

QE-SAN: a proof of concept to realize satellite navigation by optical pulsars

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ABSTRACT

The possibility of realizing autonomous satellite navigation systems by analyzing the signal emitted by pulsars has been deeply studied in the last twenty years. Experiments in the X-rays have also demonstrated the possibility of reaching positioning errors of the order of km after few days of pulsar observations; theoretically, improvements are possible but at the cost of very large sensing areas, which are not feasible for standard satellites. Recently, we have proposed the possibility of using the signal of pulsars in the visible portion of the spectrum for realizing a quasi-autonomous satellite navigation system: we have shown that it is possible to obtain a larger signal-to-noise ratio with respect to the X-ray case with a smaller instrument, providing a significant improvement in the satellite positioning.

To test the performance of this technique, we have realized a proof-of-concept instrument, the Quantum Eye for Satellite Autonomous Navigation (QE-SAN). QE-SAN is based on a commercial 28-cm diameter telescope which focuses its on-axis target on a single photon avalanche photodiode. QE-SAN has been installed at the Monte Baldo Astronomical Observatory “A. Gelodi” (Italy) and has observed the Crab pulsar for several nights, recording the arrival time of the pulsar photons with nanosecond accuracy with respect to Universal Time. The aim of this experiment is to measure the optical pulsed-fraction signal of the pulsar at the Observatory, and to compare it with the expected pulsar signal at the Solar System Barycenter: from this analysis, it is possible to reconstruct the absolute position of the Observatory, representative of a satellite navigating in the Solar System.

In this paper we present the basics of satellite navigation by optical pulsars and describe the main characteristics of QE-SAN; finally, we show the preliminary results of the measurements.

Keywords: Satellite Navigation, pulsar light curve, photon detection.

1. INTRODUCTION

Space navigation for deep-space and interplanetary missions relies on Earth-based tracking networks, such as NASA's Deep Space Network (DSN) and ESA's European Space Tracking (ESTRACK) system. These systems provide a very good positioning accuracy, of about 100-200 m at one astronomical unit from Earth [1], but their performance degrades linearly with increasing distance from Earth. In addition, ground-based operations suffer from limited bandwidth, high operational costs, and human intervention, which are presently becoming a bottleneck with the number of space missions continuously growing. To address these challenges and to provide operational autonomy to navigation systems, deep-space navigation techniques based on the on-board analysis of pulsar signal have been revisited [2][3] since the initial idea by Dows in the 70s [4].

Pulsars are rapidly rotating and highly magnetized neutron stars which emit fast periodic beams of light, with periods ranging from a few milliseconds to seconds, and with a spectrum extending from radio to gamma rays [5]. Pulsars are extremely faint objects, often embedded in an emitting nebula. The pulsating component is much weaker than the

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continuous nebula background in the large part of the spectrum, and this makes its detection possible only with dedicated instrumentation and specific data analysis techniques, which allow to reach an acceptable signal-to-noise ratio (SNR). The extraordinary rotational stability of the pulsed component of a pulsar signal is a potentially very useful datum to be used in space, as it provides a reference clock if properly measured. Using this signal as a highly stable cosmic lighthouse, pulsar-based navigation systems can be conceived, able to determine a spacecraft's position, velocity, and onboard clock offsets. These systems are based on the accurate measurements of the pulsar photon time-of-arrival (ToA) and on the cross-correlation of the reconstructed light curve against a known light curve template referred to the Solar System Barycenter (SSB). The quality of the obtained data obviously depends on the SNR of the signal, the higher the better.

Pulsars are typically discovered at radio frequencies, where the pulsed component is well detectable with respect to the background. However, the use of the pulsar radio signal for space navigation is unfeasible because it would require impractically large antennas and excessively long integration times to achieve an acceptable SNR onboard a spacecraft [3]. To overcome these constraints, research activities have focused on X-ray pulsar-based navigation (XNAV), mainly because of the relatively large number of potential sources. Moreover, in-orbit demonstration systems have been realized, such as the NASA's Station Explorer for X-Ray Timing and Navigation (SEXTANT) [6] on the International Space Station and the Hard X-ray Modulation Telescope (Insight-HXMT) mission [7]. These instruments demonstrated the capability to provide their position in the Solar System with an accuracy of the order of ~ 10 km after few days of observations. However, they also showed that XNAV systems demand either massive and complex instrumentation or very long integration times to compensate for the poor SNR, making them not suitable at present for a service navigation instrument to be installed on a satellite.

Recently, the concept of Space Navigation by Optical Pulsars (SNOP) has been introduced [8][9]. Optical navigation offers an important advantage over XNAV, made possible by the better performance of optical instrumentation over X-ray one: by narrowing the instrument field of view (FoV), the vast majority of nebular background photons can be rejected. This spatial filtering drastically enhances the pulsar-over-nebula ratio, enabling the highest SNR per integration time achieved to date in pulsar data. As a consequence, SNOP systems can reconstruct the pulsar light curve with greater accuracy over shorter integration times and using smaller instrumentation: [9] demonstrates a position accuracy of 400 m along the vector direction from the satellite to the Crab pulsar obtained (by simulation) with a telescope of 30 cm diameter, a FoV of 1 arcsec diameter and 8000 s integration time. The major issue with SNOP is that only a very small number of optical pulsars have been identified, with only three, PSR B0531+21 (Crab), PSR B0833-45 (Vela), and PSR B0540-69, having acceptable SNR for this application. This makes the estimation of all the parameters defining the satellite position in the Solar System more complex, but attainable with less resources than an XNAV system and still achieving similar or even better performance.

