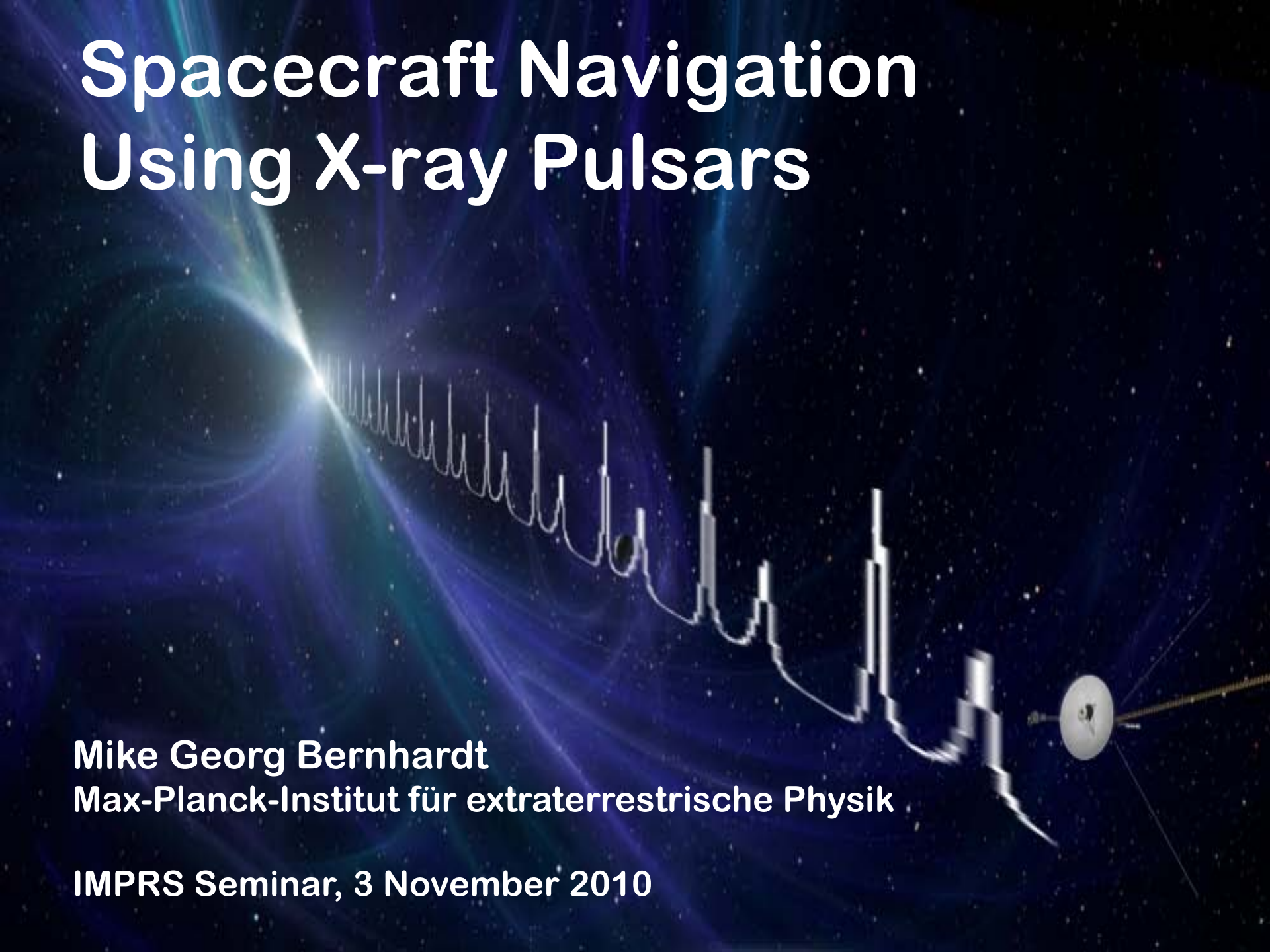
Spacecraft Navigation Using X-ray Pulsars



Mike Georg Bernhardt
Max-Planck-Institut für extraterrestrische Physik

IMPRS Seminar, 3 November 2010

Outline

1. Conventional Navigation
2. Pulsar-Based Navigation
3. First Results
4. Next Steps

1. Conventional Navigation

Radio Tracking

Deep Space Network (NASA)

Credit: NASA

Achievable Accuracy

~ 4 km per AU

Example	Max. Distance from Earth (AU)	Position Error (km)
Mars	3	12
Jupiter	7	28
Saturn	11	44
Uranus	21	84
Neptun	31	124
Pluto	50	200
Voyager 1	115	460

Disadvantages

1. Errors grow with distance
2. Not autonomous

2. Pulsar-Based Navigation

Three Steps

Step 1

Measuring pulse profiles

Step 2

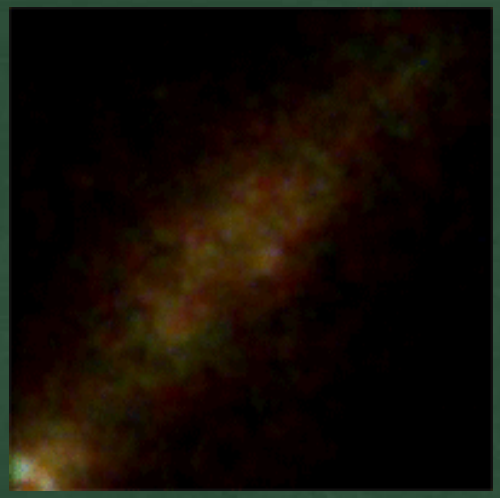
Comparing with reference profiles

Step 3

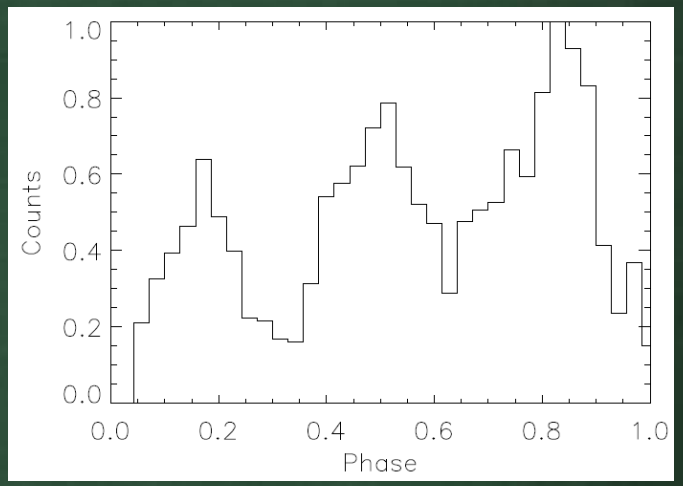
Position determination

Step 1: Measuring Profiles

Vela Pulsar

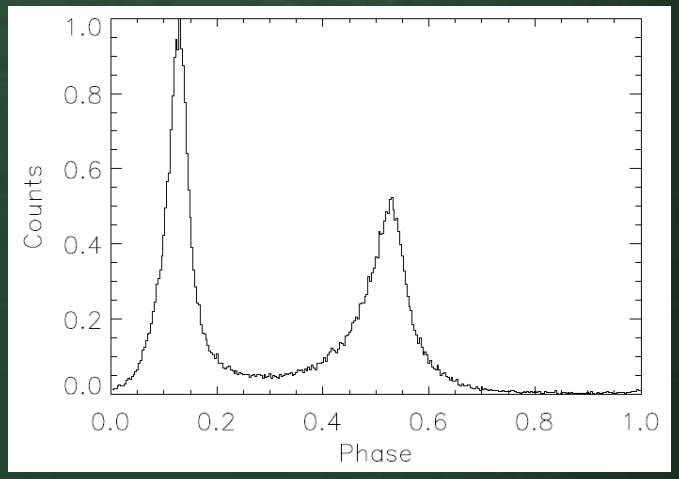


Credit: NASA/DOE/Fermi LAT Collabor.

