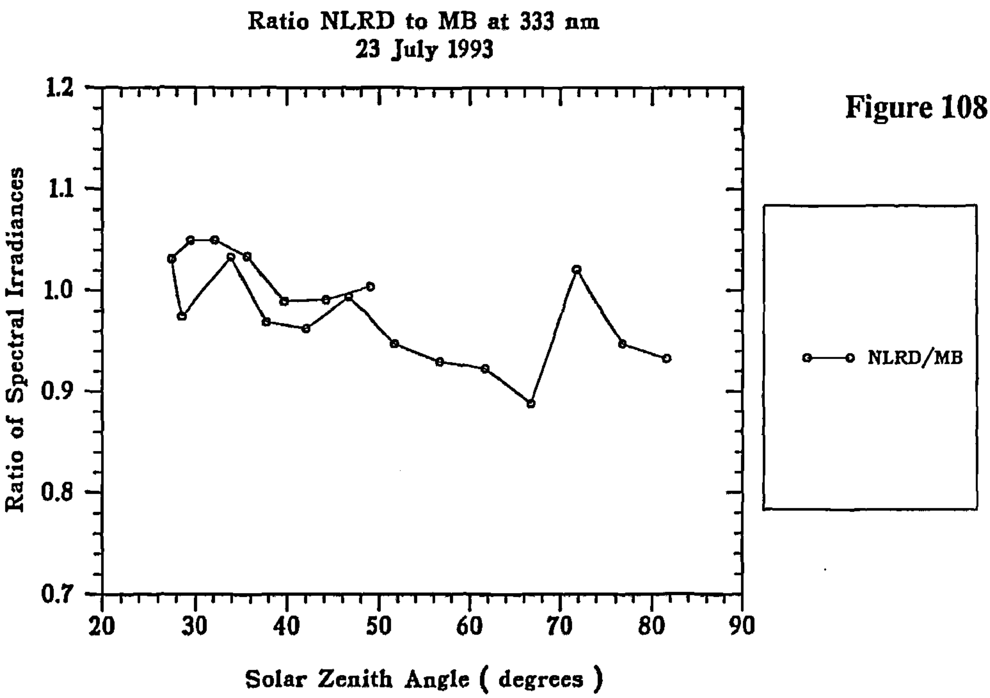

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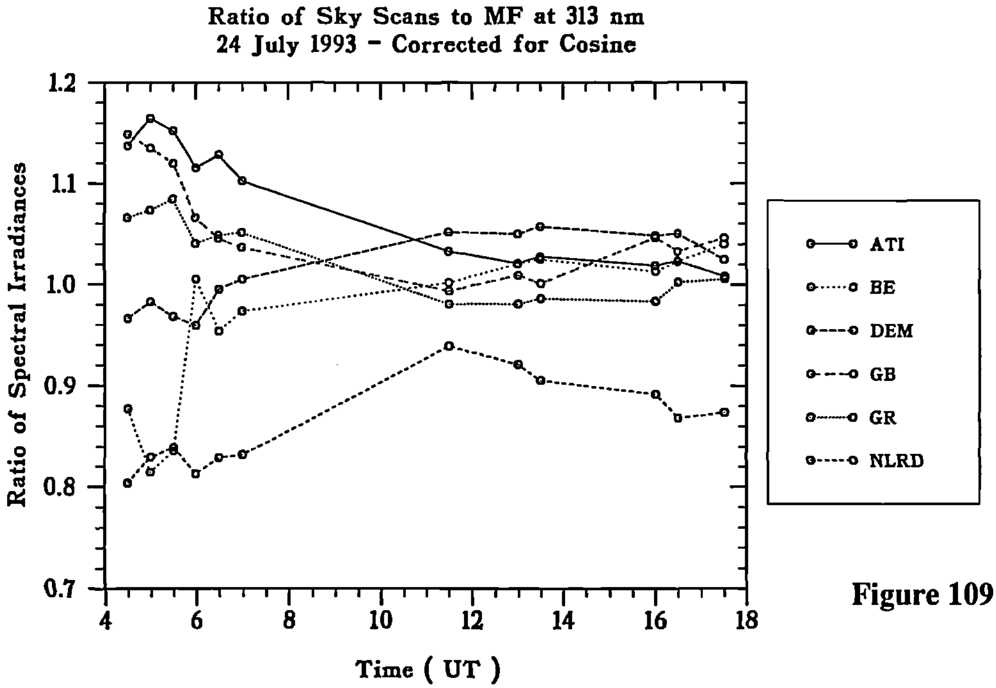

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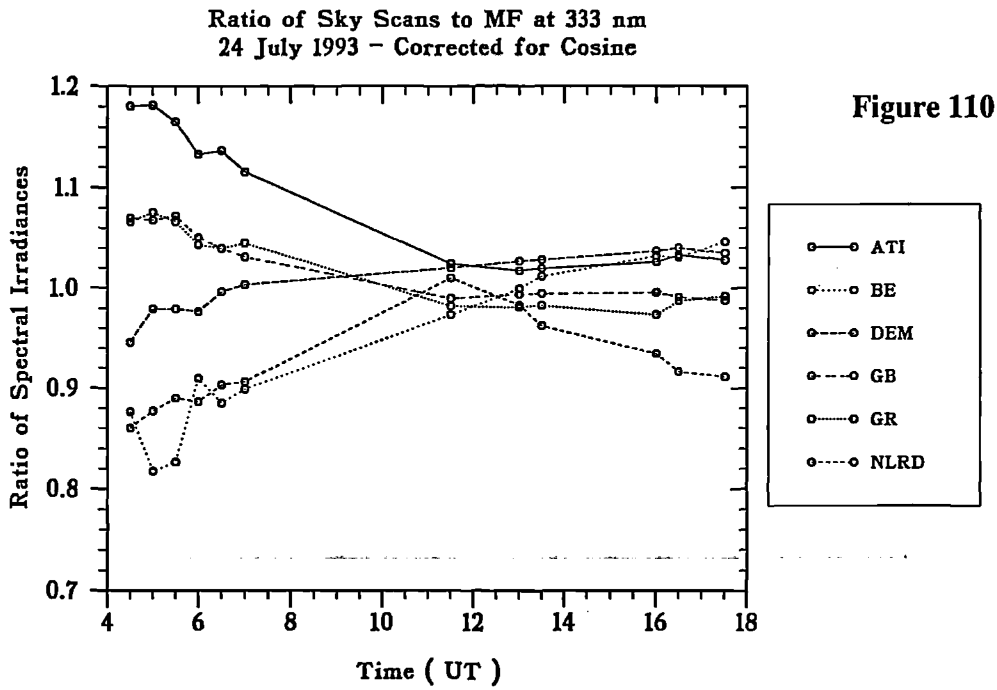

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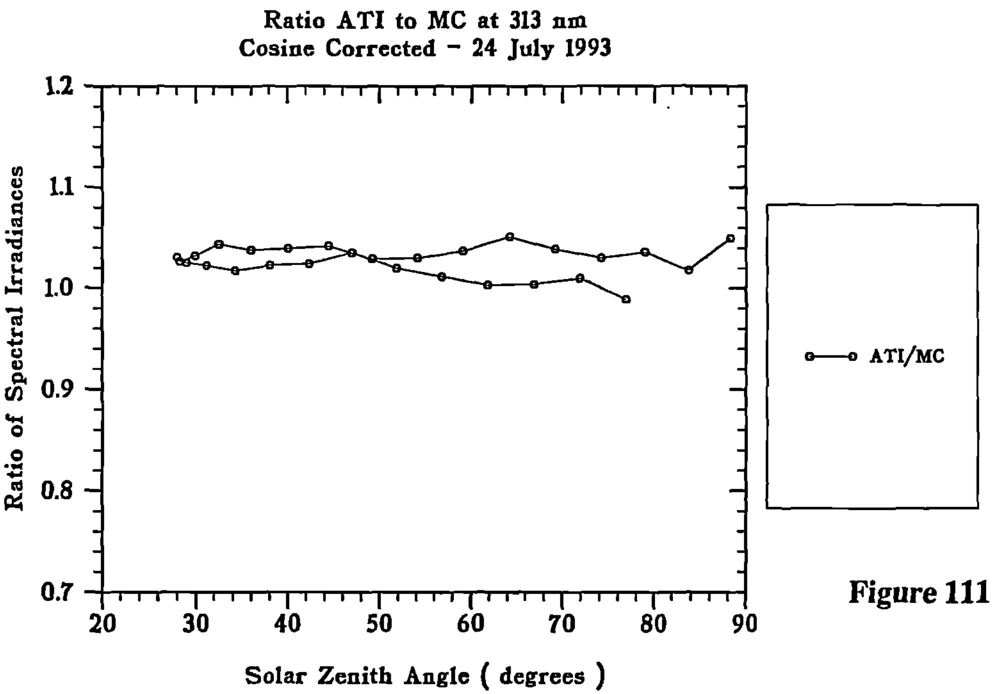

