Towards Practical Autonomous Deep Space Navigation Using X-Ray Pulsars: Overview and Simulations of Navigation Errors

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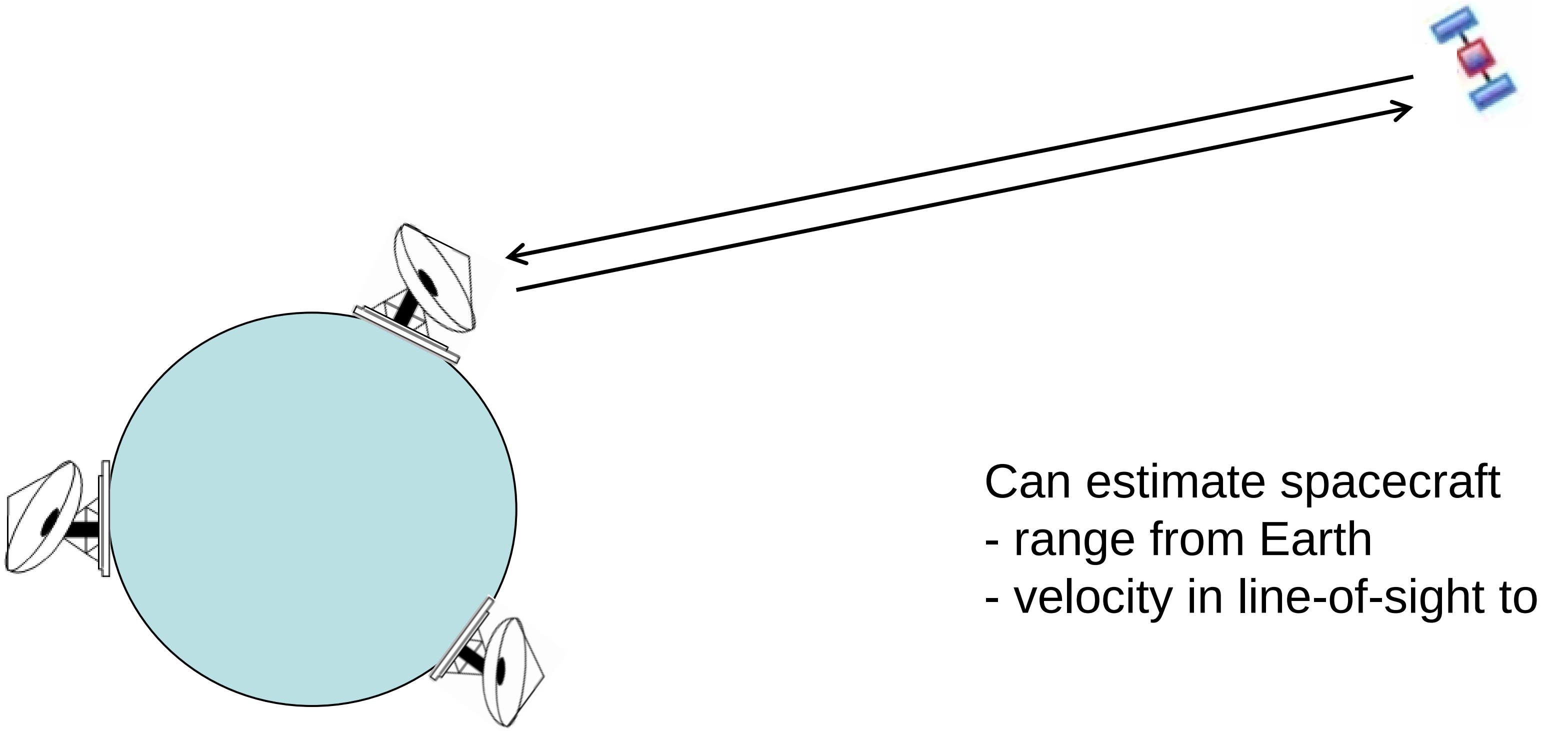
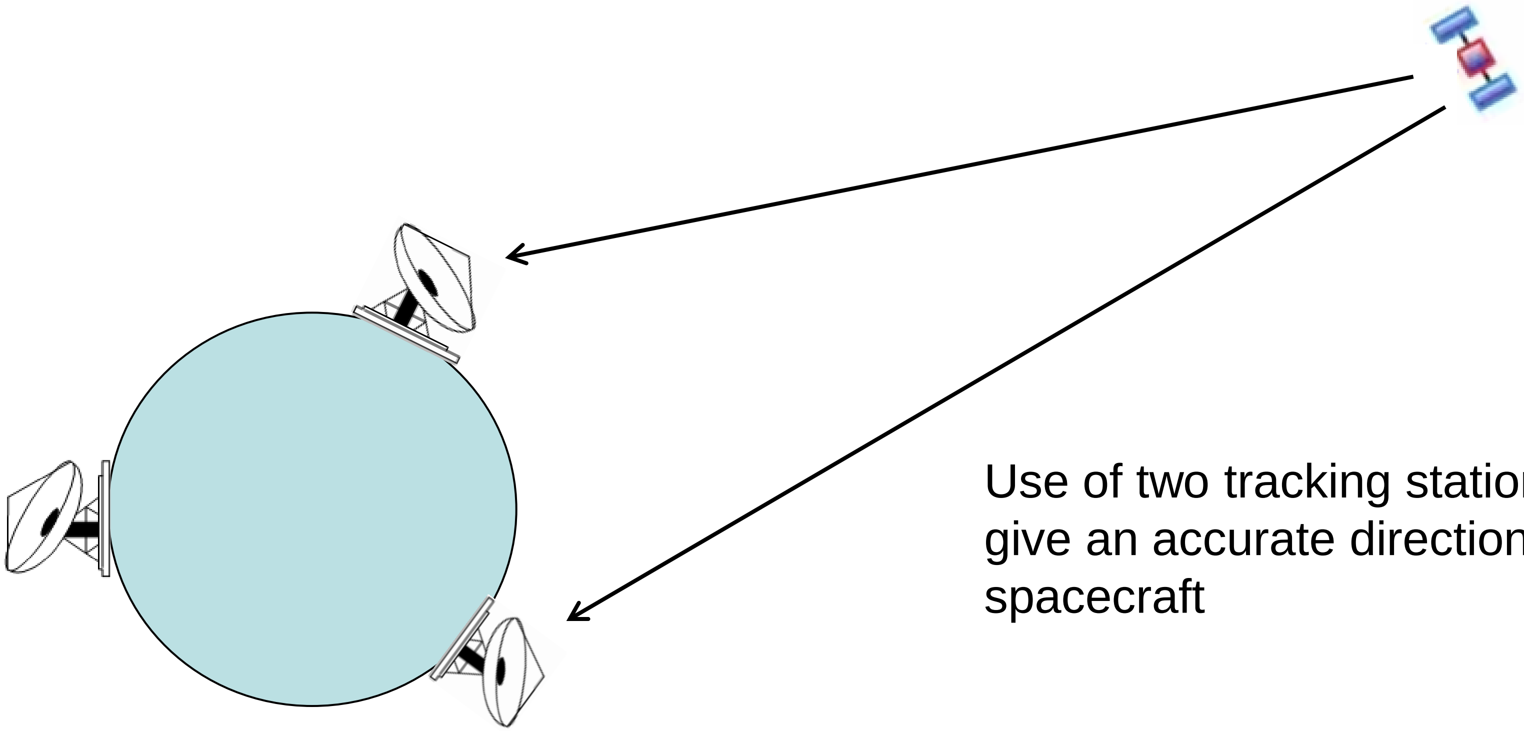
1. Introduction

