Solar System Ephemerides, Pulsar Timing, and Navigation

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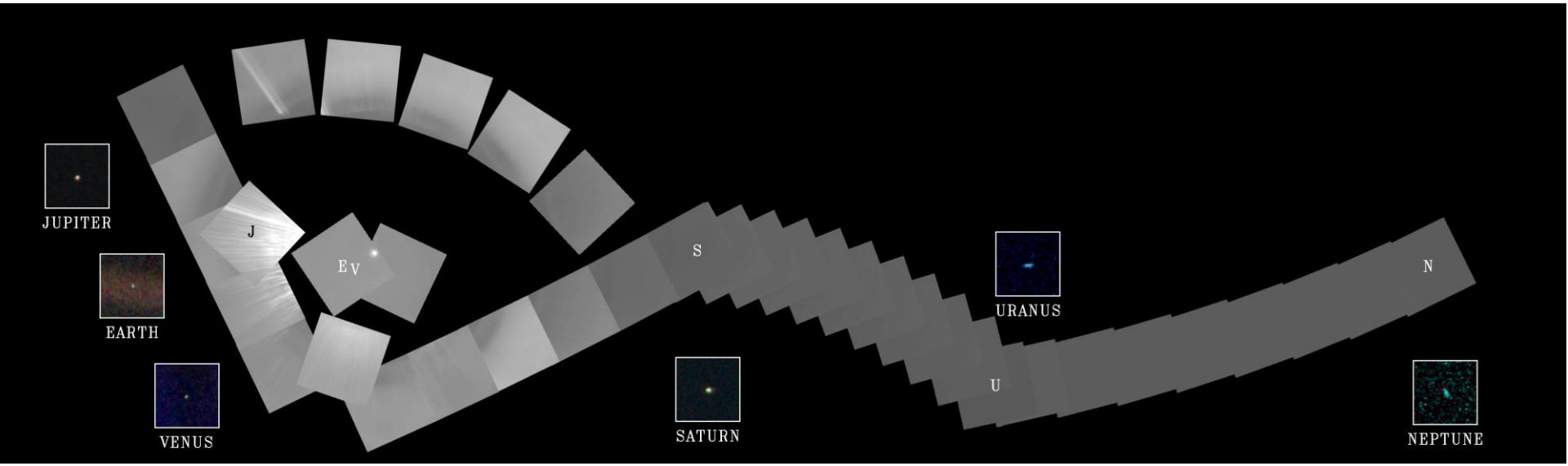
Part I: The Solar System Ephemeris

Voyager's Family Portrait

a.k.a. The Solar System



Voyager spacecraft at edge of our solar system (1990 February 14)

- **Mars obscured by scattered light in camera ("rays of light")**
- **Mercury too close to the Sun**

Credit: NASA/JPL

Spacecraft Navigation

Objective: Ensure spacecraft reaches required aimpoint

Requirements:

- **Mars landing: 100 m accuracy**
  - **winds ~ 1 m/s**
- **Other body landing: > 100 m accuracy (?)**
  - **Propulsion, terrain relative navigation**
- **Orbit insertion: ≥ 1000 m accuracy**

