Pulsar Astrophysics the Next Fifty Years
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Solar System Ephemerides, Pulsar Timing, Gravitational Waves, & Navigation

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Abstract. In-spiraling supermassive black holes should emit gravitational waves, which would produce characteristic distortions in the time of arrival residuals from millisecond pulsars. Multiple national and regional consortia have constructed pulsar timing arrays by precise timing of different sets of millisecond pulsars. An essential aspect of precision timing is the transfer of the times of arrival to a (quasi-)inertial frame, conventionally the solar system barycenter. The barycenter is determined from the knowledge of the planetary masses and orbits, which has been refined over the past 50 years by multiple spacecraft. Within the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), uncertainties on the solar system barycenter are emerging as an important element of the NANOGrav noise budget. We describe what is known about the solar system barycenter, touch upon how uncertainties in it affect gravitational wave studies with pulsar timing arrays, and consider future trends in spacecraft navigation.

Keywords. gravitational waves, methods: data analysis, ephemerides

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1. The Solar System Ephemeris

The timing of "Pulsar Astrophysics — The Next 50 Years" coincided not only with the 50th anniversary of Dame Jocelyn Bell-Burnell's efforts to understand "scruff," it coincided with the 40th anniversary for the Voyager 1 and 2 launches (1977 September 5 and August 20, respectively). The Voyager spacecraft revolutionized our understanding of the solar system with their flybys of Jupiter, Saturn, Uranus (Voyager 2), and Neptune (Voyager 2).

Among the iconic images from the Voyager spacecraft is the "Family Portrait" (Figure 1). The last images acquired by Voyager 1 before its camera was turned off to save power, the Family Portrait shows most of the planets as seen from the edge of the solar system. Obtaining it required accurate knowledge of the solar system ephemeris—the masses and orbits of the planets and minor bodies—both to navigate the Voyager spacecraft on their journeys and to know where to point the Voyager 1 camera.

Over the past 50 years, at least one spacecraft has flown past each of the planets (with multiple minor bodies), and at least one spacecraft has orbited most of the planets. These missions have been enabled by continual improvements in our knowledge of the solar system ephemeris and navigation techniques (Figure 1). Today, the orbits of the inner planets are known to a few meters, aided by the multiple orbiters at both Venus and Mars and their relatively short orbital periods. In the outer solar system, orbits are less well known, due to the fewer number of spacecraft that have visited those planets and the (much) longer orbital periods; the Saturnian orbit is the most well determined (tens of meters) due to the recently concluded *Cassini* mission.

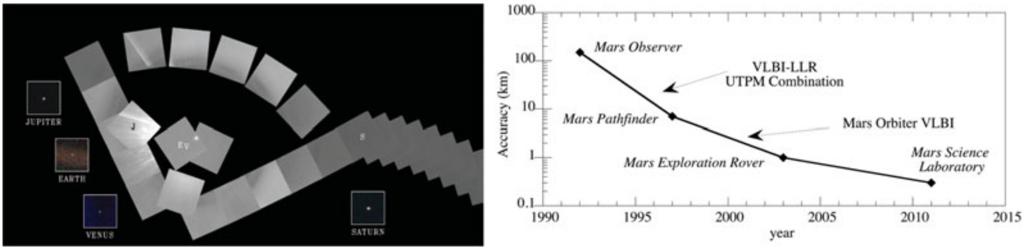

Figure 1. (*Left*) Voyager 1 Family Portrait showing most of the planets as seen from the edge of the solar system. Navigating the Voyager spacecraft, and subsequent spacecraft, on their trajectories and knowing the orbits of the planets sufficient to obtain the Family Portrait has required improved knowledge of the solar system ephemeris over the past 50 years. (Credit: NASA/JPL-Caltech) (*Right*) Improvement in the accuracy of navigation to Mars over the past nearly 30 years. While specific to Mars, a similar trend holds for navigation throughout the solar system.

