Spacecraft navigation using pulsars

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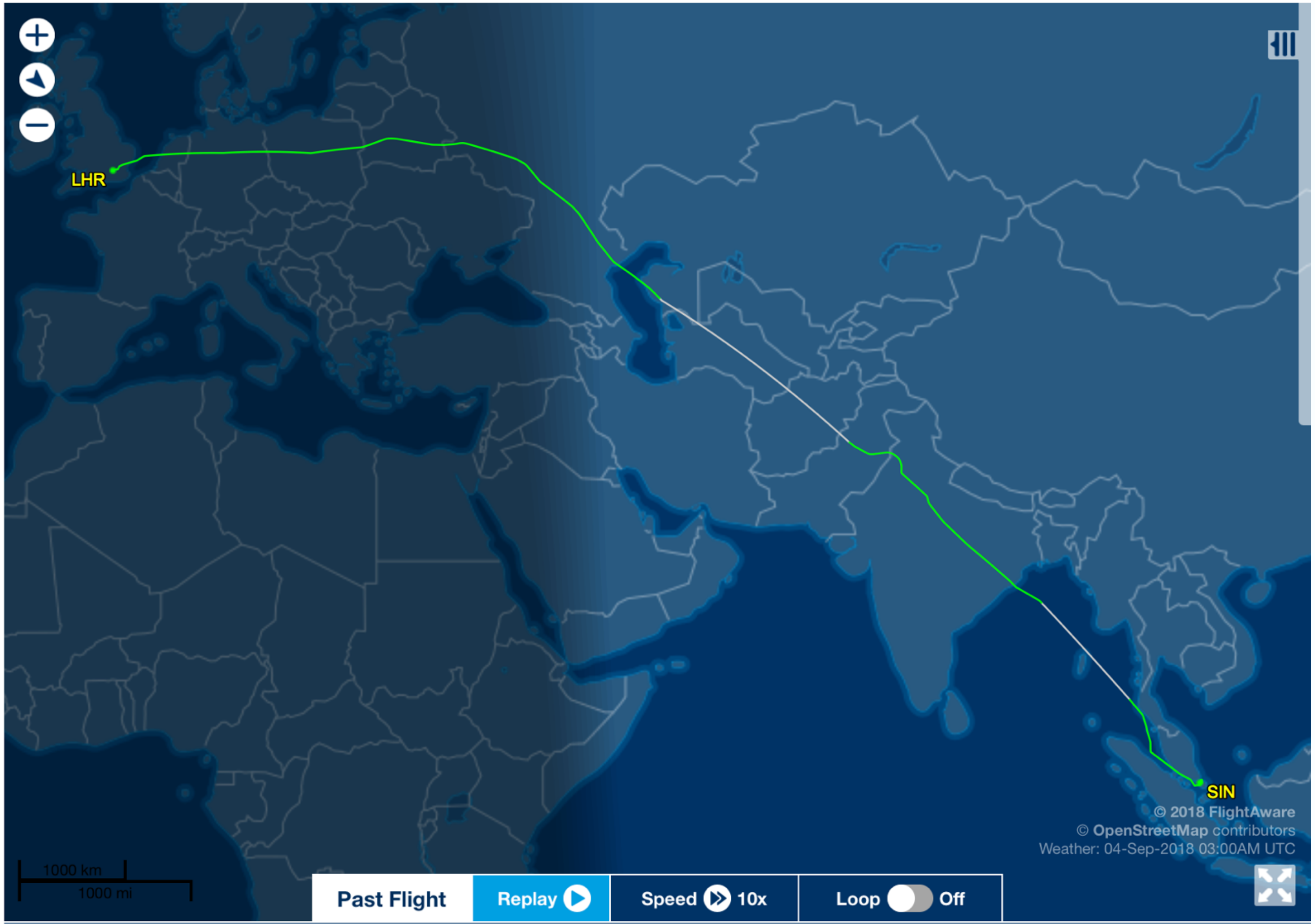
ASTRONOMY AND SPACE SCIENCE
www.csiro.au

