GLAST LAT Multiwavelength Studies
Needs and Resources

Report of the Ad Hoc Multiwavelength Observation Planning Group

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Executive Summary

Introduction

- Multiwavelength (MW) studies are intimately related to essentially all the astrophysical topics to be addressed by GLAST LAT. Essentially all of the gamma ray observations envisaged with the GLAST LAT will require observational programs at other wavelengths to extract their full value. The cost of these programs is small in comparison with the cost of the GLAST mission. Many of these programs need to start soon.

- We envision three types of multiwavelength study: *i*) identification of sources in known classes, such as blazars and pulsars, *ii)* discovery of new sources classes, and, *iii)* intensive, MW explorations of the brightest and most variable sources that will allow deep study of the source physics.

Pre-launch MW Planning

- LAT is expected to detect up to ten times more blazars than are currently cataloged. Improving existing blazar catalogs will be necessary to identify these new blazars.

Recommendation: Complete a southern hemisphere catalog of flat spectrum radio sources out to 8.4 GHz or higher frequencies, at least down to 100 mJy, and preferably to 30 mJy.

Recommendation: Complete a program of optical identifications and redshift measurements for all known flat-spectrum radio sources brighter than 100 mJy at 8 GHz.

- Contemporaneous radio timing of pulsars is essential in order to maximize the gamma-ray pulsar identification probability, but radio astronomers cannot monitor all known pulsars.

Recommendation: Use pulsar models to develop a prioritized list of radio pulsars to be monitored. Start the timing program before the GLAST launch.

- Owing to the limited angular resolution, low celestial fluxes of high-energy gamma rays, and the pervasive and relatively intense diffuse emission of the Milky Way, a model of this interstellar emission is needed for source discrimination and location determinations, as well as for studies of the isotropic diffuse emission. Some new radio observations are important to improving existing models.

Recommendation: Sponsor observations with the CfA telescope of special directions such as tangent directions of spiral arms. Encourage the NANTEN telescope team to make some observations of the Galactic center region and to carry out a search for southern intermediate-latitude clouds.

MW Activities Starting in the Early Post-Launch Time Frame

- The potential for discoveries of new classes of gamma-ray sources will be improved by using hard X-ray imaging to identify candidate objects. Optical and radio follow-up observations with candidate objects are needed to complete the MW picture of these objects.

Recommendation: Plan campaigns with Chandra, XMM, Astro E2, and (if selected) NuSTAR for high-energy X-ray studies of unidentified gamma-ray source error boxes.

Recommendation: Plan pulsar search proposals for X-ray telescopes.

Recommendation: Plan coordinated proposals with optical and radio observatories for follow-on observations of LAT sources.

MW Activities throughout the GLAST Mission

- Coordinated, simultaneous observations across the electromagnetic spectrum are expected to be extremely valuable for detailed study of blazars, particularly the physics of the jets.

Recommendation: The LAT blazar program should collaborate with existing blazar study groups wherever possible, for both Target of Opportunity campaigns and pre-planned MW campaigns.

- Pulsar studies need to be coordinated in particular with the radio observations, whose high sensitivity and excellent timing resolution provide critical data for gamma-ray pulsar studies. Long-term timing programs are needed in order to maintain absolute phase. Deep radio, optical and X-ray exposures, with timing, will be needed in order to develop true MW information about pulsars.

Recommendation: Plan a dedicated radio timing program for the pulsars expected to be brightest and most interesting to GLAST.

Recommendation: Plan follow-on proposals for radio, optical, or X-ray telescope time for LAT sources identified as pulsars in order to develop the most complete MW picture possible for these pulsars.

1. Introduction

One of the critical lessons learned from the Compton Gamma Ray Observatory was the value of multiwavelength (MW) observations. In cases such as gamma-ray bursts (GRB) and blazars, gamma rays of course contribute critical pieces of the overall picture, but vital discoveries, like the cosmological distances of GRB and the pulsar nature of Geminga required MW observations. For most unidentified gamma-ray sources, only observations at other wavelengths offer the hope of determining their true natures.

With this experience in mind, the GLAST Science Working Group and both GLAST instrument teams have planned MW studies from the outset. This report outlines the considerations for MW programs with the Large Area Telescope (LAT). The Ad Hoc Multiwavelength Observation Planning Group was charged by Peter Michelson, the Principal Investigator, to:

(1) Assess the multiwavelength observational needs, both surveys and contemporaneous observations, of the GLAST Large Area Telescope Science Program.

(2) Identify observational facilities (and possible contacts) that could meet the observational needs.

The letter establishing this committee is included as Appendix A.

This report will not address GRB in depth. Because the intensities and time scales for prompt emission from bursts are substantially different from those of more persistent gamma-ray sources, the MW considerations for GRB are also different. The GLAST Science Working Group has a Burst Committee that will involve both the LAT and the GLAST Burst Monitor (GBM). Only a limited number of GRBs will have position localizations with the LAT that are good enough (sub-arcmin) to enable in-depth studies at longer wavelengths. We will rely heavily on experiences with HETE, INTEGRAL, Swift, and the Interplanetary Network to help develop a specific strategy for GRB analysis with the LAT.

The outline of this document is:

Section 2 – Characteristics of the GLAST LAT that are important to MW observations
Section 3 – Identification/Discovery. Using MW observations to identify sources in known classes and discover new classes.
Section 4 – Exploration. MW plans for detailed study of blazars and pulsars.
Section 5 – Open issues that may influence the implementation of the LAT MW observation plan.

2. Relevant Characteristics of GLAST LAT

From the standpoint of MW observations, the critical feature of the GLAST LAT is its huge field of view, more than 2 steradians. Coupled with high sensitivity for gamma-ray detection, an observing plan that emphasizes scanning rather than pointing and the ability of the GLAST observatory to point anywhere in the sky at any time, this field of view essentially means that the LAT will rarely place any operational constraints on MW studies. In this respect, the LAT is more like an all-sky monitor than a conventional pointed telescope.

