THE BURST AND TRANSIENT SOURCE EXPERIMENT EARTH OCCULTATION TECHNIQUE

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ABSTRACT

An Earth orbiting detector sensitive to gamma-ray photons will see steplike occultation features in its count rate when a gamma-ray point source crosses the Earth's limb. This is due to the change in atmospheric attenuation of the gamma rays along the line of sight. In an uncollimated detector, these occultation features can be used to locate and monitor astrophysical sources provided their signals can be individually separated from the detector background. We show that the Earth occultation technique applied to the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) is a viable and flexible all-sky monitor in the low-energy gamma-ray and hard X-ray energy range (20 keV–1 MeV). The method is an alternative to more sophisticated photon imaging devices for astronomy and can serve well as a cost-effective science capability for monitoring the high-energy sky. Here we describe the Earth occultation technique for locating new sources and for measuring source intensity and spectra without the use of complex background models. Examples of transform imaging, step searches, spectra, and light curves are presented. Systematic uncertainties due to source confusion, detector response, and contamination from rapid background fluctuations are discussed and analyzed for their effect on intensity measurements. A sky location–dependent average systematic error is derived as a function of Galactic coordinates. The sensitivity of the technique is derived as a function of incident photon energy and also as a function of angle between the source and the normal to the detector entrance window. Occultations of the Crab Nebula by the Moon are used to calibrate Earth occultation flux measurements independent of possible atmospheric scattering effects.

Subject headings: gamma rays: observations — instrumentation: detectors — methods: data analysis — occultations — surveys — X-rays: stars

1. INTRODUCTION

The Compton Gamma Ray Observatory (CGRO), the second of NASA's Great Observatories series, was launched in 1991 April and operated in low Earth orbit (LEO) until controlled reentry in 2000 June. CGRO was responsible for many discoveries in the study of gamma-ray bursts (GRBs), accreting binaries, active galaxies, and pulsars (Gehrels & Shrader 1997; Kniffen & Gehrels 1997; Leonard & Wanajek 2000). The quest for the origin of GRBs led to the development and flight of the Burst and Transient Source Experiment (BATSE) on CGRO. BATSE pointed the way to the extragalactic origin of GRBs through mapping of burst location and number brightness distributions (Meegan et al. 1992). In addition to BATSE's primary science goals, its 9 yr of nearly continuous operation and all-sky capability allowed monitoring of the low-energy gamma-ray/hard X-ray sky using the Earth occultation technique (EOT). Prior to BATSE, the method had not been used widely by the astrophysics community for gathering spectral and intensity information about celestial sources. We show that the EOT, applied to a well-calibrated multiple detector system and without sophisticated imaging hardware, is a viable and inexpensive method for monitoring the high-energy sky. It is particularly suitable for uncollimated devices such as background or anti-Compton suppression shields, which are commonly used in X-ray and gamma-ray astronomy missions. We therefore present here a detailed discussion of how the EOT was applied to BATSE data. A listing of acronyms and abbreviations used throughout the text can be found in Appendix A, Table A1.

Historically, monitoring of the high-energy sky was accomplished in the energy range of ~1–20 keV using various types of scanning pinhole cameras, modulation collimators, or position-sensitive detectors. X-ray missions such as Uhuru (Giacconi et al. 1972), Vela 5B (Conner, Evans, & Belian 1969), the Ginga all-sky monitor (Tsunemi et al. 1989), Ariel 5 (Holt 1976), the GRANAT and EURECA WATCH monitors (Lund 1986; Brandt 1994; Castro-Tirado 1994), and most recently the all-sky monitor on the Rossi X-Ray Timing Explorer (RXTE) (Bradt, Rothschild, & Swank 1993; Levine et al. 1996) have been crucial in discovering and monitoring X-ray transients, investigating long-term periodic variations in more persistent sources, and detecting other phenomena associated with the X-ray sky. BATSE complements these instruments by monitoring the energy range from 20 keV up to about 1 MeV. This covers the lower energy portion of the non-thermal regime, where the emission is produced by a variety

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of processes such as Compton upscattering of soft photons by energetic particles, bremsstrahlung, and synchrotron radiation.

It was realized prior to launch (Fishman et al. 1982, 1984; G. J. Fishman et al. 1989, unpublished) that BATSE could serve as a sensitive all-sky monitor of pointlike gamma-ray sources. Earth occultations of point sources allow sampling of high-energy fluxes using the sharp steplike features in the background data for both pulsed and nonpulsed sources (Paciesas et al. 1985). Variations on timescales of hours to years can be investigated. The method allowed BATSE to be very successful at locating new transients, detecting unusual intensity or spectral changes, and stimulating observations in other wavelength bands. Because the EOT was enhanced and used extensively during the operational period of CGRO, we present its use in various forms and discuss a number of aspects of the technique such as source identification, sensitivity, and systematic error. Prelaunch discussions of the method can be found in Paciesas et al. (1985) and G. J. Fishman et al. (1989, unpublished). Discussions concerning the postlaunch performance and expanded capabilities can be found in Harmon et al. (1992a), Wilson et al. (1992), and Zhang et al. (1993b, 1994a). Preliminary surveys of detected sources can be found in Harmon et al. (1993a) and Robinson et al. (1997). An imaging capability was added after launch, based on the Radon transform, which greatly improved our ability to locate and identify gamma-ray sources (Zhang et al. 1993b, 1994a). Another powerful application of BATSE as an all-sky monitor was the ability to detect and monitor pulsars using Fourier analysis or epoch folding techniques. A detailed description of these methods and results from BATSE data can be found in Bildsten et al. (1997).

2. INSTRUMENTATION AND OCCULTATION GEOMETRY

2.1. BATSE Instrumentation

The Earth occultation analysis technique utilizes the large area detectors (LADs) on BATSE, which are sensitive to photons above 20 keV. The CGRO and placement of the BATSE detector modules on the spacecraft are shown in Figure 1. The LADs are composed of sodium iodide [NaI(Tl)] crystals, 1.27 cm (0.5 inch) thick by 50.8 cm (20 inch) across (2025 cm² total area of one detector). Eight modules are mounted on the corners of the CGRO with normal vectors perpendicular to the faces of a regular octahedron. Any point on the sky can be viewed by four detectors at angles less than 90° to the source direction. This gives BATSE a capability of obtaining crude locations to within a few degrees, using the count rates from a combination of detectors and the known response of each detector from photons directly from the source, and source photons scattered off the atmosphere (Pendleton et al. 1995b). This is routinely done to locate GRBs to within an accuracy of a few degrees (Pendleton et al. 1999). A full description of the BATSE detectors can be found in a number of places; see, for example, Fishman et al. (1984) and G. J. Fishman et al. (1989, unpublished).

Although Earth occultation features have been used with other gamma-ray instruments to restrict the location of point sources (e.g., Wheaton et al. 1982), to our knowledge only BATSE made use of the method for direct measurement of point-source emission. Some Earth occultation measurements have been performed with the BATSE spec-
troscopy detectors (SDs) (McNamara, Harmon, & Harrison 1995; Paciesas et al. 1998; McNamara et al. 1998). These detectors have a much smaller effective area for source monitoring (~600 cm²) than the LADs but do have an additional low-energy bandpass around 10 keV. Here we discuss the method as applied only to the LADs.

The EOT was also developed and applied to BATSE data in a separate, parallel effort at the Jet Propulsion Laboratory (JPL) (Skelton et al. 1994; Ling et al. 1996). The JPL group has recently published a description of their approach (the Enhanced BATSE Occultation Package [EBOP]) and a compendium of measurements using the technique covering the 1991 May–1994 October epoch (Ling et al. 2000). The method used by JPL was developed specifically for extraction of flux histories and spectra of point gamma-ray sources. There are primarily two major differences between the JPL method and the method we describe in this paper. First, EBOP uses a semiphysical model for the detector background count rates. The model is based on expected contributions of low-energy gamma-ray fluxes local to the LEO environment. These include cosmic-ray secondary radiation and activation products from orbital passes through radiation fields in LEO. The JPL global background model consists of a mix of the local radiation components and a combination (determined by the fit) of the SD count rates as a predictor of the low-energy background in the LADs. Secondly, the extraction of source signals is performed usually in 1 day segments, with a single fit including terms for all sources in the EBOP catalog with no a priori assumptions of their intensity. The JPL method has the advantage of potentially greater statistical accuracy at the expense of increased systematic error. The method appears to give reasonable results for bright, hard sources such as the Crab Nebula and Cygnus X-1. In some cases, for relatively weak sources, such as the neutron star binaries Circinus X-1 and Scutum X-1, the JPL method yields significant hard emission greater than ~200 keV, which is uncharacteristic for this class of sources (see discussion in § 3.2 and Fig. 8, plates 10 and 75 of Ling et al. 2000). We have not been able to confirm these unusually hard spectra with the Marshall Space Flight Center (MSFC) method, nor are they reported by other high-energy observatories.

Instead of the physical inputs used in the JPL fitting procedure, the MSFC method uses simple polynomials as the set of basis functions for fitting the background and extracting the source signal (see § 3 for details). This is equivalent to assuming that the background is smooth on a timescale of a few minutes, as discussed in § 3, with respect to count rate variations caused by cosmic-ray secondaries, activation, and other local background components. This assumption breaks down only during times of high solar flare activity, GRBs and a few flaring gamma-ray sources, which are either excluded from the analysis or flagged later at the discretion of the observer (see § 2.2 for a discussion of data selection procedures). The only source terms included in the fit are those that are thought to be active during the short 4 minute time windows. We chose to adopt the method described here over that of EBOP to minimize the effect of unpredictable systematic error and because of the real-time needs of the MSFC all-sky monitoring effort. The MSFC method also lends itself well to an iterative approach in selecting sources that may potentially interfere with the source of interest (SOI), so that a best solution
comes from building up a knowledge of the sky region within a few degrees surrounding the source.

More recently, Southampton University has undertaken a more rigorous approach in modeling the BATSE backgrounds in order to generate all-sky images and extract source fluxes using Earth occultation (Shaw et al. 2000). This method incorporates the physical background components discussed above and a mass model of the CGRO in
a Monte Carlo simulation using the radiation transport code GEANT as was done with the European Space Agency International Gamma-Ray Astrophysical Laboratory (INTEGRAL) (Lei et al. 1999). The result of the simulation is the a priori determination of the total diffuse background in the LADs at any orientation and geomagnetic coordinates of the Earth. This method offers the possibility of removing the source signal without the need for a simultaneous fit to the background.

