Pulsar Navigation in the Solar System

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Abstract—The X-ray Pulsar-based Autonomous Navigation (XNAV) was tested which use the Crab pulsar (PSR B0531+21) in the USA Experiment on flown by the Navy on the Air Force Advanced Research and Global Observation Satellite (ARGOS) under the Space Test Program recently. It provide the way that the spacecraft could autonomously determine its position with respect to an inertial origin. Now I analysis the sensitivity of the exist instrument and the signal process to use radio pulsar navigation and discuss the integrated navigation use pulsar, then give the different navigation mission analysis and design process basically which include the space, the airborne, the ship and the land of the planet or the lunar. 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. It also can less or abolish the dependence of Global Navigation Satellite System (GNSS) which include GPS, GRONSS, Galileo and BeiDou et al.

Index Terms—Navigation, Pulsar, Kalman filter

I. INTRODUCTION

THE gigantic success of celestial navigation is lead to Christopher Columbus awareness of the American continents in the Western Hemisphere in 1492. Even if it first been discovered in 1421 by ZhengHe or Viking, they all use the same way in navigation. The history of navigation use celestial origin from the ancient activity which include hunting and back to home in the night. The base principle of celestial navigation is used the moon, stars, and planets as celestial guides assuming the sky was clear in that times.

With the period of the Age of Discovery or Age of Exploration (the early 15th century and continuing into the early 17th century), many new technique be invented which include water clock, quadrant Sextant(1731,John Hadley), Chronometer(1761,John Harrison), the Sumner Line or line of position(1837,Thomas Hubbard Sumner), The Intercept Method or Marcq St Hilaire method(1875,Marcq St Hilaire) et al. The Sumner Line and Marcq St Hilaire method construct the foundation of modern nautical navigation. The lighthouse are used to mark dangerous coastlines, hazardous shoals and reefs, safe entries to harbors and can also assist in aerial navigation. For the physics and chemistry development, Gustaf Daln in recognition of his remarkable invention of automatic valves designed to be used in combination with gas accumulators in lighthouses and light-buoys(the noble prize in 1912).

After Guglielmo Marconi achieve the radio communication in 1895, navigation by radio as an aid has been practiced in Germany since 1907. Scheller invented the complimentary dot-dash guiding path, which can be seen as a ‘landmark’ for several decades of navigational aids. The first practical VHF radar system was installed on French ship in 1935. Radio navigation grow fast for the defense technique need in the World War II, the Long Range Navigation (Loran) system was invented. In 1995, it was proposed that use artificial stellar navigation. Until 1960, the first satellite navigation system, Transit, was first successfully tested, used by the United States Navy. Then it evolved to Global Positioning System(GPS). The soviet also built the similar system - GLONASS for the same reason. Now the Global Navigation Satellite system(GNSS) in the realism and dreams still have Chinese BeiDou, Indian IRNSS(Indian Regional Navigational Satellite System), French DORIS(Doppler Orbitography and Radio-positioning Integrated System) and Japanese QZSS(The Quasi-Zenith Satellite System).

An Inertial Navigation System(INS) is a navigation aid that uses the computing and motion sensors to continuously track the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. The gyroscopic compass (or gyro compass) was introduced in 1907. In 1948, the first INS be applied in V2 missile, then it be used in aeronautics, nautical and space widely.

When GPS and INS still do not grow up, celestial navigation system(CNS) spread to aeronautics by US(B-52,FB111, B-1B,B-2A,C-141A,SR-71,F22 et al.) and Soviet(TU-16,TU-95,TU-160 et al.)[1,2]. Then the star tracker (i.e. track one star or planet or angle between it) be used to determine the attitude of the spacecraft in help orient the Apollo spacecraft enroute to and from the Moon. Now the advanced star sensor(i.e. sense many star simultaneous) has been developed for the optical CCD technique improved[3].

Although GPS and INS almost can finish any job in this planet now, someone still think it is important for it can be used independently of ground aids and has global coverage, it cannot be jammed (except by clouds) and does not give off any signals that could be detected by an the others. The traditional maritime state which include US, Russia, UK, French, all spend many money in CNS for its unique advantage.