1. Introduction (ESTRACK & DSN)



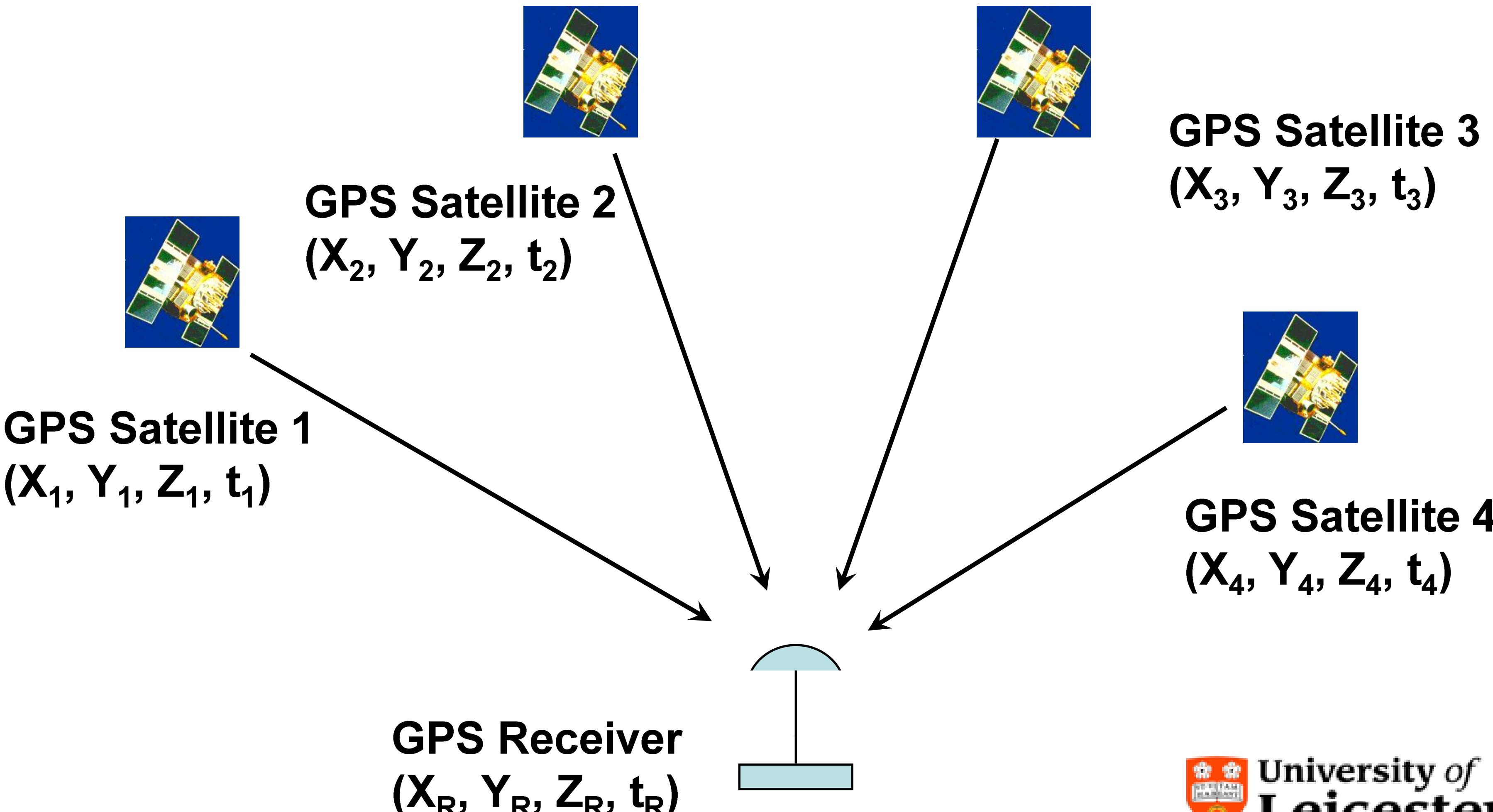
Can estimate spacecraft
- range from Earth
- velocity in line-of-sight to Earth