2.2. Data Selection

The LADs are well suited to Earth occultation measurements because of their sensitivity, uniformity in energy range, and stabilized gain. Data from two or more LADs can be easily combined or fitted jointly, depending on the application. There are two different data types that are most convenient for occultation measurements: DISCLA (LAD discriminator data) and CONT (LAD continuous data), which cover the same energy range (20 keV–1 MeV). The DISCLA data type provides four energy channels binned every 1.024 s, and the CONT data type provides 16 channels every 2.048 s.

Prior to application of the Earth occultation method, proper data selection is required to remove large fluctuations that may affect the fitting of occultation steps. When data are flagged in one stage of the selection process, they are then excluded from the occultation analysis.

The first stage of the data selection is performed on board. Several different data types are scanned, including the DISCLA type, by comparing the local background count rate to new data as they are acquired. An event may be a “trigger” when a GRB acquisition mode when a high data rate is encountered relative to the background in two or more LADs (Meegan et al. 1992). High-rate events may be caused by bursts, solar flares, bremsstrahlung from electron precipitation (Aschwanden, Schwartz, & Dennis 1998), terrestrial gamma-ray flares (Fishman et al. 1994b), or even flaring Galactic sources (Mallozzi et al. 1993). Any triggered events are flagged automatically in the data stream and identified later.

The second stage of the selection process consists of manual inspection for other events that may escape the burst trigger yet generate large transient flares. These are of a somewhat longer timescale than GRBs, usually a few tens of seconds to minutes. The fluxes from these events are generally easy to identify based on their observed timing and spectral properties. Time periods containing transient background features large enough to be detected visually (about 10% of the total background count rate) are flagged and excluded from occultation analysis along with the triggered events. The vast majority of these events are gamma-ray fluxes from solar flares or bremsstrahlung from precipitating electrons.

The last stage of the data selection consists of additional flagging of very short (less than 1 s) cosmic-ray events. These occur in only one LAD at a time when a heavy cosmic ray, such as an iron nucleus, deposits a large amount of energy into the scintillation medium. This is observed as a sharp, positive-going spike in the background data for one time bin. It is caused by long-lived phosphorescence characteristic of impurities in the NaI(Tl) crystal (Fishman & Austin 1976). The affected data bins are flagged using a spike filter prior to occultation as well as pulsar measurements.

An interesting aside to the standard data treatment discussed above is that bright and extremely variable Galactic sources are occasionally detected via the burst trigger. Such occurrences do not affect Earth occultation analyses to a large degree because the amount of data excluded in the data selection process due to intrinsic source variability is statistically insignificant. However, the extremes of variability are reduced if the burst trigger is enabled by the SOI, since the CONT or DISCLA data at the time of the trigger are rejected in our data analysis procedure. The sources for which this was known to have occurred during the mission are A0535 + 26 (Finger, Wilson, & Harmon 1996) (see Fig. 2), Cygnus X-1 (Fishman et al. 1994a), GRO J042+32 (Mallozzi et al. 1993), GRO J1744—28 (Kouveliotou et al. 1996), and 4U 1700—377 (Rubin et al. 1996b), as well as soft gamma repeaters (Woods et al. 1999). For some flaring episodes of these sources, the BATSE burst trigger threshold was raised temporarily in order to minimize the number of non-GRB triggers. Normally, the likelihood of a source being rejected in this manner for Earth occultation measurement is rather small as a result of the great difference in peak brightness of these sources and that of GRBs. It should be noted that when data are flagged and removed from the analysis, in actuality, the data are recoverable by reanalyzing the CONT or DISCLA data with less restrictive filtering criteria.

2.3. Source Occultations

In one orbit around the Earth, two occultation step features, a rise and set pair, will be superimposed on the background count rate as each point source is occulted. A measurement can be made of the intensity of a source in each energy channel at rise or set. In practice, two measurements per every orbit are not achieved. The most common reasons are passages through the upper Van Allen radiation belt at the South Atlantic Anomaly (SAA) when the detector voltage is turned off, or that CGRO is out of line-of-sight contact with the NASA Tracking and Data Relay Satellite System (TDRSS), and data that have been flagged and are not available for analysis. High-declination sources (|δ| ≥ 41°) also experience an interruption of occultations near the orbital poles (see Appendix B). Source confusion, where occultations of one source are indistinguishable from another, also limits the number of usable occultation steps. The impact of these effects combined causes Earth occultation coverage averaged over one precession cycle (~52 days) to range between 80% and 90%, at best, and at worst about 50%.

The attenuation of gamma rays by the Earth’s atmosphere and the variation in thickness of the air mass along the line of sight to the X-ray source produce the steplike features in the detector count rate as a function of time. The attenuation is 50% for 100 keV photons that pass through the atmosphere along a line of sight with minimum altitude of 70 km. For a typical orbital speed of 8 km s⁻¹, the duration of the occultation step for a source rising or setting in the plane of the spacecraft orbit is about 10 s. Therefore, occultations are relatively sharp features superimposed on the generally slower background variations caused by orbital motion around the Earth.

Several examples of occultation features, or “steps,” in the DISCLA and CONT data are shown in Figure 2. Except where otherwise noted, the date and time convention used in this paper is Truncated Julian Date
Figure 2—DISCLA data (1.024 s resolution) in low- and high-energy bands at times in which the viewing directions toward the Crab Nebula and the binary system A0535 +26 were close to face-on in an LAD. To make the occultation steps more clearly seen, zero suppression has been applied to the vertical axes. (a) Approximately 7000 s of data in the 20–50 keV band, where the background is dominated by diffuse sky flux and Earth shadowing. Crab occultation steps can be seen at ~550 (rise), 6050 (rise), and 4000 s (set). (b) Same detector in the 100–300 keV band, where the background is dominated by variations in the flux of secondary cosmic-ray flux modulated by the local magnetic field of the Earth. (c) 20–50 keV band data containing a rise and a set from occultation of the Be star X-ray pulsar system A0535 +26. Data are from a giant outburst in 1994 January–March. Individual pulses (period 110 s) can clearly be seen between the rising and setting features. Gaps in the data coverage result from either filtering or temporary loss of telemetry from CGRO to TDRSS.

(TJD) = Julian Date (JD) − 2,440,000.5 and seconds of day measured from the TJD start. Figure 3 shows a close-up view of individual occultation steps with fitting functions based on a model for the atmospheric attenuation for gamma rays (see § 3.1).

The accuracy to which the timing and magnitude of these steps can be fitted determines the performance of the EOT. We discuss three forms of the technique from which information can be obtained using BATSE data: (1) the flux and spectra extraction method, where we assume a priori knowledge of source locations, and (2) the step search and (3) the occultation imaging methods, where the source location is not required. Methods (2) and (3) are best suited for new source searches. An overall comparison of these approaches is given in Table 1.

In Appendices B and C, we supplement the discussion of the EOT by developing the mathematical framework for Earth occultation from an orbiting spacecraft. This includes

| Occultation Technique | Source Location Assumption | Data Type | Typical Energy and Channel Ranges* (keV) | Sensitivity (3 σ, 1 day) (30–250 keV) (10⁻⁹ ergs cm⁻² s⁻¹) | Source Localization Error (1 σ) b (deg) |
|-----------------------|----------------------------|-----------|------------------------------------------|-------------------------------------------------|----------------------------------------|
| Step fit with atmosphere model | Known | CONT channels 1–14 | 20–1800 | 1.1 | ≥ 0.2 |
| Step search | Unknown | CONT channels 2–8 | 30–250 | 4.6 | ≥ 1 |
| Transform imaging | Unknown | DISCLA channels 1–3 | 20–300 | 1.1 | ≥ 0.3 |

*Channel range is selectable.

b Quoted error assumes optimal limb geometry for rise and set, which should be regarded as a lower limit.

c Detection of unknown weak sources may be improved by prior subtraction of known source occultation steps.
Fig. 3a

Fig. 3b

Fig. 3.—Earth occultation step features for sources shown with a fit to a quadratic model plus source terms modeled using attenuation by the atmosphere, where the fit assumes that the background is continuous before and after the step, and a linear fit, with independent slopes on either side of the step. All fits are in CONT channel 4 (50–70 keV), (a) and (b) show Crab steps, and (c) and (d) show steps from the transient black hole candidate GRO J0422 + 32 with Crab steps within the 4 minute fitting window. The linear model gives similar results for the size of the step to the quadratic model except in the case of (d) where the presence of the Crab step induces a systematic error in the measurement of the GRO J0422 + 32 step. Vertical dotted lines represent the computed occultation time for 100 keV photons at 50% transmission using the method described in Appendix B.
expressions for timing of Earth occultation features and their use for locating point sources.

3. FLUX AND SPECTRA EXTRACTION FOR KNOWN SOURCES

3.1. Estimation of Occultation Steps in Count Rates

The count rate for a source in the LAD is extracted by simultaneously fitting occultation step features with terms for each source in the fit and a quadratic polynomial to represent the detector background. The fit is performed independently for each energy channel. Each occultation step, rise or set, is fitted over a time \( t_{\text{occ}} - \tau \) to \( t_{\text{occ}} + \tau \), which we refer to as the fitting window. Here \( t_{\text{occ}} \) represents the occultation time of the SOI and also the center of the time window. Use of a quadratic form for the background restricts the half-width of the fitting window, \( \tau \), to no more than about 120 s of data. The modeled detector count rate \( R \) in each energy channel can be represented as

\[
R(t) = \sum_{i=0}^{2} b_i (t - t_{\text{occ}})^i + \sum_{j=1}^{n} r_j T_j(t), \tag{1}
\]

where \( b_i \) are the coefficients of the background model (to second order), \( r_j \) are the source count rates including the SOI and other bright sources with occultation steps occurring within the fitting window, and \( T_j(t) \) are the atmospheric transmission functions. The number of source terms \( n \) is kept to a minimum for greatest sensitivity, at the expense of incurring some systematic error. This method is similar to that adopted in Wheaton et al. (1995) for multi-parameter least-squares fitting of data when the detector background is time variable and individual measurements are of low statistical quality. We assume that the background is smooth and adequately fitted by the second-order polynomial on the order of the size of the fitting window, \( 2\tau \). In particular, the failure of this assumption is usually caused by the presence of the data in bright pulsars, weak bursts, solar flares, and other disturbances on the timescale of the fitting window. Problematic stretches of data are mostly removed in the data selection process discussed in § 2.2. Experience shows that there are non-Poissonian components that remain in the data and must be accounted for in the analysis of results. However, most of these effects add incoherently on timescales of a day or longer.