The characteristics of the LAT that do influence planning for MW observations are those inherent to any pair-production telescope operated in space:

- Source detection is limited principally by photon statistics. At high Galactic latitudes, the limitation is the time needed to detect a few photons; at low Galactic latitudes with brighter diffuse emission to contend with, the limitation is the time needed to detect the source in the presence of the Galactic background. The LAT photon detection rate for even the brightest sources (except for gamma-ray bursts) is less than 0.1 Hz. **Table 1 below shows the LAT detection capabilities, given in a very broad approximation. In the nominal scanning mode, it shows the length of time needed for LAT to obtain a detection and to measure a gamma-ray spectrum for different source fluxes.**

- Source localization is modest by astronomical standards (although vastly better than that of EGRET): typically 10' for threshold sources and 1' for bright sources. Source identification will remain a challenge in many cases. High-energy photons are localized better than low-energy photons.

- Downlink and processing time affect the ability to respond to rapid changes (there will probably be no on-board detection of transients except bursts). With a few downlinks per day, plus the specified transmission and processing time (the Ground Station + Missions Operations Center (MOC) + Instrument Science Operations Center (ISOC) allowance is 12 hours), the LAT ISOC is unlikely to have time-critical quicklook results in less than half a day. For rapid transients, therefore, LAT may acquire useful data, but it is unlikely that LAT will be able to provide a fast trigger to the MW network.

- Although scanning mode is the default, it will be possible to point GLAST at a target during times when Earth occultation permits. Pointing increases the exposure to a given source about a factor of three compared to the scanning mode for a given length of time.

Table 1 – GLAST LAT Source Detections (nominal scanning mode, high Galactic latitude)

Source Class	Flux >100 MeV x 10^{-8} ph/cm^{2}s	Observing time needed to detect	Observing time needed for spectrum	Number of sources
Bright	100	< 1 hour	< 1 day	~8 steady ~3 flaring
Medium	10	~1 day	~ 1 week	~250
Weak	1	~1 month	~1 year	>1000

One way to begin planning for future MW studies is to review what has already been seen. The principal source of information is the EGRET results. The single largest category of sources in the EGRET catalog (60% of the total) is the unidentified objects. This large number of unidentified sources is a principal reason for a concentrated effort with LAT to identify sources efficiently. Table 2 is a summary of astrophysical source classes that were seen with EGRET or have been predicted for detection by LAT. Of necessity, any table of this sort is subjective, particularly for sources that may have been identified, numbers of sources anticipated, and types of sources that might have high-energy gamma-ray emission.

Table 2 – High-Energy Gamma-Ray Sources Known and Anticipated

Source Class	**Number known**	**Number anticipated with LAT**
Rotation-powered pulsars	6 definite 3 possible	100-500
Blazars	80 definite 50 possible	>2000
Normal galaxies	2	4-5
Gamma-ray bursts	5	>500
Unidentified sources	170	?
Supernova remnants/plerions	1 likely ~5 possible	>10
Radio galaxies	1 likely 1 possible	?
X-ray binaries/microquasars	1 likely 1 possible	?
Starburst galaxies	0	~10
Clusters of galaxies	0	?

An obvious need for broad-band MW observations applies to known gamma-ray source classes. Figure 1 shows four of these: a bright pulsar, a plerion, and two blazars - a flat spectrum radio quasar (FSRQ), and a high-frequency peaked BL Lac Object (HBL). The variety of broadband spectra illustrates the wide range of requirements at different wavelengths. As an example, IR measurements are very important for FSRQ, because their synchrotron component can peak in this wavelength range, but pulsars show little or no IR emission. For this reason, the needs are both source-dependent and wavelength-dependent.

In addition to the MW detection sensitivity requirements, which to some extent can be quantified from Figure 1, the types of measurements at different wavelengths also depend on the source class. Radio timing for pulsars is a simple example of a source-specific need.