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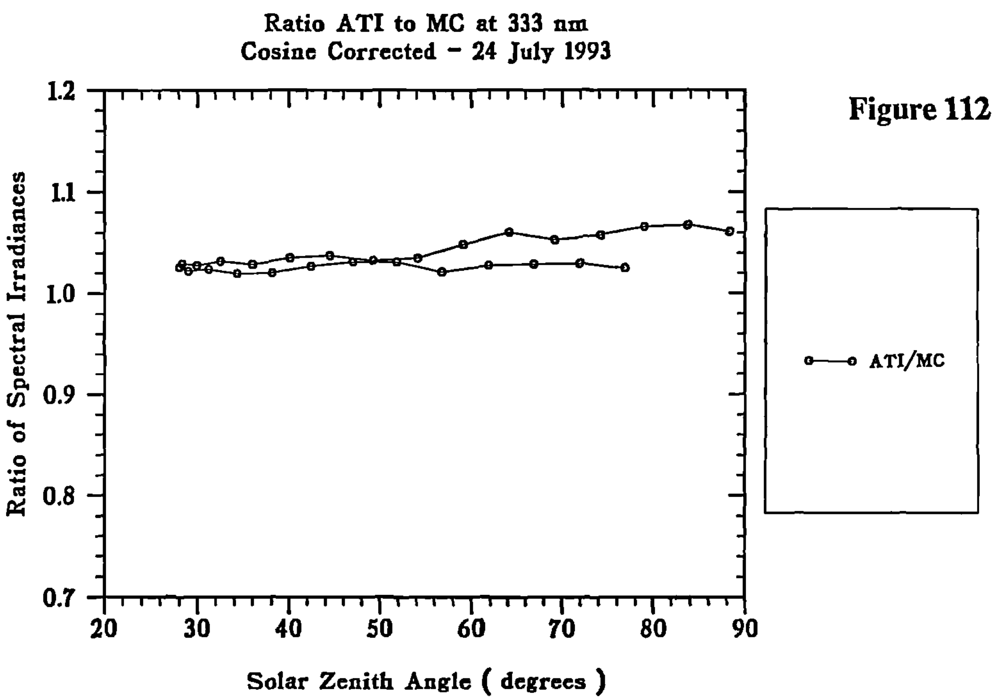