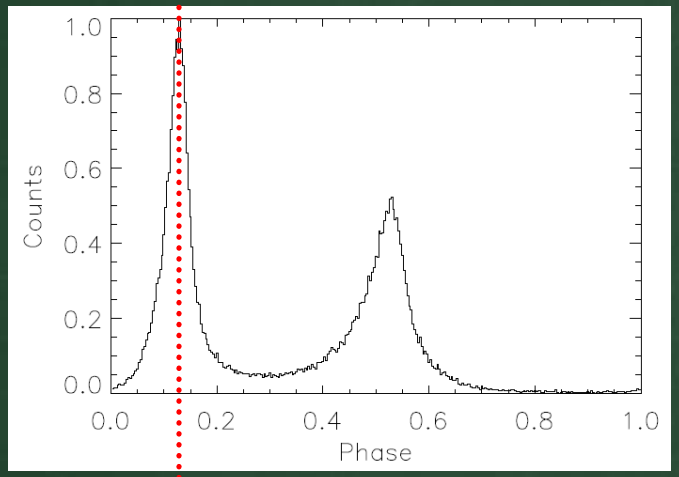


Crab Pulsar

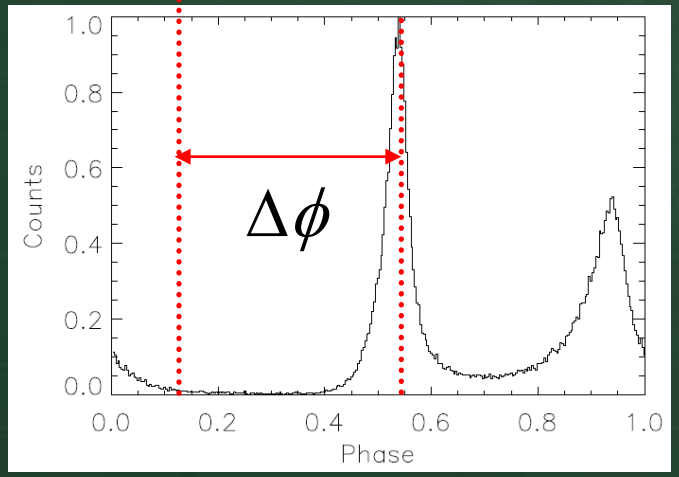
Credit: N. A. Sharp/NOAO/AURA/NSF



Step 2: Comparing Profiles

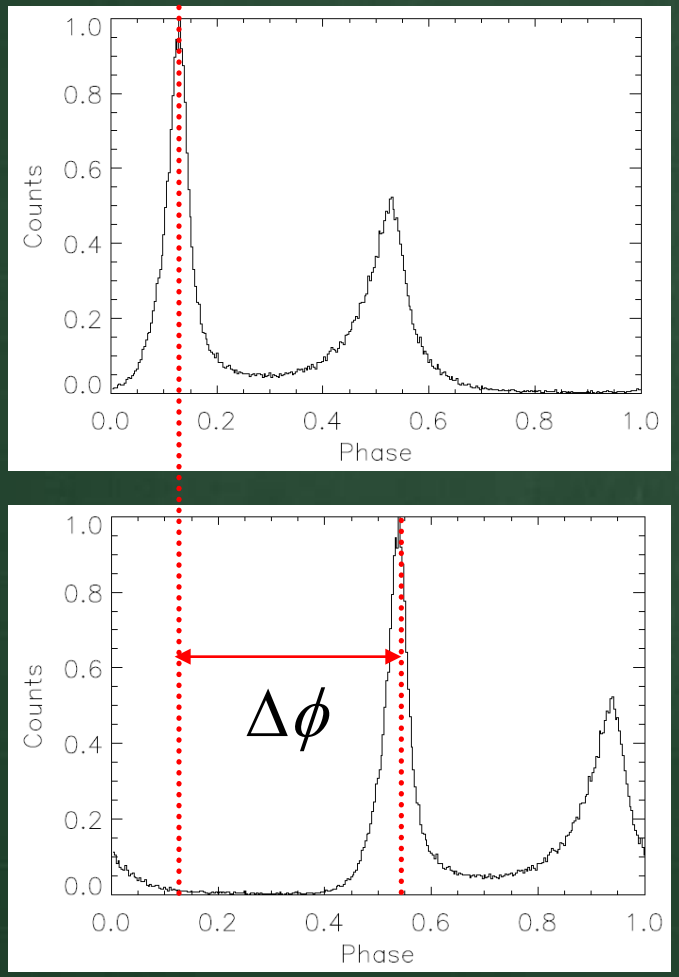


Spacecraft



Reference point

Step 3: Position Determination



Range difference along the line of sight:

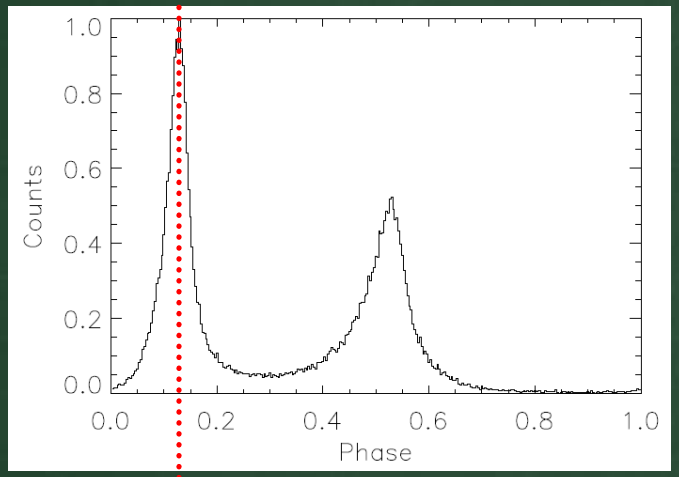
$$\Delta x = c \cdot P \cdot (\Delta\phi + n)$$

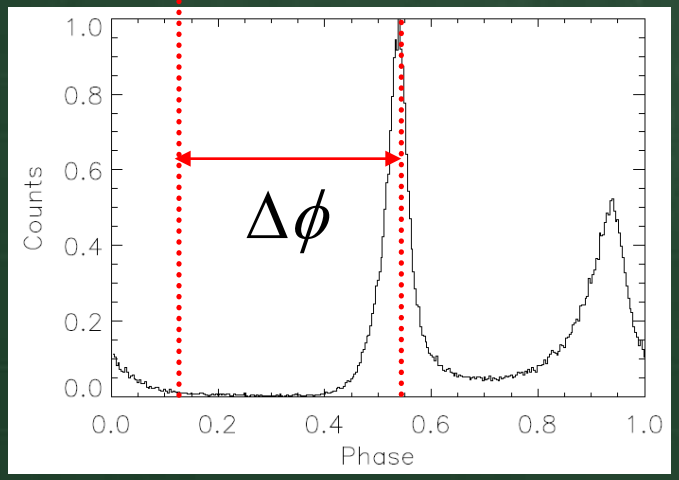
Phase shift

Pulse period

n = 0, ±1, ±2, …
(multiple solutions)