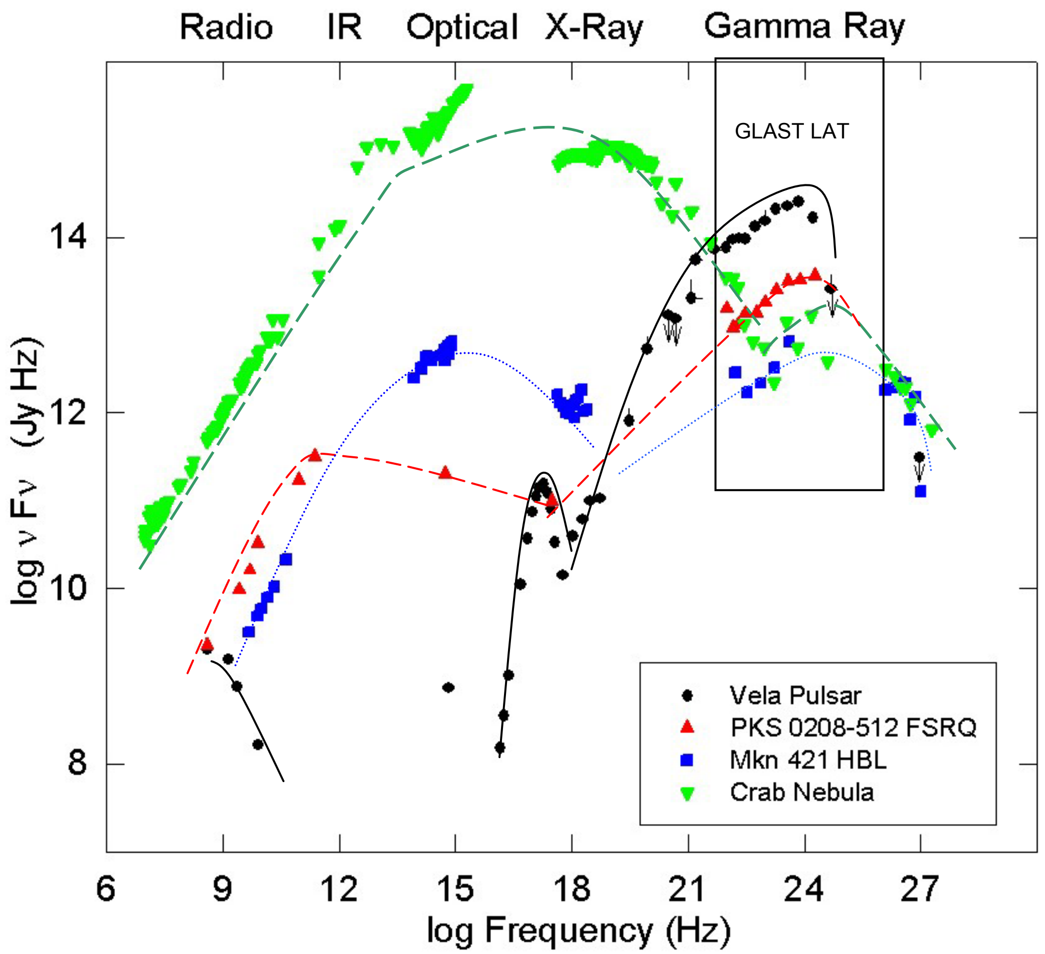

Figure 1 – Multiwavelength spectra for four identified gamma-ray sources. For the two types of AGN, not all observations were simultaneous, and these sources exhibit substantial variability. The lines connecting the data points are simply to guide the eye across the data gaps. The shaded region shows the approximate spectral and sensitivity coverage of GLAST LAT.

3. Identification and Discovery of Gamma-Ray Sources: the Multiwavelength Approach

Without a doubt, the key to getting excellent science from GLAST is to place the detected sources in a MW context. Indeed, even basic identification will rely on association with sources in other wavelength bands. We suggest two first steps for work with gamma-ray sources:

1. **Identification.** For gamma-ray sources that are readily identified with known source classes (such as blazars, pulsars, and GRB), the scientific goals emphasize detailed study of the physics of such sources. We need efficient ways to filter sources into these known classes, because we expect them to be the most numerous.
2. **Discovery.** For sources that fall outside the known source categories, the first goal must be identification. Ultimately, discovery depends on the Sherlock Holmes method: "Eliminate all other factors, and the one which remains must be the truth." MW observations are essential to establishing or eliminating possibilities.

Both of these steps fall into the category of "What are they?" The follow-on, discussed in the next section is exploration and detailed study, "What can be learned from these objects?" Figure 2 is a simple flowchart of the identification process, starting with the sources expected to be most numerous.

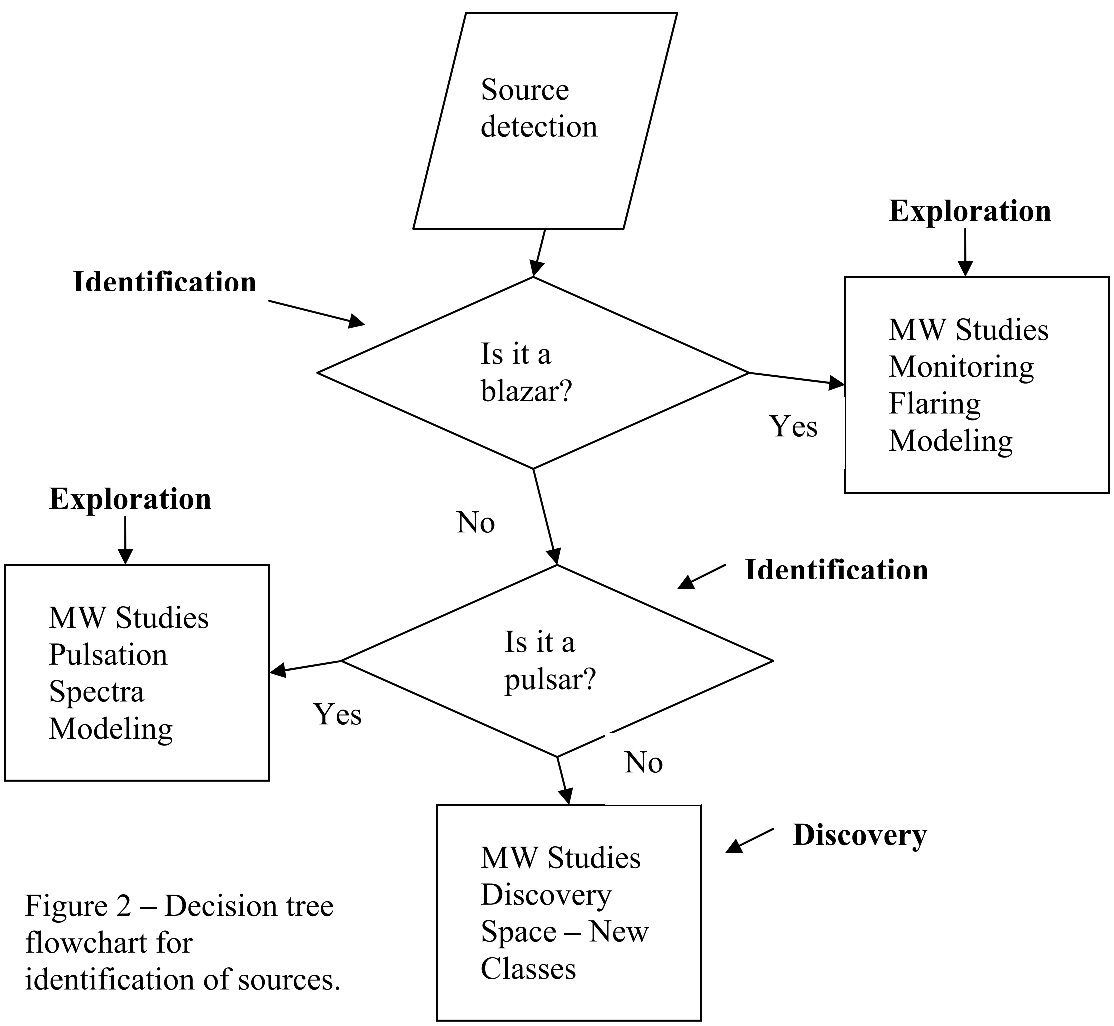

Figure 2 – Decision tree flowchart for identification of sources.

