Final Project Results Report

Deliverable ID:	D1.2
Dissemination Level:	PU
Project Acronym:	NAVISAS
Grant:	699387
Call:	[H2020-SESAR-2015-1]
Topic:	Sesar-08-2015 Communication, Navigation and Surveillance (CNS)
Consortium Coordinator:	TEK
Edition date:	19 April 2018
Edition:	00.04.00
Template Edition:	02.00.02

Founding Members
EUROPEAN UNION EUROCONTROL
SESAR JOINT UNDERTAKING

Authoring & Approval

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SJU		23/02/2018

Document History

Edition	Date	Status	Author	Justification
00.00.10	12/02/2018	First consortium iteration	Aleksandra Nadziejko/TEK	
00.01.00	20/02/2018	Final release	TEKEVER ASDS	
00.02.00	28/02/2018	Final release	TEKEVER ASDS	
00.03.00	21/03/2018	Final release	TEKEVER ASDS	
00.04.00	19/04/2018	Final release	TEKEVER ASDS	

Copyright Statement

NAVISAS

NAVIGATION OF AIRBORNE VEHICLE WITH INTEGRATED SPACE AND ATOMIC SIGNALS

This document is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 699387 under European Union's Horizon 2020 research and innovation programme.

Abstract

This document compiles the general information on the NAVISAS project. It presents the project objectives, investigation approach and project outcomes. It includes also general information on project activities, a list of technical deliverables and publications produced in the scope of the project. It presents the key results, lessons learned and recommendations for the future.

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1 Executive Summary

This document compiles the general information on the NAVISAS project. It presents the project objectives, investigation approach and project outcomes. The Project aimed to develop a concept for small aircraft to obtain alternative positioning, navigation and timing (APNT) information, when conventional GPS fails, while keeping the performance and efficiency consistent with the airspace requirements.

NAVISAS investigated multiple constellation satellite positioning systems with miniature atomic clock (MAC), miniature atomic gyroscope (MAG) and vision-based navigation. The project analyzed several paths for technology mergers for applications in small aircraft navigation, in particular: (i) standalone high grade inertial navigation system (INS) based on atomic gyros, (ii) hybridized multi-constellation multi-frequency system coupled with high grade INS, and (iii) vision-based navigation.

The research included extensive literature review on performance based navigation documentation and clarified the relevance of specific PBN aspects to small aircraft operations.

The TRL of atomic gyroscope reached TRL3 in the scope of NAVISAS. Envisioned performances are promising and could challenge currently used high grade laser gyros. Several solution at the system level have been developed to reduce the price of the entire IMU system combing 3 axis gyros, accelerometers, GPS /GALILEO /GLONASS and atomic clock for application in UAV and ULA.

Hybridization of multi-constellation multi-frequency GNSS coupled with high-grade INS has been assessed. No real benefit could be seen from the use of multi-frequency receivers when compared GPS L1 signal, nevertheless they are a good backup mean in case of unintentional interference on one GNSS frequency. Multi-constellation GNSS tight coupling with INS is an interesting approach for scenarios with frequent GNSS outages. Purely inertial performance of high-grade INS based on atomic gyros is expected to reach the one from currently used laser gyros. GNSS coupling with INS is already used in commercial aviation. GNSS hybridization with INS-based on atomic gyros achieved TRL3 in this project.

Vision-based navigation was assessed in real flight and showed good performances for RPAS navigation and light aircraft as well. It is expected to become a standard for RPAS in the coming years. The proof of concept was delivered and TRL2 was achieved.

This document includes general information on project activities, a list of technical deliverables and publications produced in the scope of the project. It presents the key results, lessons learned and recommendations for the future.

2 Project Overview

2.1 Operational/Technical Context

Airspace is a precious resource subject to mounting demand by all types of users (airliners, small aircraft, helicopters, balloons and drones). To cope with demand there's been increasing dependence on Global Navigation Satellite Systems (such as GPS) to help air navigation. The problem is if those systems fail, the Air Traffic Management (ATM) infrastructure currently in place will not be able to cope with the amount of users or deliver the expected performance. This is heightened by the rising potential and applicability of UAV solutions, which may in the near future be sharing airspace with manned aircraft in both actively managed and unmanaged airspace. Moreover, small aircraft and drones generally do not have access to conventional navigation systems equipment, due to constraints in either cost, size or power consumption.

2.2 Project Scope and Objectives

The NAVISAS project aimed to develop a concept for small aircraft to obtain alternative positioning, navigation and timing (APNT) information when satellite navigation fails while keeping performance and efficiency consistent with the airspace requirements. NAVISAS will achieve this goal by merging satellite navigation based on multiple constellations (GPS, GLONASS and GALILEO) with an advanced inertial measurement unit (IMU) based in atomic gyroscopes implemented using microelectromechanical systems (MEMS) technology (as represented in Figure 1). BEIDOU constellation was not considered in NAVISAS due to its low maturity level. Although Galileo is also at development stage, it will be a European GNSS and therefore it is expected to be widely used in Europe as soon as it becomes fully operational. During project execution the project scope has been extended and element of vision-navigation was added.