Step 3: Position Determination





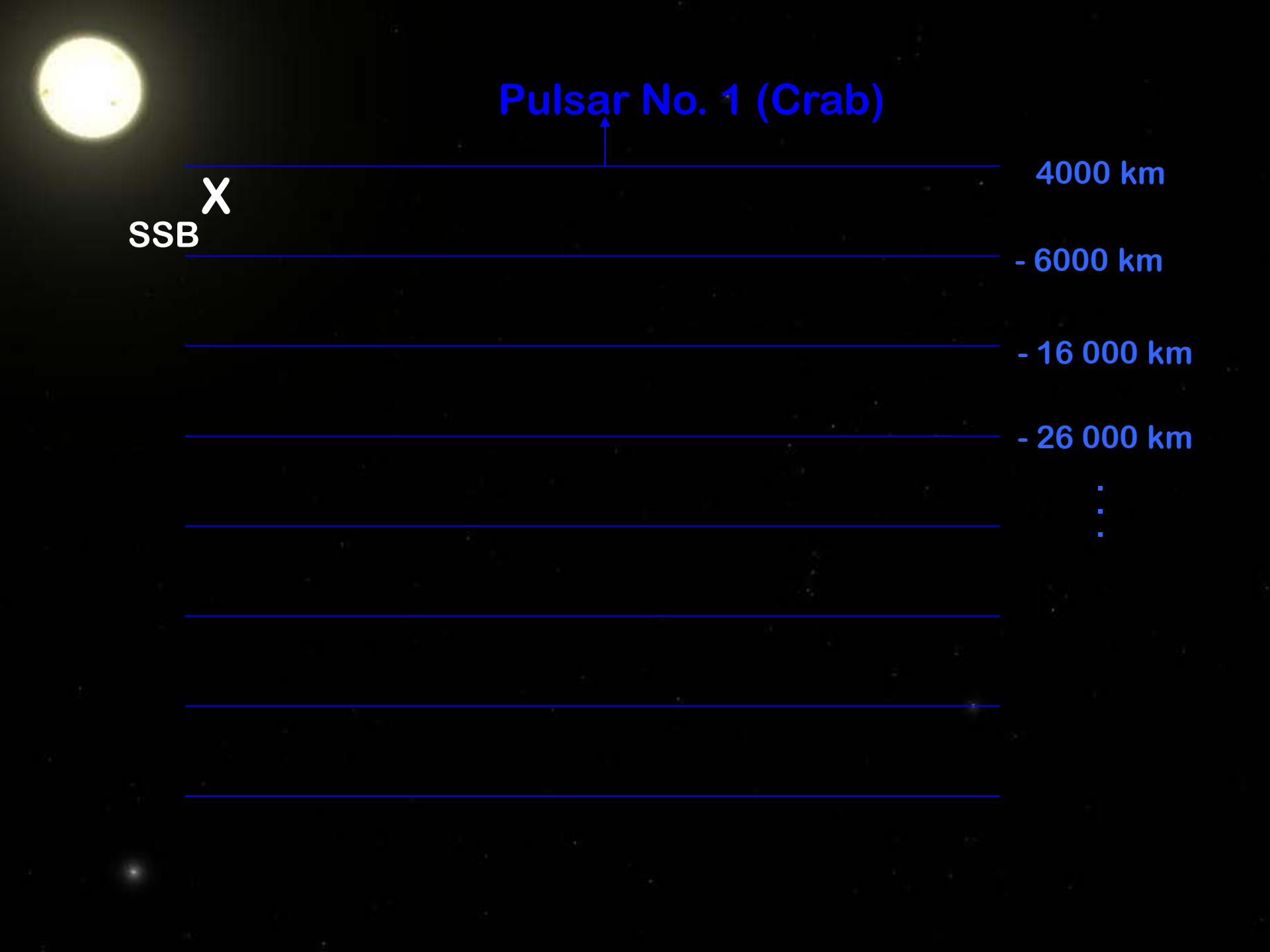
Example:
Crab Pulsar

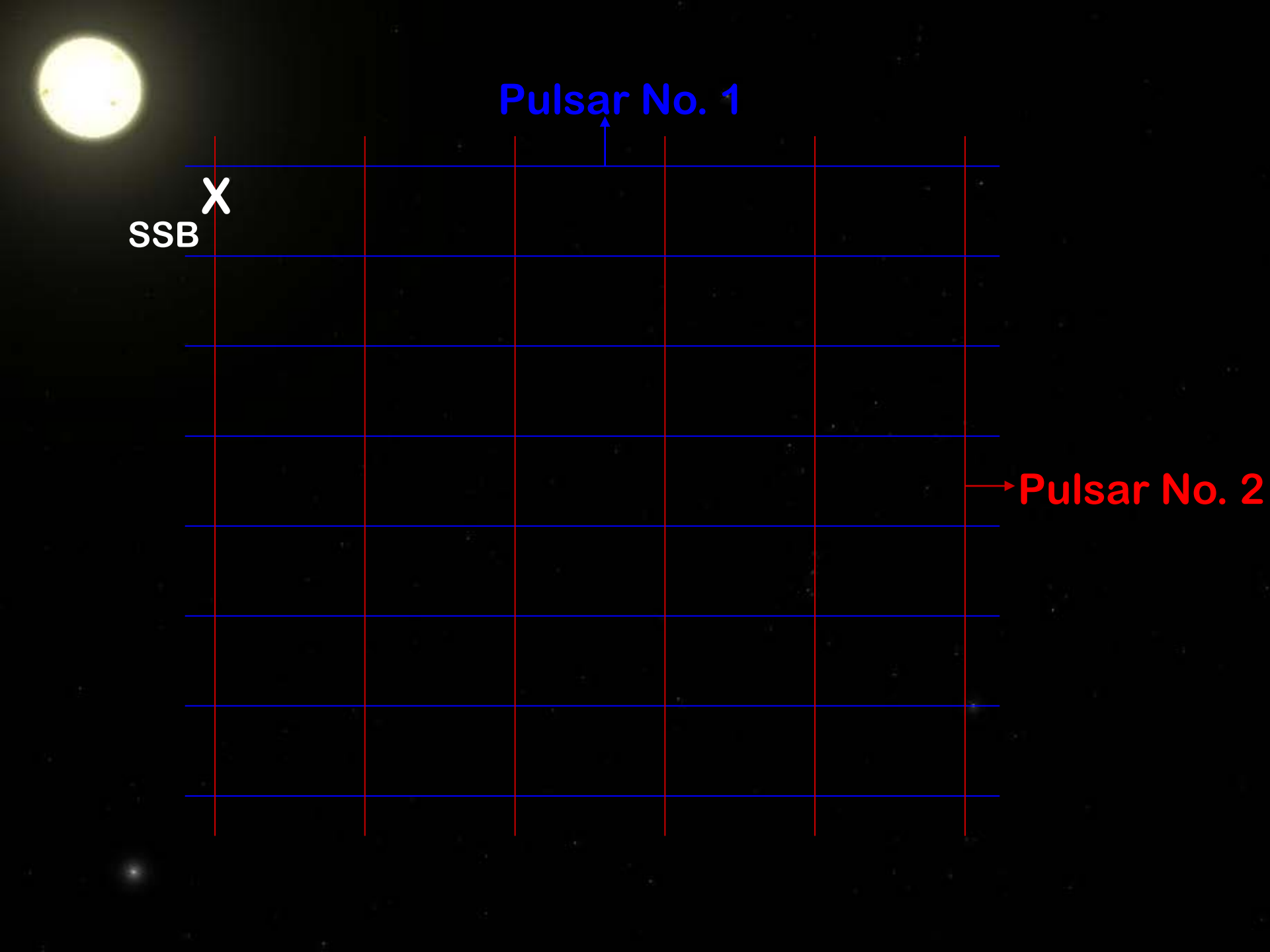
$$\Delta\phi = 0.4$$