Figure 112

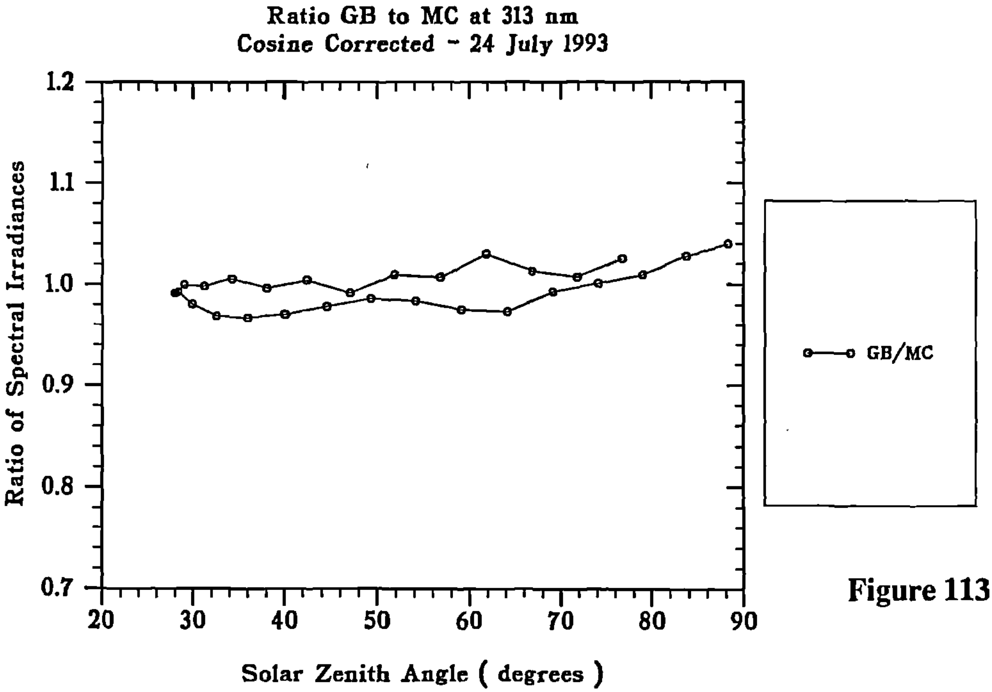


Figure 113

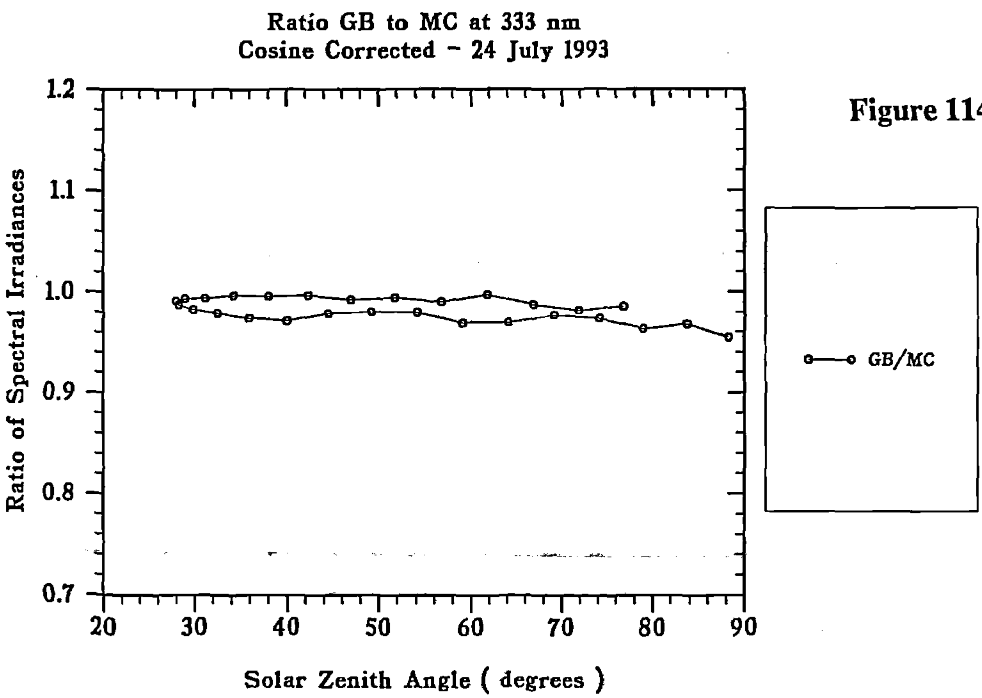


Figure 114

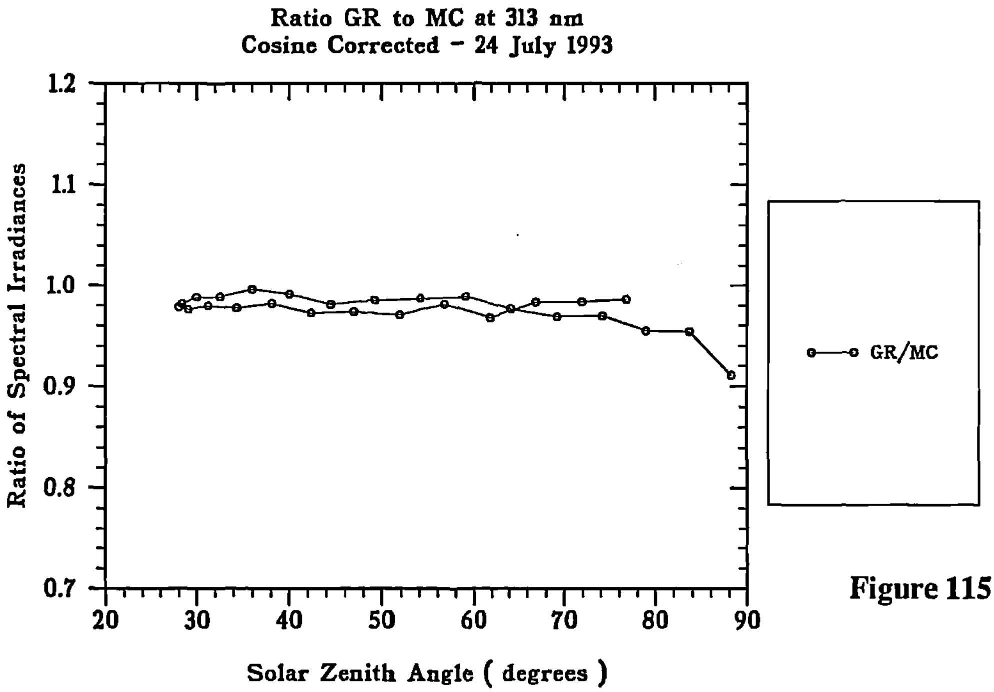
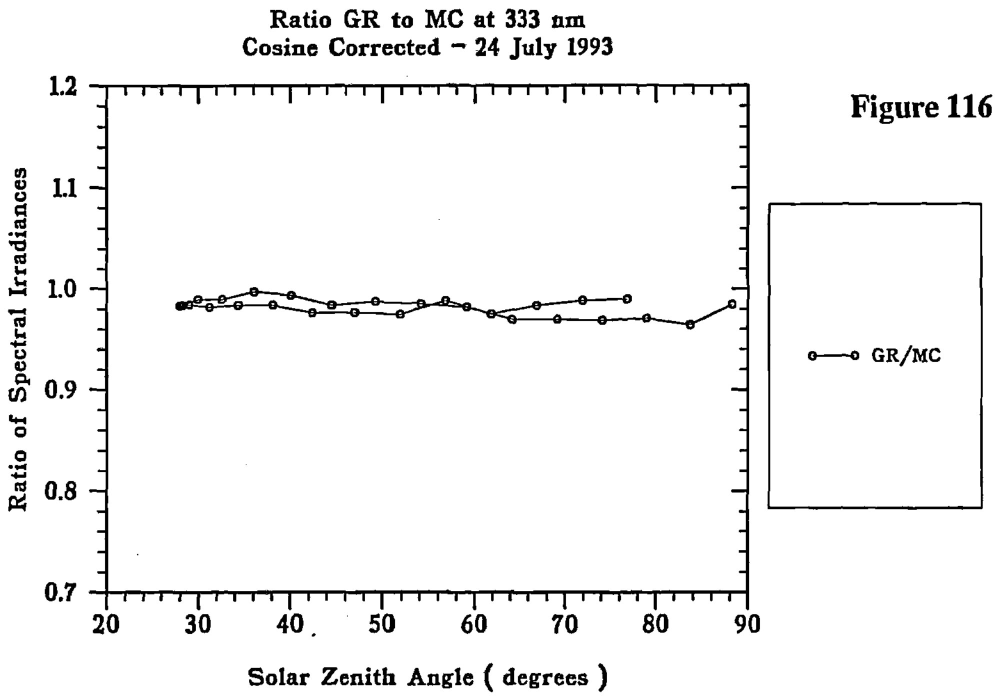


Figure 115

Figure 116



Ratio BE to MB at 313 nm
Cosine Corrected - 24 July 1993

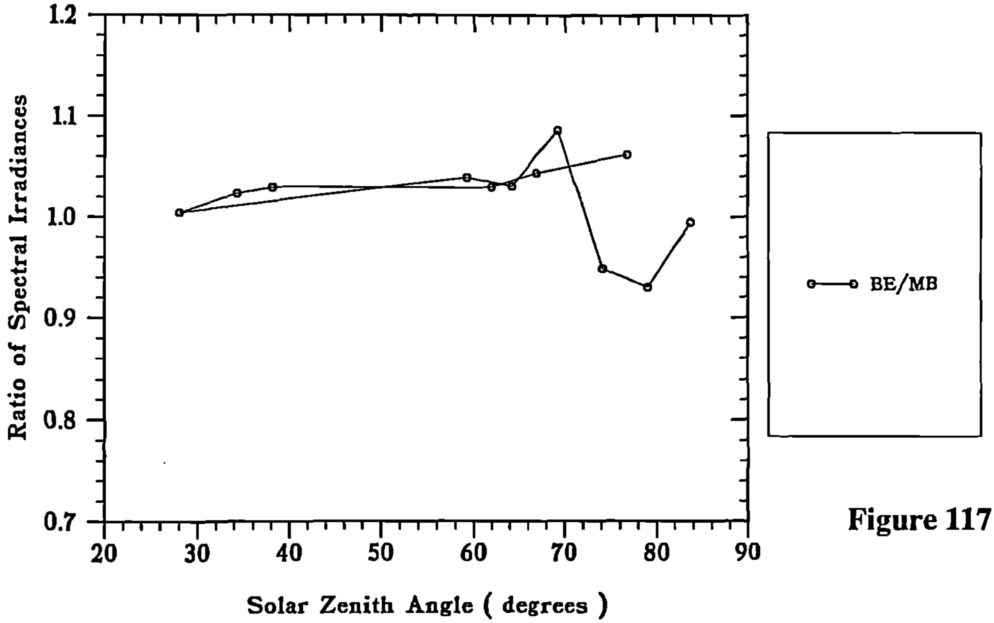
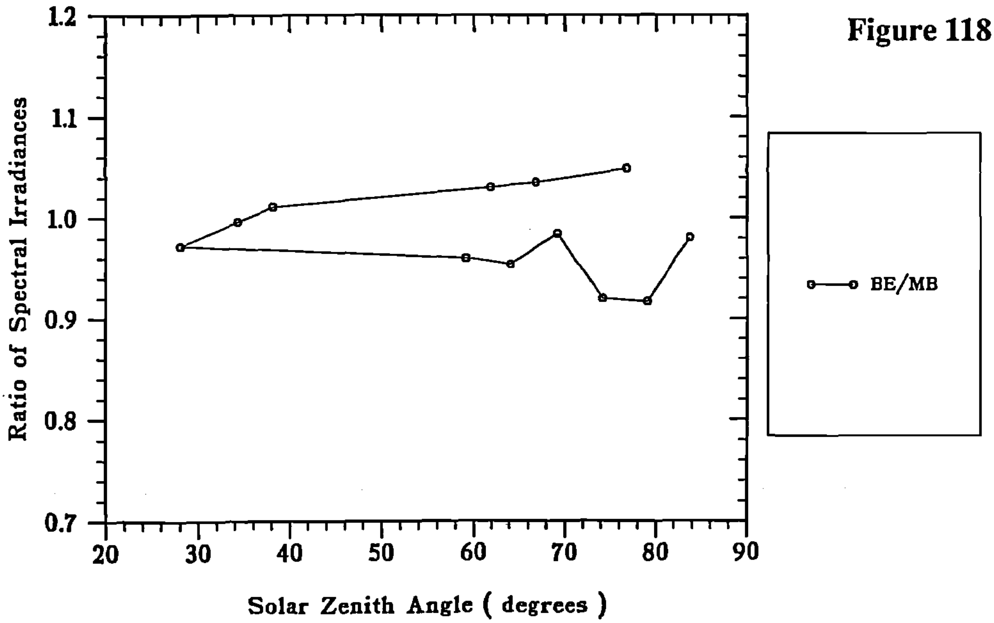


