GAMMA-RAY AND HARD X-RAY IMAGING OF SOLAR FLARES

T. A. PRINCE and G. J. HURFORD
California Institute of Technology, Pasadena, CA 91125, U.S.A.

H. S. HUDSON
University of California at San Diego, La Jolla, CA 92039, U.S.A.

and

C. J. CRANNELL
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center,
Greenbelt, MD 20771, U.S.A.

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Abstract. We discuss the scientific and technical aspects of high-resolution \(\gamma\)-ray and X-ray imaging of solar flares. The scientific necessity for imaging observations of solar flares and the implications of future observations for the study of solar flare electrons and ions are considered. Performance parameters for a future hard X-ray and \(\gamma\)-ray imager are then summarized. We briefly survey techniques for high-energy photon imaging including direct collimation imaging, coded apertures, and modulation collimators. We then discuss in detail the technique of Fourier-transform imaging. The basic formalism is presented, followed by a discussion of several practical aspects of the technique. We conclude our discussion of imaging techniques with a description of the options for detectors and grid fabrication. Several planned future high-energy imagers are described including the Solar-A hard X-ray imager, the balloon-borne GRID \(\gamma\)-ray imager, and the Pinhole/Occultor Facility.

1. Introduction

Advances in imaging techniques have made feasible high angular resolution studies of solar flares at hard X-ray and \(\gamma\)-ray energies. With new instrumentation, it is now possible to achieve an angular resolution of about 1 arc sec or better for photon energies between 10 keV and several MeV. Such capabilities allow fundamentally new types of observations of high-energy processes in solar flares.

Previous hard X-ray imaging of solar flares has been limited to energies less than about 40 keV and to angular resolutions of about 8 arc sec. Some of the results obtained for hard X-ray imaging at these energies are discussed in a companion paper in this volume by Dennis (1988). At X-ray energies below 25 keV, emission from thermal electrons is important. In contrast, at higher energies the emission is dominated by power-law electron bremsstrahlung and by nuclear processes. In this paper, we concentrate on instrumentation for imaging at energies above 40 keV, including the upper hard X-ray regime (up to 100 keV) and the low-energy \(\gamma\)-ray regime (100 keV to several MeV).
An earlier discussion of some of the instrumental issues for high-energy imaging was given by Crannell et al. (1985).

In Section 2 of this paper, the scientific motivation for high-energy imaging is outlined, along with the rationale for some of the desired instrumental performance parameters. In Section 3, imaging techniques are introduced, with specific instrument configurations discussed in Section 4.

2. Scientific Impetus for High-Resolution Imaging at Hard X-Ray and γ-Ray Energies

A primary motivation for imaging hard X-ray and γ-ray emissions from solar flares is to gain insight into the processes of particle acceleration and propagation, in order to relate the various high-energy flare phenomena to the energy release process itself. From observations during the last solar maximum with the non-imaging HXBS (Orwig, Frost, and Dennis, 1980) and GRS (Forrest et al., 1980) instruments on SMM, we have a much clearer picture of the phenomenology of flare particle acceleration (see, for example, reviews by Chupp, 1984; Dennis, 1985; and Hudson, 1985). We know, for instance, that the impulsive acceleration of electrons and ions to high energies is a common feature of solar flares, that the maximum particle energies can be quite high (tens of MeV for electrons and approaching 1 GeV for protons), and that electron acceleration processes can operate on very short time-scales (< 1 s).

Much of the current understanding of energetic particle phenomena in flares is based on timing and spectroscopic measurements. A missing element necessary for a quantitative theory of solar flare particle acceleration is an understanding of the geometry of the energy release site in the context of the pre-existing magnetic field structure. Quantitative data on the geometry of high-energy solar flares has been limited, coming from limb occultation observations (Hudson, 1978, 1986b), from stereoscopic measurements with multiple spacecraft (Kane, 1983), from statistical studies of samples of flares as a function of heliocentric angle to determine the angular dependence of photon emission (Vestrand et al., 1987; Dermer and Ramaty, 1986), from microwave imaging (see, for example, Marsh and Hurford, 1982; Kundu, 1985), and from the interpretation of particle spectra from individual flares in terms of beaming- and geometry-dependent emission characteristics such as Doppler shifts and differential photon absorption. (For a more complete discussion of results in the hard X-ray energy range, see Dennis (1988, this issue).)

Further progress in achieving a quantitative understanding of flare particle acceleration will require the study of the time-dependent spatial evolution of high-energy flare emission simultaneously with the time-dependent spectral evolution of the flare. Basic questions to be addressed include: the location, size, and number of the sites of particle acceleration in relation to magnetic field structures, the nature of the energetic particle transport, diffusion, and storage in the magnetic field environment following the initial acceleration, and the nature of the particle acceleration mechanisms. Questions relating to energetic electrons and energetic ions are considered separately in the following subsections.
2.1. Electrons

One of the first consequences of the flare energy release is the acceleration of energetic electrons. Before their energy is degraded through interactions with the ambient solar medium, these electrons can be studied either by their hard X-ray and $\gamma$-ray emission or by their microwave emission. The latter, produced by nonthermal electrons through the gyrosynchrotron process when the electrons spiral in the ambient magnetic field, can provide a field-weighted indication of the electron spatial distribution. During the previous solar maximum, observations with large interferometers such as the VLA achieved arcsecond resolution and revealed the location, size, and morphology of the impulsive phase and thermal emission. Quantitative interpretation of these images in terms of the electron spectrum and magnetic field parameters was hampered, however, by the lack of adequate microwave spectral data.