The occultation features are represented via a model function for the transmission \( T(t) \) as

\[
T(t) = e^{\mu(E)A(h(t))}, \tag{2}
\]

where \( \mu(E) \) is the energy-dependent mass attenuation coefficient of gamma rays in air (Storm & Israel 1970; Chupp 1975) and \( A(h) \) is the air mass computed along the line of sight at a given altitude \( h(t) \). \( A(h) \) is interpolated from a table of air masses (W. Wheaton 1991, private communication) for values of \( h \) between 50 and 110 km and is based on the US International Commercial Aviation Organization (ICAO) Standard Atmosphere (US Committee on Extension to the Standard Atmosphere 1962). Use of equations (1) and (2) requires precise knowledge of the spacecraft ephemeris (time and position), the direction to the SOI, and a model of the Earth that accounts for its nonsphericity (see Appendix C). To use the CONT data at their full time resolution of 2.048 s, the position of the spacecraft at the center of the time bin must be known accurately. The spacecraft position is nominally interpolated for the center of the 2.048 s time bin from the incoming ephemeris data. For most of the CGRO mission, the component of the position vector in the direction of spacecraft motion was known to less than 10 km. As a result of the sharpness of occultation profiles (~10 s), ephemeris errors even on the order of 25 km down range (about one part in 2000) can shift the step model enough to seriously affect the flux measurement. A few ephemeris problems occurred during the mission but were corrected in the data archive. The ability to measure the time of an occultation and the sharpness of Earth occultation features can be exploited to determine the location of a source as outlined in Appendices B and C.

A database of source locations, outburst times, and intensities provides information to determine whether terms for sources should be included in the fitting window. This database was built up as new sources were found either through occultation analysis (light curves and images) or from other instrument measurements. Information about source outburst intensity levels as a function of time is read from the database by the analysis software before the flux measurement is performed.

Each energy channel in the source-pointed LADs (defined to be less than 60° between the source direction and detector normal) is fitted independently to derive a count rate in each CONT channel for all sources \( r_j \) as a function of time. The statistical error \( \delta r_j \) of the \( r_j \)th term at time \( t_{\text{occ}} \) is computed from the least-squares fit of equation (1). Some physical insight into the obtainable error from the Earth occultation fits can be achieved by assuming a simple linear step function in place of the transmission function \( T_j(t) \) in equation (1) and setting \( j = 1 \) (only the SOI is considered). The uncertainty in the fit can then be extracted from the Hessian, or information, matrix (Press et al. 1992), which is to first order

\[
\delta r_j = \eta \sqrt{\frac{2R_j}{\tau}}, \tag{3}
\]

where \( \eta \) is a parameter that depends on the half-width, \( \tau \), the occultation step width, and the slope of the background across the fitting window. \( R_j \) is the detector count rate at the center of the fitting window. For an occultation step width of 10 s and \( 2\tau = 240 \) s, \( \eta \approx 3 \).

To derive a flux history, the fitting coefficient corresponding to the SOI (the \( r_j \)th term at time \( t_{\text{occ}} \) in eq. [1]) is accumulated as a function of time for later deconvolution from the instrument response. However, all the coefficients, including those for other sources in the fit and the background terms, can be written to a file for later use.

3.2. Spectral Analysis

Here we present examples illustrating the usefulness of the BATSE EOT to measure source variability and differences in spectral behavior. The technique has been used to monitor spectral state transitions in the black hole candidates GX 339 – 4 (Harmon et al. 1994; Rubin et al. 1998) and Cyg X-1 (Zhang et al. 1997). During the operational lifetime of CGRO, outbursts of monitored sources, particularly unusual ones, were made known to the scientific community through various electronic media.

The history of the source intensity and spectral behavior can be generated from the \( r_j \) in equation (1). The \( r_j \) in counts s\(^{-1}\) per energy channel per LAD, without correction for the detector response, are stored in a time-ordered file with a
beginning and ending time specified by the user. Energy spectra (flux per energy channel) and light curves showing the history of the source's intensity as a function of time can be generated from the raw history file.

The octahedral geometry of BATSE insures that at least four detectors simultaneously view a point source anywhere on the sky. The angular sensitivity of the LADs is maintained by combining statistics from two, three, and ultimately four detectors at successively larger angles from any one of the detector normals as discussed in § 3.3. Since there is no improvement in the signal-to-noise ratio (S/N) by combining data from detectors beyond about 60°, this is a convenient cutoff angle for choosing which detectors are used. Furthermore, the natural timescale for which spectral measurements are most easily obtained without changing detector combinations is the observation, or pointing period, of CGRO. Observations, where the orientation of the LADs was kept fixed with respect to celestial coordinates, last about 2–3 weeks. The specific orientation of the X- and Z-axes, which were set by the CGRO observing schedule, determined the LAD combination for viewing a point on the sky.

In Figure 4, LAD count spectra and model residuals are shown for four sources extracted using the method of the previous section. Each frame consists of source count rates as measured via Earth occultation for a set of LADs whose normal vectors are less than 60° to the respective direction of the source. All occultations of the same source have been fitted to determine the $r_j$, which are then averaged over the observation period to yield the rates (error-weighted) and uncertainty for each channel in each detector as shown in Figure 4. The number of detectors per combination ranges from two (Vela X-1) to four (Cygnus X-1).

The dotted curves represent the best-fitting model spectra for each LAD. The fitting procedure, used commonly in high-energy astronomy, is called “forward folding” (Briggs 1995). This method avoids a potentially unstable inversion of the BATSE response matrices, which have large off-diagonal elements due to the LAD's relatively shallow detection depth. (We will delay discussion of the LAD response formalism until § 3.5.) Minimization of the $\chi^2$ statistic is performed using the Levenberg-Marquardt formulation of linear least squares (Press et al. 1992). The selected spectral model is folded through the instrument response (Pendleton et al. 1995b) for all detectors in the combination to determine model count spectra. The choice of an appropriate spectral model is based on trial and error and depends on the type of source. The parameters of the model

![Figure 4a](image1.png)

![Figure 4b](image2.png)

**Fig. 4a**—Examples of count spectra and model fit residuals obtained from CONT data for the sources (a) Crab Nebula supernova remnant for TJDs 9783–9797, (b) the black hole candidate Cygnus X-1 for TJDs 10,427–10,434 in its low (hard) state, (c) the transient black hole candidate GRO J1655–40 for TJDs 10,322–10,332 in its high or very high state, and (d) the neutron star high-mass binary Vela X-1 for TJDs 10,413–10,420. The dashed histograms represent the best-fitting photon model folded through the detector response. Each observation includes two or more LADs with angles between the source and the detector normal vector of less than 60°. Residuals (measured counts minus model counts) in $\sigma$ are shown in the lower frame. The models and best-fit parameters are given in the legend of Fig. 5.
are then adjusted to minimize $\chi^2$ between the model count rates and the observed count rates for all detectors in the combination. If all 14 energy channels are used, the number of degrees of freedom (dof) is $(\text{number of LADs}) \times 14 - p$, where $p$ is the number of parameters in the model. Residuals from the model fit in number of $\sigma$ are shown below the count rate spectra for all detectors in the fit.

In Figure 5 we show the corresponding multiple-detector photon spectra after deconvolution of the response for the same four sources and observation periods as in Figure 4. The solid curves represent the best-fitting spectral model with parameters given in Figure 5. Uncertainties in the fit parameters are obtained according to the prescription of Lampton, Margon, & Bowyer (1976). Data points in photon space and associated uncertainties (here in photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) are derived by multiplying the spectral model by the ratio of the model counts to the observed counts. The channel boundaries and photon data points are averaged for the LADs after deconvolution of the response function.

Representative light curves as a function of time are shown in Figure 6. For generation of light curves, the same type of spectral fit is performed on the count spectra, usually with one or more days of occultation data, then fluxes for each point in the light curves are obtained by integrating over a specified energy range of the best-fitting spectral model. In cases in which the flux is not a parameter, the uncertainty in the flux is obtained by either analytically or numerically differentiating the fitting model with respect to the parameters. For generating light curves, the simpler spectral models, with one or two parameters, such as single power law or bremsstrahlung are best for the shorter energy range, whereas for longer integrations as shown in Figure 5, more sophisticated models can be used.

It should be kept in mind that the treatment of statistical errors in the data shown in Figures 4-6 is based on propagating the error from the source count rates extracted from occultation step fits to the raw data. The errors shown in the count spectra in Figure 4 come from direct error-weighted averaging of occultation step rates occurring over an observation period. In Figures 5 and 6, even though the proper prescription of errors in the spectral fitting parameters is given, it is important to note that the “data” in photon space are model dependent. For example, when a source is near the minimum detectable limit (see § 3.3) and the statistical significance is low, the absolute value of the data in photon space depends heavily on the choice of spectral model. A much more desirable method of obtaining accurate fluxes and/or upper limits in a given energy band is to compare the source count rate to that of the Crab Nebula.

Error-weighted averaging across CGRO pointing boundaries after deconvolution of the response is a straightforward method to increase the significance of a source signal. This is desirable for cases in searching for weaker emission or longer term variations in sources. For the light curves in
Examples of spectra in photon space derived from the count spectra of Fig. 4 for (a) the Crab Nebula supernova remnant for TJDs 9783–9797, (b) the black hole candidate Cygnus X-1 for TJDs 10,427–10,434 in its low (hard) state, (c) the transient black hole candidate GRO J1655–40 for TJDs 10,322–10,332 in its high or very high state, and (d) the neutron star high-mass binary Vela X-1 for TJDs 10,413–10,420. All data and model results are in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$. For (a) a broken power law was used with a goodness of fit 49.85 for 38 dof and the following parameters: norm = $(3.46 \pm 0.023) \times 10^{-3}$ at 45 keV, $\alpha_1 = -2.08 \pm 0.015$, break energy = $136 \pm 15$, $\alpha_2 = -2.43 \pm 0.056$. For (b) the Sunyaev-Titarchuk Comptonization model was used (Sunyaev & Titarchuk 1980) with a goodness of fit 90.55 for 39 dof and the following parameters: norm = $(2.33 \pm 0.16) \times 10^{-4}$, $kT = 49.4 \pm 1.2$ keV, and the optical depth $\tau = 2.65 \pm 0.067$ for a spherical plasma. For (c) a single power law was used with a goodness of fit of 59.53 per 54 dof and parameters norm = $(2.09 \pm 0.053) \times 10^{-4}$ at 100 keV and $\alpha = -2.70 \pm 0.036$. For (d) an optically thin thermal bremsstrahlung model was used with a goodness of fit of 11.6 per 16 dof and parameters norm = $(5.31 \pm 2.2) \times 10^{-6}$ at 100 keV and $kT = 14.6 \pm 1.4$. 