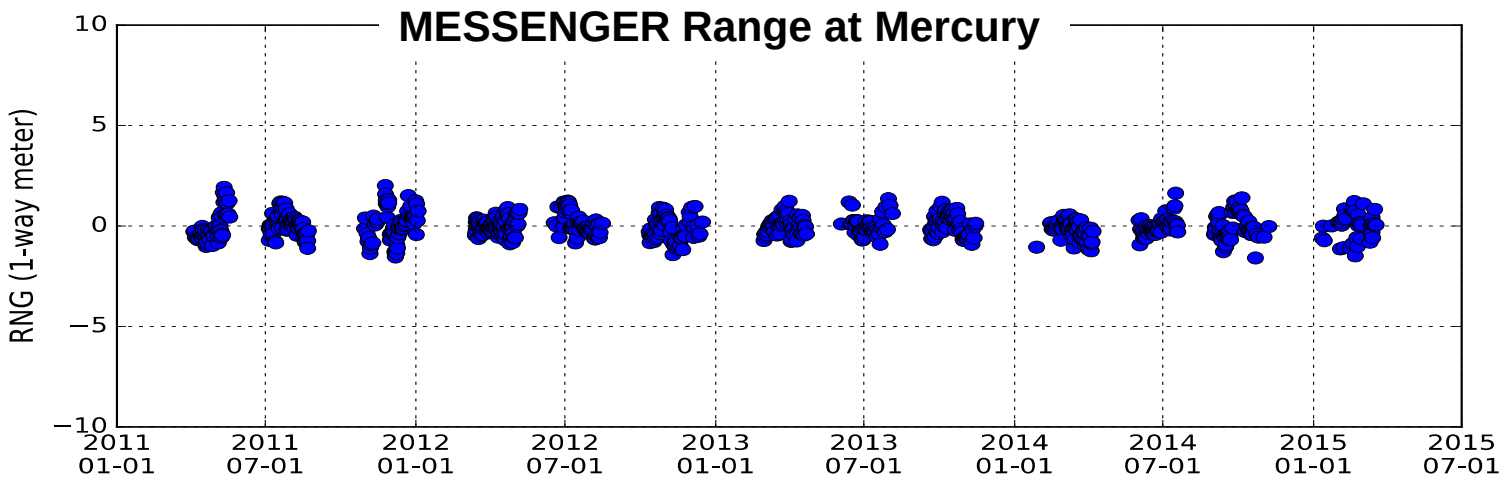
➢ **Aimpoint = state vector**

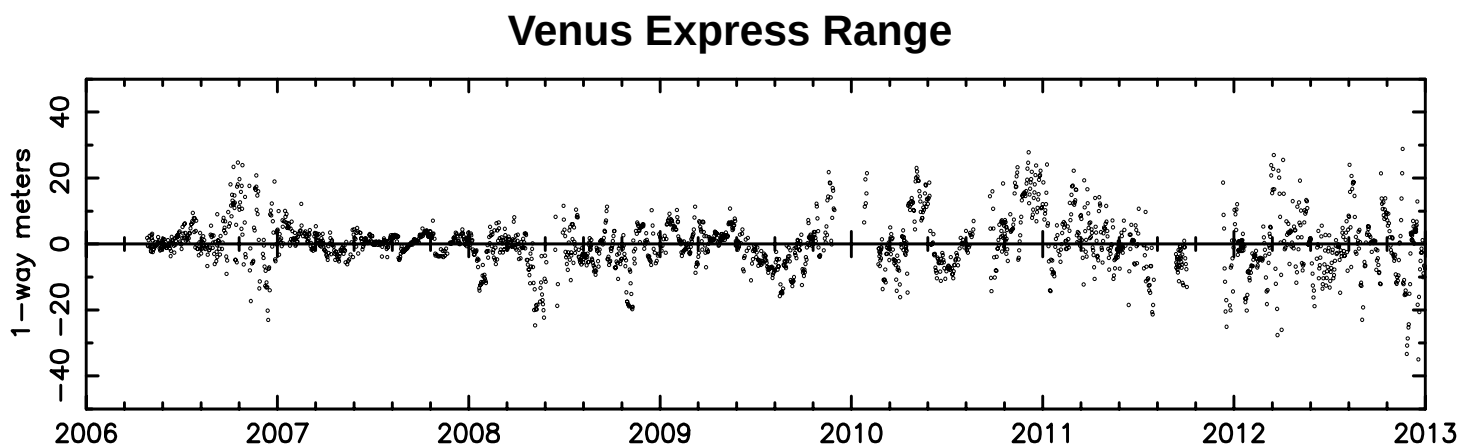
$(x, y, z; v_x, v_y, v_z)$

B-plane is normal to approach trajectory

Aimpoint at top of Mars' atmosphere is targeted to ensure accurate landing on surface

