Development of Deep-space Navigation by Pulsars in China

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Abstract—**In this paper, the fundamental framework of the celestial navigation and the development of pulsar navigation are discussed. Moreover, some results of navigation and timing of the millisecond pulsars in China are also presented.**

I. ON CELESTIAL NAVIGATION

As we know, the satellite navigation is easily disturbed and destroyed, and the performance of its concealment is bad. An autonomous celestial navigation system will overcome these drawbacks of satellite navigation. Moreover, it is recognized that navigation system could not only rely on satellites, and it is important to hold two independent positioning ways. Celestial navigation is just provided with characteristic of independent, global, charging low price and autonomous. Some scientists thought that all required techniques of celestial navigation have already existed, and any great scientific breakthrough dose not need. So it is possible for celestial navigation to instead of GPS in many fields in the future.

The rule of many celestial bodies motion relative the Earth is determinate, therefore, we may choose several celestial bodies, and using the observation data from them the position of user can be determined. Main equipments include star tracker, standard time generator etc... The tracker searches and scans the star, after that, tracking and measurement the altitude angle and azimuth angle. At last, the observed signals and standard time are inputted computer, and figuring out the position of user.

Celestial navigation possesses incomparable advantage than satellite navigation in detail as follow:

a. The navigation is based on celestial bodies, it only receives the signal from them, and it is a complete self-determination mode, therefore, it is very safe and concealment.

b. Celestial bodies have extremely anti-jamming characteristic, so the navigation possesses higher reliability.

c. The navigation is not limited by the space and time, to hold true whole universe.

d. Celestial navigation dose not need to establish ground stations and to lunch satellites, the investment is thus much less than satellite navigation.

II. ON PULSAR NAVIGATION

Pulsars first discovered in 1967 are rapidly spinning whose pulsing radio signal is very regular. These objects with more mass than the sun produce gravity 100 billion times stronger than Earth. A powerful magnetic field traps and accelerates charged particles, which beam radio waves in a cone shape through space. If Earth lies in the sweep of the beam, we receive the signal once each rotation.

Ticking like a cosmic metronome, pulsars are the most stable and accurate timekeepers. They also have valuable cosmological applications in measuring gravity waves and in defining a precise astronomical frame of reference for space navigation.

Besides pulsar can offer the most reliable timing standard, and its long-term stabilities (sampling time

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being more than one year) are currently better than those of the best atomic clock in the earth, some parameters of pulsar, such as, position and rotation periods, can be determined precisely by the astrometry. A navigation system may therefore be established based on timing and position information of several pulsars.

In deep-space navigation, when the Sun moves between Earth and the probe, no communication is possible, moreover, navigation from Earth is feasible only along the line of sight to the craft, the better solution should be autonomous navigation, and a spacecraft position needs to be tied to a precisely known natural reference frame. The better-known reference frame should be set up by the positions of remote pulsars.

Since millisecond pulsars may offer the most reliable timing standard known to us，the navigation in deep-space can benefit from using this timing information.

In despite of exhibiting an extremely high timing stability, the pulsar signals are very weak compared to a conventional radio-tracking signal, and will require sensitive detectors and electronics that can distinguish these signals from other interfering sources of background radiation.

The possibility of using pulsar signals for the positioning of spacecraft was reviewed in the Ariadna study “Feasibility study for a spacecraft navigation system relying on pulsar timing information” by the Universitat Politècnica de Catalunya and Universitat de Barcelona [2]. The study relies on millisecond pulsars, those that spin at high rates of more than 40 revolutions per second. The beauty of millisecond pulsars is that they are old and quite regular in their rotation. The fastest known millisecond pulsar is PSR 1937+211, which completes 642 revolutions every second.

The method in the Ariadna report will be to balance spacecraft mass and power constraints against the navigation hardware that will be developed. The study discusses suitable pulsar sources and derives the minimal hardware configurations that can be used to create such a positioning system. A possible catch: using several pulsar sources with different antennae seems necessary for the best accuracy, but this requires heavy hardware.

Scientists and engineers at The Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Md., are applying their expertise from many years of space research to develop deep space navigation network for satellites and deep space probes using x-ray signals from pulsars [3]. They have begun working on electronics that spacecraft equipped with X-ray sensors will be able to use to track timing signals from X-ray pulsars, those that radiate in the X-ray portion of a spectrum. Their research is directed by the Defense Advanced Research Projects Agency (DARPA), which recently awarded the Lab a contract to design critical portions of a spacecraft X-ray navigation system. The lab is working with Ball Aerospace, the Los Alamos National Laboratory and the National Institutes of Standards and Technology (NIST) on the project, known as the X-ray Source-based Navigation for Autonomous Position Determination (XNAV) program.

