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EXECUTIVE SUMMARY

XNAV: DEEP SPACE NAVIGATION WITH PULSARS

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1.0	21/05/2013	14	Creation
1.1	05/06/2013	14	Removal of copyright statements Inclusion of expected performances in - Section 4, 3rd paragraph - Section 5, 2nd paragraph

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1. INTRODUCTION

1.1. PURPOSE

This document is one of the deliverables of the contract with ESA "**XNAV:** Deep Space Navigation with Pulsars" ([AD. 1], [AD. 2]). This document has been written covering the objectives of the SoW ([AD.1]).

1.2. SCOPE

This document presents the review of the outputs and major findings obtained during the study of deep space navigation using X-ray pulsars. This document has the following structure,

- Summary of the analyses and simulations performed at beginning of the activity and the design of the instrument.
- Results of the proof of concept using real data from a X-ray space telescope and lessons learned from that validation activity
- Preliminary roadmap for XNAV development.
- Conclusions.

1.3. ACRONYMS

AD	Applicable Documents
BU	Business Unit
CFI	Customer Furnished Item
DOP	Dilution of Precision
DSN	Deep Space Network
ECRV	Exponentially Correlated Random Variable
EKF	Extended Kalman Filter
EoC	End of Contract
ESA	European Space Agency
ESTEC	European Space Research and Technology Center
FF	Formation Flying
FOM	Figure of Merit
FOV	Field of View
FP	Final Presentation
GDOP	Geometric Dilution of Precision
GNC	Guidance Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HEAO	High Energy Astrophysics Observatory
HW	Hardware
IMU	Inertial Measurement Unit
IPR	Intellectual Property Rights
ITT	Invitation to Tender
KF	Kalman Filter
KOM	Kick-off Meeting

LAN	Local Area Network
LOS	Line of Sight
LSE	Least Squares Estimator
ML	Maximum Likelihood
MLE	Maximum Likelihood Estimator
MSP	Millisecond Pulsar
MTR	Mid-Term Review
NASA	National Aeronautics and Space Administration
NHPP	Non-Homogeneous Poisson Process
NLLS	Non-linear Least-squares
PAT	Pulse Arrival Time
PATD	Pulse Arrival Time Drift
PDOP	Position Dilution of Precision
PM	Progress Meeting
PoC	Proof of Concept
PRP	Pulse Repetition Period
PSR	Pulsar
PVT	Position, Velocity and Time
RD	Reference document
RMS	Root Mean Square
S/C	Spacecraft
SI	International System of Units
SNR	Signal-to-Noise Ratio
SoW	Statement of Work
SPS	Space Systems
SSB	Solar System Barycenter
SV	Space Vehicle
SW	Software
T0	Beginning of the project
TDB	Temps Dynamique Baricentrique (Barycentric Dynamic Time)
TOA	Time Of Arrival
TT	Terrestrial Time
UKF	Unscented Kalman Filter
XNAV	X-ray Navigation
wrt	with respect to

1.4. DEFINITIONS

XNAV pair	Combination of spacecraft navigation strategy and X-ray celestial pulsing source
XNav pulsars	Autonomous navigation method using measurements based on the periodic signals of X-ray pulsars

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1 Applicable documents

Ref.	Title	Code	Version	Date
[AD. 1]	Appendix 1 to AO/1-6898/11/NL/KML, Statement Of Work, Deep Space Navigation with Pulsars	TEC-ETN/2011.90	Issue: 1 Revision 2	22/07/11
[AD. 2]	GMV proposal to ESA/ESTEC for **XNAV:** Deep Space Navigation with Pulsars (in response to ESA/ESTEC ITT AO/1-6898/11/NL/KML)	GMVAD 10463/11	1.0	03/11/2011
[AD. 3]	Negotiation Meeting MoM, ESA/ESTEC	GMV-XNAV-NM-MOM	1.0	17/04/2012

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2 Reference documents

Ref.	Title	Code	Version	Date
[RD.1]	TN-01: STATE OF ART REVIEW AND CATEGORISATION OF PULSING X-RAY CELESTIAL SOURCES AND SPACE NAVIGATION STRATEGIES	GMV-XNAV-TN01	1.1	07/09/2012
[RD.2]	TN-02: XNAV PAIR DEFINITION AND PERFORMANCE ANALYSIS	GMV-XNAV-TN02	1.1	05/12/2012
[RD.3]	TN-03: AVAILABLE AND FUTURE TECHNOLOGY FOR XNAV NAVIGATION	GMV-XNAV-TN03	2.0	08/03/2013
[RD.4]	TN-04: XNAV STUDY CONCLUSIONS	GMV-XNAV-TN04	2.0	15/05/2013

