NLR-CR-2015-243-PT16

PulsarPlane

D5.4 Final Report

Authors:	H. Hesselink, P. Buist, B. Oving, H. Zelle, R. Verbeek, A. Nooroozi, C. Verhoeven, R. Heusdens, N. Gaubitch, S. Engelen, A. Kestilä, J. Fernandes, D. Brito, G. Tavares, H. Kabakchiev, D. Kabakchiev, B. Vasilev, V. Behar, M. Bentum

Customer	EC
Contract number	ACP2-GA-2013-335063
Owner	PulsarPlane consortium
Classification	Public
Date	July 2015

PROJECT FINAL REPORT

Grant Agreement number: 335063

Project acronym: PulsarPlane

Project title: PulsarPlane

Funding Scheme: FP7 L0

Period covered: from September 2013 to May 2015

Name of the scientific representative of the project's co-ordinator, Title and Organisation:

H.H. (Henk) Hesselink

Sr. R&D Engineer

National Aerospace Laboratory, NLR

Tel: +31.88.511.3445

Fax: +31.88.511.3210

E-mail: henk.hesselink@nlr.nl

Project website address: www.pulsarplane.eu

Summary

Contents

1 Introduction **4**

1.1 Structure of the document 4

1.2 Acknowledgements 4

2 Final publishable summary report **5**

2.1 Executive summary 5

2.2 Summary description of project context and objectives 6

2.2.1 Introduction 6

2.2.2 Description of PulsarPlane concept 6

2.2.3 Detection 8

2.2.4 Navigation 8

2.3 Main S&T results/foregrounds 9

2.3.1 Navigation based on signals from radio pulsars 9

2.3.2 Pulsar signal simulator 11

2.3.3 Antenna 13

2.3.4 Receiver 15

2.3.5 Signal processing 22

2.3.6 Navigation 24

2.3.7 Operating a pulsar navigation system 30

2.3.8 Performance 31

2.4 Potential impact and the main dissemination activities and exploitation of results33

2.4.1 Feasibility 34

2.4.2 Costs, benefits and impact 35

2.4.3 Environmental impact 36

2.5 Public website 37

2.6 Project logo 37

2.7 Diagrams or photographs illustrating and promoting the work of the project 38

2.8 List of all beneficiaries with the corresponding contact names 39

3 Use and dissemination of foreground **41**

4 Report on societal implications **46**

5 Final report on the distribution of the European Union financial contribution **53**

1 Introduction

This document is the final report of the PulsarPlane project. The main objective of the PulsarPlane project is to investigate the feasibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars. PulsarPlane is a research project under the European 7th Framework Programme as a pioneering idea, i.e. technologies and concepts that have the potential to bring step changes in the second half of this century and beyond. This final report provides a summary of the project, including the main results that have been achieved in the course of the project. The project summary consists of five distinct parts, in line with the EU reporting guidelines:

- An executive summary of the project.
- A summary description of the project context and objectives.
- A description of the main S&T results/foregrounds.
- The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results.
- The address of the project public website.

Furthermore, the document contains promotion material, information on the project beneficiaries and a list of dissemination activities.

1.1 Structure of the document

The main results of the project are summarised in chapter 2, which starts with a one-page executive summary (2.1) and a four-page summary (2.2) that are intended for publication. The results are then outlined in more detail (2.3). A summary of the feasibility of pulsar navigation, its potential impacts and the main benefits is given in section 2.4. The rest of chapter 2 contains other information intended for publishing, such as the project logo and web site.

Chapter 3 contains some remarks on use and dissemination of foreground intellectual property. Chapter 4 gives an overview on the societal implications of the project. Finally, chapter 5 shows how the European financial contribution has been distributed among the beneficiaries.

1.2 Acknowledgements

We would like to acknowledge the ASTRON employees who have operated the Dwingeloo radio telescope and provided their data for the project. Pulsar Plane is a research project under the FP7-Aeronautics and Air Transport (AAT) Work Programme 2013 (FP7-AAT-2012-RTD-L0) with project number 335063.

2 Final publishable summary report

2.1 Executive summary

Pulsars are fast rotating neutron stars that emit electromagnetic radiation, which is received anywhere in our solar system as a series of very stable fast periodic pulses. Radio pulsars can act as timing sources for a navigation system, but this has not received much attention, as the signal strength of radio pulsars was deemed too weak to be useful. Advances in antenna design, analogue / RF circuitry as well as signal processing, however, could enable faster and more accurate detection of pulsar signals.

The main objective of the PulsarPlane project is to investigate the feasibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars. PulsarPlane is a research project under the European 7th Framework Programme as a pioneering idea, i.e. technologies and concepts that have the potential to bring step changes in the second half of this century and beyond.

The main benefits of a navigation system based on pulsars include resistance to jamming and spoofing, resistance to extreme space weather, resistance to failures, and political independence. PulsarPlane therefore proposes a pulsar navigation system for aircraft, providing a means for navigation without the need for ground-based or space-based equipment. The project focusses on three aspects:

1. Detection and signal processing algorithms.
2. Antenna and RF front end design.
3. Application in aircraft navigation.

The study shows that phased array antennas should be used to detect the weak pulsars. The array should have planar antenna elements in order to be mounted onto an aircraft. Dedicated receiver technology should be developed to process the signal and provide a positioning, whilst being integrated with the array. The concept of pulsar navigation is deemed feasible, but development is needed to enhance its performance.

It is difficult to make a well-founded statement on the performance of the pulsar navigation system, as there are many uncertainties. A first analysis based on current technology leads to a position accuracy of 200 – 2000 m. This accuracy is comparable to existing systems such as LORAN and is thus considered only useful for en-route ocean crossings, not for other navigation purposes.

Even with advances in technology, the accuracy of the pulsar navigation solution is unlikely to beat current GNSS. Large antennas will remain a requirement for pulsar navigation (a limitation imposed by physics, not by computing hardware). Given this limitation, the system will most likely not be usable for smaller aircraft, and certainly not for applications where a hand-held receiver is currently commonplace.

The main results of the study comprise, among others, a MATLAB toolbox for pulsar processing, a data repository with pulsar measurements from the Westerbork telescope, a list with pulsars that are suitable for use in a navigation system, design concepts of antenna and receiver, and scientific papers on pulsar navigation.

2.2 Summary description of project context and objectives

2.2.1 Introduction

Stars have been used -in what is called celestial navigation- since thousands of years by mankind. Celestial navigation was used extensively in aviation until the 1960s and in marine navigation until recently. It has been investigated for agriculture applications, utilized for military aircraft and, presumably, for intercontinental ballistic missiles.

Recently the interest in celestial navigation has sparked again with an emphasis on deep space navigation using pulsars. Pulsars are fast rotating neutron stars that emit electromagnetic radiation, which is received anywhere in our solar system as a series of very stable fast periodic pulses. A number of studies have been performed on navigating using pulsar signals; the first study performed by NASA in 1974 focused on radio pulsars, but in later years most attention was given to X-ray pulsars. Radio pulsar navigation - utilizing signals which could be detected on Earth - has not received much attention, since the signal strength of radio pulsars was deemed too weak to be useful.

Advances in signal processing, analogue RF circuit design as well as antenna design, however, could enable faster and more accurate detection of pulsar signals, using a smaller antenna size. The objective of the PulsarPlane project has been to investigate the feasibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars. PulsarPlane is a research project under the European 7th Framework Programme as a pioneering idea, i.e. technologies and concepts that have the potential to bring step changes in the second half of this century and beyond.

2.2.2 Description of PulsarPlane concept

PulsarPlane proposes a new navigation system, based on the signals received from pulsars. Pulsar navigation enables a means of navigation without the need for ground-based or space-based equipment. The project focusses on three aspects:

1. Detection and signal processing algorithms.
2. Antenna and RF front end design.
3. Application in aircraft navigation.

PulsarPlane uses radio pulsar signals: signals that can be detected on Earth. The known signals have a pulse period of 1.4 ms to 8.5 s and each signal has a unique pulse shape. Pulsars have been found everywhere in the hemisphere, the most dense area is the centre of the galaxy. Pulsar signals are extremely stable, comparable to the performance of atomic clocks. These characteristics make it possible to detect pulsars and use them for navigation.

Most pulsars emit pulses that are too weak to detect individually. Nevertheless, the periodicity of the signals emitted by pulsars makes it possible to discover thousands of pulsars, most of which are too weak to yield individually-distinguishable pulses. Consequently, a pulsar must be observed for a certain period of time and the observed data must be processed before a pulsar can be “seen”. Two signal processing methods for extracting pulsar information – epoch folding and matched filtering – have been investigated in the project.

Epoch Folding

If the period *P* of a particular pulsar is known, than the pulsar's average pulse shape (pulse profile) can be determined using the *epoch-folding* procedure. Epoch folding is the most commonly applied processing step in pulsar signal processing. Fundamentally, epoch folding refers to temporal averaging of the observed pulsar measurement with respect to the expected periodicity of the pulsar. Given a pulsar observation $y(t) = x(t) + v(t)$ where $x(t)$ is the desired pulsar signal and $v(t)$ is the additive background noise, and an assumed period *P*, epoch folding leads to

$$z_e(t) = \frac{1}{N}\sum_{i=0}^{N-1} y(t+iP) = \frac{1}{N}\sum_{i=0}^{N-1} x(t+iP) + \frac{1}{N}\sum_{i=0}^{N-1} v(t+iP) = x(t) + \bar{v}(t)$$

where *N* is the number of observed periods. When the number of integrated periods grows, the pulsar signal reinforces with each integrated period while the noise approaches to a zero mean. Assuming that the noise is a zero mean process, $\bar{v}(t)$ will have an expected value of zero for the noise while the deterministic pulsar signal will remain.

Matched filtering

The matched filter is a linear filter, *h*, that maximizes the output signal-to-noise ratio (SNR) and is very effective for Gaussian noise cancelation. Mathematically, the discrete matched filter can be considered as a convolution operator with the kernel (impulse response) h, input signal *x* and the output signal *y*:

$$y[n] = \sum_{k=-\infty}^{\infty} h[n-k]x[k]$$

It is assumed that the input signal *x* defined at time interval [0,T] and sampled at frequency f_s consists of the known deterministic signal s and additive stationary random noise *v* with variance σ^2:

$$x[k] = s[k] + v[k] \text{ , for } k=0,1,2,\ldots N-1 \text{ , and } N=T\cdot f_s$$

Then the output of the matched filter at time (*N*-1) is:

$$y[N-1] = \sum_{k=0}^{N-1} h[N-1-k]x[k] = \sum_{k=0}^{N-1} h[N-1-k]s[k] + \sum_{k=0}^{N-1} h[N-1-k]v[k]$$

The output SNR of the matched filter at time *T* is defined as:

$$SNR_{out} = \frac{\left(\sum_{k=0}^{N-1} h[N-1-k]s[k]\right)^2}{E[(\sum_{k=0}^{N-1} h[N-1-k]h[k])^2]}$$

2.2.3 Detection

To receive the pulsar signal on Earth, an antenna is necessary. Typically, large dish antennas like the ones in Westerbork and Dwingeloo in The Netherlands are used to collect data. These dishes need to be directed towards the signal source and calibrated for the pulse frequency. A new development is the use of phased array antennas, like the EMBRACE antenna in Westerbork, which will allow reception of the signal through a large array of small antennas. The difference in time of arrival of the signal at each antenna will allow determining the direction of the signal.

The application of phased arrays for aircraft navigation implies that the antennas are to be mounted on the aircraft. A small smart patch could be integrated in the aircraft (wing) structure as a top layer of the glare material. To give an idea of the required and possible size: the EMBRACE phased array antenna in Westerbork measures a surface of 150 m^2, the wing area of an Airbus A380 is 850 m^2, a Boeing 747 is 540 m^2 and that of an Airbus A320 is 122 m^2. The available wing area for most mid-size and large aircraft will therefore suffice for mounting antennas for the application of pulsar navigation.

In the project, the application of wideband phased arrays has been investigated. Our requirements stated that the antennas had to be small, allowed fast detection of the signals and could be applied in aircraft navigation. The smart patch would consist of the elements as described in Figure 1. To enable wide-band signal reception, a log periodic antenna X is proposed. A dedicated receiver with knowledge of the pulsar characteristics can be used to correlate the signal and evolve towards a better signal, in which the pulse signal is already preprocessed in the receiver.


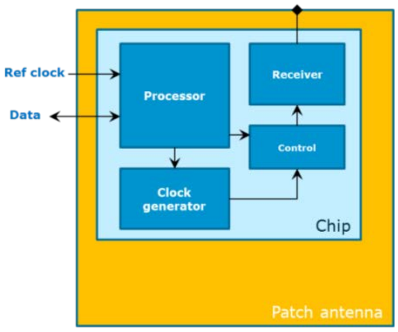

Figure 1: Wide-band log periodic antenna element and block diagram showing integrated electronics

2.2.4 Navigation

Navigation using pulsars can be done analogue to navigating with a Global Navigation Satellite System (GNSS). Through correlating the time of arrival of four signals, a position can be determined. The main challenges with pulsars are that their positions are not exactly known, they move at great velocities with respect to the Earth and the time of transmittal of a pulse cannot be retrieved: no correlation can be made between received signals and their time of transmittal. To compensate for the time information, a fifth pulsar signal is necessary.