![Graphs](image-url)
Figure 6a

Figure 6.—(a) Examples of multiyear intensity histories (1991 April–1998 July) for four persistent sources (from top to bottom): the Crab supernova remnant (40–150 keV), the high-mass binary pulsar Vela X-1 (20–50 keV), the black hole candidate GX 339 – 4 (20–100 keV), and the radio galaxy Centaurus A (20–200 keV) obtained with the EOT. Each data point represents an average of occultation steps obtained for that day or several days. (b) Intensity histories for four transient sources (from top to bottom): GRO J0422 + 32 (X-Ray Nova Persei 1992) (40–150 keV), the high-mass binary 2S 1417 – 624 (20–50 keV), GRO J1655 – 40 (X-Ray Nova Scorpii 1994) (20–200 keV), and GRO J1719 – 24 (= GRS 1716 – 249) (X-Ray Nova Ophiuchi 1993) (20–100 keV).

Figure 6, it is simply a matter of binning the flux data into longer time bins. Alternatively, it is possible to combine channel by channel data before deconvolution of the response. The fitting can then be done by retaining the total exposure to the source in each observation interval and weighting the detector response accordingly. This approach is desirable when energy spectra for weak sources (approximately a few millicrab) are required; however, sys-
tematic errors limit the ultimate flux sensitivity that can be achieved by averaging over many weeks or even years. The issue of systematic error is dealt with in later sections.

3.3. Sensitivity

We first consider the sensitivity of Earth occultation without complicating factors such as nearby point sources and imperfections in the detector response function. The sensitivity of the EOT with the BATSE LADs depends on several factors. The uncollimated detector geometry of the LADs and the fixed orientation of CGRO with respect to the sky (for a single pointing period) generate continuously varying backgrounds that range over a factor of 2 or more. The lower energy background (up to \( 100 \) keV) is dominated by the modulation of the diffuse sky flux by the Earth and at higher energies by the cosmic-ray secondary radiation as shown in Figure 2. Thus, the low-energy background exhibits a slow sinusoidal variation with the orbital
period of the spacecraft. At high energy, the background is modulated more rapidly as a result of the changes in magnetic field strength and direction. Furthermore, a given source exposes a combination of several detectors at different angles. The effective area of the LAD (the product of the geometric area and the efficiency) is also a strong function of energy just above the lower energy threshold as a result of the entrance window attenuation. It decreases more
slowly at higher energies from Compton leakage. All these factors combine to produce complex energy and time-dependent variations in the background. Nevertheless, we can use the known Crab Nebula flux as a standard candle to perform an empirical calculation of the sensitivity.

A basic representation of the instrument sensitivity to a point source of continuum emission over a specified energy range is

$$F_{\text{min}} = \frac{N_{\sigma}}{A\epsilon} \sqrt{\frac{R_B}{T_{\text{live}}}},$$

where $F_{\text{min}}$ is the minimum detectable flux for $N_{\sigma}$ standard deviations, $R_B$ is the background count rate, $\epsilon$ is the detector efficiency, $A$ is the geometric area of the detector, and $T_{\text{live}}$ is the live time of the observation. This expression does not lend itself readily to an EOT sensitivity calculation, since the background changes within the fitting window and $T_{\text{live}}$ is not a well-defined quantity. In addition, correction for a small rate-dependent electronic dead time is made at the time when CONT data in counts are converted to count rates. Therefore, we replace ($R_B/T_{\text{live}}$)$_{1/2}$ with the uncertainty $\delta r_c$ from the least-squares fitting problem (see eq. [3]), so that

$$F_{\text{min}} = \frac{N_{\sigma}}{A\epsilon} \delta r_c.$$

Note that equation (5) combined with the semianalytical expression equation (3) can be used to estimate Earth occultation sensitivity for a given background rate; however, we can use the Crab Nebula with known flux and measurement errors to obtain a more accurate calculation.

The Crab Nebula flux ($F_{\text{Crab}}$) can be related to the measured Crab count rate $r_{\text{Crab}}$ using

$$r_{\text{Crab}} = A\epsilon F_{\text{Crab}}.$$

Combining equations (5) and (6) by eliminating the area and efficiency factors yields

$$F_{\text{min}} = \delta r_c \frac{N_{\sigma} F_{\text{Crab}}}{r_{\text{Crab}}}.$$

We adopt a best-fit broken power law for the Crab Nebula spectrum in photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ obtained from HEAO A-4 measurements (Jung 1989),

$$S_{\text{Crab}}(E) = \begin{cases} \frac{3.25 \times 10^{-3}}{(E/45)^{2.075}} & \text{for } E < E_B, \\ \frac{3.732 \times 10^{-4}}{(E/E_B)^{2.48}} & \text{for } E \geq E_B, \end{cases}$$

where $E_B = 127.7$ keV. Equation (8) has been used previously in evaluating the performance of BATSE prototype LADs in balloon observations of supernova SN 1987A (Pendleton et al. 1995a). The HEAO A-4 spectrum compares well with the observed Crab Nebula spectrum during the balloon flight. We can now compute the sensitivity as a function of energy, angle, and detector combination, provided that the source flux is approximately determined.

A large body of Crab Nebula occultation data was obtained in all eight detectors in the 16 CONT data channels at many orientations of the CGRO, covering a period of about 5 yr. These data, as we discuss later in the context of systematic error, were parameterized so that the Crab Nebula source rate at any angle or energy in the LADs could be determined. The parametrization therefore automatically contains the averaged exposure and background effects typical of BATSE data and can be used to determine $r_{\text{Crab}}$ and $\delta r_{\text{Crab}}$ in equation (7).

Using equation (7) and integrating equation (8) over the appropriate energy range to obtain $F_{\text{Crab}}$, we derive the point-source sensitivity of a typical 2 week observation (approximately the length of one CGRO pointing period). This is shown as a function of energy and angle in Figures 7 and 8, respectively. As the angle to the source from the detector normal increases (Fig. 8), two, three, and four detector combinations in the octahedral geometry become more sensitive than a single detector as shown. Table 1 compares the sensitivity of the flux extraction method and the two point-source search methods discussed later.

It should be kept in mind that the sensitivity in crowded sky regions such as the Galactic center region is degraded from that shown in Figures 7 and 8 as a result of additional terms in equation (1) for known interfering sources and systematic error in the flux measurements. We discuss causes of systematic error in the next section.

### 3.4. Systematic Errors Related to Sky Location and Limb Geometry

Several sources of systematic error were identified in the use of the EOT to measure source fluxes. We have identified those based on location in the sky combined with orbital precession effects, unusual variations in the background, and also absolute flux using the instrument response. The treatment of systematic error varies depending on use of the data.

The current method of extracting flux and spectral occultation data assumes some a priori knowledge of source intensity for sources other than the SOI, i.e., a decision is made as to what sources must be included in equation (1). The selection of which sources are included in the fitting window is therefore an important determiner of the systematic error in two cases: (1) where residual sharing of flux occurs between source terms in the fitting process and (2) where sources are neglected intentionally because of an incorrect assumption about the sources’ relative intensities to the SOI, or unintentionally simply because an unknown source was present in the fitting window at the time. It is important therefore to keep a controlled database of bright source information as discussed in § 3.1. Generally, sources that exceed $\sim 0.02$ photons cm$^{-2}$ s$^{-1}$ in the 20–100 keV band (about 75 mcrab for a source with a Crab-like spectrum) are considered as sufficiently bright to be included in the fitting window. This corresponds to about 2 $\sigma$ detection in 1 day sampling by Earth occultation (see Table 1). We have chosen a modest flux level that is comparable to our 1 day sensitivity. Setting thresholds in count space would be preferable, but this adds significantly to the computational burden. A single threshold in photon space should be regarded as a first pass method in an iterative process designed to achieve best results. No account is made for the spectral differences between the SOI and potentially interfering bright sources. It is possible, for example, in a reanalysis to set finer intensity thresholds or make energy-dependent cuts.

The Crab Nebula and the black hole system Cyg X-1 generally are the most persistently bright hard X-ray to low-energy gamma-ray sources in the sky. Only
FIG. 7.—Sensitivity (3σ) for a 2 week observation of a source averaging 16 occultations a day with contributions from two LADs, as a function of energy. Energy bins correspond to CONT channel boundaries. The Crab Nebula total emission spectrum measured with HEAO A-4 (eq. [8]) (Jung 1989) is shown for comparison.

occasionally do other sources, usually transients, exceed the intensity of these objects. The Crab and Cyg X-1 are therefore dominant contributors to systematic error in their respective sky regions when their occultation steps fall into the fitting window of the SOI.

An analysis of these errors can be made by examining the limb geometry as a function of time. In Figure 9 we show the sky region near the Crab Nebula and Cygnus X-1 and surrounding sources monitored by BATSE. In each plot, two shaded regions are shown. Those bounded by dashed curves represent the set of projections of the setting limb of the Earth as the spacecraft moves through one precession cycle of its orbit. The shaded regions bounded by solid curves are the equivalent regions for the rising limb. The limb appears noncircular because of the flat sky projection.

Note that some regions of the sky are not swept by the Earth’s limb at times of occultation of the Crab and Cyg X-1. For example, the gamma-ray sources GRO J0422+32 and Geminga are located in sky regions that are not crossed by the projected limb of the Earth at times of occultation of the Crab. Light curves generated for either of these two sources show minimal deviation with precession phase due to the presence of Crab occultation steps near in time to those of the two sources of interest. In contrast, 4U 0614+091 and A0535+262 are located such that the projected setting and rising limbs of the Crab, respectively, cross them at certain times during the precession cycle. This is equivalent to the Crab and the two sources having occultations at essentially the same time for a period of 1–2 days. Light curves for these two sources will exhibit significant systematic deviations in their light curves near and at these times.