To verify the SNOP performance foreseen by the simulations, we realized a Proof of Concept (PoC) prototype instrument, with nominal performance very close to the simulated one. We named this instrument the Quantum Eye for Satellite Autonomous Navigation (QE-SAN). QE-SAN is not optimized for space applications: in fact, our limited budget essentially allowed us to use only commercial devices, properly integrated to realize a photon counting photometer. QE-SAN has been installed at the Monte Baldo Astronomical Observatory "A. Gelodi" (Italy), at 1221 m altitude, and has observed the Crab pulsar for several nights. The basic idea of this experiment is to consider the observatory as a space platform hosting QE-SAN and to use the data acquired from the Crab pulsar to reconstruct the observatory position in the Solar System. Even if QE-SAN is not the optimal telescope for this application, we found a very good agreement between simulated and acquired data.

In this paper, we are going to describe the whole process that brought us to the final measurement: in Section 2 we report on the basic concepts of a pulsar navigation system and how we simulated the data collection of QE-SAN when looking at the Crab pulsar; on Section 3 we describe the design phase of QE-SAN, of its main characteristics and of its actual performance, as measured in the lab at the completion of the instrument integration activities; finally, on Section 4 we show the use of QE-SAN at the Monte Baldo Observatory and we give some indication about the preliminary results of the data analysis.

2. PULSAR SATELLITE NAVIGATION BASIC CONCEPTS AND SYSTEM SIMULATION

2.1 Pulsar satellite navigation basic concepts

Pulsar-based satellite navigation relies on comparing the known propagation phase of the pulsed component at the SSB with the phase derived by the pulsar photon ToA's acquired by the satellite and time-referenced at the SSB: if the position

of the satellite with respect to the SSB is properly known, the two phases correspond each other; if not, it is possible to define the positioning error and so to provide the correct satellite vector by a suitable analysis of the measured data. Details about the complete data analysis can be found in [8], here we limit to summarize the main points of the process.

To realize satellite navigation by means of pulsars, the basic measurement to be implemented is the detection of individual photons from the pulsed component of the pulsar signal and the assignation to each of them of its ToA. Then, a complex data analysis is necessary.

First, to accurately reconstruct the necessary information, preventing signal degradation due to Doppler shifts induced by relative spacecraft motion with respect to the pulsar, the signal analysis must be referenced to a quasi-inertial frame, in particular the International Celestial Reference System (ICRS) centered at the SSB. For this, it is necessary to implement the so-called barycentricization process, that is re-assigning to each photon a new ToA, as if the same photon would have been detected at SSB and not at the satellite position. This is realized using suitable software codes (e.g. TEMPO2 [10]), which account for satellite position and velocity, source orientation and relativistic corrections for the photon path, such as Einstein and Shapiro delays. Then, since pulsars are very faint sources and only few photons (if any) are collected by standard telescopes per period, to reconstruct the pulse profile it is necessary to accumulate photons over multiple rotational periods, using for example techniques known as *epoch folding* [11][12] or *waterfall* [13]. This allows to determine with great accuracy the effective period T_{eff} of the pulsar starting from an expected period T_{exp} at the time of integration (the pulsar period is actually subject to a very small drift in time because of radiative energy losses of the pulsar; for example the period of the Crab pulsar increases by about 36 ns/day). Figure 1 shows a graphical representation of how epoch folding allows the reconstruction of the pulsed fraction of the pulsar signal, given a nominal period T .

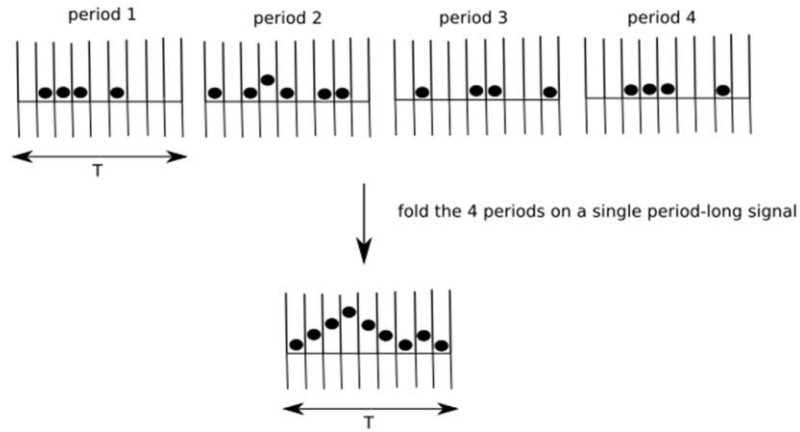


Figure 1. Graphical representation of the epoch folding technique used to reconstruct the pulsar light curve profile from the single photon acquisition and time tagging [8].

In navigation applications, epoch folding is not used to determine the rotational period which is assumed to be known, but rather to accurately measure the time at which the initial phase of the reconstructed light curve, that typically corresponds to the peak of the light curve, happens. The accuracy of the phase depends on the selected number N of time bins with which the pulsar period is going to be quantized, and a large N gives a better phase definition. But to properly identify the correct bin of the initial phase on the pulsar light curve, it is fundamental also to have a very good SNR of the reconstructed signal. And for this it is necessary to have a large number of photons, to optimize the quality of the light curve profile: this means that either long integration times or large optical aperture areas are required. Also, a suitable algorithm for optimizing the search of the phase position is required: in this case, the cross-correlation of the measured pulsed signal with a suitable template of the light curve is used [8].

