86-GHz Blazar Imaging on ARISE-VLBA Baselines
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Abstract

The detection threshold between ARISE and a single VLBA telescope is expected to be ~ 120 mJy at 86 GHz, given nominal mission parameters of a 25-meter orbiting telescope with 8% aperture efficiency and a data rate of 8 Gbit sec^{-1}. This detection threshold corresponds to the inverse Compton limit of $T_b \approx 10^{12}$ K for a baseline length of 50,000 km, and at least 200 sources should be detectable on such a baseline. The number of detectable sources will drop somewhat below 100 for a data rate of 2 Gbit sec^{-1}, or for a typical brightness temperature of 5×10^{11} K. For a baseline length of 100,000 km, the observed brightness temperature would need to be $\geq 4 \times 10^{12}$ K for a detection using a VLBA antenna; very few sources would then be detected on an ARISE-VLBA baseline unless the ARISE aperture efficiency is near 30%. Assuming the successful launch of GLAST in 2005, the nominal ARISE mission, working with the VLBA, will be able to image at least 60 gamma-ray blazars with resolution better than 100 light days, or ~ 200 blazars if a large ground telescope is used to anchor the array.

1 Introduction

A key science goal of the ARISE Space VLBI mission is the imaging of cores of gamma-ray blazars on scales of light months or less. This requires observations of moderate-to-high sensitivity at 43 and 86 GHz. In particular, it is desirable to be able to choose from a set of at least 100 detectable sources at 86 GHz. This memo addresses the resulting requirements on the mission sensitivity and the capability for detecting the desired number of sources.

2 Nominal ARISE sensitivity

The overall sensitivity of a radio telescope can be characterized by the "System Equivalent Flux Density" (SEFD) in Jy, where

$$\mathrm{SEFD} = 2.76 \times 10^3 \, T_{\rm sys}/A_e \ . \qquad (1)$$

Here, $T_{\rm sys}$ is the system temperature in Kelvin and A_e is the effective area of the antenna in square meters. The r.m.s. noise on the interferometer baseline between ARISE (telescope "A") and ground radio telescope "g" is then denoted by

$$\sigma_{Ag} = \frac{1}{\eta} \sqrt{\frac{\mathrm{SEFD}_A\ \mathrm{SEFD}_g}{2\Delta\nu\ \tau}}\ . \qquad (2)$$

Here, η is an efficiency factor due to sampling and correlation, $\Delta\nu$ is the observing bandwidth, and τ is the integration time. A typical fringe-detection threshold is $S_{\rm min} \approx 7\sigma_{Ag}$.

We assume a fixed data rate of 8 Gbit sec^{-1} for ARISE. Nominal values for 2-bit sampling at 86 GHz are $\eta = 0.88$, $\Delta\nu = 2$ GHz, and $\tau = 15$ sec. (The sensitivity for 1-bit sampling differs by only 2% from 2-bit sampling, under the assumption of a fixed data rate.) Current baseline values for the 25-meter ARISE telescope are an aperture efficiency of only 8% and a system temperature of 45 K, corresponding to $\mathrm{SEFD}_A = 3200$ Jy. For a 25-meter VLBA telescope, conservative estimates are an aperture efficiency of 0.20 and a system temperature of 150 K, giving $\mathrm{SEFD}_g = 4200$ Jy. (VLBA performance is likely to be somewhat better by 2008, particularly in the aperture efficiency.) If we assume 2-bit sampling and convert the bandwidth $\Delta\nu$ to the data rate DR, the detection threshold is given by

$$S_{\rm min}\ \approx\ 120\ \mathrm{mJy}\ \sqrt{\frac{(\mathrm{SEFD}_A/3200\ \mathrm{Jy})\ (\mathrm{SEFD}_g/4200\ \mathrm{Jy})}{(\mathrm{DR}/8\ \mathrm{Gbit\ sec}^{-1})\ (\tau/15\ \mathrm{sec})}}\ . \qquad (3)$$

3 Source Counts

A compilation of 86-GHz flux densities for sources at declinations north of $\sim -30°$ can be found in the home page of the Owens Valley Radio Observatory Millimeter Array (OVRO 1999), while measured 86-GHz flux densities south of $-40°$ are given by Beasley et al. (1997). The source counts for these areas, covering 92.8% of the sky, are given in Table 1, as are extrapolations over the entire sky. These source counts are conservative, since they certainly are incomplete. For instance, if the estimate of 67 sources down to 1.5 Jy is assumed to be complete, the standard relation $N(S > S_0) \propto {S_0}^{-1.5}$ can be used to predict the numbers of sources throughout the sky that are above lower limiting flux densities. The prediction is that there should be 123 sources stronger than 1.0 Jy, and 356 sources stronger than 0.5 Jy. Table 1 indicates that the counts may be complete to 1.0 Jy, but that more than 130 sources are missing between 0.5 and 1.0 Jy. Most of the known (and missing) sources are blazars, and 83% of the gamma-ray-detected EGRET blazars (Mattox et al. 1997) are included in the lists cited above.