At hard X-ray and $\gamma$-ray energies, bremsstrahlung is the dominant emission mechanism for energetic electrons. Because this emission is optically thin and independent of magnetic field, its quantitative interpretation is much more straightforward. One way in which this bremsstrahlung emission can be understood is in the context of a simple 'thick-target' model (Brown, 1971) in which electrons slow down and lose all of their energy in bremsstrahlung interactions with the ambient material. A possible scenario for the thick-target model is one in which a magnetic energy release at the top of a system of magnetic loops leads to heating and formation of a shock which accelerates the electrons to high energy. The electrons then propagate downward along the loop until they deposit their energy in bremsstrahlung interactions, possibly near the loop footpoints. Imaging observations of hard X-ray emission should indicate whether this scenario is valid, and if not, suggest alternative geometries for the acceleration and propagation of solar flare electrons.

2.2. Protons and Ions

While imaging of hard X-rays and microwaves has provided some information on the spatial distribution of energetic electrons, there have been few direct measurements of the geometry of nonthermal ion acceleration and transport. Indeed, until measurements were obtained with the GRS instrument on SMM during the last solar maximum (Chupp, 1984), it was not even known whether ion acceleration was a common feature of solar flares.

The nonthermal ion component is visible primarily through emission produced by nuclear interactions with ambient solar material. These interactions yield $\gamma$-ray lines such as the 0.511 MeV positron annihilation line, the 2.22 MeV neutron capture line, and nuclear de-excitation lines, as well as $\gamma$-ray continuum radiation, in particular the 'MeV excess' often observed in flares (Ramaty, Kozlovsky, and Suri, 1977; Ramaty, Kozlovsky, and Lingenfelter, 1979).

Recent studies (Chupp, 1984) suggest almost simultaneous acceleration of electrons, protons, and heavier ions to high energies. If electrons, protons, and ions share a common acceleration process, an important observational consequence of thick-target
emission is that their energy would be deposited in similar proportions at the same loop footpoints. High-spatial resolution observations of hard X-rays and γ-rays also should be able to answer definitively the question of whether the small observed delays (e.g., Forrest and Chupp, 1983) between MeV γ-rays and hard X-ray bursts are due to the loop transit time.

Several investigators have suggested a second stage or second step to the flare acceleration process. More generally, one may ask whether a single acceleration mechanism can be responsible for all observed nonthermal flare phenomena. While there is growing evidence that electrons, protons, and ions are indeed accelerated impulsively to high energies in some flares by a single acceleration process (Chupp, 1984), there are also suggestions for a slower, large-scale acceleration process operating in other flares (Bai and Ramaty, 1979; Murphy, Dermer, and Ramaty, 1987). A possible mechanism would be large-scale shock acceleration via the first-order Fermi mechanism operating in the upper chromosphere or corona. Such a mechanism should clearly distinguish itself by its spatial structure when imaged at hard X-ray and γ-ray energies.

2.3. Desired Instrumental Performance Parameters

The desired capabilities of a hard X-ray and γ-ray imager are set by the spatial, temporal, and energetic scales of the high-energy flare processes. In terms of energy range, a primary motivation for observing photons with energies above \(\sim 25\) keV is the need to isolate the accelerated nonthermal component from the hot thermal electron distribution which can dominate at lower energies. It is nevertheless important to obtain simultaneous images for photon energies down to \(\sim 10\) keV. It is then possible to place the nonthermal emission directly in the context of the commonly observed thermal X-ray emission (10–20 million K), which dominates below \(\sim 15\) keV, and in the context of the so-called ‘superhot’ component (\(\sim 30\) million K), which can be important in the 20–30 keV range (Lin et al., 1981). These hot plasmas may represent steps in the chain of thermalization of the flare energy release and so may provide links to other observational regimes. Low-energy observations (<25 keV) can also place the poorly understood onset phase emission in the spatial context of the subsequent impulsive phase to which it may be causally related.

While one energy scale is set by the transition from thermal to nonthermal emission processes at \(25\) keV or above, another scale is set by the transition from electron- to ion-dominated emission processes between 500 keV and a few MeV. Observations of emission above 500 keV are thus needed for study of the geometry of proton and ion acceleration and transport in flares. In addition, observations of emission at intermediate energies (\(\sim 100–500\) keV) are important because they can be combined with observations of microwave emission to yield both a field-weighted and a density-weighted emission measure for relativistic electrons.

In terms of spatial scale, a typical flaring magnetic loop has a scale of 10–30 arc sec. Microwave observations at 15 GHz typically show source size scales of 2–3 arc sec, while hard X-ray observations have shown flare activity both unresolved at 8 arc sec and with size scales of larger than 1 arc min. In terms of temporal scale, free relativistic
electrons have characteristic travel times of \( \sim 10 \) to 100 ms. Hard X-ray fluctuations with e-folding times as short as a few tens of milliseconds have been observed with HXRBS on SMM (Kiplinger et al., 1983).

Taking into account the energetic, spatial, and temporal scales of the flare process, the ideal hard X-ray and \( \gamma \)-ray imager should thus have spatial resolution approaching 1 sec of arc or better over an image field of several square arc min, time resolution of order 10 ms, and an energy range of at least 10 keV to 1 MeV. In addition, full Sun sensitivity for flare detection is desirable. Clearly, in any practical implementation there may be a trade-off among these capabilities.