1. Introduction (ESTRACK & DSN)



Use of two tracking stations can give an accurate direction to spacecraft

1. Position and Time from a GNSS



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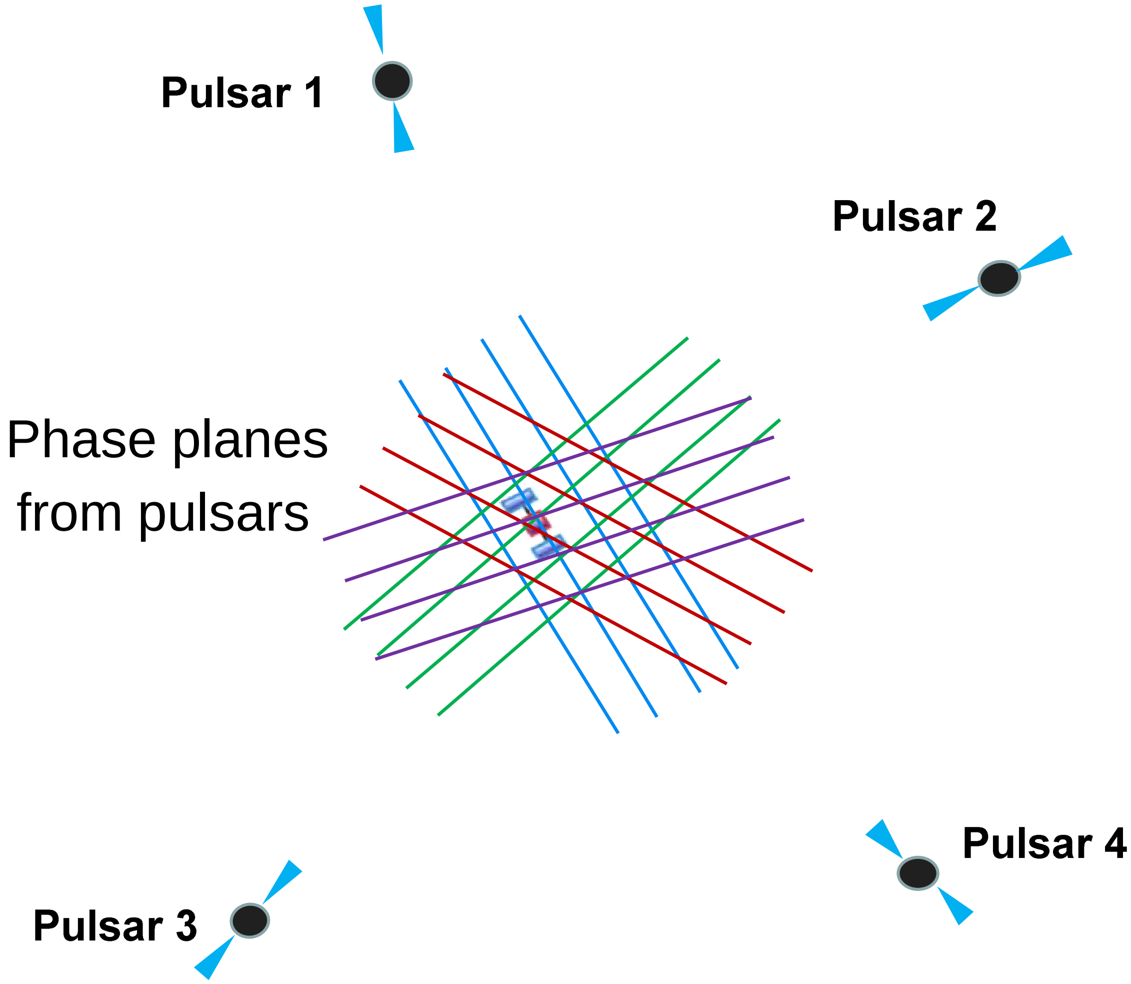
1. Absolute Navigation

