Goal #1: Scientific Knowledge

Advance new knowledge and discoveries at the frontiers of sciences while achieving increased sensitivity to gravitational waves (GWs)

	Year 1	Year 2	Year 3	Year 4	Year 5
Gravitational Wave Detection	Create structure for the analysis pipe-lines. Develop the software repository for analysis codes. Check first versions of the burst, continuous wave and stochastic pipe-lines into the repository. Hold weekly meeting of the GW Detection group. Develop group milestones for the remaining five years. Publish paper on the overlap reduction function in alternative theories of gravity.	Test all pipe-lines with simulated data and implement and compare multiple detection statistics. Have students trained on running the pipe-lines. Investigate optimal observing strategies for different sources classes. Paper on nearly-optimal techniques for continuous wave analysis. Implement the empirical noise model(s) in the analysis pipe-lines.	Run the pipe-lines on actual NANOGrav data. Are we doing the best we can with the data we have? (eg, comparison between Rutger analysis and our analysis). Publish findings on optimal observing strategies. Based on optimal observing strategies investigation, where should we search for pulsars, and how many?	Interpret results of 1713 campaign and its implications on GW detectability and fold implications into the pipelines.	
		Analyze residual spectra of all NANOGrav data and develop an empirical noise model(s). Use time-domain analyses strategies as well. Develop strategies based on what we know about noise already.	Noise analysis on each pulsar - what are its constituent parts? How can we improve sensitivity on that pulsar?	Development of a full signal+noise model for timing data sets that take into account intrinsic neutron star effects, interstellar medium effects, and instrumental effects	
	Review sources of noise that effect pulsar timing. Publish paper on findings. Publish paper on coalescence rate constraints on supermassive black hole binaries		Publish paper with a detailed study of the cosmic (super)string stochastic background signal in PTAs.	Incorporation of pulsar-specific noise models into simulations and predictions for detection of stochastic backgrounds, CW/chirped GWs and bursts.	
				Identify specific mitigation strategies to implement.	Implement mitigation strategies.
				Run SGWB analysis on most current NANOGrav dataset and submit paper including interpretation of bound on SMBBHBs.[i]	Publish results of running the SBGW pipeline on latest NANOGrav data.
				Run CW pipeline on most current NANOGrav dataset and submit paper.	Publish results of running the CW pipelines on latest NANOGrav data.
				Run BWM pipeline on most current NANOGrav data set and submit paper.	Publish results of running the BWM pipeline on latest NANOGrav data.

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				IPTA Analyses: Complete CW and BWM analyses on IPTA data sets.[ii]	
				In-depth study of BW detectability.	
				Modified F- statistic paper, integrate this into pipelines.	
		Hold first mock data challenge. Create the host website and a simple data set containing white noise with a stochastic background.		Study the benefits of combined EM/GW observations.	Publish multi-messenger astronomy (EM coincidence) paper. Publish QCD phase transition work paper.
				Develop generic burst search.	Publish results of running the generic burst search pipeline on the latest NANOGrav data.
Searching	Complete quick pass of Green Bank Northern Celestial Cap (GBNCC) data containing unidentified Fermi sources.	Process 30% of GBNCC data.	Process 60% of GBNCC data.	Continue GBNCC survey.	Complete GBNCC survey.
	Continue processing of GBT drift survey	Complete processing of GBT drift survey.	Complete processing of GBT drift survey.	Finish 3rd survey paper which announces recent discoveries.[iii]	Begin L-band focal plane array survey with GBT
			Establish list of Galactic millisecond pulsars from surveys	Enhance above list to include pulse profile data.	
Timing	Publish first NANOGrav gravitational wave background limit/detection paper and associated sanctioned data release	Second sanctioned data release.	Publish second NANOGrav gravitational wave background limit/detection paper and associated sanctioned data release.[iv]	Publish paper describing second data release.[v]	Third sanctioned data release.
	Make anyone-can-use-it (ie, well-documented) timing pipelines.	Add Mueller matrices to standard pipelines.		Publish individual-pulsar astrophysics papers based on second data release.	
		Improve post-facto RFI excision.[vi]			
	Investigate broadband timing code possibilities. (and TO)	Develop broadband timing code (incorporating profile evolution). (and TO). Investigate broadband timing code possibilities. (and TO)	Ensure broad-band timing code is implemented (and TO).		