Lister, Marscher, & Gear (1998) have imaged eight blazars at 43 GHz using the VLBA. They find peak flux densities ranging from 51% to 85% of the total flux densities for these objects, which were not selected to be more compact than "typical" blazars (Marscher, private communication). Since the radio cores are expected to be more prominent relative to the resolved flux at 86 GHz, we conservatively assume that most of the strong 86-GHz

Table 1. Incomplete 86-GHz Source Counts					
Flux (Jy)	$\delta > -30°$	$\delta < -40°$	Total	All-Sky	All-Sky Cumulative
> 10	4	0	4	4	4
5–10	5	0	5	5	10
4–5	4	2	6	7	16
3–4	6	2	8	9	25
2–3	10	1	11	12	37
1.9	3	0	3	3	40
1.8	4	0	4	4	44
1.7	2	1	3	3	47
1.6	6	2	8	9	56
1.5	8	2	10	11	67
1.4	2	2	4	4	71
1.3	2	1	3	3	74
1.2	11	2	13	14	88
1.1	9	4	13	14	102
1.0	19	3	22	24	126
0.9	6	1	7	8	134
0.8	21	4	25	27	161
0.7	18	2	20	22	182
0.6	22	5	27	29	211
0.5	4	5	9	10	221

sources will have correlated flux densities on long Earth baselines of at least 50% of their total flux densities.[1]

There is no well-determined method of extrapolating to the correlated flux densities that will be seen on baselines to ARISE, so some assumption must be made about the distribution of brightness temperatures. Here, we make the simple (but arbitrary) assumption that the 86-GHz correlated flux densities on 50,000-km ARISE baselines will be $\sim$ 20% of the total flux densities (i.e., $S_{\rm corr} \approx 0.2 S_{\rm tot}$). This actually corresponds to an assumption that the typical *observed* core brightness temperature is $\sim 1 \times 10^{12}$ K (Murphy 1998).[2] Table 2 contains the resulting estimate of the cumulative source counts as a function of 86-GHz correlated flux density on 50,000-km ARISE baselines, and also

[1]Sources that are optically thick at 43 GHz will have higher proportions of their total flux in an unresolved core at 86 GHz, while those that are optically thin at 43 GHz should have about the same fraction in the core at 86 GHz as at 43 GHz.

[2]Note that observed brightness temperatures are reduced by a factor of $(1+z)$ from the brightness temperatures in the source co-moving frames; at a typical blazar redshift of $z = 1$, the brightness temperature at the source redshift would need to be 2×10^{12} K in order to yield an observed value of 10^{12} K.

includes a similar estimate for the case in which $S_{\rm corr} \approx 0.1 S_{\rm tot}$; the latter case corresponds to a typical observed source brightness temperature of 5×10^{11} K. No correction for incompleteness has been made in this table.

Table 2. Cumulative All-Sky Counts of ARISE Correlated Fluxes at 86 GHz

Minimum Correlated Flux (mJy)	$S_{\rm corr} = 0.2 S_{\rm tot}$ $T_b(\rm obs) \approx 10^{12}$ K	$S_{\rm corr} = 0.1 S_{\rm tot}$ $T_b(\rm obs) \approx 5 \times 10^{11}$ K
2000	4	1
1000	10	4
800	16	5
600	25	7
400	37	16
380	40	17
360	44	18
340	47	20
320	56	21
300	67	25
280	71	26
260	74	26
240	88	29
220	102	32
200	126	37
180	134	44
160	161	56
140	182	71
120	211	88
100	221	126