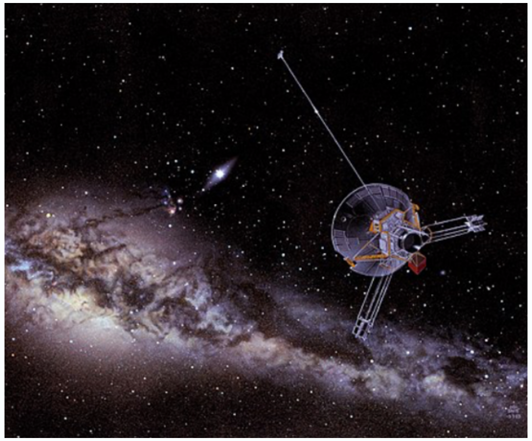
Advantages of a long flight

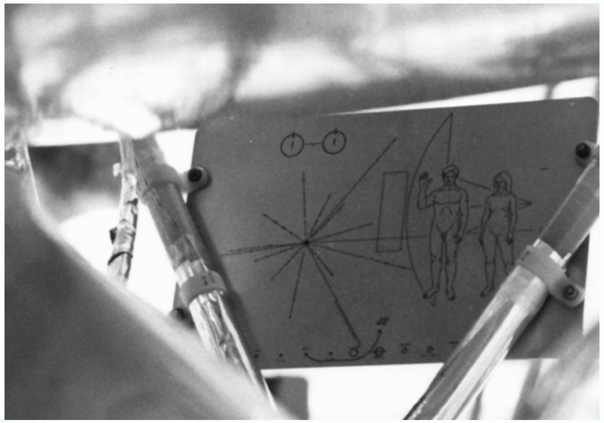
- Have time to ponder on navigation

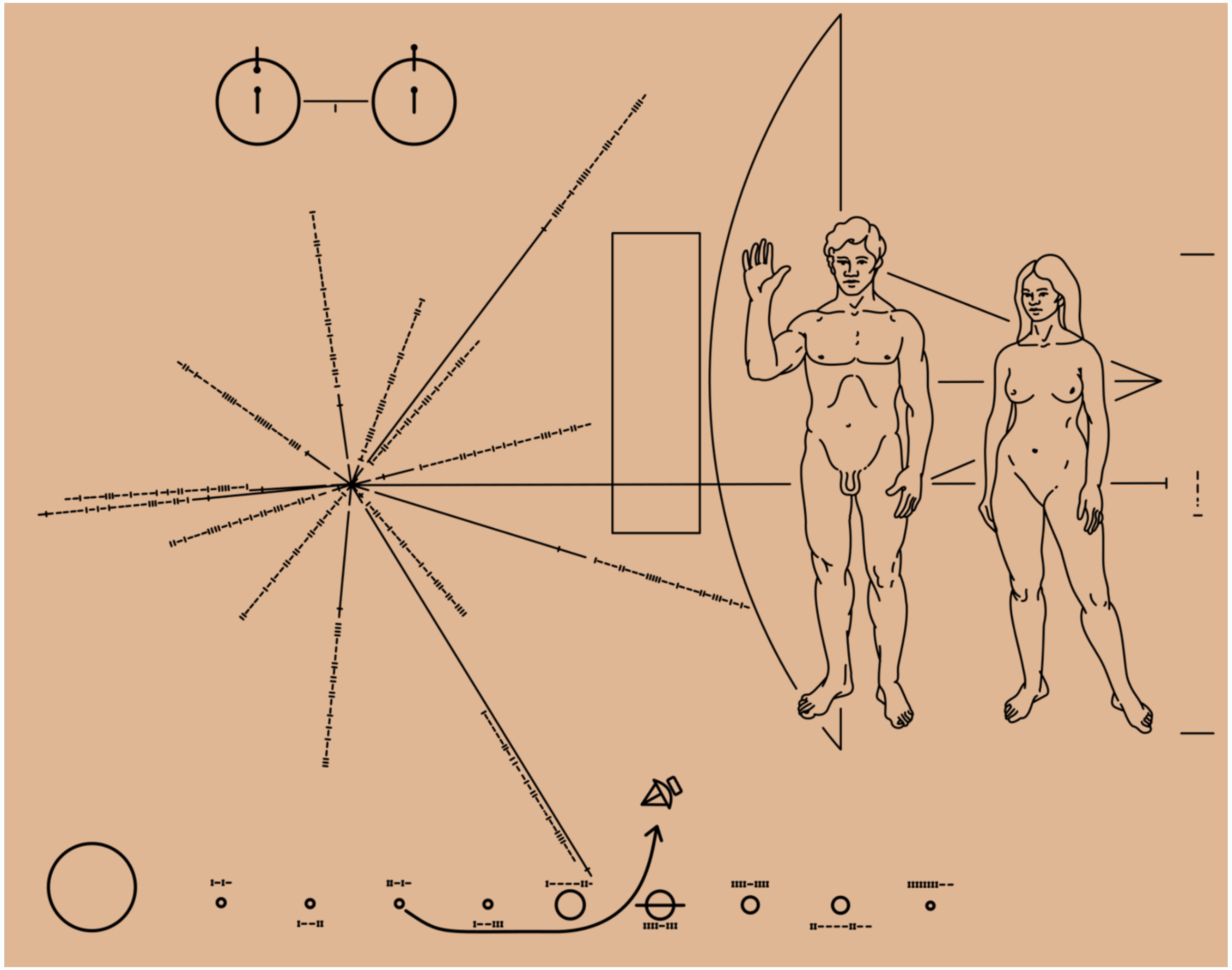
- Have time to pretend to be an alien



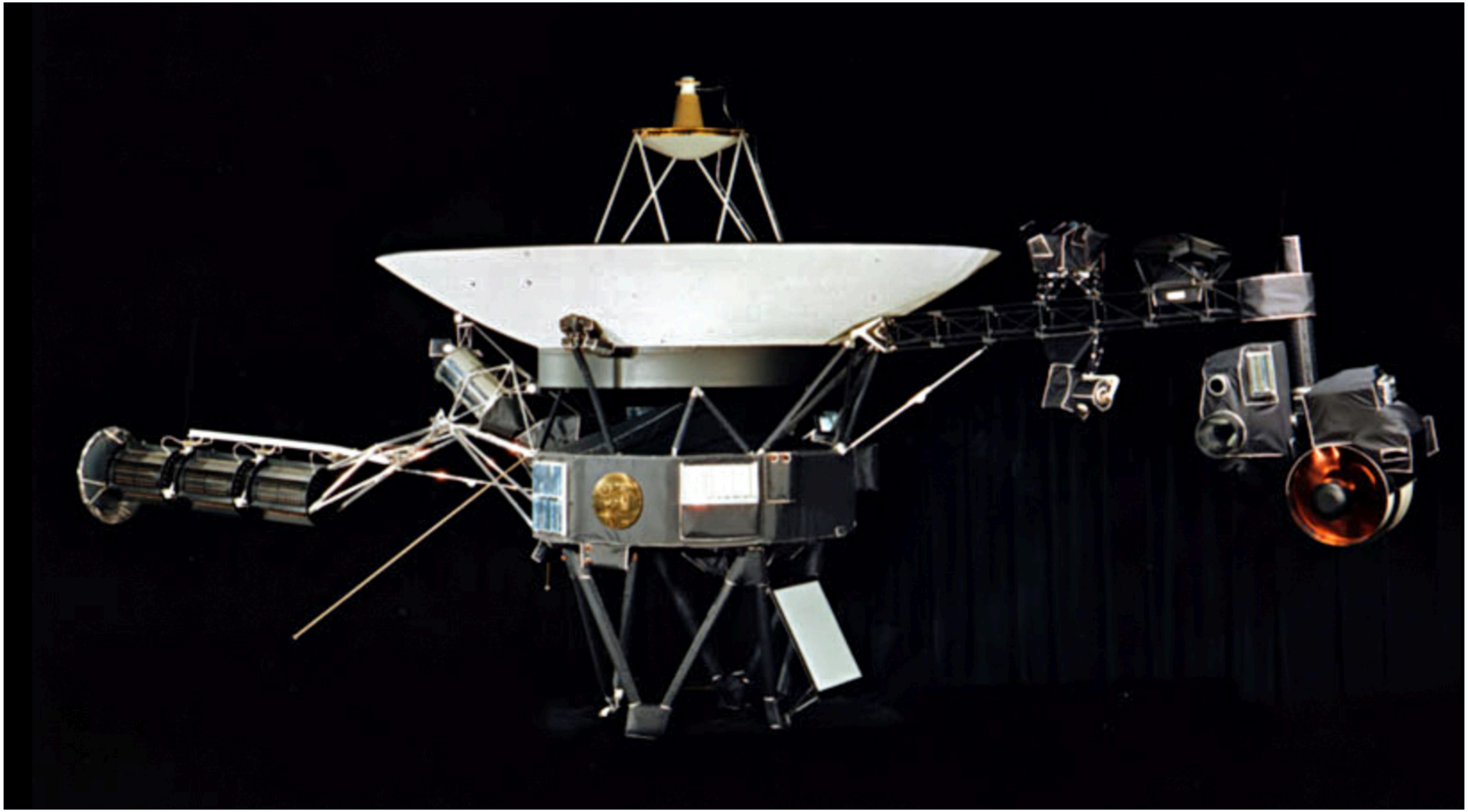
The pioneer plaque (1972 Pioneer 10 and 1973 Pioneer 11)







The Voyager space-craft: launched 1977



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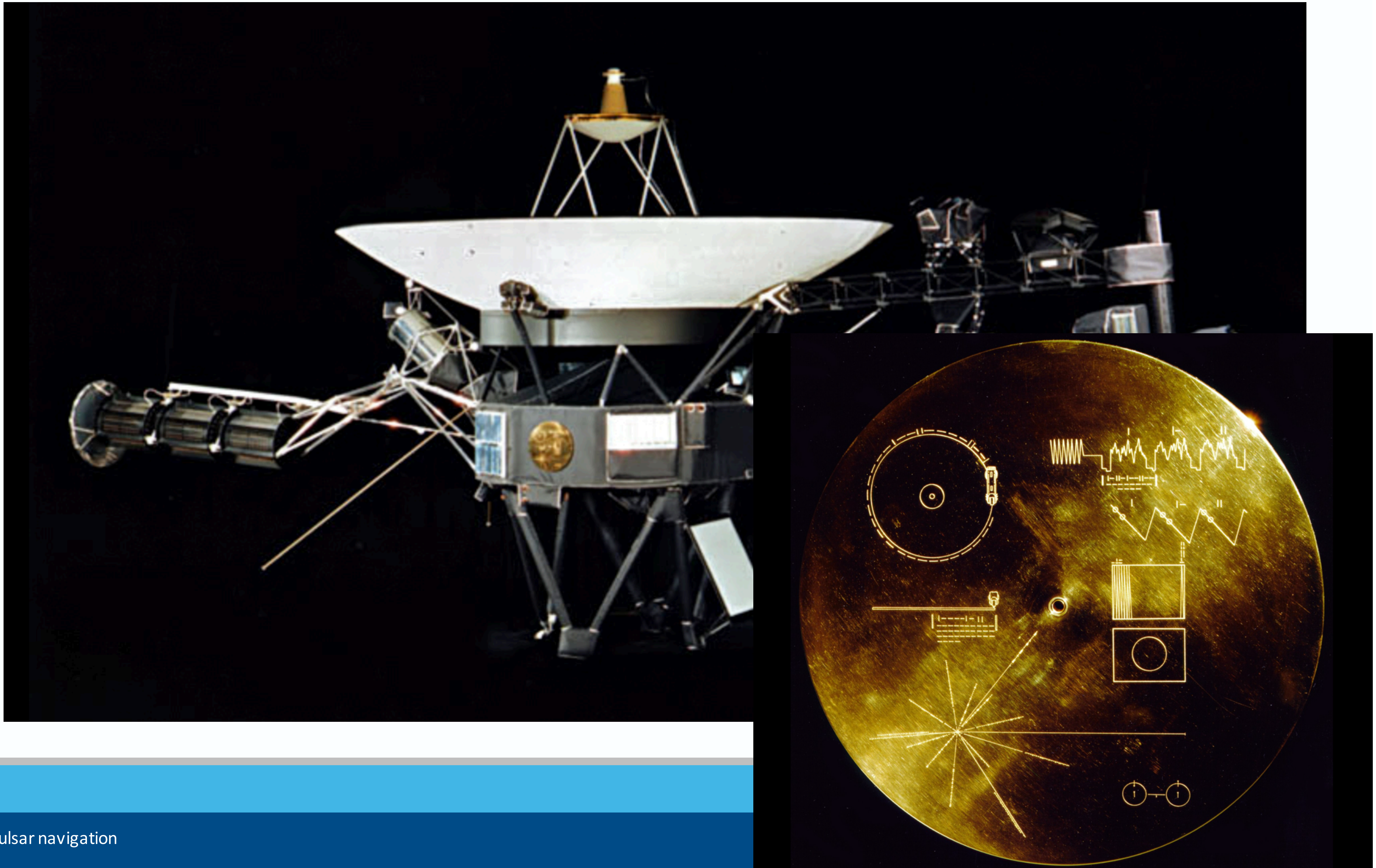
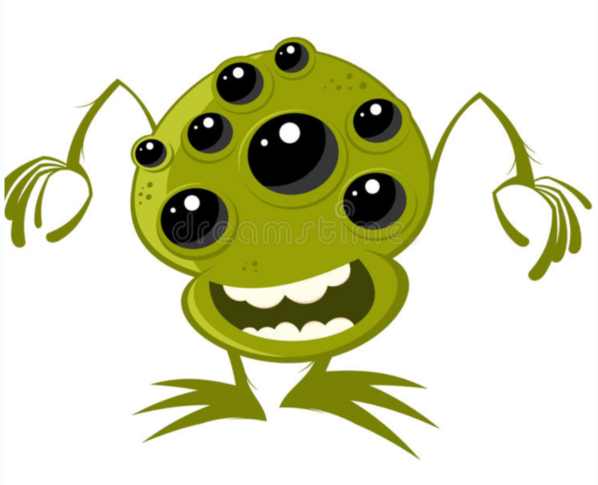
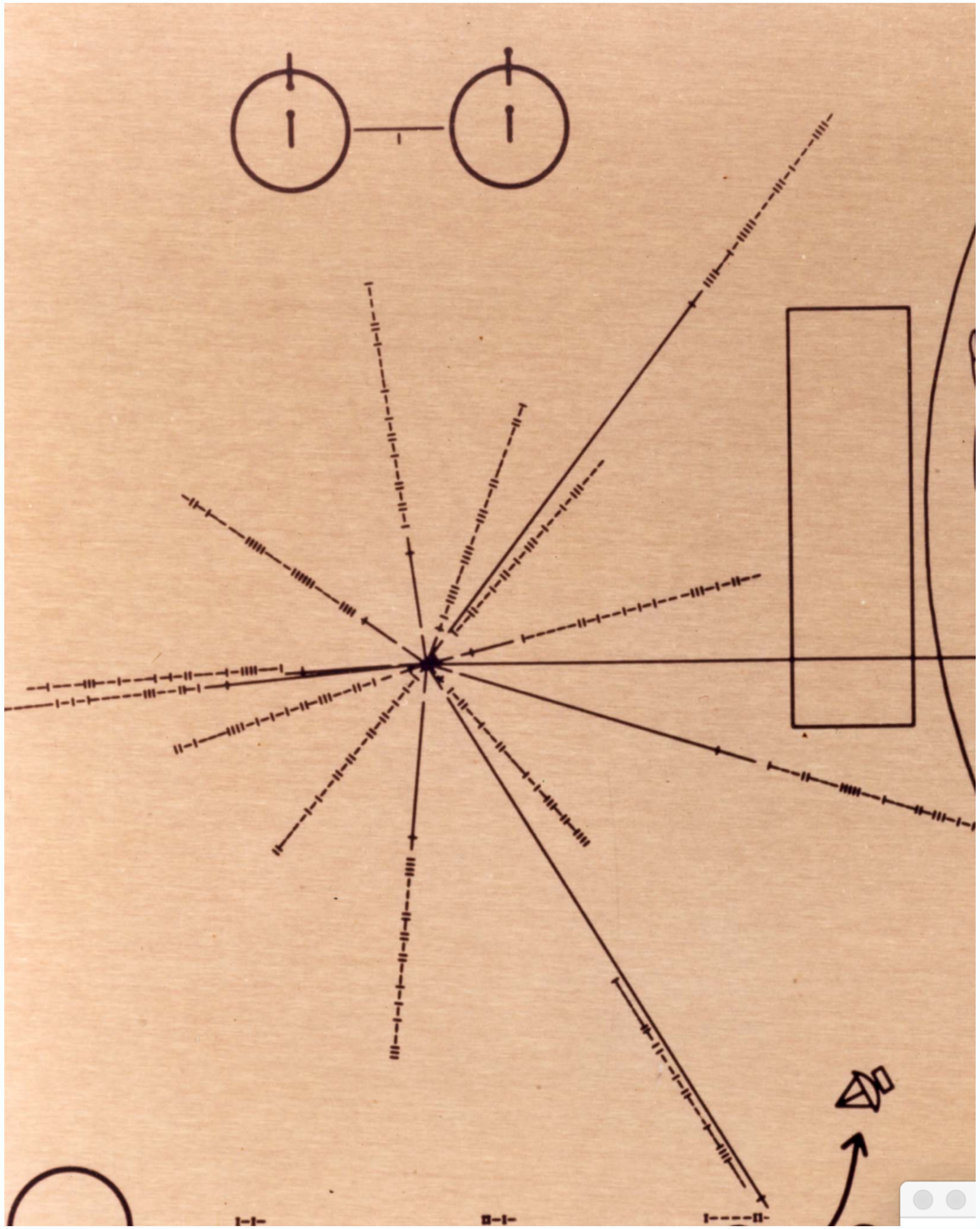
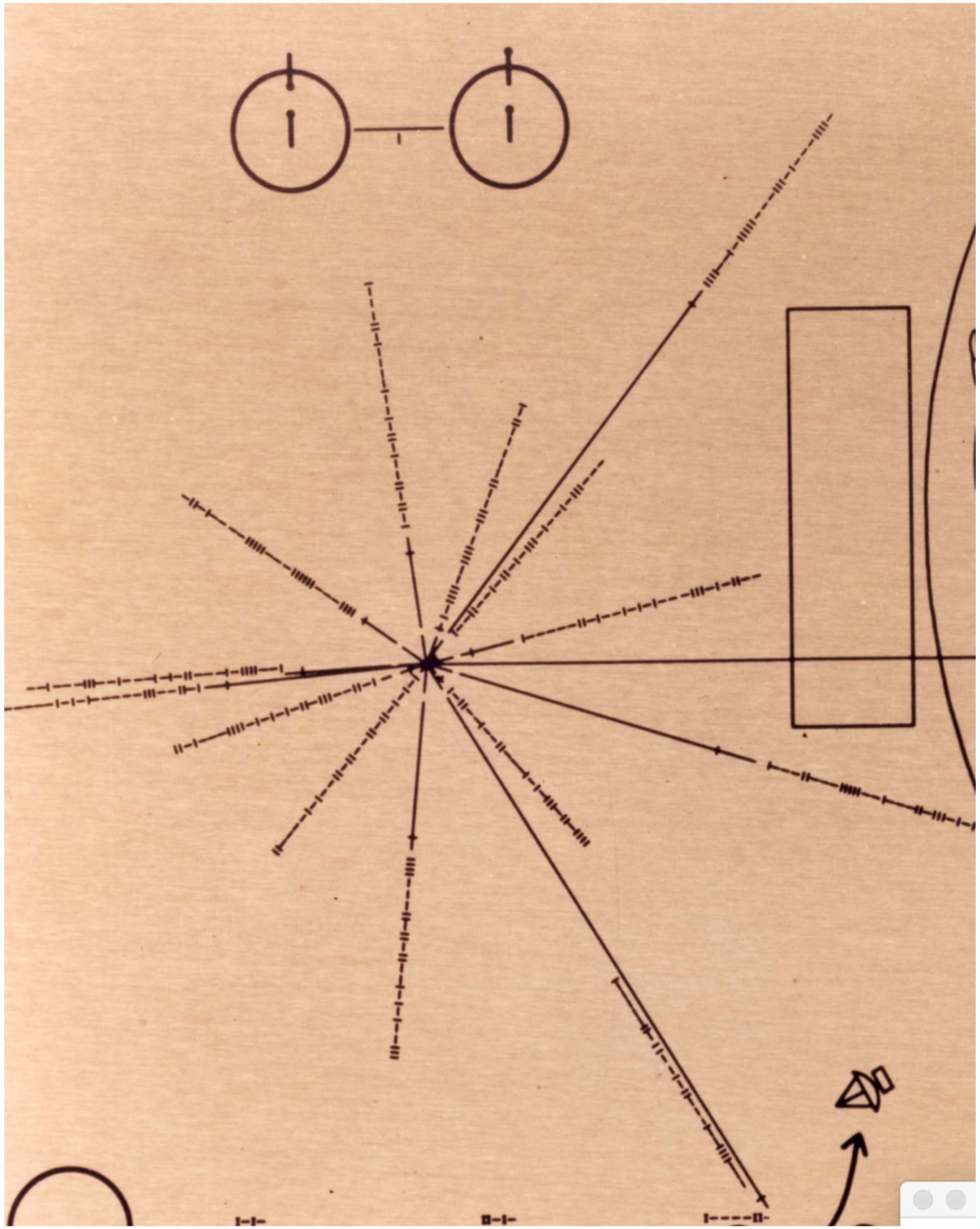


