Radio Pulsar Navigation

Jiang Dong

YunNan Astronomical Observatory, NAOs, CAS

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董江

Celestial Navigation

The history of navigation use celestial origin from the ancient activity which include hunting and back to home in the night or maritime activities. The base principle of celestial navigation is used the moon, stars, and planets as celestial guides assuming the sky was clear in that times.

The gigantic success of celestial navigation is Christopher Columbus awareness of the American continents in the Western Hemisphere in 1492.

Modern science and astronomy origin from astrometry for celestial navigation, it lead the production of Newtonian mechanics.

Today, astrometry is still the foundation of astronomy and modern surveying and mapping science, because we use it define time and space.

Figure: It is pirates make western find eastern !

Figure: Why many pirates wear eye patch?

Traditional celestial navigation can be divided into optical stars navigation and radio stars navigation. In rainy and cloudy, the optical sextant can not work.

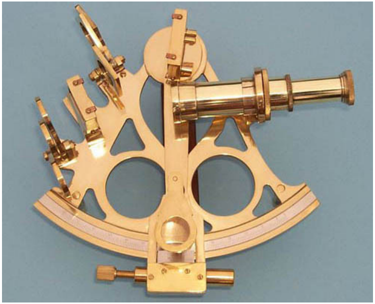

Figure: The Sextant - Latitude

Figure: The Watch - Longitude: Why Scandinavians are well in make watch ?

Figure: Collins Engineer Ted Willis, Captain John Brandt and Lt. John Kuncas of the US Navy shown with a Collins Radio Sextant that was installed on the USS Compass Island in 1959. Time Magazine, quoting Fred Haddock, Radio Astronomer of the Naval Research Laboratory, reported: "The ship's navigator can find his position just as if he had an assistant watching the sun through an ordinary optical sextant. No cloudy weather gets in the way of the radio sextant, nor can an enemy jam the radio impulses (as is possible with other radio aids to navigation, such as Loran)."

Traditional the equipment of radio celestial navigation is radio sextant, it only receive a small number of radio signal(Sun and moon), thus difficult to achieve continuous navigation, and just have the low navigation accuracy, and the equipment size is very big. So it is difficult to the application and the development.

Pulsar Navigation

After radio pulsar be discovered by Bell, J. and Hewish, A. in 1967, Downs, G. S. give the advice that use radio pulsars for interplanetary navigation in 1974 [Downs, 1974].

But in that time, both the radio and optical signatures from pulsars have limitations that reduce their effectiveness for spacecraft navigation. At the radio frequencies that pulsars emit (from 100 MHz to a few GHz) and with their faint emissions, radio-based systems would require large antennas (on the order of 25 M in diameter or larger) to detect sources, which would be impractical for most spacecraft. Also, neighboring celestial objects including the sun, moon, Jupiter, and close stars, as well as distance objects such as radio galaxies, quasars, and the galactic diffuse emissions, are broadband radio sources that could obscure weak pulsar signals [Sheikh, 2005, Sheikh et al. , 2006].

So Chester, T. J. and Butman, S. A. describe spacecraft navigation using X-ray pulsars in 1981 [Chester & Butman, 1981].

XNAV is developed by Sheikh et al. in recently, have achieve the preliminary results in X-ray band. Now the European Space Agency (ESA), Russia, France and German also have begun research it. However, these study is limited to X-ray band, only can be used in spacecraft navigation.

Prophecy?Enlightenment?