Figure 117

Ratio BE to MB at 333 nm
Cosine Corrected - 24 July 1993

Figure 118



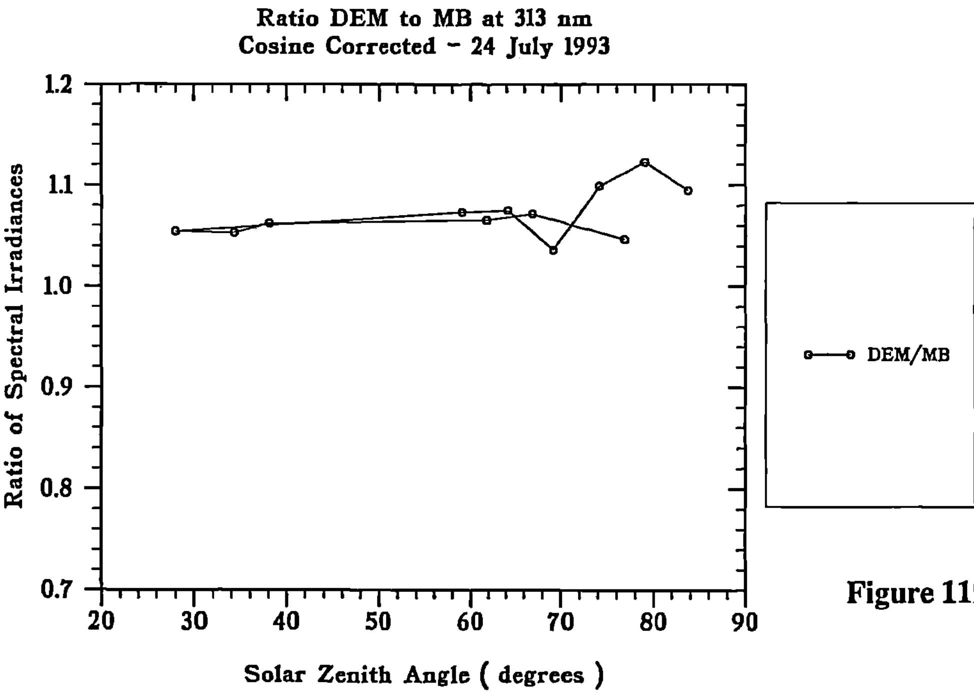


Figure 119

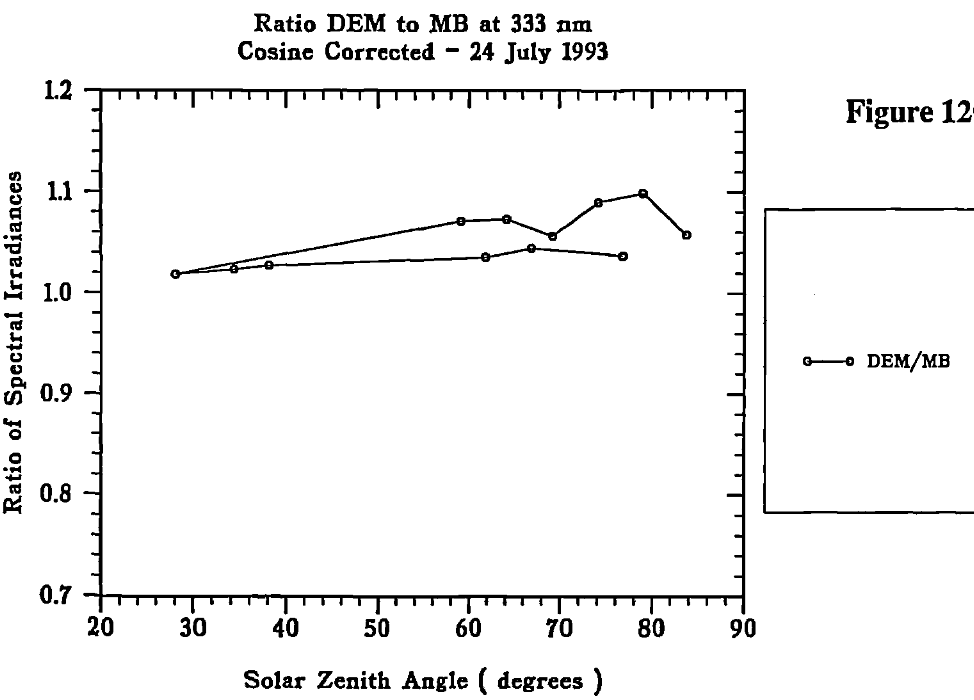


Figure 120

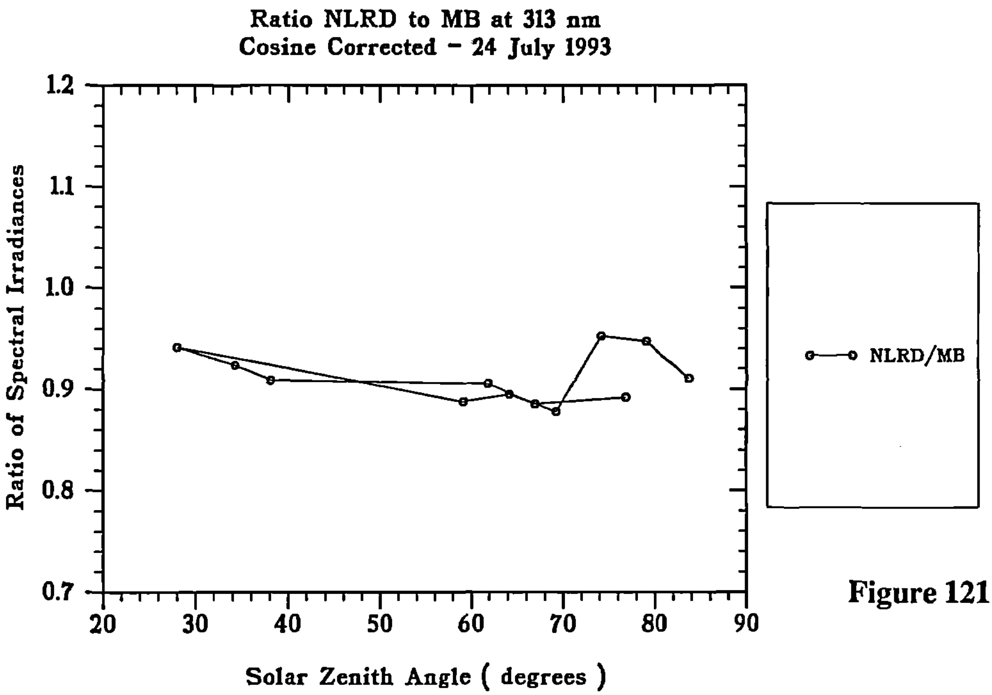
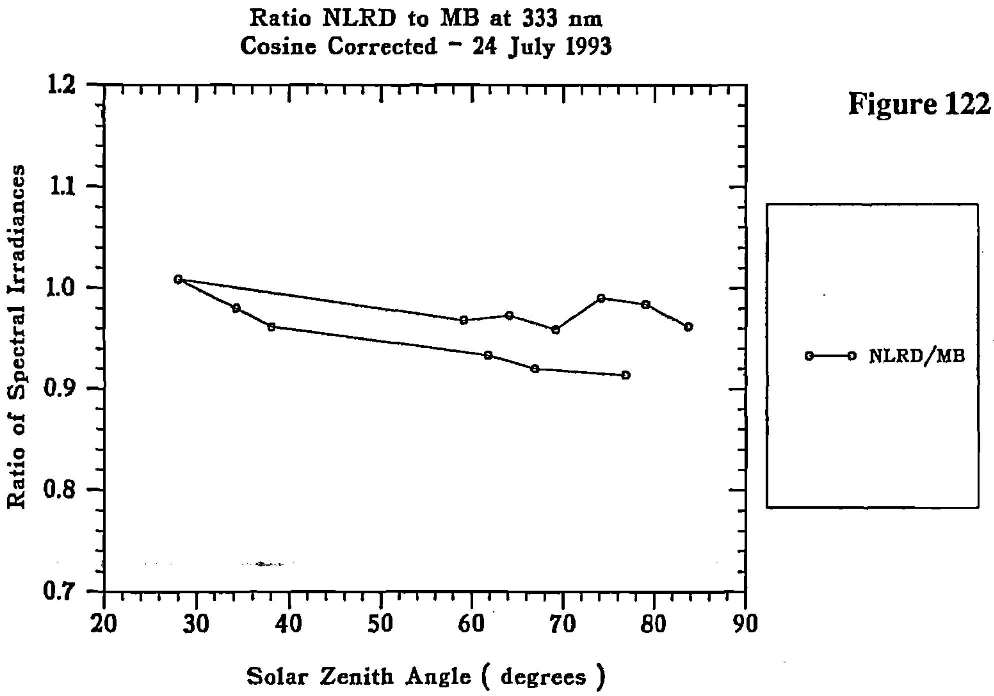