After radio pulsar been discovered by Hewish,A. and Bell,J. in 1967, Downs give a advice that use radio pulsars for interplanetary navigation in 1974[4]. 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 gigahertz) 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. So Chester and Butman described spacecraft navigation using X-ray pulsars in 1981. Then in the USA Experiment on the ARGOS, the X-ray Pulsar-based Autonomous Navigation (XNAV) were first tested which use the Crab pulsar. Dr. Sheikh constructed the complete frame about XNAV which based modern navigation technique that include Kalman filter et al.

II. X-ray Pulsar-based Autonomous Navigation (XNAV) in Spacecraft

In XNAV, the stability of pulsar as one beacon and kalman filter to represent the vehicle state lay the foundation for the navigation. Figure.1 show the principle of pulsar navigation. Pulsar as the nature lighthouse provide a continuous periodic signal. Then all signal be normalizing to solar system barycenter coordinates (SSBC). Though calculate the phase difference of pulsar’s times-of-arrival (TOA), that observed by spacecraft, we will have position and velocity by a vector computing in SSBC. The satellite’s amplitude will gain by the same way of star sensor.

A. Pulsar Clock for timing

In 1971, Reichley, Downs and Morris described using radio pulsars as clocks. Researching in-depth, radio astronomer build a stand template to pulsar timing. The character of pulsar spin be understood more deeply with the timing time increase. Pulsar especially millisecond pulsars (MSP) be thought the nature most stable clock. The data show some pulsar stability than atomic clock in the timescale greater than one year. So pulsar time not only is one independent clock to spacecraft but also even can inject to GPS in a long term. But currently utilized methods of timing pulse have errors on the order of hundreds of nanoseconds based upon their implementation simplifications, which should be addressed if improved accuracies are required.

B. Kalman Filter for position and velocity

The Kalman filter is an efficient recursive linear filter that estimates the state of a dynamic system from a series of noisy measurements. It can predict the motion of anything for it recursive, even the signal have noise for that use the dynamic state estimate the system. Though Thiele, T.N. and Swerling, P. developed a similar algorithm earlier, that is Kalman saw the applicability of his ideas to the problem of trajectory estimation for the Apollo program, leading to its incorporation in the Apollo navigation computer. Kalman filter is an important topic in control theory and control systems engineering, and an important method of least-squares estimation. It is used in a wide range of engineering applications which include radar tracking, control system, communication, guiding and navigation, computer vision, prediction in weather and economy, biomedicine, robot et al. In XNAV, that is significant like it in INS and the traditional CNS (i.e. star sensor). We can use navigation kalman filter measure pulsar range and phase, spacecraft clock, then compare with the signal which come from pulsar, so we will have position and velocity through delta-correction et al.

In the future XNAV, the system noise can’t be ignore which origin from all signal processing. Pulsar’s proper motion must be accurate measurement for we must first know the beacon position. That must be point that use one pulsar also can finish XNAV if integrate with INS or star sensor.

III. Navigation use radio pulsar

When Downs advised that use radio pulsars for interplanetary navigation in 1974, the antenna and electronic technique can’t finish this job and pulsar signal process still has been studying. In 1988, Wallace planned use of radio stars for all weather navigation. In fact, radiometric sextant be widely applied on submarine and aircraft carrier et al in Soviet and Russia for example the Cod Eye.

Now I think the exist instrument can achieve radio pulsar navigation although micro-strip antennas can not. The reason that is technique development and the pulsar signal process be cognized more deeply. We will have position and velocity by a vector computing in SSBC. Though calculate the phase difference of pulsar’s times-of-arrival (TOA), that observed by spacecraft, we will have position and velocity by a vector computing in SSBC. The satellite’s amplitude will gain by the same way of star sensor.

A. Pulsar signal process in astronomy Vs the requires of engineer project Vs the reliable of technique

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

\[ S_{lim} = \frac{\sigma \beta T_{sys}}{G \sqrt{BN_{p} \tau_{obs}}} \]  

where \( \sigma \) is a loss factor, taken to be 1.5 (One-bit sampling at the Nyquist rate introduces a loss of \( \sqrt{2/\pi} \) relative to a fully sampled signal. The principal remaining loss results from the non-rectangular bandpass of the channel filters). \( \beta \) is the detection signal-to-noise ratio threshold, taken to be 8.0. \( T_{sys} \) is the system temperature, \( G \) is the telescope gain, \( B \) is the receiver bandwidth in Hz, \( N_{p} \) is the number of polarizations and \( \tau_{obs} \) is the time per observation in seconds. The gain for parabolic antennas \( G\delta Bi = 10Lg4.5D/\lambda_02 \) in this form, \( D \) is Diameter of dish, \( \lambda_0 \) is center of wavelenth , 4.5 is parameter which static by experience.