Once the phase of the pulsar measured at the satellite at time t_1 is reported at the SSB, it is compared with the nominally known phase at SSB at the corresponding time. From the difference between the two it is possible to estimate the orbital position inaccuracy along the spacecraft-pulsar direction. After the position correction is implemented at the spacecraft level, a new measurement can be taken, at a following time t_2 , with the spacecraft that has moved to a different position along its orbit. It is evident that the process for estimating the satellite position is an iterative one, where any iteration

improves the phase alignment result and hence the generation of a more precise light curve, leading to a more accurate final measurement.

2.2 Simulation of a navigation system based on pulsar

To estimate the actual performance of a SNOP system, we realized a software which simulates the signal collected by a telescope with very small FoV pointed on the brightest visible pulsars [8]. For distributing the photons in time with the proper light curve and background we reconstructed analytical light curve templates for the brightest visible pulsars; for getting the correct photon rates, we considered the data we obtained with either Iqueye [14] or Aqueye+ [15] when observing the pulsars. For the Crab pulsar case, we used the data obtained with the 1.8 m diameter telescope Copernicus in Asiago (Italy), where the photometer Aqueye+ is usually installed, where we have the best statistics: the mean photon rate collected from the Crab pulsar is about 1000 photons/s, while the one coming from its nebular background (over a field of view of about 5 arcs diameter) is about 4500 photons/s. These values are affected by the dark counts of the detector (~ 700 – 800 counts/s), but since this noise has a Poisson distribution with constant time average, we considered it as a noise contribution included in the background. Because of the similarity of the instruments, that is a two-mirror telescope followed by a lens optical train and a silicon photon counting sensor, we simply assumed that the system throughput of the SNOP instrument is the same of Aqueye+ coupled to the telescope. By simple geometric considerations on the values of the collecting area and on the angular size of the FoV, assuming for simplicity a uniform nebula spatial distribution, we could then estimate the count rate at the SNOP focal plane of both the pulsed and the background components. As an example, Figure 2 shows the result of simulating the signal collected with a 30 cm diameter telescope and 10 arcsec circular FoV when observing the Crab pulsar for 1800 s, after proper folding. Results like this can then be used to provide a value of the pulsar phase and then propagate the positioning error of the spacecraft.

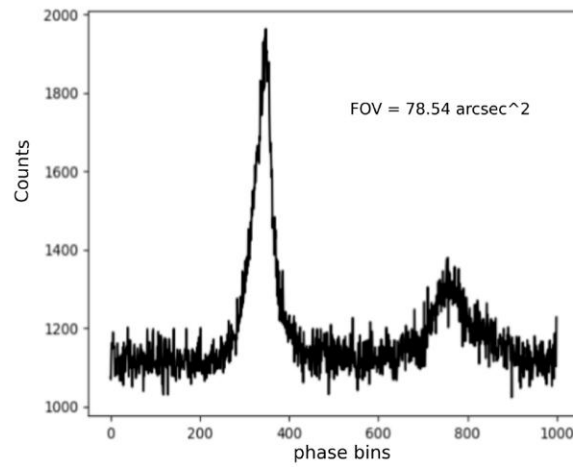


Figure 2. Simulation of the signal collected with a 30 cm diameter telescope and a circular FoV of 10 arcsec diameter centered on the Crab pulsar, with an integration time of 1800 s. Here the period has been divided in 1000 time bins; in ordinate the values are counts per time bin [8].

3. QE-SAN DESIGN, MAIN CHARACTERISTICS AND OPTICAL PERFORMANCE

QE-SAN consists of three major subsystems: the Opto-Mechanical Assembly (OMA), the Acquisition and Control System (ACS), and the Pointing and Tracking System (PTS). The OMA includes an Optical Head (OH), a Photon Counting Photometric Channel (PCPC), and a Context Camera Channel (CCC).

The instrument's primary light collection subsystem relies on a Celestron CGX-L 1100 Schmidt-Cassegrain-type telescope with an effective aperture diameter of 279.4 mm and a total focal length of 2800 mm. The telescope has a front Schmidt corrector plate to mitigate spherical aberration and two corrective internal lenses after reflection from the secondary mirror, yielding a flat, coma-free, and diffraction-limited focal plane over most of the visible spectrum. The selection of commercial components was mandated by contract guidelines, as QE-SAN is considered as a PoC instrument; this had the consequence that the instrument is not optimized in compactness compared to a dedicated optical design.

At the focal plane of the telescope, a custom field-separator flat mirror inclined at 45° to the optical axis with a 0.5 mm central hole splits the incoming field of view: the central on-axis light beam of ~ 37 arcsecond FoV, passes undeviated through the central aperture into the PCPC. Simultaneously, the outer field of view, spanning more than 15 arcminutes, is reflected at 90° into the CCC. Figure 3 shows the optical layout of QE-SAN.