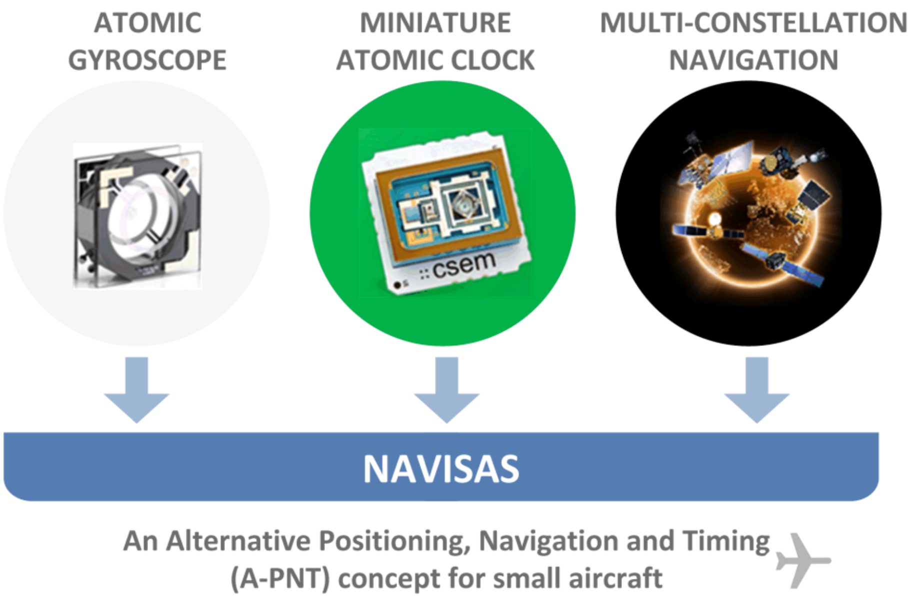

Figure 1: Early NAVISAS building blocks before the inclusion of vision-based navigation.

NAVISAS paved the way for a new cost effective instrument that can be used by small aircraft to ensure navigation performance levels consistent with evolving airspace and air traffic. The NAVISAS concept aims at improving the flight safety level, as well as the ATM performance and efficiency.

2.3 Work Performed

The work within the Project was divided into 5 Technical Work Packages (WPs).

WP2: NAVISAS Requirements and Specifications. The consortium defined "small aircraft" (see the figure below), most common small aircraft operations and missions today and what these may look like in the future. An extensive literature review on performance based navigation documentation was conducted. Upon consultations with EUROCONTROL and SESAR experts, the relevance of specific PBN aspects to small aircraft operations was clarified. The most relevant and probable scenarios for loss of GNSS have been analysed. Requirements were derived for all of the NAVISAS building blocks depicted in Figure 1. Applicability to a commercial aircraft was considered along with an estimation of potential market. The resulting preliminary NAVISAS functional block diagram is shown in Figure 6.

The results of this work can be found in deliverable D2.1 NAVISAS Requirements document.

Figure 2: NAVISAS addressed small aircraft: UAV, VLA, UL and GA. Images present TEKEVER's UAV AR5 and aircraft from SHARK and Diamond Aircraft.

WP3: SoA and analysis of Building Blocks for small aircraft APNT. WP3 established the state of the art in terms of navigation techniques specifically for small A/C as defined by the project and commercial aviation in general and in the field of atomic clocks and atomic gyros. It also defined and carried out a number of laboratory tests with MEMS cells for MAG (see Figure 3) to clarify the state of the art on the integration of atomic clocks and atomic gyros and to monitor the TRL progress of the MAG technology as indicated in the table below (the starting TRL for MAG was TRL2). The final activity of WP3 was the development of an operational concept for the small A/C segment.

The results of this work can be found in deliverable D3.1 Building Blocks for Small Aircraft APNT.

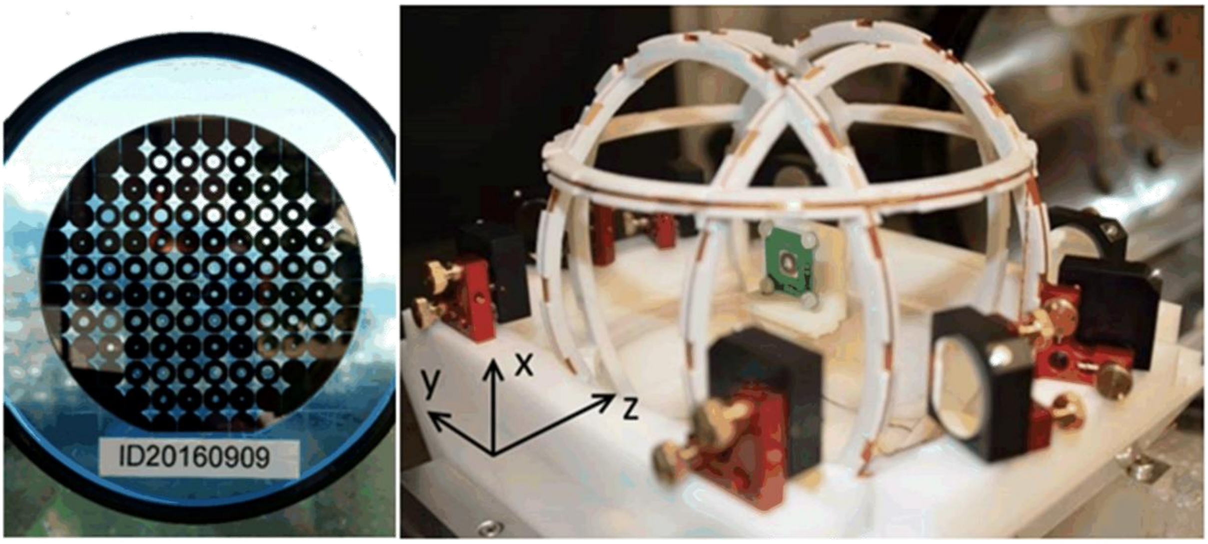

Figure 3: Left: MEMS fabricated atomic vapour cells for MAG pictured on blue tape. Right: MEMS cell in PCB holder fixed in a test setup.

Laboratory tests	
TRL2+	MAG MEMS cell fabrication for miniature atomic gyroscopes (MAG) and characterization with a good long-term stability and lifetime of the cells.
	Measurement of the noble gas atoms relaxation and dephasing times.
	Contactless MEMS cell temperature stabilization system.
TRL3	Cost reduction analysis by combination of MAG and MAC fabrication processes and s/s

Table 1: Summary of tests.

WP4: APNT concept for small aircraft. The detailed system-level concept of the small aircraft APNT was established. A variety of GNSS receivers available on the market and GNSS and INS integration architectures was analysed as well as a possibility to integrate MEMS cell atomic clock (see Figure 4) and share some subsystems between MAC and MAG. The receivers' compatibility with NAVISAS requirements, trade-offs on GNSS+INS solution performance / integration level versus implementation costs and finally a performance of hybridized dual-constellation / inertial positioning were assessed. A number of laboratory tests supporting TRL progression of atomic gyroscope to TRL4 was accomplished (see Figure 5). The consortium introduced also the concept of vision-based navigation, upon SJU approval.