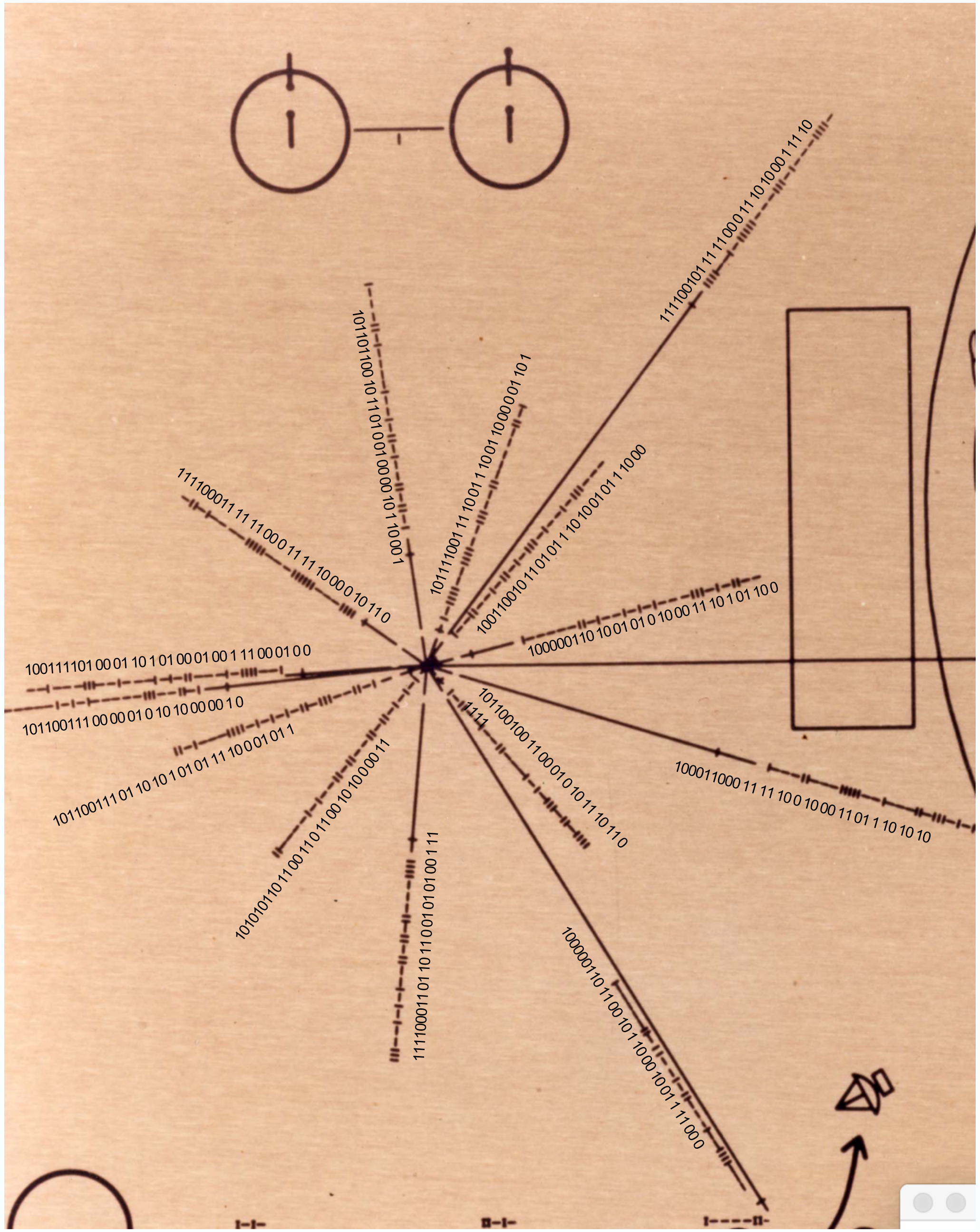


Need good eye-sight!

