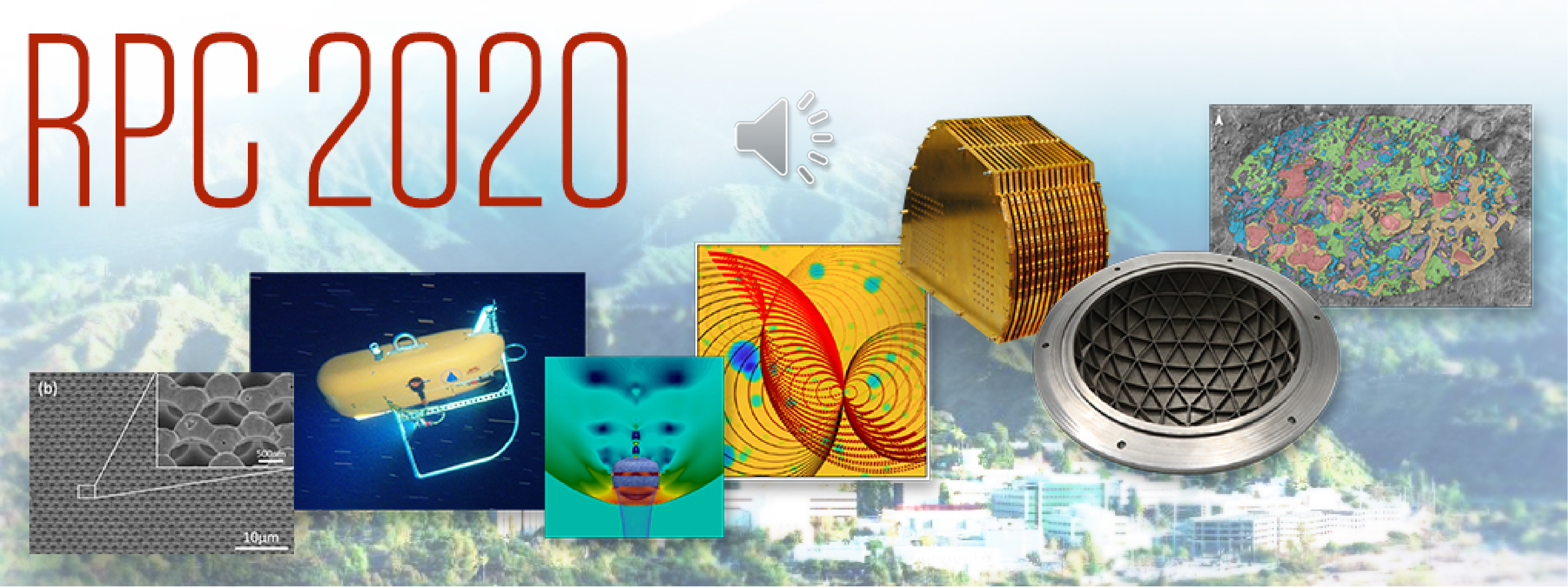

Virtual Research Presentation Conference

A Spacecraft Bolt-On Pulsar X-ray Receiver Concept for Autonomous Navigation and Timing

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Program: Topic

Assigned Presentation # RPC-117

Jet Propulsion Laboratory
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Tutorial Introduction

