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Kalman Filter Analysis for Orbit Estimation using Pulsars for Interplanetary Missions

M Thameemunnisha*. M P. Ramachandran**

**ISRO Satellite Centre, Bangalore, 560017*
India (Tel: 080-25084414; e-mail: nisha@isac.gov.in).
*** ISRO Satellite Centre, Bangalore, 560017 India (e-mail:*
mprama@isac.gov.in)

Abstract: Autonomous Navigation in Interplanetary Missions is the main challenge due to lack of dense ground tracking network measurements. This paper presents a novel technique for determining spacecraft position and velocity using celestial X-ray sources, such as pulsars. It portrays the formulation of the pulsar measurements and describes the development of a noise model for X-ray Navigation and brings out the cumulative efforts in this developing field. In addition to that, it also covers the blending of the pulsar-derived measurements with a Kalman filter for continuous determination of position and velocity of an Earth orbiting spacecraft. Several sampling analysis are presented to establish the expected performance using measurements obtained from models of pulsed X-ray signals. This is the first step and future efforts shall make the orbit estimation more sophisticated.

Keywords: Pulsar, Kalman Filter, Orbit Estimation, GPS, Sampling

1. INTRODUCTION

Orbit determination (OD) is very important in interplanetary missions. Pulsar based orbit determination has gained more interest recently. These celestial sources provide unique signals that can be detected by sensors placed onboard the spacecraft, see Wood; Chester and Butman. Detection and processing of pulsar signals along with time of arrival information can be used to generate the range measurements with respect to an inertial frame.

The aim of using pulsars is to achieve autonomous and absolute orbit determination in space faring missions. This requires phase information available with the detector and this is some way to go. However the next and intermediate step could be relative orbit determination which is carried out currently.

Generally interplanetary missions need multiple stations tracking for extended periods that are prohibitively expensive. Orbiting around Lagrangian points is one of them as in ADITYA. It may also be noted that usually we have tracking at least from Bangalore Indian Deep Space Network (IDSN). This is always available in the mission. The orbit for next few hours until next OD is carried out is also available. This orbit is called reference orbit in this paper. And relative orbit estimated is to follow the reference orbit and arrest any deviations that could happen especially as it happens in Halo orbits.

1.1 Closeness to GPS

Stars, Moon and Sun have been used as navigational aids and described in ancient texts all over the world. Today they are still used with help of sun sensors and star sensors to realize both attitude and orbit. Man made constellation namely Global Positioning System (GPS) is used in earth observing spacecrafts wherein accurate knowledge of position is essential. This constellation is at an altitude of 20,000 km and is reliable in aiding many Low Earth Orbiting Satellite Missions. This concept achieved is fructified with the advent of the atomic clock. The marked difference is in using radio wave broadcast of time and using a stable atomic clock. The frequency and deduced range enables to determine the position of the orbiting satellite possessing the GPS receiver by triangulation from three satellites. Fourth satellite enables to accurately determine the time. Using dual frequencies and resolving phase ambiguities have shown in estimating the position accuracies close to centimetres. Pulsar based orbit determination closely resembles the GPS.

1.2 Pulse emission and Detector size

A pulsar or neutron star is the result of a massive star that has exhausted its nuclear fuel and undergone a core-collapse resulting in a supernova explosion. Young, newly born neutron stars typically rotate with periods on the order of tens of milliseconds, while older neutron stars through energy dissipation eventually slow down to periods on the order of several seconds. A unique aspect of this rotation is that the pulsations can be extremely stable and predictable. Pulsars have been found to emit throughout the radio, infrared, visible (optical), ultraviolet, X-ray, and gamma-ray energies of the electromagnetic spectrum, see Sheikh and Becker. However, detection within the X-ray band allows for the development of more compact detectors than other bands.

The detector technology and material mass have seen more research and development activities.

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The detector size in the past have been huge that deter any possibility of having it onboard. The literature, as in Becker et al (2013), has three kinds of detector technologies: the glass pore, silicon drift and active antenna. The glass pore has a mass of 25kgs to 5 kg and can help to measure range accurately from 5km to 10km in space. In the case of active antenna assembly of 15kg with 250W, the accuracy can be 5kms. This development will surely reduce the total mass and power requirement and give 5kms and less accuracy.