Pulsar signal suffer dispersion due to the presence of charged particles in the interstellar medium. The dispersion delay across a bandwidth of \( \Delta \nu \) centred at a frequency \( \nu \) is

\[ \tau_{DM} = 8.30 \times 10^{3} \text{DM} \Delta \nu \nu^{-3} \text{ s}, \]  

where the dispersion measure, DM, is in units of cm\(^{-3}\) pc and the frequencies are in MHz. To retain sensitivity, especially for short-period, high-dispersion pulsars, the observing bandwidth must be sub-divided into many channels to use to incoherent dedispersion or achieve the coherent dedispersion. Now a filterbank system have been developed to digital filterbank (DBF) which base field-programmable gate array (FPGA). The coherent system also enter a fast advanced period with multi-core multi-PC cluster development and PC price decrease. In recently, the advantage of graphics processing unit (GPU) and FPGA in computing be attracted attention, and plan 9 as a an open-source distributed system have been tested.
by the creators of Unix from Bell Labs. If the Plan 9 can fuse Multi-core CPU, GPU and FPGA, construct one computing server and use different advantage of it, That will easily finish many scientific computation which include coherent dedispersion.

From 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. The table 1 is the list of the strong radio pulsar source, we can observed it even if use 3-4 meter antenna in microwave, some HAM have given the pulsar profile use the similar telescope[31].

In XNAV, they use pulsar Time of Arrival(TOA) Measurements gain the position[10]. In radio waveband, can we not only use TOA but also use single pulse of pulsar if the antenna is enough big, for example, in SIGINT(SIGnals INTElligence) satellite. Navigation using pulsar single pulse different with XNAV use pulsar TOA, that will have more precision than use TOA for it direct access to phase information and less the error box in the measuring process.

In radio pulsar, the strong flux density pulsar usually is young pulsar for example Vela et al., but it take place Glitch that is spin faster than past, that is abnormal phenomenon in young pulsar for example Vela et al., but it take place Glitch use wavelet to detect in signal or normalizing it to a gaussian signal on the premise can magnify the weak pulsar signal through plus a gaussian effect. And many MSP in globe cluster, its position unstable for the complex gravitational potential.

Navigation of use pulsar just for a continuous pulse signal during mission time which during tens of minutes to several years. When I penetrate the system of pulsar navigation as one systems engineering, I think navigation system use radio pulsar is feasible absolutely. Besides increasing observation times et al. mentioned above, I think some modern digital signal processing(DSP) technique can apply to pulsar signal navigation which include signal enhancement, signal reconstruct and singularity detection et al. The hypothesis of pulsar signal is gaussian be used in study pulsar emission geometry although it don’t be validated directly by observation[32]. In navigation, we just need the information from phase, so we can magnify the weak pulsar signal through plus a gaussian signal or normalizing it to a gaussian signal on the premise of keep period steadiness. Glitch can use wavelet to detect in time[33] when use several strong radio pulsar in short time mission. So we can rule out the interference difference, whether using single pulse or TOA. The navigation system must leave a copy of raw data to astronomer for the best filter is construct a good pulsar noise model by it.

B. Pulsar tracker

The parabolic dish usually be used in radio astronomy. But the conventional telescope will bring the control problem in spacecraft for the big dish is so weight. Figure.2 is a radio telescope in Nasu Pulsar Observatory which the same like Arecibo radio telescope in single dish[34]. It will less the difficult of control if use it in vehicle. So we can use this telescope achieve pulsar tracker like star tracker easily.