3. XNAV PERFORMANCE ASSESSMENT AND PRELIMINARY DESIGN

3.1. XNAV PERFORMANCES

XNAV stands for X-ray Navigation. In general sense, it applies to any measurement technique producing an estimate of the spacecraft state from the observation of those celestial X-ray sources that can compare with today's atomic clocks in terms of regularity and stability. In this project, the use is restricted to the estimation of translational state –comprised of position and velocity- and time. Moreover, the effort is mainly focused in millisecond X-ray pulsars (MSPs), celestial sources that emit X-ray pulses with periods in the 1-50 ms range.

Different navigation methods for XNAV have been analysed, namely

- Position, velocity and time determination with GNSS-like navigation strategy using 4 or more X-ray highly stable pulsing source.
- Position, velocity and time determination using Δ-TOA (Time Of Arrival) measurements from single source, from discontinuous observation arcs.
- Position, velocity and time determination using Δ-TOA measurements from single source based on continuous phase and frequency tracking.
- Relative position velocity and time determination between space vehicles.

All the navigation methods make use of the same pseudo-observables,

- Pulse arrival time (PAT) - aka TOA - , qualitatively equivalent to ranging with faraway emitters.
- Pulse arrival time drift (PATD), qualitatively equivalent to range-rate or Doppler measurement.

Extensive Monte Carlo simulations including all the known sources of error in the navigation chain have been performed to assess

- The suitability of different X-ray pulsars
- The performances of the different techniques to compute the observables for navigation
- The navigation strategies for different space missions.

The main results of these Monte Carlo simulations are summarized below. In addition to these results sensitivity analyses (Monte-Carlo based) have been used to derive the initial error budget and the instrument specifications. The main error sources that impact the instrument design are the number of collected photons (related to the detector size and the integration time) and the timing accuracy.

- Among the different algorithms processing the photon time series to produce the observables (PAT and PATD) - which are the input to different navigation filters - the maximum likelihood provides the best accuracy in the estimation of the PAT (TOA) and PATD.
- The best pulsars in terms of performances (from the list derived at the beginning of the study) are
  - Crab (PSR B0531+21)
  - PSR B1821-24 (M 28)
  - PSR B1937+21
  - PSR B0540-69
- For **planetary orbiters**, the orbits shall have a long period to permit many observations. Given the considered integration times (10.000 s) the resulting orbits are quite high but they might be useful for some applications.
  - For instance, in **Mars** for high elliptic orbits resulting after the first insertion manoeuvre (insertion manoeuvres are split in several burns to avoid large propellant penalization due to gravity losses) or during aerobraking, or in **Jupiter** for orbits that explore the Galilean moons.
  - The observation of more than one pulsar is interesting to improve the reactivity (converge time) and minimize the black-out periods due to occultation or Sun exclusion.
  - In some very high-energy orbits (long period) discontinuous tracking can be acceptable. This is for instance the case of **Halo orbits** around libration points in the Earth-Sun system.

- For **interplanetary cruise**, three pulsars are needed to obtain complete observability of the orbit. The performances are very promising and low frequency measurements (1 observation per week) can be acceptable. For higher reactivity, e.g. after manoeuvre execution, quasi-simultaneous observation of three different pulsars (continuous tracking) might be required during short time intervals.

The timing accuracy has a strong impact on the instrument design. Thus deeper analyses are conducted to identify the impact of the timing requirements on the navigation performances. The outputs of these analyses are used to select the timing requirement on the XNAV instrument.

We have taken into consideration the case of use of observing three pulsed sources (the best triplet for XNAV) during 10 000 s to determine the spacecraft position. The Crab pulsar turns out to be the dimensioning source, demanding **532 ns** of clock resolution in order to not to degrade the PAT accuracy in more than 10% with respect to the perfect resolution case.