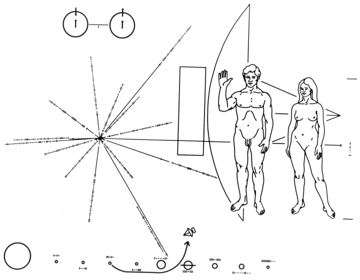

Figure: The Pioneer10

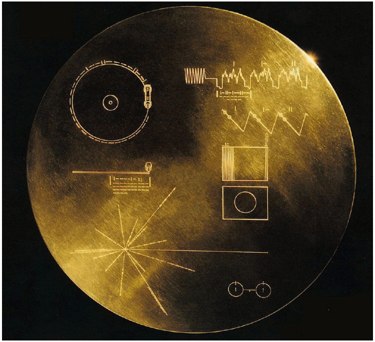

Figure: Voyager

Radio Pulsar Navigation

Jiang Dong's analysis show that we will have the stability profile (signal-to-noise is 5) that use a 2 meters antenna observe some strong sources of radio pulsar in 36 minutes which based on the today's technology. So the pulsar navigation can give the continuous position in deep space, that means we can freedom fly successfully in the solar system use celestial navigation that include pulsar and traditional star sensor [Dong, 2008]. From our analysis, the small antenna (even two meters) or the small optical or infrared telescope (even one meter), can receive the stable pulsar signal, which means that in radio, optical and infrared bands also can achieve the pulsar navigation. This work expanded the application range of pulsar navigation, made it can use in the aerospace, aviation, maritime, ground and underwater. So pulsar navigation avoid the disadvantage of the traditional radio celestial navigation technology.

Jiang Dong give three pulsar navigation models that based on pulsar timing process and astrodynamic, and make sure that the model which based on the relationship between the accuracy of TOA and the position of the telescope is suitable for navigation. It is simple and have more advantages than the other models. In this model, the most stable pulsar PSR J0737-4715 can provide the position accuracy is 300 m and 1 us time accuracy which does not require any technological breakthroughs. The best TOA of it can have 100 ns and 30 m in the solar system which is better than star sensor [Dong, 2011].

Why we can use Radio Pulsar in Navigation System Today?

Your mobile phone has more computing power than all of NASA in 1969.
NASA launched a man to the moon.
You launch a bird into pigs.

Figure: Angry Birds

Figure: NASA Apollo

Why we can use Radio Pulsar in Navigation System Today?

In 1970s, radio astronomer just can use several MHz (MegaHz) band to receive signal. Now the receiver bandwidth can reach tens of GHz (GigaHz) for the technological development that include broadband feed and digital electronics et al.
This is the reason that we can use small antenna to radio pulsar navigation.

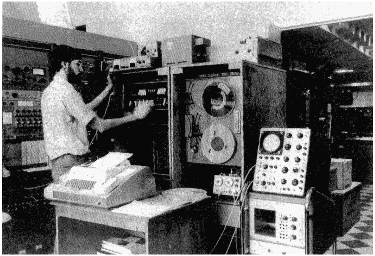

Figure: The instrument of find PSR B1913+16 in 1970s [Hulse, 1994].

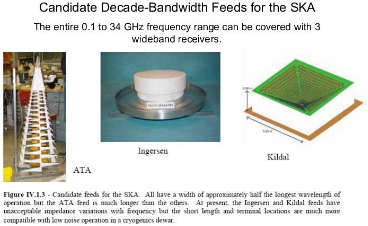

Figure: From Technology for the Next 50 Years, Sandy Weinreb @ NRAO 50th, 2007

The strong sources of radio pulsar.

Name Pulsar	Period (S)	DM ($cm^{-3}pc$)	W50 (ms)	S400/S1400 (mJy)	relation with Glich(G)
J0332+5434	0.71452	26.833	6.6	1500/203	
J0953+0755	0.25306	2.958	9.5	400/84	
J0747−4715	0.00576	2.64476	0.969	550/142	
J0738−4042	0.37492	160.8	29	190/80	
J0835−4510	0.08933	67.99	2.1	5000/100	G
J1456−6843	0.26338	8.6	12.5	350/80	G
J1644−4559	0.45506	478.8	8.2	375/310	G

The strong source in radio pulsar, all can use to navigation when aovid glitch noise. 1 Jy $\equiv 10^{-26}$ W/m^2/Hz.

