Executive Summary

A study on Deep Space Navigation with Pulsars has been carried out in accordance with ESA Statement of Work Reference: TEC-ETN/2011.90, Issue 1, Revision 2. The UK National Physical Laboratory (NPL) was the prime contractor with University of Leicester (UL) as a sub-contractor.

The limitations of current spacecraft navigation systems, such as the NASA and ESA Deep Space Networks (DSN), have led to increasing activity around the world in studying the feasibility of 'XNAV'. This potential technique would exploit the time variability of cosmic X-ray sources and in particular the stability in the periodic signal from X-ray pulsars. The main objective of this study was to determine the feasibility of deep space navigation using XNAV based on X-ray pulsars. This has been established by identifying the best combination of navigation strategy and X-ray pulsars with respect to performance considering current and future X-ray instrumentation. The benefits of such a technique are increased spacecraft autonomy, improved position accuracies and much lower mission operating costs due to the substantial reduction in the use of the associated DSN ground-based systems.

Simulations of Position, Velocity and Time (PVT) uncertainties for different combinations of pulsars and navigation strategies show that the best XNAV performance is achieved using a focussing X-ray instrument. The present limiting factor is often due to errors in the pulsar positions. It is found that the pulsar PSR B1937+21 has potential for the greatest positioning accuracy, of order 2 km, for ranges up to 100 AU (three times the range to Neptune) after 6 hours observing with a focussing instrument of effective area ~50 cm^2. However, this would be a one-dimensional solution, in the direction of the pulsar. The DSN would take at least 26 hours in this scenario. One possibility is of using an XNAV system to improve position knowledge in co-operation with the DSN. Here, XNAV would enable higher accuracies in the two position axes perpendicular to the spacecraft line-of-sight from Earth. There is also potential for a three-dimensional XNAV solution by observing three pulsars sequentially.

X-ray instrumentation suitable for use in an operational XNAV subsystem (as opposed to an astrophysical research context) must be designed to require only modest resources, especially in terms of size/volume, mass and power. A system with a focussing optic is required in order to reduce the sky and particle background against which the source must be measured. Potential instrumentation has been designed and is in development, in the context of the Mercury Imaging X-ray Spectrometer for ESA's BepiColombo mission to Mercury. Possible lower-cost designs have also been identified. It is also concluded that absolute time on-board the spacecraft is one of the limiting factors for spacecraft autonomy. This could be improved by use of a sufficiently accurate space-qualified atomic clock.

A high-level navigation algorithm together with real data for the Crab pulsar from an X-ray astronomy satellite (RXTE) have been used to demonstrate key elements of technology and processing required in an XNAV system. This shows that it is feasible to develop a 'ground' demonstrator using data from such a mission to validate XNAV processing algorithms and uncertainties. Simulations of pulsar data should be used to complement real data together with appropriate navigation software. The feasibility of a 'flying' demonstrator has also been assessed and a programme for raising TRL levels of instrumentation proposed. An XNAV system such as this would have a strong science case for inclusion in a future planetary science or astronomy mission.