Details of the NAVISAS APNT were compiled in deliverable D4.1 NAVISAS APNT concept.

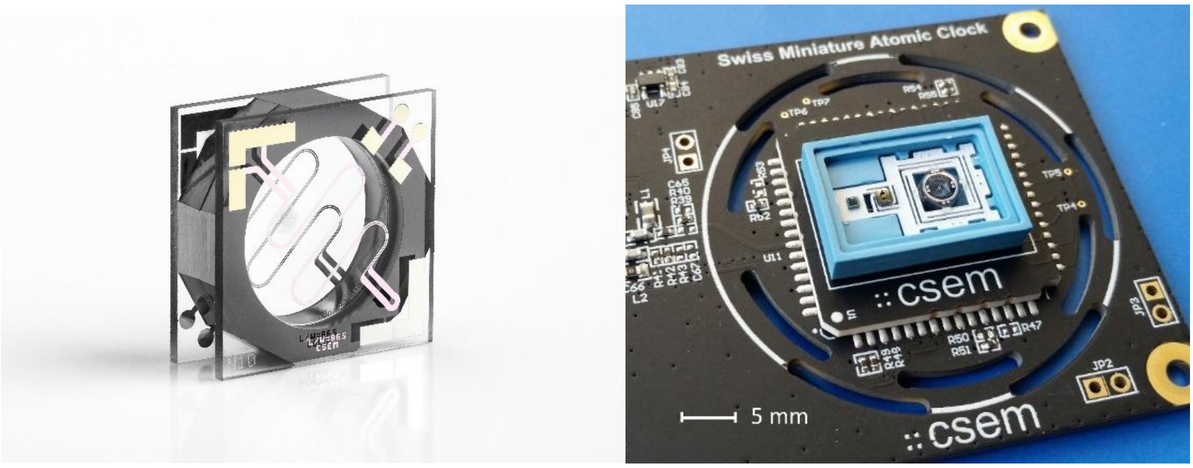

Figure 4: MAC@CSEM. Left: functionalized MEMS cell; Right: MAC prototype at TRL5-6 level.

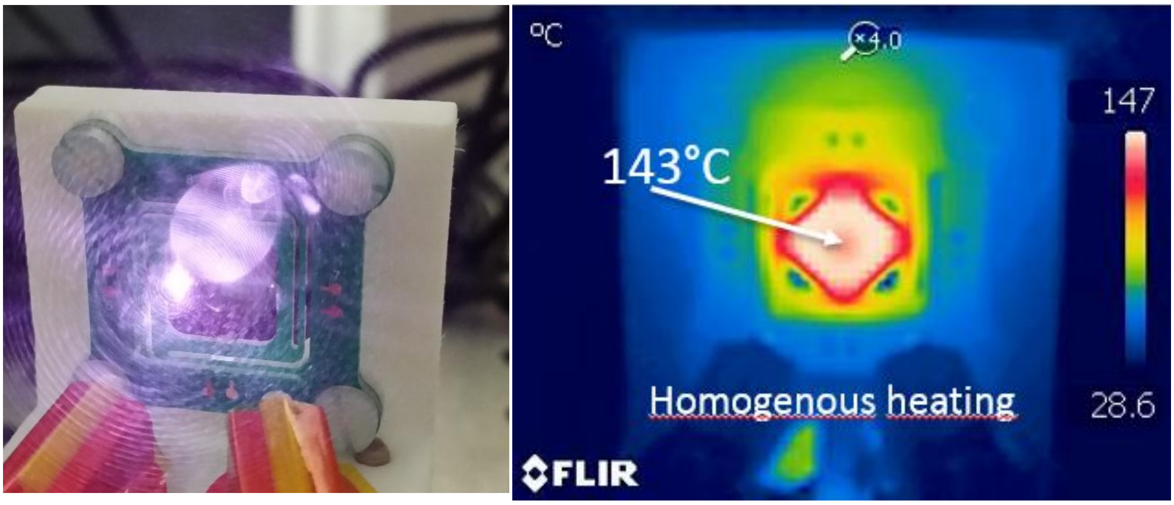

Figure 5: Contactless temperature stabilization system of MEMS cell in MAG.

WP5: Assessment of the technology benefits for aircraft navigation and ATM system. WP5 summarized the project results, assessed the performance of NAVISAS APNT and provided the APNT roadmap. Results from experiments on vision-based navigation for light aviation and associated trade-offs between the performances, cost and complexity of the solution were thoroughly evaluated, taking into account such aspects as safety, reliability and regulatory constraints. NAVISAS advanced APNT development roadmap was prepared. Results of this work were compiled in D5.1 and D5.2.

WP6: Dissemination and Exploitation. The dissemination and exploitation activities handling all communication of project activities during its execution and planning of exploitation strategy of the project results have been performed. They allowed the project to gain a certain visibility and attract the interest of potential stakeholders from both the avionics and automotive markets. The main results of the project were reported at AERO Friedrichshafen, European Frequency and Time Forum EFTF, World ATM Congress, International Conference on Quantum Technologies.

2.4 Key Project Results

2.4.1 Introduction to NAVISAS A-PNT

NAVISAS functional block diagram is shown in the following figure. The NAVISAS project has focused at the building blocks delineated with a dashed rectangle.