Another important issue, closely tied to the question of time resolution, is that of sensitivity and dynamic range. One can expect to observe about 100 flares per year whose peak flux above 25 keV is \( \sim 1 \) photon per second per cm\(^2\). Above 200 keV there is only about 1 flare per year at the large flux level of 1 photon per second per cm\(^2\). This clearly indicates that to achieve high time resolution, instrumental collecting area must be substantial and must be used efficiently. On the other hand, above 10 keV one can expect to see events with \( \sim 1000 \) photons per second per cm\(^2\) at least once a month, indicating that concerns about instrumental saturation also must be addressed.

A summary of the desired capabilities are listed in Table I.

| Desired characteristics of a \( \gamma \)-ray and hard X-ray imager |
|---|---|---|
| Energy range | 10 keV to 1 MeV |
| Angular resolution | \( \leq 1 \) sec of arc |
| Field of view | Full Sun sensitivity |
| Time resolution | \( \leq 10 \) ms |

3. Experimental Approach

3.1. Imaging Techniques

Mirrors and lenses are not applicable at energies above a few keV. Consequently, hard X-ray and \( \gamma \)-ray imaging require the use of collimation schemes. These fall into two broad categories: ‘direct imaging’ collimation schemes and multiplex collimation schemes (for a formal treatment of collimation imaging, see Barrett and Swindell, 1981).

In direct imaging collimation, each detector resolution element views a different part of the image field. Multi-grid collimators which use this technique, such as those for the HXIS experiment on SMM (van Beek, 1976), can provide angular resolution of about 8 arc sec, but at the expense of a large number of detector elements (1 per pixel), restricted field of view, small effective area, and strict instrumental alignment requirements. For arc sec imaging, these factors become prohibitive.
Multiplexing schemes, in which all detectors view the entire image field, yield potentially higher sensitivity, larger field of view, and relaxed alignment requirements. Coded-apertures, modulation collimators, and Fourier-transform techniques fall into this category. Each of these techniques involves 'coding' the photon signal temporally or spatially on the detectors.

A coded-aperture system acts like a multiple pinhole camera, coding the information of the incoming photons in the form of overlapping images on the detector (Mertz, 1965; Dicke, 1968). The pattern of holes in the aperture is chosen so that a unique image of the source can be reconstructed from the spatial distribution of photons on the detector. Uniformly redundant arrays (Gunson and Polychronopoulos, 1976; Fenimore and Cannon, 1978; Cook et al., 1984) are one particularly attractive choice for the hole pattern. To achieve fine angular resolution, high-spatial resolution detectors and large detector/ aperture separations are needed (Hudson and Lin, 1978). Such requirements have limited the use of coded-aperture systems for solar imaging in the past, but advanced coded-aperture instruments are planned using the capabilities of the Pinhole/Occulter Facility and the Advanced Solar Observatory (see Section 4).

Modulation collimator systems utilize two grids, each having parallel linear slits, separated by a distance which is large compared with the slit width. The collimator grids are then rocked or rotated to temporally modulate the incident photon flux (Oda, 1965; Bradt et al., 1968; Schnopper, Thomson, and Watt, 1968). Detectors with spatial resolution are not required. Rotation modulation collimators have been used for the solar hard X-ray imager on Hinotori (Makishima et al., 1977) and have been used for imaging cosmic sources on SAS-3, Ariel-V, and Hakucho (e.g., Mayer, 1972; Sanford, 1975; Kondo et al., 1981; also Theinhardt et al., 1984). Scanning modulation collimators have been used for solar hard X-ray observations from balloons (Takakura et al., 1971) and numerous times for cosmic hard X-ray sources imaging (e.g., Oda et al., 1976; Pelling et al., 1987). Typically, multiple pairs of grids are needed to sample a wide range of angular scales.

3.2. Fourier-transform imaging

In Fourier-transform imaging (Makishima et al., 1977) the 'coding' of the detected photons is arranged to yield direct measurements of specific Fourier components of the source distribution. These can then be processed, as is done with radio interferometer data, to yield an image of the source. The basic formalism for Fourier-transform imaging was discussed by Hurford and Hudson (1979) in an unpublished report. We review several basic results and concepts here.

There are several different approaches to Fourier-transform imaging, employing a variety of spatial and temporal modulation techniques. One type of Fourier-transform imaging of particular interest for solar observations makes use of spatial modulation of the incident photon beam as distinct from any temporal modulation. Because systems employing temporal modulation require a scanning motion of the detector system, the time required to obtain a complete image is determined by a combination of photon statistics and motion time-scale. In a properly designed system, the motion needed to
acquire an image can be small and good time resolution can be maintained. Alternatively, a Fourier-transform technique that uses spatial modulation needs no motion and thus allows instantaneous photon-limited imaging. It is, therefore, well-suited to observation of fast time variability in phenomena such as solar flares. Because Fourier-transform imaging provides potentially the highest spatial and temporal resolution for solar flare studies, and because it has not been extensively discussed in the literature, we devote a considerable portion of this section to its discussion. We note that several planned hard X-ray and γ-ray instruments will use Fourier-transform techniques. These instruments will be described in Section 4.