Mercury and Venus Data





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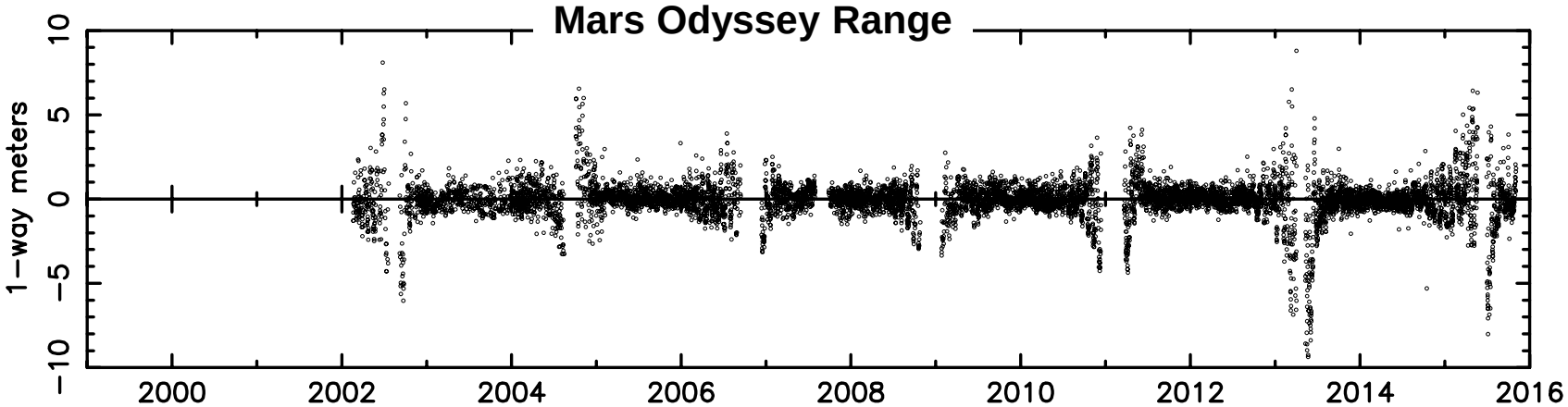
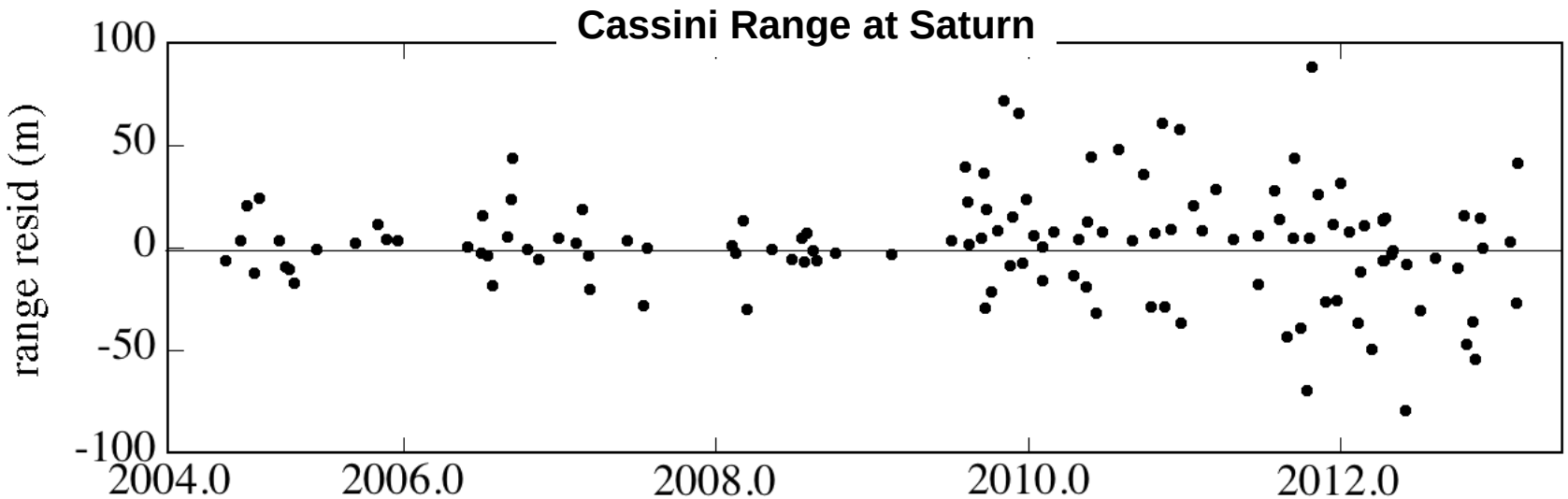
Mars and Saturn Range





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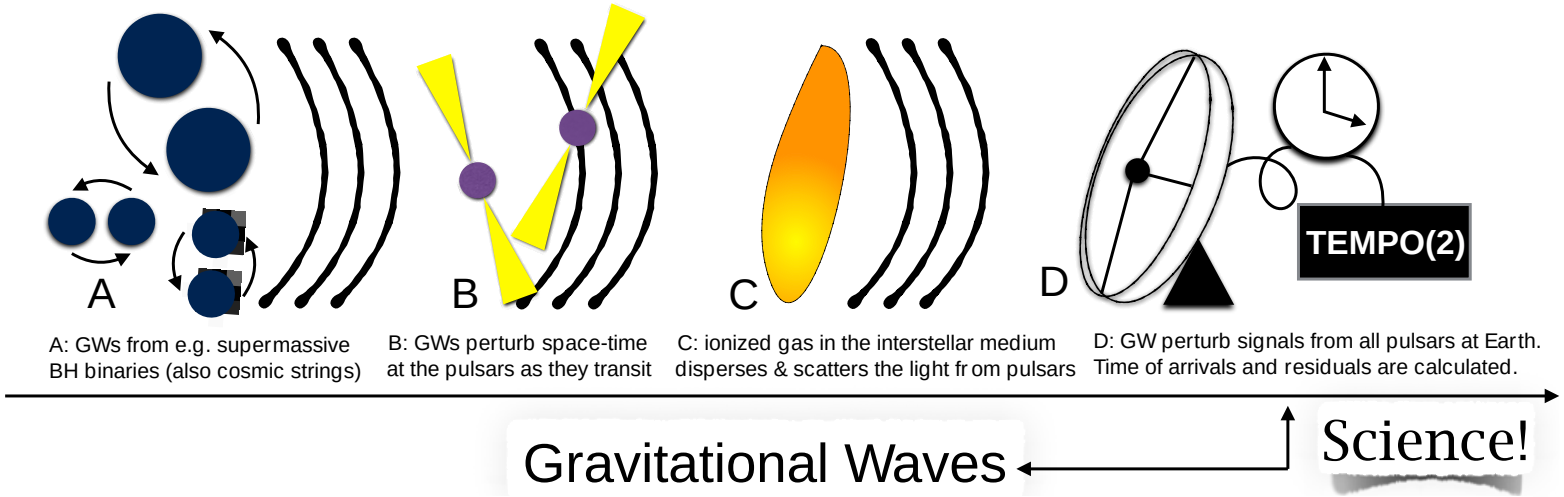
Part II: The Solar System Ephemeris and Pulsar Timing