- Similar to GPS (Sheikh et al 2006, Sheikh et al 2007)

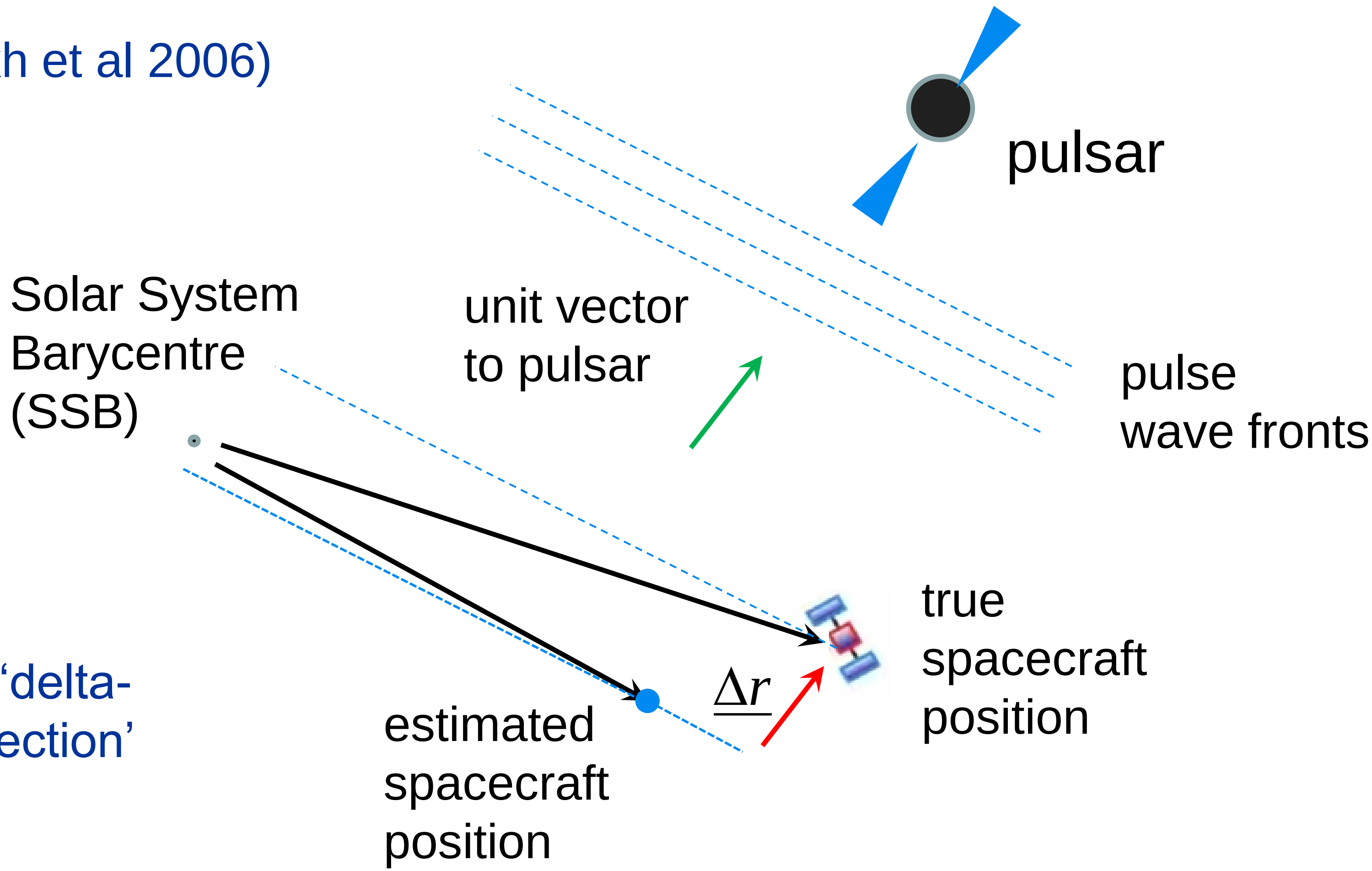
- enables spacecraft 3D position & clock offset from TAI from cold-start