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	Begin to develop automated system for calculating TOAs at each observation (and CY).	Finish developing automated system for calculating TOAs at each observation (and CY). Begin to develop automated system for calculating TOAs at each observation (and CY).[vii]			
	Ramp-up operation of Green Bank and Arecibo Ultimate Pulsar Processors (GUPPI/PUPPI) (robust pipeline, integration with control system at Arecibo etc.).	Ramp-up operation of Green Bank and Arecibo Ultimate Pulsar Processors (GUPPI/PUPPI)	Develop next generation of timing instruments.		
		Integration of PUPPI with control systems at Arecibo			
		Ramp-down operation of ASP/GASP.			
	Begin to analyze Wideband Arecibo Pulsar Processor (WAPP) data collected over past five years parallel to ASP.	Finish analyzing Wideband Arecibo Pulsar Processor (WAPP)data collected over past five years parallel to ASP			
	Begin to analyze historic Mark IV and ABPP data to lengthen timespan of observations.	Continue analyzing historic Mark IV and ABPP data to lengthen timespan of observations, adding to ASP timing. Begin to analyze historic Mark IV and ABPP data to lengthen timespan of observations, adding to ASP timing.			
Cyber-Infrastructure	Develop mechanisms to ensure that all desired data products and information are included in the database.	Ensure that all desired data products and information are routinely uploaded to the database.		Query CALs separately from PSR scan, associate with corresponding PSR scan through scripts, etc.	Make available a suite of python scripts to directly access database for use with various groups' pipelines/other software.
	Develop system for automated transfer of raw data into repositories.			Implement automatic uploading of data files at GBT/AO. [viii]	
	Develop schema by which GWB group can grab TOAs from the database.	Make sure user interface to database is user-friendly rather than just functional.		Distinguish TOAs etc. as belonging to specific pipelines/versions of pipeline.[ix]	Notifications about new additions to database for subscribers.

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	Year 1	Year 2	Year 3	Year 4	Year 5
	Develop automated system for computing and distributing clock corrections.[x]	Get international partners to contribute their clock corrections to this system.[xi]		Update web interface to include query to reproduce Demorest et al, full upload/download-ability of data products, and various diagnostic plots/trends.[xii]	Update web interface to include "quick-look" residuals for a query.
Gravitational Wave Source Physics and Astrophysics				Re-reduction of 3C66B astrometry completed.[xiii]	Develop, apply framework to interpret strong PTA limits on the GWB.
				Develop framework to interpret blind PTA limits on continuous wave sources (What free parameters are there? How are these constrained by EM observation and how are they constrained by PTA limits?)[xiv]	Perform analysis to detect/constrain alternate theories of gravity with PTA data.
				Submit VLBA proposal for Offset-BLR Eracleous et al. targets to search for binary SMBHs.	Understand average astrophysical properties of bursts with memory (distance, mass distribution).
				Paper on VLBA observations of double-peaked [OIII][xv]	Paper on full multi-messenger interpretation of 3C66B, including new PTA limits.
				Elect a group Chair.	Paper on Eracleous et al. Offset-BLR VLBA targets
				Organize AAS special session on GW Astrophysics.	Identify specific current/future surveys or instruments capable of PTA-target GW source identification (bursts, CWs).
				Apply for IAU special session on GW Astrophysics for 2015 IAU General Assembly.	Write whitepaper on how to perform/design GW triggers: i.e. if we detect a GW burst or CW, what should we look for to identify its host and what instruments should we use?

