MeerKAT Large Survey Programs

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1. Introduction

Breakthrough Listen's observing campaign with MeerKAT telescope is commensal - while the primary science large survey programs (LSPs) are observing, BL will be able to form their own small "pencil" beams to observe any objects that fall within the primary science beam. Thus, our target list must be derived, to the greatest extent possible, from the anticipated pointings of each of the primary LSPs. The LSP target lists themselves aren't completely finalized for all LSPs, so in some cases conservative estimates needed to be made. The following table outlines all LSPs that I considered in development of the target list, with detailed notes about how each program was addressed. For each program, targets in the list were drawn from the subset of all Gaia DR2 objects that meet our quality filters (see appendix), a subset of 32 million objects from the 1.7 billion in Gaia DR2. Additionally, I added nearby stars that are too bright for Gaia, or otherwise absent from the catalog. Finally, there is a "volume complete" sample of all high-quality Gaia objects within 160 pc, to accomodate unanticipated pointings.

Project	Goal	Number of pointings	time per pointing	Total Time (hrs)	N objects in 32M sample	Frequency (GHz)	Comments
MHONGOOSE	30 galaxies	30	55 hrs	1650	5636	1.4	Pointings: https://mhongoose.astron.nl/sample.html
LADUMA	Single deep obs	1	3424 hrs	3424	166 1597[1]	1.4	Pointing: 03:32:30.4, -28:07:57[2] http://www.laduma.uct.ac.za/
Fornax	Deep survey of Fornax galaxy cluster	91	~10 hr each*	900	16,240	1.4	Specific pointings detailed in paper[3], but don't have RA/Dec's yet; Total area is 11.8 deg[2]
MeerTime MSP	100 millisecond pulsars	100	0.5 hrs once per month each	2160	34,430[4] 26,527[5]	1.4	100 of the brightest millisecond pulsars including PPTA[6] and Nanograv MSPs[7]
MeerTime Binary	Binary pulsars not in globular clusters	17*	0.5 hrs once per month each	1440	8,790	1.4	High v/c pulsars w Dec < 0, PB < 1 day and MinMass $> 0.3\ M_\odot$[2]
MeerTime 1000 PTA	Timing 1000 pulsars isotropically distributed	1000	5-10 min obs 1 per month each	720	521,205[8] 1,016,495[9]	1.4	~1000 brightest flux in ATNF cat
MeerTime Globular Clusters	GC's with known pulsars	30*	1-2* hrs per month	1080	41,611	1.4	All GC's with known pulsars
TRAPUM Globular Clusters	GCs both with and without known pulsars	30 + 5[10,*]	4hr each obs x 2 obs each	320	9,719	1.4	Will overlap and share data with MeerTime GC. This info reflects GCs not observed with MeerTime (GCs without confirmed pulsars)
TRAPUM Fermi Sources	Identifying new pulsars from Fermi detections	~100-200[11]	0.5 hrs each	338	87,379	1.4	Targets generated from list of 260 objects in Fermi-LAT catalog with low variability, 2 deg out of gal plane, & unassoc
TRAPUM Nearby Galaxies	Obs of nearby galaxies	3*	~10-20* hrs	226	33,844	1.4	M33, SMC, LMC multiple pointings in each
MIGHTEE L- and S-band	Deep obs of well studied ex-gal fields	24+20+7+1 (L-band) 24+7+1 (S-Band)	16 hrs (L-band) 12.7 hrs (S-band)	979 (L-band) 948 (S-band)	14,545	1.4 (L-band) 2-4 (S-band)	L-band fields: E-CDFS, XMM-LSS,ELAIS-S1, COSMOS S-Band fields: E-CDFS, ELAIS-S1, COSMOS
Volume Complete	Accomodate any unknown pointing	N/A	N/A	N/A	658,215 [12]	Any	Every Gaia high quality source within 160 pc
Not in Gaia					57		Sources in Isaacson et al. (2017) target list with no Gaia id
				Total:	1,187,641		

*Unconfirmed. Number represents the number of pointings contributing to the target list ('N objects' column value)

[1]Total targets in Gaia catalog in pointing, no quality cut

[2]Private communication

[3]https://arxiv.org/pdf/1709.01289.pdf

[4]From pointings that will for sure be observed

[5]From the 55 MSPs in ATNF catalog in MeerKAT FOV which could potentially be observed

[6]Reardon et. al. 2016

[7]nanograv.org/data/ ; Nanograv sources timed by GBT and Parkes+Aricebo

[8] From 1000 brightest PSR in ATNF catalog (in any band) not already on other PSR obs lists.