The next two sections describe MW methods and resources for identifying LAT sources in the best-known source classes: blazars and pulsars. Approaches for discovery using unidentified sources are considered in the next section, and the MW issues of establishing a model for the diffuse emission are covered in a following section.

3.1 Identifying Gamma-Ray Blazars

Blazars represent by far the largest class of identified gamma-ray sources. This subclass of Active Galactic Nuclei (AGN) is detectable across the electromagnetic spectrum. Coupled with their known variability, this broadband emission makes blazars ideal candidates for MW observations.

Extrapolations from the EGRET data indicate that the LAT will detect far more blazars than are currently cataloged as such. In his talk at the LAT Collaboration meeting in Rome, for example, Giommi showed the ASDC catalog, which has 1250 blazars (http://glast.gsfc.nasa.gov/science/lat/sept03/PGiommi.pdf), far fewer than the several thousand or more expected. An early goal of the LAT MW program should be to create an all sky blazar catalog large enough to contain most putative LAT blazers. Although extensive, deep, single-epoch radio catalogs exist (e.g. Green Bank 6 cm - GB6, Parkes-MIT-NRAO - PMN), other measurements (some or all of these) are often needed to establish a blazar, such as:

- Flat-spectrum radio emission extending to frequencies well above 5 GHz
- Core-dominated radio emission
- Variability at all wavelengths
- Measurable polarization at radio and optical wavelengths
- Redshift (to establish distance)

We must have an excellent filter for selecting blazars, ideally with all needed data in place before the mission starts. Radio surveys can effectively select blazar counterpart candidates at high latitude, at least those like the presently identified EGRET blazars, which have flat or inverted GHz spectral indices. Our experience with EGRET sources shows that even with ~1º error regions, useful association with compact flat spectrum radio sources can be made down to S_{5GHz} ~100mJy, and that to this limit radio-loud blazars represent 70% of the high latitude source population. With LAT quality localizations, this may be pushed to <30mJy. A simple extrapolation of the EGRET IDs suggests that this will account for ~1000 of the sources detected in the 1 year survey. Ideally before launch we would have cataloged all flat spectrum compact radio sources to this ~30mJy limit, which is comparable to the flux limit of the high frequency all sky surveys (eg. PMN). If this can be done before launch, we will have ready-made IDs for a substantial fraction of the survey sources. In the north the Cosmic Lens All-Sky Survey (CLASS) 8.4GHz survey together with NRAO VLA Sky Survey (NVSS)/ Faint Images of the Radio Sky at Twenty-cm (FIRST) provide the necessary radio data. No comparable survey exists in the South and a useful goal is to motivate a southern hemisphere survey, at least to 100mJy, before the mission. NVSS plus new VLA AnB snapshots at 8.4GHz should allow this study to DEC=-40º. Further south we must rely on the Sydney University Molonglo Sky Survey (SUMSS) plus new Australia Telescope Compact Array (ATCA) observations. The ongoing ATCA 20 GHz survey may provide useful data.

Recommendation: Complete a southern hemisphere catalog of flat spectrum radio sources out to 8.4 GHz or higher frequencies, at least down to 100 mJy, and preferably to 30 mJy.

A further useful exercise would be to obtain optical identifications and redshifts for these sources down to S_{5GHz} ~100mJy and m~22-23. There should be about 2000 such sources at |b|>10º and a survey of this scale can be largely completed with 4-5 m class telescopes. An ongoing effort at the Hobby-Eberly telescope will get ~30% of this survey done; this sort of project is well suited to a queue scheduled spectroscopic telescope.

Three examples of pilot projects to accomplish the goal of expanding the number of known blazars are:
1. The Deep X-Ray Radio Blazar Survey (DXRBS) compares X-ray sources with flat-spectrum radio sources. X-ray selected blazars are not necessarily gamma-ray blazars, however, and X-rays are not unique identifiers of blazars.
2. Sowards-Emmerd, Romani, and Michelson have shown that compact, flat-spectrum radio sources are a good identifier of blazars. Using optical follow-up for redshift determination, their analysis has found a substantial number of new blazars in the EGRET source catalog.
3. The ASI (Italian Space Agency) Data Center Blazar Candidate sample uses cross-correlation between NVSS and ROSAT All Sky Survey (RASS) radio and X-ray surveys, plus optical magnitudes in the blazar range from the Guide Star Catalog 2 (GSC2), producing over 7400 candidates.

Recommendation: Complete a program of optical identifications and redshift measurements for all known flat-spectrum radio sources brighter than 100 mJy at 8 GHz.

At low latitude, optical confirmation of blazars seen through the plane may be difficult, but radio properties, supported by correlated X-ray/IR variability should allow us to secure many of these identifications. Table 3 shows some resources that might be used to expand the catalog of blazars.

Table 3 – Resources for identifying blazars

Measurement	Facility	Possible Contact
Radio spectrum Radio mapping Radio variability	VLA/VLBA	
Radio spectrum	Metsahovi	
Radio variability	Green Bank	
Radio spectrum Radio mapping Radio variability	Parkes	
Redshift	Keck, Hobby-Eberly, ESO, 4 m telescopes, others	
Radio polarization		
Optical polarization		

3.2 Identifying Gamma-Ray Pulsars

In the Galactic plane we can assume that some of the sources will show pulsations at the periods of energetic pulsars, based on analyses of EGRET data. Also some high latitude fields may host radio pulsars, either the high latitude tail of the young Galactic population or millisecond pulsars (MSP). As for the blazars, once the LAT survey provides positions, deeper searches of fields without clear associations should be pursued. For the young pulsars, it is important to complete such searches while the GLAST mission is active, as timing solutions derived from later observations may not be sufficiently accurate for recovery of the pulsars in the archive. For the MSP, the high timing stability means that the need for prompt discovery is less pressing. At high latitude the limited electron column is a significant help in pulse search efforts, and the optimal search frequency may be as low as 600MHz.