This is illustrated in Figure 10, where we show the time dependence of the angle between the locations of the sources (a) GRO J0422+32 and (b) 4U 0614+091, as well as the closest approach points of the Earth’s limb projection that intersect the Crab Nebula over a period of 200 days, or about four precession cycles. The corresponding light curves over the same time intervals are shown. GRO J0422+32 is not detected during this time, but 4U 0614+091 is detected consistently but variable (\( \sim 0.01 \) photons cm\(^{-2}\) s\(^{-1}\)). The minimum angle for the setting limb of Crab approaching GRO J0422+32 is about 3\(^\circ\), and therefore the occultation steps are well separated. However, the setting limb of the Crab crosses the location of 4U 0614+091, and the occultations become superposed for a few days every precession cycle (e.g., around TJD 9900). The corresponding light curve for 4U 0614+091 shows systematic deviations at these times due to residual sharing of source signal as we approach the conjunction of the setting occultation steps. Our general treatment of these light curves is to reject the measurement of occultation steps of 4U 0614+091 that fall within 10 s of the Crab steps (\( \sim 0.7\) s). The amount of signal sharing depends on factors such as
the broadness of the occultation features (governed by the elevation angle, $\beta$, of the source above the CGRO orbital plane; see Appendix B) and the steepness of the background. Sometimes a cut is made on the step measurements when the angle between the limb and the source location is less than $2^\circ$, which unfortunately creates or increases gaps in coverage when both the rising and setting limbs have poor geometries for separating the flux from the SOI from interfering sources. Here we derive an average systematic error as discussed below to account for this effect.

**Fig. 8.**—Sensitivity curves (3 $\sigma$) for a 2 week observation with the LADs as a function of angle from the normal vector of the LAD entrance window for combinations of one (continuous curves), two (lower rows of diamonds), three, and four LADs (higher rows of diamonds). Three different energy channels are shown.

**Fig. 9a**

**Fig. 9b**

**Fig. 9.**—Sky regions near (a) the Crab Nebula and (b) the black hole candidate Cyg X-1. Superimposed are shaded regions that represent the portion of the sky subject to Earth occultation when the Earth’s limb crosses the Crab or Cyg X-1. Other sources that are routinely monitored with BATSE are also shown. See text for a more detailed explanation.
Fig. 10a—(a) Angle between the closest approach points of a given source location, here GRO J0422+32, with the rising (top panel) and setting (middle panel) limbs of the Crab Nebula as a function of time for the period TJD 9800–10,000. The corresponding light curve of GRO J0422+32 for the same period is also shown (bottom panel). Note that the closest approach of the setting limb of the Crab to GRO J0422+32 is about 3°. (b) Same type of plot for the source 4U 0614+091. Note that the setting limb of the Crab periodically crosses the location of 4U 0614+091, when occultations occur at the same time for both sources.
Our investigation of several sources of systematic error illustrates that it is difficult to quantify the total systematic error precisely. Unknown systematic errors due to source confusion are time and sky location dependent. An additional source of systematic error, discussed in the context of source step searches, is the presence of nonstatistical background fluctuations (red noise and coherent pulses) from bright X-ray sources. We generally characterize these as background components that are, in practice, unpredictable.

Another source of error that we have not treated rigorously is the diffuse Galactic emission along the Galactic plane (Valinia & Marshall 1998). Under appropriate limb conditions, the diffuse component may have a sufficiently sharp profile in Galactic latitude at energies in the sensitive range of BATSE to create occultation steplike features in the background and/or to increase the amount of cross coupling between background and source terms in the fit. At this time, we have not tried to separate the diffuse component from possible weak point-source contamination in the Galactic bulge region. Although the presence and structure of the ridge are scientifically interesting, modeling of this component is best done in context of a global background model and so is beyond the scope of this paper.

We wish, nevertheless, to estimate a total average systematic error (source confusion plus unpredictable background variations). To do this, we created a grid covering the Galactic plane in areas where sky-dependent systematic error is a significant problem as shown in Figure 11. The grid has points every 3° along the Galactic plane with two sets of grid points at 6° and −6° Galactic latitude. Grid points within 2° of known bright occultation sources were excluded, yielding a total sample of 156 points.

In Figure 12 we show the average flux from each grid point averaged over a 7.2 yr period and the standard deviation of 1 day flux averages from the beginning of the CGRO mission, in 1991 April, to 1998 July, as a function of Galactic longitude, l. The standard deviations are clearly broader than predicted for a Gaussian distribution about zero flux due to systematic errors from various effects (1 σ = ∼ 0.01 photons cm⁻² s⁻¹). We find broadening factors of about 30%–60% in excess of normal statistics, strongest near the Galactic center, and near bright, variable sources such as Vela X-1 (l = −96°9) and Cygnus X-1 (l = 71°3). There are also small positive and negative trends in the average fluxes for the 156 test points. Absolute values are less than ∼ 0.01 photons cm⁻² s⁻¹, with the exception of the Galactic center itself. Even though small, the Galactic bulge region between 60° and −60° shows a clear effect, presumably due to weak X-ray and gamma-ray sources in greater numbers, and/or a Galactic ridge component. The trends for Galactic latitude are similar, but narrower in spatial extent. These results are used to estimate systematic error in the BATSE Earth occultation catalog of low-energy gamma-ray sources (B. A. Harmon et al. 2002, in preparation).

3.5. Systematic Errors due to Detector Response Model

The response matrices for the BATSE LADs have been described elsewhere (Pendleton et al. 1995b), as well as their use for locating GRBs (Pendleton et al. 1999). The matrices are an ordered, discrete representation of the BATSE gamma-ray detectors’ response characteristics and thus are used for all types of studies such as bursts, distant point sources, solar flares, and atmospheric gamma-ray phenomena. They are designed to convert background-subtracted

![Sky grid, consisting of 162 points, used for determination of location-dependent systematic error](image-url)
source counts to incident photon spectra. The main parameters used to characterize the response are the incident photon energy, the measured detector output energy, and the angle between the detector normal and the source direction. LAD prototypes were used in balloon flight observations of SN 1987A and the Crab (Pendleton et al. 1995a), for which an early version of the matrices eventually used for BATSE was developed. A Monte Carlo simulation was used to generate the BATSE LAD responses based on a well-known electromagnetic cascade/transport code called EGS (Ford et al. 1978, 1985) and a mass model for the LAD, its mount, and more crudely, the remainder of the CGRO spacecraft. Prior to launch, the LAD modules were calibrated using angular response and absolute efficiency test data taken with radioactive sources (J. P. Lestrade 1989, 1991, unpublished; Horack 1991). The Monte Carlo simulations were then optimized using the test data.

Scattering of source radiation off the upper atmosphere can produce substantial fluxes in near Earth-pointed detectors, when a point source is well above the horizon. For example, scattered radiation from an overhead GRB can contribute to the measured flux by as much as 50% (Pendleton et al. 1999). However, for Earth occultation, which is near line of sight to the horizon for the source direction, our simulations indicate that the atmospheric scattering is negligible. Therefore, only the direct response matrices need be used for deconvolving fluxes as described here.

In the course of our science analysis of Earth occultation data, two significant systematic effects were found that could be traced to the response model. (1) The CONT channel boundaries were difficult to calibrate using a simple function of energy, especially below 100 keV, as a result of nonlinearities in the onboard analog electronics. This created unacceptably large residuals in spectral model fits and model-dependent flux measurements. (2) The instrument response for near face-on flux measurements was underpredicted in the model. This caused fluxes for sources near the normal direction to an LAD, less than about 20°, to be artificially high by as much as 30%. Unfortunately, these two sources of systematic error were not understood prior to the launch of CGRO, and corrections to the response using in-flight data were complicated as a result of the coupling of the two effects.

Preece et al. (1994) and Pendleton et al. (1994) have used various data types to better determine the effective energies of the CONT channel boundaries. Each approach is different, and, although neither appears to be superior to the other, both schemes are an improvement over the preflight calibration (J. P. Lestrade 1991, unpublished), which makes no adjustments for the electronic nonlinearity. Both the Pendleton and Preece algorithms are incorporated into the analysis of BATSE occultation data. For this work, all spectra and light curves were determined using the Pendleton algorithm, which optimizes the channel boundaries using Earth occultation and pulsar data in a joint analysis (Pendleton et al. 1994).

To more fully investigate the LAD response as a function of photon energy and source aspect angle, i.e., the angle between the detector normal and the source direction, the Crab Nebula occultation data set for all eight detectors in the 16 CONT data channels at many orientations of the
CGRO was used. An example of these data is shown in Figure 13 for CONT channel 3 (40–50 keV) as a function of angle in LADs 0, 1, 2, and 3. We find that the Crab count rate is a smooth function of angle and highly reproducible. This is consistent with the Crab Nebula flux being constant to within about 5% fractional rms for the 20–100 keV band over the 5 yr sampling period (see Fig. 14). The dotted curve represents the modeled response of the known Crab Nebula flux (eq. [8]), before (four top panels) and after (four bottom panels) response corrections (described below) have been applied, and the solid curve (same in top and bottom panels) represents an empirical fit used to characterize the Crab rates as a function of energy and angle (Laird 1996). For all energy bands, and at intermediate aspect angles (20°–70°), the agreement between data and the response model is excellent. However, in the lowest CONT channels (1–3), as in the four top panels of Figure 13, the model underpredicts the actual measured Crab rate as we approach the normal direction to the detector face, yielding a flat response at angles of 20° or less, whereas the true response is more forward pointed as indicated by the data. This effect was partially attributed to the simplifying assumptions made in the LAD response model for the detector entrance window.

The entrance window consists of two 0.635 cm layers of a lightweight aluminum-epoxy composite, called HEXEL, interleaved with other low-Z (charge) materials to minimize attenuation of the low-energy photons. The HEXEL provides support and optical insulation for a plastic scintillator in front of the NaI crystal for charged particle rejection. Viewed from the direction of incoming photons, the HEXEL appears as a close-packed hexagonal array, or “honeycomb,” of cells. The cells are about 0.3–0.5 cm in diameter and irregularly shaped with no alignment of cell walls between the two layers, creating a difficulty for Monte Carlo modeling. In the original response matrix generation (Pendleton et al. 1995b), the HEXEL is treated as uniform layers of aluminum of reduced effective thickness.

During the mission, we surmised that the entrance window allowed more flux into the detector than was predicted in the Monte Carlo model of the LADs. The aluminum-epoxy is very thin in the direction of the normal to the detector face but thickens faster than 1/cos θ as the angle increases, acting as a low-energy collimator. We therefore performed calibration tests of an entrance window for the LADs at Eastern Kentucky University (EKU) (Laird 1996) to quantify this effect. The results revealed an energy and angular dependence due to the double HEXEL layer consistent with the known composition of the material.