- requires simultaneous observations of 4 or more pulsars
  -could be in sequence
  -use X-rays



1. ‘Delta-correction’ Technique using TOAs of a Single Pulsar

(Sheikh et al 2006)



Δr : ‘delta-correction’

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2. X-ray pulsar catalogue

2. X-Ray Pulsar Catalogue

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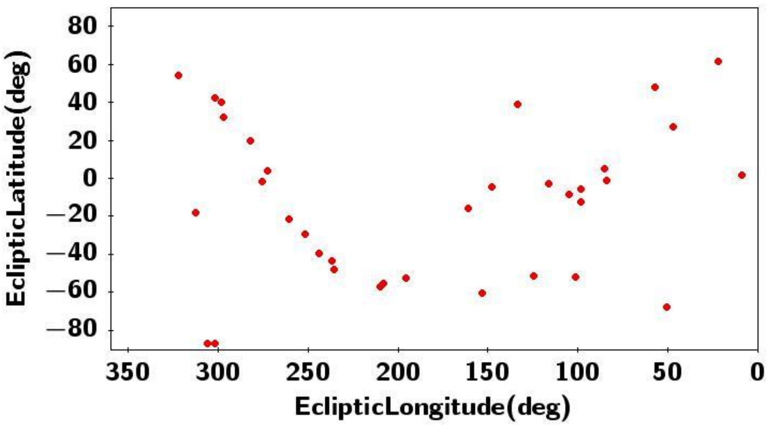
- ~2000 known pulsars, most discovered in the radio band
- ~100 known rotation-powered X-ray pulsars (Becker 2009)
- ~35 with detected pulsed X-ray emission and measured pulse profile
  - Rotation periods ~few ms – ~100s ms
  - ‘millisecond’ pulsars best: periods <20 ms, high stability



Sky, ecliptic coordinates

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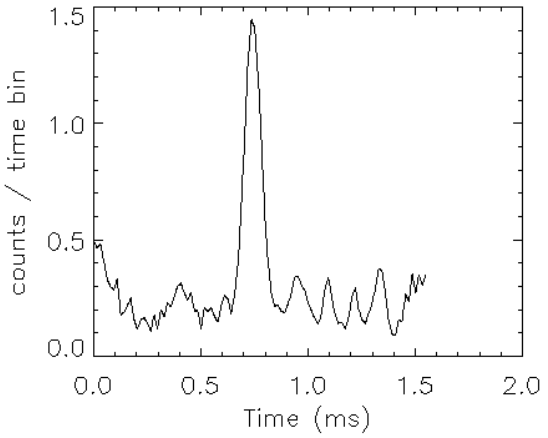
2. Range Error Budgets

- Error on measured pulse TOA x *c*
  = error on measured spacecraft range due to instrument

- Pulsar-dependent factors include
  - pulsar total X-ray flux
  - cosmic-ray background flux
  - pulse profile shape/width



- Observing instrument-dependent factors inc
  - effective area
  - source-detection area
  - total observation duration
  - focussing or collimator

2. Range Error Budgets

- For most cases a **simple, analytic formula** was used for the range error estimate
(from basic statistics):

$$\sigma_L = c\,\sigma_{TOA} = c\,\sigma_\phi\,P \sim K\,c\,HWHM_{pulse} / SNR$$

- For a small number of pulsars with the lowest range errors, **simulation of pulse profile signal** allows test of formula & detailed examination of specific cases.

- Analytic formula & simulation agree to within factor ~3 → validates formula/ranking.

- These enable us to generate a ranking for the pulsars according to likely utility for XNAV.

2. Range errors (T_{obs} =10 hrs) for MIXS-T, F=1 m, A= 50cm^2

Pulsar name	Range error for collimator-based detector (m)	Range error for focussing-based detector (m) ie MIXS-T
PSR B1937+21	5000	1200
PSR B0531+21 (Crab)	400	700
PSR B1821-24	30000	2750
PSR J0218+4232	30000	2900
PSR J0205+6449	30000	14000
PSR J1012+5307	850000	23000
PSR J0437-4715	200000	16400
PSR B0540-69	50000	30000
PSR J0030+0451	550000	38000
PSR B1509-58	90000	56000

Preliminary results shown above

3. Navigation error analysis

3. Navigation Error Analysis

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- Simulated errors for 3 navigation strategies

1) Absolute navigation using 4 pulsars
2) Absolute navigation using 3 pulsars with an accurate time reference
3) Delta-correction using a single pulsar

- Used all possible pulsar combinations
- Two major error components
  - range errors X-ray instruments
  - pulsar position errors in the sky.
- Included an error component due to the timing model
- Used instrument range errors given previously for MIXS-T instrument
- Results for a spacecraft at a distance of Neptune (30AU within the ecliptic plane)

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3. Navigation Error Analysis

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In absolute navigation using 3 pulsars, position is given by (Graven et al 2008)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \begin{bmatrix} \frac{cT_1}{2\pi}\phi_1 \\ \frac{cT_2}{2\pi}\phi_2 \\ \frac{cT_3}{2\pi}\phi_3 \end{bmatrix}$$