4 Detectable Sources for ARISE

We assume that a ground telescope with a sensitivity comparable to that of a VLBA antenna (such as an element of the Australia Telescope) will be used in the Southern Hemisphere. Then, Table 2 shows that the total number of detectable sources is near 210 if a typical observed brightness temperature of 1×10^{12} K is assumed, or about 90 for an observed brightness temperature near 5×10^{11} K. A correction for incompleteness would raise the number of sources to more than 300 if $T_b(\rm obs) \approx 1 \times 10^{12}$ K, but would have little effect if $T_b(\rm obs) \approx 5 \times 10^{11}$ K. Table 3 summarizes the number of detectable sources as a function of data rate, given that all other parameters remain fixed, for the two different values of the observed brightness temperature. (No incompleteness correction has been made.) This table indicates that the number of detectable sources is reduced below the desirable threshold of 100 for a data rate less than 4 Gbit $\sec^{-1}$. In addition, the reduction in detectable sources is dramatic if the observed brightness temperatures are significantly lower than 10^{12} K, so the data-rate requirement depends critically on the assumed brightness temperature distribution. It might be possible to gain back a factor of 1.5–2 by using global fringe-fitting with the VLBA, but this improvement is not assumed because of the lack of experience at 86 GHz. Other options for recovery of a larger number of sources are discussed below.

Table 3. Detectable 86-GHz Sources for ARISE-VLBA Baseline

Data Rate (Gbit $\sec^{-1}$)	Detection Threshold (mJy)	Number	
		$T_b(\mathrm{obs}) \approx 1 \times 10^{12}$ K	$T_b(\mathrm{obs}) \approx 5 \times 10^{11}$ K
8	120 mJy	211	88
4	170 mJy	147	50
2	240 mJy	88	29
1	340 mJy	47	20

4.1 Extended Integration Time

It may be feasible to extend the effective coherent integration time by using phase-referencing of the ground telescopes, in order to calibrate out the effects of the atmosphere. If the ARISE orbit error is 10 cm, and it de-correlates over a 13-hr orbit, the effective acceleration error of $\sim 4.6 \times 10^{-9}$ cm $\sec^{-2}$ would accumulate to 18° (0.3 radians) in ~ 2700 sec. Ground-telescope phase-referencing with an on-source duty cycle of only 30% would then increase τ to 800 sec, and the fringe-detection threshold might be reduced by a factor of ~ 7. However, this would require changing sources on a time scale of a few seconds, which will be very difficult (or impossible) for the ground telescopes.

4.2 More Sensitive Ground Telescopes

If a lower data rate were used, the number of detectable sources could be increased substantially by using a large ground telescope as an anchor. For instance, the Green Bank Telescope (GBT) is expected to have an SEFD of ~ 200 Jy, compared to the value of 4200 Jy assumed for a VLBA telescope. Use of the GBT thus would reduce the detection threshold by a factor of ~ 4.6. In the Southern Hemisphere and near the equator, the more sensitive phased Millimeter Array could be used. Table 4 illustrates the potential number of sources that could be detected, given a telescope with GBT sensitivity in the Northern and Southern Hemispheres. Since the telescopes mentioned here will not be dedicated to VLBI, they probably will not be available for a large fraction of their time with ARISE.

Instead, they would more likely be used for occasional highly rated observations of weak sources at 86 GHz.

Table 4. Detectable 86-GHz Sources using GBT Baseline Assumed $T_b(\mathrm{obs}) = 1 \times 10^{12}$ K		
Data Rate (Gbit sec^{-1})	Detection Threshold	Number
8	26 mJy	> 1000
4	37 mJy	> 1000
2	52 mJy	> 500
1	74 mJy	> 300

4.3 Impact of a Smaller ARISE Antenna

There occasionally has been discussion of building a space telescope for ARISE that has a solid central surface that operates at 86 GHz, with the outer sections working only at lower frequencies. If such an antenna were built, and a 3-meter central portion had an aperture efficiency of 0.5, its SEFD at 86 GHz would be $\sim 35,000$ Jy, a factor of 11 worse than the nominal value. The number of detectable sources is given in Table 5. This table shows that such a small antenna would be inadequate at any feasible data rate for a baseline to a VLBA antenna, but might be able to observe a satisfactory number of sources if large amounts of time on the GBT were available. Of course, imaging would be very difficult with such a large disparity between the sensitivities of the space telescope and the ground telescopes, so the actual situation is probably worse than that depicted in Table 5.

Table 5. Sources for 3-meter ARISE Telescope Assumed $T_b(\mathrm{obs}) = 1 \times 10^{12}$ K				
Data Rate	VLBA Antenna		GBT	
(Gbit sec^{-1})	Threshold	Number	Threshold	Number
8	400 mJy	37	87 mJy	~ 250
4	570 mJy	26	124 mJy	210
2	800 mJy	16	175 mJy	140
1	1130 mJy	8	247 mJy	83

5 Brightness-Temperature Threshold

Murphy (1998) has found a detection threshold of $T_b(\mathrm{obs}) \approx 6 \times 10^{11}$ K for ARISE on a 40,000-km baseline to a VLBA telescope, or 1×10^{12} K on a 50,000-km baseline, given an

8-Gbit $\sec^{-1}$ data rate and telescope sensitivities similar to those quoted in this document. For a 100,000-km baseline, the observed threshold rises to 4×10^{12} K, corresponding to $T_b(z = 1) \approx 8 \times 10^{12}$ K. If a large telescope such as the GBT were used to anchor the ground array, the observed limits would be reduced to 1×10^{11} K for a 40,000-km baseline, or 8×10^{11} K for a 100,000-km baseline.