To cope with the movement of the movement of the earth with respect to the pulsars, an almanac will need to be provided, which contains a detailed list of pulsars with their pulse arrival times on a fixed location. The almanac can also be used to guard pulsar quality and provide information on newly found pulsars. The technical concept is presented in Figure 2.

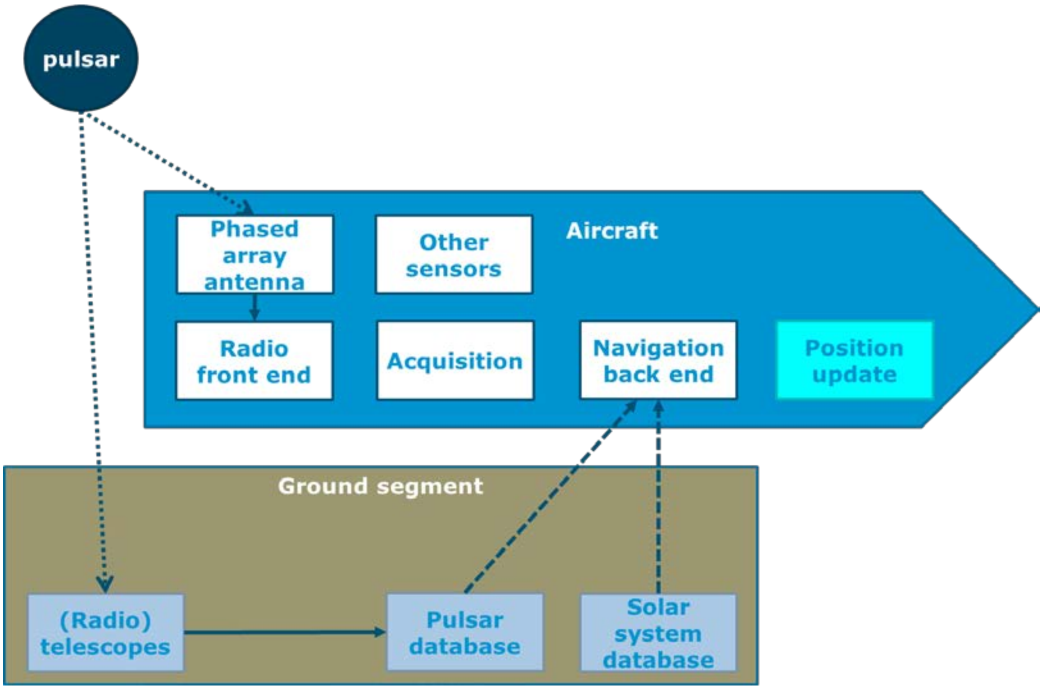

Figure 2: Concept of pulsar navigation

2.3 Main S&T results/foregrounds

The objective of the PulsarPlane project is to investigate the feasibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars. This summary of the project results starts with the fundamentals of (radio) pulsar are described as well as technical aspects of radio pulsar navigation such as antennas receivers, and signal processing. Next, the set up and main results of the project will be described and, finally, the impact that pulsar navigation can have is elaborated. The main project results can be summarised as follows:

- A MATLAB toolbox for pulsar processing.
- Pulsar measurements from the Westerbork telescope.
- Scientific publications and papers.
- A sound radio receiver concept.
- The concept makes specific use of the cyclo-stationary nature of the pulsar signal.
- The concept requires TOA measurements, no specific pulsar science is involved.
- It was found that pulsars with a clear auto correlation peak are best for navigation.

2.3.1 Navigation based on signals from radio pulsars

Pulsars are fast rotating neutron stars that emit electromagnetic radiation along their magnetic axis. The signal is received anywhere in our solar system as a series of pulses with periods in between milliseconds and up to 10 seconds (1.4 ms up to 8.5s). Pulsar signals are extremely stable; comparable to or even better than that of atomic clocks. These characteristics make it possible to detect them and use them for navigation: the pulsar can be compared to a light house.

Each pulsar emits pulses in a wide frequency range with a unique shape. Most pulsars emit pulses that are too weak to detect individually. Nevertheless, the periodicity of the signals enables discovering thousands of pulsars, most of which are too weak to yield individually-distinguishable pulses. Consequently, the observed data must be processed before a pulsar can be seen.

The very first pulsar was discovered by Jocelyn Bell in 1968 and since then a larger number of other pulsars (PSRs) have been discovered, see Figure 3. Not only the number of known pulsars has increased rapidly but also the geometric spread of these pulsars on the hemisphere has improved, although still most pulsars can be found in the plane of the Milky Way. For a navigation system, it is important that the 'transmitters' are placed in different directions relative to the user to minimise the Dilution-Of-Precision (DOP).

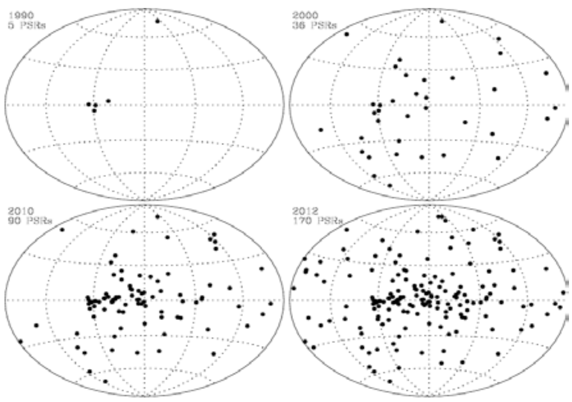

Figure 3: Known pulsars (PSRs) in 1990, 2000, 2010 and 2012 plotted on the hemisphere

Pulsar observation data has been collected using the radio telescope shown in Figure 4, the Dwingeloo Radio Telescope (DRT), the Netherlands. This is single-dish radio telescope with a diameter of 25 m. The DRT, which is owned by ASTRON, is mostly used by radio amateurs and amateur astronomers and it is operated and maintained by volunteers.

Figure 4: Dwingeloo Radio Telescope

Comparing the pulsar signals to the L1 C/A signal of GPS gives an idea of the strength (or rather weakness) of pulsar signals. The signal strength of pulsars is expressed in terms of milli-Jansky (mJy):

1 Jy = 10-26 W/m2/Hz = -260 dBW/m2/Hz

The strongest pulsar known is Vela and it has a signal strength of about 5000 mJy = -253 dBW/m2/Hz. Most pulsars have signal strengths between 1-10 mJy. The signal strength of GPS–L1 C/A is -133.1 dBW/m2. The signal has a bandwidth of 2.046 MHz and therefore, expressed in Jy it is 2 MJy = 2000000000 mJy. Hence, even the weak signal from GPS is much stronger than the strongest known pulsar signal.

For a navigation system, it is essential that the transmitters have very stable clocks. Pulsars can provide stable frequency standards and the variance of the millisecond pulsars -the most stable astronomical clocks- is comparable to that of atomic clocks. Figure 5 shows the stability of two radio pulsars and selected atomic clocks using a third-order polynomial variation of the clock phase. It can be concluded that the clock stability of the described pulsars can rival that of the selected atomic clocks.

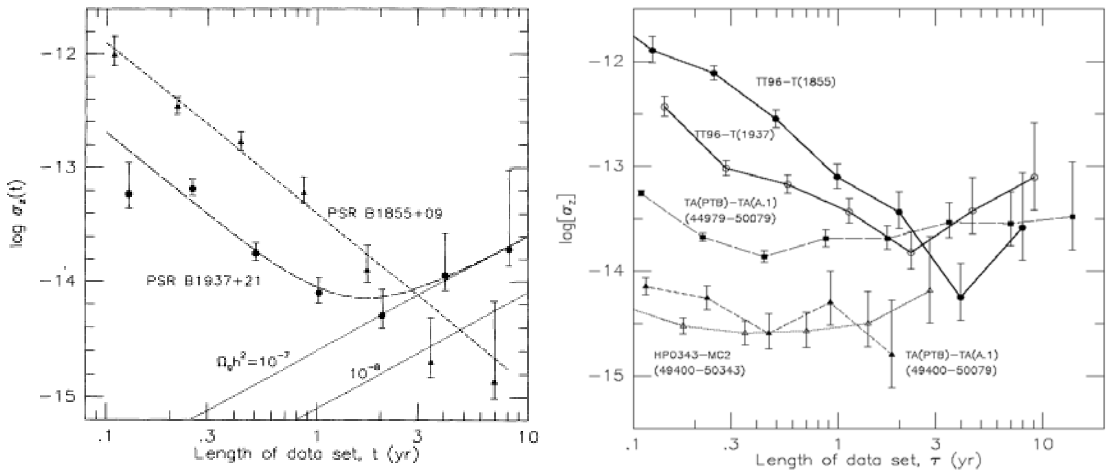

Figure 5: Timing stability of selected radio pulsars (left) compared to that of atomic clocks (right)

2.3.2 Pulsar signal simulator

A pulsar signal simulator has been developed for performing research to signal processing algorithms. The simulator takes a pulsar from the EPN pulsar database to create a dispersed or de-dispersed signal for any period of time, with the correct levels of Signal-to-Noise Ratio (SNR). It also considers the experienced Doppler shift by the signal due to receiver – transmitter motion. The results include a working 'generic' pulsar simulator capable of creating a variety of dispersed and Doppler-shifted pulsar signals based on known pulsar profiles, written in Matlab and thus easily accessible to the scientific community.

A Dilution-Of-Precision (DOP) charting and analysis of pulsar signal sources has been set up. The charting and analysis of the DOP problem for pulsar navigation involved the collection, iterative comparison, and selection of the best pulsars that minimize DOP from all known pulsars that have been detected to emit a signal in the radio frequency range.

Using several criteria based on critical pulsar parameters, all pulsars were listed in terms of quality, after which all feasible combinations of pulsars needed to perform successfully navigation were evaluated for their DOP value, and subsequently listed as well in terms of minimum DOP.

Two specific scenarios were used to chart the DOP – problem locally – a situation where the receiver is close to a planet, such as that when the an airplane is flying on Earth, and that of a spacecraft in deep space, with the first scenario producing a map of DOP for various times and locations on Earth.

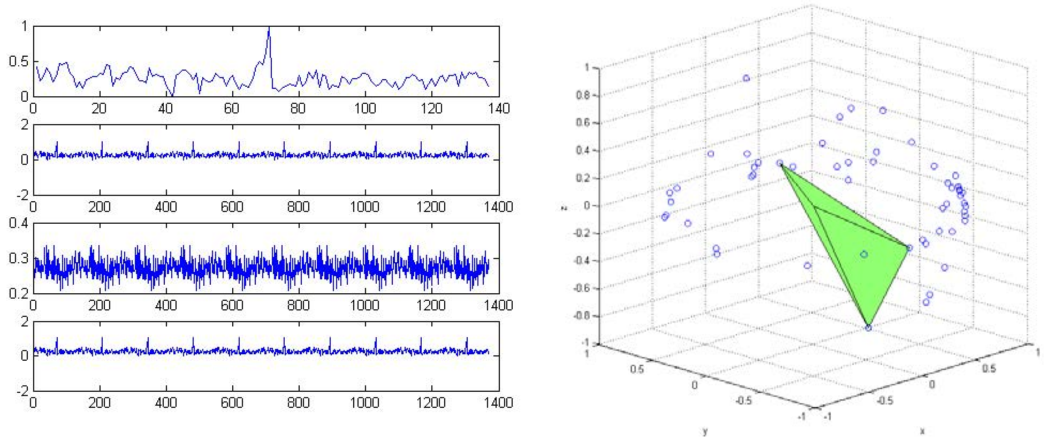

Figure 6: An example plot of a single pulse profile (topmost) extended over a period (second from the top), dispersed (third) and finally de-dispersed back. The right figure is an example of the running algorithm for evaluation the DOP of various pulsar star combinations.

Besides the listing of DOP values for various combinations of pulsars, the major result in the DOP charting and analysis included the creation of a DOP-map for Earth that gives the GDOP for a certain receiver antenna. This map, or a map based on the same principles can be used to evaluate the DOP for any given antenna, and as the DOP is a geometrically and thus fundamentally a limiting factor for navigation, whether it is possible to navigation with pulsars in certain regions of the Earth at certain times.

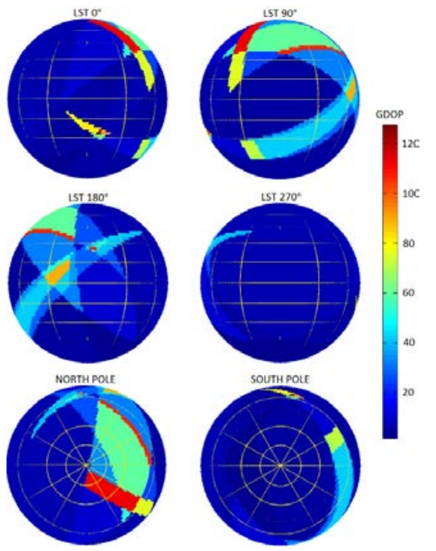

Figure 7: A pulsar DOP map on a planet surface, where it is shown the GDOP at a certain local sidereal time

The developed pulsar simulator is capable of being flexibly used in pulsar signal processing as a signal substitute. The DOP problem produced a set of DOP-minimized pulsar combinations for navigation, and a DOP-map for the feasibility of navigating on Earth using a certain type of receiver antenna.