Unit vectors of pulsar positions

T_1, T_2 … = pulsar period

ϕ_1, ϕ_2 … = measured phase

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3. Navigation Error Analysis

In absolute navigation using 3 pulsars, position errors are given by (Graven et al 2008)

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \begin{bmatrix} \frac{cT_1}{2\pi}\Delta\phi_1 \\ \frac{cT_2}{2\pi}\Delta\phi_2 \\ \frac{cT_3}{2\pi}\Delta\phi_3 \end{bmatrix} - \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \begin{bmatrix} \Delta x_1 & \Delta y_1 & \Delta z_1 \\ \Delta x_2 & \Delta y_2 & \Delta z_2 \\ \Delta x_3 & \Delta y_3 & \Delta z_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$\Delta\phi_1$, $\Delta\phi_2$ … = phase measurement error

Errors in unit vectors of pulsar positions

A similar approach to above can be used for the 4 pulsar case.

3. Absolute navigation using 3 & 4 pulsars at 30 AU

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Preliminary results

Parameter	PSR B1937+21,PSR B1821-24, PSR J0437-4715		PSR B1937+21, PSR B0531+21, PSR J0437-4715	
	T_{obs}=10 hr	T_{obs}=1 hr	T_{obs}=10 hr	T_{obs}=1 hr
Position error (km)	45	140	80	150
Velocity error (ms^{-1})	0.7	23	0.6	20

Parameter	PSR B1937+21,PSR B1821-24, PSR J1012+5307, PSR J0437-4715	
	T_{obs}=10 hr	T_{obs}=1 hr
Position error (km)	60	130
Velocity error (ms^{-1})	0.9	23

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3. Delta-correction method using a single pulsar at 30 AU

Parameter	PSR B1937+21		PSR B0531+21	
	T_{obs}=10 hr	T_{obs}=1 hr	T_{obs}=10 hr	T_{obs}=1 hr
Position error (km)	2.0	5.0	34	35
Velocity error (ms^{-1})	0.03	1.0	0.05	1.0

3. Navigation Error Analysis

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- Curekendall & Border 2013 describe that DSN positioning in the plane of the sky approaching ~ 1 nrad using Delta-DOR ie 150 m at 1 AU and 4.5 km at 30 AU.

- XNAV 3D position errors at 30 AU from the SSB and using observations times of 10 hours are about an order of magnitude greater than those given above for DSN (assuming this to be 4.5 km at 30 AU). This would be for a potential realistic X-ray instrument that could be used as a spacecraft sub-system. These errors would reduce by averaging over longer observations. XNAV also allows potential of spacecraft autonomy and may be most useful during the cruise phase.

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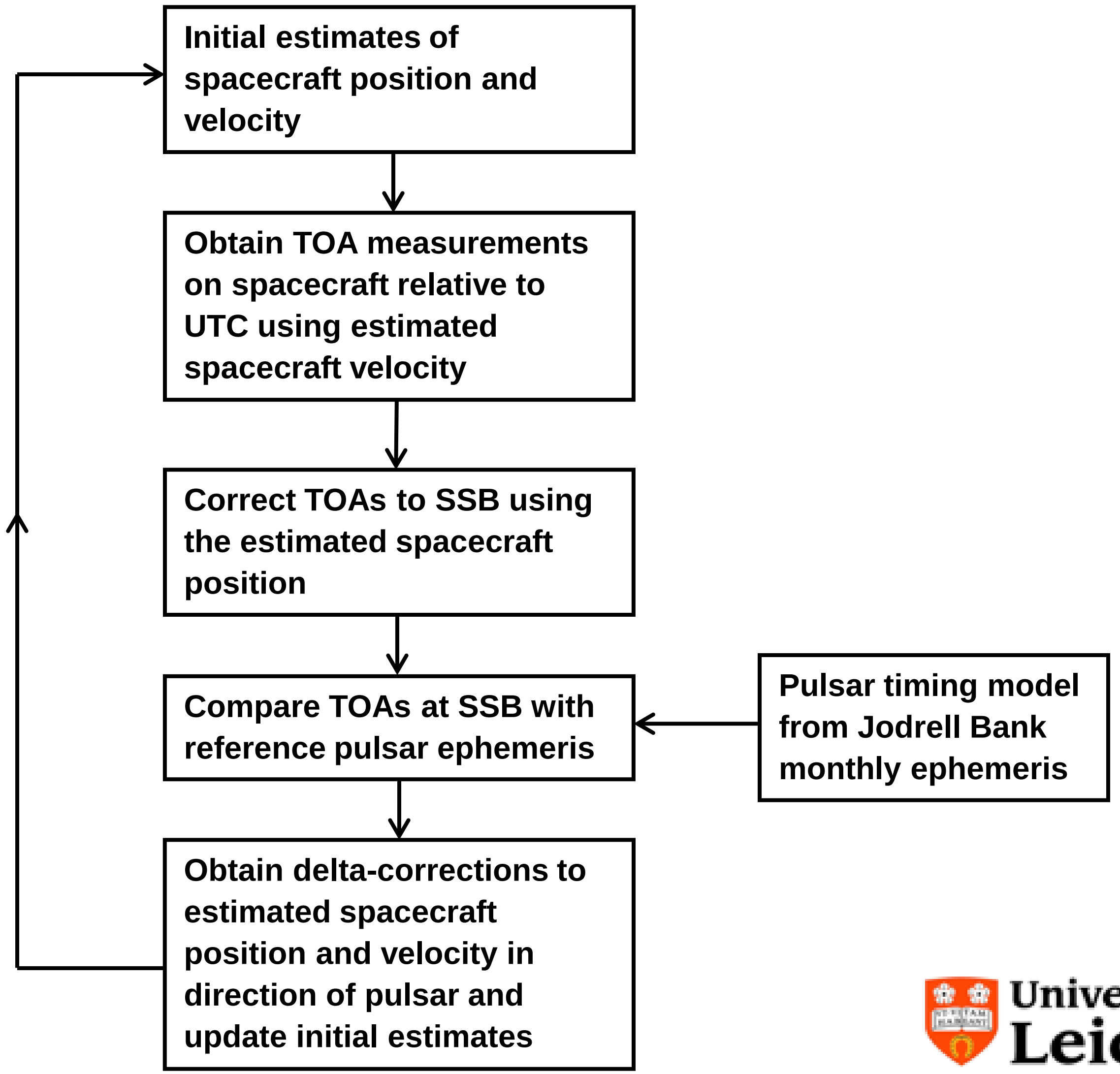
4. High level demonstration of basic elements of XNAV