3.2. XNAV INSTRUMENT DESIGN

The XNAV instrument design is a trade-off including the following core tasks and factors:

- Maximisation of telescope effective area with minimised focal length and aperture diameter
- Matching of the angular resolution with the size of individual detector pixel
- Minimisation of the pixel size to minimise the time tagging error, but keeping the pixel size large enough to cover effectively the focal plane where signal from the source is focussed by the telescope
- Minimisation of the dead area of both the telescope aperture (MPO grid structure) keeping the angular resolution and telescope focusing effectiveness high.
- Minimisation of the dead area within the detector array without loss of functionality and performance (e.g. cross-talk problems)

The effectiveness of the XNAV instrument is dominated by the effective area of the instruments' optics in the desired energy range (0.5 – 10 keV chosen), and therefore significantly different size of optics to acquire equal navigation performance is required for objects that differ several orders of magnitude in X-ray intensity from each other. As the background flux density is directly proportional to the angular area of the measured background, the angular resolution to keep the source brighter than the background is proportional to the square root of the source brightness. Thus, the fainter the source, the better resolution is needed.

As the X-ray instrument is a photon counting device, and the navigation methods require very accurate timing of measurements, the other core parameter featuring the performance of the instrument is the time stamp accuracy of measured photons. Each incoming photon is absorbed in a random position of the detector inside the area corresponding with the angular resolution of the optics. On the other hand, the charge drifting to the collecting electrode has a finite maximum velocity. This leads to an uncertainty of incoming time, which can be derived from the distribution of absorption-electrode distances of the possible absorbing locations in the active detector. The uncertainty is proportional to the diameter of the detector.

An evaluation of the feasibility of a collimator optics for the navigation instrument, if Crab Pulsar is used as the navigation source is performed. The consideration is necessary, since Crab is so bright in X-rays that the source itself can be well resolved from within very large angular area of X-ray background.

The instrument technology needed for Deep Space Navigation using X-ray Pulsars is available and can be designed and manufactured to fly in a few years for the brightest navigation source candidate, the Crab Pulsar.

As results of the analyses, the instrument technology review results in the following proposed solution, when the critical XNAV requirements and also general requirements are taken into account.

The main components of the XNAV instrument are,

- Focusing glass-based MPO X-ray telescope of size depending on the chosen navigation source(s)
- Focal plane detector system including a 19-element (TBC) SDD detector array and instrument electronics including FEE and BEE.
- The exact size of the array is determined on the basis of

  - 1) the focal length and angular resolution of required optics and,
  - 2) the required time stamp accuracy.

The baseline instrument design is the following.

- The instrument consists of an MPO telescope, which is a modification of the MIXS-T telescope for BepiColombo with less stringent angular resolution requirement and larger pore size, an SDD based 19 element array as the focal plane detector, and compatible electronics.
- The total mass of the system is 10 kg
- The dimensions are 100x25x25 cm^3 (LxHxW)
- The power consumption of the whole system is ~30 W.

High-Level Design of Instrument for Demonstration mission

To minimize the mass and size of the instrument, and thus the cost of the demonstration mission, the brightest of the potential navigation sources, the Crab Pulsar is chosen as the basis for the technical requirements of the instrument requirements and its design.

The instrument proposed is based on assuming the following performance requirements leading to the smallest instrument that can produce data of adequate quality to perform a feasible demonstration. The instrument might not sufficient for proper demonstration of XNAV techniques with the shortlist sources fainter than the Crab Pulsar.

The basic features of a minimum demonstrator instrument are the following.

- The total mass of the system is 8 kg
  - The mass estimate is conservative, and the final mass can be significantly lower.
- The dimensions are 50x15x15 cm^3 (LxHxW)
- The power consumption of the whole system is ~15 W.
  - No Peltier cooling included.
- The instrument requires a pointing accuracy of 0.5 degrees and stability of 0.25 degrees during 1000 s (this value is still TBC because the pixels around the central one will collect photons even if the pointing is not perfect).

4. XNAV PROOF-OF-CONCEPT USING REAL DATA

The purpose of this proof-of-concept assessment is to validate the XNAV concept by applying the selected navigation algorithm to the processing of real X-ray astronomy data.

In the present case, the data source is the XMM-Newton observatory. The performance features of existing and past X-ray space missions shows that none of them fulfil the timing accuracy requirement of XNAV. Even the "timing missions" (e.g. Rossi-XTE) produce data with total time stamp error well over one microsecond.