C. Pulsar sensor

The phased array antenna or radar have seen in recent years breakthroughs that lead to capabilities not possible only a few years ago. This is exemplified by the development of GaAs integrated microwave circuits called monolithic microwave integrated circuits (MMIC) which makes it possible to build active electronically scanned arrays (AESAs) having lighter weight, smaller volume, higher reliability and lower cost[35]. Figure.3 is AESAs of F22 which namely AN/APG-77 and built by Northrop Grumman. This phased array easy achieve pulsar sensor (i.e. observe several pulsar simultaneously) when it work in passive mode[36]. The phased array feed also can apply in pulsar sensor when use one dish.

D. Integrated Navigation with pulsar

Integrated navigation with pulsar in CNS and INS even GNSS is realistic path in the future mission. It will increase the reliability and redundancy of navigation or guiding system[37]. The multi-waveband pulsar navigation also is interesting, for instance, use 1 meter optical telescope[38] or 1.2 meter infrared telescope[39] can gain the crab pulsar profile, those observation system also easily load in one truck. In integrated navigation, system analysis and modeling, system state estimation, filter design, information synchronization and system fault tolerance filter design all is important.

IV. PULSAR NAVIGATION IN THE SOLAR SYSTEM

Like giving different produce in different place by navigation systems division of Northrop Grumman Corporation, pulsar navigation also need use different system in each mission[40; 41; 42].

A. In the space based and the airborne

In deep space explore, X-ray pulsar tracker suitable for most small spacecraft in usually for it even can use a 30CM detector have crab pulsar profile. But it can’t finish pulsar sensor mission now. We can have spacecraft attitude from star sensor and gain position et al. from pulsar. In International Space Station(ISS) or Laser Interferometer Space Antenna(LISA) et al., the biggest vehicle, the dish like Figure.2 is well in mission time. In radio astronomy, we will have more accurate profile and timing in the same time which compare with X-ray astronomy for the different detection method. For some satellite in orbit which include GPS, the Tracking and Data Relay Satellite System (TDRSS) et al., that need precise time, radio tracker like Figure.2 is good choice for it will have a best clock in long term. SIGINT(SIGnals INTElligence) satellite is the biggest spaceborne antenna for intelligence-gathering by interception of signals, whether between people (i.e., COMINT or communications intelligence) or between machines (i.e., ELINT or electronic intelligence), or mixtures of the two. Its diameter even arrive at 150 meter. Radio pulsar signal must be strong noise for it like Crab pulsar to the Ballistic Early Warning Site(BMEWS)of US Air Force[43]. For some airborne vehicle (F22, B2, blackswift et al.) and sub-orbit spaceship(hot eagle or aurora in legend), pulsar sensor
like AN/APG-77 of F22 is best choice for its mission need change attitude frequently.

The Snark(SSM-A-3/B-62/SM-62, Northrop) was the only intercontinental surface-to-surface cruise missile(ICCMs) ever deployed by the US Air Force, but was operational for only a very short time because it was already made obsolete by the new Intercontinental Ballistic Missile(ICBMs). It first achieve CNS(star tracker) in astronautical. P-29(i.e. SS-N-18, Stingray) is Submarine-launched ballistic missile which first achieve one integrated navigation system between INS and CNS(star sensor), and it first be launched many simultaneous for have this integrated navigation system. The Snack and the Stingray both the large vehicle which easily equip pulsar tracker or sensor and it can be used in reconstruct the solar system which include dig well in Mars for water et al.(44). With the distance increase, the radiometric tracking of deep space network(DSN) will decrease in accuracy(45), and it can’t work when spacecraft in the other side of sun. But pulsar can’t be effected in that place.

B. At the shipboard and submarine

The big ship all have the radar or antenna for communication et al.(35). Some special shipfor example Yuan Wang tracking shipcan use to test pulsar navigation in nautical. The interesting thing is whether it can be used in submarine for pulsar can be observed in 12.6MHz(46). Project 667 submarines (NATO reporting name Delta) are Soviet-built strategic nuclear missile submarines which have two VLF/ELF communication buoys. Navigation systems include SATNAV, SINS, Cod Eye(radiometric sextant), Pert Spring SATCOM. It usually use the enormous antenna net(array underwater) to realize VLF/ELF communication, may be it can receive pulsar signal after a coherent dedispersion.