Period searches of the gamma rays from LAT sources will allow direct identification of some pulsars, one case where MW observations are not essential for identification. Nevertheless, the availability of known periods and period derivatives from another wavelength band will always provide a higher level of confidence for any pulsar detection.

Pulsar timing and monitoring is planned by the radio pulsar community. This effort is organized by Steve Thorsett, one of the GLAST Interdisciplinary Scientists. Radio timing for all known pulsars is not practical. We need some way to choose the pulsars of most interest.

In order to study phase relationships of pulses and to add data over long time intervals, we need absolute phase information. This requires continued timing of pulsars, along with occasional collection of Dispersion Measure (DM) information from radio measurements.

Recommendation: Use pulsar models to develop a prioritized list of radio pulsars to be monitored. Start the timing program before the GLAST launch. Plan a dedicated radio timing program for the pulsars expected to be brightest and most interesting to GLAST.

Some X-ray-detected pulsars have weak or undetectable radio emission. Another lesson from EGRET is that for young pulsars the radio and gamma-ray beams are not coincident, and a number of sources may be `Geminga-like'. Imaging X-ray studies (including soft X-ray searches for near-isotropic thermal emission) can probe the pulsar model, even when the radio beam misses the Earth line-of-sight. Duplication of the Geminga identification via soft X-ray pulsations will however require very deep observations and even if XMM and Chandra are available, such searches will likely only secure a few identifications out to ~1kpc.

Recommendation: Plan pulsar search proposals for X-ray telescopes.

Table 4 shows some radio resources for pulsar observations.

Table 4 Radio Resources for Pulsar Observations

Measurement	Facility	Possible Contact
Radio timing/search	Parkes	
Radio timing/search	Arecibo	
Radio timing/search	Allen Array	
Radio timing/search	Green Bank	
Radio timing/search	Jodrell	
Radio timing/search	VLA	

3.3 Unidentified Sources: Discovery Space

Once a large number of sources has been filtered into known classes, then the more difficult task of identifying new source classes can focus on the remainder, which represents discovery space for GLAST LAT. The previous sections have discussed methods for identifying and studying the two largest known source classes. For sources where these methods do not yield identifications, many approaches are available.

The wealth of readily-accessible archival astronomical data has been a tremendous boon to efforts at source identification and modeling. Facilities include MW, searchable archives such as NED and SIMBAD, along with many catalogs of radio, infrared, optical, X-ray, and gamma-ray sources. Databases of this sort are the first stop in trying to identify any gamma-ray source. Such comparisons will certainly be part of the work in building a LAT source catalog. Even with the greatly-improved error boxes of LAT compared to EGRET, however, a positional association with a catalog object is not a guarantee of a physical relationship.

Coordinated observations during or immediately post-survey will be crucial for positive identifications. With its high duty cycle and uniform coverage, correlated variability studies with the LAT will be a powerful identification tool. This can of course only be done during the active mission. We hope and expect that a number of relatively well localized bright sources will *not* yield to this strategy of looking for correlated variability. Here deep MW observations for the best few sources will be required to place strong constraints on the Spectral Energy Distributions (SED) of possible counterparts (cf. Figure 1) and, we expect, identify new source classes.

EGRET did find other high latitude| sources that are not radio bright, hence not good blazar candidates. Some may be radio-faint blazars and BL Lacs – deep follow-up radio imaging can select candidates for such sources relying on LAT survey localizations; however at low fluxes the identifications will be statistically less secure. Definitive identifications will in general require detection of correlated variability with longer wavelength (especially mm-far IR) emission.

The high latitude non-blazar/non-pulsed sources will likely show some correlation with other cataloged extragalactic objects. One counterpart class that has been discussed is galaxy clusters. Here the emission will be produced by cosmic ray protons and electrons deriving from earlier generations of radio sources and intergalactic shock waves. Another is starburst galaxies where inverse Compton scattering of X-ray photons be freshly accelerated electrons within young supernova remnants could be the source. Limits on variability should allow improved isolation of such extended source classes. This is one area where we can expect the LAT survey to reveal some surprises.

Evidence of energetic particle creation by young $<10^5$y pulsars can also be found from the isotropic wind nebula or pulsar wind nebula (PWN) emission. Although some specific source characteristics may motivate particular searches (e.g. non-variable, extended gamma-ray emission could be a molecular cloud, a supernova remnant, a galaxy, or a cluster of galaxies), we suggest that a generic approach to gamma-ray source identification is to work from X-rays downward in energy. If a plausible X-ray counterpart can be identified, then the arcsec X-ray imaging (vs. arcmin gamma-ray position) may facilitate finding longer-wavelength counterparts.

This is where X-ray imaging can make the greatest headway on the unidentified Galactic population. Here >2keV sensitivity is key for the typically distant, absorbed sources and it will be useful to obtain follow-up observations with XMM and Chandra. A commitment, likely from Key Project proposals, to ~20ks exposure of ~100-300 Galactic error boxes, not covered to comparable depth in the limited existing plane surveys, would provide a sensitive search for energetic plane sources as well as much serendipitous Galactic survey science. Diffuse non-thermal (α~0 to -0.3) polarized radio emission is a second hallmark of PWNe, and survey follow-up of the best localized sources at cm wavelengths will also provide useful indirect evidence for pulsar wind nebulae and other particle/gamma-ray sources.

Recommendation: Plan campaigns with Chandra, XMM, Astro E2, and (if selected) NuSTAR for high-energy X-ray studies of unidentified gamma-ray source error boxes.

After all of these natural extrapolations of past identification work fail, we end up with the set of unassigned objects that must represent new source classes. In the process of eliminating blazars and pulsars, we will have accrued substantial constraints on the SEDs of possible counterparts. For the best-localized sources the full panoply of modern astronomical instrumentation can be brought into play. Then the fun begins!