2.3.3 Antenna

The primary goal of the research into antennas and front-end receiver design is to increase the signal-to-noise ratio of pulsar signals using the smallest antenna possible. This, however, poses a problem, as the antenna gain is directly proportional to its effective area. The following aspects are important:

- Small antennas are required for practical reasons.
- A higher signal-to-noise ratio allows for more accurate time of arrival detection.
- A higher signal-to-noise ratio makes it easier (faster) to track the pulsar.
- A higher signal-to-noise ratio reduces the computational requirements for signal processing.

An antenna array of planar antennas can be embedded in the wings to provide electronic beam steering and high gain. Considering the available wing area of an airplane, achieving sufficient antenna gain would be possible. Table 1 provides a list of several airplanes currently operating with their wing surface areas.

Table 1: List of selected airplanes and their wing surface areas

Aircraft	Wing Area (m^2)
Airbus A380	845
Boing 747	540
Airbus A320	122
Fokker 100	93
Cessna Citation 1	26

Considering the required area of the antenna, it can be concluded that wing area of an A380 airplane already has the potential to be used for fast signal detection. However, other airplanes in the list can also accommodate an antenna at the expense of either wider receiver bandwidth or longer integration time. But future airplane concepts may provide even more area, see Table 2.

Table 2: Available antenna area on aircraft

Type	Typical wing area	Hull diameter and length	Available antenna area wing	Effective antenna area hull	Available antenna area aircraft
Large Blended Wing Body	$1250m^2$	Integrated	$750m^2$ ()		$750m^2$
Large widebody	$554\text{-}845m^2$	6-7m 73-76m	$250\text{-}380m^2$	$120\text{-}150m^2$	$370\text{-}530m^2$
Medium widebody	$443\text{-}467m^2$	6m 60-76m	$200\text{-}210m^2$	$100\text{-}125m^2$	$300\text{-}335m^2$
Small widebody	$325\text{-}360m^2$	5.5m 56-68m	$145\text{-}160m^2$	$85\text{-}100m^2$	$230\text{-}260m^2$
Single aisle	$120\text{-}130m^2$	3.5-4m 33-44m	$55\text{-}60m^2$	$30\text{-}50m^2$	$85\text{-}110m^2$
Regional jets	$90\text{-}100m^2$	3m 30-35m	$40\text{-}45m^2$	$25\text{-}30m^2$	$65\text{-}75m^2$

Future generations of aircraft may consider the pulsar navigation antenna as part of their structure design, e.g. as an integrated layer in the Glare structure, see Figure 8.

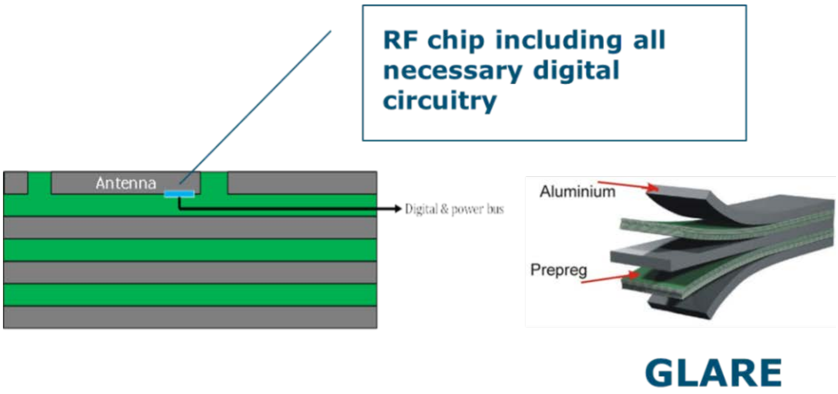

Figure 8: Antenna integration in layered wing skin

An option for applicability in smaller aircraft is to increase the bandwidth to sample the received signals. This reduces the size of the antenna significantly (see Figure 9). In that case, wide-band antennas need to be considered. These shall be planar as well to be able to be fitted onto the wing surface. The technology for wide-band planar log-periodic antennas appears to be the best for the pulsar navigation application. The integration of a phased array antenna into a flexible wing may pose some problems, but these can likely be resolved. Smart patch antennas can be integrated in the wing surface.

In order to receive multiple pulsars at the same time, one solution can be using multiple (moving) antennas with high gain facing different directions. Since we are targeting to place the antennas on an aircraft, an antenna design that interferes less with the aerodynamics of the airplane is considered. One of the possible locations to place the antenna is on the wings of an airplane. Planar antenna designs can be embedded in the wings without interfering with the aerodynamics of the airplane.

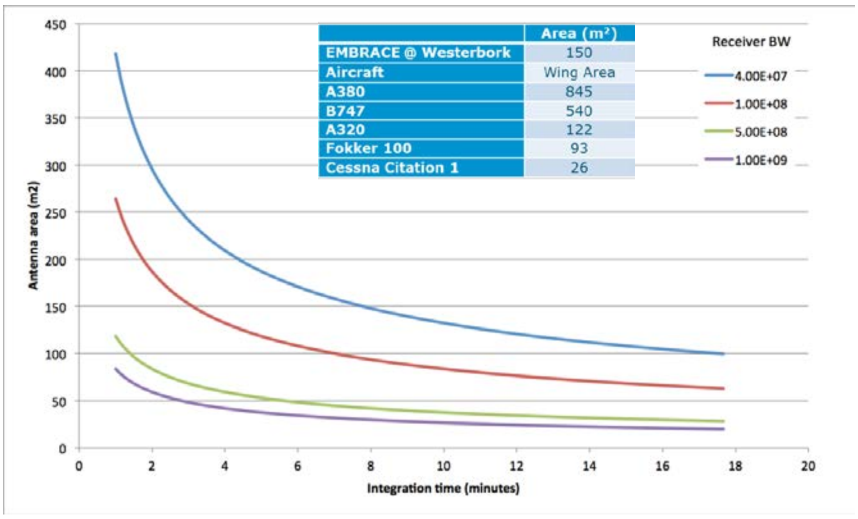

Figure 9: Antenna area vs. integration time for different receiver bandwidths

The shape of an antenna is one important parameter to determine its performance characteristics. One of the main characteristics we are looking for is the antenna bandwidth. Considering the fact that it is important to collect the pulse energy as much as possible and the receiver should be flexible in selecting the operation band, the frequency independent antenna types have been considered in this study.

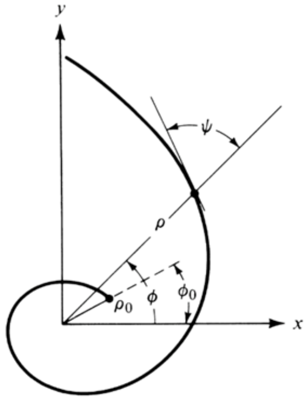

Figure 10: A planar single spiral wire antenna

It is shown that if the geometrical configuration of an antenna can be described by only angles, it is frequency independent. The planar spiral antenna is one such antenna configuration. Figure 10 depicts a planar single spiral wire antenna. The geometry of the planar spiral antenna can be expressed by the following equation:

$$r|_{\theta=\pi/2} = \rho = \begin{cases} \rho_0 e^{a(\phi-\phi_0)} & \theta = \pi/2 \\ 0 & \text{elsewhere} \end{cases}$$

where (ρ, ϕ, θ) is the polar coordinate of points on the spiral, ϕ_0 is the initial angle, ρ_0 is the initial radial distance and $1/a$ is the rate of expansion of the spiral. Spiral antennas can be placed in an array to benefit from electronic beam steering and increased gain.

Summarizing, the realisation of an integrated phased array antenna on a large airplane is deemed feasible. The computation and power requirements for the signal processing of a phased array antenna are not considered a problem, given the expected advances in computing technology.

2.3.4 Receiver

The characteristics of pulsar signals are very challenging for a receiver, as the signal is extremely weak and has a large bandwidth. Therefore, the nature of the signal, being a pulsed signal, suggests a receiver architecture similar to those used in Impulse-Radio Ultra Wideband (IR-UWB) systems using time-based modulation techniques. The positive news of our application is that the pulsar signal is very precise in time and that we just want to detect the signal and no more information should be retrieved as it would be the case in a communication or satellite navigation system application.

The weak signal requires a coherent detection structure with precise timing synchronization to detect the pulsar signal. The observation band used for detecting the pulsar signal is in the middle of two strong narrowband interferers present around the 90 0MHz and 1.8 GHz from GSM/UMTS. These interferers define all the front-end dimensioning: it determines the use of accurate high order filters; it determines the

Analogue/Digital Converter (ADC) resolution; it determines the use of a fast RSSI to prevent the system from saturating due to fast varying interferer level. Furthermore, all circuit blocks should add low noise. This structure should be controlled by the digital output both for finding the pulsar and for locking on.

The main objectives of this part of the work are:

1. To study the feasibility of a radio pulsar signal receiver, intended to provide real-time data for pulsar navigation algorithms.
2. To explore different radio frequency (RF) front-end architectures and define specifications for both narrowband and ultra-wide band (UWB) RF front-ends.
3. Finally, to evaluate the impact of the receiver front-end on the navigation system accuracy and conclude which is the most advantageous architecture for this purpose.

Pulsar signal

In order to set the global and particular requirements of the pulsar signal receiver, a study on the pulsar signal statistical characteristics was performed. A mathematical model, which fully explains the radio pulsar signal characteristics is developed and can be modelled by:

$$s(t) = a(t).p_{rot}(t) = a(t).\sum_{n=-\infty}^{\infty} p_{rot}(t - nT_P)$$

where $a(t)$, is the pulsar intrinsic stationary random process, responsible for the wideband (GHz) nature of the pulsar signal and $p_{rot}(t)$ is the periodic signal due to the pulsar rotation as depicted in Figure 11.

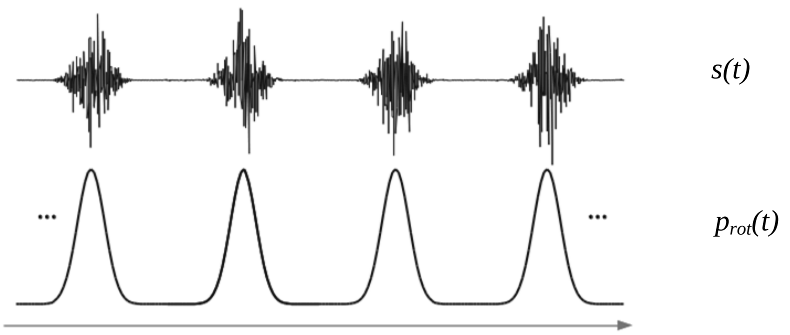

Figure 11: Pulsar signal model: top) pulsar signal $s(t)$ and bottom) pulsar rotation signal $p_{rot}(t)$

Due to the multiplication in the equation, the signal $s(t)$ is cyclostationary. The pulsars observed on Earth display rotation periods that range between 1.4 milliseconds and 8 seconds. Given the nature of pulsars a wideband receiver is needed to capture as much energy as possible of such a weak signal. However, there are technical limitations for amount of bandwidth that a receiver can handle, mostly related to the sampling frequency requirement for the ADC. Since current state-of-the-art ADCs for medium to high resolutions (number of bits>10) are limited to around 1 GSps (giga-samples per second), a Nyquist-rate ADC will only allow receiver bandwidths lower than 500 MHz. In addition, the pulsar signal arrives at Earth already below the noise level, due to the cosmic background noise. The signal-to-noise ratio for a given pulsar i and considering all the relevant noise contributions can be expressed as:

$$\mathrm{SNR}(i) = \frac{\alpha A_e 10^{-26} S_i^p \left(\frac{f_{rec}}{f_{ref}}\right)^{\beta_i}}{k_B (T_{sys} + T_{sky})}$$

Therefore, the receiver system noise should be as low as possible in order not to further degrade the already low SNR of the pulsar.

Another important feature of the pulsar signal is shown in , where the SNR value for the 15 best pulsars for navigation purposes is shown, for a frequency range from 0.1 to 10 GHz, a receiver with $T_{sys} = 15$ K (NF ≈ 0.2), and an effective antenna area of $A_e = 10\ \mathrm{m}^2$.

A sweet spot is observed around 1 GHz, where the SNR of most pulsars is highest. Therefore, the receiver observation frequency should be as close as possible this optimum frequency. However, it should not be lower than 1 GHz, since the multipath (time) scattering due to the atmosphere becomes an important issue and limits the accuracy of timing estimates.