Pulsar Timing and Solar System Ephemeris



$$t_{SSB} = t_{topo} + t_{corr} - DDM/\nu^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

Lorimer & Kramer, eqn. (8.6)

$$\Delta_{R\odot} = -\mathbf{r} \bullet \hat{\mathbf{s}}/c$$

Lorimer & Kramer, eqn. (8.7)

Solar System Ephemeris

What Do We Want?

$$\sigma_{TOA} = \sigma_{GWB} + \sigma_{SSB} + \ldots + \sigma_{random}$$

$$\sigma_{GWB} \sim 10 \text{ ns}$$

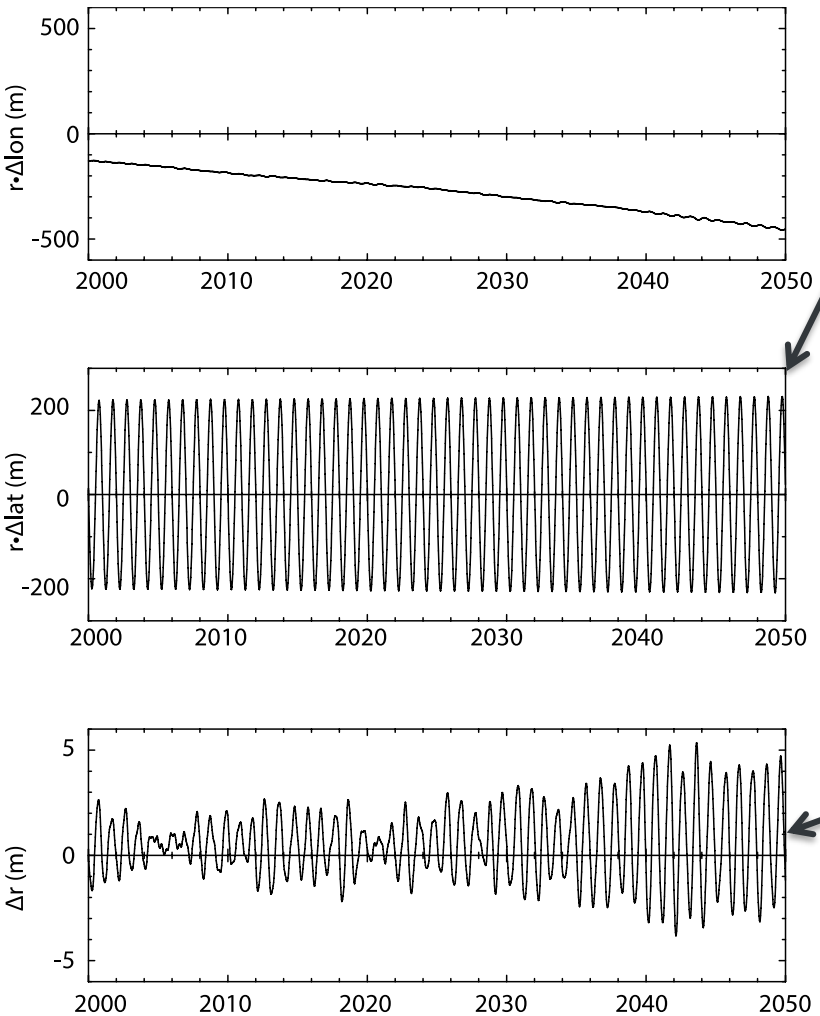
[reasonable expectation based on current astrophysics uncertainties]

$$\sigma_{SSB} \sim \sigma_{GWB}/3 \sim 3 \text{ ns} \sim 1 \text{ m}$$

[cf. 100 m ~ 300 ns]

- **See also S. Taylor's talk.**

Earth relative to Sun, DE421 – DE430



- **Change in ecliptic longitude at 2000.0 and variation in latitude reflect VLBI accuracy.**
  - **1.5×10^8 km*0.3 mas ~ 200 m**
- **Earth-Sun distance stable to ~5 m**