2. Gravitational Waves, Pulsar Timing, and Solar System Ephemerides

Precision timing involves the transformation of the pulse time of arrival at a telescope located on the Earth into a (quasi-)inertial frame, typically taken to be the solar system barycenter (Lorimer & Kramer 2004). Among the corrections is one for the Roemer delay,

$$\Delta t_R = \frac{\mathbf{r}_{\mathrm{SSB}} \cdot \hat{\mathbf{n}}}{c}, \tag{2.1}$$

where $\mathbf{r}_{\mathrm{SSB}}$ is the vector between the Earth and the solar system barycenter, $\hat{\mathbf{n}}$ is the unit vector in the direction of pulsar, and c is the speed of light. With $r_{\mathrm{SSB}} \sim 1$ au, $\Delta t_R \approx 500$ s.

Detecting low frequency ($f \sim 10$ nHz) gravitational waves (GWs) has emerged as an increasing focus for precision pulsar timing among national and regional consortia. It is reasonably well established that most major galaxies host central supermassive black holes (SMBHs), and the merger of galaxies should result in the two SMBHs falling to the center of the merger product, under the influence of dynamical friction (e.g., Begelman *et al.* 1980; Khan *et al.* 2016). The two SMBHs should form a binary, which in most scenarios, begins to radiate GWs and harden, with the two SMBHs eventually merging (e.g., Sesana 2013). The ensemble of SMBH binaries should produce a GW background. Initial expectations were that the GW background would be isotropic (e.g., Jaffe & Backer 2003), but recent work has addressed whether individual binaries could produce an anisotropic GW background or even be detectable (e.g., Mingarelli *et al.* 2017).

The expected magnitude for pulse arrival time distortions due to low frequency GWs is $\Delta t_{\mathrm{GW}} \sim 10$ ns. Clearly, detecting low frequency GWs requires knowledge (and control, where possible) of the various contributions to the timing "noise budget." The connection between the knowledge of the solar system ephemeris and GW detection is now clear. Ideally, uncertainty in the barycenter should be $\sigma_{\mathrm{SSB}} < \Delta t_{\mathrm{GW}} \sim 10\,\mathrm{ns}$, corresponding to knowledge of the position of the barycenter to of order a few meters.

Unfortunately, knowledge of the barycenter at this precision does not exist. The dominant contribution to the uncertainty results from the outer solar system, notably from Jupiter, Uranus, and Neptune. The *Cassini* mission improved the knowledge of Saturn's mass and orbit, and the Juno mission is expected to provide similar improvements for Jupiter, but no orbiter has visited Uranus or Neptune. Moreover, uncertainties in their masses and orbits are degenerate with uncertainties in the orbit of Jupiter, which is the dominant contribution to estimating the position of the barycenter.

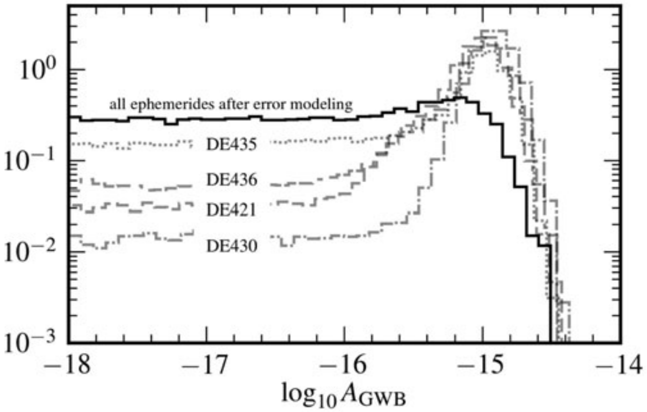

Figure 2. Illustration of the effect of solar system ephemerides uncertainties on gravitational wave detection, from the forthcoming NANOGrav 11 Year analysis. Different ephemerides produce different posterior distributions (as labeled) of the stochastic GW background amplitude, for a power law in characteristic strain ($h[f] \propto A_{\mathrm{GWB}} f^{\alpha}$). The solid curve shows the resulting posteriors, which are essentially indistinguishable, if the masses of the outer planets and the orbital parameters of Jupiter are included in the GW analysis. The value of the posterior at small $\log_{10} A_{\mathrm{GWB}}$ is proportional to the Bayes ratio for the data favoring a model with no GW background to a model with a GW background. The differences between the curves are apparent and demonstrate that not accounting properly for uncertainties in the ephemerides could result in an erroneous detection or missing a true detection.