Given these brightness temperatures, the assumptions made in Section 3 can be summarized in a useful way. The estimate of $\sim$ 210 detectable sources for ARISE above a threshold of 120 mJy (Table 2) assumed that those sources have cores with observed 86-GHz brightness temperatures above the T_b threshold. Since blazars are beamed toward the observer, the brightness temperatures are expected to be near or above the inverse Compton limit in most cases. Thus, in general, we can expect $T_b(\text{obs}) \geq 10^{12}$ K, as found in the TDRSS experiments (Linfield et al. 1989). Most of the 210 sources above 600 mJy in total 86-GHz flux will then be detectable by ARISE on baselines up to $\sim 50,000$ km (cf. Murphy 1998 for the brightness temperature calculations). However, on baselines near 100,000 km, the detection requirement of $T_b(\text{obs}) \approx 4 \times 10^{12}$ K would be higher than the highest brightness temperature observed with centimeter-wavelength Space VLBI, with either TDRSS (Linfield et al. 1989) or VSOP (Preston et al. 1999). Therefore, the evidence is that very few sources would be detectable at 86 GHz on a 100,000-km ARISE baseline, but that a maximum ARISE orbit altitude of 40,000 km (and corresponding maximum baseline length of 50,000 km) is fairly well-matched to the properties of blazars.

Table 6. Required Aperture Efficiency for Threshold of $T_b(\text{obs}) = 1 \times 10^{12}$ K

Baseline Length (km)	Aperture Efficiency
50,000	0.08
60,000	0.12
70,000	0.16
80,000	0.20
90,000	0.26
100,000	0.32

If it is desired to fly ARISE at an apogee altitude of 100,000 km, observations of a large number of blazars would require a sensitivity increase of a factor of 4 to achieve a detection threshold of $T_b(\text{obs}) = 1 \times 10^{12}$ K at 86 GHz. This would mean that a 25-meter ARISE antenna must have a total aperture efficiency greater than 30% at 86 GHz, rather than the low efficiency of 8% that is currently assumed. Table 6 gives the aperture efficiency that would be required (assuming 8 Gbit $\sec^{-1}$ and $T_{\text{sys}} = 45$ K) in order to achieve a brightness temperature detection threshold of 10^{12} K on baselines ranging from 50,000 to 100,000 km.

6 Linear Resolution

The linear resolution for a 50,000-km baseline can be computed for the class of gamma-ray blazars detected by the EGRET instrument. If we assume $H_0 = 65$ km sec^{-1} Mpc^{-1} and $q_0 = 0.1$, then the ARISE resolution for most of the blazars listed by Mattox et al. (1997) will be between 100 and 200 light days; 8 of the 38 objects with measured redshifts would have resolution better than 100 light days. The left-hand panel of Figure 1 shows the linear resolution available for each of these EGRET blazars.