For the purposes of navigation, APL engineers are focusing on “rotation-powered” pulsars. In addition, several universities, particularly the University of Maryland, have laid the technical foundation for successful spacecraft navigation using signals from pulsars.

Using X-ray pulsar timing data obtained from the Chandra X-ray Observatory and other space-borne X-ray telescopes, APL is evaluating various traditional and non-traditional tracking loop technologies, including novel variations on the traditional Kalman Filter, a numerical method used to track a time-varying signal in the presence of noise.

In addition to their other roles on XNAV, NIST and Los Alamos will provide critical support for processing the raw X-ray data prior to its insertion in the APL-developed algorithms and tracking loops. Ball Aerospace will perform the system integration tasks needed to fly an X-ray experiment aboard a spacecraft or the International Space Station.

Once the XNAV team can demonstrate the ability to recover and track X-ray timing signals, engineers will develop the navigation algorithms necessary to convert the timing data from pulsars into a three-dimensional, real-time navigation fix referenced to the center of our solar system.

III. DEVELOPMENT OF NAVIGATION AND TIMING OF PULSARS IN CHINA

Since 1990s, some research results have been achieved by Chinese scientists in the fields of pulsar timing and navigation.

1. An observatory of pulsar, Nanshan Observatory in Urumqi, was founded. It is an international observation base of pulsar. In 2002, the base was cooperated with Hongkong University, Beijing University, the National Observatory of Australia, Jodrell Bank observatory of England, completed the project of arrival time of "18cm" pulsars observation and study.

2. A 50m telescope and a 500m telescope (FAST) are being established in China, the latter is located the Guizhou province. After finished, these will greatly increase the level of observation and study of pulsars.

3. A timing system of pulsar was developed at the Nanshan 25m radio telescope operated by the Urumqi Astronomical Observatory of China. The de-dispersing is provided by a 2×128×2.5MHz multi-channel filter and digitizer system. Regular timing observation of more than 80 pulsars had been performed duration 10 months. A glitch in crab pulsar was detected [4].

4. Using wavelet decomposition an algorithm of pulsar time scale was designed. Moreover, based on the analysis of the pulsar time scale and the atomic time scale, a frequency fluctuation of TAI was discovered [5].

5. Based on the measurements of the arrival time of the pulsars emitted from the millisecond pulsars, pulsar time and ensemble pulsar time were preliminarily established after the necessary time-space transformation, and the correction and parameter fitting are applied to the measurements [6]. In addition, a binary pulsar time was defined based on the orbit phase of a pulsar in a binary system.

6. A long-term pulsar flux was monitored using the 25m radio telescope of Urumqi station at 327MHz [7]. The structure function of PSR B0329+54 was obtained. The observed refractive time scale for the pulsar is 20d, the modulation index is 0.2, and the observed slope is 1.04. The agreement between the predicted and the observed refractive time scale and modulation index is surprisingly good.

7. In Miyun Radio Observatory of Beijing, a major project is to build a telescope with 45m single dish antenna that works as an element adding to the MSRT to increase the sensitivity. Some of its roles are to study the pulsar, radio variable sources and interstellar scintillations [8].

8. A set of timing residuals of PSR B1855+09 was analyzed with $\sigma_y(\tau)$ and $\sigma_z(\tau)$ respectively, the result indicates that $\sigma_z(\tau)$ is more suitable for pulsar stability study comparing with $\sigma_y(\tau)$ [9].

9. Timing stability for some millisecond pulsars was analyzed [10], the results show that millisecond pulsars PSR J0437-47 is a perfect celestial clock, its timing stability is obviously better than PSR B1855+09 and some atomic time scales. Long-term stabilities of PSR B1937+21 and PSR J1713+07 seem limited by low frequency timing noise. However, they may contribute to make an ensemble pulsar time scale. In addition, uniform distribution on the sky of target millisecond pulsars is needed and some common millisecond pulsars for timing of pulsar timing array (PTA) are also important, information on errors of atomic time scale and ephemeris may be derived and gravitational wave may be detected from PTA. In the future, powerful square kilometer array (SKA) will make contribution to new pulsar search and high precision timing observation of millisecond pulsars.

10 . Based on wavelet analysis and wiener filtration, a new ensemble pulsar time algorithm is presented [11], which can remove the impact of noise effectively. The pulsar timing residuals are separated in different components by wavelet transform, and the impact of atomic clock is removed by wiener filtration, at the end, the ensemble pulsar time can be obtained by inverse wavelet transform.

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