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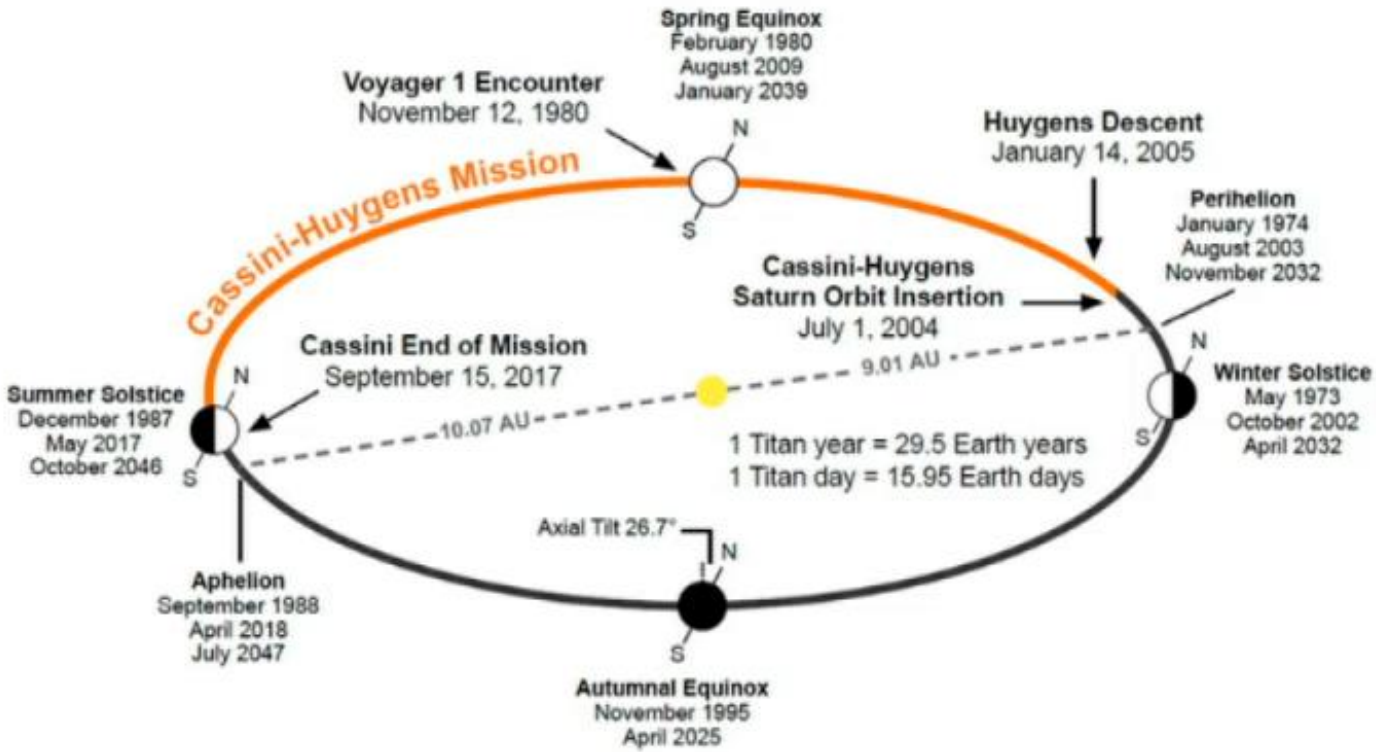
Outer Planets

Large Mass, Long Lever Arm, Little Data



cf. timing model for PSR J1024-0719

Hörst 2017

Spacecraft Navigation and Solar System Ephmeris

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- **Orbit insertion: ≥ 1000 m accuracy**

➢ **Might know more later in July**

B-plane is normal to approach trajectory

Aimpoint at top of Mars' atmosphere is targeted to ensure accurate landing on surface