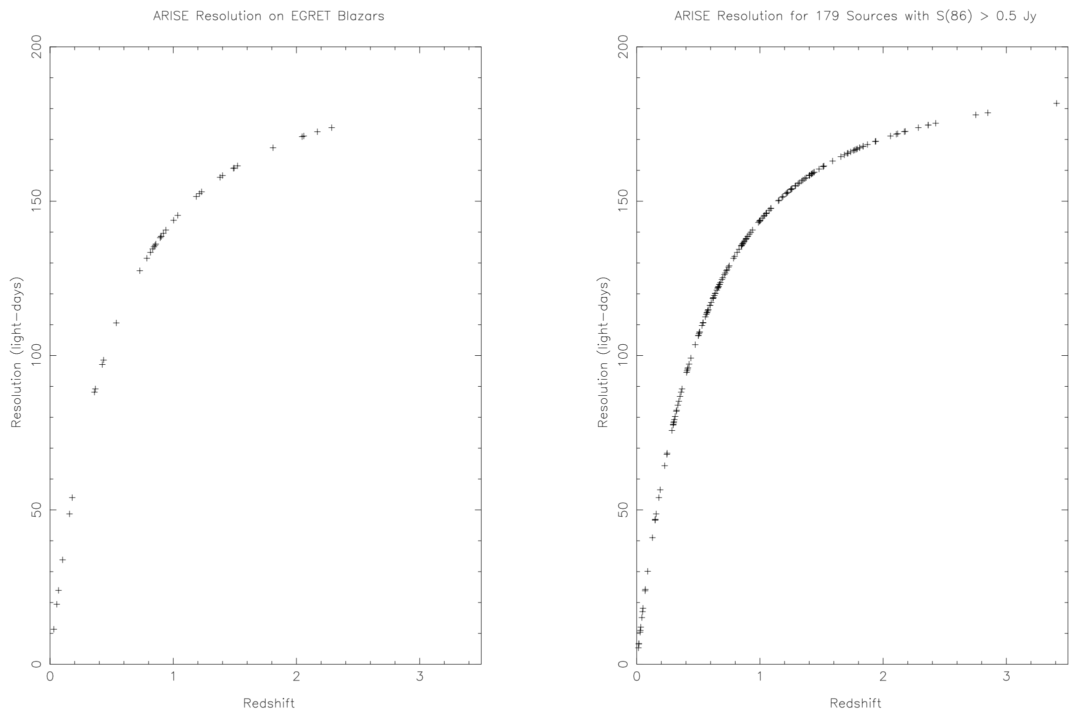

Figure 1: Redshift and linear resolution of ARISE at 86 GHz, assuming a baseline length of 50,000 km. *Left:* The 38 EGRET blazars listed by Mattox et al. (1997) that have known redshifts. *Right:* The 179 compact sources, from the OVRO calibrator list (1999) and Beasley et al. (1997), which have $S(86\ \mathrm{GHz}) \geq 0.5$ Jy and measured redshifts. Almost all these sources will be detected by GLAST.

Finally, we note that the GLAST mission will have a gamma-ray sensitivity 30 times better than EGRET. Assuming $N(S > S_0) \propto {S_0}^{-1.5}$, GLAST should detect more than 6000 active galactic nuclei (AGNs) in gamma rays, 150 times more than seen by EGRET. This should include all the AGNs that are strong at 86 GHz, and many more. The right-hand panel of Figure 1 shows the linear resolution available for the 179 sources from Beasley et al. (1997) and the OVRO calibrator list (1999) that have 86-GHz flux densities of 0.5 Jy or greater and measured redshifts.[3] Figure 2 is a histogram of the available resolution, in intervals of 10 light days. This figure shows that about 41 of the 179 sources can be observed with a resolution better than 100 light days on a 50,000-km baseline, with 16 sources having resolution better than 50 light days, and about 10 better than 20 light days. If we correct for incompleteness in these catalogs and the associated estimates, all the numbers of sources should be increased by at least 50%, to about 60 detectable objects with resolution better than 100 light days and 15 such objects with resolution better than 20 light days.

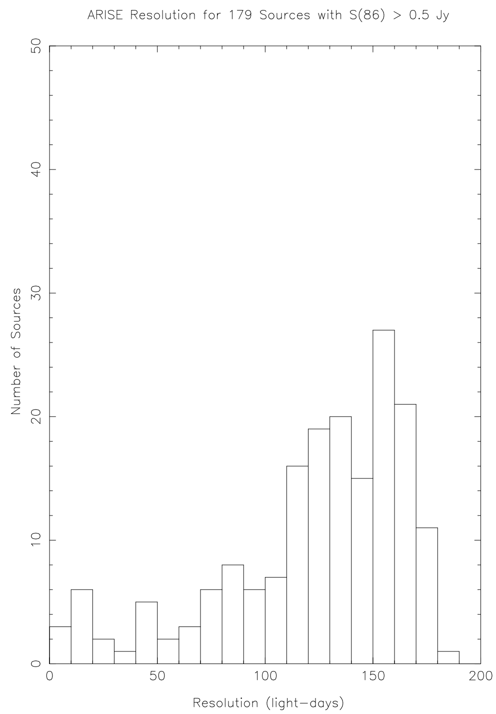

Figure 2: Histogram of linear resolution available for ARISE at 86 GHz, assuming a baseline length of 50,000 km. The (incomplete) source sample includes the 179 compact sources from the OVRO calibrator list (1999) and Beasley et al. (1997) which have $S(86\ \text{GHz}) \geq 0.5$ Jy and measured redshifts.

[3] Note that this list contains several gravitationally lensed sources; no attempt has been made to account for the fact that lensing permits better intrinsic resolution in those objects.

Acknowledgments

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