4. High level demo of XNAV using RXTE data for Crab pulsar

- Have used ~2000 s of crab pulsar data obtained from the RXTE online database.
- 3.35 s (100 pulses) of data used to derive each TOA.
- Each TOA has 140 μs uncertainty.
- The uncertainty of the timing model is 4 ms due to a glitch in the pulsar two days earlier.
- Assumed that a typical timing model has an uncertainty of 100 μs when there is no glitch. Have simulated a new data-set using the real data to demonstrate a case where there is no glitch.
- An initial estimate of spacecraft position used.

4. High level processing used



4. Algorithm Output Data

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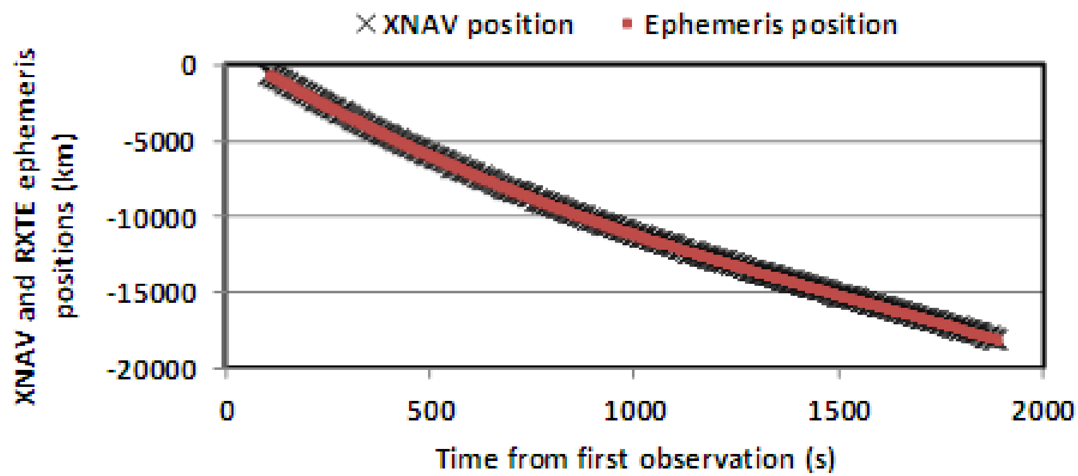