Recommendation: Plan coordinated proposals with optical and radio observatories for follow-on observations of LAT sources.

3.4 Diffuse Emission: A Special Case

Another aspect of GLAST LAT that involves MW studies is the modeling of the diffuse emission, an important element in analysis. A good model of the interstellar emission of the Milky Way is needed because at low latitudes the emission is relatively intense and quite structured. Because of the limited angular resolution of gamma-ray telescopes and the limited gamma-ray statistics, detection of point sources is generally by model fitting, i.e., by extracting a limited number of parameter values from the observations. Incorrectly modeled interstellar emission could result in errors in derived positions for point sources, or even false detections. Even at higher latitudes, the intensity of the interstellar emission is comparable to or greater than the isotropic extragalactic intensity. Accurate measurements of the latter depend on careful characterization of the former.

Models of interstellar gamma-ray emission are necessarily multiwavelength because they depend on surveys of tracers of the interstellar medium (radio and microwave) as well as on determinations of the interstellar radiation field from surveys of infrared and near infrared emission (as well as models of the stellar radiation fields).

- The sky coverage of the H I surveys is complete. We will want to use the Leiden-Dwingeloo survey, which has been publicly available for several years, and its southern complement, the Villa-Elisa survey, which is not yet published. The time scale for the public release of the Villa-Elisa survey needs to be determined; use of the survey may require collaboration with IAR (Argentina) and MPIfR.

- In CO, the composite surveys of the CfA 1.2-m and its southern twin at Cerro Tololo have adequate coverage of the Galactic plane and of large, nearby molecular clouds, although recently-discovered, small angular diameter (~0.25º) molecular clouds at high latitudes have not been completely surveyed. These will be detected but not resolved by the LAT. Also, in some special directions, notably the Galactic center and the tangent directions of the spiral arms, we will also want small-scale surveys of optically thinner species (like $C^{18}O$) or tracers of higher density (like HC_3N) to reliably trace the distribution of the interstellar gas. The CfA 1.2-m telescope and the NANTEN (Nagoya University) 4-m telescope at Las Campanas, both survey instruments, may be available to undertake these observations, either by collaboration or via direct support from the LAT project.

Recommendation: Sponsor observations with the CfA telescope of special directions such as tangent directions of spiral arms. Encourage the NANTEN telescope team to make some observations of the Galactic center region and to carry out a search for southern intermediate-latitude.

4. Exploration of Gamma-ray Sources with Multiwavelength Observations

Identification/discovery of gamma-ray sources is a critical first step, but the ultimate goal is to study the physics of the objects that have been detected. Exploratory investigation of LAT sources with MW observations is an essential element of extracting insights about the physical mechanisms at work. For any source class, modeling will reveal expected behavior at many wavelengths. MW observations therefore become tests of hypotheses. We can illustrate the process by considering the two major known source classes: blazars (which are variable) and pulsars (which have periodic emission but are fairly stable in gamma rays over long time scales). Other source classes will have similar needs.

4.1 Monitoring Blazars

Extensive work of this type has been done and is continuing. In light of the breadth of work being carried out already, the LAT team should make a serious effort to link our work (or maintain existing links) with some of these programs.

Recommendation: The LAT blazar program should cooperate with existing blazar study groups wherever possible, for both Target of Opportunity campaigns and pre-planned MW campaigns.

Because time variability, in particular the delays between different wavelength bands for recognized events, is such a powerful discriminator for modeling blazar emission, monitoring of blazars is valuable. The LAT itself will be an excellent monitor, although it cannot make measurements on very short timescales (< 1 hr) and it has a significant response time due to transmission and pipeline analysis. The principal MW challenges for monitoring are the need for long-term and relatively continuous monitoring. Such requirements point to radio, optical, and hard X-ray bands (ASM, Swift) as most promising; few of the other space-based observatories have the wide fields of view or ability to repeat measurements needed for monitoring.

Monitoring programs are most practical for well-established, bright blazars (the opposite of those being identified by the process described in a previous section). Use of smaller telescopes allows more complete coverage. LAT should plan to build on existing programs, working with scientists who have been doing this sort of monitoring while trying to encourage other observers to join.

Two existing programs of particular note are:

The Whole Year Blazar Telescope [WYBT] (http://www.to.astro.it/blazars/webt/news.html#news17). Gino Tosti is an affiliated scientist who works with this group.

GLAST Telescope Network [GTN] (http://www-glast.sonoma.edu/gtn/index.html) is our own effort to coordinate optical observations emphasizing small telescopes, handled through the Education and Public Outreach group at Sonoma State University.

Table 4 summarizes some monitoring resources.

Table 4 – Some Blazar monitoring programs

Measurement	Facility	Possible Contact
Radio monitoring	Metsahovi	
Radio monitoring	Michigan	
Radio monitoring	VLA/VLBA	
Optical monitoring	ESO	
Optical monitoring	WYBT	
Optical monitoring	GTN	
Optical monitoring	Perugia	
Optical monitoring	Crimea	
X-ray monitoring	RXTE	
X-ray monitoring	Swift	
TeV monitoring	VERITAS	
TeV monitoring	Magic	
TeV monitoring	HESS	
TeV monitoring	CANGAROO	

4.2 Coordinated Multiwavelength Campaigns for Blazars

The EGRET experience was that the brightest gamma-ray blazars and those with the biggest flares were not necessarily on the list of blazars that were being monitored at longer wavelengths. There is also no assurance that the blazars seen by EGRET will be the most interesting ones for the LAT. For these reasons, LAT planning should include preparation for MW campaigns in addition to those that arise from optical, radio, and X-ray monitoring programs. In order to accomplish this goal, we need to have observers available at all wavelengths to respond (if possible) to blazars that become interesting due to gamma-ray observations. For ground-based observations, having multiple observers is important due to day/night and weather conditions that can impact potential observations.