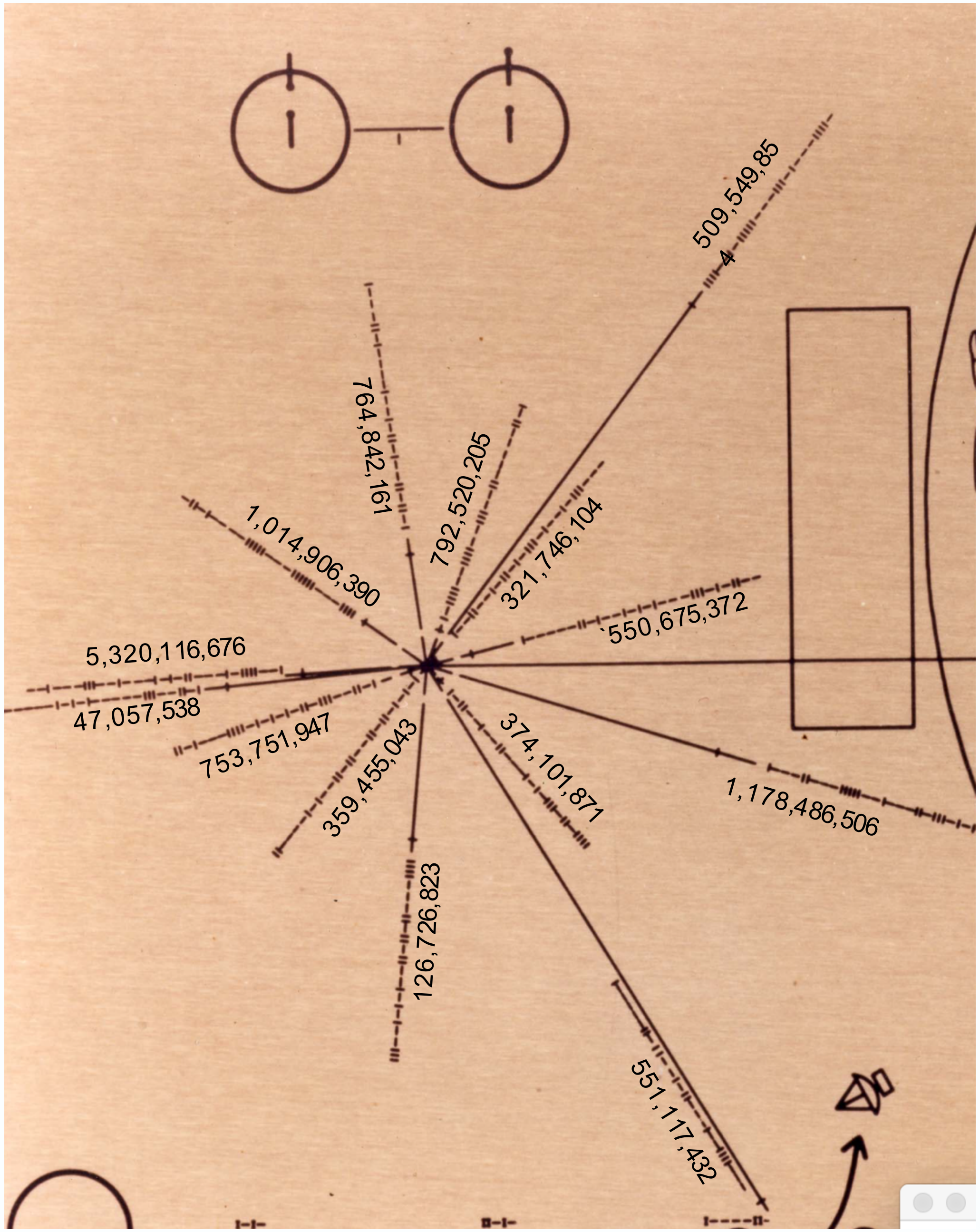


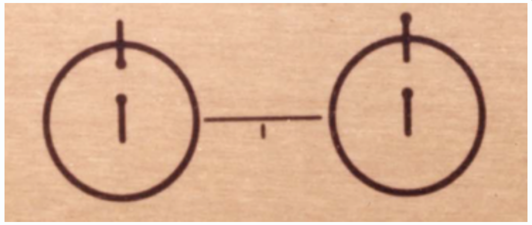


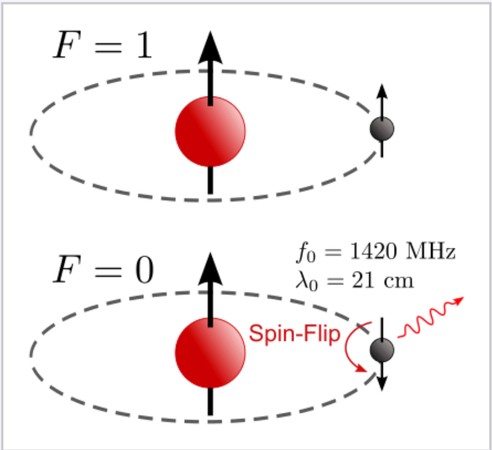
Convert to binary numbers



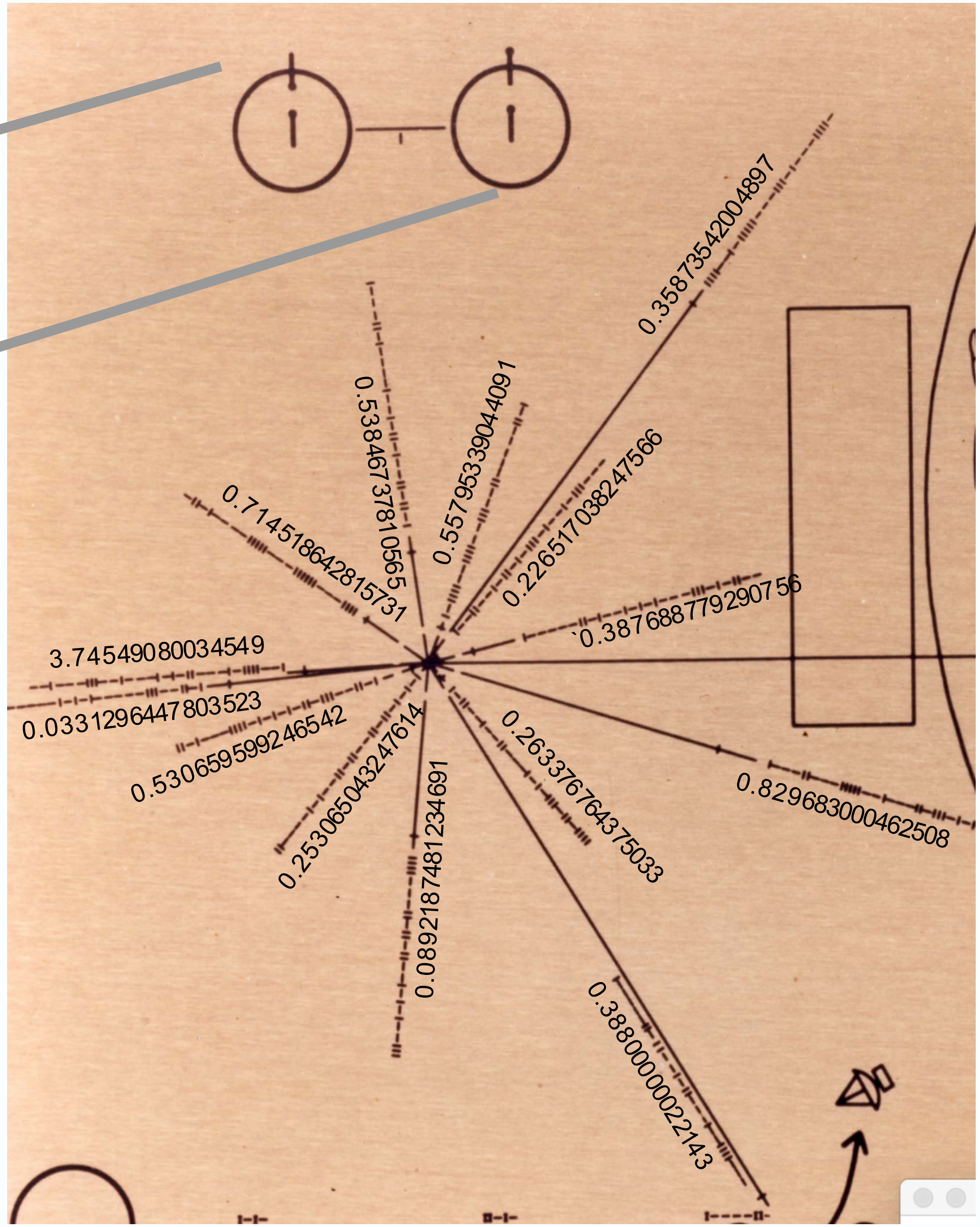
Convert from binary







Hydrogen 21-centimeter line



Spin-flip transition of the hydrogen atom:
1420405751.7667±0.0009 Hz
1/1420405751.7667 = 7.04024183763126e-10 sec

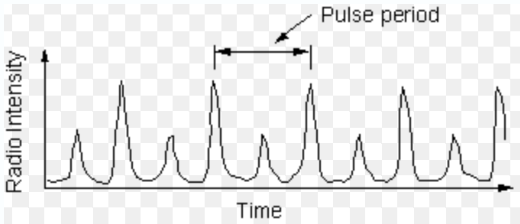
Convert to our units of time (seconds)

What do these values represent?

Pulsars …

… are rapidly rotating neutron stars

… are beacons/light-houses/clocks in space

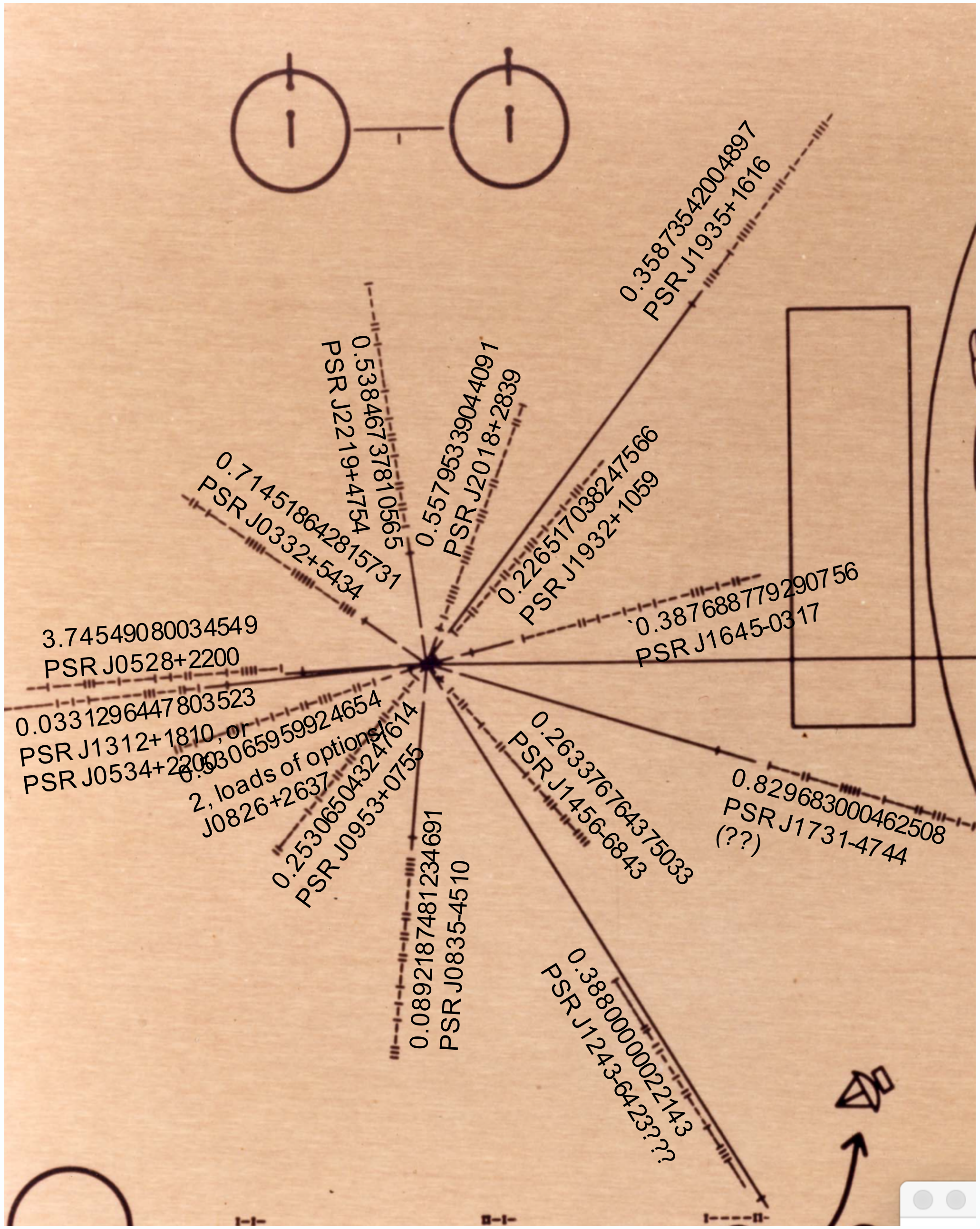


Have “fixed” pulse periods. Can we relate the “values” to pulsar periods?