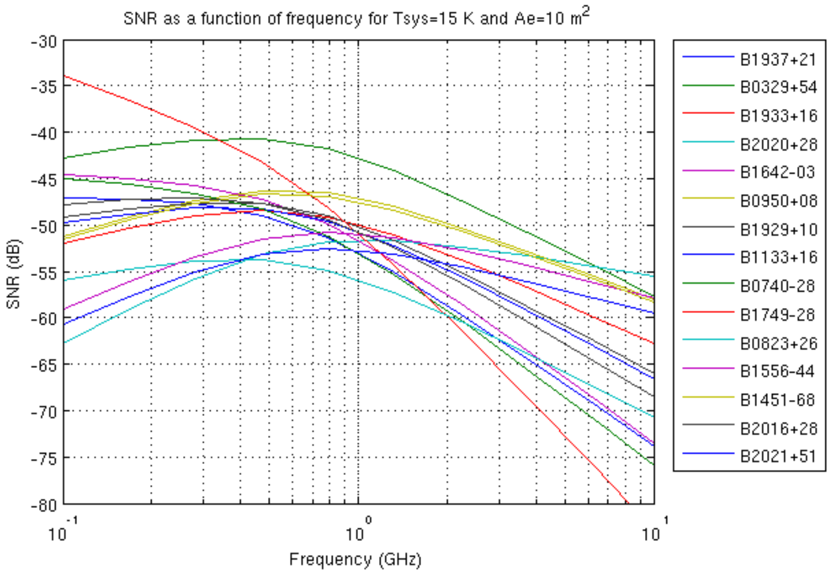

Figure 12: SNR as a function of observation frequency for the 15 best known radio pulsars, considering an antenna effective area of 10 m² and T_{sys}=15K

To select the central observation frequency, both the bandwidth requirement and the surrounding interference is taken into account. Figure 3 shows the largest interferers found on Earth, around these frequency ranges. We can observe that between the two GSM interferers, 900 and 1800 MHz, the spectrum has no large interferers. GPS bands are present but they are weak interferers. In addition, at 1.42 GHz, there is a reserved frequency, with a small bandwidth, for space observations.

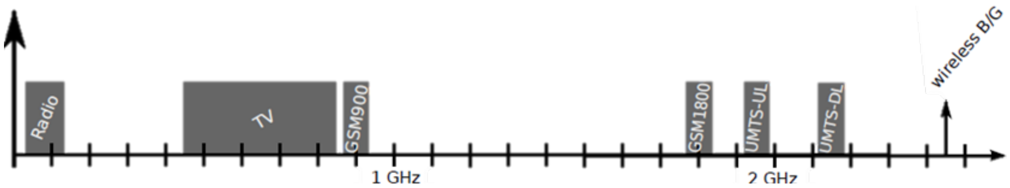

Figure 13: Radio frequency interference

To take advantage of the "free" spectrum, the receiver central frequency should be 1.4 GHz and the bandwidth should be as large as possible. However, problems are expected if a larger than 400 MHz bandwidth is used, as the interferers will also be sampled and it may not be possible to accommodate such a large dynamic range.

Topology evaluation

The RF pulsar receiver is required to deal with extremely weak signal strengths, since the received signal-to-noise ratio on Earth is very small. Furthermore, it should also be able to deal with the interference, and amplify the signal to detectable values on state-of-the art ADCs. Three different RF receivers were proposed, studied and evaluated: a conventional wideband low-if receiver (Figure 14), a sub-sampling direct RF receiver (Figure 15) and an optimum quadratic receiver using pulsar statistics directly (Figure 16).

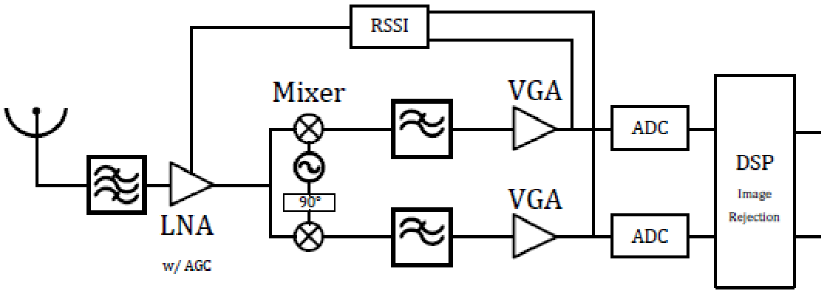

Figure 14: Low-IF topology with RSSI block diagram

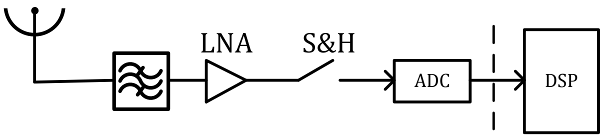

Figure 15: Subsampling topology block diagram

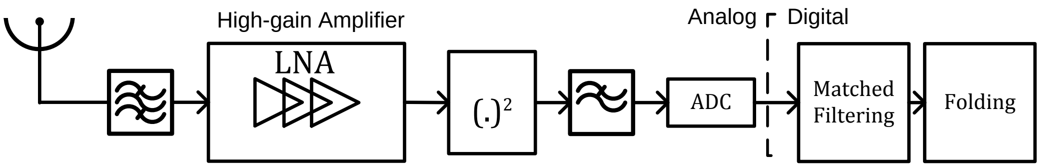

Figure 16: Optimum quadratic receiver block diagram

A low Intermediate Frequency (IF) receiver architecture is a compromise between a homodyne receiver topology (also known as Zero-IF or Direct-Conversion), which is immune to image frequency problems, and a conventional (high-IF) heterodyne receiver, which has no DC-offset demanding specifications. A low IF allows relaxing the ADC specifications to a feasible level. Furthermore, the gain and attenuation values are distributed nicely over the various blocks of this receiver.

The topology functionality can be explained briefly as follows: the RF signal incoming from the antenna is first filtered by a band pass filter, in order to attenuate interferers as much as possible and also to limit the bandwidth of the signal of interest. Afterwards, the signal is amplified by a Low Noise Amplifier (LNA), which is also responsible for minimizing the noise contribution. The signal is down-converted to an intermediate frequency (IF), then filtered for further image rejection and further amplified to use the full input dynamic range of the ADC. Note that the use of a Received Signal Strength Indication (RSSI) combined with a variable gain LNA is employed, in order to explore, at all times, the full input dynamic range of the ADC.

This RF front-end does not improve the SNR of the pulsar signal, since its strength will always be below the noise floor. Therefore, the receiver effort is to reduce the interference-to-noise ratio, in order to raise the noise level to values detectable by the ADC. In addition, it also down converts the signal to an IF frequency defining the ADC sampling rate. For simplicity, the noise added by the receiver is disregarded for now. The frequency plan for a pulsar signal is shown in Figure 17, placing the pulsar signal in the spectrum, as well as the image bands and the highest known interferers.

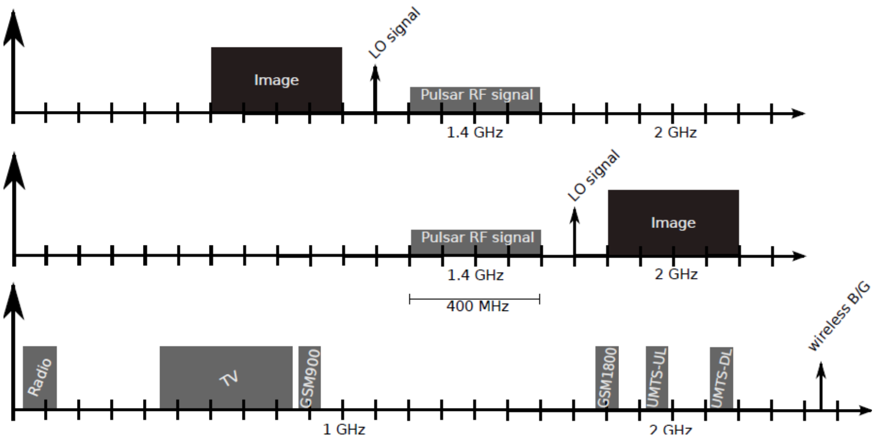

Figure 17: Receiver frequency plan

The local oscillator (LO) frequency is selected for the IF to be as low as possible, allowing the relaxation of the ADC specifications in terms of sampling rate. However, the IF shall also be high enough to avoid pink noise sources (like flicker noise in electronic devices, most notably in MOSFET transistors). Many interferers with much higher power levels than the pulsar signal fall into the signal images and thus are also sampled by the ADC. Therefore, the choice of the LO frequency should take the image interferers into account. Furthermore, state-of-the art ADCs with medium to high resolutions (>10 bits) are limited to sampling frequencies of around 1 GSps. This value imposes an upper limit on the selection of the IF, since the signal thus cannot be sampled beyond 500 MHz according to the Nyquist theorem.

Following these restrictions, the IF frequency was selected to be 250 MHz, which places the signal bandwidth from 50 to 450 MHz. This selected IF value allows two values for the LO frequencies, 1.15 or 1.65 GHz. To select among these two options, the power levels of the interferers located in the image frequency bands are considered. The TV broadcast has one of the higher transmitted powers, therefore, in order to avoid having this signal in the image, the LO frequency is selected to be 1.65 GHz. However, in this high side LO frequency, there is still the GSM and UMTS power levels, which are much higher than the pulsar signal.

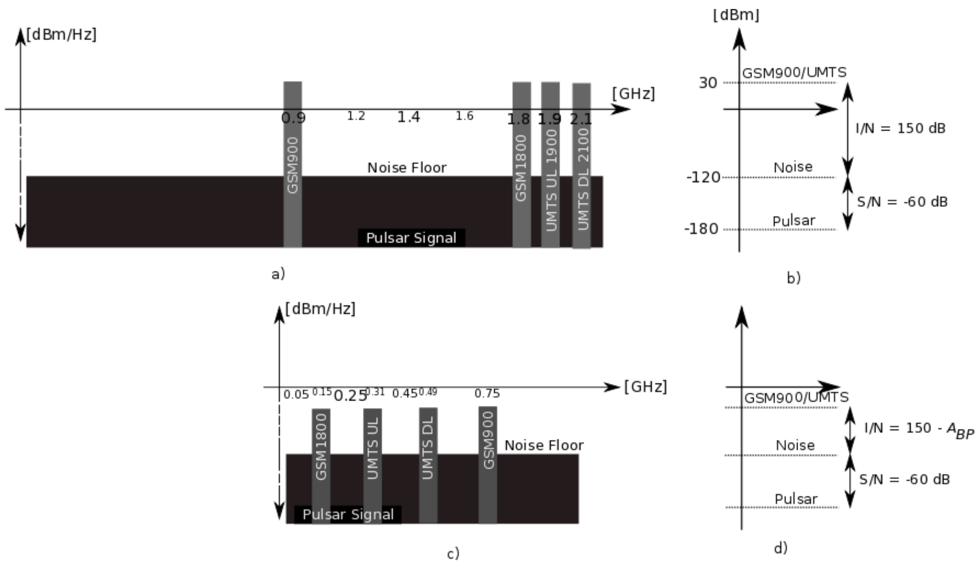

Figure 18: Input signals a) frequency spectrum b) power levels integrated over 400 MHz bandwidth c) down-converted signal spectrum and d) power levels of down converted signals integrated over 400 MHz bandwidth (ABP is the band pass filter attenuation)

Regarding Figure 18, when down converting the signal, GSM 1800 and UMTS UL fall inside the pulsar signal bandwidth. Both have similar transmitted power which can be higher than 30 dBm. This worst case situation imposes a very challenging band pass filter in the first stages of the receiver, as it will be explained later. Furthermore, after the mixer, there will not be any change in the interference to noise level regarding these two interferers, since every amplifying stage will increase both the interference in-band images and the noise floor. Therefore, the ADC dynamic range is defined by the band pass filter before the mixer.

The thermal noise power can be determined, as follows:

$$N_i = kT_0B$$

giving approximately -120 dBm, where k is the Boltzmann constant, T_0 is the room temperature 290 K, B is the 400 MHz bandwidth. Taking into account the sampling frequency requirement (1 GSps), it can be stated that dynamic ranges over 80 dB (14 bits) are beyond state-of-the-art ADCs. Therefore, high-order band pass filtering is required at the input to attenuate the interferers (GSM900 and 1800) as much as possible. State-of-the-art filters with such demanding specifications can be achieved using cavity or SAW type band pass filters. A survey on off-the-shelf filters has shown that a 90 dB attenuation at the GSM frequencies is achievable using cavity filters, having a small insertion loss as low as 0.4 dB.

Furthermore, the low pass filter, located after the mixer, which is responsible for attenuating as much as possible the images outside the band, also has demanding specifications, since the interferers are close to the band of interest, UMTS DL is at 490 MHz, and there is just 40 MHz of guard band between the band of interest and the interferer. The amplifiers in this low-IF topology chain, the LNA and the VGA, are required to amplify as much as possible the signal without exceeding the maximum input of the ADC. Therefore, their maximum gain will be constrained by the band pass filter attenuation on the interferers. These amplifier stages should be adjustable, according to the level of interference, which is present at each moment, in order to exploit the full dynamic range of the ADC at all times. This reasoning leads to the use of an RSSI block controlling the gain.

Up to this moment, the noise of the receiver blocks is ignored. The blocks contribution to the overall total noise factor of the receiver F_{rx}, follows the Friis noise equation:

$$F_{rx} = F_{BPfilter} + \frac{F_{LNA} - 1}{G_{BPfilter}} + \frac{F_{Mixer} - 1}{G_{LNA}G_{BPfilter}} + \cdots$$

An important feature of this equation is that the overall noise figure is primarily established by the noise of the first gain stages, the subsequent stages will have a diminished effect on it. Therefore, it is very important to control the gain of the LNA, using the RSSI, since it reduces the impact of the noise from the following blocks. Considering this, we will have always the maximum gain possible in the LNA leading to the minimum receiver noise at all times.

An important aspect is that the system noise (NF_{rx}), adds up to the thermal noise, as shown in Figure 19.