We shall concern here only about range measurement and not phase measurement.

2. PULSAR MEASUREMENTS AND NOISE

2.1 Range measurements

To observe a source, an X-ray detector is initially aligned along the line of sight to the chosen source. This usually is along the celestial pole. Once photon events from this source are positively identified, components within the detector system record the time of arrival of each individual X-ray photon with respect to the system's clock to high precision. During the total observation time of a specific source, a large number of photons will have each of their arrival times recorded. There are many approaches to arrive at the pulse time of arrival as discussed by Sheikh et. Al (2004). The pulse shapes are catalogued.

Due to the unique, periodic, nature of the signal produced by these sources, pulse time-of-arrival (TOA) information, which can be deduced as range data can be used to update and then compute three-dimensional position and velocity solutions. As detector systems can be produced to monitor the whole sky, simultaneous observations of multiple source signals from different directions allow this concept to produce full 3-D solutions. Spacecraft that have accurate clocks onboard, can track these signals over time to maintain full dynamic trajectory solutions.

High accuracy measurements from these celestial sources can be utilized within the algorithms to produce improved spacecraft navigation solutions. The estimated accuracy of the arrival time measurement is an important aspect for navigation. It is important to determine the TOA with an accuracy that is determined by the magnitude of the Signal-to-Noise-Ratio (SNR) of the measured source profile. In order to select the pulsars for autonomous navigation, the ranging accuracy of pulsars has to be analyzed based on their properties.

Such a method for estimating accuracy is used in the present analysis that computes the SNR of a source, see Becker and John Hanson et. Al, based upon the known X-ray characteristics of the source, without requiring raw observation data.

$$\text{SNR} = \text{function}\,(F, A, P, B, d, t) \qquad (1)$$

F - Total observed flux A - Detector area
P - Pulsed fraction B - Background radiation flux
d - Duty cycle of a pulse t - total observation time

The accuracy of the range measurement, R, can be computed using the speed of light, c, and the pulse TOA accuracy, w, see Downs.

2.2 Noise sources

The various noises in the pulsar measurements includes Source noise (steady and periodic), diffuse X-ray background noise, Cosmic Background Noise, Detector Noise, Local clock noise, Source shape uncertainty, pulse period uncertainty, source phase jitter, etc.

The primary source of error in the navigation solution is the ability to measure the TOA of the pulse train from each source while contending with shot noise inherent in the faint signal, the diffuse X-ray background, cosmic ray events and detector back ground. The SNR of the measurement (and hence the accuracy of the TOA estimate) can be improved by using a larger detector, or increasing the observation time. However, physical limits of the spacecraft and mass considerations will limit the maximum possible collection area of the detector. Thus, the problem becomes one of extracting the most of photon impression from an observation in order to minimize the required detector area and observation time. This may require certain attitude rate and jitter control. Yet in interplanetary missions this is achievable.

3. SIMULATIONS

3.1 Noise and Range Simulation

Various sources that affect the pulsar measurement and the time of arrival were identified. These had been modelled. The geostationary communication satellite GSAT-10 orbit was used. Any other trajectory could have been used. The extent measurement error would have been of the same order. This noise affects the range accuracy in pulsars. Also included is the timing measurement uncertainty. An algorithm using the modelled error sources was programmed. It has to be noted that the pulsars used for simulation are along the pitch axes of GSAT-10. The instantaneous noise (in km) is shown in the following plots (Fig. 1, Fig. 2, and Fig. 3). Simulated instantaneous noise along the three axes is given below(y axis is in km).

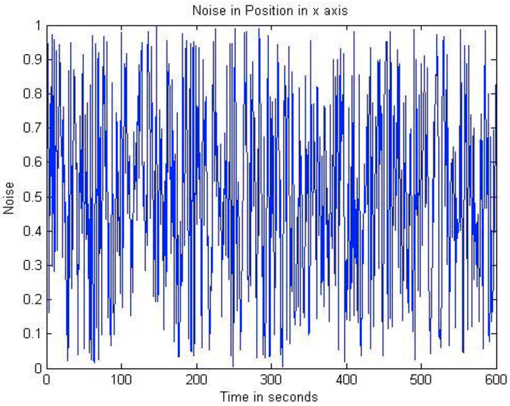

Fig. 1. Simulated instantaneous noise along the X axis