- Pulsars are slowing down.

- The pulse periods would have been correct at launch – not now!

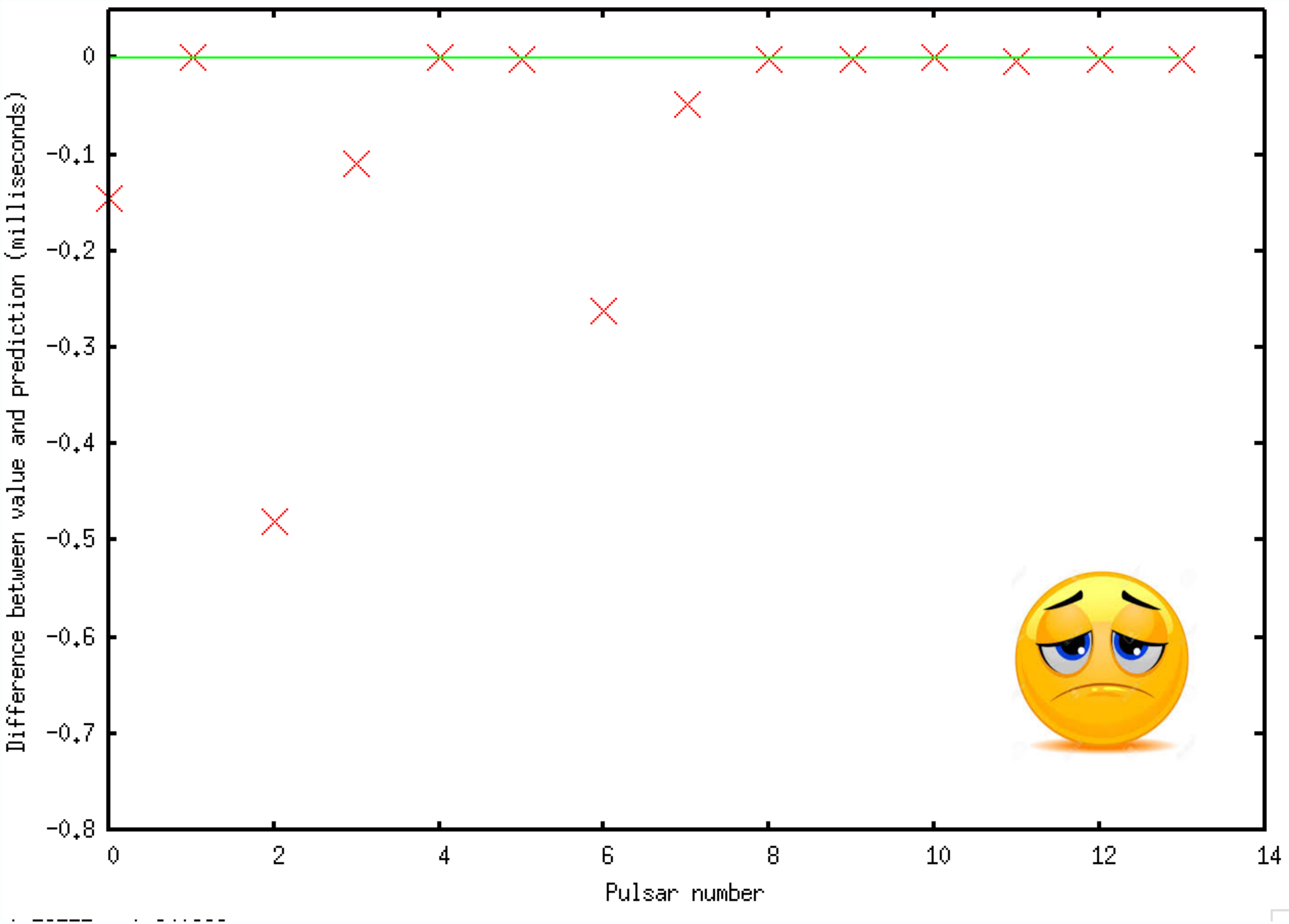
- 2 million year time-scale for discovery



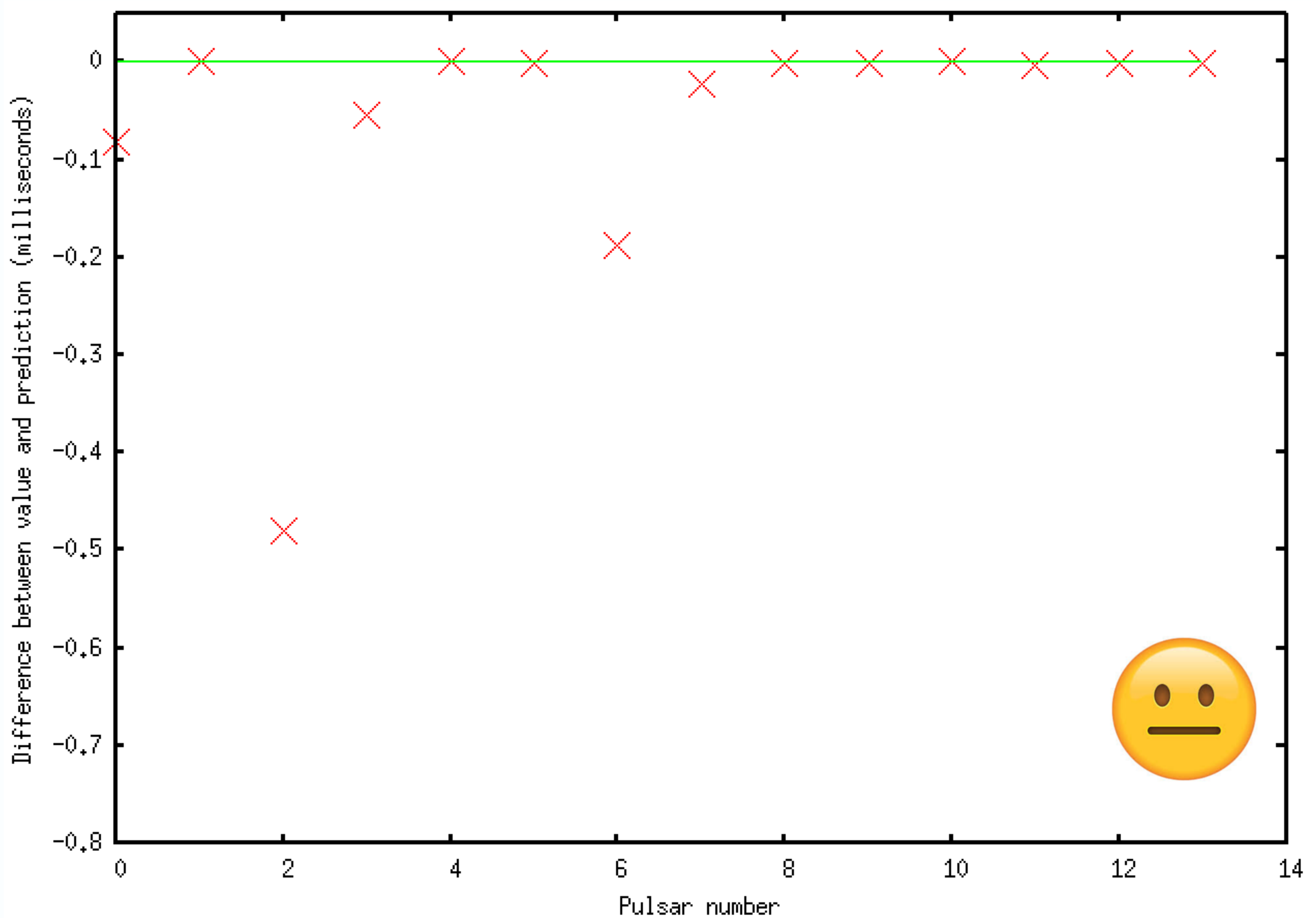
What do we have?

Pulsar	Diagram pulse period (s)	Alien catalogue period (s)	Alien catalogue slow-down rate (s/s)	Alien catalogue epoch
PSR J1731-4744	0.829683000462508	0.82982878524	1.63626E-13	50939
PSR J1456-6843	0.263376764375033	0.2633768148933	9.826E-17	46800
PSR J1243-6423	0.38800000022143	0.388480921041	4.5006E-15	46800
PSR J0835-4510	0.0892187481234691	0.089328385024	1.25008E-13	51559.319
PSR J0953+0755	0.253065043247614	0.2530651649482	2.29758E-16	46375
PSR J0826+2637	0.530659599246542	0.53066051169	1.70932E-15	46450
PSR J0534+2200	0.0331296447803523	0.0333924123	4.20972E-13	48442.5
PSR J0528+2200	3.74549080034549	3.74553925030	4.00530E-14	54200
PSR J0332+5434	0.714518642815731	0.714519699726	2.048265E-15	46473
PSR J2219+4754	0.53846737810565	0.5384688219194	2.765209E-15	46599
PSR J2018+2839	0.55795339044091	0.5579534804225	1.481058E-16	46384
PSR J1935+1616	0.35873542004897	0.3587384107696	6.0025237E-15	46434
PSR J1932+1059	0.226517038247566	0.226517635038	1.157426E-15	46523
PSR J1645-0317	0.387688779290756	0.387689698034	1.780431E-15	46515