We consider in this paper a Fourier-transform imaging technique in which a source is viewed simultaneously through multiple ‘subcollimators’, each of which measures one Fourier component of the source distribution. A subcollimator consists of a pair of widely separated collimator grids which form a modulation pattern of incident photons on position-sensitive detectors. Each collimator grid is a set of parallel, equally spaced slits. The spacings of slit centroids in the front and rear grids are \( s_1 \) and \( s_2 \), respectively, and a small difference between \( s_1 \) and \( s_2 \) produces a characteristic triangular modulation (Moiré) pattern of an incident beam of parallel photons at the detector (see Figure 1). The separation of the two grids is \( D \) and it is assumed that the rear grid is close to the front face of the detector. The axis of a grid is defined to be the direction perpendicular to the slits in the plane of the grid and is labeled by the unit vector \( \hat{a} = a_x \hat{x} + a_y \hat{y} \). We assume a small angle approximation for the entire field of view. The distribution of

Fig. 1. A schematic drawing of a Fourier-transform subcollimator and detector. The incident flux of photons on the detector is indicated, showing both the low- and high-frequency components present in the actual event distribution. Behind the detector is a schematic of the idealized measured triangular distribution resulting from the ‘smoothing’ of the detector response. Fourier-transform imaging is based on measurements of the amplitude and phase of the fundamental frequency of this periodic triangular distribution.
detected photons on the detector per unit area per unit time (in photons cm\(^{-2}\) s\(^{-1}\)) is then given by

\[
N(x) = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} f(\theta) A_{12}(x, \theta) \, d\theta + N_B ,
\]  

(1)

where \(N(x)\) is the count distribution as a function of position along \(\hat{a}\), \(N_B\) is the contribution from a uniform detector background, and \(f(\theta)\) is the 1-dimensional angular source distribution (photons cm\(^{-2}\) s\(^{-1}\) rad\(^{-1}\)) along the \(\hat{a}\) direction:

\[
f(\theta) = \int_{\psi_{\text{min}}}^{\psi_{\text{max}}} I(\theta, \psi) \, d\psi .
\]  

(2)

The angle \(\theta\) is measured along the \(\hat{a}\) direction, \(\psi\) is the angle measured perpendicular to \(\hat{a}\), \(\{\theta_{\text{max}}, \theta_{\text{min}}, \psi_{\text{min}}, \psi_{\text{max}}\}\) define the boundaries of the field of view, and \(I(\theta, \psi)\) is the source flux angular distribution (in units of photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)).

The function \(A_{12}(x, \theta)\) in Equation (1) is the unitless detector/grid response function that gives the probability that a photon arriving from angle \(\theta\) will pass through grids 1 and 2 (front and rear) and be detected at position \(x\). This function is the product of the two-grid aperture transmission functions and a detection efficiency function convolved with the detector point spread function. Neglecting the finite thickness of the grids and detector,

\[
A_{12}(x, \theta) = \int_{-L/2}^{L/2} \epsilon(x') A_1(x' + D \theta) A_2(x') \text{psf}(x, x') \, dx' ,
\]  

(3)

where \(L\) is the detector length in the \(\hat{a}\) direction, \(\epsilon(x)\) is the detection efficiency at position \(x\), \(A_1(x)\) and \(A_2(x)\) are the front and rear grid aperture transmission probabilities, and \(\text{psf}(x, x')\) is the point spread function of the detector, i.e., \(\text{psf}(x, x')\) is the probability per unit length that a photon arriving at position \(x'\) will be assigned a position \(x\). The integral of \(\text{psf}(x, x')\) over the detector is normalized to unity. For simplicity, we have assumed that the source can fully illuminate any location on the rear grid, i.e., the ‘shadow’ of the front grid completely overlaps the rear grid. We also assume for simplicity in the following discussion that \(\epsilon(x)\) is constant across the detector.

For an ideal system with perfect detector resolution, \(A_{12}\) depends only on a linear combination of \(x\) and \(\theta\), i.e., \(A_{12}(x, \theta) = A(\phi)\), where \(\phi = 2\pi(x/P + D\theta/s)\) can be considered a ‘phase’ since \(A(\phi)\) can be shown to be periodic. In defining \(\phi\), we have set \(s = s_1\) for convenience and \(P\) is the spatial period of the modulation given by \(P = s_1 s_2/(s_2 - s_1)\). If a detector actually were to have perfect spatial resolution and the grids were ideal, the response function would contain high-frequency components with period \(s_2\) (see Figures 1–3). However, for practical detectors with position resolution larger than the slit spacing, the high-frequency components are suppressed. If the
resolution is small compared to the modulation period, the system response function $A(\phi)$ is well-represented by a periodic triangular function of amplitude $\frac{1}{2}$ and period $2\pi$. That is, $A(\phi)$, when averaged over a slit period, has peak values of $\frac{1}{2}$ and minimum values of 0, with linearly interpolated intermediate values.

The essence of Fourier-transform imaging is that each pair of collimator grids allows the measurement of the phase and amplitude of a particular Fourier component of the source angular distribution, where the angular frequency is given by $D/s$. Specifically, the Fourier component of the source distribution is related to the event position distribution by

$$F(u, v) \equiv \frac{1}{\pi} \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} f(\theta) \exp \left[ -i \frac{2\pi D\theta}{s} \right] d\theta = \frac{\pi}{P} \int_{-P/2}^{P/2} N(x) \exp \left[ i \frac{2\pi}{P} x \right] dx , \quad (4)$$

where $u = u\hat{x} + v\hat{y} \equiv (D/s)\hat{a}$. By using grid pairs with a variety of slit spacings and orientations, the source distribution is sampled at a variety of $(u, v)$ points.

Once the phase and amplitude have been measured at numerous points in $(u, v)$ space, an image of the source region can be reconstructed using standard radio interferometry analysis techniques such as CLEAN (Hogbom, 1974) and maximum entropy (Gull and Daniell, 1978; Cornwell and Evans, 1985). These techniques have been demonstrated at $\gamma$-ray energies by Palmer and Prince (1987).