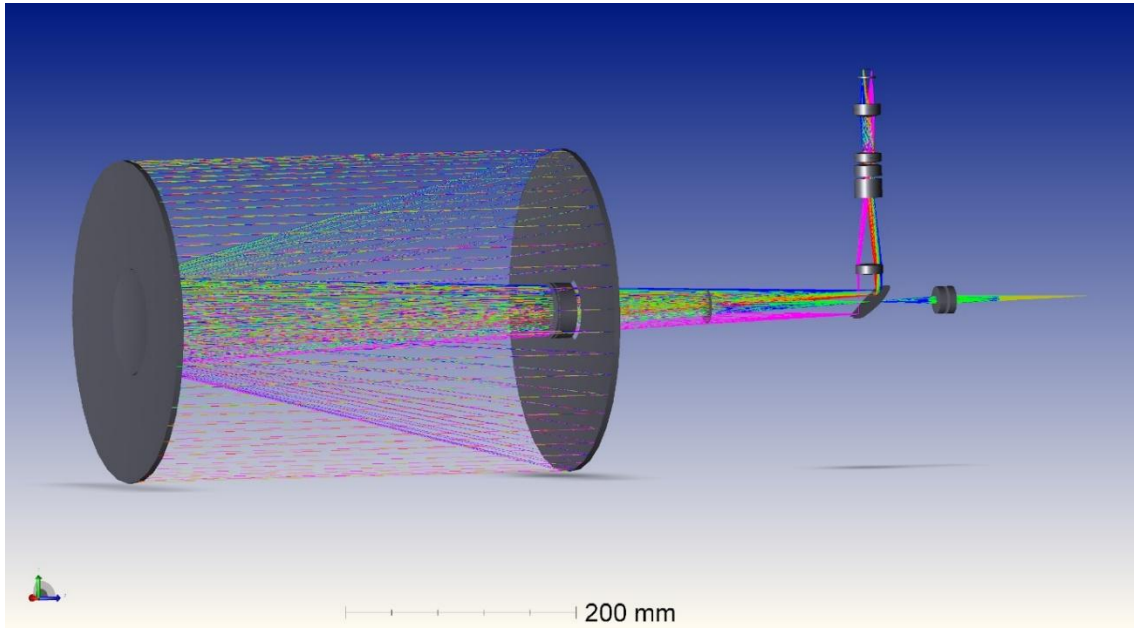


Figure 3. Optical layout of QE-SAN. On the left there is the two-mirror Celestron telescope which collects the light and focuses it at the position of the splitting mirror, tilted by 45° with respect to the optical axis. The following straight path with the two doublets is the PCPC, while the path deviated at 90° is the CCC, with a more complex optical train. The sensors are not represented in this figure.

The PCPC is designed as a relay optical system utilizing two identical achromatic doublets arranged in a mirrored layout to minimize residual aberrations; it slightly magnifies the central portion of the telescope focus passing through the mirror at the PCPC detector. The overall focal length of the telescope combined with the PCPC relay optics is 3100 mm. Ray-tracing simulations in Zemax OpticStudio confirm diffraction-limited imaging performance, with nominal spots smaller than the Airy disk ($\sim 14 \mu\text{m}$). The target detector for the PCPC is a COUNT-10C Single Photon Avalanche Diode (SPAD) from Laser Components, selected for its ultra-low dark count rate and high temporal resolution. Its active area has a sensitivity decreasing with the radial distance, being optimized in the central $100 \mu\text{m}$ diameter central portion. Given the system focal length, the FoV portion filling this area corresponds to about 6.5 arcsec: this is the portion of the Crab nebula which is collected by QE-SAN. The fast pulses emitted by the SPAD at each photon detection are fed into a Time-to-Digital Converter (TDC) referenced against a Pulse Per Second (PPS) signal provided by a GPS receiver. This enables to time tag each detected photon with a very high-precision Universal Time Coordinated (UTC) ToA.

The CCC acts as a wide-field monitoring and tracking system: it is used to check the centering of the Crab pulsar on the hole in the splitting mirror and to track the telescope during the long observations using some reference stars. The CCC is designed as a modified Cooke triplet, consisting of five achromatic doublet lenses. The system collects the off-axis light reflected by the splitting mirror on a radial field angle ranging from 0.01° to more than 0.25° . The CCC focuses this light onto an Omegon VeTEC 432 M Mono camera featuring a 1.7-megapixel Sony IMX432 monochrome CMOS sensor (1600×1100 active pixels, $9 \mu\text{m}$ square pixel pitch, $14.1 \times 9.9 \text{ mm}^2$ total area). Zemax simulations showed that the main residual aberrations are field curvature and distortion, but substantially of negligible effect since over 80% of total energy from a source at infinity is enclosed within 2×2 pixels (Nyquist criterion). The context camera can be operated at relatively fast frame rates, to provide almost real-time tracking images to monitor pointing stability and prevent target drift.

Mechanically, the OMA relies on an Anticorodal 6063 aluminum alloy optical junction box housing the 45° field-splitting mirror. The splitting mirror mount allows full six-degree-of-freedom positioning (X, Y, Z translation and pitch, yaw, roll adjustment) via shimmed locking mechanisms. Internal surfaces are treated with black anodization to suppress stray light. The PCPC and CCC optical barrels are realized using standard series modular tubes reinforced by external steel support rods and cage plates to ensure structural rigidity. A custom M30 fine-pitch threaded interface connects the assembly to the telescope rear flange. The SPAD is enclosed within a dedicated protective aluminum housing featuring precision X-Y shim alignment and thermal management to maintain operating temperatures between 10°C and 40°C during cold night sky observations. We also run finite element modeling to validate the structural stability against gravitational sag across varying elevation angles.