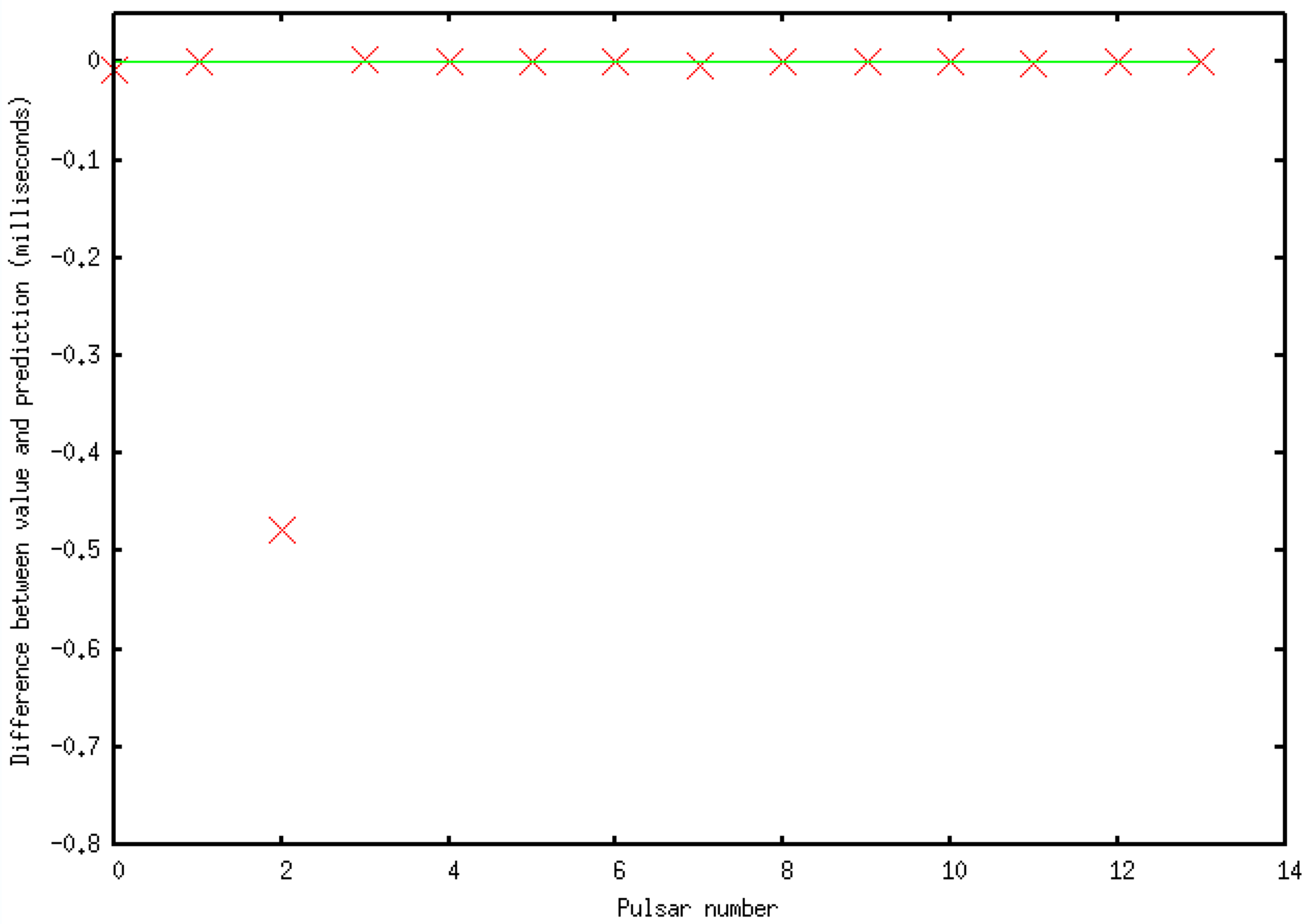
How well do the values match up?



Assume date of launch was MJD 46400 (Dec 1985)



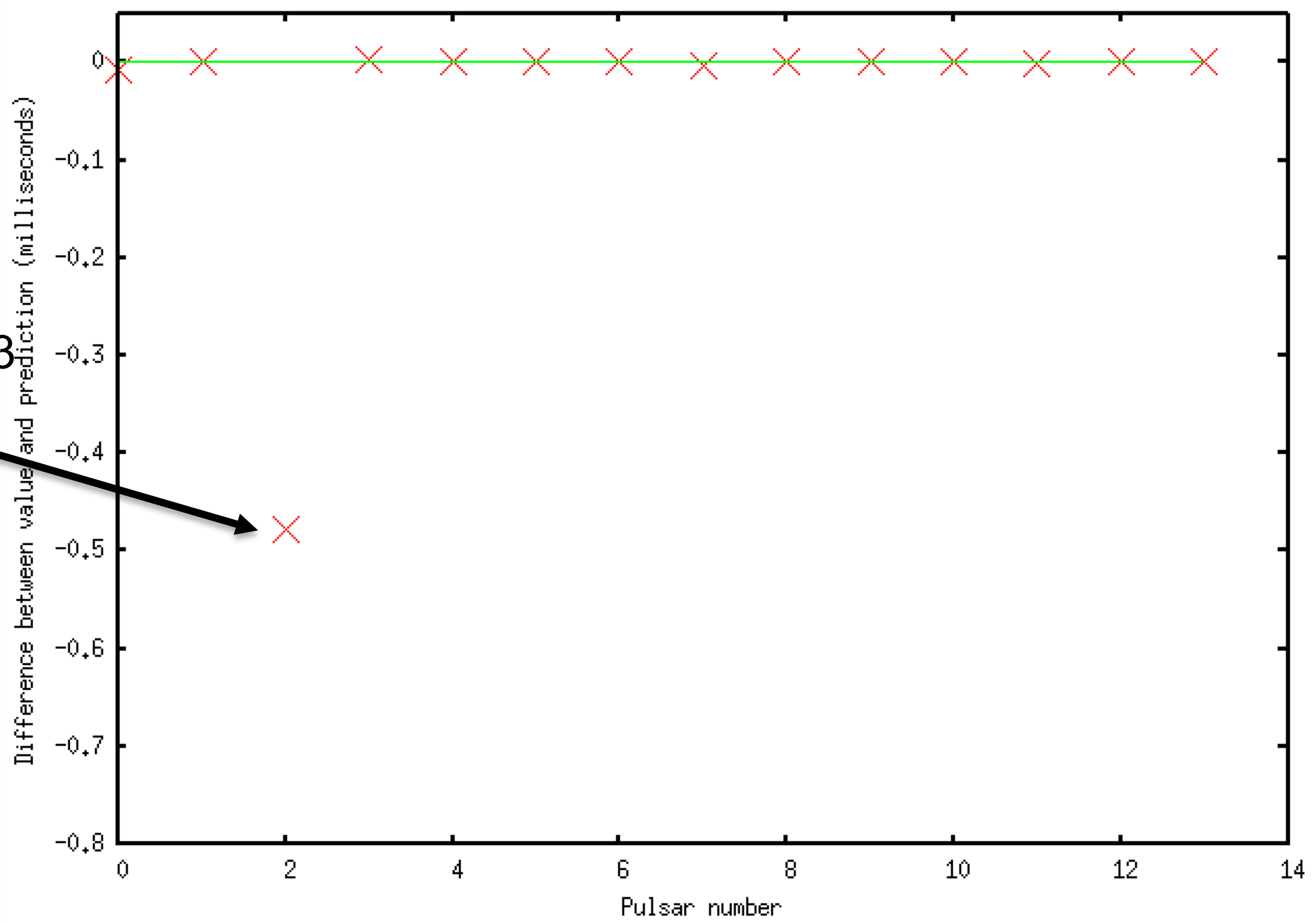
Assume date of launch was MJD 41200 (6th Sept. 1971)



Launch date 3rd March 1972 – MJD = 41379

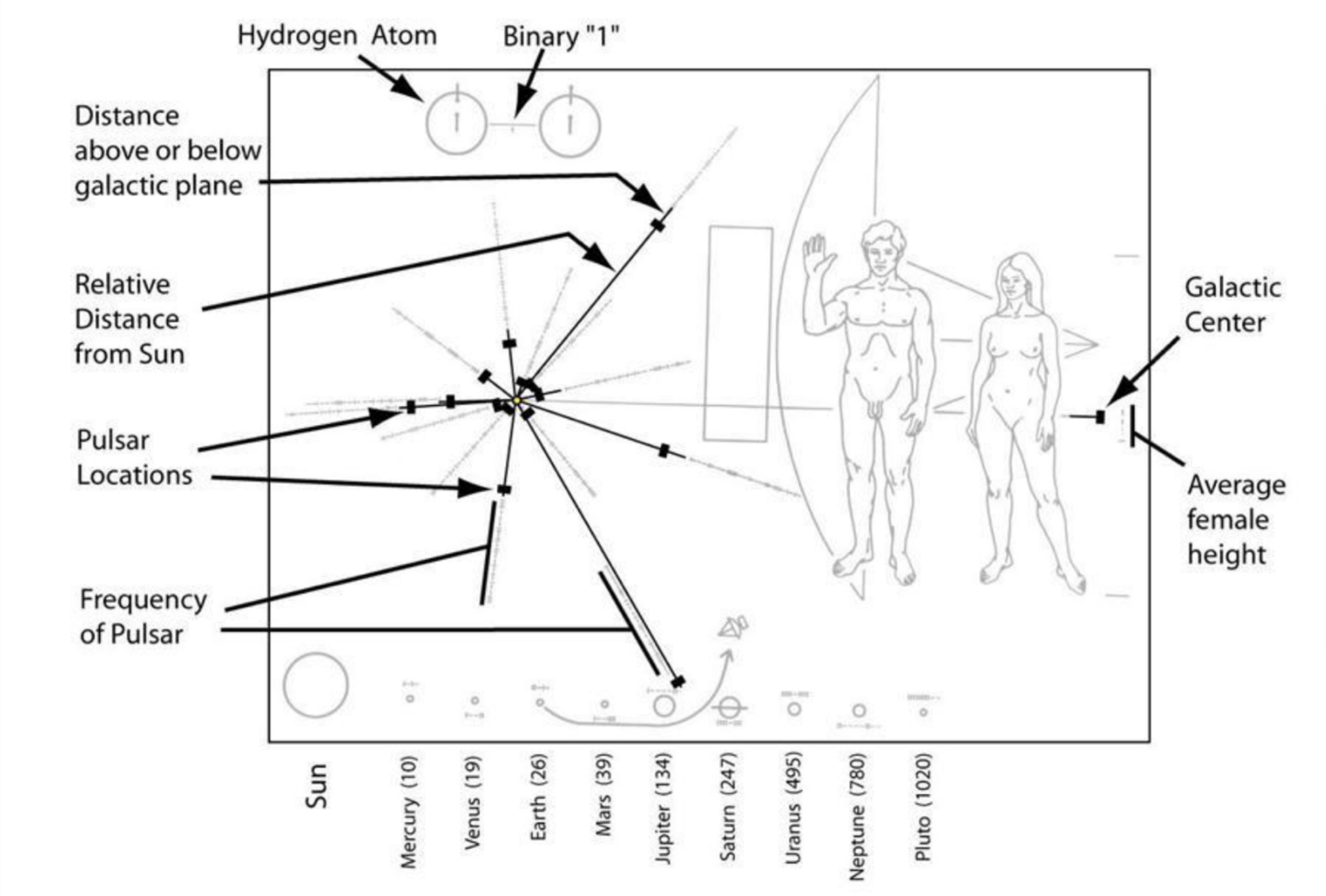
Assume date of launch was MJD 41200 (6th Sept. 1971)

PSR J1243-6423



Launch date 3rd March 1972 – MJD = 41379

Can triangulate to get position of launch ..