3.3. PRACTICAL CONSIDERATIONS

The preceding discussion contains the essential elements of Fourier-transform imaging. While a detailed discussion of the finer points is beyond the scope of this paper, a few aspects of the technique should be noted. To discuss these quantitatively, we define (as in Hurford and Hudson, 1979) a complex visibility:

$$V(P) = \frac{2}{L} \int_{-L/2}^{L/2} N(x) \exp \left[ i \frac{2\pi}{P} x \right] dx , \quad (5)$$

which for an ideal system is a direct measure of the corresponding Fourier component of the source intensity distribution.

We comment on the following considerations:

(1) The triangular modulation pattern actually contains information about Fourier components of the source with an angular frequency larger than $D/s$ due to the fact that the triangular pattern contains higher odd harmonics of the fundamental frequency $1/P$. However, as pointed out in Hurford and Hudson (1979), the visibility of a higher ($n$th) harmonic decreases like $1/n^2$ for a compact source, that is, $V(P_n) = V(P_1/n^2$, where $P_n = P/n$. In addition, finite detector resolution or grid imperfections preferentially degrade the visibility of the higher harmonics so that the higher frequency information would rarely be useful in practice.

(2) In some practical designs, it is desirable to use discrete detector elements, leading
to a ‘binning’ of the photon position distribution on the detector plane. It can be shown (Hurford and Hudson, 1979) that for $M$ bins per subcollimator period, the visibility $V_M$ is $V_M = V_\infty \text{sinc}(\pi/M)$, where $V_\infty$ is the visibility for a detector with perfect position determination, and $\text{sinc}(x) \equiv \sin(x)/x$. For example, the use of four discrete detectors for one subcollimator period reduces the visibility by 10%. More generally, consider a detector with uniform point spread function $\text{psf}(x, x') = \text{psf}(x - x')$, and ignore detector edge effects. Because of the convolution involving the detector point spread function, the visibility is $V_\delta = V_\infty \times F_{\text{psf}}(1/P)$, i.e., the visibility is reduced by the Fourier transform of the detector point spread function, $F_{\text{psf}}$, evaluated at the spatial frequency $1/P$.

(3) Because the modulation pattern is one-dimensional, it is sufficient to use detectors with spatial resolution in one direction only. In this case, it would be highly desirable to arrange for the axis of the modulation pattern to be along a convenient detector axis rather than along the axis of the grids, $\vec{a}$. This can be accomplished through a small difference in orientation between the upper and lower grids.

We describe this effect as follows. Let $\vec{k}_1 = \vec{a}_1/s_1$ be the vector describing the spatial modulation of the front grid, and $\vec{k}_2 = \vec{a}_2/s_2$ describe the spatial modulation of the rear grid, where $\vec{a}_1$ and $\vec{a}_2$ specify the directions perpendicular to the grid slits in each case. We now draw an analogy to the case of continuous waveforms:

$$\cos(\vec{k}_1 \cdot \vec{x}) \cos(\vec{k}_2 \cdot \vec{x}) = \frac{1}{2} [\cos((\vec{k}_1 + \vec{k}_2) \cdot \vec{x}) + \cos((\vec{k}_1 - \vec{k}_2) \cdot \vec{x})].$$

In this case, the low-frequency modulation has a characteristic wave vector, $(\vec{k}_1 - \vec{k}_2)$. Similarly, it can be shown that for the square-wave modulation of the grids, the characteristic triangular modulation pattern will have direction and spatial frequency described by $(\vec{k}_1 - \vec{k}_2)$. When $\vec{k}_1$ and $\vec{k}_2$ are parallel but have slightly different frequencies, we have the case of aligned grids discussed previously. The geometry is shown in Figure 2. For the case of grid pairs with a difference in both orientation and spatial frequency, the axis of the modulation pattern is different from that of either of the two grids. This geometry is shown in Figure 3. Thus, by independently choosing the spatial frequency and orientation of the grids, we may arrange an arbitrary period and orientation of the modulation pattern matching the geometry and spatial resolution of the detectors. In particular, the detectors can have one-dimensional position resolution and can all be oriented in the same direction.

(4) It is important to consider tolerances on alignment of the upper and lower grids. A translation of the two grids relative to each other in the plane of the grids has the primary effect of causing a shift in the fringe position without reducing the fringe amplitude. Thus, it is sufficient to have $a posteriori$ knowledge of the relative grid positions. These must be known to a fraction of the slit width, $s_1$. Real-time control of the relative positions of the grids is not necessary. Relative twist of the two grids changes the period and orientation of the modulation pattern. For a one-dimensional detector, an uncontrolled relative twist of angle $\delta$ reduces the visibility by a factor $\text{sinc}(\pi/M_\delta)$ where $M_\delta = L \tan \delta/s$. Note that the requirement for the control of twist is dependent on the number of slits per grid, $L/s$, and thus only indirectly related to the angular resolution, $s/D$. 
Fig. 2. (a and b) Two grids with the same orientation but different spatial frequencies. Overlaying the two grids results in the modulation pattern of (c). The modulation pattern is oriented parallel to the grids. Note that maximum average local transmission is $\frac{1}{2}$. 
Fig. 3. (a and b) Two grids with different orientations and spatial frequencies. Overlaying the two grids results in the modulation pattern of (c) which has a different orientation than either grid. Note also the difference between the modulation in Figures 2(c) and 3(c). While the two patterns differ in their high-frequency modulation, the low-frequency modulation is essentially the same in both cases. A detector with spatial resolution larger than the slit spacing will thus detect a similar event distribution in either case. The reader may wish to produce an overhead transparency of Figures 2(a–b) and 3(a–b) to investigate the possible modulation patterns.
(5) It should be noted that the Fourier-transform technique can be diffraction limited at energies for which the diffraction limit is rarely considered (Lindsey, 1978). Figure 4 shows the diffraction limit versus energy for several different grid separations under the Rayleigh criterion for a single slit. The limiting angle, $\Theta_D$, is taken to be $2\lambda/s = \Theta_D = s/D$, where $\lambda$ is the photon wavelength. The exact calculation for multiple slit collimators is treated by Lindsey (1978).