Figure 121



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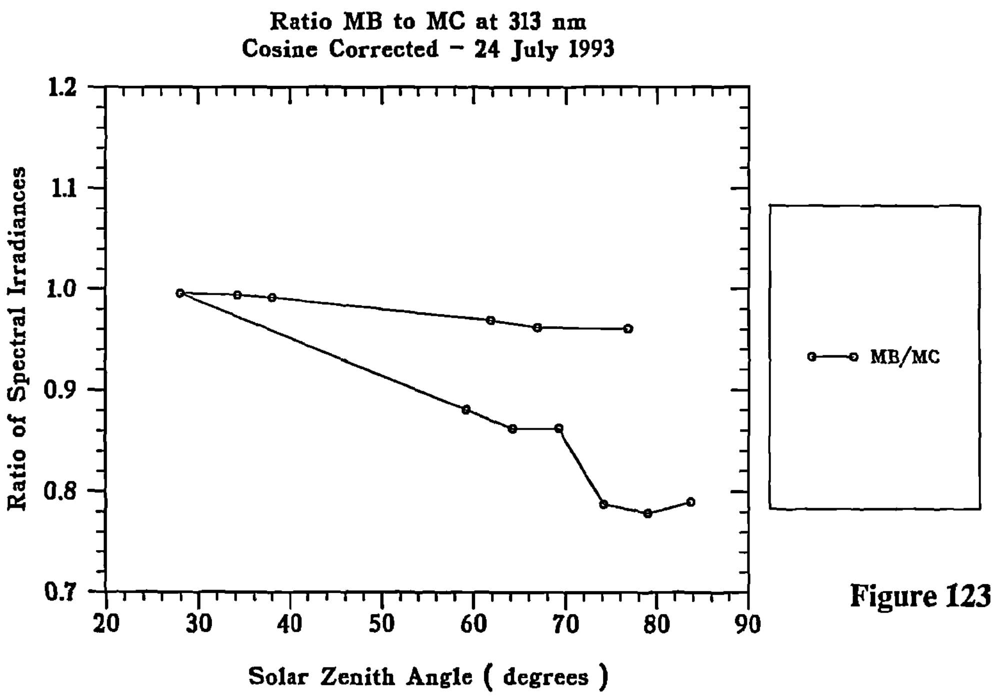


Figure 123

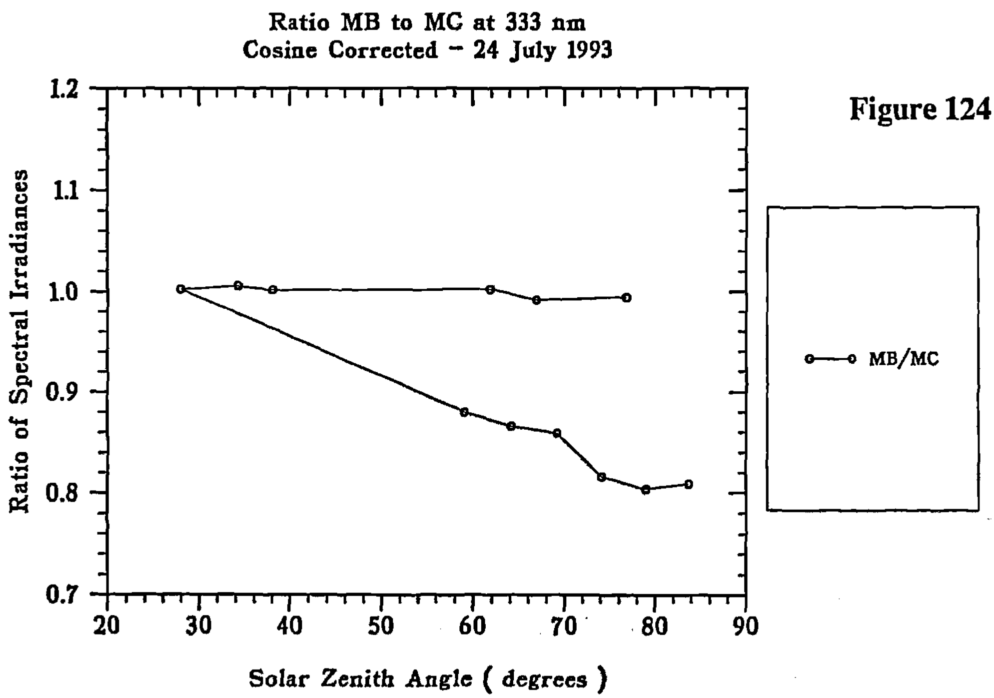


Figure 124

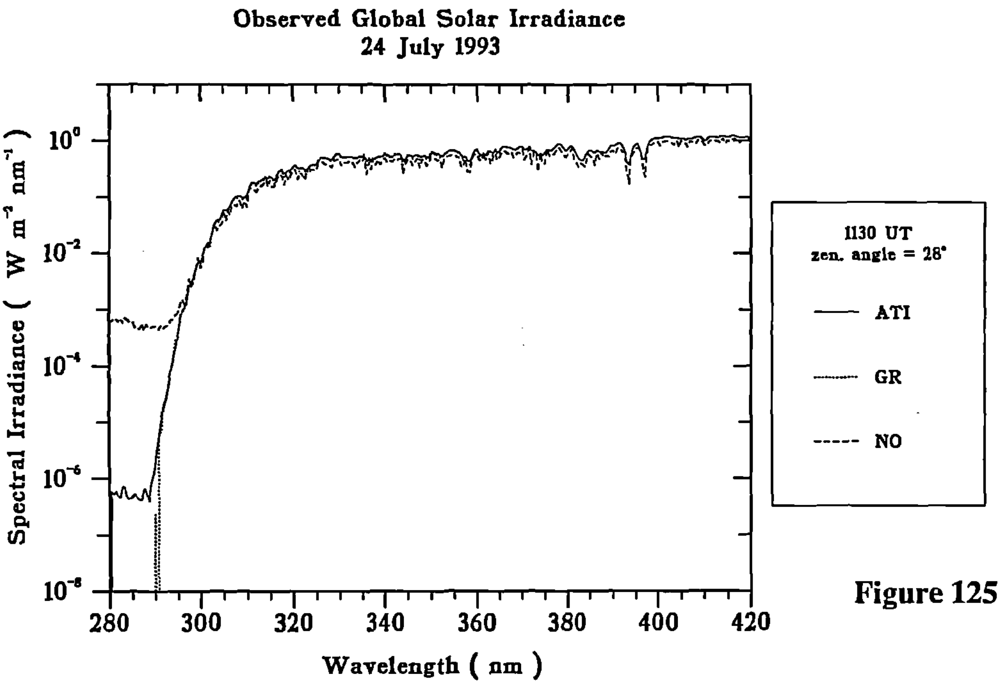
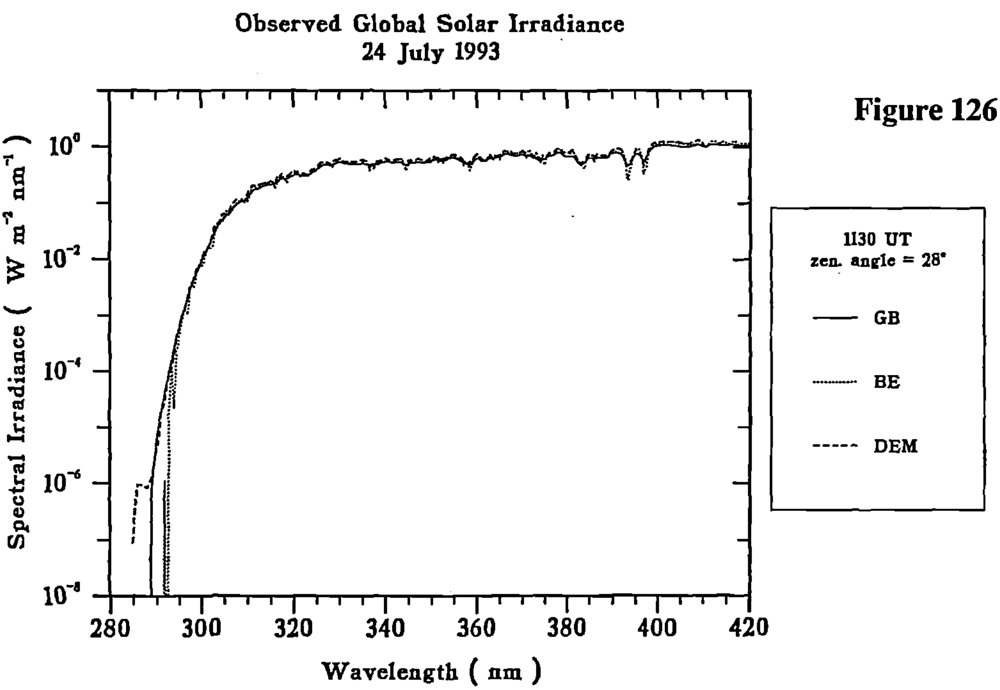