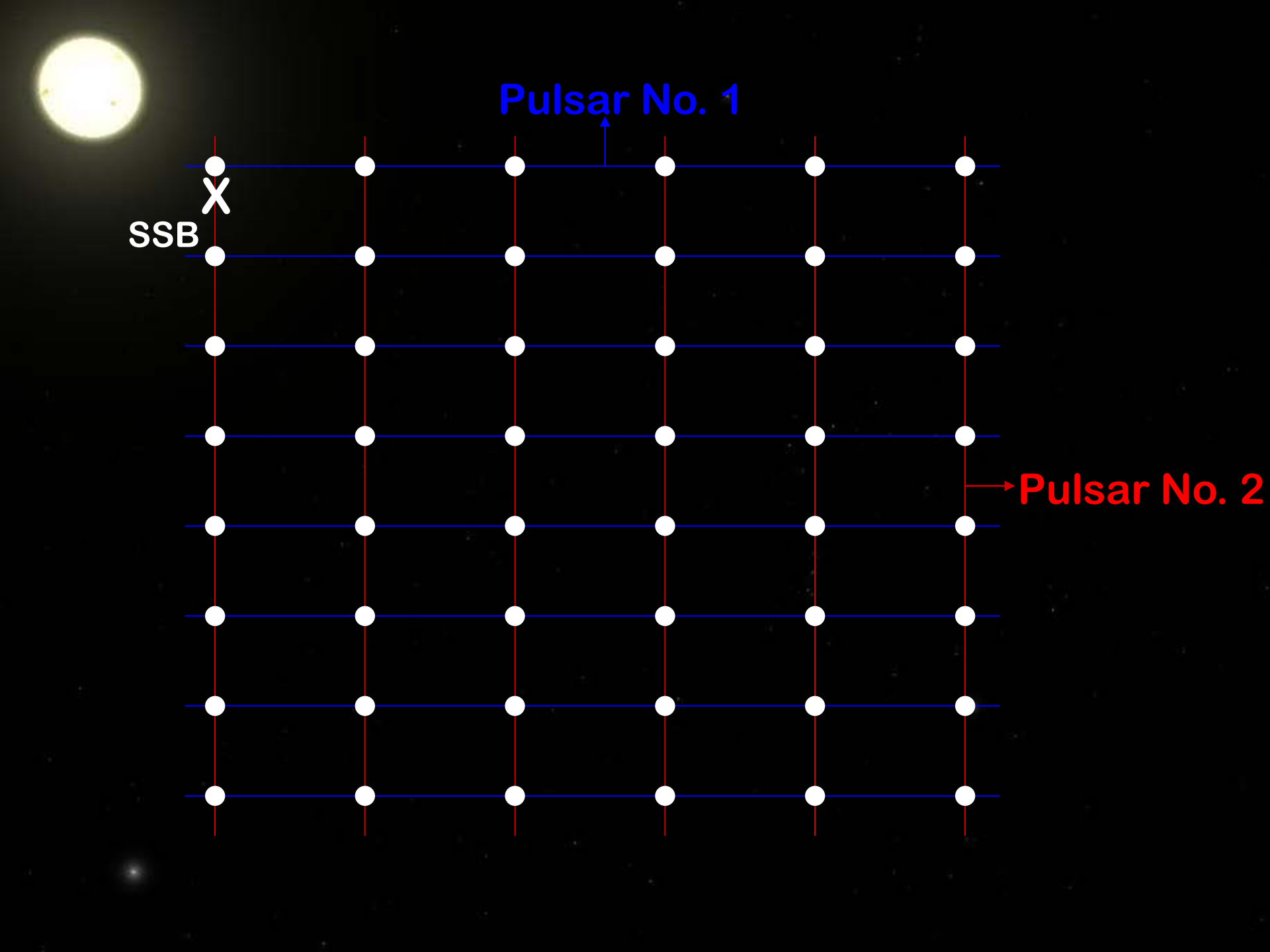
$$P = 33.085\,\text{ms}$$

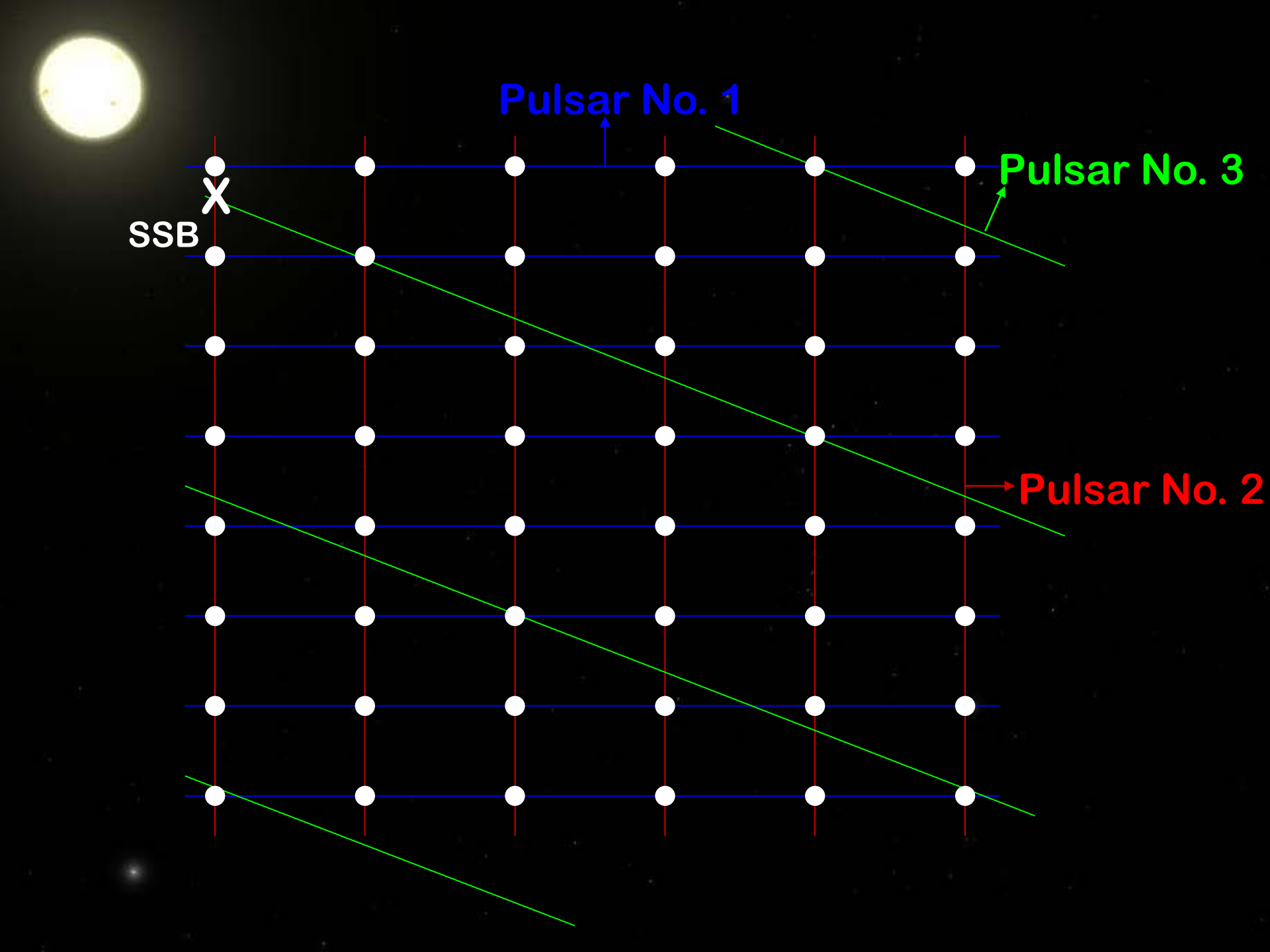
$$\Delta x = c \cdot P \cdot (\Delta\phi + n)$$