![Figure 4. Diffraction limit for Fourier-transform imaging under the Rayleigh criterion.](image)

3.4. System Design/Choice of $(u, v)$ Coverage

In principle, complete imaging of a field of $n^2$ pixels requires measurement of $\sim n^2$ Fourier components. Because this sampling condition can seldom even be approached in practical imaging systems, the choice of which Fourier components to measure with a given instrument involves a tradeoff of sensitivity, resolution, and image quality. These factors impact practical system design in terms of grid fabrication and detector size, complexity, and spatial resolution.

As is the case for a radio interferometer, measurements with very low spatial frequencies (which do not resolve the source) do not yield any information about source size or structure, while observations of very high spatial frequencies (which overresolve the source) do not yield any signal. Thus the selection of which spatial frequencies to measure depends on the a priori knowledge of the source size scales as well as its complexity. Images obtained previously at a variety of wavelengths indicate that a wide range of spatial scales may be relevant (from $\sim 1$ to $\sim 100$ arc sec). To cover such a wide range, one might use a logarithmic range of spatial frequencies and then borrow mathe-
matical techniques such as the CLEAN algorithm from the radio domain to help compensate for the relative dearth of measurements. Alternatively an instrument optimized for a more limited range of spatial scales can approach measurement requirements for ideal imaging.

3.5. Hardware implementation

So far in Section 3, we have concentrated on general techniques for imaging. Here we discuss several hardware implementation options for these techniques (see articles in *Nucl. Instr. Meth.* **221**, 1984 for other discussions).

3.5.1. Detectors

A wide variety of detectors can be employed in high-energy photon imaging. In Fourier-transform and coded-aperture imaging, detectors with spatial resolution are usually required, as distinguished from those for modulation collimator systems that do not require position sensitive detectors. Detectors suitable for modulation collimator systems can be similar to those used in spectroscopy studies (see Gehrels et al., 1988, this issue).

For a given angular resolution, coded-aperture systems generally require much finer spatial resolution than do Fourier-transform systems. As an example, assuming a 50 m separation between the coded-aperture mask and the detector (see the discussion on the P/OF coded-aperture imager in Section 4), a detector resolution of at least 1 mm is needed to achieve an angular resolution of 4 arc sec. In contrast, in Fourier-transform systems, the spatial resolution primarily influences the number of Fourier components sampled and is to first order independent of the angular resolution. A detector resolution of 1–2 cm is sufficient to obtain 1 arc sec angular resolution in practical systems. In actuality, the Fourier-transform method can even be implemented using large discrete detectors without position resolution (see, for example, Ogawara, 1988, and the discussion of Solar-A in Section 4).

Currently, the large-area detectors capable of 1 mm or better resolution include multiwire gas proportional chambers, gas drift-chambers, and liquid Ar or Xe detectors. Gas chambers are typically several centimeters thick and filled with Xe to provide a reasonable interaction cross section for photons up to about 50 keV, although somewhat higher energies can be achieved with high-pressure systems. Five centimeters of Xe gas at 1 atmosphere has a photopeak efficiency of $\sim 52\%$ and a typical energy resolution of 10% at 20 keV. Better resolution, $\sim 5\%$ at 20 keV, can be obtained with gas scintillation detectors. All these gas detectors are capable of millimeter spatial resolution, for which a basic limit is the path length and drift of the conversion electrons in the counter gas.

Liquid Ar and Xe detectors have not yet been used in high-energy astronomy and must be considered as developmental, although they show considerable promise as large-area detectors with good spatial resolution and large photon interaction cross sections.
section. Current developmental detectors have achieved an energy resolution of \(\sim 3\%\) at 1 MeV (for Ar at high fields, Edmiston and Gruen, 1978), better than the \(\sim 6\%\) achieved with NaI scintillators. Spatial resolution of a fraction of a millimeter is also possible. The attraction of liquid Xe detectors is their high density and correspondingly high photon-interaction cross section. A 5-cm thick liquid Xe detector has a photopeak efficiency of \(\sim 66\%\) at 500 keV.

Inorganic scintillation detectors, including NaI(Tl), Cs(Na), and CsI(Tl), are attractive for those applications such as Fourier-transform imaging that do not demand extremely high-spatial resolution. They can provide good photon detection efficiency (approaching 100\% at 100 keV) and moderate energy resolution (\(\sim 15\%\) at 100 keV). Spatial resolution is typically achieved in one of two ways: (1) use of discrete detectors to sample the photon distribution, or (2) 'scintillation camera' techniques in which a single scintillation detector is viewed by several photo-detectors such as photomultiplier tubes. In the latter technique the position is determined by the ratio of the signals in the photo-detectors. Typical scintillation cameras can achieve resolutions as good as 0.5 cm (1\(\sigma\)) at 100 keV. Discrete detector systems are limited primarily by the necessity of using many small, individual detectors.

