National Aeronautics and Space Administration

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

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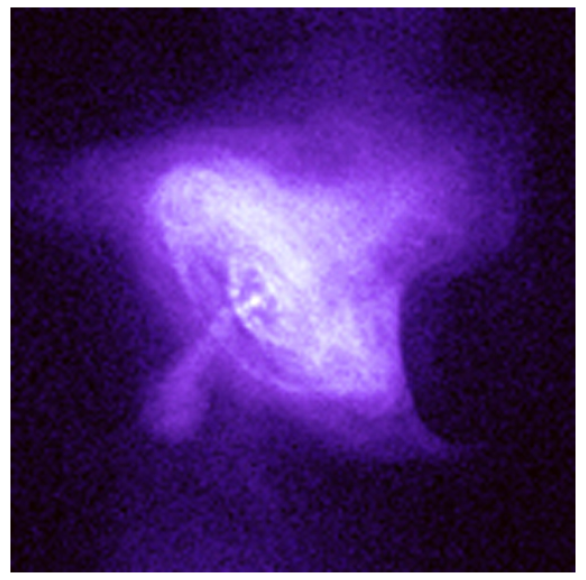
OBJECTIVES:

To expand potential applicability of autonomous pulsar-based navigation, the team developed, characterized, and studied a miniature bolt-on prototype X-ray instrument receiver. The biggest innovations intrinsic to this effort are the use of a polycapillary X-ray focusing optic in the receiver, and adaption of the M2020 PIXL instrument design to include a high-precision timing source sufficient for pulsar-based navigation.

The result is a scalable, prototype pulsar-based navigation instrument concept, akin to a star tracker in size, mass, and power (5-10 kg, 5-10W), with supporting simulation, analysis, and laboratory testing to assess performance of various miniaturization strategies and provide a roadmap for future hardware optimization and eventual in-flight demonstration and use.



(Image Credit: NASA/CXC/SAO)

Figure 1: The Crab Nebula has a millisecond pulsar in the center

BACKGROUND:

Millisecond pulsars (**Figure 1**) (rapidly rotating neutron stars) exhibit atomic clock-like stability offering a long imagined opportunity for use as beacons for autonomous. The NICER-SEXTANT investigation demonstrated the feasibility of using pulsars for navigation with a precision of 5-10 km (Gendreau et al. 2016). However, the size of the instrument, a refrigerator-sized X-ray astronomy telescope, made the use of this technique prohibitive for space applications.

The team recognized an opportunity to apply recent developments in miniature X-ray instrumentation for space, leveraging JPL's work on the PIXL X-ray Fluorescent spectrometer (Mars 2020 Instrument; Allwood et al. 2018). We paired a stable, high-accuracy time reference and a high-efficiency polycapillary X-ray focusing optic with the PIXL design, resulting in a complete prototype pulsar navigation instrument concept that can be used, along with the sophisticated pulsar navigation covariance estimation modeling (Chen et al. 2020) to characterize end-to-end performance for autonomous navigation applications.