The HEXEL was found to account, however, for only a portion of the observed forward-angle response deficiency and only in the lowest three energy bands (20–60 keV). An
additional detector- and angular-dependent effect was observed between the Crab data and model predictions over the angular range (0°–20°) and the entire energy range (20–2000 keV) of the LADs. We attribute the additional deficiency to the adoption of a power series in cosine of the aspect angle (Pendleton et al. 1995b) that was used to interpolate response matrices between the Monte Carlo results at a predetermined set of angles. This function (Fig. 13, four top panels dotted curves) is flatter in the forward direction than the Crab data predict as shown in Figure 13. A more physical function, including the triangular response of the HEXEL at low energies and the cosine of the geometric area (Laird 1996), was used to fit the data (Fig. 13, solid curves) instead.

Ideally, it would be best to regenerate the response matrix model with the forward-angle response properly treated, but operationally it is more convenient to consider the effects discussed above as additive and determine an effective correction to account for the discrepancy of model and data.

Using the empirical fits as shown in Figure 13 as a benchmark, we derived total corrections to the response model, including both the entrance window and empirical angle corrections. The response matrix is multiplied by a factor of the form

$$A \exp \left(-B \theta - 2\mu \tau_{\text{eff}} + 2\mu \frac{t}{\cos \theta}\right)$$  \(9\)

prior to spectral fitting. Here \(\tau_{\text{eff}}\) represents the effective thickness of the HEXEL derived from the EKU measurements, and \(\mu\) is the energy-dependent attenuation coefficient for aluminum. The constant \(A\) is determined by matching the model and data for each detector at 0°. The constant \(B\), which determines the sharpness of the angular correction, was adjusted to reduce the residual difference between the dotted and solid curves in the four top panels of Figure 13. Neither \(A\) nor \(B\) is energy dependent, and \(B\) has the same value for all detectors. The corrections given in equation (9) have been incorporated into all spectra and intensity histories presented in this paper and in the catalog of low-energy gamma-ray sources (B. A. Harmon et al. 2002, in preparation).

A histogram of the average daily Crab Nebula fluxes as a function of time before and after the correction is shown in Figure 14. The histogram of flux measurements after correction is more symmetric and less skewed toward higher fluxes. The fractional rms of the measured Crab flux has dropped from about 5.2% to 4.3% in the 20–100 keV band.

3.6. Absolute Flux Calibration

We attempt here to perform an absolute calibration of the Earth occultation flux measurements using the Crab Nebula emission as a standard candle. We break the absolute flux determination into two parts. First, we compare Earth occultation measurements of the Crab Nebula with lunar occultations of the same source to avoid any systematic effects due to using the Earth and surrounding atmosphere as an occulting disk, and also independent of the BATSE response model. Second, we compare observations of the Crab Nebula with other high-energy instruments, assuming that the Crab is a steady source of high-energy emission.

From 1993 April to 1994 January, the Crab Nebula was occulted several times by the Moon. Since the Moon has no atmosphere, lunar occultations can in principle be used to...
measure the absolute Crab intensity without the systematic uncertainty due to atmospheric scattering. To find when the Crab was being occulted by the Moon, we first searched for minima in the angle between the Earth-Moon vector and the unit vector to the Crab. Next we did more detailed calculations to see if the Crab was being occulted by the Moon, we first searched for a step model for the Crab-Moon occultation as follows. We assumed the Crab Nebula to be an extended source with a step model for the Crab-Moon occultation as follows. We

\[ \tau = \frac{D_{\text{Crab}}}{D_{\text{Moon}}} \Delta t, \]  

(13)

where \( D_{\text{Crab}} \) is the angular extent of the Crab Nebula, \( D_{\text{Moon}} \) is the maximum angular extent of the Moon (1900''), and \( \Delta t \) is the total time the Crab is occulted by the Moon. For each pair of steps (a set and a rise), both steps were fitted simultaneously. Background data were used from 110 s before the first step fitted until 110 s after the last step fitted. An example of a fit with this model is shown in Figure 16.

Using a grid search to find the best value of \( D_{\text{Crab}} \), we minimized

\[ \chi^2 = \sum_{p=1}^{M} \sum_{k=1}^{N_p} \sum_{i=1}^{N_{\text{chan}}} \sum_{j=1}^{N_{\text{det}}} \frac{(\sum_{t} \left[ r_{ijk}(t_k) - \frac{y_{ijk}(t_k)}{\sigma_{ijk}} \right]^2)}{\sigma_{ijk}^2}, \]  

(14)

where \( M \) is the number of pairs of rises and sets, \( N_p \) is the number of data points for pair \( p \), \( N_{\text{chan}} \) is the number of energy channels used, \( r_{ijk} \) is the BATSE count rate in energy channel \( i \) and detector \( j \) at time \( t_k \), and \( y_{ijk}(t_k) \) is the count rate model evaluated at time \( t_k \) for energy channel \( i \), detector \( j \), and pair \( p \). The energy channels used correspond to 20–300 keV. Our best fit to the angular extent of the emission region of the Crab Nebula, assuming uniform emission, was \( D_{\text{Crab}} = 131'' \pm 5'' \). This agrees well with previous results from lunar occultations of the Crab (Staubert et al. 1975).

To compare BATSE Earth and Moon occultation measurements of the Crab, we used the characterization of the BATSE Earth occultation count rates for the Crab as a function of energy, aspect angle, and detector from empirical fits as shown in Figure 13 with our fits to lunar occultations. Figure 17 shows the comparison between lunar occultations with our extended source model (eq. [12]) and Earth occultation measurements. We find that the Crab flux values from Moon occultation are on average about 95.5% ± 1.9% of those measured with Earth occultation. Although the results we have obtained depend on the assumed model of the Crab Nebula emission, we believe that the error due to this effect is small. The Earth occultation fluxes are systematically higher by a few percent. This could be due to the simple atmospheric model we use, which neglects scattering of source flux off the atmosphere away from the line of sight. Atmospheric scattering is substantial at more oblique angles to the atmosphere and is a significant effect in determining GRB locations (Pendleton et al. 1999). For near line-of-sight scattering into the field of view (FOV) of the detector at rise or set, however, we do not calculate significant contributions to account for the observed effect.

### Table 2

Times of Lunar Occultations of the Crab Nebula in BATSE Cont Data

| Day (TJD) | Set Time (s) | Rise Time (s) | LADs Viewing the Crab |
|-----------|-------------|---------------|-----------------------|
| 9103...... | 10645       | 11150         | 0, 1                  |
| 9212...... | 39061       | 39487         | 1, 3, 5, 7            |
| 9239...... | 74328       | 74543         | 1, 3, 5, 7            |
| 9376...... | 20809       | 21036         | 5, 7                  |
| 9376...... | 27098       | 27633         | 5, 7                  |
Fig. 16.—Example of fits to BATSE CONT 40–50 keV data for LAD 7 for lunar occultations of the Crab using an extended source model for the Crab.

Observations of the Crab Nebula spectrum using a simple broken power-law model for fitting data between 20 keV and 1 MeV have been performed with a Naval Research Laboratory balloon experiment (Strickman, Johnson, & Kurfess 1979), HEAO (Jung 1989), the Oriented Scintillation Spectrometer Experiment (OSSE) on board the CGRO (Much et al. 1996; M. S. Strickman 1999, private communication), and the Gamma-Ray Imaging Spectrometer (GRIS) (Bartlett 1994). In Figure 18 we show the measured BATSE spectrum of the Crab Nebula compared to these measurements based on the broken power-law fit, a confidence region obtained by varying the high- and low-energy spectral indices, and the break energy separately by 3 $\sigma$ (see eq. [8]). The spectrum is a composite result of fitting...

Fig. 17.—Ratio of Crab lunar occultations to Crab Earth occultations integrated over the 20–320 keV energy band. Each point represents the ratio of the average integrated intensity from lunar occultations to that of Earth occultations for each detector and each day.
F. 18.—Comparison of various instrument data for high-energy observations of the Crab Nebula. The shaded region represents a variation in the parameters of the broken power-law fit and data from various instruments used by permission (see text).

The discrepancy between BATSE and OSSE is quite significant below ~150 keV (15%-20%) and has been documented previously by Much et al. (1996). No adequate explanation for this has resulted from our analysis. We have eliminated the possibility of atmospheric scattering and corrected systematic errors due to the response model. In fact, a normalization of our data to the OSSE results at 100 keV (difference is about ~16%) forces the effective area of the LAD (~1700 cm²) to be roughly the same as its geometric area (2025 cm²)! A comparison to other published instrumental results, with the exception of GRIS (Fig. 18), suggests that the OSSE response at lower energies (less than about 150 keV) is overestimated. The OSSE Crab Nebula spectrum tends to increase the change in photon spectral index from above and below the break energy (120–200 keV). The GRIS balloon-borne germanium detector also shows a breaking spectrum in this energy range, but the discrepancy of these data with BATSE is the largest of all instruments. Again, the reason is unknown but underscores the difficulty in precision normalization of gamma-ray astronomy telescopes, which typically involve complex background and detector response effects. In our BATSE calibration exercise, we have looked for overall consistency between the eight LADs and compared the basic mechanism of occultations by the atmosphere to those by the Moon.

4. SEARCH TECHNIQUES FOR UNKNOWN SOURCES

4.1. Single Step Searches

After the data selection process as described in § 2.2, a daily search of BATSE CONT data was routinely performed to find occultation features of the brightest hard X-ray/gamma-ray sources below the GRB trigger level. The sensitivity of the search method depends on a variety of factors such as the shape of the source spectrum, energy bandpass, the number and orientation of detectors with respect to the source used, and the behavior of the background. Sources that reached levels of about $4.6 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ (about 200 mcrab for sources with Crab-like spectra) are detectable with the step search method (see also Table I).
Data in each LAD are first summed over the CONT data channels where the best S/N for sources with Crab-like spectra is obtained (30–200 keV). A series of fitting tests are then performed on a contiguous data segment within a fitting window of 4 minutes centered on a test time \( t_{\text{occ}} \). We then determine if an occultation step is present in the background somewhere within the window. Once a segment has been tested, positive or negative results are logged for post-analysis, and the window moves or "slides" to the next data segment. To maximize the sensitivity of the sliding search, a grid of points along the Earth's limb is calculated at \( t_{\text{occ}} \).

Using a cosine function to represent the response of the detector, the combinations of the eight LADs (out of a possible 28) with the best S/N for each point are determined. These combinations are then tested at the corresponding limb points.