The preferred X-ray source was the Crab pulsar, the strongest source in the sky, but limitations with the instrument prevented the use of such source. Therefore a fainter source (LMC pulsar or PSR B0540-69) has to be used. The expected range performance for the Crab pulsar in XNAV is 100 m (1σ), while for the pulsar B0540-69 is 5 km (1σ).

The assessment has proceeded as follows

- The processing of the initial 90% of the detection events has allowed us to obtain an experimental template of the source, as well as its phase law.
- The remaining 10% of the detection times has been fitted to the experimental template providing the navigation observable.
- The latter estimates have been compared with the values predicted by the experimental phase law, and the observed difference has been found to agree with its foreseen dispersion.

Figure 4—1 shows the meaning of the observable, the initial phase of the observed profile referred to the template, i.e., which phase in the template corresponds to the folding epoch of the folded profile. This will allow computing the time of arrival of such phase to the SSB using the phase law from the template.

An important remark deserves the reader's attention. It has been noticed that the XMM observations showed an unexpectedly strong background. This may degrade only slightly the performances when navigating with the Crab pulsar, but will probably have a large impact on the performances with fainter sources. The reasons for the strong background emission have been explained, and design and operation measures have been proposed for alleviating its effects.

The strong background degrades the navigation performance and the obtained position difference is 31.7 km. It is clear that these values are not useful for navigation because the experiment conditions are far from the nominal defined for XNAV application. The next step is comparing this measurement error with the expected performances obtained with the XMM-Newton characteristics (not optimal for navigation purposes) and with the short duration of the observation arc.

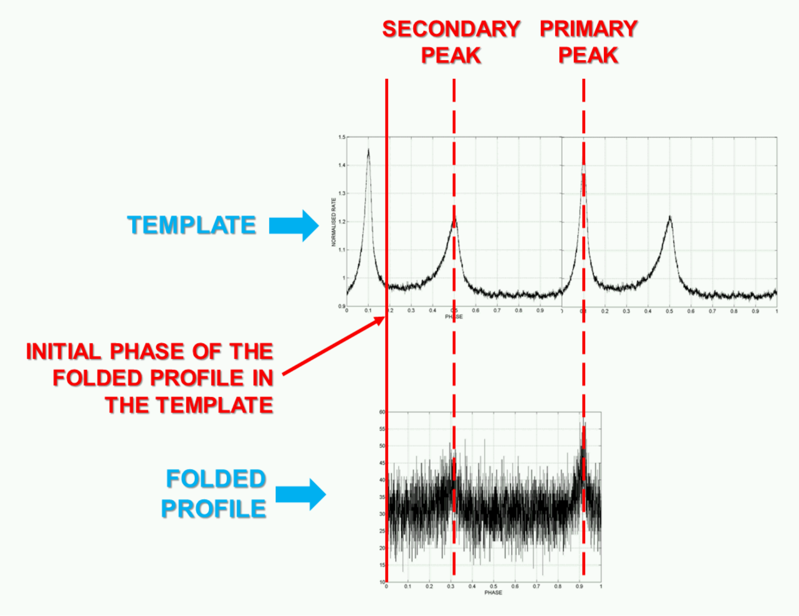

Figure 4—1: Example of matching template with folded profile.

Initially the process of computing a template with real data is validated by comparing the computed template using 90% of the data from XMM-Newton with the existing profile in the literature (in this case from Chandra space telescope). The fit of Chandra's available template and the obtained template from XMM-Newton is illustrated by Figure 4—2. It is been checked that the fit RMS agrees well with the prediction for ~1 hour of XMM data and obtained background in the real data.