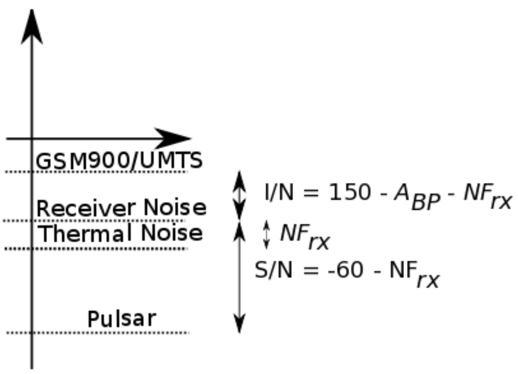

Figure 19: Power levels integrated over a 400 MHz bandwidth considering thermal noise and

The noise of the receiver reduces the dynamic range requirement of the ADC and thus has a negative impact on the processing of the signal. Therefore, the receiver system noise should be kept as low as possible. Regarding the system temperature, and considering an uncooled solution, $T_{sys} = 100$ K (NF ≈ 1.29 dB), if an antenna temperature T_{ant} of 25 K (NF ≈ 0.36 dB) is considered, the receiver should be able to keep the noise temperature as low as 75 K (NF ≈ 0.99 dB). This condition results on an extremely challenging receiver to design, however feasible with state-of-the-art technology.

Summarizing, several solutions are possible depending on the interference levels considered. However, all of them require highly demanding filters and state-of-the-art ADCs with high resolution and sampling rate. Furthermore, the LNA has to be ultra-low noise, to reduce the impact of the noise from the remaining blocks.

Optimum quadratic receiver

Figure 16 shows the block diagram of the theoretical optimum quadratic receiver, developed based on the pulsar signal statistical proprieties. A MATLAB simulator of this receiver was developed to validate the architecture, and is presented in detail in the project deliverable D3.2. This receiver shares the same initial blocks (filter, LNA) as the low-IF receiver. Therefore, it shares the similar block specifications, since the same interference problems exist.

After the amplifier, the square function block squares the signal to recover the rotation signal of the pulsar. This is a consequence of the pulsar signal being cyclo-stationary. Therefore, since this signal is very narrowband (on the order of a few kHz; at most 30 kHz) the processing bandwidth may be strongly reduced. In addition, by using a low-pass filter, the in-band noise is reduced and since the signal bandwidth is now reduced to tens of kHz, lower sampling rates can be used, namely sub-MSps frequencies, as opposed to the GSps sampling frequency requirement from the previous proposals, being this the main advantage of this architecture. Since the in-band noise is reduced, the SNR is improved before the analog-to-digital conversion, contrary to the other proposed architectures. This fact impacts the digital processing part, since less folding will be required to achieve the same SNR obtained using other common architectures.

However, some anticipated implementation problems can be observed and discussed. A larger gain before the quadratic operation is required, since this block will reduce the signal strength. This can be implemented by using several tuned amplifying stages that will amplify the signal and attenuate the interferers in sequence, resulting in an overall increase of the filtering order and avoiding each gain stage to saturate. This technique is already used in UWB receivers. In addition, DC coupling processing is required after the quadratic device. This drawback needs to be carefully addressed in the design, due to the occurrence of offsets and flicker (1/f) noise. Further studies in this topology are required, in order to establish the system block requirements and evaluate these DC issues.

Disregarding these probable issues, which require further study, this topology brings the most promising results. It allows improving the SNR, while none of the other presented architectures has this ability. This important difference, allows easing the required digital processing required to recover the signal from the noise. Furthermore, this new architecture allows a significant relaxation of the receiver building block specifications. The sampling frequency is reduced to sub-MHz frequencies allowing the use of higher resolution ADCs, therefore reducing the data-throughput to a rate that permits real time processing and permitting the accommodation of much higher interference levels.

The proposed “quadratic block” receiver architecture is deemed feasible for use on-board an aircraft. It can increase the signal-to-noise ratio while staying within the present technological boundaries for analogue-digital converter circuitry. The processing requirements for this architecture are lowered. The architecture makes optimal use of the fact that the pulsar signals are known, and only the time of arrival must be determined accurately. No major technical obstacles are foreseen in the implementation of such a receiver architecture.

2.3.5 Signal processing

Two signal processing methods for extracting pulsar information – epoch folding and matched filtering – have been investigated in the project.

Epoch Folding If the period *P* of a particular pulsar is known, than the pulsar's average pulse shape (pulse profile) can be determined using the *epoch-folding* procedure. Epoch folding is the most commonly applied processing step in pulsar signal processing. Fundamentally, epoch folding refers to temporal averaging of the observed pulsar measurement with respect to the expected periodicity of the pulsar. Given a pulsar observation $y(t) = x(t) + v(nt)$ where $x(nt)$ is the desired pulsar signal and $v(t)$ is the additive background noise, and an assumed period *P*, epoch folding leads to:

$$z_e(t) = \frac{1}{N}\sum_{i=0}^{N-1} y(t+iP) = \frac{1}{N}\sum_{i=0}^{N-1} x(t+iP) + \frac{1}{N}\sum_{i=0}^{N-1} v(t+iP) = x(t) + \bar{v}(t)$$

where *N* is the number of observed periods. When the number of integrated periods grows, the pulsar signal reinforces with each integrated period while the noise approaches to a zero mean. Assuming that the noise is a zero-mean process, $\bar{v}(t)$ will have an expected value of zero for the noise, leaving only the pulsar signal.

Matched filtering

The matched filter is a linear filter, *h*, that maximizes the output signal-to-noise ratio (SNR). It is very effective for cancelling Gaussian noise. Mathematically, the discrete matched filter can be considered as a convolution operator with the kernel (impulse response) *h*, input signal *x* and the output signal *y*:

$$y[n] = \sum_{k=-\infty}^{\infty} h[n-k]x[k]$$

It is assumed that the input signal *x* defined at time interval [0,T] and sampled at frequency f_s consists of the known deterministic signal s and additive stationary random noise *v* with variance σ^2:

$x[k] = s[k] + v[k]$, for $k=0,1,2,\ldots N-1$, and $N=T \cdot f_s$

Then the output of the matched filter at time (*N*-1) is:

$$y[N-1] = \sum_{k=0}^{N-1} h[N-1-k]x[k] = \sum_{k=0}^{N-1} h[N-1-k]s[k] + \sum_{k=0}^{N-1} h[N-1-k]v[k]$$

The output SNR of the matched filter at time *T* is defined as:

$$SNR_{out} = \frac{\left(\sum_{k=0}^{N-1} h[N-1-k]s[k]\right)^2}{E[(\sum_{k=0}^{N-1} h[N-1-k]h[k])^2]}$$

As a starting point for our work, three one-hour observations of the following pulsars were obtained:

- B0329+54 – this is one of the strongest pulsars known. It is approximately 2600 light years away from Earth and has a rotational period of 0.71452 s.
- B0531+21 – this is also known as the Crab pulsar. It is a fast rotating young pulsar with a rotational period of 33 × 10−3 s.
- B0950+08 – one of the closest pulsars at approximately 850 light years with a period of 0.253 s.

The pulsars are observed at a centre frequency of 1330 MHz. The bandwidth of the data is approximately 30 MHz, sampled at a sampling rate of 70 MHz and at a precision of 10 bits/sample. The primary conclusion is that the standard epoch folding is not good enough for pulsar navigation. An algorithm is required that can (strongly) reduce the number of pulses required for detection, or alternatively, strongly increase the accuracy of the time of arrival using the same number of pulses.

2.3.6 Navigation

This section describes how local peak timing information of specific pulsars is used for navigation. Much of this text was taken from chapter 5 of the MSc thesis of Antti Alexander Kestilä, who describes the "back-end model" of a pulsar navigation system, i.e. the subsystem that takes pulsar peak timing information and computes a position based on this information.

The front-end of the system can detect pulsars and provide precise timing information on the peaks of the pulsar signals. The back-end uses a method based on the Time-Of-Arrival (TOA) of the pulsar signals. Positions are determined in a barycentre frame of reference to which all pulsar observations are linked. The centre of the frame of reference is the Solar System Barycentre (SSB), which is the centre of mass of our solar system. Note that Earth moves within this frame of reference.

The primary mechanism for positioning is TOA transfer. One observer is at a fixed location in an inertial reference frame and measures the time of arrival τ_{ref} of a pulse. A second, mobile, observer observes the same pulse and measures its time of arrival. The observed time difference can be used to determine the relative distance of the two observers in the direction of the pulsar. Provided that pulsar timing information is known for the centre of a reference frame, TOA information can also be used to determine the observer's position in the inertial reference frame.

As radio-pulsars are extremely predictable sources, pulse arrival times can be predicted and propagated from a given epoch of the reference timeframe up to the current date. In practice, the two observers cannot tell if they are measuring the same pulse, so there is an integer-ambiguity problem to solve. This is done, similar to the LORAN system, by observing multiple pulsars simultaneously. For a 3-dimensional position solution, at least 4 pulsars must be tracked: one for each direction and a fourth to remove the integer ambiguity. In practice a fifth pulsar is required to resolve receiver clock errors, similar to GNSS. TOA transfer provides a position estimate in a chosen reference system, but no velocity estimate. By differentiating between subsequent position estimates a velocity vector can be obtained.

Figure 20 illustrates the TOA concept. Assume that 3 pulsars have been observed at time τ_{ref}. For each pulsar we know the phase at time τ_{ref} at our position. The iso-phase lines indicate where each pulsar has the observed phase. The blue pulsar observation tells us we are somewhere on a blue line; however we do not know which line (integer ambiguity). The red pulsar observation limits our possible location to intersections of blue and red lines. By adding the 3rd, green pulsar the number of possible solutions is drastically reduced or even made unique. In three dimensions the problem is similar but the lines are replaced by iso-phase planes, and at least 4 pulsars are required.

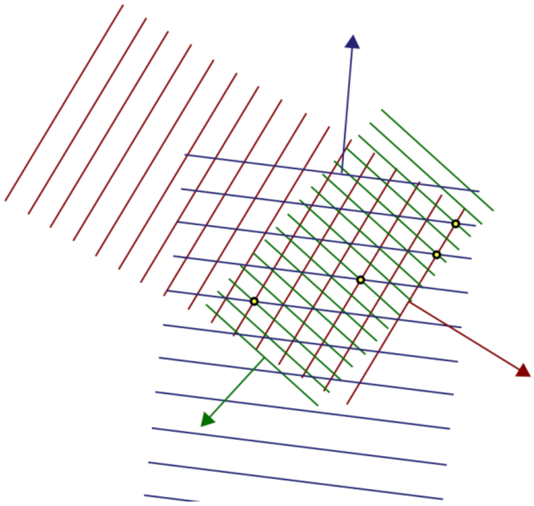

Figure 20: 2D representation of pulsar TOA position resolution

Two alternative methods exist that could be used: the Doppler shift method and the pulse decay method.

The Doppler shift method detects the change in pulsar frequency caused by the relative movement of the observer with respect to the reference frame. It is assumed that the pulsar “base period” is known for the centre of the reference frame. Based on this information for multiple pulsars, three velocity components of the observer can be estimated. After a coordinate transformation, the velocity of the observer in the frame of reference can be determined.

The Doppler shift method does not directly provide a position estimate. It can however be used in theory for positioning by integrating velocity components over time from a known starting point. In practice, this is not an option for aircraft as a standalone method as the update rate of changes to the speed vector is considerable higher than the expected update rate of the pulsar navigation system. This will make any method of integration quite inaccurate after some integration time.

The pulse decay method takes advantage of the fact that a pulsar’s period shows a very stable rate of change (typically a decline) in time. This means that two observers with different distances to a pulsar will observe different pulse periods: the observer nearest to the pulsar will measure a *slightly* longer pulse period. Taking advantage of the predictability of the pulse period, this can be used to estimate a 3-component position vector with respect to the centre of a reference frame.

The pulse decay method only provides a position estimate, not a velocity estimate. Unlike the Doppler method however, this position reference is “absolute” and does not depend on the time and date of the reference almanac (only on that of the local almanac, which is stored inside the receiver), nor on any forms of integration. It is likely that this method will not be applicable for aviation purposes as the changes in pulse period length are likely considerable smaller than the expected pulsar period changes as a result of the dynamic moving aircraft.

2.3.6.1 Pulsar database

To enable pulsar navigation, it is necessary to have precise information about a set of well-known pulsars (arrival times, pulse profiles, positions, and directions). For the effective detection and tracking of pulsars, it is necessary to know the pulse shape of each pulsar. Information about the pulse period and the pulse arrival times at a reference location is used for determining a position. All this information is stored in a database called a pulsar almanac. The almanac must be regularly be updated as pulsars sometimes have glitches, and to compensate for integration errors which could grow large in time.

Pulse shape information is determined using regular radio astronomy antennas on the ground. Furthermore, for each pulsar the exact arrival times of the pulses are detected using radio astronomy antennas. The arrival times of the pulses are related to a reference clock. All pulse arrival times are then translated to the centre of a reference coordinate system, with its origin at the solar barycentre. This is a logical choice as all pulsar positions are commonly specified in terms of the same reference frame. The coordinate transformation requires a database of solar system orbits. With the pulse arrival time information in the almanac, an extrapolation of the pulse arrival times can be made into the future, as well as to other locations in space. This information is used to determine a position.