Figure 125



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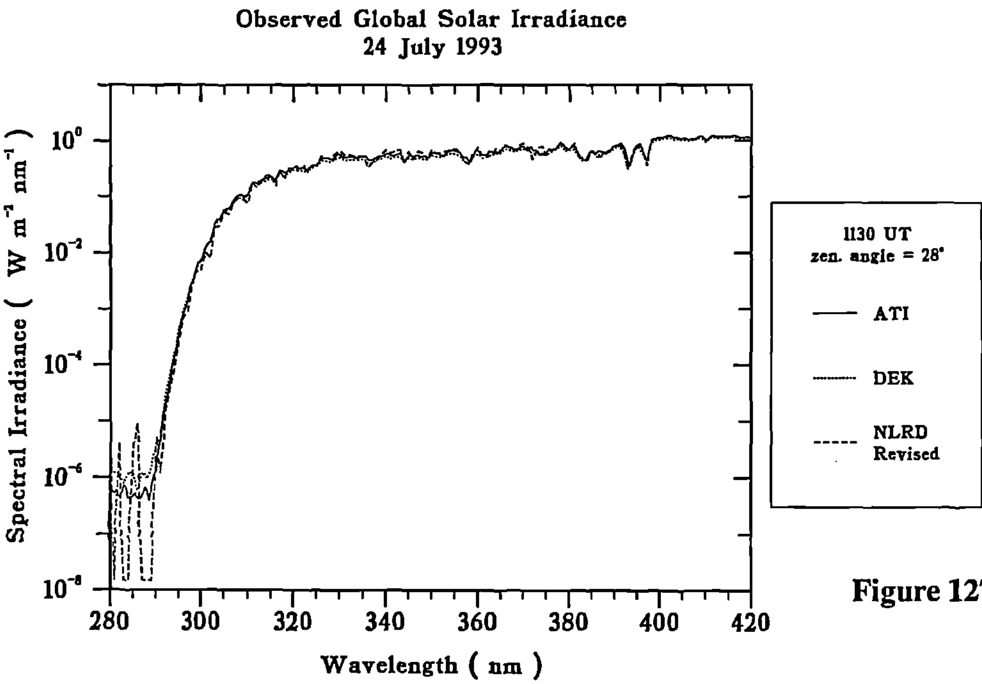

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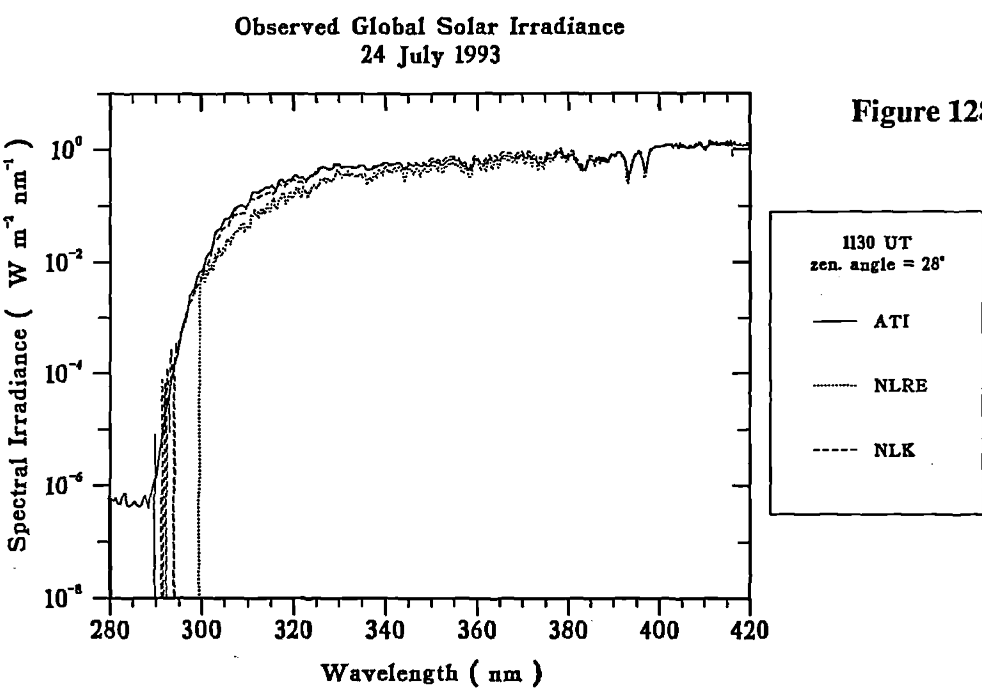

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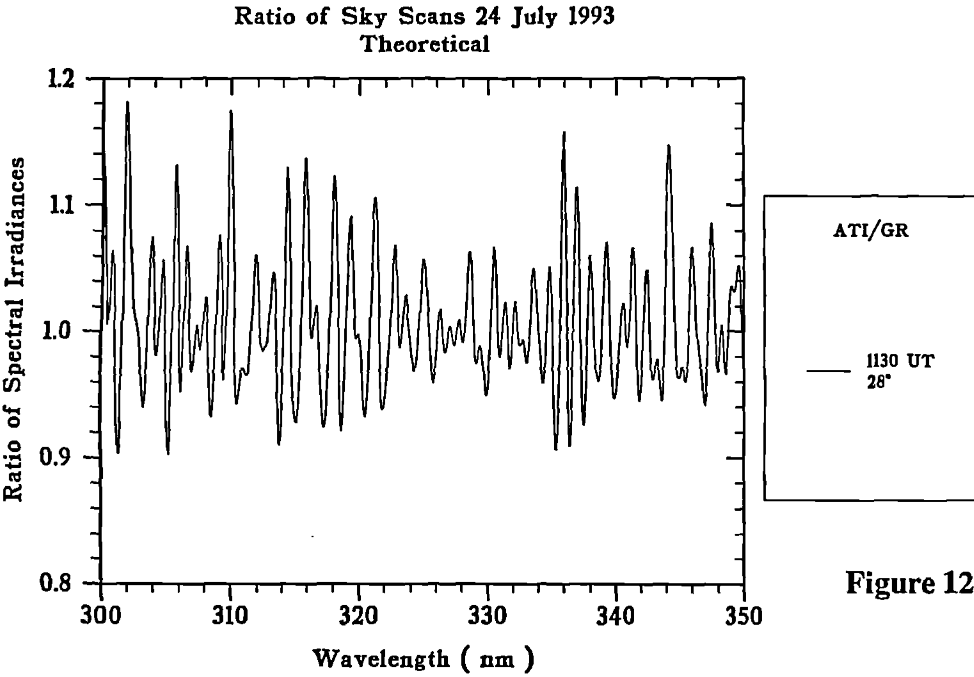

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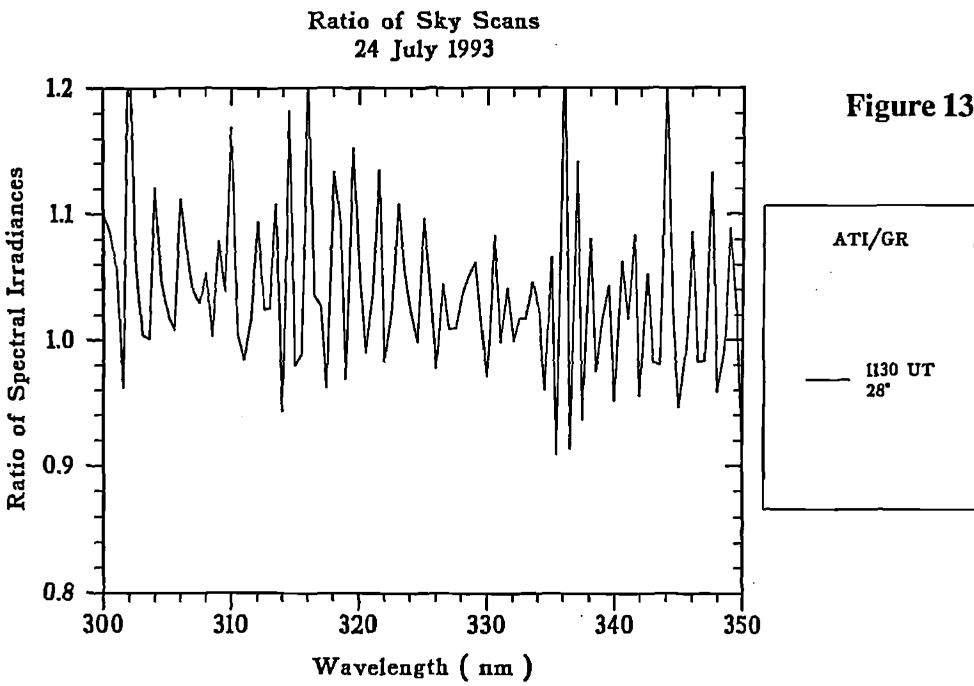