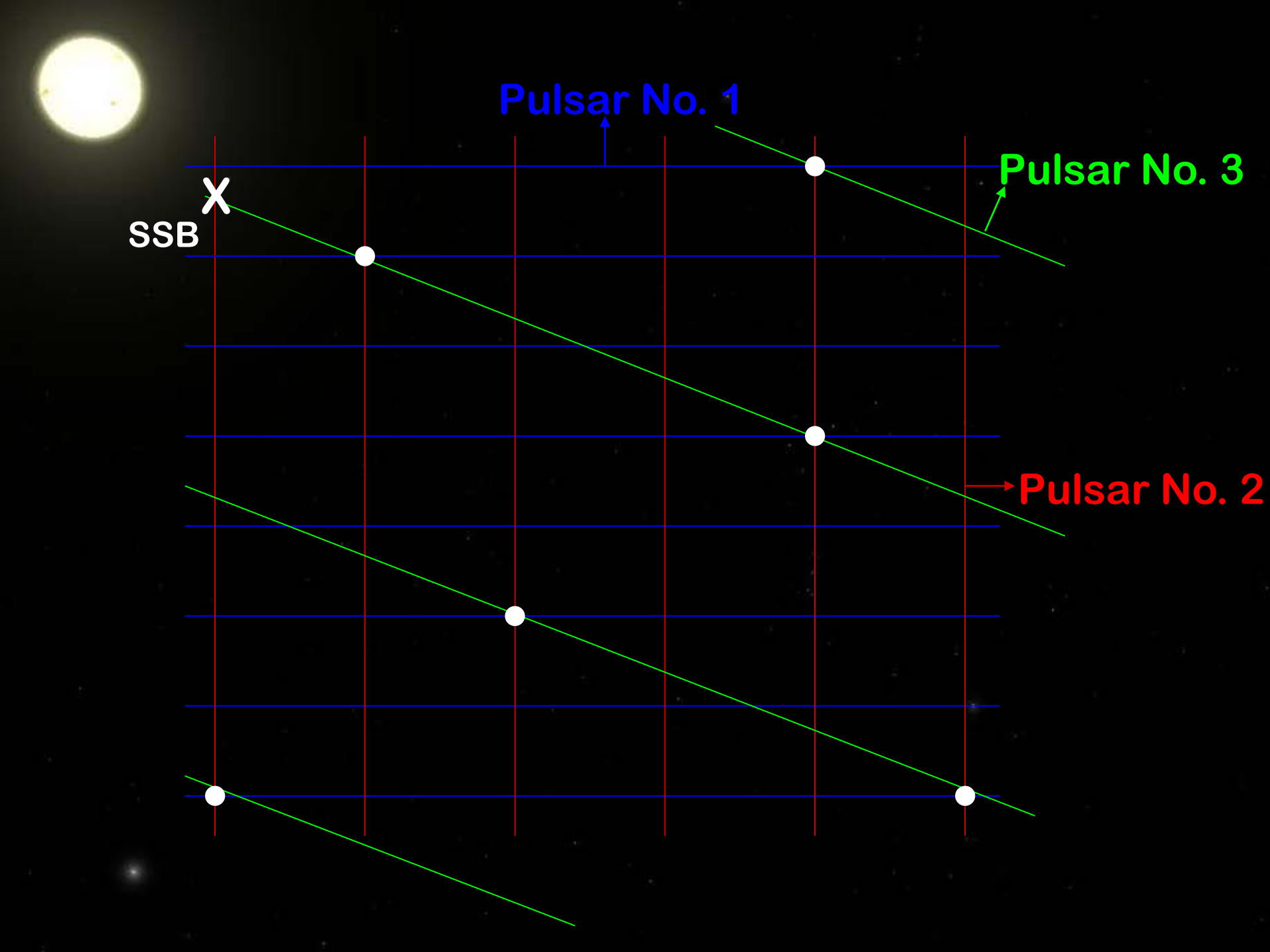
$$\frac{\Delta x}{\text{km}} \approx 4000 + n \cdot 10\,000$$

