[NASA and China are developing X-ray pulsar-based navigation and timing (XNAV) for faster,autonomous and secure space missions]

Pulsars are highly magnetized, rotating neutron stars that emit electromagnetic radiation at regular intervals. They radiate energy across a broad range of frequencies, but they are most visible in their X-ray beams. Pulsars emit powerful beams in opposite directions as they spin. These beams are observable only when they're pointed toward Earth, making it seem as if these objects pulse (hence the name). In some cases, this apparent pulsing occurs with the predictability and consistency of an atomic clock.

X-ray pulsar-based navigation and timing (XNAV) is a theoretical navigation technique whereby the periodic X-ray signals emitted from pulsars are used to determine the location of a vehicle, such as a spacecraft in deep space. A vehicle using XNAV would compare received X-ray signals with a database of known pulsar frequencies and locations. Similar to GPS, this comparison would allow the vehicle to triangulate its position accurately (±5 km).

Current spacecraft navigation systems rely on global network of large ground-based radio antennas like NASA's Deep Space Network (DSN) and ESA's European Space Tracking (ESTRACK). These networks require a spacecraft to communicate with ground-based systems for months or years, while XNAV would enable autonomous navigation, minimizing the necessity of communications with Earth. Moreover, the new method is expected to provide faster estimation of spacecraft location as current systems are limited by the time delay at great distances. XNAV is also seen as the cheaper alternative for radio-based systems, as it would require reduced ground infrastructure and because X-ray telescopes can be made smaller and lighter.

Keith Gendreau, an astrophysicist at NASA’s Goddard Space Flight Center and a team of NASA researchers announced in Jan 2018 that they had finally proven that pulsars can function like a cosmic positioning system. With the help of an enhancement known as the Station Explorer for X-ray Timing and Navigation Technology (aka Sextant), Neutron Star Interior Composition Explorer (NICER), a pulsar-measuring instrument was able to determine the station’s position in Earth’s orbit to within roughly three miles—while it was traveling in excess of 17,000 miles per hour. SEXTANT is a NASA-funded project at the Goddard Space Flight Center that tested XNAV on-orbit on board the International Space Station in connection with the NICER project.

On 9 November 2016 the Chinese Academy of Sciences launched an experimental pulsar navigation satellite called XPNAV 1. XPNAV-1 will characterize 26 nearby pulsars for their pulse frequency and intensity to create a navigation database that could be used by future operational missions. The satellite is expected to operate for five to ten years. XPNAV-1 is the first pulsar navigation mission launched into orbit.

In 2014, a feasibility study was carried out by the National Aerospace Laboratory of Amsterdam, for use of pulsars in place of GPS in aircraft navigation. The advantage of pulsar navigation would be more available signals than from satnav constellations, being unjammable, with the broad range of frequencies available, and security of signal sources from destruction by anti satellite weapons

Pulsar-Based Navigation System Gets Tested on Space Station

On June 1, the Neutron Star Interior Composition Explorer (NICER) was installed aboard the space station as the first mission dedicated to studying neutron stars, a type of collapsed star that is so dense scientists are unsure how matter behaves deep inside it, says NASA. "If you took Mount Everest and squeezed it into something like a sugar cube, that's the kind of density we're talking about," said Keith Gendreau, the principal investigator for NICER at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

NICER, which will be robotically mounted to the outside of the station, contains 56 X-ray mirrors to illuminate the structure and inner workings of neutron stars. Of particular interest are pulsars, which are fast-spinning neutron stars with especially luminous magnetic fields. "NICER is designed to see the X-ray emission from those hot spots," Arzoumanian said. "As the spots sweep toward us, we see more intensity as they move into our sightline and less as they move out, brightening and dimming hundreds of times each second."

NICER will also provide scientists and technologists with a unique opportunity to make advances in deep space navigation. Its X-ray measurements will record the arrival times of pulses from each neutron star it observes, using the regular emissions of pulsars as ultra-precise cosmic clocks, rivaling the accuracy of atomic clocks such as those used inside GPS satellites. Built-in flight software – developed for the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) demonstration – can see how the predicted arrival of X-ray pulses from a given neutron star changes as NICER moves in its orbit. The difference between expected and actual arrival times allows SEXTANT to determine NICER's orbit solely by observing pulsars.

Although spacecraft in Earth orbit use the same GPS system that helps drivers navigate on the ground, there's no equivalent system available for spacecraft traveling far beyond Earth.

"Unlike GPS satellites, which just orbit around Earth, pulsars are distributed across our galaxy," said Jason Mitchell, the SEXTANT project manager at Goddard. "So we can use them to form a GPS-like system that can support spacecraft navigation throughout the solar system, enabling deep-space exploration in the future."