[9]Drawn from all 1742 pulsars in the ATNF catalog with flux values and not observed with MSP or Binary or GC program, which represents possible targets for this program

[10]30 GCs in MeerTime (not duplicated in count) plus 5 new GCs (included in count

[11]100-200 will be chosen. But 809 meet the criteria for possible target.

[12]Overlaps with LSP objects have been removed from this number already

2. Notes

- LADUMA: single poinging coordinate from PI Sarah Blythe
- MeerTime MSPs: Targets aren't finalized. Convo with Scott Ransom: Parkes Pulsar Timing Array (PPTA) and Nanograv targets will certainly be timed. Also MSPs in the ATNF catalog with decl below -35 deg, because they were discovered by Parkes and haven't been timed before. So these make up the initial set of targets that are pretty certain to be timed with MeerKAT. The second set are the brightest MSPs in the ATNF catalog, and represent possible MeerTime MSP pointings.
- MeerTime Binaries: Selected all PSRs in ATNF catalog with PB$<$1 day, Minmass $>$ 0.3 $M_{\odot}$, per email with Matthew Bailes, but removed any that are associated with globular clusters, because they will be observed in MeerTime GC.
- MeerTime 1000 PTA: Per convo with Matthew Bailes, they expect to time 1000 brightest pulsars in the ATNF cataog. The N objects numbers are Gaia sources within the beam of pointing at all ATNF PSRs with a flux measurement in any band, not already on the MSP or Binary or GC list. That is 1742 objects, more than 1000, but it represents the list of objects which could be targeted with MeerTime 1000 PTA. That gave 1M Gaia targets on its own. So I restricted it to just the 100 brightest (in any flux band; I limited any of the flux values to $>$1.5, which gave 1071 objects) and that gave 312,000 Gaia targets.
- MeerTime Globular Cluster: Taken from all of the globular clusters with known pulsars, found in this reference: http://www.naic.edu/~pfreire/GC_plots/pulsars_in_GC_150.pdf. I also expanded the search radius around each to angular diameter of 1.5 deg (from 0.8 default) to accommodate dithering within the cluster.
- Fornax objects are based on all Gaia objects within a box around the Fornax cluster. The paper (https://arxiv.org/pdf/1709.01289.pdf) shows specific pointings, which make an irregular shape, but does not give RA/DEC. I obtained an RA/Dec list from the PI Paolo Serra . But to be conservative and avoid a lot of overlaps, I retrieved all objects within a box that fully encompassed all of the pointings. The box centered at 03:38:29.083, -35:27:02.67 and extends RA-5,RA+3 and Dec-3,Dec+2.
- TRAPUM Globular Clusters: They will overlap and share data with MeerTime GC. Major difference is they will look at GC's for which no pulsars are known, but which they must be there (ref: private communication with Scott Ransom). Specifically Lillar 1, NGC 6388, Omega Cen, 2MASS-GC01, 2MASS-GC02. These are the only GC's that make up the pointings used in this table entry.
  PI Ben Stappers
- TRAPUM Fermi Sources: Per Scott Ransom, they will observe Fermi sources from this catalog: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/3FGL-table/#ExportTableData that are "unassociated" and more than 2 degrees out of the galactic plane. 809 sources from Fermi LAT catalog meet criteria, although Scott says ultimately 100-200 will be chosen. So to narrow it further, Scott suggested that the most pulsar-like objects have low variability index, below about 40 (according to his plot). So I applied that filter and it generated 260 objects. That is the

list the target list targets are pulled from. Rene Breton is source lead but was on vacation and unable to respond to inquiries at time of writing.