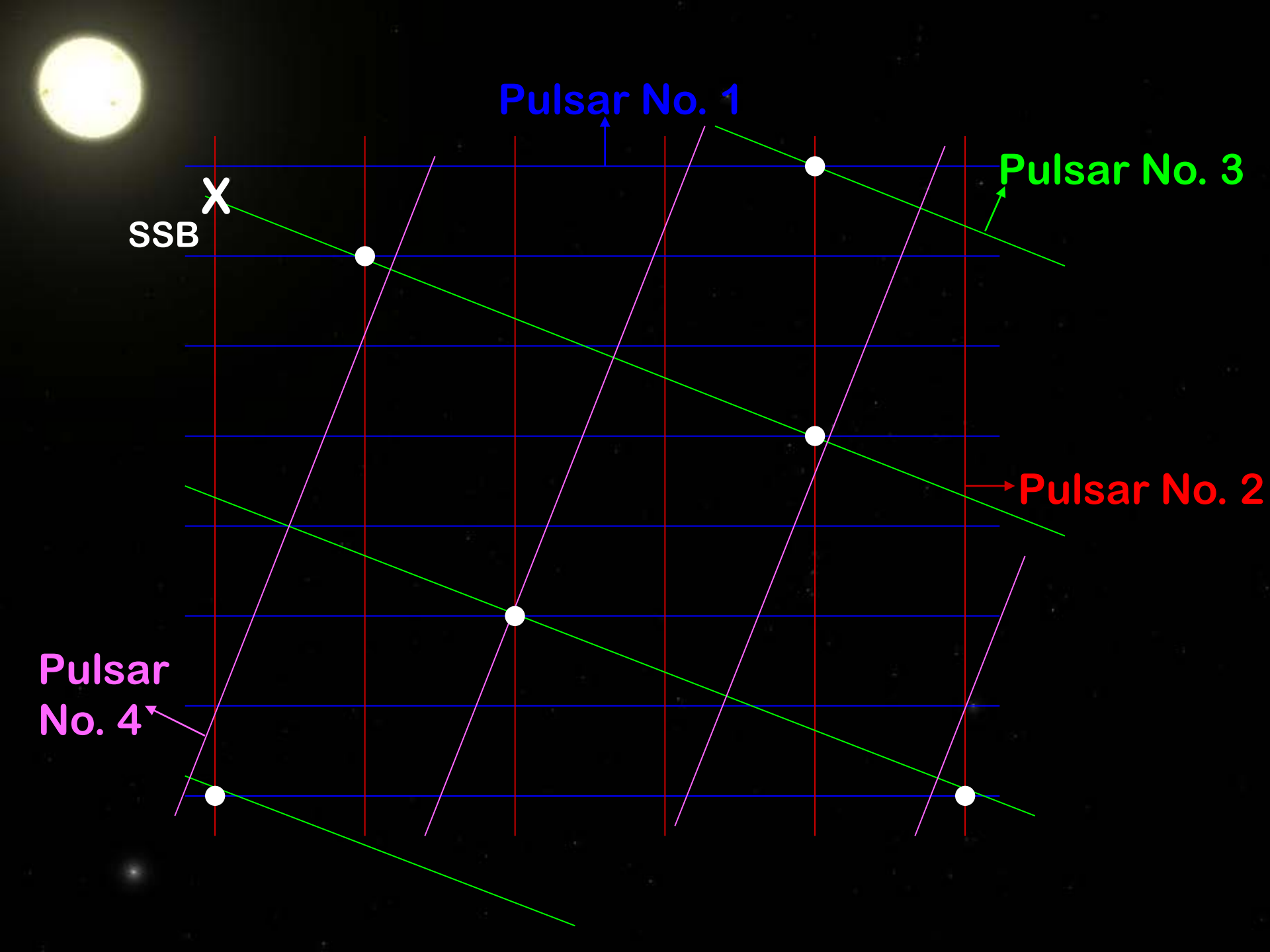

Pulsar No. 1 (Crab)
SSB
X
4000 km
- 6000 km
- 16 000 km
- 26 000 km

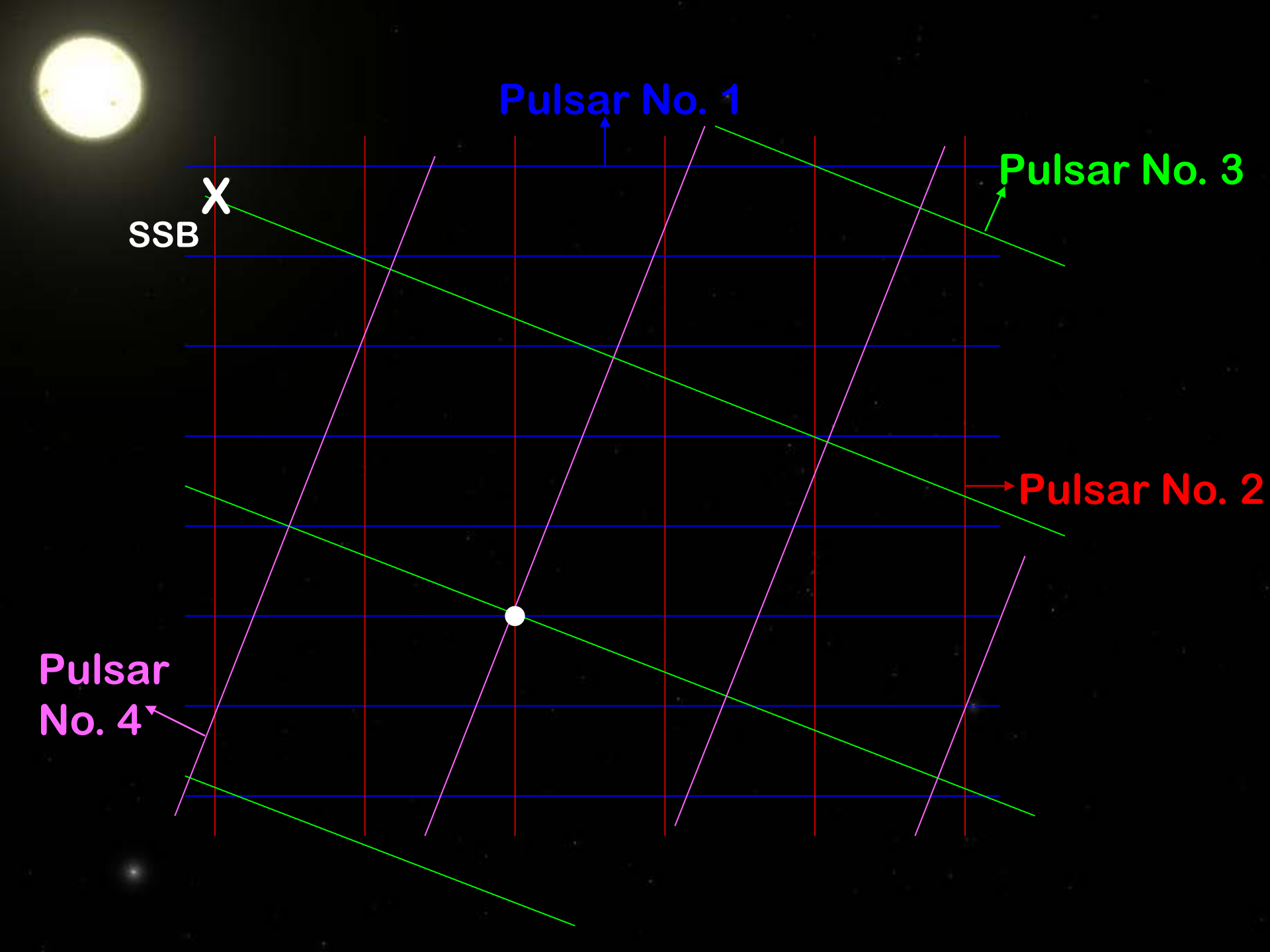

Pulsar No. 1
SSB
Pulsar No. 2

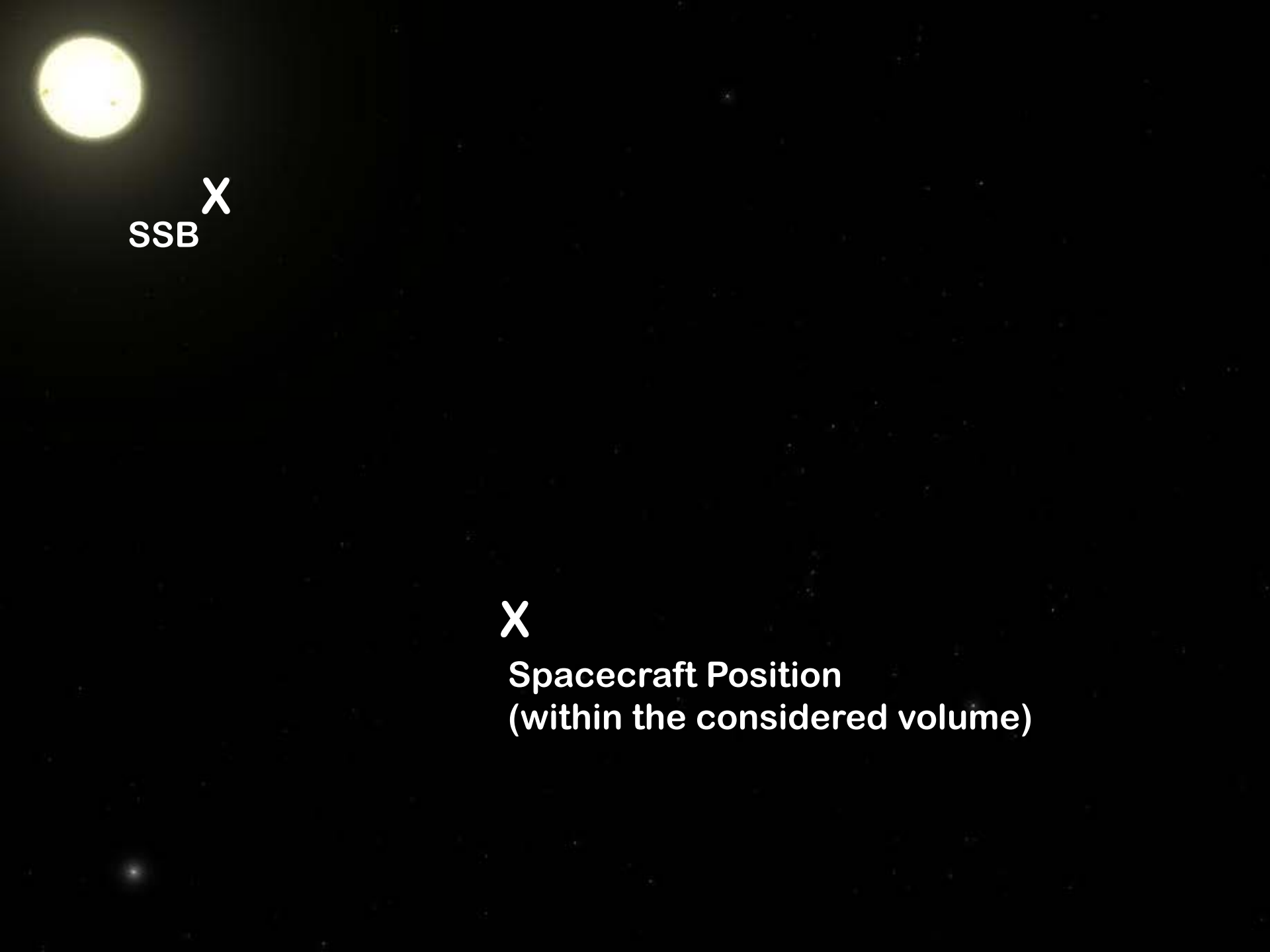

Pulsar No. 1
SSB
Pulsar No. 2


Pulsar No. 1
Pulsar No. 3