Finally, the ACS consists of two parallel data streams: on one side there are the photon ToAs generated by the SPAD/TDC which are sent to an acquisition and data storage PC; on the other there are the context frame acquisitions produced by the CCC camera which are sent to a secondary PC running automated centroiding software on the reference stars and tracking information. The latter is computed in real time and sent to the PTS to drive the closed-loop guiding automated into the Monte Baldo Observatory high-precision equatorial mount. Figure 4 shows two photos of QE-SAN at the end of the alignment activities performed in our optics lab.

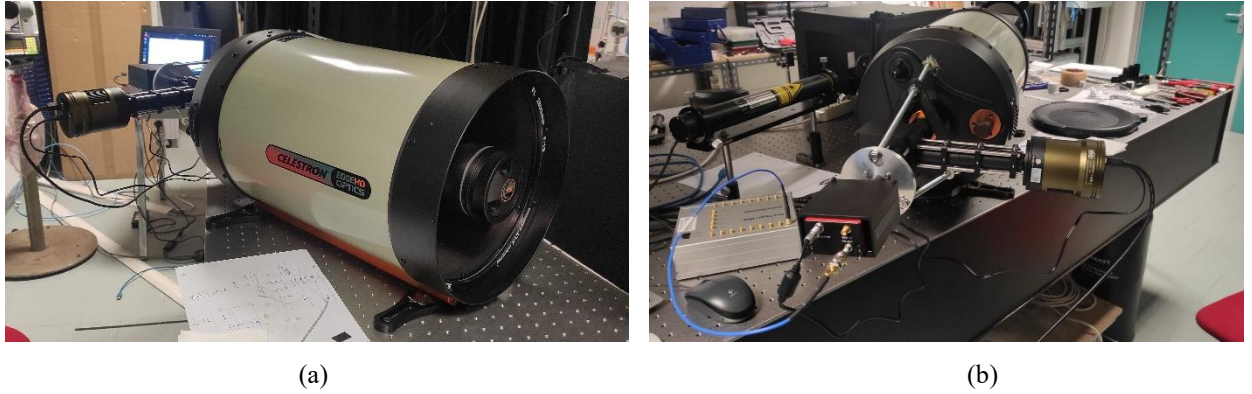


Figure 4. Front-side (a) and back-side (b) views of QE-SAN during the alignment activities in the lab. In (a) the Celestron telescope is in front view; in (b) the SPAD on the PCPC and the CCC camera are the most evident components; the structure of the optical path after the telescope focus has been rod-reinforced to provide better stability of the instrument at the telescope.

To check the optical performance of QE-SAN, we have generated a collimated light beam, effectively simulating the light of a distant star. For this, we used an off-axis parabolic (OAP) mirror with a pinhole at its focal point illuminated either by a laser beam or by a white LED. Given the 10 μm pinhole size, and the 635 mm focal length of the OAP, the light beam after reflection from the parabola has a residual divergence of $(10 \mu\text{m} / 635 \text{ mm}) = 15.7 \mu\text{rad}$. Because of the different focal lengths of the illuminating system and QE-SAN at the PCPC focal plane, we expect a magnification $M = \frac{3100}{635} = 4.9$ between the two systems: this implies that the image of the 10 μm pinhole at the SPAD will be nominally, that is aberration-free, of about 49 μm . For checking the image quality at the PCPC focal plane we cannot use the SPAD, being it a photometer and not an imaging system. Thus, for seeing the pinhole image at the SPAD position, we used a lab CMOS camera, 2k $\times$ 2k square pixels of 5.5 μm size. At the end of the alignment activities, the quality of the image was similar to the one shown in Figure 5, that is of the order of 50-60 μm FWHM, well in line with the expectations.

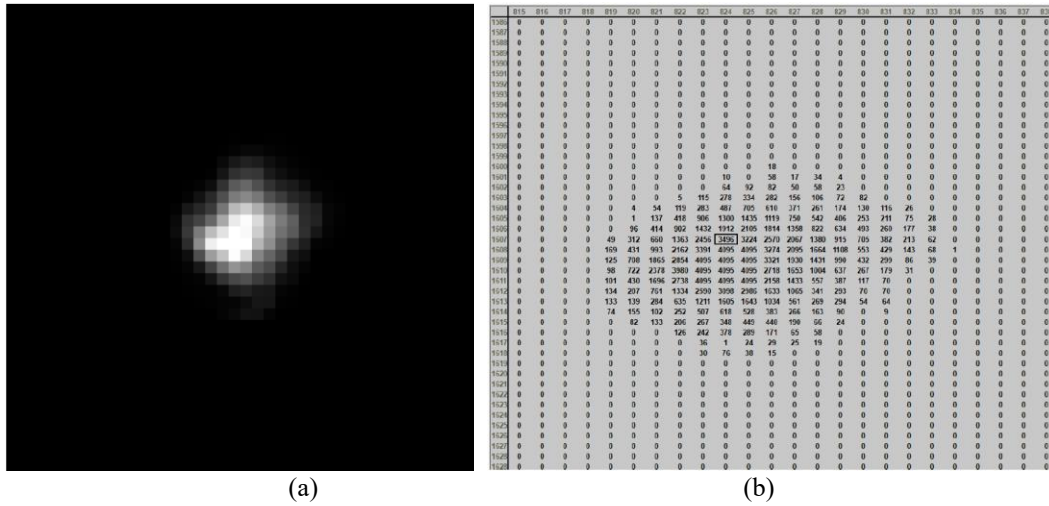


Figure 5. (a) Image of the on-axis source in a condition very close to the optimal alignment. (b) The corresponding numerical values of the pixel intensities.