God create the World using the Mathematical? OR we Just can use mathematical predict the unknown

The sensitivity of radio pulsar observation system (i.e. the raw limiting flux density) is given by the radiometer equation:

$$S_{\mathrm{lim}} = \frac{\sigma\beta}{(\mathrm{B N_p} \tau_{\mathrm{obs}})^{1/2}} \frac{\mathrm{T_{sys}}}{\mathrm{G}} \left(\frac{\mathrm{W}}{\mathrm{P - W}}\right)^{1/2} , \qquad (1)$$

From the above described, we can use low-noise receivers, a relatively wide bandwidth and long observation times to observed pulsar although it is relatively weak radio sources if there are not a large radio telescope. Using the equation 1, we use 2 M antenna (If the telescope efficiency is 0.4, $\mathrm{A_e} = 0.4 \times \pi(2/2)^2 \simeq 1.256\ \mathrm{m}^2$, $\mathrm{G} \simeq 4.55 \times 10^{-4}\ \mathrm{KJy}^{-1}$), $\mathrm{T_{sys}}$ is 40 K, 28 GHz bandwidth (2 G - 30 G), $\mathrm{N_p}$ is 2, τ_{obs} is 36 min, so we have $\mathrm{S_{lim}} \simeq 0.0803\ \mathrm{Jy} = 80.3\ \mathrm{mJy}$. The table 11 is the list of the strong radio pulsar source, it show that we can observed those pulsars which use 2 meter antenna in 36 minutes. If we set τ_{obs} is 4 min, 4 M antenna, we have $\mathrm{S_{lim}} \simeq 60.3\ \mathrm{mJy}$.

Pulsar Navigation Equations which like GPS system

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = \left([tr_i + b - t_i]c\right)^2 \; . \tag{2}$$

The receiver has four unknowns, the three components of GPS receiver position and the clock bias $[x, y, z, b]$, b denote the clock error or bias, the amount that the receiver's clock is off, so $i = 1{,}2{,}3{,}4$. Another useful form of these equations is in terms of pseudoranges, which are the approximate ranges based on the receiver clock's uncorrected time so that $p_i = (tr_i - t_i)c$. Then the equations becomes:

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc \; , \tag{3}$$

here $i = 1{,}2{,}3{,}4$.

In this equation, a pulsar's position and pseudorange define a sphere, centered on the pulsar with radius equal to the pseudorange. The position of the receiver is somewhere on the surface of this sphere. Thus with four pulsar, the indicated position of the pulsar receiver is at or near the intersection of the surfaces of four spheres. In the ideal case of no errors, the pulsar receiver would be at a precise intersection of the four surfaces. In the above equation, the pulsar receiver can be anywhere in the solar system because this area is covered by all pulsar which be studied at the earth in the theory. And if the accuracy of the receiver's clock is badly like RXTE, we still can have the position information from pulsar because the receiver's clock error can be corrected from pulsar clock [Rots et al. , 2004].

Deep Space Network Vs Radio Pulsar Navigation

With the distance increase in deep space explore, the radiometric tracking of deep space network (DSN) will decrease in accuracy [Thornton & Border, 2005], and it can't work when spacecraft in the other side of sun. But pulsar can't be effected in that place.
The same technique can use in lunar rover, Mars rover and rover in the others terrestrials, Mercury and Venus. The virtue is obvious, when the rover in the back of the others planet or lunar, DSN can not work and human can not built GNSS for the other planet in long term. So the radio pulsar navigation is one and only method at any place of the other planet surface day and night in the future explore.