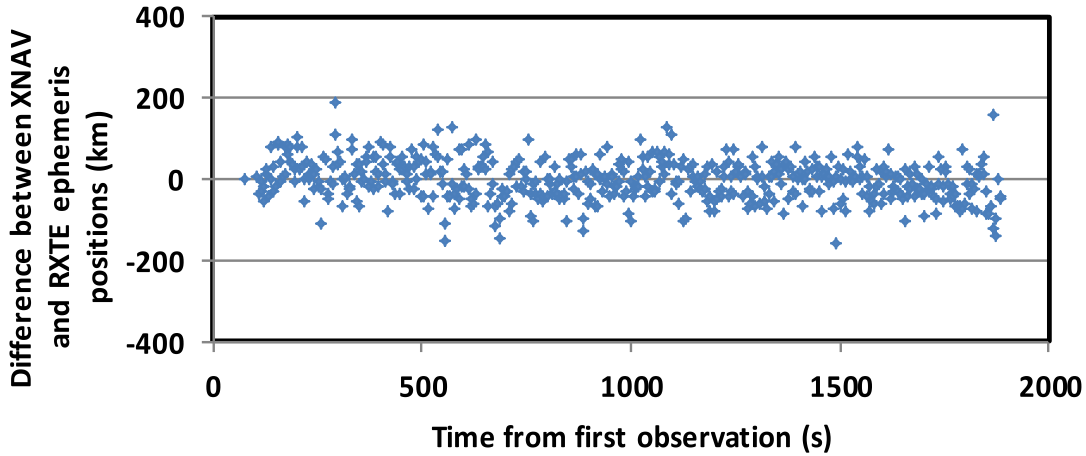

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4. Key results

- 3.35 s of Crab data enable a position accuracy of 50 km.
- Have assumed a typical uncertainty in the timing model of 100 μs and simulated a data-set using real data.
- This gives a first demonstration of XNAV positioning.
- Spacecraft positioning accuracy needs to be scaled appropriately for a specific instrument.

5. Technology

5. Technology

- Concentrated on focussing instrumentation

- Requirements:
  - Large collecting area
  - High timing accuracy (<~1 μs)
  - Low mass, volume, power

- Must be able to be implemented as a spacecraft subsystem

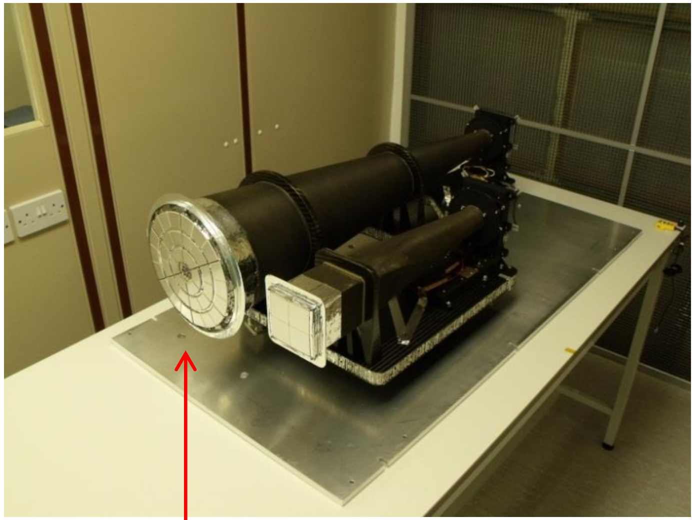
- Instrument pointing at pulsars is a technology challenge.

- An absolute time reference is a limiting factor for spacecraft autonomy.

5. Technology

X-ray telescope utilising low-mass Micro-Channel Plate (MCP) optics: being developed at University of Leicester for first use in space on ESA/JAXA BepiColombo mission to Mercury (MIXS – Mercury Imaging X-ray Spectrometer):

- MIXS-T: Wolter-I MCP optic
  - Total instrument mass ~10 kg
  - Focal length 1 m
  - Effective area ~50 cm^2
- Flight Model has now been delivered to ESA.



Bepi-MIXS optical bench assembly (Structure Thermal Model). **MIX-T (left)**: Wolter-I MCP optic + DEPFET APS detector

5. Preferred Technology

- Single telescope module
- Photon energy range: ~0.5 – 8 keV
- Accommodation requirements (incl. DPU+PSU):
  - mass <~12 kg
  - power ~16 W
  - volume:
    - telescope ~260x260x1000 mm^3
    - DPU+PSU ~2x[320x170x55] mm^3
  - Spacecraft to provide ability to point XNAV instrument around sky

6. Summary

6. Summary

- DSN enables positioning in the plane of the sky using Delta-DOR to 150 m at 1 AU and 4.5 km at 30 AU.

- Focussing instrument has lower errors than a collimator.

- Results show XNAV 3D position errors at 30 AU using observation times of 10 hours are about an order of magnitude greater than the best accuracy expected from DSN (assuming this to be 4.5 km at 30 AU). This would be for a potential realistic X-ray instrument that could be used as a spacecraft sub-system. These errors would reduce by averaging over longer observations. XNAV also allows potential of spacecraft autonomy and may be of most benefit during the cruise phase.

- In the best case, the spacecraft position error is 2 km after 10 hour observing of PSR B1937+21 at 30 AU. This is in the pulsar direction only.

6. Summary

- Pulsar position errors are one of the limiting factors. If these could be reduced sufficiently, the spacecraft positioning errors would immediately be reduced.
- Could use X-ray pulsars with DSN for improved positioning. This could enable higher accuracies perpendicular to the direction of Earth.
- A high-level navigation algorithm and data for the Crab pulsar have been used to demonstrate key elements of an XNAV system.
- Potential instrumentation has been developed, in the context of the Mercury Imaging X-ray Spectrometer for ESA's BepiColombo mission.