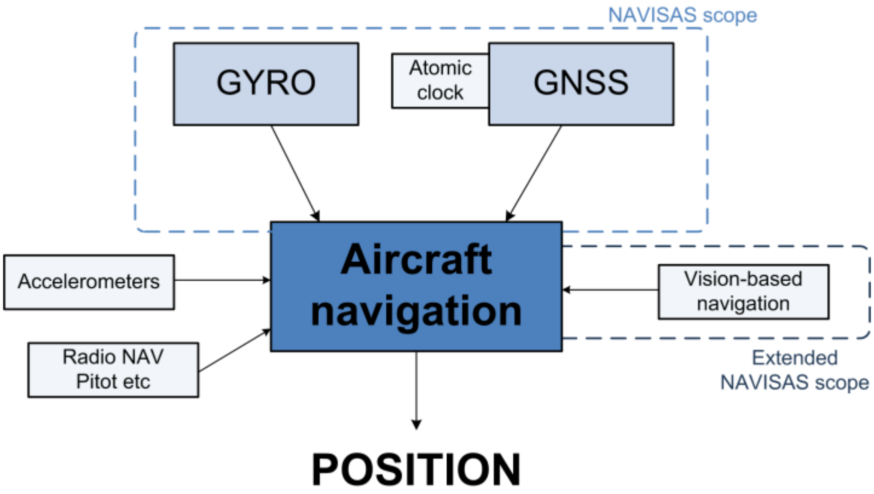

Figure 6: Preliminary NAVISAS functional block diagram.

2.4.2 Miniature atomic gyroscope and miniature atomic clock

The project allowed the advancement of the atomic gyroscope from TRL2 to TRL3 level. This was achieved via fabrication of dedicated MEMS alkali atomic vapour cells and testing their performances against model predictions. The targeted partial pressures of gas constituents in the cells have been achieved. Measured nuclear spin relaxation and decoherence times allowed us to refine the model predictions for the gyroscope performance (Figure 7). They confirmed that a navigation grade gyroscope can be reached using MEMS atomic cell fabrication technology.

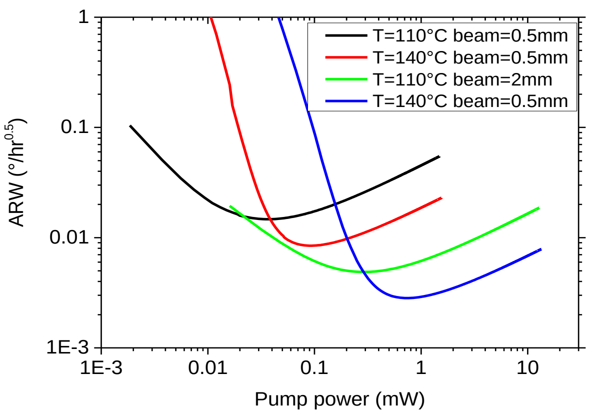

Figure 7: Angle Random Walk (ARW) of MAG at TRL3 level vs cell temperature, pump beam diameter and power.

A table below represents MAG benchmarking (TRL3 was reached) and comparison to competitive navigation grade solutions. NAVISAS MAG aims to deliver navigation grade performance, as used in commercial aviation, but at significantly low cost.

Table 2: NAVISAS MAG target benchmarking.

	NAVISAS MAG Specifications at TRL3	Equivalent NMR technology demonstrator*	Equivalent product (Laser Gyro)
Range	500°/s ***	3500 °/s	900 °/s
Fourier frequency	100 Hz ***	300 Hz	1000 Hz
Bias stability	0.001 °/hour ****	0.02 °/hour	0.0035 °/hour
ARW	0.0029°/sqrt(Hz) **	0.005 °/sqrt(Hz)	0.0035° /sqrt(Hz)
Effective scale factor	$2{\cdot}10^6$pulse/rev ***	~1·pulse/rev (0.998592 pulse/rev)	~$1.1{\cdot}10^6$ pulse/rev (1164352 pulse/rev)
Scale factor non-linarity	<5 ppm ***	4 ppm	5 ppm
Volume	<100 cm^3 ****	10 cm^3	300 cm^3
Weight	<200 g ****	N.A.	454 g
Price	**TARGET: <2 000 € ******	**N.A.**	**~ 20 000 €**

* T. G. Walker, M. S. Larsen, Advances in Atomic, Molecular and Optical Physics, Vol 65, pp 373-401 (2016)
** Verified from measured data
*** By design
**** Target value

The cost reduction of the gyroscope was identified as an important design driver for the introduction to the small aircraft market. This gyroscope will bring added value to small aircraft, providing the aircraft with a capability that competitive solutions from this market do not offer. NAVISAS MAG will provide coasting at the time when GPS loss occurs, or even provide navigation capabilities when the pilot decides to turn to the airport. In small aircraft, NAVISAS MAG could serve not only as a backup emergency solution, but as a main navigation tool, for instance in specific UAV operations (short in time, for instance 1 hour.

Several solution at the system level have been developed to reduce the price of the entire IMU system combing 3 axis gyros, accelerometers, GNSS and atomic clock for application in UAV and ULA. For instance, SoA in atomic clocks technology identified its values over competitive solutions; a brief summary is presented in the following Table 3.

	TCXO (typic.)	OCXO (typic.)	Standard Rb (typic.)	Equivalent product 1	CSEM SwissMAC	CSEM SMAC^{3}P
Freq. stablility (1 day)	1E-8 (1s)	1E-10 (10µs)	1E-12 (0.1µs)	1E-11 (1µs)	1E-11 (1µs)	2E-11* (1µs)
Freq. stablility (1 year)	1E-5	1E-6	2E-10	1E-9	1E-9	1E-9*
Size (cm^3) (PP only)	0.025 (-)	5 (-)	220 (40)	16 (0.8)	50 (6)	5 (1.4)
Power cons. (mW) (PP only)	10 (-)	400 (-)	11'000 (-)	125 (20)	500 (200)	- (50*)
Price ($)	10	250	850	1'400	300*	150*

* expected performance

Table 3: Comparison of relevant oscillators and clocks. The last columns also presents measured and expected target MAC performances.

2.4.3 Technologies hybridization

Multi frequency receivers are robust and efficient backup mean in case of unintentional interference on one GNSS frequency. Several aspects of technologies hybridization were assessed and compared to GPS L1 hybridizations existing in commercial aircrafts:

- Multi-GNSS constellation navigation with INS based on atomic gyros coupled,
- Navigation based on multi-constellation multi-frequency receivers,
- Purely inertial performance using IMU based on atomic gyroscope,
- GNSS performance gain coming from inclusion of MAC

Even a privacy protecting device available on consumer market and used without any intention of being applied against an aircraft directly can cause a loss of GNSS reception in a significant area. As soon as all GNSS signals are lost the positioning accuracy will be dominated by the quality of inertial system. Upon running simulations for different signal outages scenarios, it was concluded that multi constellation approach provides an increased number of visible satellites and may be of interest in urban environment where masking or multipath is more frequent as presented on the figure below. It however doesn't protect against interference. It becomes useless when all frequencies are lost, for example during an intentional jamming event. Furthermore, GNSS-INS coupling techniques may improve navigation in scenarios with low GNSS availability.