- TRAPUM Nearby Galaxies: Scott Ransom says LMC, SMC, and M33 will definitely be observed in this program. I used the most conservative (largest) reference value for the angular extent of each of them (which was found in NED) and retrieved every target within that radius.

- TRAPUM Fly's Eye: A large-sky observing mode with each dish on a separate pointing at 0.8 deg beam diameter x 64 dishes = 51.2 deg^2 fov. Covered by volume complete sample.

- MeerTrap: Trapum's commensal transient search. No new targets for that.

- MIGHTEE L/S band: Outlined in detail here https://arxiv.org/pdf/1709.01901.pdf. They will cover the E CDFS (With one pointing overlapping with LADUMA at a shallower depth, forming a "wedding cake" strategy) (24 pointings), XMM-LSS (20 pointings) (Not observed in S-band), ELAIS-S1 (7 pointings), and COSMOS (1 deep pointing). 16 hr per pointing L-band, 12.7 hrs per pointing S-band. Pointings are specified in the paper, but as they overlap significantly, and their exact RA/Dec isn't given, I drew targets from a box around the cluster of pointings. All fields will be observed in both bands (except XMM-LSS), so I only drew targets once to cover both programs. The paper states there will be one pointing in the COSMOS field, however I couldn't determine the exact RA/Dec of the pointing. The COSMOS field website gives RA/Dec of the center, and states that it covers a 2 sq deg area. So I took targets within a 2 sq degree circle centered at that point.

- ThunderKAT: It appears all pre-planned targets have been dropped, and ThunderKAT will only operate to follow up on transient events. This means the pointing can't be predicted. So it will be covered with the volume-complete sample.

- Volume complete: ~30% of MeerKAT time is discretionary, so the pointing can't be predicted in advance. So I have added a "volume complete" sample list of all Gaia targets in our quality cut sample out to a specific distance, with overlaps with other pointings removed. Covers any unanticipated pointings or pointings left off of other lists. Includes all objects within 160 pc, including stars too bright to be in Gaia (taken from the 5 pc volume complete list of Isaacson et al. (2017)).

- Not in Gaia: All of the targets in the Isaacson et al. (2017) target list that don't have corresponding Gaia source ids. This could be for many reasons, such as being too bright (Gaia only measured >mag 3). All of these are on other catalogs like Hipparcos and GJ; many are the nearest stars to us. Thus if one of them happens to fall within a beam, it would be nice to know it and be able to observe them. All entries in the table for these sources come from the values in Isaacson et al. (2017), and not from Gaia measurements. 'G mag' entries for these are therefore actually V mags. I did update the reference epoch to J2015.5 from J2000 to match Gaia.

- Total: Sum of all Gaia high-quality targets on the target list, with overlapping duplicated sources removed (thus the numbers in the N objects column won't necessarily add up to the total, because some might overlap. However, the N objects number for the volume complete list does have duplicates removed)

A. Gaia DR high data quality filters

I applied the following filters to Gaia DR2 catalog to create a subset of ~32 million objects as the starting point for developing the target list. These filters are adapted from Gaia Collaboration et al. (2018).

`parallax_over_error` > 20
`phot_g_mean_flux_over_error` > 50
`phot_rp_mean_flux_over_error` > 20
`phot_bp_mean_flux_over_error` > 20
`phot_bp_rp_excess_factor` $> 1.3 + 0.06\times($`phot_bp_mean_mag -phot_rp_mean_mag`$)^2$
`phot_bp_rp_excess_factor` $> 1.0 + 0.015\times($`phot_bp_mean_mag -phot_rp_mean_mag`$)^2$
`visibility_periods_used` ≥ 8
`astrometric_chi2_al / astrometric_n_good_obs_al-5` $< 1.44 * greatest(1, exp(-0.4 *$ (`phot_g_mean_mag` $- 19.5)))$

REFERENCES

Gaia Collaboration et al. 2018, ArXiv e-prints, arXiv:1804.09378

Isaacson, H., et al. 2017, Publications of the Astronomical Society of the Pacific, 129, 054501

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