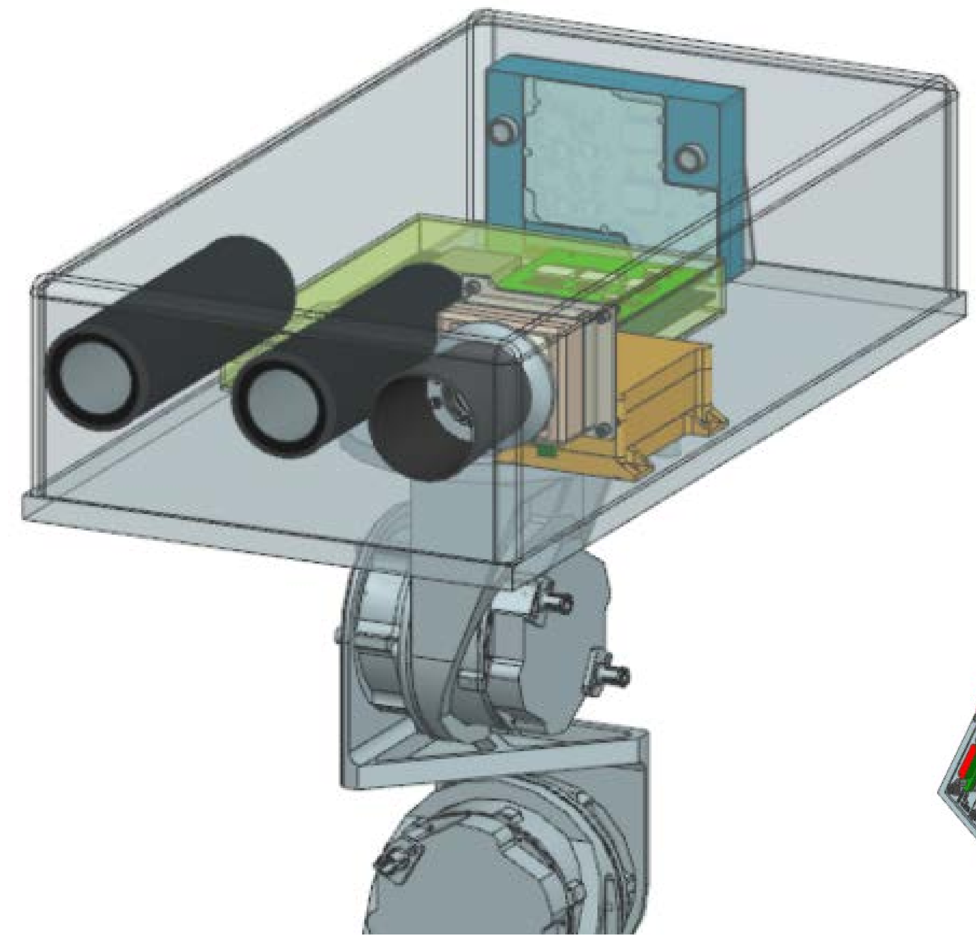
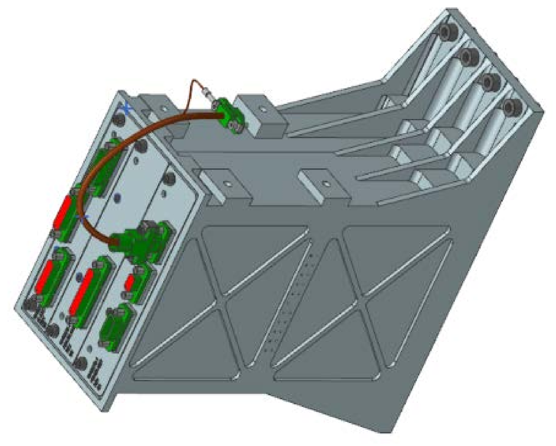


__Figure 2__: Concept for a Pulsar Observing Instrument for Navigation and Timing with scan platform, X-ray receiver with two 3.5-cm optics, and wide-angle camera star tracker (Left) and main instrument electronics (Right), both leveraging PIXL flight electronics and chassis designs.



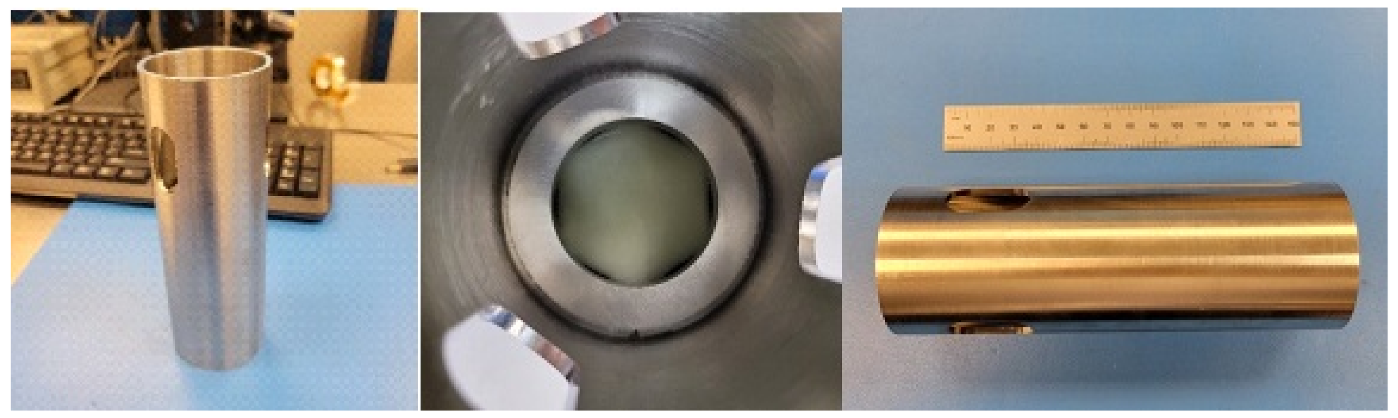


Figure 3. 3.5-cm diameter x 6.5-cm long polycapillary optic package with alignment features to mount an angular filter.