Within the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), this uncertainty in the knowledge of the ephemeris is being taken into account in the GW analysis. Modeling of time of arrival residuals now include uncertainties in the masses of Jupiter, Uranus, and Neptune and in the orientation of the orbit of Jupiter (Figure 2).

Over the next 50 years, improvements in the solar system ephemeris may be possible, though it is not clear that they will be sufficient to obtain $\sigma_{\mathrm{SSB}} < 10$ ns. For instance, connecting data from the *Galileo* and Juno missions may improve knowledge of Jupiter's orbit substantially. Alternately, it may be possible to incorporate pulsar timing data into determination of the solar system ephemerides, but such an ephemeris would not be independent for the purposes of pulsar timing.

3. Navigation, Pulsar Timing, and the Solar System Ephemeris

There has been a long standing interest in (semi-)autonomous navigation of deep space spacecraft, including the use of X-ray pulsars (e.g., Chester & Butman 1981; Sheikh *et al.* 2006; Deng *et al.* 2013; Shemar *et al.* 2016). There are even initial tests of the concept in low-Earth orbit (e.g., Zheng *et al.* 2017; Neutron star Interior Composition Explorer/Station Explorer for X-Ray Timing and Navigation [NICER/SEXTANT]).

In general, considerations of the performance of an X-ray navigation system have not taken into account uncertainties from knowledge of the solar system barycenter. Other considerations also suggest that X-ray navigation is likely to be of limited use beyond geosynchronous orbit:

Target body-relative navigation: X-ray navigation obtains positions relative to the barycenter. While such positions may be useful during a mission's deep-space cruise, many missions also require target body-relative navigation. Examples include the portion of *Cassini*'s Grand Finale Mission during which it passed only 50 km above the surface of Enceladus and many small-body missions (e.g., Rosetta at Comet 67P/Churyumov-Gerasimenko, the Hayabusa 2 mission to 162173 Ryugu, the planned Lucy mission to Jupiter Trojan asteroids, and the planned Psyche mission to 16 Psyche). Sheikh *et al.* (2006) speculated on how target body-relative navigation could be accomplished, but we are unaware of analysis demonstrating that likely mission requirements could be achieved; Rong *et al.* (2016) described a possible implementation but augmented the X-ray navigation with an optical camera.

Science measurements: Radio navigation has enabled Radio Science. For instance, a prime science goal for the Juno mission is to determine the interior structure of Jupiter (Bolton *et al.* 2017), which is achieved via the radio communication-navigation system; a similar study of Saturn's interior was enabled by *Cassini*'s radio communication-navigation system (Edgington & Spilker 2016). A typical time scale for orbit determination during Radio Science measurements is 100 s, and future missions may require measurements on 10 s time scales. By contrast, X-ray navigation position determinations are estimated to require 3000 s or longer (e.g., Shemar *et al.* 2016).

Separate communications infrastructure: At radio frequencies, navigation and communications are accomplished with the same equipment. While integrated optical communication-navigation payloads are not yet available, conceptually these functions can be merged (e.g., Ely & Seubert 2015), and autonomous optical navigation has been demonstrated (Deep Space 1, Rayman *et al.* 2000). Even if an X-ray communication-navigation payload were developed, it would only be applicable in free space. A separate system, at radio or optical frequencies, would be required for communication to the surface of the Earth (or through a planetary atmosphere).

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