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Interstellar Medium Mitigation	Create a first draft of a comprehensive ISM error budget following Ryan Shannon's thesis work and Cordes & Shannon 2010 error budget paper.	Create a first draft of a comprehensive ISM error budget following Ryan Shannon's thesis work and Cordes & Shannon 2010 error budget paper.[xvi]		Initiate and conduct dynamic spectrum (plus timing) observations of at least one NANOGrav pulsar with approximately weekly cadence. Compare coherent and incoherent IMM strategies using various metrics in addition to "smaller rms residuals."[xvii]	Initiate short-term, rapid cadence line of sight (LOS) characterization observations for three more NANOGrav pulsars.
	Complete an analysis of cyclic spectroscopy (CS) signal-to-noise ratio.	Develop parallel mitigation pipelines using a) standard and b) CS mitigation strategies. Begin to employee these on standard NANOGrav timing data.[xviii]	Make a first year assessment of the relative success of the two mitigation pipelines. Determine what, if any, modifications need to be made.	Complete an assessment of NANOGrav's DM correction method. Determine the detailed effect it has on GW density models. Plausible density models include theoretically simple models as well as that plus deterministic structures and other complicating factors, such as spatially intermittent turbulence. Publish a paper on this.[xix]	Integrate a comprehensive IMM strategy into the NANOGrav timing pipeline and assess its effectiveness using detailed noise budget analysis techniques.
				Publish papers on the following topics: 1) J1713+0747 global observations scintillation analysis, 2) Correcting scattering broadening with cyclic spectroscopy, 3) Assessing cyclic spectroscopy PBF reconstruction as a function of SNR and t_scatt, 4) Results from a real-time spectroscopy backend, 5) Analysis of time delays from standard NANOGrav data runs, and 6) Correcting for scatter broadening delays in high precision timing data.[xx]	Conduct a 24-hr global observing campaign on J1909-3744 (or other appropriate pulsar) and analyze its scintillation properties.

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	Year 1	Year 2	Year 3	Year 4	Year 5
				Initiate short-term, rapid cadence line of sight (LOS) characterization observations for three NANOGrav pulsars in addition to the longer-term study previous mentioned.[xxi]	Determine IMM contributions to the noise budget of the top 10 most important NANOGrav pulsars.
Noise Budget				Analysis of 5-yr ASP/GASP data sets from Demorest, et al. 2013, as we have been doing. Reported first as a technical memo to inform the collaboration, and eventually incorporate into an ApJ paper.[xxii]	Analysis and characterization of IPTA data sets.
				Development of scaling laws for noise terms in timing data for use in detection calculations, projections for future instruments, and recommendations for observing strategies.	
				Development of a mathematical measurement model based on data results.	
				Analysis of timing variations from pulse amplitude and phase variations (“jitter”) for MSPs and canonical pulsars.	
				Analysis of current GUPPI/PUPPI data sets. Similar goals as for the ASP/GASP data. Chracterization and understanding of improvements and update noise budget model as needed.	
				Initial analysis of J1713+0747 global campaign data.	Continued analysis of J1713+0747 global campaign data.
				Initial software suite of tools for noise characterization.	Version 2 of software suite for noise characterization.

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Strategic Planning	Ensure that an L+Sband receiver is an official project at GB and Arecibo.		Ensure that an L+Sband receiver is an official project at GB and Arecibo.	Apply for the Mid-Scale and Physics Frontier Center	Secure funding for continuation of international meetings and student research visits (SAVI?)
	Meet with Jim Ulvestaad and Ed Seidel to discuss new facilities and upgrades to existing facilities.		Meet with Jim Ulvestaad and Ed Seidel to discuss new facilities and upgrades to existing facilities.	Engage the broader physics and astrophysics community (Organize strategic talks at conferences and facilitate writing papers with external co-authors).	Increase interaction with China and FAST.
	Complete TOA analysis on current MSPs to decide how much additional observing time on GBT and Arecibo we should be requesting.		Complete TOA analysis on current MSPs to decide how much additional observing time on GBT and Arecibo we should be requesting.	Lobby for GBT and Arecibo.	Secure funding for NANOGrav baseband data storage.
				Meet with Fleming Crimm.	Establish NANOGrav Advisory Board
	Publish "living" NANOGrav white paper on the arxiv.		Publish "living" NANOGrav white paper on the arxiv.	Have meeting with the GW community to discuss detection protocols (host GWIC meeting)	Establish GW detection protocols.