Pulsar Timing and Solar System Ephemeris

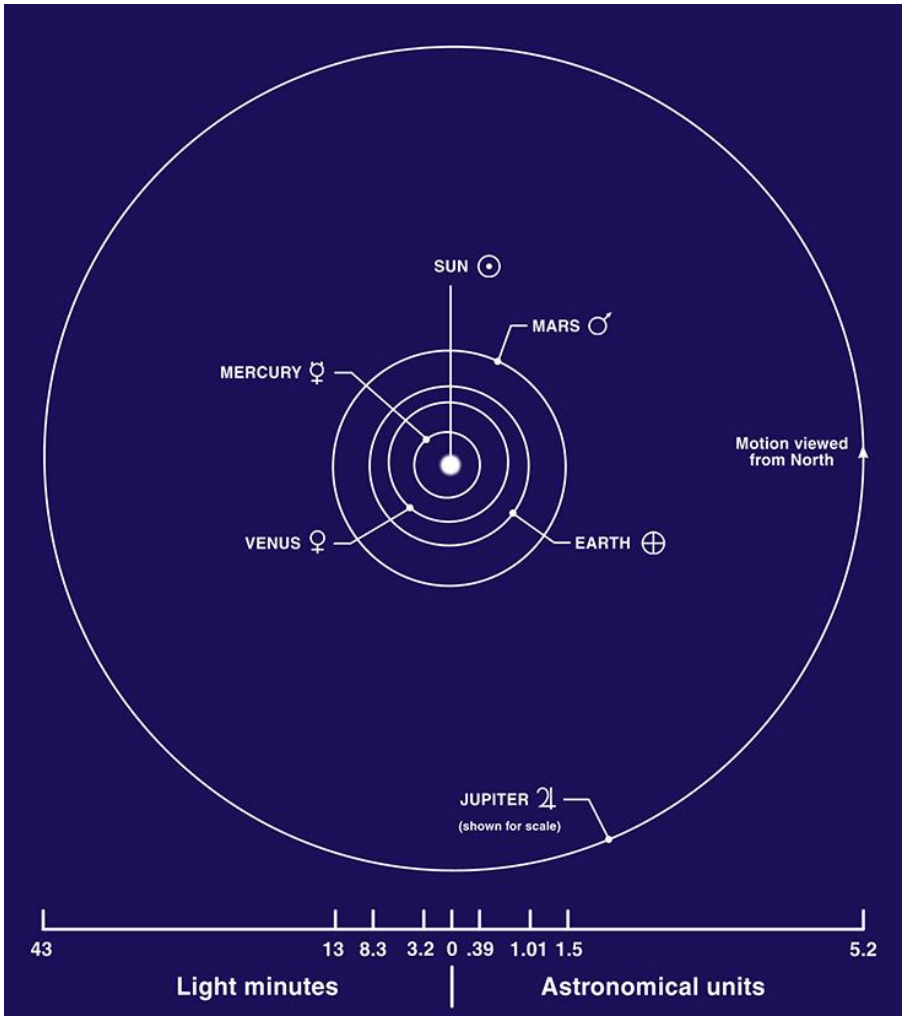
Or, Why Bother with the Spacecraft People?

Make a pulsar-based solar system ephemeris?

- **cf. IPTA solar system project**

Challenge: Enough good pulsars?

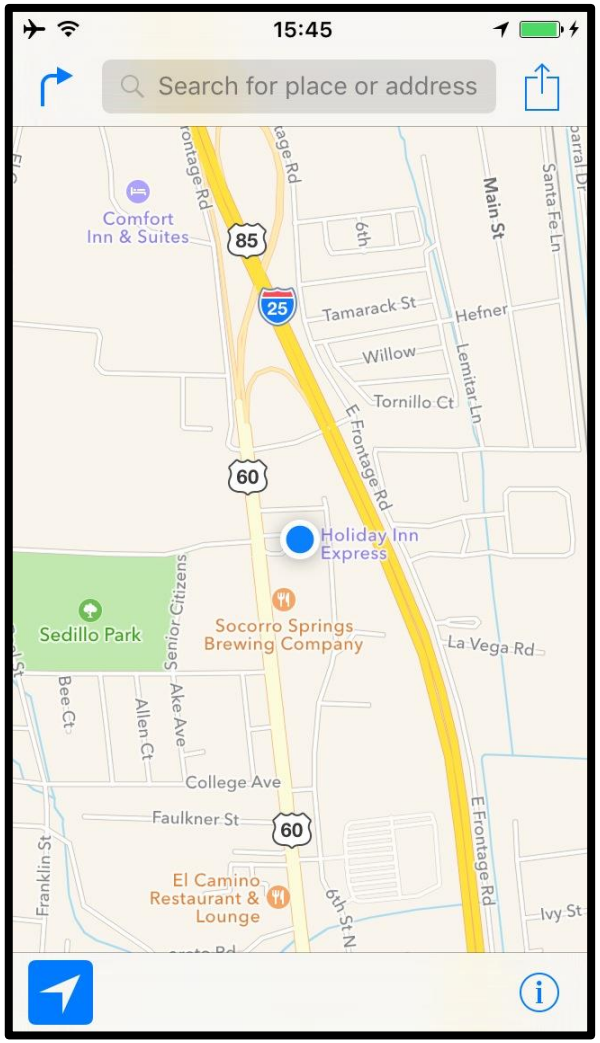
Best pulsars for constructing frame are best for GW study …