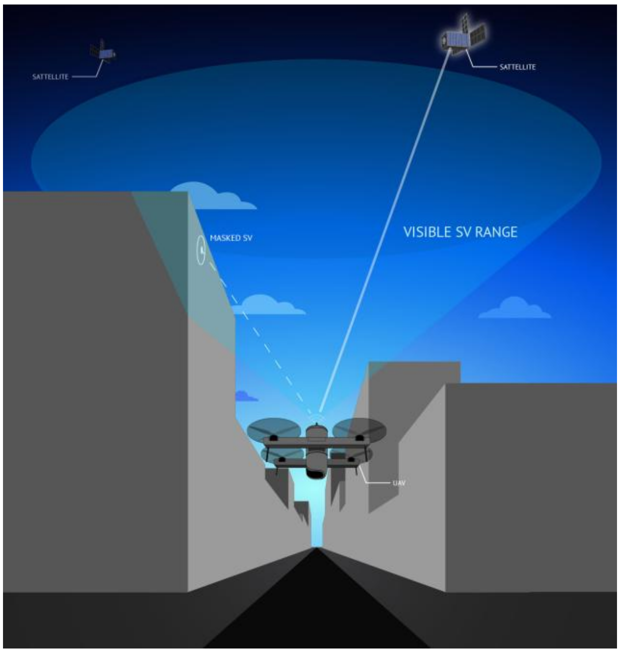

Figure 8: UAV receiving GNSS signal.

The main finding of the project is that an INS based on MEMS accelerometers and atomic gyros could reach the performances of a high-grade inertial reference unit (2Nm/h). It could provide the same capability and allow RNPx coasting for a lower cost, see Table 4.

Conditions	High-grade gyros	Very high-grade gyros	Reference high-grade gyros
Two constellations and two frequencies, with reduced visibility	HIPL ≤ 20 m		
Two constellations, loss of one frequency	HIPL ≤ 40 m		
Loss of one constellation and one frequency	HIPL ≤ 80 m		
Severe loss of one constellation and one frequency	RNP 1 during 2000 s RNP 0.3 during 1000 s RNP 0.1 during 500 s	RNP 1 during 2 hours RNP 0.3 during 1500 s RNP 0.1 during 800 s	RNP 1 during 1 hour RNP 0.3 during 1200 s RNP 0.1 during 600 s
Pure inertial	RNP 2 : 2000 s RNP 1 during 1500 s RNP 0.3 during 800 s RNP 0.1 during 400 s	RNP 2 : 2 hours RNP 1 during 1500 s RNP 0.3 during 800 s RNP 0.1 during 400 s	RNP 2 : 1 hour RNP 1: 1500 s RNP 0.3 : 800 s RNP 0.1 : 400 s

Table 4: Performances achieved in the GNSS partially-denied situations.

The change from conventional crystal oscillator to a miniature atomic clock in GNSS receiver would bring numerous advantages to GNSS performance such as faster recovery from signal outages, improvement of dilution of precision, better availability and solution accuracy and finally increased robustness to spoofing detection, since wannabe spoofers will find themselves more constrained regarding the clock drift.

2.4.4 Vision-based navigation

Vision based navigation has been confirmed as a very promising technology for VMC applications ranging from UAV to light aircrafts. Thales and SHARK performed flight tests of a prototype vision-based navigation system in order to assess its actual performances for light aircraft and compare against performances obtained when mounted on UAV. Some pictures from conducted tests are presented in the Figure 9. Around 1% - 2% drift was demonstrated, therefore confirming the usefulness of this concept as long as VMC flight is considered. It could provide a low cost A-PNT capability with very acceptable performance to continue the mission during a GPS outage.

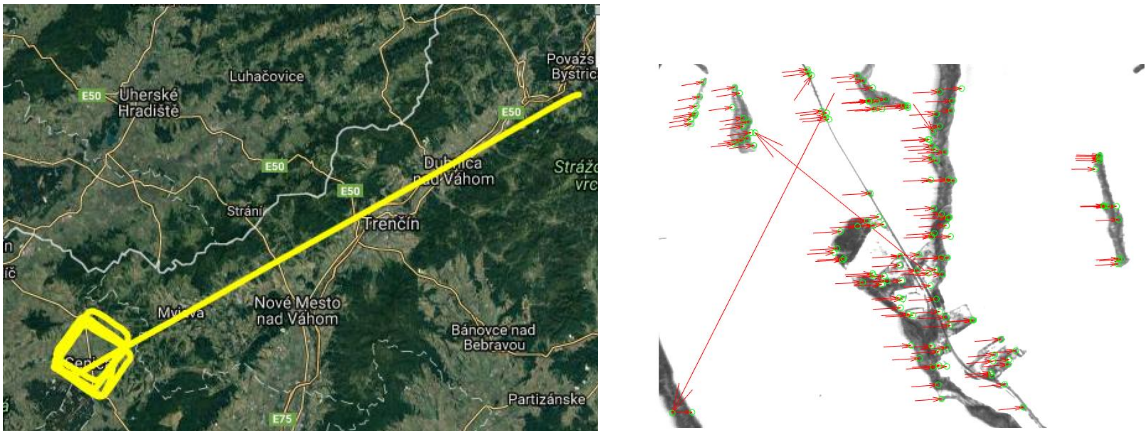

Figure 9: Left: Trajectory selected for performance estimation. Right: Processed image of vision base navigation system

2.4.5 Cost-Benefit analysis

The Cost-Benefit analysis of NAVISAS A-PNT for different End-Users (Commercial Aircraft, GA/UL/VLA and UAV markets) was conducted and is presented in the following table. We find that MAG is an interesting solution for all of these markets, while vision-based navigation is mainly attractive for a small aircraft. This approach is found promising for VFR flights or emerging applications such as UAV operations in urban environments.