One possible approach to organizing such campaigns is to follow the EGRET model and announce blazar targets through IAU Circulars and mailing lists, requesting supporting observations. To some extent, this paradigm is mandated by the requirement that the LAT make public announcements of transients. The MW challenge is not the announcement itself but having a true cross-section of the electromagnetic spectrum represented by observers who can gain quick access to telescope time. The monitoring programs already in existence provide a starting point that we should enlist. We also need additional observers, especially in those areas requiring access to space instrumentation, due to the heave oversubscription of satellite telescope time.

The sort of challenging, coordinated MW campaigns needed to deeply probe the source physics need to be organized before the mission begins and triggered during early operation. Such resource-intensive campaigns can be conducted for only a few of the brightest sources. We envision organizing campaigns on a handful of known flat spectrum radio quasars and BL Lacs. It is likely that a limited number of triggered campaigns tied to major source flares should also be pursued. Again the wide field of view and scanning nature of the LAT program means that other wavebands will limit the scope and duration of the coordinated efforts.

Two existing programs have developed plans for MW campaigns:

The Whole Earth Blazar Telescope [WEBT] (http://www.to.astro.it/blazars/webt/homepage.html). John Mattox is one affiliated scientist who works with this group.

European Network for the Investigation of Galactic Nuclei through Multifrequency Analysis [ENIGMA] (http://www.lsw.uni-heidelberg.de/users/swagner/enigma.html). Stefan Wagner has been a contact with this group.

Another relevant observational feature is that blazars detected by EGRET were often seen in high states before the brightest short flares occurred (although this could be partly a selection effect). As a working hypothesis for MW planning, a high gamma-ray state for a blazar could be a useful trigger for a campaign designed to catch large flares. These ideas are already reflected in the GLAST Transient Policy document developed by members of the Science Working Group.

Coordinated MW campaigns are one of the more difficult challenges facing GLAST LAT. Organizing such campaigns, even informally, is a major effort. Nevertheless, the potential scientific return is extremely high. Two basic approaches are planned:

- Arranged MW campaigns set a time and then organize observers across the spectrum. Because of its large field of view, GLAST LAT can readily participate in almost any campaign of this sort. The primary effort is to make sure that LAT scientists are in close touch with any community that might be planning such a campaign. The facilities are whatever can be arranged by the leaders of the campaign.

- Target of Opportunity campaigns can be based either on LAT results or on monitoring carried out at other wavelengths. The resources that can be brought to bear for this type of campaign depend largely on observers' proposals, weather, location, and time of year (for ground-based observatories). The approach is to announce to a broad community of observers that "something interesting" has happened, then work to coordinate whatever observations can be made. Success is strongly dependent on having a broad geographic and wavelength spectrum of observers lined up in advance to answer such a call. A principal MW effort by the LAT will be to promote cooperation of this type.

Table 5 lists some possible MW campaign resources.

Table 5 Some resources for MW campaigns

Measurement	Facility	Possible Contact
Radio	Metsahovi	
Radio	VLA	
Radio	VLBI	
Radio	Green Bank	
Radio	Parkes	
Radio	Michigan	
Radio	VLBA	
Sub-mm	SEST	
IR	Spitzer	
Optical	ESO/ENIGMA	
Optical	WEBT	
Optical	GTN	
Optical	Perugia	
Optical	Crimea	
X-ray	Chandra	
X-ray	XMM	
X-ray	RXTE	
X-ray	Swift	
X-ray	Astro E2	
X-ray	NuSTAR	

TeV	VERITAS	
TeV	Magic	
TeV	HESS	
TeV	CANGAROO	

4.3 Multiwavelength Exploration of Pulsars

Once a LAT source has been identified as a pulsar, either through direct period search, radio time comparison, or X-ray time comparison, a MW follow-on program will reveal more information about the source. Deep radio, optical and X-ray exposures, with timing, will be needed in order to complement the gamma-ray detection into true MW information about pulsars, both young and millisecond. Although pulsars are known to be rotating neutron stars, there are many aspects of these objects that remain mysteries. Joseph Taylor once noted that we know how pulsars pulse, but we are less confident that we know how pulsars shine. The particle acceleration locations and processes are still subjects of debate, and MW observations can help elucidate these issues.

A key observable of pulsar emission is the light curve. MW observations have shown that pulse profiles are not the same across the spectrum, reflecting a variety of geometric effects and physical processes. Measurements of optical and X-ray light curves are important additions to the radio and gamma-ray data. In optical and X-rays, most pulsars are not bright objects, and so the largest observatories may be required to make the needed measurements: Keck, VLT, and similar optical observatories in the optical, and Chandra and XMM in the X-ray.

The broad-band energy spectrum, and the phase-resolved energy spectrum of a pulsar also reflects the different physics that can be found – coherent emission at radio, thermal at X-ray, and nonthermal magnetospheric emission at high energies. As the ground-based gamma-ray telescopes push their energy thresholds lower, they should complement the LAT observations of the known high-energy cutoffs in pulsar energy spectra.

Recommendation: Plan follow-on proposals for radio, optical, or X-ray telescope time for LAT sources identified as pulsars in order to develop the most complete MW picture possible for these pulsars.

5. Some Issues to Consider

5.1 Availability of Needed Resources

An important aspect of the LAT MW program will be to confirm the interest and availability of the facilities listed here.

Particularly for MW efforts that require quick or extended observations, there appear to be two “choke points” in the planning:

- Far-Infrared. The synchrotron peak of many FSRQ lies in this region, but the only available resource is Spitzer, which is expected to be heavily subscribed and will lose cooling during 2008, early in the GLAST mission.

- X-rays, especially soft X-rays. FSRQ are typically not bright in soft X-rays, requiring focusing telescopes for detection. The major facilities are Chandra and XMM, which may remain largely committed to large-scale programs during the GLAST era. Astro E2 may be helpful, and there may be other small X-ray missions (like NuSTAR and Astro G, which are proposed but not yet funded, and MAXI, which is supposed to be attached to the International Space Station) in the GLAST era. Figure 3 is a summary of some present and future high-energy space missions.