SSB
Pulsar No. 2


Pulsar No. 1
Pulsar No. 3
X
SSB
Pulsar No. 2


Pulsar No. 1
Pulsar No. 3
X
SSB
Pulsar No. 2
Pulsar
No. 4

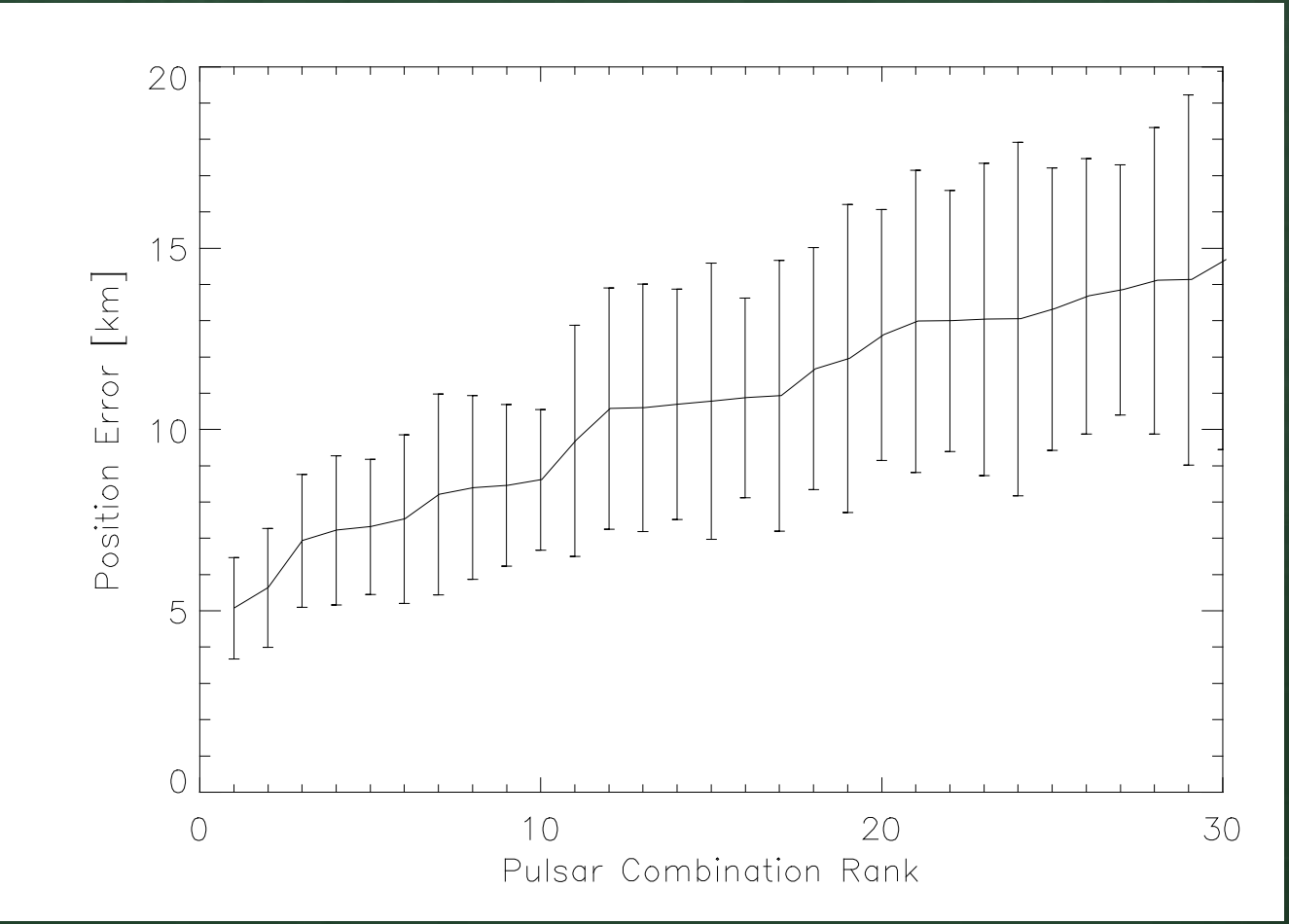

Pulsar No. 1
Pulsar No. 3
X
SSB
Pulsar No. 2
Pulsar
No. 4


SSB
Spacecraft Position
(within the considered volume)