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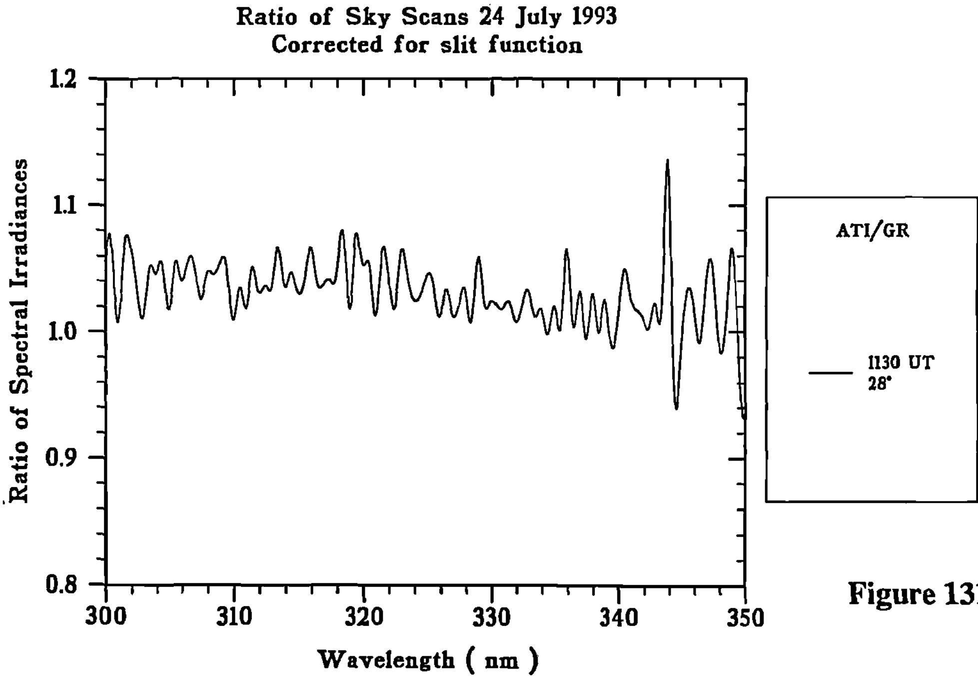

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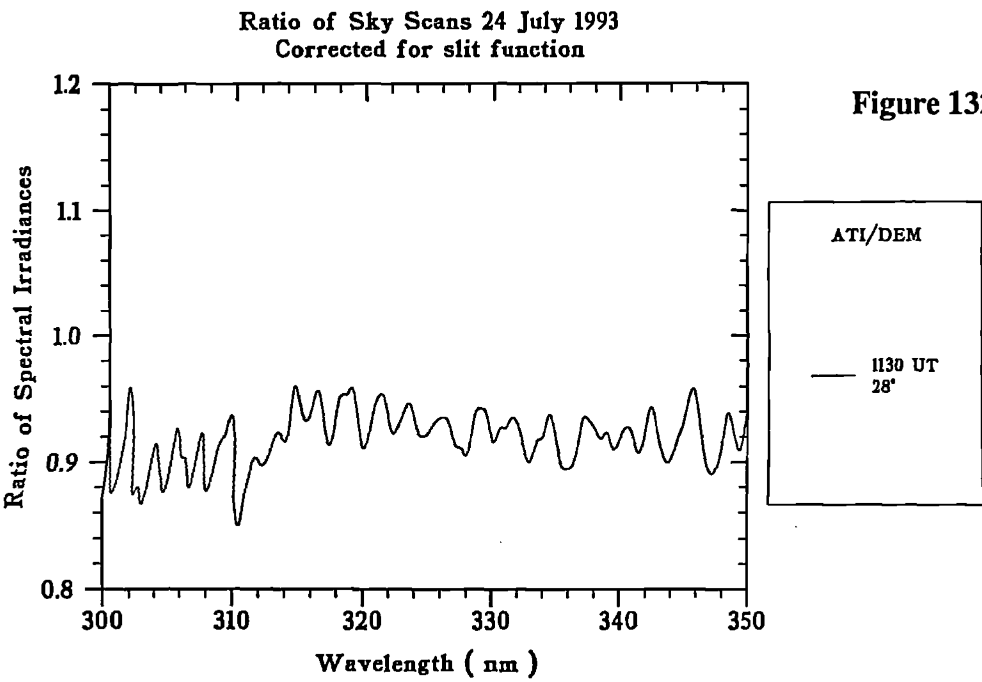

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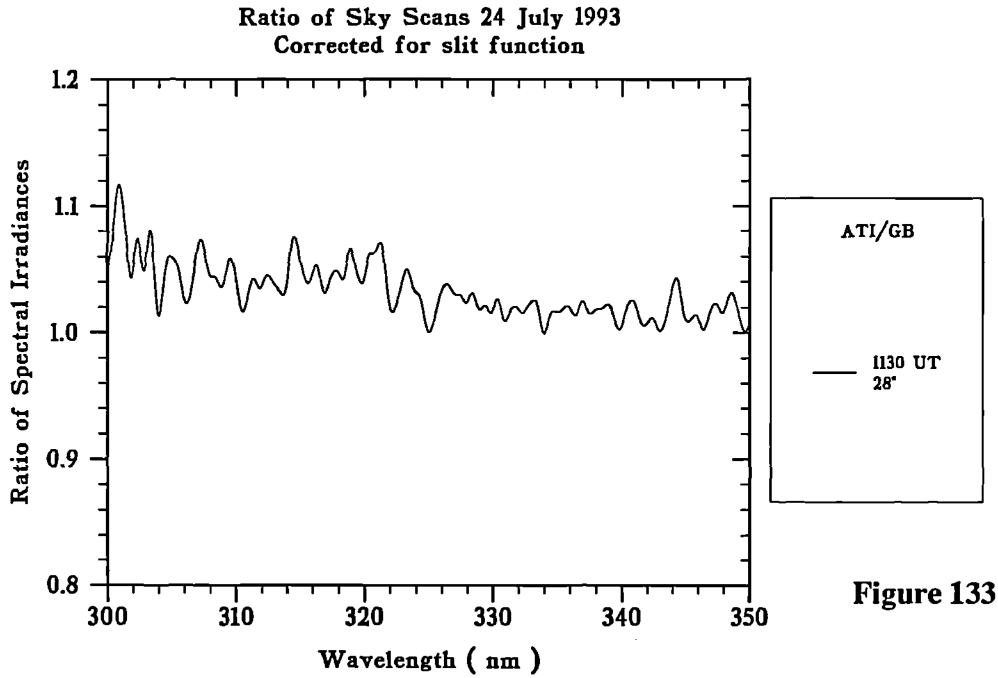
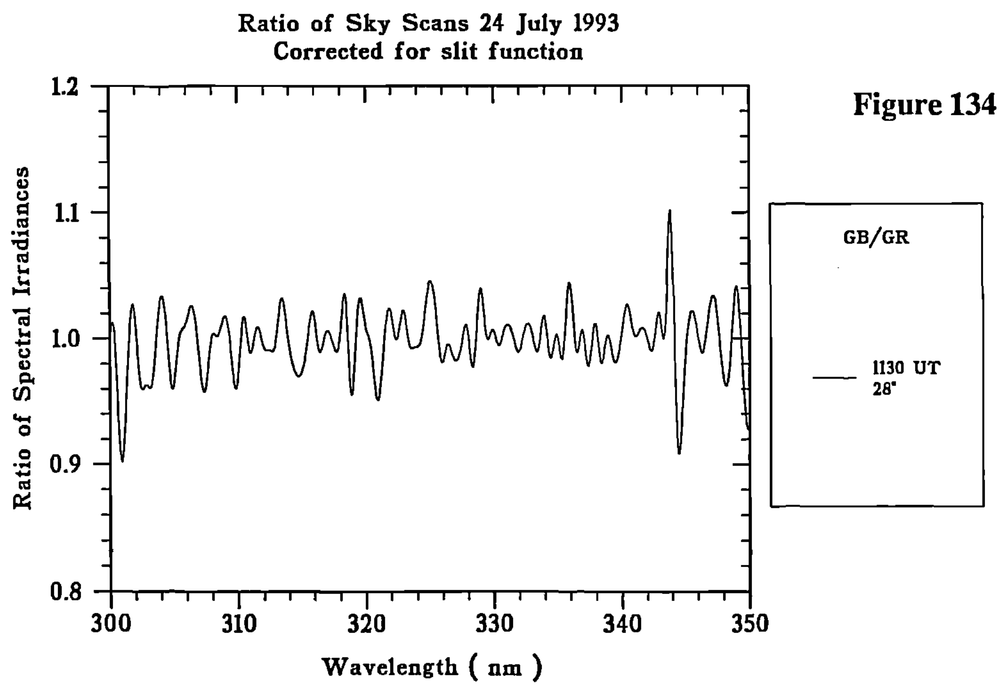
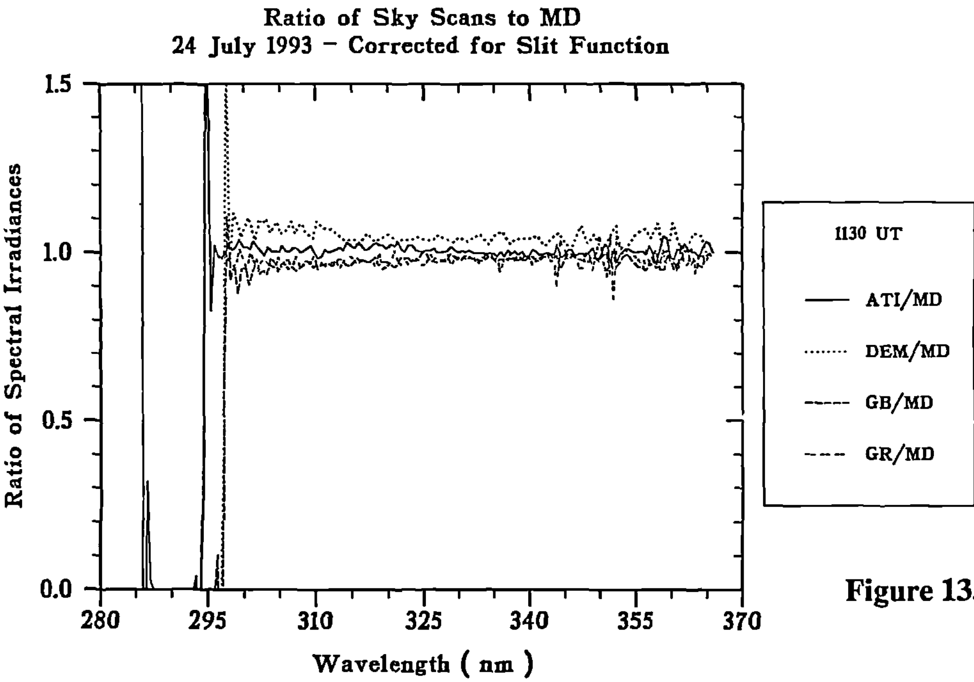