To verify the optical quality of the CCC, we set on the OAP focal plane a USAF target in place of the pinhole, which provided an extended source and that was clearly illuminating the large majority of the CCC FoV. The aberrations at the outer FoV induced by the use of a simple OAP collimator have been estimated by simulations; even if not really negligible at the FoV edges, this is not a real problem for the actual use of the telescope when there will be stars filling the camera FoV. Thus, we just limited to check that the residual aberrations were symmetrically distributed over the FoV.

In addition, another important task we had to perform was to define the position of the SPAD sensitive area on the context camera FoV. For this, we acquired the two channels simultaneously, still using the lab camera on the PCPC. Figure 6 shows a photo of the acquisition PC monitor, where the images acquired by the two cameras are both shown.

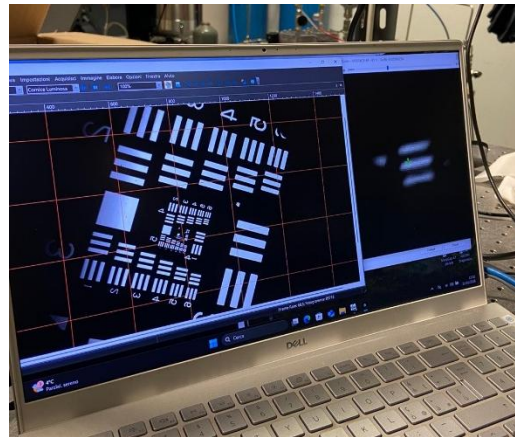


Figure 6. View on the acquisition PC monitor of the images simultaneously acquired both with the CCC camera (left), where the central portion of the USAF target is visible (group 2 and smaller), and with the lab CMOS camera set at the SPAD focus position (right), where just a small portion of three element lines are visible.

Figure 7 shows the qualitative image analysis that has been done to define in detail which part of the CCC FoV was going to be collected by the PCPC. On the left of the image there is a zoom on the innermost and smallest groups of the USAF target acquired by the CCC camera. The large dark green area corresponds to the portion of the mirror with the hole and that is not reflected on the CCC; this surface is not elliptical, as expected, because in the hole realization the mirror was chipped, and a small portion of reflecting surface has flaked off. The alternate red-green line elements shown on this

aperture have been manually added to the image to reproduce the missing portion of the target image. The comparison with the image on the PCPC focal plane on the right, allowed to define the actual portion of the FoV passing through the hole, highlighted in light green. It is also interesting to observe that the line element imaged on the lab camera is number 6 of group 6. Accounting for the system magnification, the width of these lines is about $22\ \mu\text{m}$ (which corresponds to ~ 90 line pairs per mm) and we can clearly distinguish them with large contrast; we can also see that their intensity is decreasing at the edges of the aperture, showing some vignetting. This provides an indication about both the very good image quality obtained, and the fact that it is necessary to center with great precision the target on the hole aperture to avoid any vignetting.

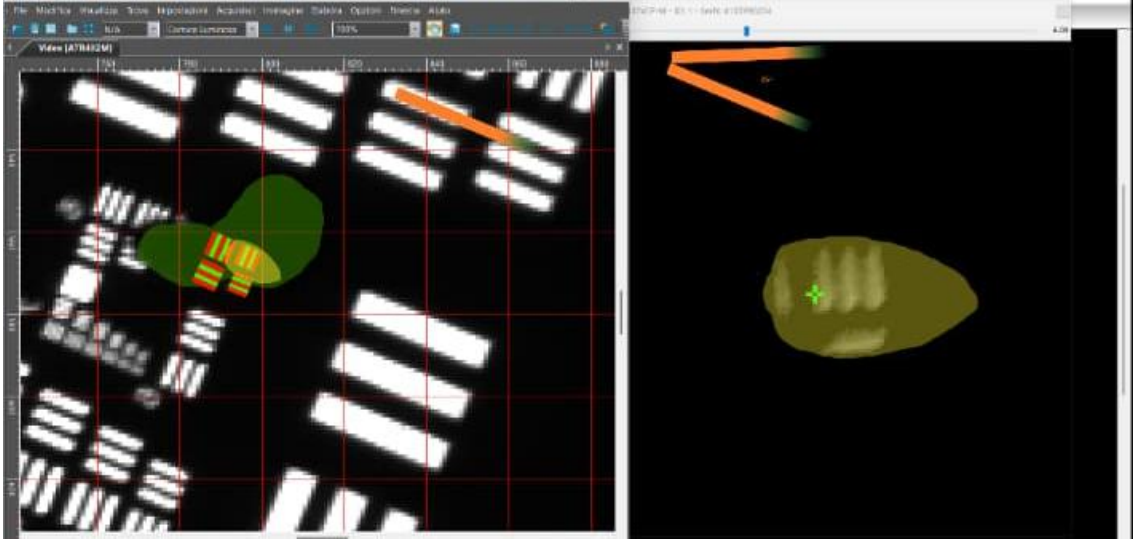


Figure 7. View on the acquisition PC monitor of the images acquired both with the CCC camera (left), where the central groups of the USAF target are shown, and on the lab CMOS camera set at the SPAD focus position. The light green colored area shows the FoV passing through the mirror hole.