5.3.2. Grid Fabrication

The slit width of the grids determines the resolving power of the imaging system, while the thickness of the grids determines the photon attenuation and, therefore, affect the sensitivity of the imaging system. As a consequence, it is important to develop the technology for fabrication of thick grids of high-Z material with fine slit dimensions. For example, to obtain 1 arc sec resolution with a 10 m grid separation required the finest grids to have a slit width of \(\sim 50\ \mu\text{m}\) and a center-to-center slit spacing of nominally 100 \(\mu\text{m}\). To attain the required attenuation of \(\gamma\)-rays up to 1 MeV, a thickness equivalent to 5–10 mm of tungsten is required.

Among the approaches that have been identified for fabrication of appropriate grids for hard X-ray and \(\gamma\)-ray imaging are: (1) Electrical discharge (EDM or ELOX) machining; (2) vertical stacking of high-Z material sheets (e.g., tungsten or tantalum) with the slit pattern photo- or laser-stretched into the material; (3) stacking of planes of stretched high-Z wire grids; and (4) horizontal stacking of high-Z material slits, with spacers providing the required slit width.

Method (1) is probably the method of choice for fabrication of coarser grids \((s_1 \geq 1\ \text{mm})\). Methods (2) and (3) are adaptations of methods previously used for construction of X-ray and hard X-ray collimators. They are probably applicable to medium scale grids, and may be adaptable for fabricating grids in the 50\(\mu\text{m}\) range. Method (4) may be the optimum method for constructing the finest scale grids. Prototype 50\(\mu\text{m}\) steel grids have recently been produced using this method (van Beek, 1987). Grid fabrication techniques are discussed in more detail in Crannell et al. (1985).
4. Future Instrumentation

Solar hard X-ray imaging remains in its infancy, since fundamental energy-release angular scales have not yet been observed. Following this metaphor, solar $\gamma$-ray imaging is still in its embryonic phase, having not yet been born as of the time of writing.

The next generation solar hard X-ray and $\gamma$-ray imagers will likely make extensive use of Fourier-transform techniques. These techniques can be implemented in a wide variety of configurations depending on the characteristics of a given space mission. Specific configurations have been proposed for free-flying satellites, balloons, shuttle missions, and the space station. The earliest versions are anticipated to be that on the Japanese Solar-A satellite to be launched in August 1991, and a NASA balloon payload being developed for the next solar maximum. We describe these briefly before discussing the possibilities for a considerably more powerful instrument, P/OF, a major component of the Advanced Solar Observatory. We summarize in Table II several past experiments and the possible future missions, insofar as their parameters are now known.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Dates</th>
<th>Resolution</th>
<th>Imaging technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon</td>
<td>1971</td>
<td>79.2 arc sec (FWHM)</td>
<td>Scanning modulation collimator</td>
<td>Takakura et al., 1971</td>
</tr>
<tr>
<td>SMM</td>
<td>1980</td>
<td>8 arc sec (FWHM)</td>
<td>Direct imaging</td>
<td>van Beek et al., 1980</td>
</tr>
<tr>
<td>Hinotori</td>
<td>1981</td>
<td>28 arc sec (FWHM)</td>
<td>Rotation modulation collimator</td>
<td>Takakura et al., 1983</td>
</tr>
<tr>
<td>GRID</td>
<td>1991</td>
<td>1.6 arc sec (FWHM)</td>
<td>Fourier-transform</td>
<td>Crannell et al., 1987</td>
</tr>
<tr>
<td>P/OF</td>
<td>1997</td>
<td>0.2 arc sec (FWHM)</td>
<td>Fourier-transform and coded aperture</td>
<td>Hudson, 1986a</td>
</tr>
</tbody>
</table>

4.1. Solar-A

The Solar-A hard X-ray telescope (Ogawara, 1988) will employ a Fourier-synthesis collimator system with 64 subcollimators. The Fourier-transform technique used for Solar-A differs from the method discussed in Section 3. In the Solar-A instrument, the front and rear grids of a subcollimator have identical slit spacing and a single discrete detector measures the resultant amplitude of the flux passing through the two grids. By using a pair of such subcollimators which differ by 90 deg in phase and comparing their output with a measurement of the unmodulated flux, one obtains measurements of a single Fourier component. With 64 subcollimators the Solar-A instrument thus measures the equivalent of 32 Fourier components simultaneously. The ultimate angular resolution will be approximately 5–7 arc sec. The field of view will be the full solar disk, with a synthesis aperture of about 2 arc min. The effective area is approximately 90 cm$^2$ with an array of 64 discrete NaI scintillation counters as the amplitude detectors. The energy range will be approximately 5–100 keV, covered in four energy bands. Solar-A,
with considerably improved sensitivity over HXIS on SMM, and considerably improved angular resolution over Hinotori, should provide the next significant improvement in hard X-ray imaging capability. The combination of full-Sun imaging and 5–7 arc sec resolution should yield a large catalog of hard X-ray flare observations for study at an angular resolution better than the best achieved to date for only a small sample of flares.

4.2. GRID

Prospects for space-based high-resolution γ-ray imaging observations during the coming solar maximum (∼1991) are restricted by the serious deficit in flight opportunities and the brief time interval in which development must be accomplished. High-altitude, long-duration, scientific ballooning provides an opportunity for making solar γ-ray observations by providing the heavy-lift capability that is needed for possible γ-ray imaging payloads. A hard X-ray and γ-ray imaging instrument for balloon-flight applications is under development (Crannell et al., 1987) and is known as the Gamma-Ray Imaging Device or 'GRID on a Balloon'.