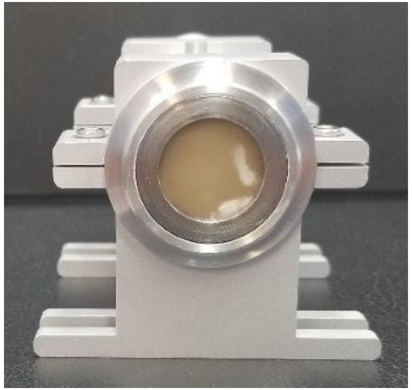
Abstract

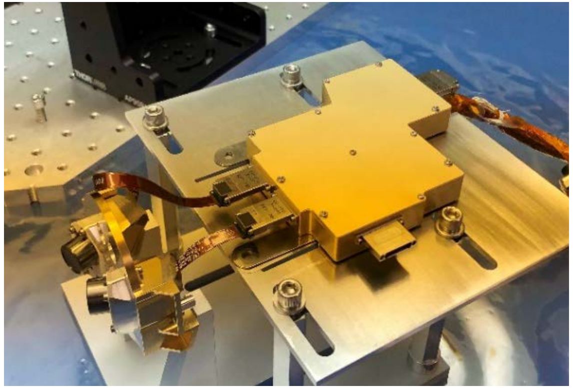
The objective of this task is to develop and characterize a miniature bolt-on prototype X-ray receiver instrument for autonomous deep space navigation with scalable X-ray collection area that could be further developed for an in-flight demonstration.

The instrument concept leverages heavily on the M2020 PIXL instrument flight designs. Only two adaptations to PIXL designs are needed for our application including use of a polycapillary focusing optic on the X-ray detector and modification of the PIXL digital timekeeping process to include a high-precision timing source for improved accuracy of incoming X-ray events.

The prototype instrument is developed in coordination with the X-ray navigation covariance modeling tools developed by JPL, which in turn will be interfaced with the JPL AutoNavigation tools, lowering the threshold for future Pulsar Navigation efforts to integrate with the standard Mission Design tools and providing independent validation of the Pulsar Navigation models.

The main deliverable from this task is a scalable prototype Pulsar Navigation instrument akin to a star tracker in size, mass, and power (5-10 kg, 5-10W), with supporting simulation, analysis, and laboratory testing to provide a solid concept for future Pulsar Navigation in-flight demo.





Problem Description

a) Context (Why this problem and why now)

- Enables new mission concepts for deep space reducing Deep Space Network use for Navigation.
- Builds on recent M2020 PIXL investment to fill a need for autonomous deep space navigation.
- Builds on prior RTD investments developing algorithms for Pulsar Nav. modelling and expands the JPL AutoNavigation toolset.

b) SOA (Comparison or advancement over current state-of-the-art)

- NASA Goddard's SEXTANT (NICER instrument on ISS) is huge. It has a large array of 56 X-ray Silicon Drift Detectors paired to an array of 56 large collimating optics. This architecture leads to a very large size (refrigerator).
- XPulsar Nav. 1 Chinese spacecraft (2016 launch) – also a very large instrument, unsuited to Pulsar Nav.
- DSN/radio ranging is accurate along boresight but has angular error that increases with earth distance.
- Pulsar Nav. becomes competitive to DSN/radio methods at roughly the distance of Jupiter (~5 km accuracy).

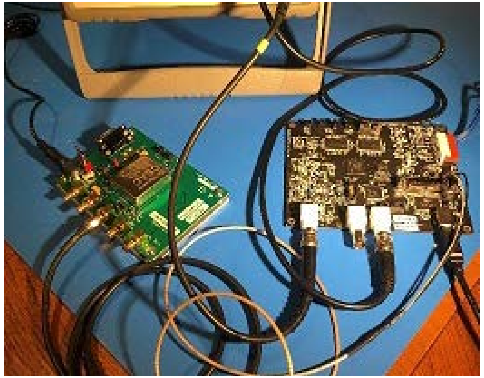
c) Relevance to NASA and JPL (Impact on current or future programs)

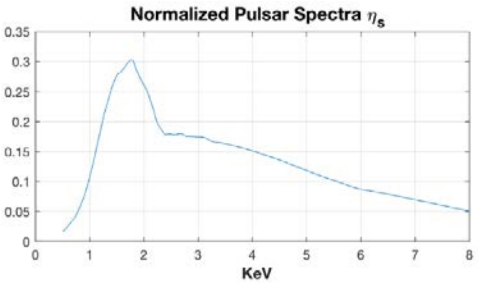
- Current Pulsar Nav. instruments are not practical due to the large size.
- Demonstrates that existing PIXL miniature X-ray spectrometer designs could be adapted for Pulsar Nav. instruments.
- Demonstrate the feasibility of a smaller, lighter, more efficient optic that passively increases the collecting area.
- Pulsar Nav. provides unique on-board autonomous navigation capability for spacecraft.
- Provides accurate, autonomous position knowledge at large distances from Earth without the DSN infrastructure.