Star Sensor and Radio Pulsar in Navigation

Table: Comparing in Star Sensor, Radio Pulsar and Maser

	Star Sensor	Radio Pulsar
Position	100m	30-300m(J0737-4715)
Time	NO	100ns-1us(J0737-4715)
Velocity	0.1m/s	*
Attitude	1”	*
All-weather	NO	YES

This table show the navigation capability of star Sensor and radio Pulsar. The asterisk means that the relevant areas being studied now and still no clearly result. We show the navigation capability of star Sensor and radio Pulsar. We give the contrast that include the position, time and velocity et al. in star sensor, radio pulsar. Pulsar is the only celestial which can provide time for it has a stable periodic signal in the time series. The asterisk means that the relevant areas being studied now and still no clearly result. Because pulsar navigation run in radio waveband, its have ability of all-weather work, star sensor can not do it.

The different sides(graviational wave, cosmic string, SMBH, Binary SMBH, solar wind, pulsar clock, pulsar navigation) of one Diamond(pulsar timing model)

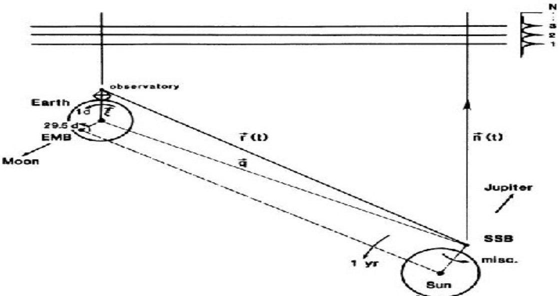

Figure: The astrometric model of pulsar timing [Backer & Hellings, 1986]

The best timing model in detect graviational wave
= the best correction model in pulsar time(clock) [Hobbs's talk, Cordes's talk]
= the best estimator model in pulsar navigation [Maximum-Likelihood Estimation, Markov chain Monte Carlo, Bayes et al.]

The different sides of one Diamond

Figure: The different sides(graviational wave, cosmic string, SMBH, Binary SMBH, space weather, pulsar clock, pulsar navigation) of one Diamond(pulsar timing model)

When using Pulsar to detect graviational wave(cosmic string, SMBH, Binary SMBH), it make this Country should be protected.
When using Pulsar to time(clock, navigation), it provide the technology to protect this Country.

In astronomy, Just pulsar research(er) can do it in the same time.

Now the Second Age of Discovery or Age of Exploration in the solar system is beginning, pulsar as nature beacon in the Milky Way will make human freely fly in the space of solar system. Pulsar navigation give a path which do not depend on DSN, so it less huge cost in the outer space and the interplanetary navigation. It make the spacecraft of the private company not only enter the outer space but also voyage to the other planet. After some pioneer explore, if we can find one mode to gain profit, may be tour or dig ore that include He_3 in lunar and diamonds in Uranus and Neptune [Knudson et al. , 2008], the new manufacturing about space travel will lead people into a new economic era, and the real Second Age of Discovery or Age of Exploration will begun. That is extraordinary in the human evolution to type II of Kardashev civilizations.

Figure: Space X: Falcon 9, Dragon spacecraft, May 16 2012

Figure: Elon Musk

40M Telescope in YunNan Astronomical Observatory, NAOs

NOW, Feed:S(2GHz, 500MHz),X(8GHz,500MHz) Receiver: One RF is cooled, 300MHz(180MHz) Backend: PDFB4.

We can timing 100-150 pulsar (which include B1937+21 and J0437-4715, $\sim$ 100us)Now.

Next Year: Feed: L-Ka(18cm, 13cm, 6cm, 1.3cm) Polarization.

Figure: Welcome your visit and Collaboration !

Chinese Pulsar Timing Array(CPTA)?

40M in YunNan(If feed refrom in 2013)
65M in ShangHai(First Light in 2013)
500M FAST in GuiZhou(2016?+X)
110M+X(X>1) in XinJiang(20XX); 80M*12(20XX)

Acknowledgements

Most of words and pictures come from internet directly or indirectly that include my papers and WIKI et al.
Courtesy of WIKI et al.

40M Telescope in YunNan Astronomical Observatory

Thanks, Please give the advices and comments.

Figure: Welcome your visit and Collaboration !

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