	Commercial Aircraft market	GA/UL/VLA market	UAV market
MAG	MAG challenges state-of-the-art laser gyros at lower cost Complex and expensive certification process of the sensor	MAG as a high-grade gyro that becomes affordable to GA/UL/VLA MAG provides coasting in GPS outages and time and comfort to reverse to other navigation mean and divert to the nearest airport. The GA End-User can add value to an aircraft such as emergency backup navigation tool Probably will be smaller and lighter than current inertial systems Market-based pricing based on cockpit avionics modules requires strong price limitation on MAG.	Currently UAV rely heavily on GNSS receivers. INS based on MAG could provide coasting, assuring the UAV platform (and hence UAV operator) navigation capabilities. Navigation capability relying solely on INS for specific RPAS missions (short in time) Probably will be smaller and lighter than current inertial systems
MAG+MAC	The consortium will provide reliable MAG with great performance, at the cost of more complex integration	The consortium will provide reliable MAG with great performance, at the cost of more complex integration The GA End-User can add value to an aircraft such as emergency backup navigation tool Not significant price difference between MAG alone and MAG+MAC	The consortium will provide reliable MAG with great performance, at the cost of more complex integration It is a reliable navigation solution in GPS-challenging environment such as urban canyons Not significant price difference between MAG alone and MAG+MAC
Avionics Box	Not interesting as avionics box because of certification issues	It is an interesting solution for aircraft manufacturers developing new aircraft (because the replacement of currently used avionics might not be viable) it requires more effort from the consortium to integrate all elements into one module	Currently used avionics in UAVs is relatively cheap It is an interesting solution, but its final price is crucial it requires more effort from the consortium to integrate all elements into one module
Vision-based navigation	Not applicable because of technology limitations	Performances measured (1 – 2 % drift) allow using this solution for navigation in Visual Meteorological Conditions (VMC) flights. It is expected to be very affordable solution.	It is limited in monochromatic environments, e.g. flight above open water or clouds, but could be used in urban operations. It is expected to be very affordable solution.

Table 5: Cost and Benefit Analysis of NAVISAS

2.4.6 NAVISAS A-PNT roadmap integration in the evolving needs of aeronautics environment

A-PNT technologies studied by SESAR do not directly target GA neither ultra-lights or UAVs. Only GA aircraft are considered in the short-term A-PNT concept by maintaining a VOR beacon network. If required, GPS-only aircrafts could be managed by ATC through conventional vectoring. It is important to note that in case of GPS loss ADS-B and mode S transponder position would also be unavailable; ATC would rely only on primary radar data. Except for WAM which does not require airborne modification for general aviation all other short-/ mid-term techniques consider airborne navigation equipment not embedded in ultra-light aircrafts or UAV (DME, Loran..).

Several additional factors should be taken into account:

- General aviation or ultra-light pilots usually have less training and experience than commercial pilots. In particular, recurrent training may be non-existent, especially for VFR pilots. The sudden loss of GPS may be felt as very strong reduction in safety margin especially in marginal VFR conditions. Cases where general aviation pilots became totally confused following a GPS failure have been reported.
- VFR navigation is more and more relying on a user friendly 2D-map using GPS position and pilots tend to reduce the search of visual references to confirm their position. In addition, most of the general aviation pilots flying with GPS have not being using VOR or NDB for years and may struggle to revert to conventional aids if needed.
- Ultra-light aircrafts tend to have similar characteristics than general aviation aircraft however may be less equipped in term of navigation equipment (no VOR or NDB receiver). A GPS loss may have an even worse impact at pilot level.
- Small/medium size UAV are mostly relying on GPS and may not have any additional navigation means, nor always provide a radio link between UAV pilot and ATM. Even in VFR conditions no reversion navigation capability (even visual through cameras) could be available in case of GPS loss.

Atomic gyros investigated in the scope of this project could be a “buy time” and coasting solution when flying en-route until GPS signals are reacquired for VFR and IFR pilots (although IFR pilots are trained to revert to VOR/NDB beacons in case of GPS signal loss). The pilot would have time and comfort to revert to other navigation mean and divert to the nearest airport if needed.

As far as UAVs are concerned APNT is a more important point. As GPS is today the corner stone of UAV navigation, a backup mean is more than welcome to continue operations in case of GNSS loss which may be more frequent at low altitude. Vision-based navigation is already available on some UAVs and vision-based development kits can be found for sale for a few hundred dollars. It is expected that high-end drones performing safety-of-life missions will be fitted with such a capability in the coming years.

Eventually when atomic gyros become available, lower cost inertial systems may be used in place of vision based navigation, allowing Instrument Meteorological Conditions (IMC) APNT as well. Such new capability may increase the scope of safety-of-life operations for UAV by providing an all-weather safe, accurate and dissimilar navigation mean.

Furthermore, results obtained in the scope of this project show that atomic gyros will be reliable enough to provide navigation capability based solely on INS (although within a limited time intervals). That is particularly interesting for specific RPAS missions (short in time, for instance with time duration 1 hour).

The TRL roadmap of INS&GNSS hybridized solution is expected to follow the atomic gyroscope roadmap. Given the high TRL of INS&GNSS solutions, the hybridized solution is limited by TRL progress of atomic gyro. The overall NAVISAS A-PNT is limited also by TRL of vision-based navigation. This roadmap is depicted on the following figure.

Powering the GNSS from the MAC will bring a number of advantages to navigation, in particular in GPS outages or deliberate attacks on UAVs' navigation systems. Given the fact that there is no GNSS receiver on the market that supports external clock source and copes with NAVISAS requirements (small, low-power, affordable), an effort should be put to development of a new type of GNSS receiver with a possibility of connection to external clock source.