The final alignment activity consisted in setting the SPAD sensor at its focus position. For this, we replaced the USAF target with the pinhole, to return to have an on-axis point source, we fixed the SPAD on its holder, and we adjusted its position until we finally locked it when the maximum count rate was obtained.

4. PRELIMINARY RESULTS BY THE CRAB OBSERVATIONS

To verify its actual performance for a potential SNOP application, QE-SAN has been deployed to the observation site, the Monte Baldo “A. Gelodi” astronomical observatory (see Table 1 for the observatory coordinates used for the data analysis), with the task to observe the Crab pulsar (see Figure 8). Here, QE-SAN has operated according to the dual-loop ACS framework previously described: when a photon is detected by the SPAD, the latter sends a high-speed electrical pulse to the TDC which provides a ToA; the TDC is also coupled to the GPS and provides its PPS, used as UTC referencing. The raw timestamp stream is saved by a dedicated control computer running a custom capture software. At the same time, the CCC camera streams raw starfield frames over a high-speed interface to a secondary control computer. The starfield image, at the observatory, is continuously monitored by a dedicated guidance software, which analyzes the positions of reference stars within the 15 arcminute tracking field and maintains the target in position.

During observation runs, the capture software specifically realized for QE-SAN acquisition control provides an immediate check of the data quality, by executing a real-time data folding process using a pre-defined pulsar period. As an example of the type of information provided by this software, Figure 9 shows a photo of the acquisition computer monitor: in a just few minutes, the Crab pulsar's characteristic double-peak light curve profile is obtained, confirming that the target is centered on the SPAD. Even if this quick data analysis is definitely not accurate because the photons ToAs are not corrected in phase and are not SSB barycentered, this is a very helpful tool during the observing runs, because it allows to be sure of the pulsar centering on the SPAD without waiting for the post-processing of the data.

Table 1. Position information of the Monte Baldo “A. Gelodi” astronomical observatory as obtained by GNSS (WGS84/ITRS datum).

Latitude	N45°41’51.4673”
Longitude	E10°51’31.6549”
Ellipsoidal height	1268.896 m
Height above MSL	1221.079 m

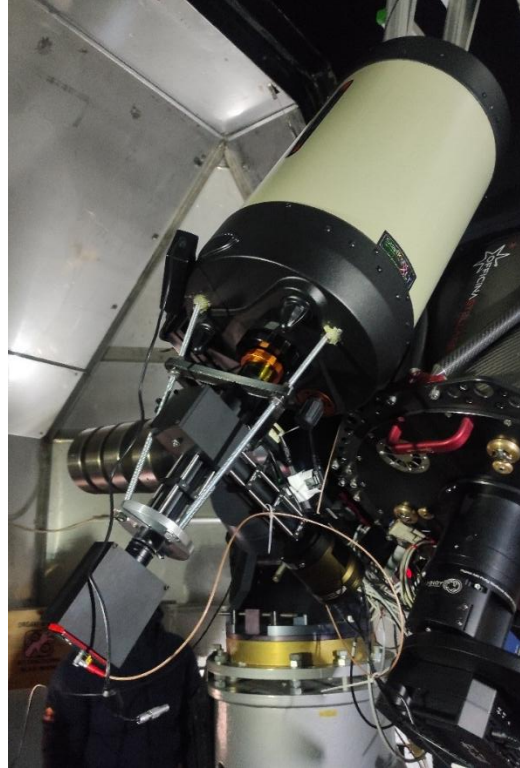


Figure 8. Photo of QE-SAN installed at the main structure of the Monte Baldo observatory.

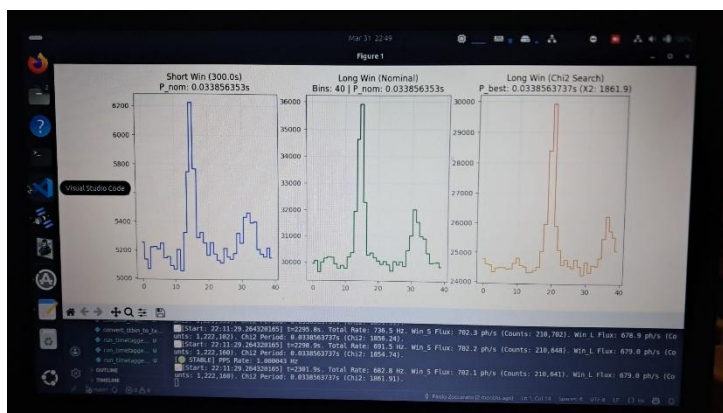


Figure 9. The coarse (40 bins) light curves of Crab pulsed signal obtained in real time during the observations.

At the end of the acquisitions, the stored data are post-processed, using precise ephemeris parameters to provide the actual UTC ToA of each detected photon with nanosecond precision. As an example of the data quality, Figure 10 shows on the left the Crab pulsar light curve (one period) obtained by folding a 30-minute exposure data across high-resolution 1000 time bins. This detailed light curve matches very well the shape of the reference profiles generated by the simulation software (see Figure 10 right) provided the QE-SAN geometric parameters. This result is extremely important because it validates both the indications provided by the simulation software, and the expected performance of QE-SAN.