The higher frequency waves (that is, the shorter the wavelength), the more easily be absorbed by water. So radio signal reach deeper than optic, but the big antenna net is more difficulty than optic telescope in control. In project 667, missile tube about 2 meter, it can observe pulsar signal underwater if less one missile and built one 2 meter optic or infrared telescope which the same like solar tower. US navy develops two-way radio communication for submerged submarines(47). Those technique carry out will benefit to launch one submarine to the four gas giants(Jupiter, Saturn, Uranus, and Neptune) for understand hydro-geology and interiors et al.(44).

C. On the land of planet and lunar

In the navigation system, the reliability and redundancy is very important. GPS is a system that spend a lot of money and high maintenance costs(48). So Ai GuoXiang et al. develop Chinese Area Positioning System(CAPS) that using the communication satellite and Wang AnGuo made the navigation theory that based on the measurement of radio signal that from celestial and the carrier signal of man-made objects, without having to decode. The above system just application et al.(35). Some special shipfor example Yuan Wang tracking shipcan use to test pulsar navigation in nautical. The interesting thing is whether it can be used in submarine for pulsar can be observed in 12.6MHz(46). Project 667 submarines (NATO reporting name Delta) are Soviet-built strategic nuclear missile submarines which have two VLF/ELF communication buoys. Navigation systems include SATNAV, SINS, Cod Eye(radiometric sextant), Pert Spring SATCOM. It usually use the enormous antenna net(array underwater) to realize VLF/ELF communication, may be it can receive pulsar signal after a coherent dedispersion.

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After my analysis, the small antenna(even three meters) or the small the optical(or infrared) telescopes(even 1 meter), can receive pulsar signal, which means that in radio, optical and infraredbands also can achieve the pulsar navigation. This greatly 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. Thus greatly promoted the research of CNS. In recently, Coll, B.
and Tarantola, A. give the analysis of pulsar navigation in the Milky Way that base general relativity theory. If we can understand the effect of pulsar emission area, may be we can use it navigation in the Milky way.

Soviet astronomer Kardashev N.S. proposed a scheme for classifying advanced technological civilizations. He identified three possible types and distinguished between them in terms of the power they could muster for the purposes of interstellar communications. A Type I civilization would be able to marshal energy resources for communications on a planet-wide scale, equivalent to the entire present power consumption of the human race, or about \(10^{13}\) watts. A Type II civilization would surpass this by a factor of approximately ten billion, making available \(10^{26}\) watts, by exploiting the total energy output of its central star. Finally, a Type III civilization would have evolved far enough to tap the energy resources of an entire galaxy. This would give a further increase by at least a factor of 10 billion to about \(10^{36}\) watts. Carl Sagan estimated that, on this more discriminating scale, the human race would presently qualify as roughly a Type 0.7. In the Age of Discovery, that is CNS make human freely voyage in the sea. So it make human civilization increase to higher type. 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. That is extraordinary in the human evolution to type II of Kardashev civilizations.

During the economic crisis the hope in the private company of the aerospace industry for instance SpaceX, SpaceDev and ASTER Labs, Inc. et al., pulsar navigation give a path which do not depend on DSN, so it less huge cost in the interplanetary navigation, that make the spacecraft of the private company not only enter the 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) in the interplanetary navigation, 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.

ACKNOWLEDGEMENTS
The author thank DARPA make someone invent Internet and open it for public.

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TABLE 1

| Name Pulsar       | P (S) | DM (S) | W50 (mJy) | S400/S1400 (mJy) | 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 | 2.6476 | 0.969     | 550/142          |         |
| J0738−4042        | 0.37492 | 160.8  | 29        | 190/80           |         |
| J0835−4510        | 0.08933 | 67.99  | 2.1       | 5000/1000        | 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 avoid glitch noise.

Fig. 1. A schematic view of the subject system for navigation utilizing sources of pulsed celestial radiation.

Fig. 2. Photograph of the array at Nasu Radio Interferometer. Eight equally spaced, 20-m diameter, fixed spherical antennas are shown in this figure.
Fig. 3. The AN/APG-77 is a multifunction radar installed on the F-22 Raptor fighter aircraft. The radar is built by Northrop Grumman. The figure come from wiki [http://en.wikipedia.org/wiki/AN/APG-77] accessed Nov 30 2008