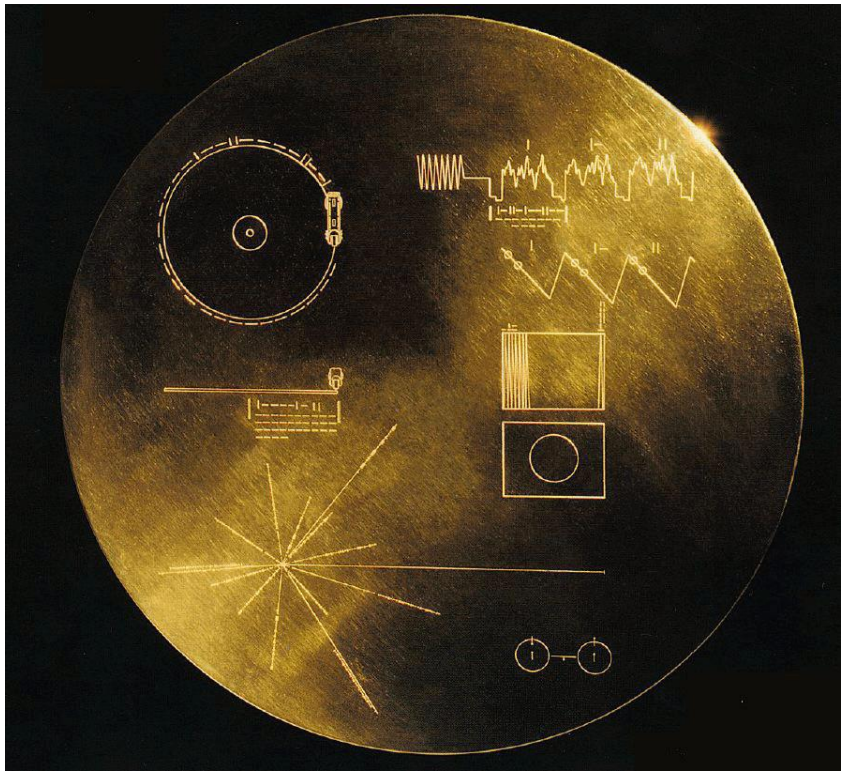


Part III: Navigation

Position Determination vs. Navigation

"You Are Here" vs. "To Go From Point A to Point B"





Credit: NASA

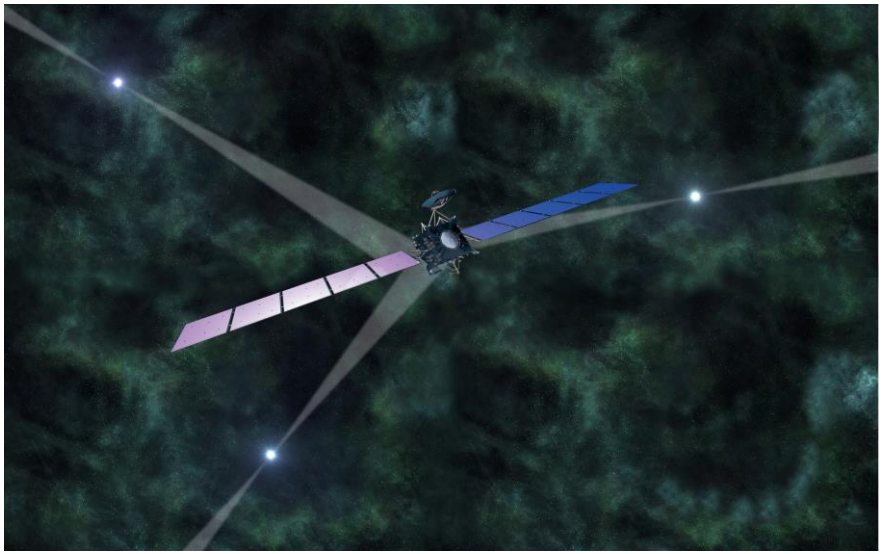
Deep Space Navigation and Position Determination

$\mathbf{r}_{PD} = f(t_{PD})$

$t_{PD} = t_{SSB} + t_{corr} - D\mathrm{DM}/\nu^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$