The first test is a linear fit over the fitting window for each LAD combination to locate deviations from a background of approximately constant slope. If the goodness of fit (\( \chi^2 \)) per dof is above a threshold (usually set to \( \geq 1.0 \)), a second fit is performed over the same fitting window using a template step function to determine if the deviation is caused by a source occultation (\( \chi^2 \) required for an occultation step is typically \( \leq 1.3 \)). A third fit is then made to estimate the best time \( t_{\text{occ}} \) of the occultation and the maximum significance of a step. The significance cutoff is set to a minimum of 2 \( \sigma \) to avoid large numbers of spurious step detections.

The results of an occultation search for a single day are shown in Figure 19. The significance of detected occultation steps is plotted as an LAD number (0–7) as a function of time elapsed from the beginning of the spacecraft orbit for each orbit searched. The plotted symbol corresponds to the LAD number (0–7) with the most significant step in the combination of detectors. The time zero is the time of the first data packet for the day. Plotted in this way, detected steps from the same source cluster at a specific time, although a shift of a few seconds occurs in the occultation time folded on the orbital period as a result of the orbital precession, which is about 0.5 per orbit. The times of bright source occultations, such as those for the Crab and Cygnus X-1, are shown on the plot. Significances above zero and below zero indicate rising steps and setting steps, respectively.

This method allows a quick determination of occultation times of bright transient or flaring sources from which the location of a source can be deduced from the orientation of the Earth’s limb at rise and set. In Appendices B and C we describe a graphical method for localizing a point source based on the time of occultation steps.

The single step search/graphical method for determining source locations was used primarily in the early part of the CGRO mission, prior to 1993, after which we developed Earth occultation imaging to improve our ability for source localization. Two effects severely limited the sensitivity of

![Figure 19](image-url)
the single step search. In the first place, orbit-to-orbit variations in the background make it impractical to combine raw data for different orbits. A change in the background of a few percent from one orbit to the next can induce features in the background that mimic occultation steps. Without a reliable predictor of the background or a de-trending algorithm, orbit-by-orbit data cannot be folded to increase the sensitivity (this is overcome in the imaging technique discussed in the next section). The second problem is the presence of subthreshold transient features that escape the manual flagging procedure or are impractical to flag. An example is the presence of bright long-period \((P \approx 100\) minutes) pulsar signals in the background data. Pulses from sources such as Vela X-1, GX 301-2, or other bright high-mass binary transient systems are a source of nonstatistical noise. This problem was partially overcome by increasing the length of the fitting window and the bandpass for the search, at the expense of sensitivity to softer spectrum sources.

In general, the accuracy of the EOT for determining a source's sky position depends very strongly on the orientation of the Earth's limb at the time of detection. If the rising and setting limbs are nearly parallel, which is true when the source direction is very close to the orbital plane of the spacecraft, it is obvious that the positional accuracy along the limb direction can be very poor. On the other hand, allowing orbital precession to move the limb geometry into a more favorable configuration can greatly improve positional accuracy. In a situation of optimal limb geometry, the width of the occultation feature itself and the \(S/N\) limit the ultimate positional accuracy. The spatial resolution perpendicular to the limb is determined by the width of the occultation step in time, which takes about \(8/\cos \beta \) s, where \(\beta\) is the angle of the source with respect to the orbital plane (see Appendix B). For a 90 minute orbit, the angular resolution on the sky is \((8 s/5400 s)360^\circ, or \sim 0^\circ.5\). Table I gives a lower limit on the positional error, considering these factors. For the step search method, the best obtainable accuracy was \(\sim 1^\circ\) with a simple step function consisting of a fitted line for the background and a steeper line with a step width of 10 s. We were able to improve our locational accuracy to \(\sim 0^\circ.2\) by comparing the step search results to the predicted shape of the Earth occultation features from the atmospheric attenuation model (§ 3.1). Usually a few iterations on the source location were required to achieve the best agreement with the data that were available at that time. Examples of the use of this method are given in Harmon et al. (1992b), Paciesas et al. (1992), and Harmon et al. (1993b) for the sources 4U 1543-47 (0:25), GRO J0422+32 (0:68), and GRO J1719-24 (=GRS 1716-249) (0:14), respectively, where the number in parentheses is the difference in degrees between the reported BATSE location and that of the optical counterpart from the electronic database SIMBAD.

### 4.2. Occultation Imaging

Occultation features in the time domain can be transformed into spatial information for construction of images. This enhanced the ability of BATSE to locate and identify much weaker sources than the step search algorithm permitted and considerably increased the effectiveness of the instrument as an all-sky monitor (Zhang et al. 1993b, 1994a). It also allowed us to obtain positional information more efficiently and easily for new transient sources and to discriminate between sources in crowded regions such as the Galactic center.

Occultation transform imaging is conceptually similar to techniques used for many years in radio astronomy (Bracewell 1956) and medical X-ray tomography (Gullberg & Tsiu 1989) to convert essentially one-dimensional scanning measurements into two-dimensional images. Using the Earth as a stable occulting disk, the limb is projected onto the sky. As the limb of the Earth (an arc, not a straight line) sweeps through a chosen region of the sky, the LADs record the count rate as a function of time. The location of the spacecraft is well known, and thus the location and orientation of the limb projected on the sky can be determined accurately. For point sources along the limb, a change occurs in the detector count rate as shown in Figures 2 and 3. For a single location on the sky, the intersecting Earth's limb will change its angle as a result of precession of the spacecraft orbit. If enough one-dimensional strips are sampled, an image can be generated.

Image reconstruction is achieved via the Radon transformation (Deans 1983) and the maximum entropy method (MEM) (Huesman et al. 1977). Use of the Radon transformation to represent the limb projection limits sky images to an FOV of about \(20^\circ \times 20^\circ\). Larger images produce distortion of point-source locations near the edges of the FOV.

We begin with a forward transform from the image space (sky pixels) to the data space (count rate vs. time), which is accomplished in two steps. First, a curved Radon transform is applied (Deans 1983) for the defined FOV. This is performed numerically since no analytic form is available to describe the limb arc on the sky. In the second step, a high-pass Butterworth filter from the Radon space to the data space is executed using a fast Fourier transform (FFT). The Butterworth filter was chosen over a differential filter (Zhang et al. 1995) used in a first generation of the imaging system (Zhang et al. 1993a) since it gives a better \(S/N\), 80% versus 50%, and was also less sensitive to spikes in the background data. The data are then filtered with the same algorithm; however, the data (DISCLA) usually contain gaps due to flagging of fast timescale variations in the background, SAA passages, or loss of telemetry. The best method we have found to fill data gaps is to make a simple linear interpolation. The result is a flattened data residual with bipolar-shaped features of finite width for point-source occultations with the slowly varying background components removed (Paciesas et al. 1995).

Finally, the data space to image space reconstruction is performed using the MEM (Gull & Skilling 1984). The backward transform is physically a smearing of the original image with the forward transform function and thus defines the direction in which the iterative process converges. The maximum entropy principle is used as a stopping criterion since an exact reconstruction is not achievable as a result of the presence of noise and imperfect sampling forced by the available limb projections.

Monte Carlo simulations have been performed to confirm the reliability and sensitivity of the images (Zhang et al. 1995). A simulated image and occultation data (after filtering) for two closely spaced point sources using data that contain rises and sets separated by 2 days are shown in Figure 20.

Examples of images are shown in Figure 21 for sources along the Galactic plane. The location accuracy near the center of a \(10^\circ \times 10^\circ\) image is \(\geq 0^\circ.3\) for a best-case
geometry (nearly perpendicular limb samplings), with a sensitivity in the 20–100 keV range of about $\sim 1.1 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ (75 mcrab for a source with a Crab-like spectrum) for a 1 day integration. Computer memory requirements limit the number of days that can be combined into one image, although we have achieved integrations of 15–20 days, with a sensitivity between 10 and 20 mcrab. For locating a new source, generating an image such that a source is near the center of the FOV produces a sensitivity and positional accuracy that are close to the standard flux extraction method (see Table 1). The chief advantage of the imaging method is that it requires less a priori knowledge of a new source location and the details of orbital precession and the presence of interfering sources are naturally taken into account. Thus, the method allowed deep imaging of short-lived transients (a few days) and identification of weak high-energy emission from low-mass X-ray binaries (Barret et al. 1996), active galaxies (Malizia et al. 2000), and supernova remnants (McCollough et al. 1997). Examples of new transients located with this method are GRS 1009–45 (Zhang et al. 1993a) ($0:39$) and GRO J1655–40 (Zhang et al. 1994b) ($0:31$), where the number in parentheses is the difference in degrees from the BATSE-reported location of the source and that of the optical counterpart from SIMBAD.

5. CONCLUSION

We have shown various aspects of the EOT for point-source studies with the BATSE LADs. The technique is applicable to all-sky monitoring or obtaining time- and energy-dependent information about hard X-ray and low-energy gamma-ray sources and yields positional informa-
Examples of Earth occultation transform imaging for various regions along the Galactic plane.

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APPENDIX A

TABLE A1
LIST OF ACRONYMS AND ABBREVIATIONS

| Acronym or Abbreviation | Meaning |
|-------------------------|---------|
| BATSE .................. | Burst and Transient Source Experiment |
| CGRO ................... | Compton Gamma Ray Observatory |
| CONT ................... | Large area detector continuous data |
| DISCLA ................ | Large area detector discriminator data |
| EBOP ................... | Enhanced BATSE Occultation Package |
| EGS ..................... | Stanford electromagnetic cascade and transport code |
| EKU .................... | Eastern Kentucky University |
| EOT .................... | Earth occultation technique |
| FOV .................... | Field of view |
| GEANT .................. | Southampton electromagnetic cascade and transport code |
| GRB .................... | Gamma-ray burst |
| GRIS ................... | Gamma-Ray Imaging Spectrometer |
| HEAO ................... | High Energy Astronomical Observatory |
| HEXEL .................. | Honeycomb-like aluminum-epoxy composite |
| HEXTE .................. | High-Energy X-Ray Timing Experiment |
| ICAO ................... | International Civil Aviation Organization |
| INTEGRAL ............... | International Gamma-Ray Astrophysical Laboratory |
| JPL .................... | Jet Propulsion Laboratory |
| LAD .................... | Large area detector |
| LEO .................... | Low Earth orbit |
| MEM .................... | Maximum entropy method |
| MJD .................... | Modified Julian Date (Julian Date - 2,400,000.5) |
| MSFC ................... | Marshall Space Flight Center |
| OSSE ................... | Oriented Scintillation Spectrometer Experiment |
| PCA .................... | Proportional Counter Array |
| RXTE ................... | Rossi X-Ray Timing Explorer |
| SAA .................... | South Atlantic Anomaly |
| SD ..................... | Spectroscopy detector |
| S/N .................... | Signal-to-noise ratio |
| SOI .................... | Source of interest |
| TDRSS .................. | Tracking and Data Relay Satellite System |
| TJD .................... | Truncated Julian Date (Julian Date - 2,440,000.5) |
| WFC .................... | Wide Field Camera |

APPENDIX B

BASIC FEATURES OF OCCULTATION TIMING

The geometry and timing of Earth occultations of a celestial source are most simply understood for an idealized model where the orbit of the spacecraft is assumed to be circular, the precession of the orbital plane is ignored, and the oblateness of the Earth is ignored.