GRID will be based on the Fourier-transform imaging technique described in Section 3. The instrument will contain 32 subcollimators with a uniform distribution of slit orientations and a logarithmic distribution of slit spacings corresponding to the range of angular dimensions from 1.6 arc sec to a few arc min. For all the subcollimators, the slit spacings and the angles between the grid pairs are chosen so that the resultant Moiré patterns are each a single intensity-contrast cycle and are all oriented in the same direction. This arrangement enables all the detector modules to be identical and co-aligned for optimum utilization of the space within the telescope canister.

GRID is shown schematically in Figure 5. The aspect system, indicated by small circles in the telescope endplates, will be the Solar Disk Sextant (Sofia et al., 1984). The anticipated characteristics and capabilities of GRID are summarized in Table III. GRID should have an energy range that extends to 1 MeV, including the positron annihilation line at 511 keV, and its sensitivity should be about three orders-of-magnitude better than the Hard X-ray Imaging Spectrometer on the Solar Maximum Mission. Flights of GRID during the coming solar maximum should not only enable high-sensitivity imaging at γ-ray photon energies, but should also serve as a scientific and technical precursor of the Fourier-transform instrument on the Pinhole/Occulter Facility (see below).

| TABLE III |
| Characteristics and capabilities of GRID |

| Detector type       | Scintillation counters |
| Detector area       | 480 cm²                |
| Energy range        | 20 keV to 1 MeV        |
| Subcollimator material | Tungsten and tantalum |
| Number of subcollimators | 32               |
| Sensitivity         | >100 flares per week  |
| Angular resolution  | 1.6 arc sec           |
| Field of view       | Full Sun              |
| Expected flight duration | 15 days              |
Fig. 5. (a) Schematic representation of GRID showing the telescope integrated into a balloon payload and (b) an exploded view showing the end plates holding the grid subcollimator pairs and the Solar Disk Sextant together with the canister housing the detector modules.
4.3. **Pinhole/Occluder Facility (P/OF)**

The Pinhole/Occluder Facility (see Tandberg-Hanssen et al., 1986, for descriptions of the instrumentation and science objectives) represents the definitive future realization of the techniques discussed in this paper, and we will describe its hard X-ray and γ-ray imaging capabilities briefly here. Note that the original conception of P/OF (Hudson and Lin, 1978) envisioned separate spacecraft for the mask and detector systems; with such an arrangement a very large separation can be imagined. Within the scale of a single spacecraft, however, a maximum scale of about 50 m seems appropriate. We also note that in addition to the hard X-ray and γ-ray imagers, P/OF contains significant UV and white light instrumentation for coronal studies (see Tandberg-Hanssen et al., 1986).

P/OF achieves high angular resolution simply by virtue of its large scale (see Figure 6): the 50-m baseline offers a diffraction-limited angular resolution as fine as 0.2 arc sec above 10 keV by use of the Fourier approach. Given a detector with spatial resolution of 1 mm, simple coded-aperture techniques using a single mask yield 4 arc sec. The P/OF baseline payload envisions using both approaches to get high

![Pinhole/Occluder Facility](MSFC-82-ST 2849)

Fig. 6. Illustration of the Pinhole/Occluder Facility (P/OF). The Fourier-transform telescope is in the left corner of the mast at the end of the boom and the coded-aperture instrument is in the upper corner. P/OF is depicted deployed from the shuttle.
resolution at high energies (Fourier) and high sensitivity over large fields of view (coded aperture). Table IV lists the important parameters of the P/OF hard X-ray and γ-ray imaging facility (Lin and Dennis, 1986).

<table>
<thead>
<tr>
<th>Characteristics of P/OF</th>
<th>Coded-aperture imager</th>
<th>Fourier-transform imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution</td>
<td>4 arc sec</td>
<td>0.2 arc sec</td>
</tr>
<tr>
<td>Field of view</td>
<td>Full Sun</td>
<td>5 arc min</td>
</tr>
<tr>
<td>Energy range</td>
<td>2 to 70 keV</td>
<td>2 keV to 1 MeV</td>
</tr>
<tr>
<td>Energy resolution at 20 keV</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>at 662 keV</td>
<td>–</td>
<td>7%</td>
</tr>
<tr>
<td>Time resolution</td>
<td>1 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>5000 cm²</td>
<td>25 cm² × 100 subcollimators</td>
</tr>
</tbody>
</table>

Successful imaging of solar hard X-rays and γ-rays at the sub-arc-sec scale would provide a dramatic step forward in our understanding of high-energy phenomena in solar flares. These phenomena cannot, however, be fully understood in the absence of other data that can characterize the plasma environment of the flare. In particular, high-resolution imaging of the solar photosphere, with a capability for the measurement of subtle velocity fields and solar magnetism, seems to be a prerequisite, as eventually do observations of chromosphere, transition-region, and coronal emissions with fine resolution. The desired optical observations would come from the Orbiting Solar Laboratory (OSL). The sum of all these measurements comprises the Advanced Solar Observatory, considered as a state-of-the-art collection of instruments covering all the important bands of the spectrum. The development of the Advanced Solar Observatory represents a major undertaking, comparable to the Apollo Telescope Mount (Skylab) instruments of the 1970’s; we envision that its deployment could take advantage of the resources of the Space Station now being developed.

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