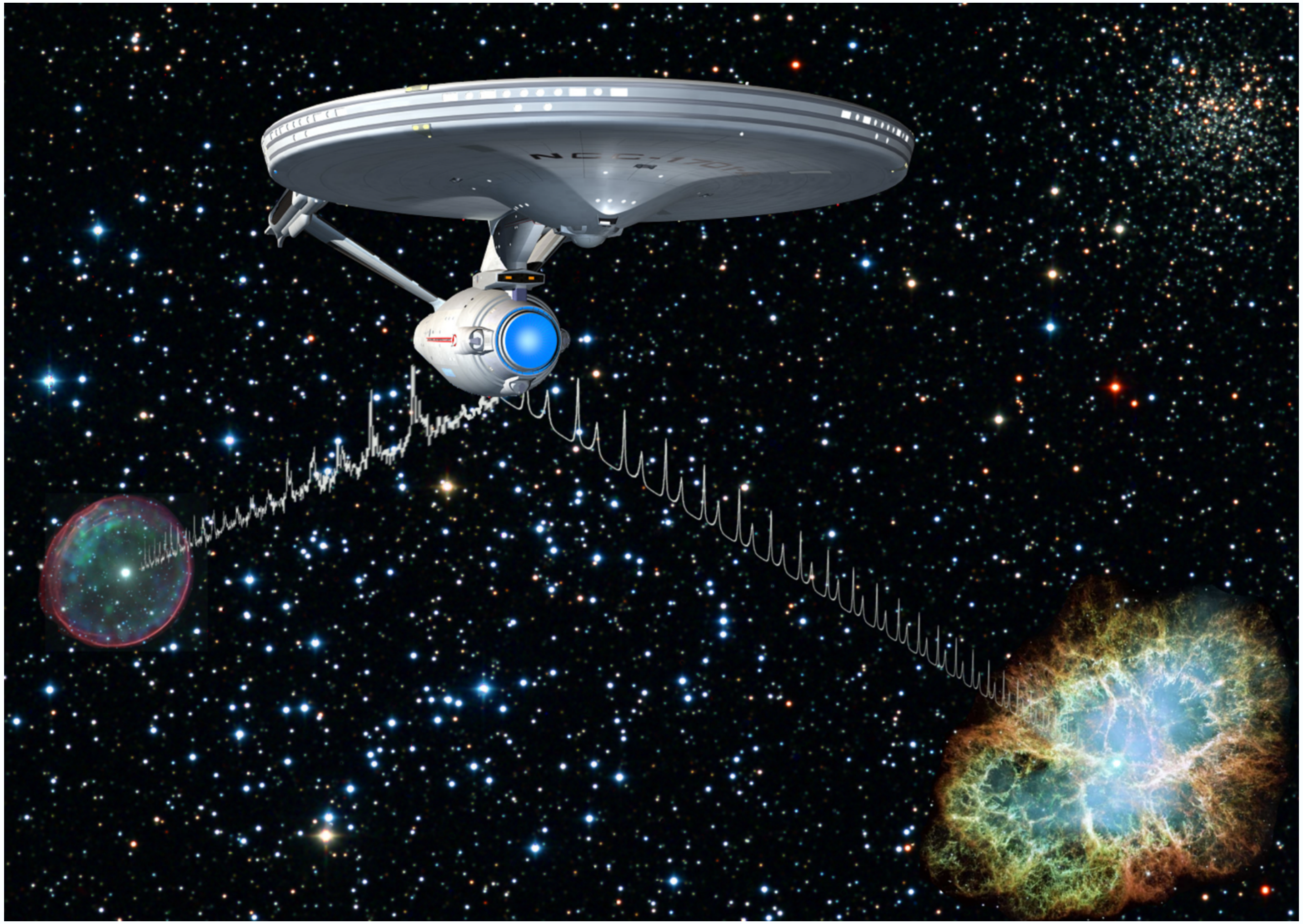


The diagram can give an approximate date of launch and position of our Solar system with respect to a defined set of pulsars!

Basic idea works! Why don't we navigate using pulsars already?

https://launiusr.wordpress.com/2017/05/08/robotic-emissaries-to-the-stars/

Can pulsar navigation really work?



http://www.xray.mpe.mpg.de/~web/psrnav/PSR-Nav_3.jpg

It has been tried …

2016

Now

https://www.infographicbee.com/x-ray-navigation/

https://www.infographicbee.com/x-ray-navigation/

TECHNOLOGY

What Happens If GPS Fails?

Despite massive reliance on the system's clocks, there's still no longterm backup.

SCIENCE & TECH 12 JULY 2016

What would we do if GPS failed?

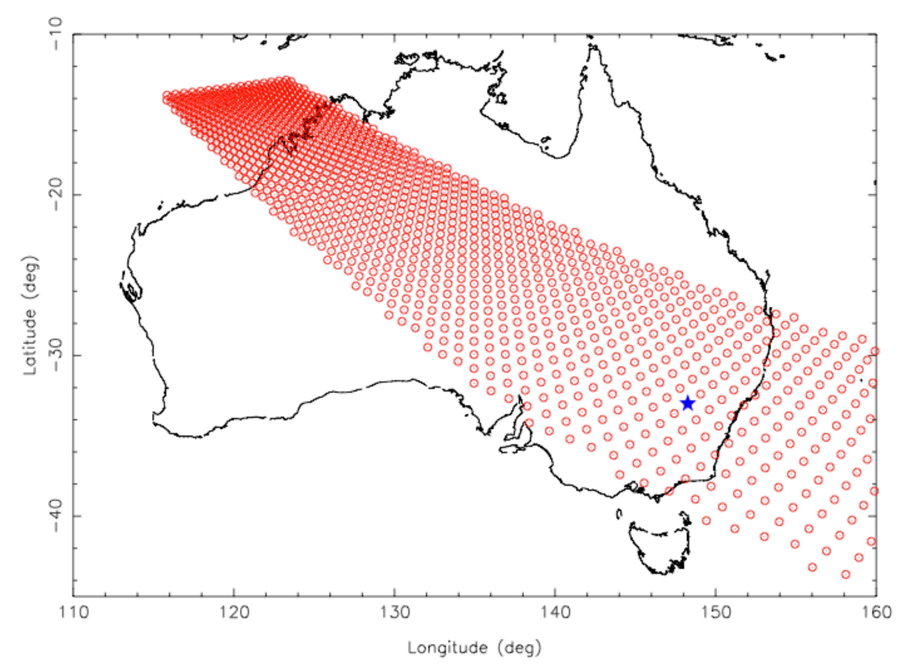
As our dependence on the Global Positioning System grows, a potential failure of its satellites would spell disaster.

GPS attacks risk maritime disaster, trading chaos

Example: where is the Parkes telescope?

Unpublished work by G. Hobbs and X. You

1. Assume that we're on the Earth's surface
2. Use Parkes timing observations and fit for position of Parkes



Proof of concept – where is Parkes?

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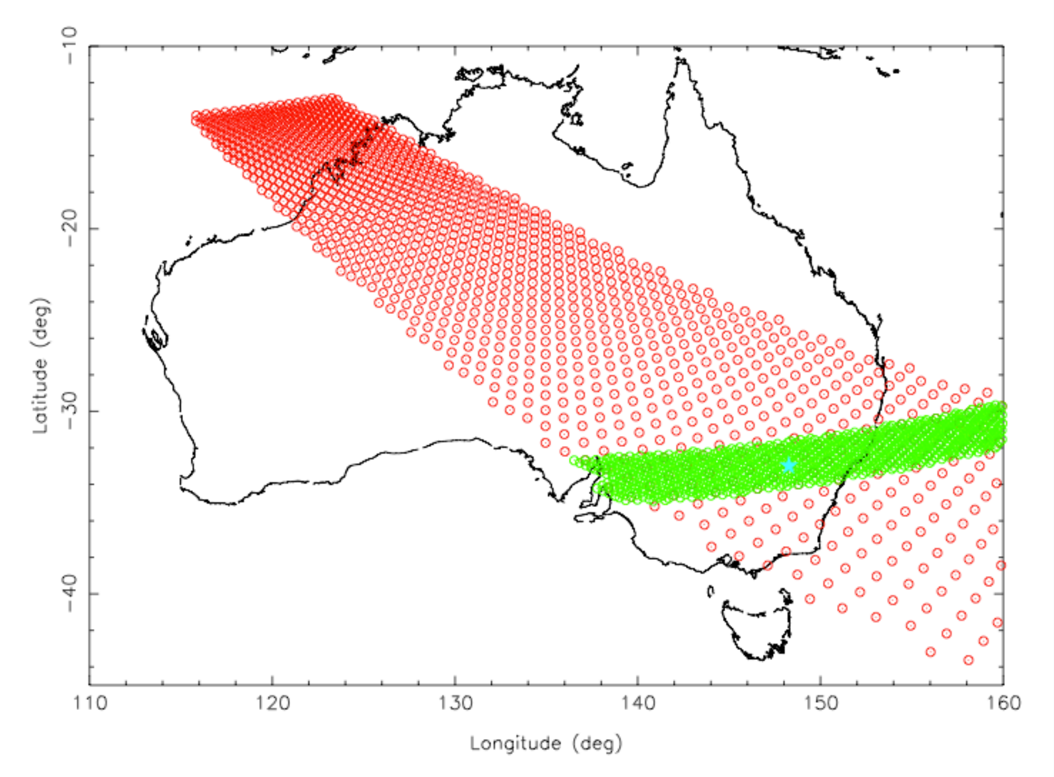