"It all comes back to the A-word: autonomy," says NASA's Jason Mitchell, an aerospace technologist at Goddard and project manager for the Sextant project. When a spacecraft can determine its location in space independently of infrastructure on Earth, "it lets mission planners think about navigating in places they wouldn't otherwise be able to navigate," he says.

Pulsar navigation could allow spacecraft to perform maneuvers behind the sun, for example (signals to and from the DSN cannot cut through our parent star). In the more distant future, missions at the fringes of our solar system and beyond—in the Oort cloud, for example—could perform maneuvers in real time, based on self-determined coordinates, without having to wait on instructions from Earth.

Installation on the space station provides scientists and technologists with an opportunity to develop a multi-purpose mission on an established platform.

"With the NICER-SEXTANT mission, we have an excellent opportunity to use the International Space Station to demonstrate technology that will lead us into the outer solar system and beyond, and tell us about some of the most exciting objects in the sky," Gendreau said.

China launches ‘XPNAV-1’ X-ray Pulsar Navigation Satellite for space mapping

The X-ray pulsar, developed by Aerospace Science and Technology Corp. Fifth Academy, was sent into space from the Jiuquan Satellite Launch Center aboard a Long March-11 solid fuel rocket, which also carried the Xaiaoxiang-1 and three Lishui-1 satellites. The move brings autonomous spacecraft navigation and a more precise deep-space GPS one step closer to reality.

The X-ray pulsar captures X-ray signals emitted from pulsars. By mapping those signals, they can be used to determine spacecraft location in deep space, which will eliminate the hours-long delays incurred in using ground-based navigation like the Deep Space Network and European Space Tracking network. Some pulsars emit radiation with the precision of an atomic clock.

The satellite is equipped with two detectors that test its functions and outline pulsar contours to create a database for navigation. The sensors need to be able to sort the pulsar blasts from background noise. Space Daily reported the satellite will detect emissions from 26 nearby pulsars. Chief scientist Shuai Ping said the database could be completed within 10 years.

X-ray pulsars consist of a magnetized neutron star that draws gas from a companion normal star, forming a rotating disk that channels the gas to its magnetic polls, resulting in the generation of intense energies. They are found in deep space, and scientists say they could act like signal buoys. Pulsars cannot be studied on earth because the X-ray signals are blocked by the atmosphere.

Researchers perform detailed simulations for XNAV feasibility

Meanwhile, team of researchers, led by Setnam Shemar of NPL, has lately published a paper in Experimental Astronomy, detailing simulations that bring the new navigation system one step closer to reality.

The simulations made by the team provided crucial measurements regarding the future development of the XNAV method. The scientists concluded that at the distance of Neptune (about 30 astronomical units from the Earth), a 3-D location of a spacecraft with an accuracy of 18.6 miles (30 kilometers) can be calculated by locking onto three pulsars. Moreover, they estimated that even an accuracy of 1.25 miles (2 kilometers) can be achieved when locking onto a particular pulsar, called PSR B1937+21, for 10 hours. Due to the fact that PSR B1937+21 is a millisecond pulsar, completing almost 642 rotations per second, and thanks to its very stable rotation, it is capable of keeping time as well as atomic clocks.

However, major challenges still need to be overcome to develop this system as a 'GPS' in space, including the availability of a practical system, for steering the telescope to sufficient accuracy and reducing further the required pulsar observation times and the craft positioning errors. One limiting factor is the error to which the position of each pulsar in the sky is known.

"If, in the next couple of decades, these can be reduced by a factor of 10 using ground-based radio telescopes such as the Square Kilometre Array, then depending on the size and type of instrument used on the craft, and assuming the noise in the pulsar measurements is lower than the uncertainty contributed by the pulsar position error, it may be possible to get accuracies on the order of five kilometers (3.1 miles) at 100 astronomical units. This is roughly two-and-a-half times the distance to Pluto," Shemar said.

He added that even an accuracy of 650 feet (200 meters) would be possible in one dimension, but only along the direction of the pulsar PSR B1937+21. These errors would increase proportionately with distance.

The scientists emphasize that as well as X-ray, a practical instrument for radio observations should also be properly considered. Initially, a system may offer the most benefit in the outer solar system, particularly during the interplanetary cruise phase.

According to the authors of the paper, the main challenge for the future is how to implement X-ray telescopes in XNAV systems. They should have low enough mass, power and volume to make them attractive as subsystems to put onto the spacecraft. The team suggested a method of using the evolution of existing technologies, but much work is still needed to optimize and develop this idea.

References and Resources also include

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