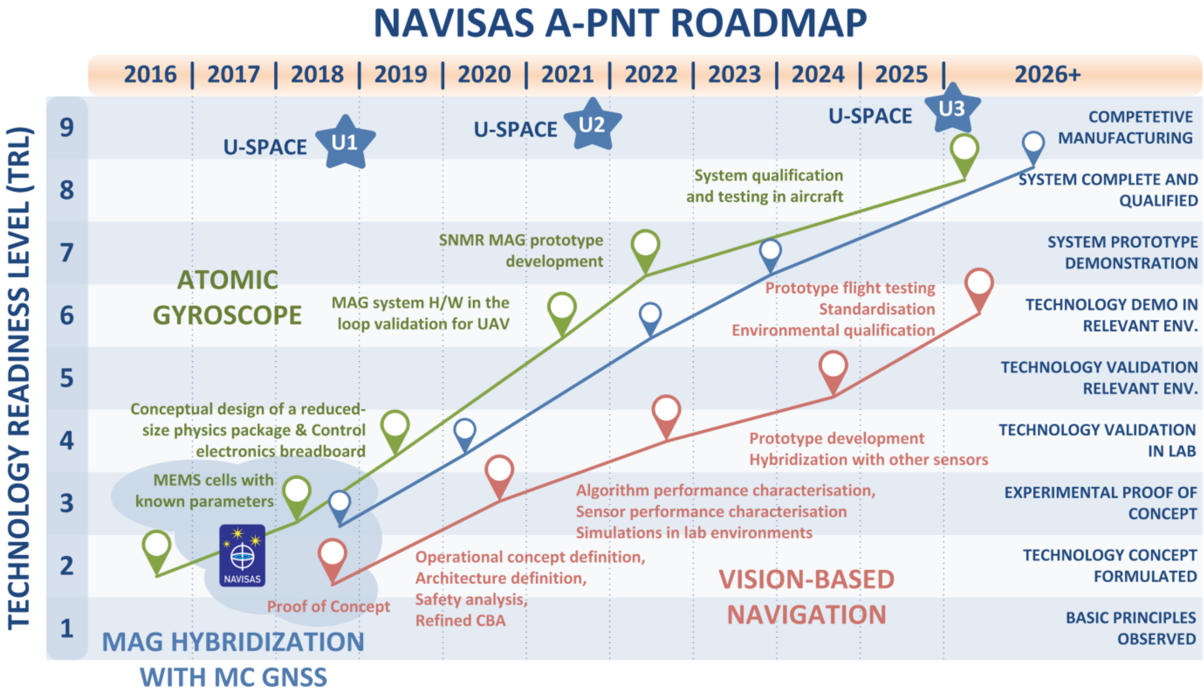

Figure 10: NAVISAS A-PNT elements roadmap.

Figure 10 includes also some information on timeline of U-SPACE services (based on the SESAR Roadmap for safe integration of drones into all classes of airspace). The following data were used in the figure:

U-SPACE U1: 2019 - end of industrialisation incl. Standardisation & Regulation

U-SPACE U2: 2022 - end of Exploratory and Industrial Research

U-SPACE U3: 2025 - end of Exploratory and Industrial Research

U-SPACE will be a set of services designed to support safe, efficient and secure access to airspace for large numbers of UAVs. It will provide an enabling framework to support routine drone operations as well as clear and effective interface with manned aviation, ATM/ANS service providers and authorities.

Figure 11 depicts NAVISAS A-PNT envisioned timeline versus RPAS Concept of Operation (CONOPS) prepared by ICAO CONOPS. A strong push to research on vision-based navigation is needed so that it reachesTRL6 before 2025 and it is possible to use this opportunity for testing of NAVISAS technologies as A-PNT for RPAS in more complex environment like urban.

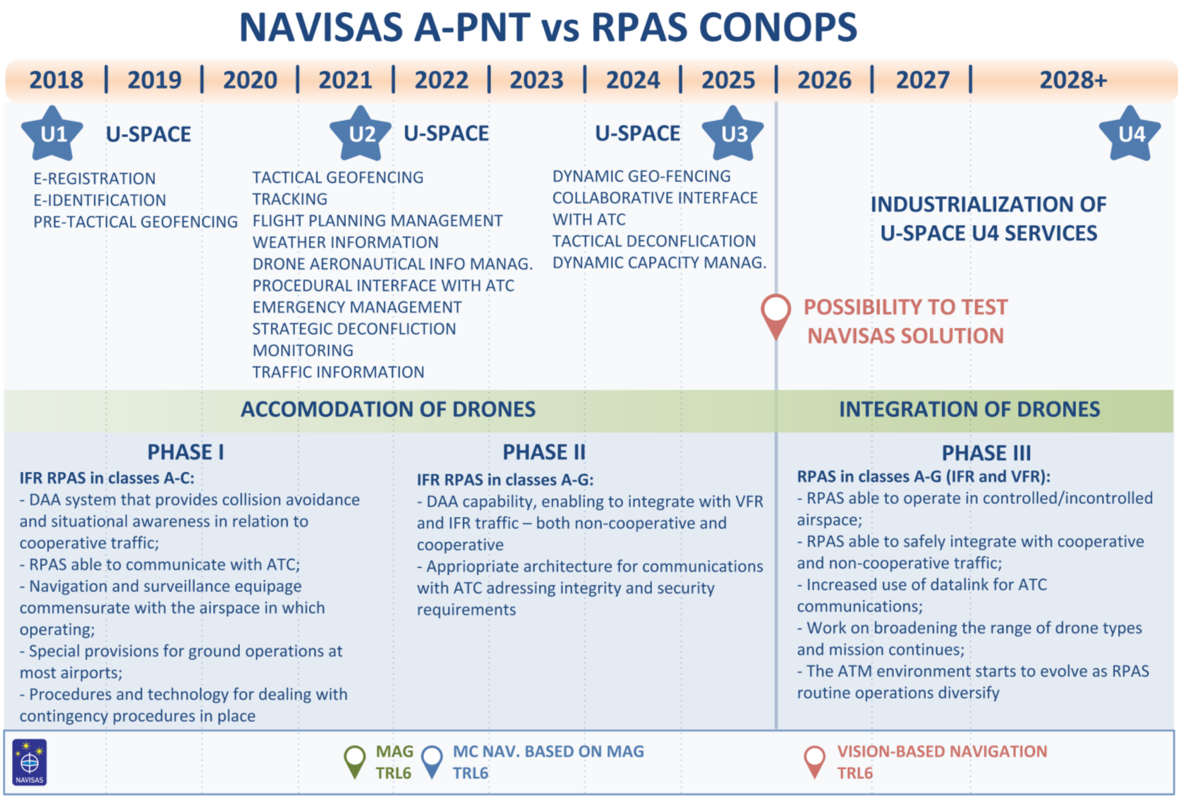

Figure 11: NAVISAS A-PNT versus RPAS CONOPS (based on [SESAR17, ICAO17])