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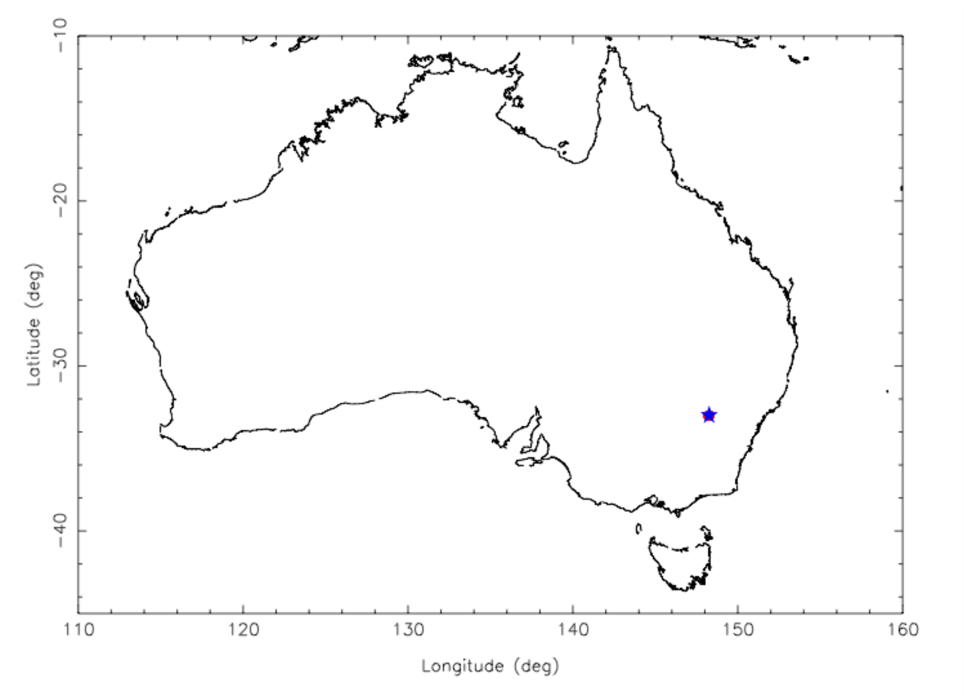


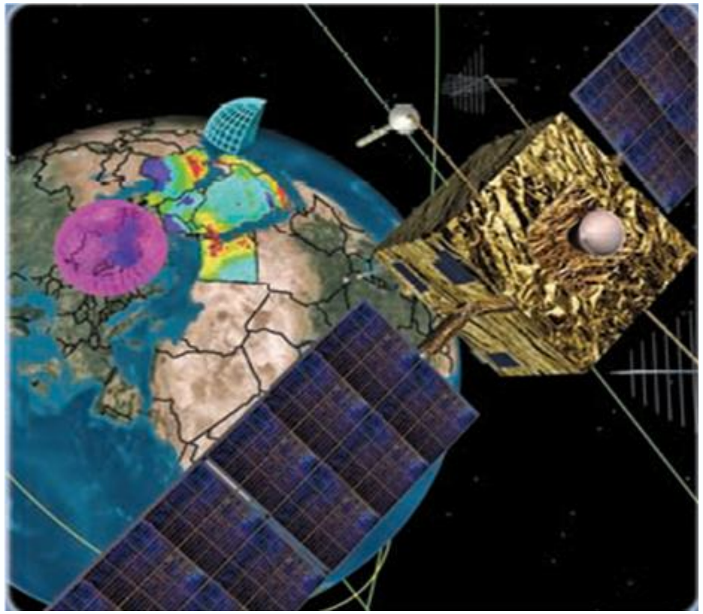
Use millisecond pulsar (PSR J0437-4715)

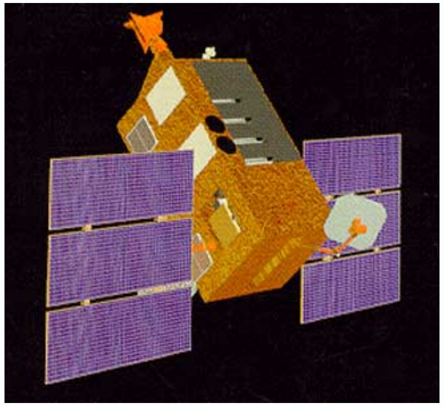
Correct position to within a few kilometers

Can navigate spacecraft: Earth to Mars trajectory (Deng, Hobbs et al. 2013)

1. Can't fit the Parkes telescope on top of your car! => try smaller telescope => X-ray telescopes!
2. Can we use millisecond pulsar observations to determine the position and velocity of a spacecraft travelling from Earth to Mars?
3. Use software to simulate trajectory – accounts for gravitational field, Solar pressure etc.
4. Assume large ground-based radio telescope to get pulsar timing model before launch
5. Assume XTE-type X-ray telescope on-board the spacecraft

http://www.master-flight-training.org/images/AGI_STK.jpg





Two algorithms studied

1. Algorithm 1: assumes no prior knowledge of the space-craft trajectory
2. Algorithm 2: makes use of a dynamics model for the space-craft motion
3. Result: position estimation better than 10km
4. Result: velocity estimation better than 1m/s

https://cordis.europa.eu/docs/results/335/335063/final1-pulsarplane-poster.pdf

An antenna array of planar antennas can be embedded in the wings to provide electronic beam steering and high gain. Considering the available wing area of an airplane, achieving sufficient antenna gain would be possible. Table 1 provides a list of several airplanes currently operating with their wing surface areas.

Table 1: List of selected airplanes and their wing surface areas

Aircraft	Wing Area (m^2)
Airbus A380	845
Boing 747	540
Airbus A320	122
Fokker 100	93
Cessna Citation 1	26

Future generations of aircraft may consider the pulsar navigation antenna as part of their structure design, e.g. as an integrated layer in the Glare structure, see Figure 8.

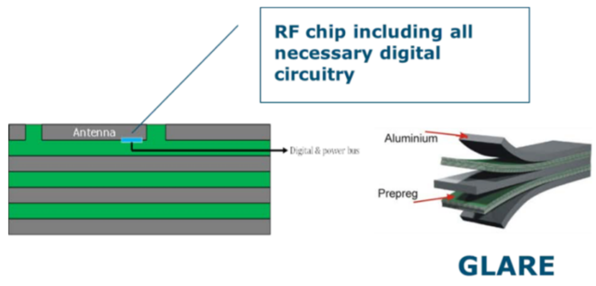


Figure 8: Antenna integration in layered wing skin

https://cordis.europa.eu/result/rcn/175976_en.html

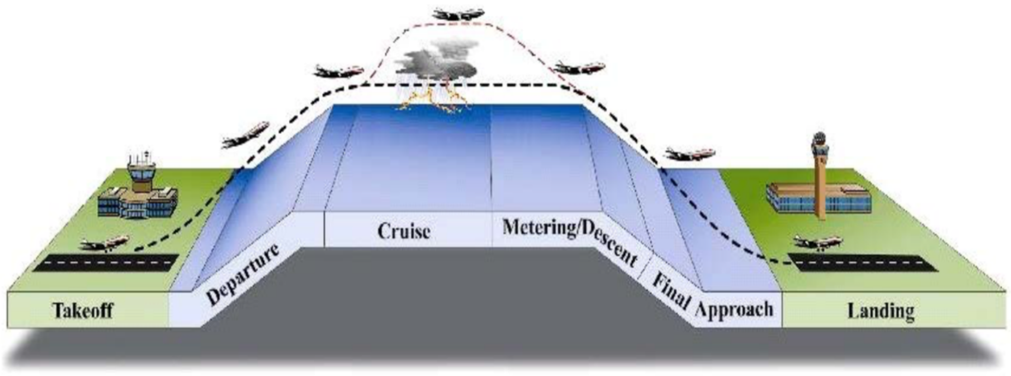


Figure 21: Separate phases of flight from origin to destination

Table 5: Performance of radio navigation systems

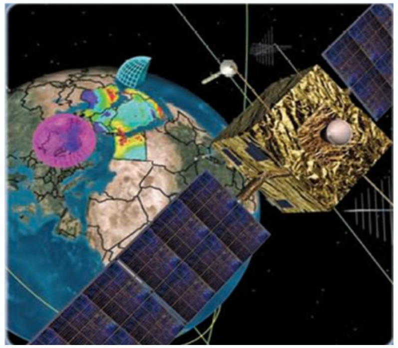
System	World-wide Coverage	Continuous	2/3/4D	Accuracy
Loran-c	No	Yes	2D	250 m
Omega	Yes	Yes	2D	2-4 km
Transit	Yes	No	2D	<100 m
GNSS	Yes	Yes	4D	<10 m
Radio-pulsar	Yes	Yes	3 or 4D	200 m – 2 km

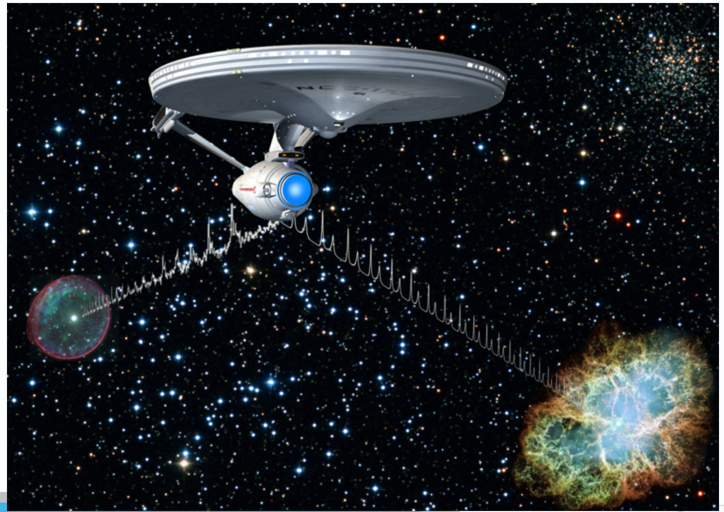
To summarise the conclusions regarding feasibility of pulsar navigation:

- The signal can / should be received with a phased array antenna
- The antenna can be mounted in / on an aircraft wing surface
- The processing can be fast enough with adequate on-board processing power
- The complete signal does not have to be recovered – just the time of arrival will do
- Navigation will be similar to GPS, but with differences (use of an almanac)

Conclusions

- Various groups around the World are taking pulsar navigation projects seriously
- The basic idea works
- Obtaining positions to 10s of kms is possible. Higher precision is not impossible, but challenging
- Applications to space-craft and terrestrial navigation
- *I'm glad that the Qantas pilot was not using pulsar navigation to get me safely to Sydney.*





Thank you

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A GLONASS receiver (red dot) on England's east coast gave position fixes in the North Sea (blue triangles)

The General Lighthouse Authorities of the UK and Ireland have issued a map illustrating the effects of last week's failure in "Russia's GPS" system.

Satellites of the GLONASS network experienced a half-day outage when bad data was uploaded to spacecraft.

The GLA map shows a GLONASS receiver at Harwich giving corrupted position fixes that were off by more than 50km.

The Authorities say the 2 April event is a timely reminder that alternatives to satellite navigation are essential.

https://www.bbc.co.uk/news/science-environment-26957569