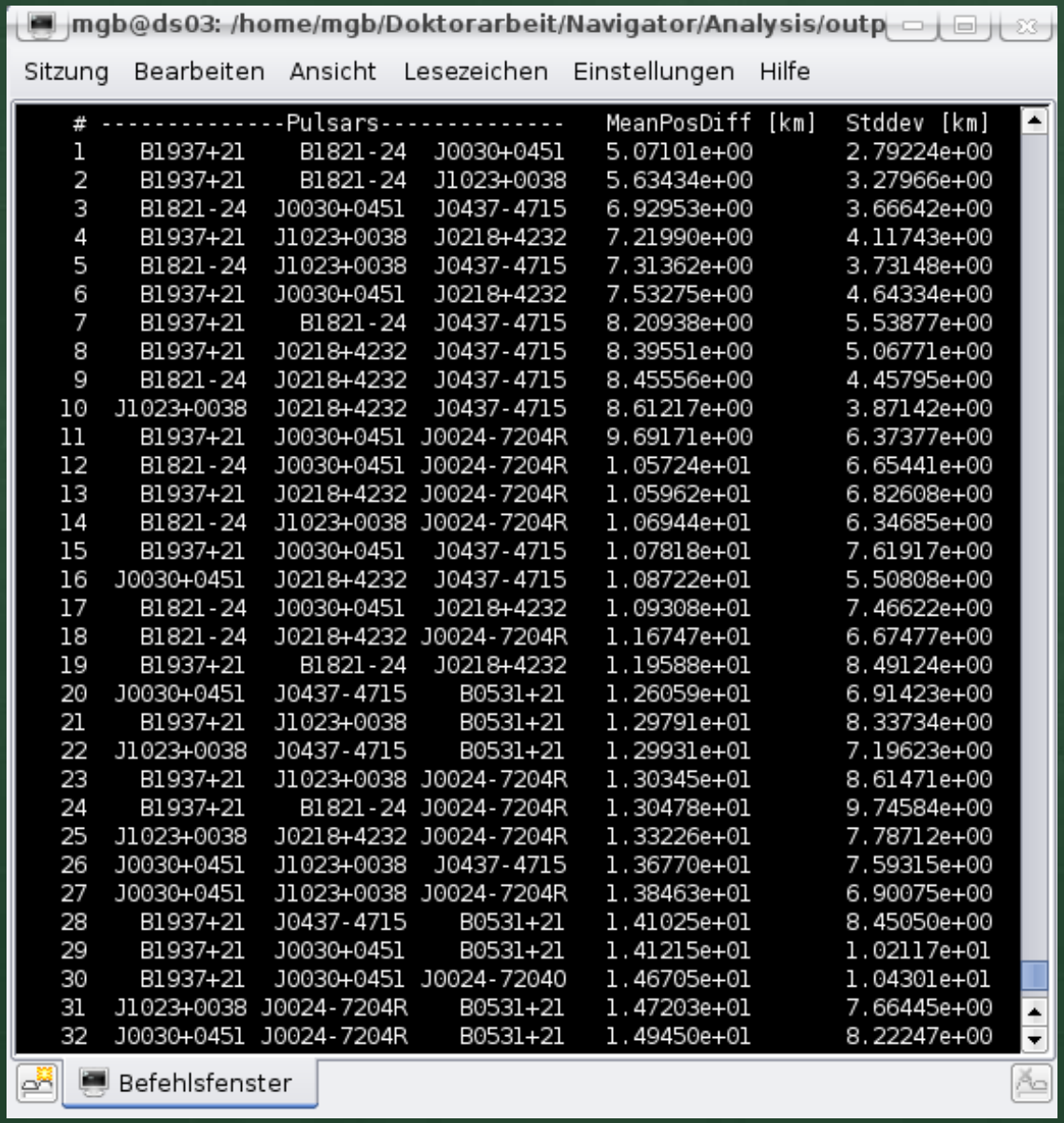
3. First Results

Pulsar Combinations

The best 30 (of 32 509 possible) pulsar 3-combinations:



Pulsar Combinations



#	Pulsars			MeanPosDiff [km]	Stddev [km]
1	B1937+21	B1821-24	J0030+0451	5.07101e+00	2.79224e+00
2	B1937+21	B1821-24	J1023+0038	5.63434e+00	3.27966e+00
3	B1821-24	J0030+0451	J0437-4715	6.92953e+00	3.66642e+00
4	B1937+21	J1023+0038	J0218+4232	7.21990e+00	4.11743e+00
5	B1821-24	J1023+0038	J0437-4715	7.31362e+00	3.73148e+00
6	B1937+21	J0030+0451	J0218+4232	7.53275e+00	4.64334e+00
7	B1937+21	B1821-24	J0437-4715	8.20938e+00	5.53877e+00
8	B1937+21	J0218+4232	J0437-4715	8.39551e+00	5.06771e+00
9	B1821-24	J0218+4232	J0437-4715	8.45556e+00	4.45795e+00
10	J1023+0038	J0218+4232	J0437-4715	8.61217e+00	3.87142e+00
11	B1937+21	J0030+0451	J0024-7204R	9.69171e+00	6.37377e+00
12	B1821-24	J0030+0451	J0024-7204R	1.05724e+01	6.65441e+00
13	B1937+21	J0218+4232	J0024-7204R	1.05962e+01	6.82608e+00
14	B1821-24	J1023+0038	J0024-7204R	1.06944e+01	6.34685e+00
15	B1937+21	J0030+0451	J0437-4715	1.07818e+01	7.61917e+00
16	J0030+0451	J0218+4232	J0437-4715	1.08722e+01	5.50808e+00
17	B1821-24	J0030+0451	J0218+4232	1.09308e+01	7.46622e+00
18	B1821-24	J0218+4232	J0024-7204R	1.16747e+01	6.67477e+00
19	B1937+21	B1821-24	J0218+4232	1.19588e+01	8.49124e+00
20	J0030+0451	J0437-4715	B0531+21	1.26059e+01	6.91423e+00
21	B1937+21	J1023+0038	B0531+21	1.29791e+01	8.33734e+00
22	J1023+0038	J0437-4715	B0531+21	1.29931e+01	7.19623e+00
23	B1937+21	J1023+0038	J0024-7204R	1.30345e+01	8.61471e+00
24	B1937+21	B1821-24	J0024-7204R	1.30478e+01	9.74584e+00
25	J1023+0038	J0218+4232	J0024-7204R	1.33226e+01	7.78712e+00
26	J0030+0451	J1023+0038	J0437-4715	1.36770e+01	7.59315e+00
27	J0030+0451	J1023+0038	J0024-7204R	1.38463e+01	6.90075e+00
28	B1937+21	J0437-4715	B0531+21	1.41025e+01	8.45050e+00
29	B1937+21	J0030+0451	B0531+21	1.41215e+01	1.02117e+01
30	B1937+21	J0030+0451	J0024-72040	1.46705e+01	1.04301e+01
31	J1023+0038	J0024-7204R	B0531+21	1.47203e+01	7.66445e+00
32	J0030+0451	J0024-7204R	B0531+21	1.49450e+01	8.22247e+00

First results published in:

Bernhardt, M. G., Prinz, T., Becker, W., Walter, U., 2010, *"Timing X-ray Pulsars with Application to Spacecraft Navigation"*, in proceedings of "High Time Resolution Astrophysics IV" PoS(HTRA-IV)050

4. Next steps

Next Steps

1. Higher-order terms:
   - Relativistic effects
   - Geometrical effects
2. What is the achievable arruracy?
3. Technical issues:
   - Detector types
   - Effective detector area, sensitivity, temporal resolution, etc.

Thank you!