Figure 133

Figure 134





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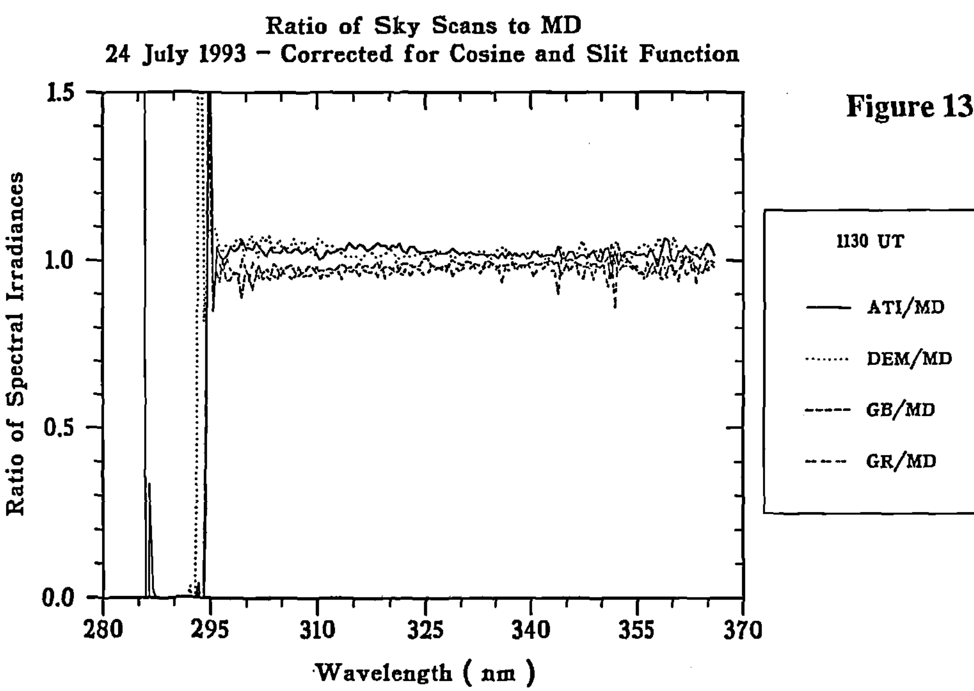

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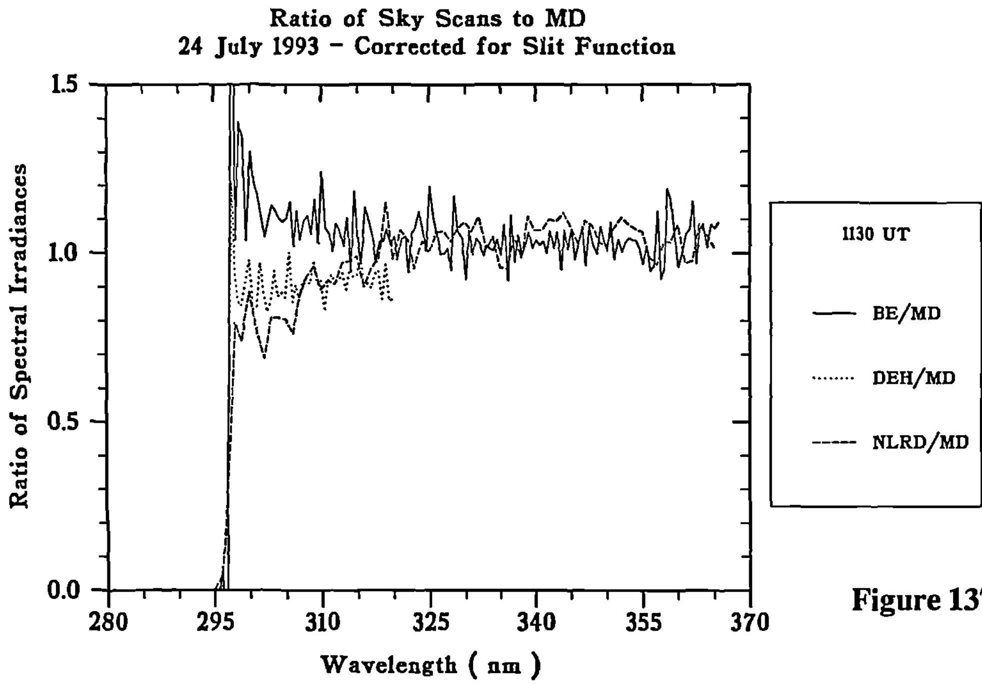

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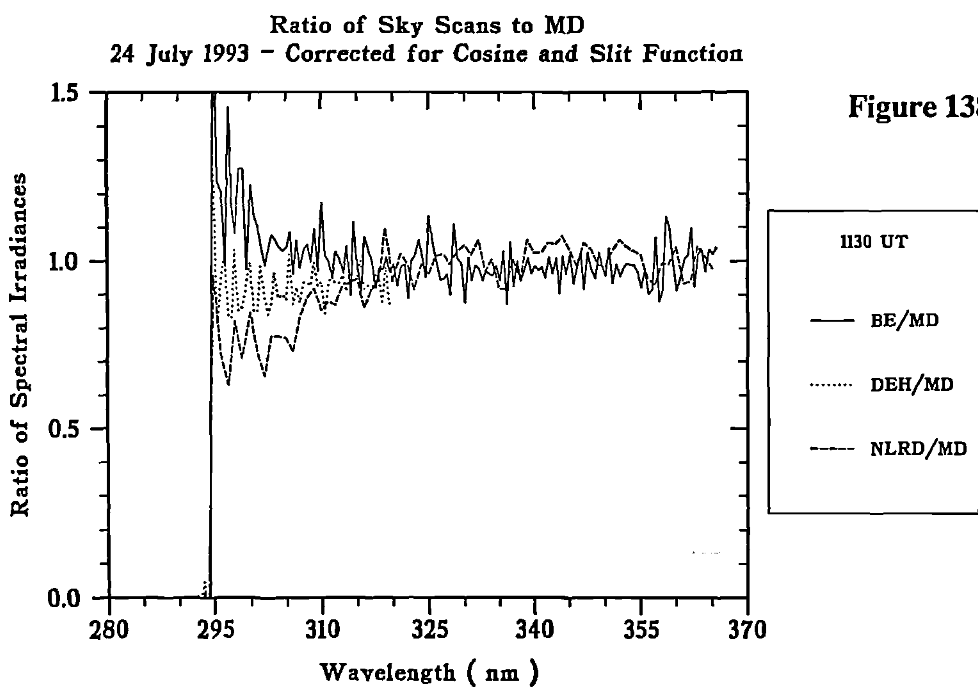

Figure 138

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