Methodology

a) Formulation, theory or experiment description

- Pulsar Nav. performance is dependent on X-ray collection area. Demonstrating that an optic can be used to increase the collection area will be an enabling technology for Pulsar Nav.
- If this works, the idea is to increase the collection area further than currently available commercially, with a custom optic design.
- Select a better time reference for Pulsar Navigation and adapt the digital time keeping process to use the better clock and filter X-rays by energy to optimize the signal to noise.





b) Innovation, Advancement

- Develop and characterize a miniature prototype bolt-on instrument for pulsar navigation (Pulsar Nav.) for deep space and planetary spacecraft.
- Adding a compact front end optic to an existing miniaturized space-based X-ray spectrometer to increase the X-ray collection area by factor of between 4x and 25x in area.
- Develop Pulsar navigation instrument algorithm interfaces to JPL AutoNavigation toolset.

Results

a) All Year 1 goals were met except for assembly of the delivered prototype components for system level testing. This was deferred due to COVID work from home orders. Specially:

   a) We built and characterized a large polycapillary optic increasing the effective aperture by a factor of 3.6x

   b) We performed a trade study on various time reference options, selected one, and integrated it into a commercial analog to the PIXL Digital electronics running modified PIXL-based FPGA code implemented to record Time of Arrival with filters optimized to increase the SNR for Pulsar Nav.

   c) The work on characterizing the FPGA and electronics timing error gave us a good solution for both the vendor board level characterization and JPL end-to-end characterization of the instrument timing, whereby all instrument *and GSE* timing is based on the same CSAC reference via the FPGA. We demonstrated electronics time uncertainty is smaller than a single 20MHz clock cycle.

   d) We developed a methodology for similarly characterizing the X-ray detector.

   e) We developed and demonstrated a test setup whereby an individual X-ray event can be simulated at a known time, and compared to the observed and recorded time by the instrument to demonstrate time keeping knowledge and performance.

   f) We derived an error budget and made several modifications to the covariance analysis tool to better represent the expected performance of the subject instrument and inform various hardware trade studies. The covariance tool now incorporates new parameters for the entrance aperture size, clock accuracy and drift, and the optical efficiency as a function of both acceptance angle and photon energy.

   g) Updated photon count rates for both pulsar sources and background noise were computed based on mapping their spectral radiances from the sky to the detector, taking into account their energy spectrum and various geometric and optical properties of the receiver hardware.

   h) The covariance analysis tool now also models the negative impact of imperfectly known pulsar locations on the sky

Significance and Next Steps

a) Significance

- Through this work, we discovered a high sensitivity to acceptance angle of the incoming X-rays, leading to the realization that a polycapillary optic acts as a non-physical filter, blocking background photons that are not collimated with the pulsar signal.
- We find that for Pulsar NAV, the CSAC clock has nearly identical performance to a Cassini-class Ultra Stable Oscillator. While the USO outperforms initially, they have almost identical long term performance and the CSAC clock can be installed on-board without a separate USO.
- Finally we discovered that the time-tagging accuracy has a very small impact on long term performance. With a good model for the on-board clock the solution converges with up to 10us timing uncertainty. 1 us timing uncertainty should be very easy to achieve.

b) Next steps

- Assemble the prototype instrument and test timing accuracy of the end-to-end system.
- Investigate Fabricating larger polycapillary optics with our optic vendor XOS.
- Implement the pulsar Navigation algorithms in AutoNavigation toolset and compare independent results.
- Seek further funding in FY’22 for an in-flight demo.

Publications and References

[A] Po-Ting Chen, Ben Dunst, David S. Bayard, Walid Majid, Robert Sharrow, and Jason Speyer. *Covariance Analysis Tool for Pulsar-Based Navigation*, JPL Document D-106380, September 25, 2020.

[B] Ben Dunst, Po-Ting Chen, David S. Bayard, Walid Majid, Robert Sharrow, and Jason Speyer. *Performance Analysis of Scalable Bolt-On X-ray Receiver Concept for Pulsar Navigation*, JPL Document D-106381, September 25, 2020J.