$\Delta_{R\odot} = -\mathbf{r} \bullet \hat{\mathbf{s}}/c$

Lorimer & Kramer



Credit: MPE/W. Becker; ESA

- $\boldsymbol{\sigma_{PD} = f(\sigma_{SSB}; \ldots)}$

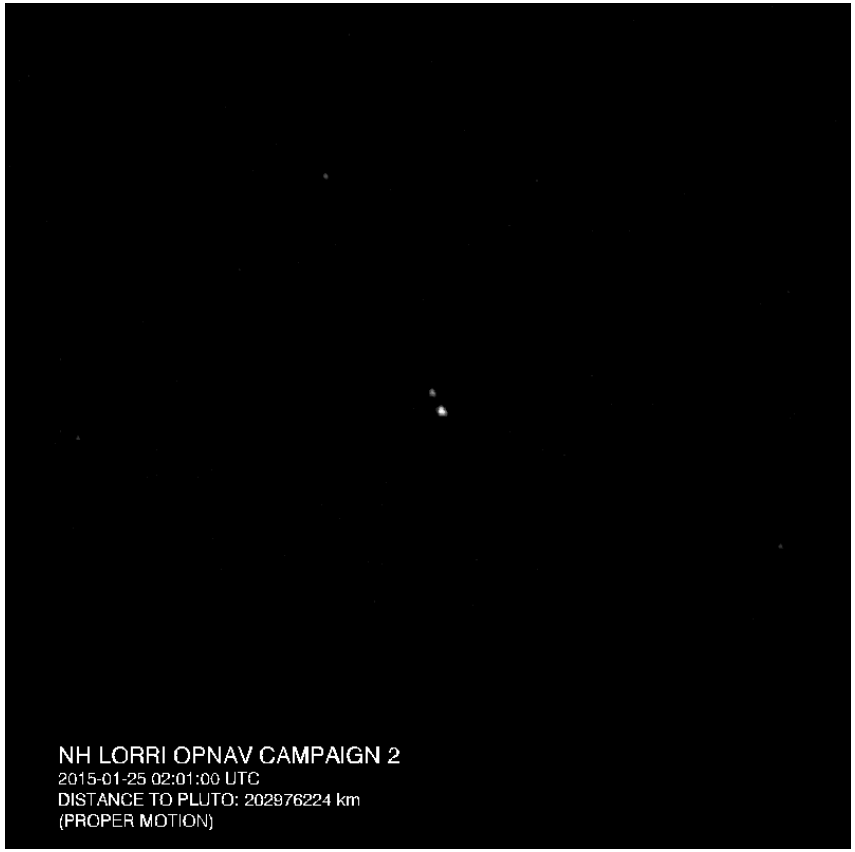
  $\boldsymbol{\sigma_{SSB} \sim 100}$ **m**

  $\boldsymbol{\sigma_{PD} \propto \sigma_{SSB}/\sqrt{N}}$ **?**

- **|v| ~ 30 km/s**

Optical Navigation

New Horizons approaching Pluto



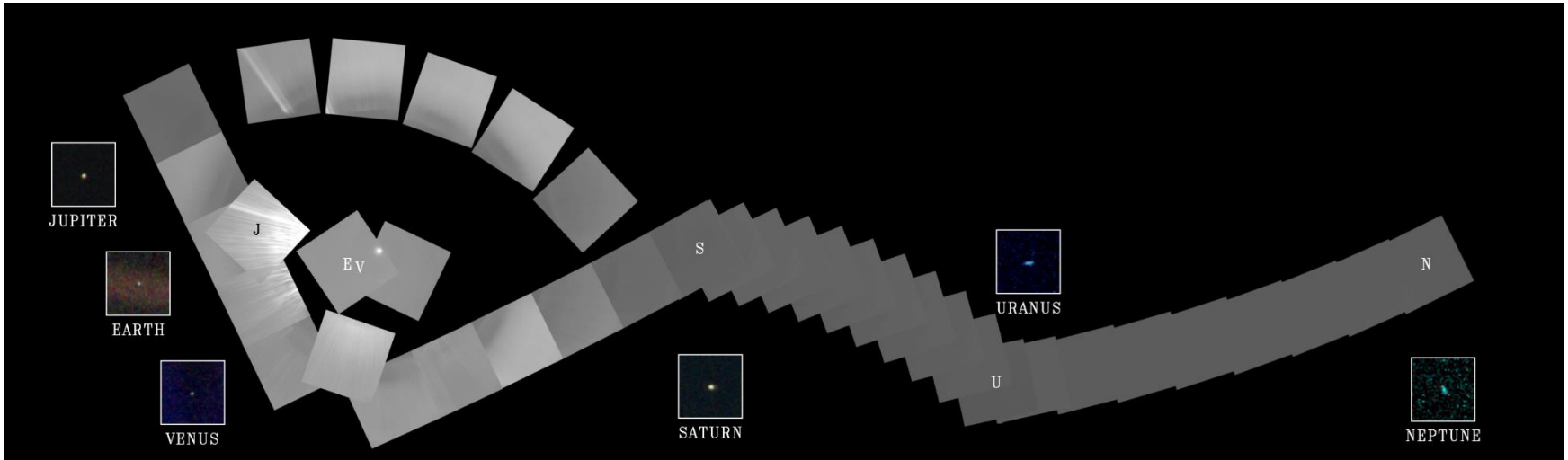
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

~~**Enterprise approaching α Cen A**~~
Juno approaching Jupiter

Credit: NASA/JPL

Summary

- **Solar system barycenter is critical element for pulsar timing and GW studies**
- **Little spacecraft navigation need for improved determination of barycenter (~ 100 m)**
- **GW study or barycenter determination? Probably cannot do both with current census**
- **Implications for pulsar-based position determination**



Backup