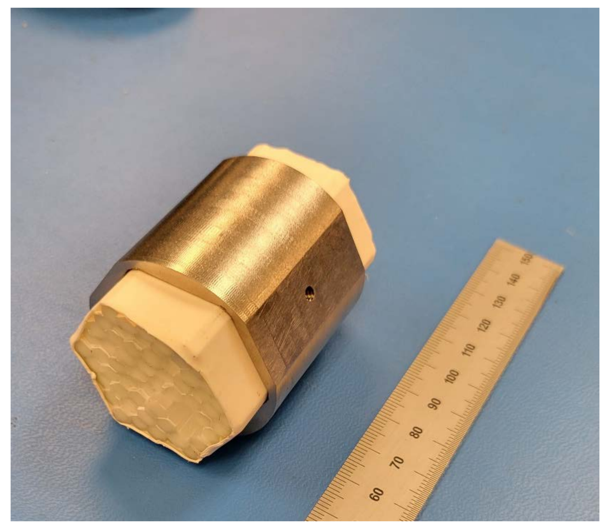
APPROACH AND RESULTS:

The team successfully demonstrated that the PIXL instrument could indeed be adapted into a high-heritage pulsar-based navigation instrument in a practical, compact, low power package (5-10kg, 5-10W) (**Figure 2**). To optimize the pulsar instrument performance, the team compared hardware and mission design options using the JPL covariance pulsar navigation tools, adapting and building additional capacity into these tools and validating results with JPL's AutoNav solutions. **These results prove that the miniature instrument concept is shelf-ready for future missions.** The team recognized two design parameters that most significantly affect navigation accuracy: (1) aperture size (*larger aperture size is better*), and (2) the field-of-view (*smaller angle-of-acceptance is better*) (**Figure 6**).

We worked with optic supplier, XOS (East Greenbush, NY) to manufacture a 3.5-cm diameter optic only 6.5-cm in length (**Figure 3**). Our analysis and modelling indicate that a 10-cm diameter optic would be the optimal size to support pulsar navigation and could be built at XOS with some upgrades in the facility furnace used to heat, stretch and shape the optic during manufacturing. Our analysis showed improved throughput with a 10-cm optic with only 20-cm length vs the 100-cm optic on NICER-SEXTANT; a tremendous advancement toward miniaturization of pulsar navigation instrumentation.

In addition to demonstrating larger optic manufacturability, we worked with XOS to design, build and test a high-resolution collimating filter to improve signal-to-noise for pulsar navigation (**Figure 4, 5**). One of the drawbacks of polycapillary optics is that the comparatively larger acceptance angle (0.5-deg) allows more background X-ray noise to enter the detection system. This is nominally 5-times larger than the NICER-SEXTANT optic's acceptance angle and results in significantly greater noise in the polycapillary-based instrument. **However, XOS successfully built a compact angular filter element that reduces the angle-of-acceptance by a factor of almost 10, to 0.06-degrees**. This is equivalent to nearly half of the NICER-SEXTANT angle-of-acceptance (0.1-degrees), representing a reduction to the noise in our optic by a factor of ~100. The filter design, assembled with the optic, opens the door to a revolution in miniature X-ray optic capability for both pulsar navigation and X-ray astronomy instruments.

Figure 4. Angular filter element developed to reduce the X-ray background noise entering the measurements. Mounted in front of the polycapillary optic it rejects X-rays that are not sufficiently collimated with the signal.



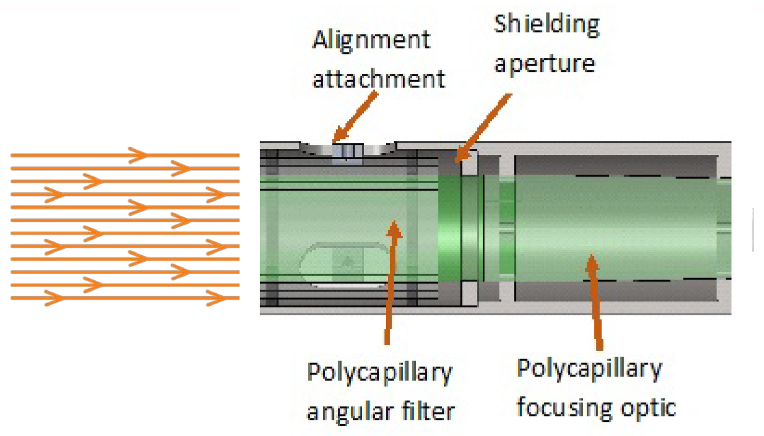


Figure 5. Rendering showing how the polycapillary angular filter mounted in front of the polycapillary focusing optic is packaged. This filter dramatically reduces the angle in which background X-ray noise can get into the detector signal chain, dramatically increasing the Signal-to-noise ratio by ~100x.

SIGNIFICANCE OF RESULTS

Using polycapillary optics significantly reduces the size of the largest element of an X-ray telescope. Previously, miniaturization has meant reduced performance. However, the collimating angular-filter blocks noise so effectively that performance is maintained (or improved), despite drastic reductions in size. Of all the advancements made in this effort, this filter is perhaps the most significant. With it, a pulsar instrument can be built in a traditional, bolt-on navigation instrument package, due to its compact nature..