2.3.6.2 Solar system movements database

The solar barycentre (centre of gravity of our solar system) is used as the generic reference point for the arrival times of pulses. This reference point is the most stable in our solar system in respect to the arrival of pulses. Around this centre of gravity solar objects (e.g. sun, planets, and moons) revolve. Furthermore, the Earth revolves around its own axis. On a fixed point on the Earth, the arrival time of pulses changes slightly over time as the Earth moves around the barycentre. These movements of the solar objects are determined by the astronomical community and known with high precision. They can be extrapolated over long periods. The formulas and associated parameters for the movement of the solar objects are stored in a solar system movement database. This information is required for generating the pulsar almanac. It is important to take other implementation factors such as vibration of the wings into account in future stages of the study.

2.3.6.3 Required navigational performance

Any future navigation system for aircraft must comply with the RNP requirements for specific types of operations. Once the navigation system can comply with these specifications it can be used for these types of operations. This means that operational concepts for navigation will be uncoupled from the underlying navigation technologies. This is also true for pulsar navigation. Only when a pulsar navigation system will not be able to comply with the RNP specifications special additions to the generic operational concept for navigation will be needed.

Navigation performance requirements for 2050 can be expected to be more stringent and based on the availability of multi-constellation Global Navigation Satellite System GNSS (i.e. next generation GPS, GALILEO, and GLONASS) delivering higher accuracies and maximum integrity levels. Table 3 gives an overview of the current navigation performance requirements on space-based systems. The definitions (according to ICAO) of the performance measures are the following:

- *Horizontal accuracy (95%):* Global average horizontal positioning accuracy for 95% of the time.
- *Vertical accuracy (95%):* Global average vertical positioning accuracy for 95% of the time.
- *Integrity:* A measure of the trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of the system to provide timely and valid warnings to the user (alerts)
- *Time-to-alert:* The maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment enunciates the alert.
- *Continuity:* That quality which relates to the rarity of signal interruptions. The level of continuity of service is expressed in terms of the probability of not losing the pulsar signals.
- *Availability:* The portion of time the system is to be used for navigation during which reliable navigation information is created.

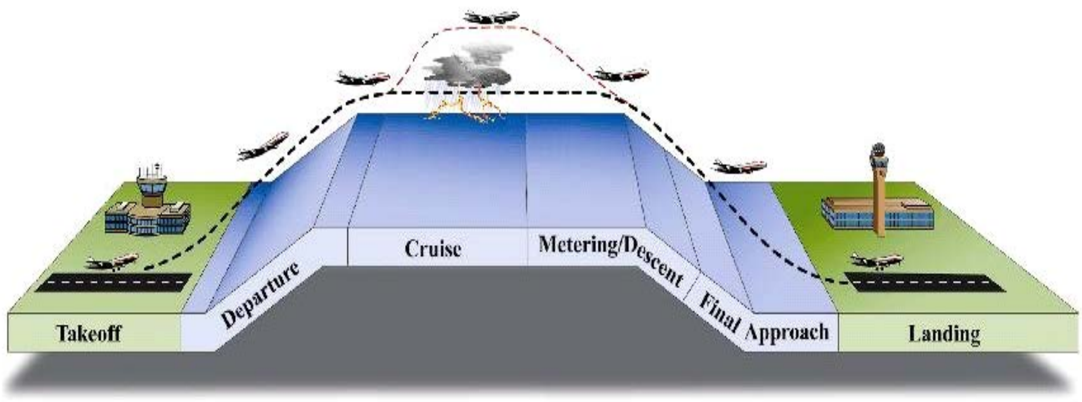

Figure 21: Separate phases of flight from origin to destination

The phases of flight can be divided into the following types including their definitions:

- *Take-off:* During take-off, the aircraft transitions from the runway into the air. The take-off during good visibility conditions is done visually. In reduced visibility conditions, the aircraft may need lateral navigation assistance.
- *Departure:* After take-off, the aircraft climbs to the cruise altitude. The aircraft moves along a Standard Instrument Departure route and must stay within certain vertical boundaries.
- *Cruise:* During cruise flight, the aircraft remains level. The aircraft follows a pre-specified route that has been cleared by air traffic control. The aircraft must navigate along the cleared route. Sometimes step climbs/descents are performed.
- *Approach:* After the cruise flight, the aircraft descents to the arrival airport. The aircraft follows a standard arrival route towards the Terminal Manoeuvring Area. Within the TMA, the aircraft navigates along an area navigation route or follows radar vectors provided by air traffic control.
- *Final approach:* The descent phase gets the aircraft in front of the runway. There, the aircraft follows a standard descent path to the runway using a navigation system that has also height information.

- *Landing:* Landing is the final phase of the flight, where the aircraft returns to the runway on the ground. During landing, the aircraft gets guidance for a controlled descent to the runway. This is even possible during reduced visibility conditions dependent on the quality of the navigation system.

Table 3: Signal-in-space performance requirements [ICAO Annex 10 incl. AM88-A, 6th Edition, July 2006]

Typical operation	Accuracy horizontal 95% (Notes 1 and 3)	Accuracy vertical 95% (Notes 1 and 3)	Integrity (Note 2)	Time-to-alert (Note 3)	Continuity (Note 4)	Availability (Note 5)
En-route	3.7 km (2.0 NM)	N/A	$1 - 1 \times 10^{-7}$/h	5 min	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1 - 1 \times 10^{-7}$/h	15 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1 - 1 \times 10^{-7}$/h	10 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
Approach operations with vertical guidance (APV-I)	16.0 m (52 ft)	20 m (66 ft)	$1 - 2 \times 10^{-7}$ in any approach	10 s	$1 - 8 \times 10^{-6}$ per 15 s	0.99 to 0.99999
Approach operations with vertical guidance (APV-II)	16.0 m (52 ft)	8.0 m (26 ft)	$1 - 2 \times 10^{-7}$ in any approach	6 s	$1 - 8 \times 10^{-6}$ per 15 s	0.99 to 0.99999
Category I precision approach (Note 7)	16.0 m (52 ft)	6.0 m to 4.0 m (20 ft to 13 ft) (Note 6)	$1 - 2 \times 10^{-7}$ in any approach	6 s	$1 - 8 \times 10^{-6}$ per 15 s	0.99 to 0.99999

Note:

1. The 95th percentile values for GNSS position errors are those required for the intended operation at the lowest height above threshold (HAT), if applicable.
2. The definition of the integrity requirement includes an alert limit against which the requirement can be assessed. For Category I precision approach, a vertical alert limit (VAL) greater than 10 m for a specific system design may only be used if a system-specific safety analysis has been completed.

It can be expected that the minimum requirements regarding individual navigation systems in 2050 will be at least at the same level as the most stringent requirement for aircraft navigation that are currently under consideration for the next generation of navigation systems (e.g. Advanced RNP). For relative navigation concepts such as the cruiser-feeder concept even more stringent requirements can be expected (e.g., docking operations). It can be assumed that such applications will require a combination of different types of positioning and ranging sensors to be able to meet the requirements on accuracy and integrity.

Table 4: Minimum Navigation System Error performance (single navigation system) as is assumed for 2050 flight operations

Flight Phase	Accuracy horizontal (95%)	Accuracy vertical (95%)	Integrity	Time-to-alert	Continuity	Availability
En-route Oceanic/remote	2 NM	n.a.	$1x10^{-7}$/h	5 min	$1x10^{-4}$/h	0.99
En-route continental	0.4 NM	n.a.	$1x10^{-7}$/h	15 s	$1x10^{-4}$/h	0.99
Arrival	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99
Initial Approach	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99
Intermediate Approach	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99
Non-precision approach	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99
Final Approach	52 ft	66 ft	$2x10^{-7}$/ approach	10 s	$8x10^{-6}$/15s	0.99
Missed Approach	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99
Departure	720 ft	n.a.	$1x10^{-7}$/h	10 s	$1x10^{-4}$/h	0.99

This table indicates what the minimum navigation performance is that can be expected of an individual navigation system to be used in 2050. A single navigation system can be combined with a second or third navigation system to improve the availability and continuity. When the accuracy of the individual navigation systems that are combined is comparable, the overall navigational accuracy can also be improved.

The above table shows that, to be able to function as a navigation system for airplanes, the accuracy of the position solution should be at least 200 m. The accuracy is determined by the estimation of the time delay, which is the difference between time-of-arrival of the signal and the expected time from the pulsar template. The better the signal can be mapped onto the pulsar template, the better the accuracy. Hence, a high signal-to-noise ratio (SNR) of the received signal is needed as well as a precise pulsar template. The SNR is defined by the strength of the pulsar, the size and quality of the antenna, and the performance of the signal processing.

As the pulsar signals are rather weak (-50 to -60 dB), the combination of the antenna and receiver should have a combined gain of at least 70 dB, but preferable 100 dB, to be able to detect the pulsars and provide a position solution. Wide-band antennas are able to obtain as much signal as possible and the gain can be increased by creating an array of wideband antenna elements, up to a level of about 40 dB. Higher gains can only be achieved by very large arrays (up to 800 m^2 for a gain of about 48 dB) or by choosing a range in the higher frequency bands. For now, a large array of wide-band planar spiral antennas appears to be the best choice for a pulsar navigation system on board an aircraft.

The proposed design for the signal processing in the receiver is first to remove the white noise from the signal by a moving average filter with jumping window combined with epoch-folding. Then, a matched filter is used to map the incoming signal to the pulsar template. With cross-correlation, the time delay can then be found. Evaluation of the methods using existing data from the Westerbork radio observatory shows that a gain of about 40 dB is possible, leading to an overall SNR of about 20 dB. This is almost enough to obtain the level of accuracy that is needed for aircraft navigation systems.

2.3.7 Operating a pulsar navigation system

To operate a pulsar navigation system there are a number of operational steps that need to be taken. First of all, there are operational steps on the ground related to the generation of databases to be used by the pulsar navigation systems. Secondly, there are a number of steps to be taken to be able to operate a pulsar navigation system on-board.

2.3.7.1 Ground segment

For the pulsar navigation system to be able to operate, there are two types of information needed: a pulsar database and a solar system movements database. The pulsar database contains information on the pulsar identification names, the pulsar directions in the barycentre reference system, the pulsar signal shapes, and the formula and parameters regarding the pulse timing at the centre of the barycentre reference system. The pulse timing is related to a global reference time. The solar system movements database contains the parameters for a detailed movements model of the earth in the barycentre reference system including its rotation around its axis. The timing of the movement is related to a global reference time.

A global and independent organization shall be responsible for the generation, updating, and distribution of the pulsar database and solar system movements database. This organization specifies the standards, the underlying models, reference frameworks, and validation methods, to which these databases have to comply. Furthermore, it will contract astronomical institutions with (radio) telescopes to generate at regular intervals the pulsar database and solar system movements database. There is a need for the usage of radio telescopes on both the Northern and Southern hemisphere to be able to cover the complete sky. Furthermore, a method shall be developed to check the quality of the generated data for the databases, for instance by having multiple radio telescopes generating the same datasets for comparison. The radio telescopes need to be calibrated before each generation of the updated database. Furthermore, it can be considered to check the pulsar navigation system accuracy at a number of fixed locations with known positions using the new databases.

Once the pulsar database and solar system movement database are validated, they can be made available for distribution to the users. For this a standard distribution method (e.g. ground-to-air communications network) to update aircraft on-board databases can be considered. These on-board databases can well be updated, when aircraft are at the gate for the turnaround.

2.3.7.2 Air segment

The flight crew must ensure that, during the turnaround process, the pulsar database and solar system movement database are updated to the latest available version. This process step shall be included on the pre-flight checklist. The flight crew shall verify that the latest databases are used, e.g. through another means of information distribution (e.g. NOTAM), to ensure that they operate with the correct databases. Furthermore, the on-board reference clock needs to be synchronized with an external reference clock.

Once the databases are incorporated, the pulsar navigation system shall perform a health check by comparing its position estimation with the position estimation of other on-board navigation systems. In case of any unexpected inaccuracies, this can be reported to the flight crew before the start of the flight. After this the pulsar navigation system can be used in conjunction with any of other navigation techniques. The overall navigation system will use the position and performance information from all separate navigation systems (including the pulsar navigation system) to provide a best estimate of the current position including its accuracy estimate. The overall navigation system will indicate to the flight crew what the main source is for the position estimate. So depending on the integrity of the separate navigation systems the overall navigation system will switch between navigation sources.

So the pulsar navigation system will for the pilot point of view operate similar to any of the other navigation systems on-board. No special types of operational methods to operate the pulsar navigation system are needed, but the system could be used for advanced operational concepts like relative separation using a combination of measurement system and relative operations (formation flying) involving several aircraft that communicate their measurements.

2.3.8 Performance

As pulsar navigation is still very much a theoretical application, it is difficult (or even impossible) to make a well-founded statement on the performance of the navigation system as a whole. The expected sensitivity of future antennas can be quantified and the performance level of upcoming signal processing techniques can be guessed, but there are many uncertainties. Hence, it remains difficult to estimate the performance (accuracy, reliability) of a future pulsar navigation system. To judge the accuracy of the system as a whole, a rough estimate is made based on the expected performance of individual components. This rough estimate indicates whether the right order of magnitude of accuracy and reliability can be achieved to continue with the concept of pulsar navigation. A summary of the feasibility per system component (antennas, signal processing, and receiver front end) is provided.