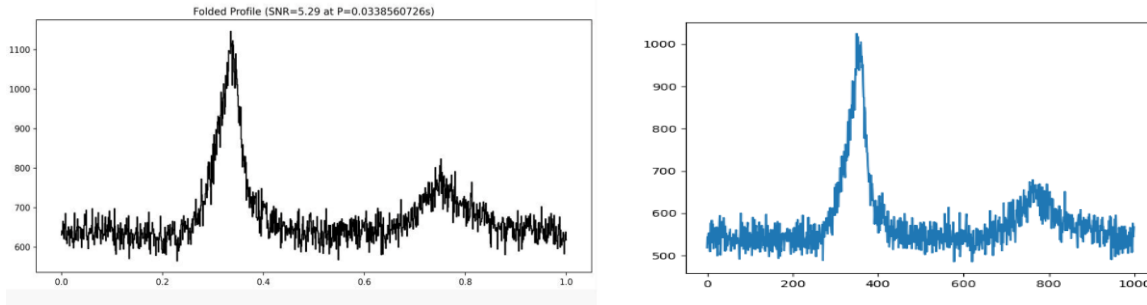


Figure 10. One period light curves obtained from 30 minutes of Crab pulsar observation after folding (counts per time bin in ordinate); the phase is divided in 1000 time bins. Left: measured data (the phase in abscissa is normalized to 1); right: simulated light curve under the same conditions.

We have observed the Crab pulsar over five nights on March 2026 (on the 19th, 23rd, 24th, 30th, 31st). Unfortunately, due to the period of year, with the window for observing the Crab pulsar getting shorter day by day, and the not always optimal weather conditions, we had to limit the observations to just 2-3 hours per night. This prevented us from completing the planned measurements, so we plan to return to observe as soon as the Crab pulsar will be visible from the Observatory again.

We are however already in the process of analyzing the acquired data, to get some preliminary indication about the effective QE-SAN performance. With respect to a dedicated SNOP system installed on a satellite, with which it is expected to reach about 700 m of satellite positioning accuracy with an integration time of half an hour [9], QE-SAN will definitely not be as accurate. There are in fact several factors which limit its performance. The first is that while for a space application it is possible to assume a FoV diameter as small as 1 arcsec, in QE-SAN it is 6.5 times larger: this value was set both by opto-mechanical constraints associated to the limited available resources, and by the fact that on Earth the seeing is affecting any astronomical observation, usually providing star image spots of the order of 1.5-2.5 arcseconds FWHM if the observing site is not optimal in terms of seeing. Clearly, the larger FoV the higher the pulsar nebula background reaching the SPAD, reducing the SNR: as shown in [9], this factor is providing alone a worsening of the positioning accuracy by a factor >2 . A second limitation is still associated to the presence of the Earth atmosphere, which produces a diffused background with respect to an observation from space, and so again a smaller SNR. Also, considering the Earth as a “platform” hosting QE-SAN and using a SNOP technique to define the Observatory trajectory in the Solar System is significantly different with respect to the case of a having the instrument on board of a satellite. In fact, one of the parameters that need to be used in the data analysis is the mass of the hosting platform, to consider any non-gravitational effect affecting the orbit between following measurements. Unfortunately, the Earth mass is known with an uncertainty of 0.01%, a significantly large error when propagated through the calculation used to reconstruct the Observatory trajectory. Because of all these limitations, we do expect to finally get an orbit reconstruction determination in the ICRS accurate at ~ 2 -3 km. Even if a precise analysis has not been done yet, this value is substantially confirmed by the quality of the measured light curve shown in Figure 10 (left), which shows that it is possible to define the phase of the measured pulsed signal with a few microseconds accuracy given a 30-minute exposure.

This result confirms the validity of the SNOP approach for satellite navigation, demonstrating that its performance are better than XNAV, needing less resources. Clearly, this analysis has been realized on the brightest visible pulsar, the Crab one, so this is a “best result”; when looking also at less bright visible pulsars, to get the complete 3D positioning of the platform in the ICRS, the out-of-range (that is not along the Crab direction) positioning performance will be poorer. However, in these cases, it will be possible to take longer integrating times to improve the measurement accuracy, and the good positioning datum obtained by the Crab pulsar will help in reducing the errors.

5. CONCLUSIONS

In this paper we have first described the basic concepts for space navigation by using pulsars, and have then presented the design, the laboratory activities, and the initial field deployment of QE-SAN, a proof-of-concept instrument designed to validate a SNOP technique. By utilizing a commercial 28-cm telescope equipped with a single photon avalanche photodiode and thanks to a narrow spatial filtering which effectively suppresses background nebular radiation, QE-SAN achieves a signal-to-noise ratio suitable for realizing SNOP within an acceptable timeframe.

Field observations of the Crab pulsar conducted at the Monte Baldo Astronomical Observatory confirmed the operational viability of the payload. The instrument demonstrated nanosecond UTC photon time-tagging and produced 30-minute high-resolution folded light curves that closely mirror theoretical simulations, with a potential measurement of the pulsar pulsed component phase as accurate as few microseconds. QE-SAN is not optimized for space applications, being a PoC instrument realized with COTS components, and it potentially reaches a positioning accuracy of the order of 2-3 km along range observing the Crab pulsar; however, based on the same principles, a more compact and more performing instrument could be realized for a potential satellite use.

The QE-SAN results and suitable simulations confirm that optical pulsar navigation can deliver sub-kilometer positioning accuracy and precise onboard clock synchronization using relatively small, lightweight optical dedicated instruments in relatively short measurement times. Future development will focus on refining the joint orbit determination algorithms, evaluating additional optical pulsar targets (e.g., PSR B0833-45 and PSR B0540-69), and transitioning the ground-based prototype design into a space-qualified in-orbit-demonstrator.

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