Pulsar navigation creates significantly greater navigation autonomy, offloading overprescribed Deep-Space Network (DSN) resources, reducing staffing during long cruise phases, and providing GPS and ground-independent backup navigation. It will be mission enabling for small and medium-sized spacecraft that cannot afford traditional ground-based navigation options and may have defense applications as well.

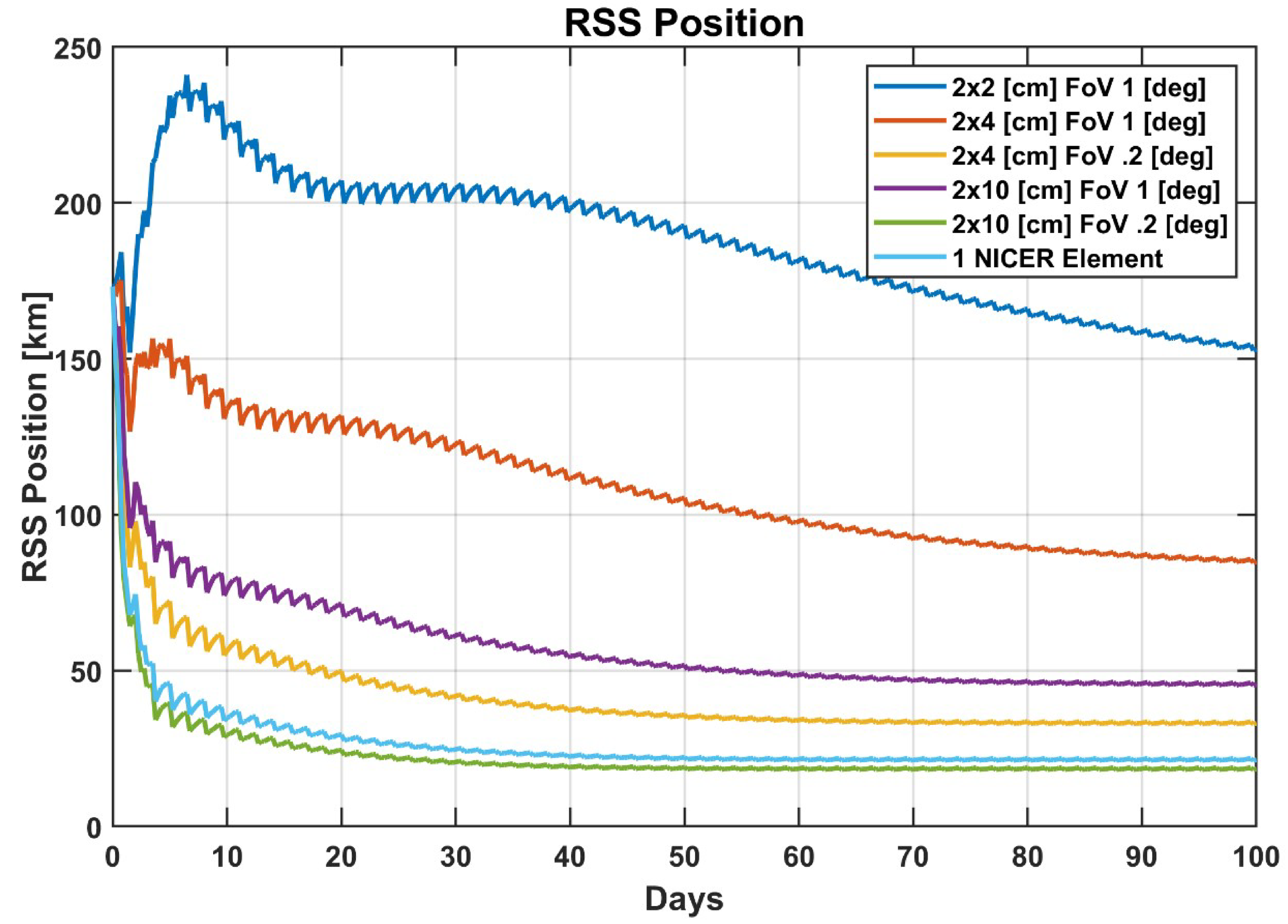


Figure 6. A Pulsar Navigation Instrument, with two, 2-cm diameter optics like those built in 2020 can achieve 153-km position uncertainty while a two 3.5-cm diameter optic configuration like the one built in 2021 could achieve about 85km uncertainty. Our analysis shows increasing the optic to 10-cm diameter, could improve this to 65-km position uncertainty for an otherwise similar performing optic with 0.5-deg angle-of-acceptance. Improving rejection of background X-Rays by reducing the angle-of-acceptance by a factor of 5, with an angular filter like we built in 2021 (denoted as "2x4 [cm]FoV .2[deg]" and "2x10 [cm] FoV .2 [deg]") could cut the uncertainty to 33-km and 18.4-km respectively. **The latter achieves ~15% better overall performance to a single NICER element (21.4-km).**

REFERENCES

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