The primary factor determining feasibility of pulsar navigation for aviation is positioning accuracy. There are many other important factors (reliability, update frequency, etcetera) but the accuracy is dominant by far. If the system cannot achieve an adequate positioning accuracy (e.g. better than 100 m), it will never be used as better alternatives are available. The overall positioning accuracy can be very crudely estimated with the following equation:

$$P_x = c \cdot P_t \cdot DOP + v \cdot \delta t_u$$

Where P_X is the positioning accuracy in m, c is the speed of light in m/s, P_t is the timing accuracy in s, v is the aircraft speed in m/s, δt_u is the update frequency in s. *DOP* is the so-called dilution of precision, a common terminology in GNSS indicating how the relative position of the GNSS satellites affects the position accuracy. If all four satellites (pulsars) are seen at a 45^0, a very good horizontal and vertical accuracy can be achieved. If the satellites are almost straight overhead, a very poor horizontal accuracy is achieved. For now, the distinction between vertical and horizontal accuracy is ignored.

The first term of the equation describes the precision of the instantaneous position measurement. The second term introduces a practical position error: if the vehicle position is measured once per second while moving, the last position update deviates from the current position, depending on the time since the last update. This error can best be handled by a dedicated Inertial Navigation System (INS). Such a system is required anyway to allow effective tracking of pulsars with a beam forming antenna.

The timing accuracy is the precision with which the arrival time of a pulse can be determined. This accuracy depends on a lot of factors. Only a rough estimate of the combined accuracy can be made using the simple folding algorithm. Assuming an antenna size of 200 m^2 with a final signal-to-noise ratio of 40 dB, the expected timing accuracy for a very strong pulsar using 125 foldings is approximately $7 \cdot 10^{-6} - 7 \cdot 10^{-7}$ s, depending on the filter type used and the number of integration periods.

With some simplifying assumptions (stated below), results can be obtained that should be interpreted as upper bounds on the performance attainable by a real pulsar navigation system implementation. The results shall not be regarded as quantitatively rigid but rather as qualitative indicators of the attainable navigation accuracy. Nevertheless, it is expected that the navigation accuracy obtained in a more realistic environment should not differ significantly from the accuracy reported here. The assumptions are:

- Pulsars are considered available independently of the Earth location. In other words, a uniform pulsar distribution is assumed.
- Only the 45 best known pulsars are considered. Five pulsars from this list were disregarded due to lack of important information.
- The geometrical ambiguity problem is not addressed; it is assumed that the set of pulsar used is able to solve this ambiguity.
- The dilution of precision (DOP) problem is not considered; as with the ambiguity problem, it is assumed that the set of considered pulsars provides enough geometrical information to render the consequences of this effect negligible.

These simplifications allowed to obtain upper-bounds for the localization RMS error as a function of the integration time used in the receiver, for a bandwidth B=400 MHz. These results are parameterized by the antenna area and the receiver noise temperature. The receiver uses only one polarization channel and the $N_P = 5$ best pulsars. This number of pulsars is considered representative of a practical scenario because it will likely be sufficient to solve the geometrical ambiguity problem. The values of T_{min}in the figure are the minimum integration time required to ensure detectability of all pulsars i.e., $T_{min} = max\{L_{min}(i)\}/B$. This also avoids timing ambiguity and ensures timing estimates with variance close to the Cramer-Rao bound.

With an antenna with effective area of $A_e = 100\ \mathrm{m}^2$ and a noise temperature of $T_{rec} = 15\ \mathrm{K}$, an accuracy of about 2500 m can be achieved in 10 minutes. An accuracy of 1050 m requires one hour of integration time. Even with a much smaller antenna with $A_e = 10\ \mathrm{m}^2$, a 7000 m accuracy is possible with about 2 hours of integration time. For an uncooled receiver with $T_{rec} = 100\ \mathrm{K}$, the error increases: an accuracy of 5180 m is possible with $A_e = 100\ \mathrm{m}^2$ and one hour of integration time.

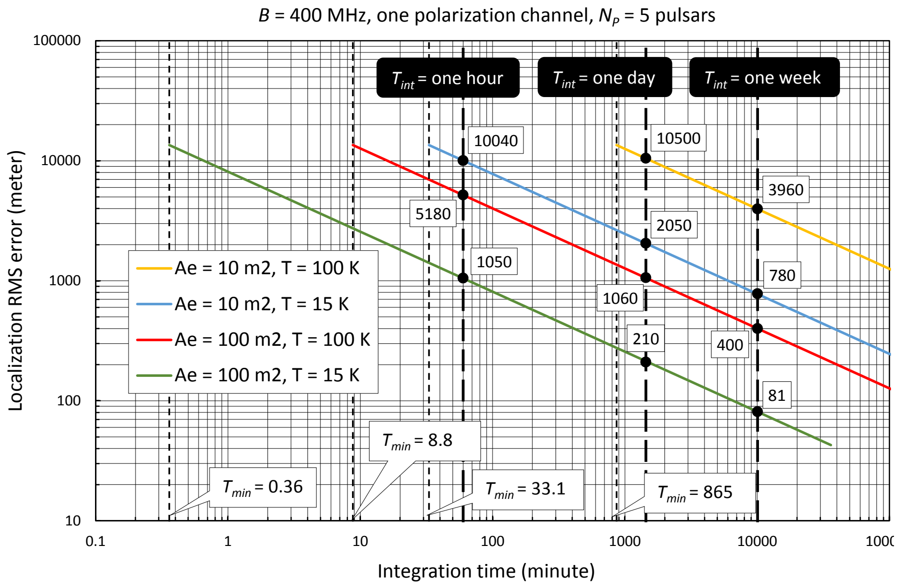

Figure 22: Localization RMS error as a function of integration time for B = 400 MHz, one polarization channel and N_P *= 5 best pulsars*

Assuming an optimal DOP of 1.0, the expected timing accuracy leads to a position accuracy of 200 – 2000 m. This accuracy is comparable to existing systems such as LORAN and is thus considered only useful for en-route ocean crossings, not for other navigation purposes. However, using a smarter folding algorithm as described in the signal processing report, significant advances can be expected. With an average DOP of 3.0 (angles of 120^0 between satellites), a positioning accuracy of ~100 m can be achieved. Such a level of accuracy would be good enough for en-route navigation and initial landing approaches, but not for final approaches where meter-level accuracy or better is required.

Summarizing, the accuracy of the navigation solution is unlikely to beat GNSS. Large antennas will remain a requirement for pulsar navigation (a limitation imposed by physics, not by computing hardware). Given this limitation, the system will most likely not be usable for smaller aircraft, and certainly not for applications where a hand-held receiver is currently commonplace. It is therefore unlikely that pulsar navigation could replace GNSS. Investments for GNSS infrastructure will therefore still be required, which is an important input for a cost/benefit analysis.

2.4 Potential impact and the main dissemination activities and exploitation of results

The objective of the PulsarPlane project was to investigate the feasibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars. In this section we will evaluate if radio pulsar navigation can provide these essentials required for navigation in aviation, and if it could be a serious alternative to existing systems, particularly for GNSS. After the evaluation of the feasibility, the major costs, benefits and impacts of pulsar-based navigation are listed, assuming of course that the technology is successfully developed and implemented in the future. The environmental impact is evaluated separately.

2.4.1 Feasibility

Pulsars are stable transmitters at predictable locations for the users. There are a relative large number of known radio pulsars, so measurements of at least 5 suitable radio pulsars could be made if a system with sufficient sensitivity could be developed. Known pulsars show timing stability similar to that of atomic clocks, which is sufficient for accurate navigation. A challenge for a pulsar based navigation system is that the radio pulsar signals are not synchronized, making precise instantaneous navigation impossible as each observation will add another unknown to the equation (the time offset of the pulsar to the system's time). The pulsar signals do not contain absolute timing information; therefore the periodicity of the signals must be used instead for synchronization.

Each pulsar has its own periodicity and profile. For GNSS, positioning accuracy is based on the measured time of arrival of a code. For the GPS C/A code, the code period is 1 ms. As one code period of 1ms is about 300 km at the speed of light, this is not accurate enough for navigation. However, a code is subdivided in 1023 chips, 1 chip representing about 300 m. The code phase can be tracked with an accuracy of a fraction of a code chip, resulting in instantaneous positioning with an accuracy of meter level. Modern GNSS signals have higher chip-rates improving the achievable positioning accuracy. For pulsar signals, there is only a dual or single (depending on the orientation of the pulsar towards the Earth) peak during the pulse period and, as signals of the pulsars are not synchronized, the expected instantaneous positioning resolution will be limited compared to GNSS systems. Resolution can be improved by integration which is expected to work better for vehicles with low dynamics such as interplanetary spacecraft.

Table 5 summarizes the performance of the navigation systems described in this paper in terms of worldwide and continuous coverage, 2D / 3D / 4D positioning (4D means including time) and accuracy. For radio pulsar navigation the accuracy depends directly on the signal strength. This means that, assuming the same antenna gain as used in GNSS, the accuracy will be much lower than GNSS. This is resolved by using a much larger, more sensitive antenna. The next challenge is then to develop radio pulsar receivers which are light and compact enough for selected applications and available within an appropriate budget.

Advances in signal processing, in analogue RF circuit design as well as in antenna design will in the future enable faster and more accurate detection of very weak radio pulsar signals, using a smaller antenna size. Recommendations have been made in the project reports on the overall feasibility of pulsar navigation. Technology steps have been identified that need to be taken before the benefits of pulsar navigation as a breakthrough technology can be exploited to a sufficient extent and impact. Summarizing, the development of a radio pulsar navigation system for aircraft is deemed feasible in the future. However, the expected accuracy is not expected to match the present accuracy of GNSS systems. In the early years of GPS, people doubted that it was technically feasible to develop a navigation system based on such weak signals. It may well be that history will repeat itself in the case of pulsar navigation.

Table 5: Performance of radio navigation systems

System	World-wide Coverage	Continuous	2/3/4D	Accuracy
Loran-c	No	Yes	2D	250 m
Omega	Yes	Yes	2D	2-4 km
Transit	Yes	No	2D	<100 m
GNSS	Yes	Yes	4D	<10 m
Radio-pulsar	Yes	Yes	3 or 4D	200 m – 2 km

To summarise the conclusions regarding feasibility of pulsar navigation:

- The signal can / should be received with a phased array antenna
- The antenna can be mounted in / on an aircraft wing surface
- The processing can be fast enough with adequate on-board processing power
- The complete signal does not have to be recovered – just the time of arrival will do
- Navigation will be similar to GPS, but with differences (use of an almanac)

2.4.2 Costs, benefits and impact

The main costs of a GNSS system are on the system side: expensive satellites and extensive ground systems are maintained. On the users side the cost are extremely low: for the low-end receiver these can be as low as a few Euros for a receiver on a chip. In contrast, a pulsar-based navigation makes use of a signal that is freely available. However, it places a larger burden on the user side. The very weak signals require large antennas and powerful computational equipment to perform the pulsar detection and navigation. This means that a pulsar receiver, at the current state of technology, will be very bulky and very expensive. Although some of these costs will disappear with expected future technological developments in computing hardware, others (the required antenna size) will not, as they are limited by physics. This high cost will be a limitation, especially for the initial adoption of pulsar navigation. A slower adoption will also reduce the impact of the system.

Nevertheless, the advantages of radio pulsar navigation are obvious; there is a wide range of applications from interplanetary missions where GNSS is not available. For terrestrial applications (notably aviation) it could be applied as a fully independent backup for GNSS. This would make other, older systems such as DME, VOR and LORAN largely redundant, which could lead to cost savings. A main advantage of pulsar navigation is that there is no space and ground segment required, which means that the signal in space cannot fail. The wideband signal is more difficult to jam, and the receiver can be made less sensitive to interference. Finally and perhaps most importantly, pulsar navigation is not depending on a system under control by a specific country: there is no political dependence. The system is therefore very robust: the signals cannot fail, they are hard to jam, and the system cannot be shut down inadvertently or on purpose. Together, these advantages make pulsar navigation a very interesting alternative for GNSS, where the need for an independent backup system is growing as people become more reliant on the availability of GNSS systems. Even though pulsar navigation is very unlikely to replace GNSS, this role of a vital backup system could become of major importance in the future.

Finally, there is a catastrophic scenario called the “Kessler syndrome” where a collision in space would cause a cascade of collisions. This would eventually lead to an orbital environment so full of debris that existing satellites would be disabled, and no further satellites could be launched for a long time. Although very pessimistic, the scenario is not seen as impossible given the current growth of space debris in orbit around Earth. Pulsar navigation would be a very important alternative solution in this destructive scenario.

To summarise the main benefits and impacts of pulsar navigation for aviation:

- Resistance to jamming and spoofing
  Due to the wide-band signal from the pulsars and the amount of pulsars available for navigation, the system cannot be easily jammed or spoofed, as long as the receivers are properly designed.
- Resistance to extreme space weather
  Although a strong solar flare may temporarily block the pulsar signals, afterwards the system will function as normal.
- Resistance to failures
  Without a space segment and with limited dependence on a ground segment, the probability of a partial or complete system breakdown is very low for pulsar navigation. The concept of an array with many smart antenna elements provides a high level of local redundancy to mitigate local failures on-board an airplane. As such, pulsar navigation can be seen as the perfect back-up system for GNSS.
- Political independence
  GNSS can be disabled, disturbed, or shut down at will by its owner and operator. If a system can become completely unavailable at any time, it is dangerous to rely on it in operational applications such as aviation. With the availability of several independent GNSS, this is however becoming less of an issue.
- Backup navigation system for aviation
  It is only a matter of time before GNSS navigation becomes commonplace in aviation, also for automated landing approaches currently using ILS. (Currently GNSS is mostly used by smaller aircraft as it is not certified for automated landing approaches). The availability of an independent backup system would ease the transition and increase acceptance of these new navigation systems in navigation.