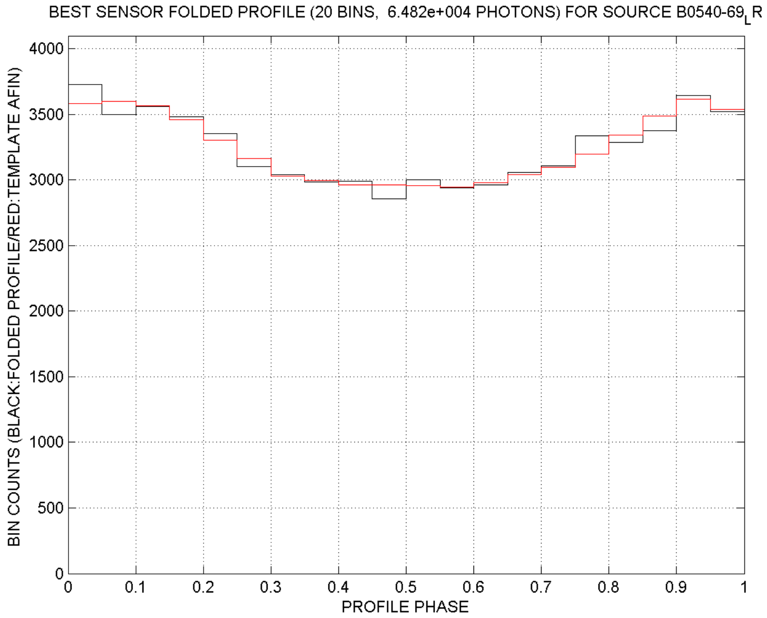

Figure 4—2: Fit of obtained template from XMM-Newton (black) with Chandra template (red)

The expected performances of the XMM-Newton measurement have been obtained after simulation of 1000 cases for each subinterval of the XMM detection times. The purpose is to simulate the real data obtained from XMM-Newton in a Monte Carlo simulation to obtain representative statistics on the XNAV performances using XMM-Newton instrument in the available data arc.

The RMS of the differential measurement of range is 448.4 km. The real measurement error (31.7 km) represents only one point but is well within this statistic (0.07 standard deviations).

An additional batch of Monte Carlo simulations has been executed to compute the expected navigation performance when observing during 10.000 s in the environment presented by XMM-Newton real observation arc. Thus, the difference with respect to the previous performances is only the integration time (from 360 s to 10.000 s). Now, the RMS of the differential measurement of range is 68.2 km. This is one order of magnitude better than the current arc duration.

5. CONCLUSIONS AND ROADMAP

The XNAV concept has been analysed in detail. The performances obtained from simulations have been validated successfully using real data from XMM-Newton space telescope.

The performances obtained using real data are not in line with the XNAV performances (100 m for the Crab pulsar) due to limitations in the XMM-Newton instrument operations. We have been forced to use a source much fainter than the Crab pulsar and surrounded by a background much stronger than expected.

Nevertheless, using the instrument data it has been possible to generate templates and produce measurements. The validation of the XNAV concept has comprised the following steps

- Computation of a measurement using real data only, i.e. a long arc to compute the reference template and a shorter arc to obtain the measurement.
- Comparison of the obtained template using the real data with the existing template in the literature from another space telescope (Chandra) in the same energy range.
- Computation (via Monte Carlo simulation) of performances of XNAV in the same environment of the XMM-Newton data.

All these validation steps have produced consistent results. It means that the performances derived from the extensive simulations, fit with the required statistics the obtained results from the real data. The fit seems conservative (predicted dispersion is much larger than the obtained with real data, suggesting conservative approach in the simulations) but it must be noted that only one measurement is produced from real data.

Based on the lessons learned and the results obtained during the study, a high level roadmap for development of XNAV is presented below.

- Additional **tests** with existing **data from space telescopes** to assess in better conditions the performances of XNAV. The tests shall produce **multiple measurements** in order to obtain statistics with significant confidence level.
- Refinement of **X-ray sources**, based on the obtained results from these performances.
  - The candidate list shall be consolidated with a re-assessment of XNAV performances and refinement of instrument to observe fainter objects with required performances.
- Additional observation campaigns to obtain more **accurate templates** for the selected X-ray sources (e.g. XMM-Newton could be arranged to obtain adequately accurate pulse profiles for millisecond pulsars in the brightness range of ~1/10 of Crab in X-rays).
- Technology development for **demo mission**, possibly in Earth orbit in ~2016-17 (test of XNAV could be included in an existing mission as payload of opportunity).
  - SW development for navigation chain (from current TRL 2-3 to TRL 6 in 2 years). It shall consider the use in LEO environment (autonomous operations).
  - Development of XNAV instrument using presently available technological solutions focusing on navigation performances (not system level requirements like mass or size). A pre-flight model of an XNAV instrument could be designed and procured within 3-4 years from the start of the project.
- Development of dedicated instrument for specific mission with technology available within 10 years.
  - The most relevant technology seems the MPO telescopes (optimization of the micro-pore structure and manufacturing and coating processes)

END OF DOCUMENT