[i] Preliminary data release is scheduled for February 3rd, 2014. This only gives us 6 months to analyze the data and submit a paper. Our strategy is to finalize Bayesian noise modeling, and run optimal statistic, to set upper limits. We may or may not have time to try out other more recently developed techniques.

[ii] IPTA data set is not available for analysis.

[iii] First GBNCC survey paper about to be published.

[iv] Goal is to submit paper in spring 2014.

[v] Goal is to submit paper in spring 2014.

[vi] Will arrange for undergraduate students at NRAO to work on this.

[vii] Other database items are higher priority.

[viii] Raw data is routinely uploaded from GBT and Arecibo by observers and cyber-infrastructure working group members, but it is not fully automated yet.

[ix] Not available yet, but is near the top of the list of priorities.

[x] This has taken a backseat to other milestones that we felt needed more focused attention. Clock corrections are not currently in the database structure.

[xi] See above for clock correction comment.

[xii] Demorest et al. data release is not yet available as a query, but is available on the data website. However, one can now download raw data and various data products, such as TOAs, ephemerides, etc., and several diagnostic plots are automatically generated on the website for a given query.

[xiii] We have been working on other projects and the current NANOGrav data is not sensitive enough to put strong limits on this target (awaiting 8-year data or IPTA data sets).

[xiv] We have not developed a framework but have worked with the results of J. Ellis's CW work to come up with a sound (and easily translated to the astrophysical community) interpretation. A paper is also in preparation to report on the improvement of limits/parameter estimation using electromagnetically-derived binary parameters.

[xv] Lazio is working on a paper, 90% complete.

[xvi] This work is being performed in conjunction with the Noise Budget Working Group. Recent work does estimate scattering delays for a large number of NANOGrav pulsars and use that to estimate the resulting contribution to the uncertainty/error on the measured TOAs.

[xvii] Regular observations of J2317+1439 are being conducted at Arecibo Observatory. Those observations are now paused due to the earthquake damage at Arecibo, but this pause is being used to begin to mature some of the analysis tools needed.

[xviii] Using primarily GUPPI, and more recently PUPPI, data, scattering delay times have been estimated for NANOGrav pulsars and the resulting magnitude for the error in the TOA estimated. This work has been in the "standard" approach. This work has also included measuring how the scintillation bandwidth varies with observing frequency. In addition to being essential for the wide-band scattering delay measurements, the frequency scaling results can also be used to analyse different models of the interstellar medium. An implementation of cyclic spectroscopy in real time was demonstrated, and parallel observations using the standard NANOGrav timing observations and with cyclic spectroscopy can be run at both observatories. After a short, initial period in which cyclic spectroscopy was in routine use, it is now in the process of being more robustly integrated into both telescopes' control systems. A cyclic spectroscopy-directed campaign towards J1643-1224, which seemed like a promising candidate for correction, was just completed, and data analysis is underway. Complementing it has been simulations of the extent to which cyclic

spectroscopy is able to determine, and then mitigate, ISM effects. A pipeline for cyclic spectroscopy analysis of NANOGrav data does not yet exist. Moreover, existing work is suggesting that cyclic spectroscopy may not warrant the development of an extensive pipeline.

[xix] The framework for an assessment of the DM correction method has been developed, but it has not yet been matured to the extent of determining its effect on estimates of the GW background or signal

[xx] In all cases, paper outlines or fairly mature drafts have been developed. For #1, the initial analysis of the global campaign on J1713+0747 has identified correlated red noise in the residuals which can be accounted for by a model of profile evolution as a function of frequency combined with varying scintillation patterns across the entire band. This was likely unseen before because of the smaller bandwidths of the previous generation of backends and because of the relatively small number of scintles in the typical 20 minute NANOGrav observation. With this campaign, at telescopes with sufficient S/N, this extra source of noise that results partially because of the ISM is now becoming detectable. Work is ongoing to determine the effects of the ISM on timing accuracy at these integration spans. For #5, see discussion above.

[xxi] Proposals have been submitted, but no observing time has yet to be awarded.

[xxii] A memo is in preparation.