2.4.3 Environmental impact

The environmental impact of pulsar navigation has been discussed in the impact report D5.3. At first glance, the benefits of pulsar navigation for the environment are large: as there is no space segment involved, all rocket launchers become superfluous. There is no space pollution (debris remaining in orbits) and much less pollution on earth (only a small ground segment needed consisting of radio telescopes already in use for astronomy). No artificial radio signals are generated; therefore no frequency band pollution is caused (apart from the naturally present pulsar signals). It is likely however that a (wide) frequency band for detection would have to be protected from disturbance and excluded from other uses.

The main factor determining the environmental impact of pulsar navigation however, is the question if it could replace GNSS altogether. Given the projected accuracy of pulsar navigation, this is deemed very unlikely. The best achievable scenario is that pulsar navigation serves as an important independent backup system to GNSS. This means that all environmental benefits related to the space segment of GNSS are neglected: the GNSS system will not be discontinued. Nevertheless, pulsar navigation itself will still remain a "green" navigation system causing little environmental impact.

2.5 Public website

The address of the public project website for PulsarPlane is

http://www.pulsarplane.eu

At this website a short project description can be found with the objectives, and a list of the partners involved. An example page can be found in Figure 23.

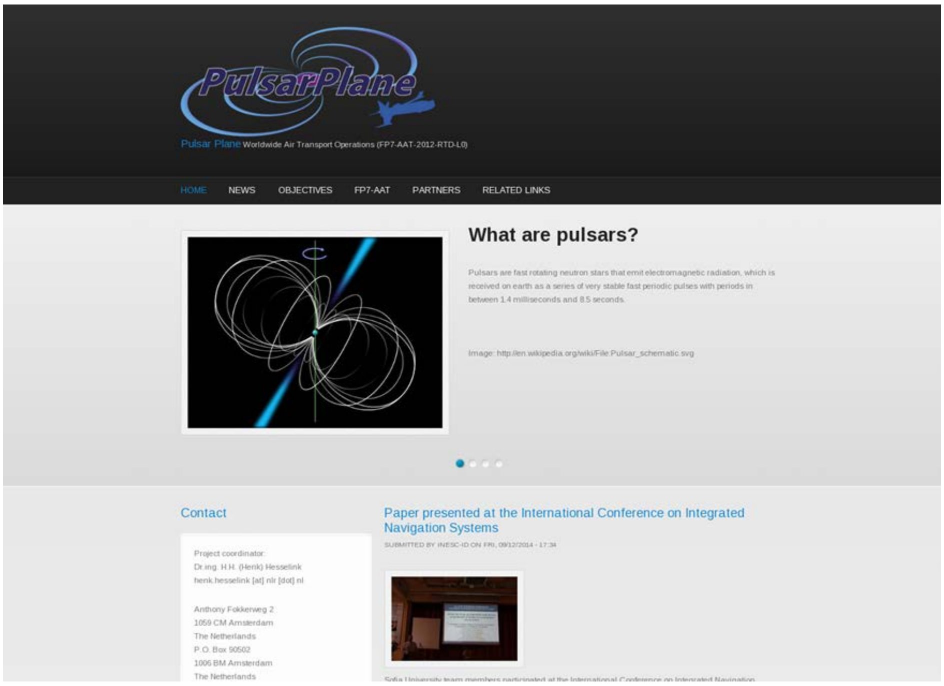

Figure 23: web portal

2.6 Project logo

The project logo can be seen in Figure 24.

Figure 24: Project logo

2.7 Diagrams or photographs illustrating and promoting the work of the project

The PulsarPlane project has been presented at several occasions. The latest poster can be found in Figure 25. A picture of the team can be found in Figure 26.

Figure 25: PulsarPlane poster

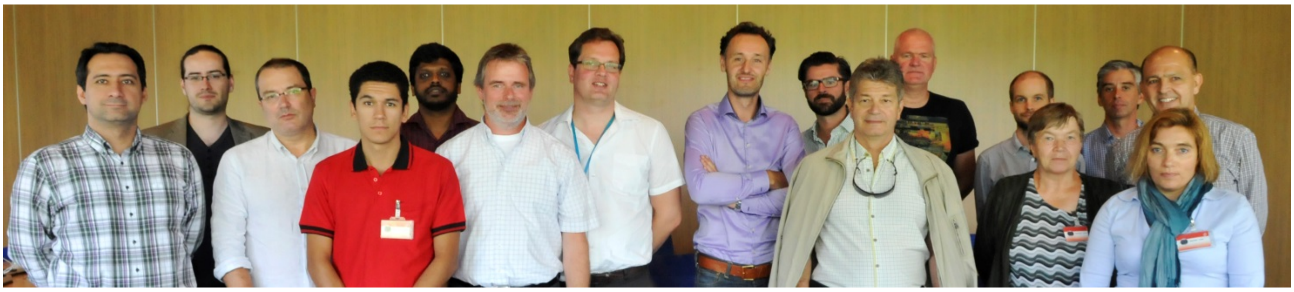

Figure 26: PulsarPlane team

2.8 List of all beneficiaries with the corresponding contact names

The project has been carried out in a consortium, led by NLR. Other beneficiaries are Technical University of Delft, Aalto University, INESC-ID, Sofia University, and the Technical University Twente.

Contact person for the project is

Henk Hesselink
henk.hesselink@nlr.nl
Tel. +31.88.511.3445

Points of contact for all project beneficiaries are:

National Aerospace Laboratory, NLR Henk Hesselink henk.hesselink@nlr.nl Tel. +31.88.511.3445
Delft University of Technology, TUD Richard Heusdens r.heusdens@tudelft.nl Tel. +31.15.27.83.544
Aalto University Antti Kestilä antti.kestila@aalto.fi +358.45.131.06.09
INESC-ID Jorge Fernandes jrf@ist.utl.pt :+351.21.3100.327

University of Sofia – Hristo Hristo Kabakchiev ckabakchiev@yahoo.com +359.2.9308.200
Technical University of Twente, TUT Mark Bentum m.j.bentum@utwente.nl +31.53.489.9111

3 Use and dissemination of foreground

Section A (public)

This section includes two tables:

- Table A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Table A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TABLE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[1] (if available)	Is/Will open access[2] provided to this publication?
1										

[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

TABLE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[3]	Main leader	Title	Date/Period	Place	Type of audience[4]	Size of audience	Countries addressed
1	Conference	University Sofia	"Study of CFAR Algorithms for Signal Acquisition in Radio Pulsar-Based Navigation", IEEE International Conference on Integrated Navigation Systems (ICINS)	26-28th May 2014	St. Petersburg, Russia	Scientific Community	30	Worldwide
2	Conference	NLR	"PulsarPlane: A Feasibility Study for Millisecond Radio Pulsar Navigation", International Astronautical Congress (IAC)	28th August – 2nd September 2014	Toronto, Canada	Scientific Community	30	Worldwide
3	Conference	INESC-ID	"Radio Pulsar Receiver Systems for Space Navigation", 8th European Symposium on Aerothermodynamics for Space Vehicles (ATD)	2-6th March 2015	Lisbon, Portugal	Scientific Community	30	Europe
4	Conference	INESC-ID	"A Study on the Accuracy of Radio Pulsar Navigation Systems", European Navigation Conference (ENC)	7-10th April 2015	Bordeaux, France	Scientific Community	30	Europe
5	Conference	University Sofia	"Time of Arrival Estimation in Pulsar-Based Navigation Systems", Signal Processing Symposium (SPS)	10-12th June 2015	Debe, Poland	Scientific Community	30	Europe
6	Conference	University Sofia	"Detection and Estimation of Pulsar Signals for Navigation", International Radar Symponsium (IRS)	24-26th June 2015	Dresden, Germany	Scientific Community	30	Europe
7	Poster / Exhibition	NLR	PulsarPlane: A Feasibility Study for Radio Pulsar Aircraft Navigation", SESAR Innovation Days (SIDs)	25-27th November 2014	Madrid, Spain	Scientific Community	200	Europe

[3] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[4] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

8	Workshop	TU Twente	"Signals from Space, from the cosmic dawn to pulsars for navigation", one-day "Signals from Space" workshop.	7th February 2014	Enschede, The Netherlands	Scientific Community	50	The Netherlands
9	Presentation	NLR	Public lecture in the National Ruimtevaart Museum (in the Netherlands),	1st February 2014	Lelystad, The Netherlands	Scientific Community / Civil Society	50	The Netherlands
10	Presentation	TU Delft	presentation about the PulsarPlane project for the general public at the amateur astronomical society Metius in Alkmaar.	25th April 2014	Alkmaar, The Netherlands	Civil Society	30	The Netherlands
11	Presentation	NLR	"A Feasibility Study for Millisecond Radio Pulsar Navigation", for the students and staff at Instituto Superior Técnico (IST), Lisbon, Portugal.	14th May 2014	Lisbon, Portugal	Scientific Community (higher education)	30	Portugal
12	Article published in popular press	NLR	The largest newspaper in the Netherlands (de Telegraaf): "Galileo wijst de weg"	25th January 2014	The Netherlands	Civil Society	1000's	The Netherlands
13	Article published in popular press	INESC-ID	An article about the PulsarPlane project appeared in the INESC-ID newsletter	29th September 2014	Portugal	Scientific Community	100's	Portugal
14	Article published in popular press	NLR	Technisch Weekblad (Weekly Technical Magazine) wrote on article on the project's results	29th May 2015	The Netherlands	Scientific Community	1000's	The Netherlands
15	Article published in popular press	TUT	An article about the project will appear in the TU Twente magazine	July 2015	The Netherlands	Scientific Community	100's	The Netherlands

Section B (Confidential[5] or public: confidential information to be marked clearly)
Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[6]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[5] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[6] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[7]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[8]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

---

19 A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

8 A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

4 Report on societal implications

To assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects, the following tables will detail questions on the project. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	335063
Title of Project:	PulsarPlane
Name and Title of Coordinator:	Drs. Ing. H.H. Hesselink

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	*0Yes* ◙*No*
2. Please indicate whether your project involved any of the following issues (tick box) :	***NO***
RESEARCH ON HUMANS	
• Did the project involve children?	
• Did the project involve patients?	
• Did the project involve persons not able to give consent?	
• Did the project involve adult healthy volunteers?	
• Did the project involve Human genetic material?	
• Did the project involve Human biological samples?	
• Did the project involve Human data collection?	
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	

• Did the project involve Human Foetal Tissue / Cells?	
• Did the project involve Human Embryonic Stem Cells (hESCs)?	
• Did the project on human Embryonic Stem Cells involve cells in culture?	
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	
• Did the project involve tracking the location or observation of people?	
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	
• Research having direct military use	0 Yes ◙ No
• Research having the potential for terrorist abuse	

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		1
Work package leaders		3
Experienced researchers (i.e. PhD holders)	2	16
PhD Students		1
Other		

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ ◙	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	○	○	○	○	○
❑	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑	Organise conferences and workshops on gender	○	○	○	○	○
❑	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

◙ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

◙ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

◙ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

◙ Main discipline[9]: 2.1 Civil engineering

○ Associated discipline[9]: | ○ Associated discipline[9]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ ◙	Yes No

[9] Insert number from list below (Frascati Manual).

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

- ◙ No
- ○ Yes- in determining what research should be performed
- ○ Yes - in implementing the research
- ○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ◙	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- ◙ No
- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ◙ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise **Environment** External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy **Research and Innovation** Space Taxation **Transport**	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ◙ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	-
To how many of these is open access[10] provided?	
How many of these are published in open access journals?	
How many of these are published in open repositories?	
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[11]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		-
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	-
	Registered design	-
	Other	-

17. How many spin-off companies were created / are planned as a direct result of the project?	-
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑ Increase in employment, or	❑ In small & medium-sized enterprises
❑ Safeguard employment, or	❑ In large companies
❑ Decrease in employment,	✓ None of the above / not relevant to the project

[10] Open Access is defined as free of charge access for anyone via Internet.

[11] For instance: classification for security project.

❑	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs: Difficult to estimate / not possible to quantify	*Indicate figure:* ◙

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ◙ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ◙ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

❑	Press Release	√	Coverage in specialist press
√	Media briefing	√	Coverage in general (non-specialist) press
❑	TV coverage / report	√	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
√	Brochures /posters / flyers	√	Website for the general public / internet
❑	DVD /Film /Multimedia	√	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

√	Language of the coordinator		
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 **Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]**

1.2 **Physical sciences (astronomy and space sciences, physics and other allied subjects)**

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 **Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]**

2.3. **Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)**

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

5 Final report on the distribution of the European Union financial contribution

This report shall be submitted to the Commission within 30 days after receipt of the final payment of the European Union financial contribution.

Report on the distribution of the European Union financial contribution between beneficiaries, see table below:

Beneficiary	*Final amount of EU contribution per beneficiary in Euros*
NLR	
TUD	
Aalto	
INESC-ID	
Sofia University	
TUT	
Total	