The basic geometry is shown in Figure 22. We adopt a coordinate system in which the spacecraft orbit is in the $x$-$y$ plane. The source is located at an azimuthal angle $\phi$ from the $x$-axis and an angle $\beta$ above the orbital plane. The spacecraft is located at radius $r_{sc}$ and azimuthal angle $\phi_{sc}$, which increases in time at a rate of $2\pi/P_{\text{orbit}}$. The angle $\theta$ between the direction to the source and the direction to the Earth from the spacecraft is given by

$$\cos \theta = -\cos (\phi - \phi_{sc}) \cos \beta .$$  \hspace{1cm} (B1)

As shown in Figure 23, this angle is related to $h$, the minimum height of the line of sight above the surface of the Earth, by

$$r_E + h = r_{sc} \sin \theta ,$$  \hspace{1cm} (B2)
where \( r_E \) is the Earth radius. In the middle of an occultation step we define

\[
\theta = \theta_{occ} = \sin^{-1} \left( \frac{r_E + h_{occ}}{r_{sc}} \right),
\]

(B3)

where \( h_{occ} \) is the altitude for 50\% transmission. For a spacecraft altitude of 500 km and an occultation altitude of 70 km, \( \theta_{occ} = 69.6\). If the source is too far above or below the orbital plane, \( |\beta| > \theta_{occ} \), the source is always visible and no occultations are seen. Earth spans an opening angle of \( \sim 140^\circ \), or about 30\% of the sky for a spacecraft altitude of 500 km. The oblateness of the Earth causes the CGRO orbit to precess with a cycle of about 53 days. Hence, during the precession cycle, if the angle in which a vector in the direction a source makes with the orbital plane \( \beta \) exceeds 69\%, occultations will cease. The duration of this gap in occultation coverage is

\[
\tau_{gap} = 2 \frac{P_{precession}}{2\pi} \cos^{-1} \left( \frac{\sin \theta_{occ} - \cos i \sin |\delta|}{\sin i \cos \delta} \right),
\]

(B4)

where \( \delta \) is the declination of the source, \( P_{precession} \) is the precession period, \( \theta_{occ} \) is the angle between the geocenter and the Earth's limb at 50\% transmission as seen from the spacecraft, and \( i \) is the inclination of the spacecraft orbit. For a 500 km altitude orbit with \( i = 28^\circ4 \), \( P_{precession} = 53.4 \) days. We have then

\[
\tau_{gap} = \Delta\Omega (6.74 \text{ day}^{-1})^{-1},
\]

(B5)

where

\[
\Delta\Omega = 2 \cos^{-1} 1.97 \sec \delta - 1.85 \tan \delta.
\]

(B6)

These time gaps occur for sources with declinations in the range

\[
\theta_{occ} - i < |\delta| < \pi - i - \theta_{occ}
\]

(B7)

or \( \pm (41^\circ2 - 82^\circ) \).

Otherwise, a rise and set are seen each orbit at the spacecraft azimuth angles

\[
\phi_{sc}^r = \phi - \cos^{-1} \left( -\frac{\cos \theta_{occ}}{\cos \beta} \right),
\]

\[
\phi_{sc}^s = \phi + \cos^{-1} \left( -\frac{\cos \theta_{occ}}{\cos \beta} \right),
\]

(B8)
FIG. 23.—Geometry of the line of sight from the spacecraft to the source

where the label \( r \) is for source rise, \( s \) for source set. The duration of either occultation step is given by

\[
\Delta t_{\text{occ}} \approx \left( \frac{P_{\text{orbit}}}{2\pi} \right) \left( \frac{\Delta h}{r_{\text{sc}} \cos \theta_{\text{occ}}} \right) \frac{\sin \theta_{\text{occ}}}{\sqrt{\cos^2 \beta - \cos^2 \Theta_{\text{occ}}}},
\]

where \( \Delta h \) is the difference between the 90\% and 10\% transmission altitudes.

If we measure the times of a pair of rising and setting occultations, we can determine the location of the source. Figure 24 shows the projection on the sky of the limb of the Earth at the time of rise and set for a source with \( \phi = 0^\circ \) and \( \beta = 50^\circ \). These rising and setting limbs are the locus of directions \((\phi, \beta)\) that satisfy equation (B8) with \( \phi_{\text{sc}} \) fixed at its value at the source rise or set. For a given pair of rising and setting occultations there are two possible source locations, one above and one below the orbital plane. This ambiguity must be resolved by using the direction sensitivity of the detectors or other means. If the two occultation times are measured with an accuracy of \( \sigma_t \), then the errors on the estimate for the source location can be shown to be

\[
\sigma_\phi = \frac{\sigma_t}{\sqrt{2\Delta t_{\text{occ}}}} \left( \frac{\Delta h}{r_{\text{sc}} \cos \theta_{\text{occ}}} \right) \frac{\sin \theta_{\text{occ}}}{\sqrt{\cos^2 \beta - \cos^2 \Theta_{\text{occ}}}},
\]

\[
\sigma_\beta = \frac{\sigma_t}{\sqrt{2\Delta t_{\text{occ}}}} \left( \frac{\Delta h}{r_{\text{sc}} \cos \theta_{\text{occ}}} \right) \frac{\tan \theta_{\text{occ}}}{\tan \beta}.
\]

APPENDIX C

ACCURATE OCCULTATION CALCULATIONS

Precise predictions of occultation times or calculations of the Earth limbs at given times require the use of an accurate
F. 24. — Rising and setting limbs for a source at $\phi = 0^\circ$ and $\beta = 50^\circ$

The Earth’s surface is approximately an oblate ellipsoid given by

$$x^2 + y^2 + (1 - f)^{-2}z^2 = a^2,$$

where $x$, $y$, and $z$ are geocentric Cartesian coordinates with the $z$-axis aligned with the North Pole, $f = 1/298.257$ is the flattening factor of the Earth, and $a = 6378.136$ km is the Earth’s equatorial radius. Near the Earth’s surface, constant atmospheric density surfaces can be approximated by ellipsoids of the same oblateness. If the spacecraft is at position $R = (x_{sc}, y_{sc}, z_{sc})$, the source is in direction $\Omega = (\Omega_x, \Omega_y, \Omega_z)$, and $h(s)$ is the height above the surface of a point on the line of sight at a distance $s$ from the spacecraft, then we have

$$[a + h(s)]^2 = (x_{sc} + s\Omega_x)^2 + (y_{sc} + s\Omega_y)^2 + (1 - f)^{-2}(z_{sc} + s\Omega_z)^2.$$  \hspace{1cm} (C2)

The minimum height and its distance along the line of sight are given by

$$h_{\text{min}} = \left\{ x_{sc}^2 + y_{sc}^2 + (1 - f)^{-2}z_{sc}^2 - \frac{x_{sc}\Omega_x + y_{sc}\Omega_y + (1 - f)^{-2}z_{sc}\Omega_z}{\Omega_x^2 + \Omega_y^2 + (1 - f)^{-4}\Omega_z^2} \right\}^{1/2} - a,$$  \hspace{1cm} (C3)

$$s_{\text{min}} = -\frac{x_{sc}\Omega_x + y_{sc}\Omega_y + (1 - f)^{-2}z_{sc}\Omega_z}{\Omega_x^2 + \Omega_y^2 + (1 - f)^{-4}\Omega_z^2}. \hspace{1cm} (C4)$$

If $s_{\text{min}}$ is negative, then the minimum occurs in the direction from the spacecraft away from the source, and the source is visible, since that spacecraft is above any significant atmosphere.
To accurately calculate the projection of the Earth's limb on the sky at a given time, we take advantage of a linear transformation that maps the oblate Earth into a sphere. For a vector $X$ we set

$$x = X_x, \quad y = X_y, \quad z = (1 - f)X_z.$$  \hfill (C5)

Then equation (C1) reduces to $|X|^2 = a^2$. The transformed geometry of the occultation is like that discussed in Appendix B. Given the spacecraft position $R$ and velocity $V$, we compute a set of orthonormal (in the transformed space) basis vectors:

$$e_1 = \frac{R}{|R|}, \hfill (C6)$$

$$e_3 = \frac{R \times V}{|R \times V|}, \hfill (C7)$$

$$e_2 = e_3 \times e_1.$$  \hfill (C8)

Then with $\theta_{occ} = \sin^{-1} \left( (a + h_{occ})/|R| \right)$ we compute the direction vectors

$$\Omega(\psi) = -e_1 \cos \theta_{occ} + e_2 \sin \theta_{occ} \cos \psi + e_3 \sin \theta_{occ} \sin \psi,$$

where the parameter $\psi$ ranges from $-\pi/2$ to $\pi/2$ for the rising limb and from $\pi/2$ to $3\pi/2$ for the setting limb. After transforming the direction vectors back to our original coordinate system, we then compute right ascensions $\alpha(\psi)$ and declinations $\delta(\psi)$ along the limb of the Earth:

$$\alpha(\psi) = \tan^{-1} \left( \frac{\Omega_z(\psi)}{\Omega_x(\psi)} \right),$$

$$\delta(\psi) = \tan^{-1} \left( (1 - f)\Omega_y(\psi)[\Omega_z^2(\psi) + \Omega_y^2(\psi)]^{-1/2} \right).$$  \hfill (C11)

The precession of the plane of the spacecraft orbit causes the orientation of the rising or setting limb passing through a source to change cyclically with the precession period (50 days for a near Earth orbit with $23^\circ$ inclination). If limbs are plotted for a new source for a number of days, the precession allows the location ambiguity discussed in Appendix B to be resolved.

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