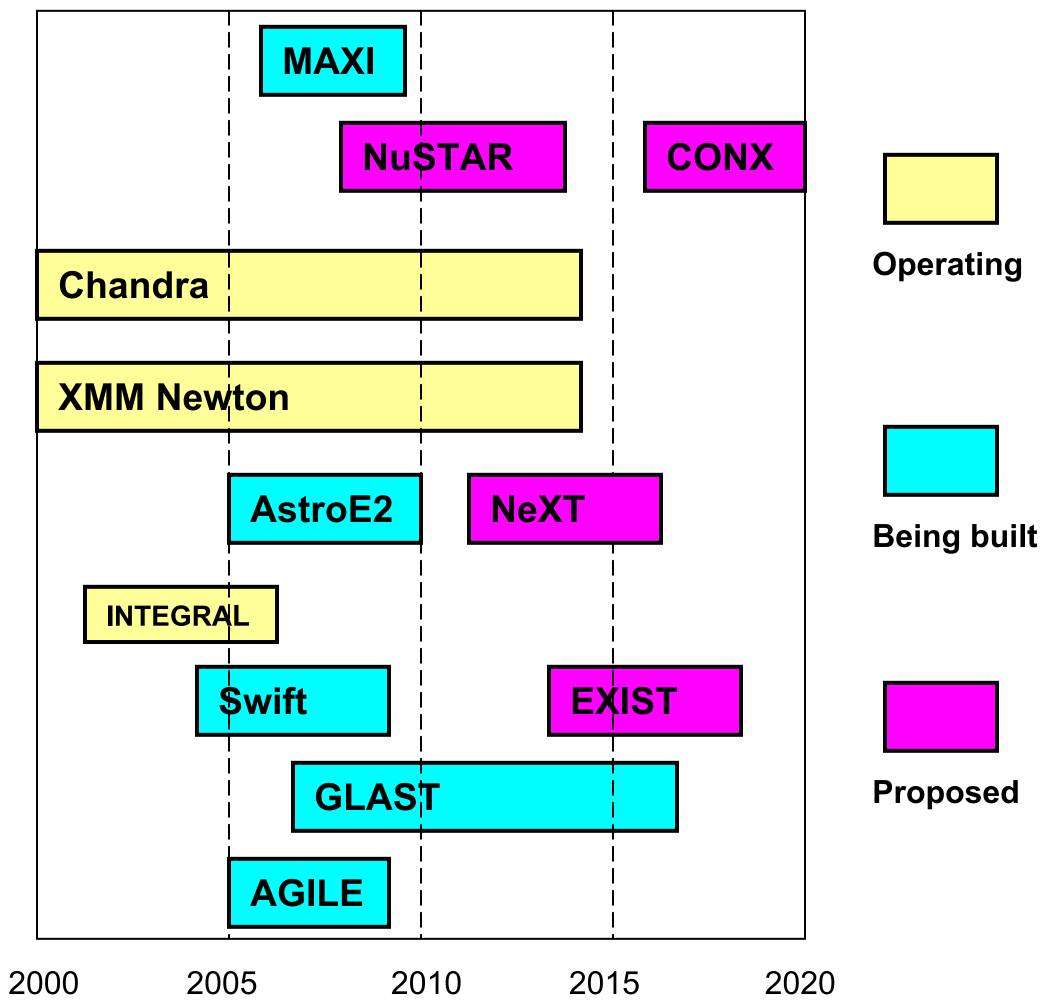

Figure 3 – some present and future high-energy missions.

5.2 Implementation

This committee was deliberately not charged to develop an implementation plan. However, several issues are already apparent:

- How do we maintain the MW effort after the first year, when all the data become public?
- How do we prioritize our MW efforts between the discovery of new classes of faint or transient source and the detailed study of the brightest members of known source classes?
- How do we balance the desire for competitive, peer-reviewed science opportunities with the rights of the existing LAT team?
- How should new, major contributors to the MW campaign be incorporated into the LAT team?
- How do we persuade NASA to invest in a “Legacy” or “Treasury” program that will largely involve the support of MW observations before and during the LAT mission?

Since others have already thought about these issues, what models of MW studies can GLAST LAT learn from? Some examples:

a. XMM Survey Science Center, http://wave.xray.mpe.mpg.de/xmm/ssc.
b. INTEGRAL
c. Swift burst coordination group
d. Organizers of MW campaigns
e. Spitzer Space Telescope legacy program

Appendix A – Establishment of the Ad Hoc Committee

Dear Dave and Roger,

I am writing to ask both of you to be co-chairs of an Ad Hoc Multiwavelength Observation Planning Group for the GLAST LAT Project. The purpose of this planning group is to look broadly at the multiwavelength observational needs required to support maximizing the science we can do with the LAT. There are clearly a wide range of capabilities that would benefit the mission that range from rapid follow-up, contemporaneous observations of transients to redshift determinations of extragalactic GLAST sources. We need to assess what observations we desire from radio to x-ray wavelengths and TeV observations and what facilities might provide these observations.

I envision that this planning group would be relatively small and would produce a short white paper by Feb 1, 2003 (TBR). The white paper would serve as the basis for developing a more detailed implementation plan.

Below is a draft charge. Please suggest changes. I suggest that we have a conference call early next week to discuss how to proceed. Let me know of available times on Monday afternoon or Tuesday morning before 9:30 am (in units of Pacific time). I will be at GSFC on Wednesday and Thursday for the first GLAST User's Committee meeting. We could probably work in a 20-30 minute discussion on those days if necessary.

Regards,
Peter

Draft Charge to Ad Hoc Multiwavelength Observation Planning Group
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(1) Assess the multiwavelength observational needs, both surveys and contemporaneous observations, of the GLAST Large Area Telescope Science Program.

(2) Identify observational facilities (and possible contacts) that could meet the observational needs.

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