2.5 Technical Deliverables

Reference	Title	Delivery Date[1]	Dissemination Level[2]
Description			
D2.1	NAVISAS Requirements document	12/09/2016	PU
	NAVISAS Requirements document compiles requirements from small aircraft (including UAVs) concerning APNT systems and		

[1] Delivery data of latest edition

[2] Public or Confidential

	ATM point of view. It includes also the particular requirements in regards to gyroscopes, atomic clocks and GNSS coupling.		
D3.1	Building Blocks for Small Aircraft APNT	16/06/2017	PU
	This document provides an overview of the state of the art of navigation techniques (including those applicable to small aircraft) and an analysis of the state of the art for atomic clocks and atomic gyros. Furthermore, it reports on the experiments carried out on NAVISAS atomic gyro and atomic clock. Finally, the document proposes an operational concept for the use of NAVISAS by small aircraft.		
D4.1	NAVISAS APNT concept	21/12/2017	CO
	This document presents further results of experiments carried out on micro-gyroscope components and a concept for combined atomic clock and gyros for navigation for small aircraft. This document compiles also results of investigation of multiple GNSS constellation navigation and its integration with INS. Finally, it includes assessment of critical subsystem, which is the Inertial Measurement Unit. It derives the performance of the IMU based on atomic gyroscope and MEMS accelerometers.		
D5.1	NAVISAS assessment report	16/02/2018	CO
	This document presents the Assessment of the technology benefits for small aircraft navigation and ATM system. Atomic gyros and vision based navigation technologies are addressed through this document in terms of description of achievable performances, and associated safety and security benefits for regulations and ATM. For cost and implementation reasons, in the context of A-PNT, UAV, general and light aviation are candidates to technologies other than traditional inertial systems and ground based infrastructures as DME/VOR used for commercial aviation solutions.		
D5.2	Advanced APNT development roadmap	16/02/2018	CO
	This document gives an overview of possible options for A-PNT implementation (technologies, operations) and associated roadmap for all aviation segments (commercial, general and light) as GNSS is increasingly used as the main localization and navigation mean.		

Table 6: Project Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

Code	Name	Project contribution	Maturity at project start	Maturity at project end
CNS-0002-B	*Rationalisation of NAV systems/infrastructure for Step2*	*NAVISAS contributed to the improvements of navigation for small aircraft and RPAS by providing A-PNT without involvement of ground infrastructure and expensive equipment.*	*TRL2*	*TRL3*
CTE-N13a	*A-PNT (Alternative Positioning Navigation and Timing)*	*NAVISAS contributed to the definition of A-PNT for small aircraft and RPAS by proposing atomic gyroscope stand-alone or hybridized with multi-constellation GNSS and vision-based navigation as potential solutions.*	*TRL2*	*TRL3*

Table 7: Project Maturity

NAVISAS addressed very specific topic of A-PNT only for small aircraft, which represents very small group of aerospace users. Findings of the consortium have shown that the European ATM Master Plan lacks requirements for GA and RPAS in terms of navigation performance. The consortium proposes to add new Operational Improvement (OI) focused solely on small aircraft and RPAS.

3.2 Maturity Assessment

Table 8 - ER-IR Maturity Assessment of the project.

Thread	ID	Sub-ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS	OPS.ER.1		Has a potential new idea or concept been identified that employs a new scientific fact/principle?	Achieved	The idea for navigation based on the new atomic gyros has been presented in the D2.1 and further described in detail in D3.1 and D4.1. Furthermore, these deliverables also described other investigated A-PNT technologies that can be combined with the atomic gyros such as GNSS&INS coupling or vision based navigation.
OPS	OPS.ER.2		Have the basic scientific principles underpinning the idea/concept been identified?	Achieved	The project identified scientific principles of proposed A-PNT technologies, in particular background of atomic gyroscope, GNSS receiver & INS hybridization and vision-based navigation. Scientific principles relevant to investigated technologies have been described in detail in D4.1.
OPS	OPS.ER.3		Does the analysis of the "state of the art" show that the new concept / idea / technology fills a need?	Achieved	D2.1 and D3.1 have covered the SoA of relevant topics such as PBN-related requirements and necessary performance applicable to small aircraft and drones and navigation. D3.1 proposes a number of operational concepts for using small aircraft and drones where NAVISAS concept could fulfill the need of small aircraft for cost efficient navigation systems that do not rely solely on ground infrastructure and expensive onboard equipment.
OPS	OPS.ER.4		Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?	Partial - Non Blocking	The underpinning atomic gyro technology behind the NAVISAS gyros is described in detail in D3.1 and D4.1. We believe the NAVISAS concept of combining atomic gyros with cost efficient atomic clocks and other navigation techniques such as

					video or multi-frequency (possibly multi-constellation) GNSS will provide small aircraft and drone users with a capability which will implicitly be useful also for the ATM system
OPS	OPS.ER.5		Are the relevant stakeholders and their expectations identified?	Achieved	End-Users needs have been identified already in the NAVISAS requirements development stage (D2.1) and they have been further analyzed in D3.1 (CONOPS). The stakeholder map is presented in D5.3.
OPS	OPS.ER.6		Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance benefits?	Achieved	We believe the technology proposed in NAVISAS could bring performance benefits for the drone and GA/personal transport operating environments. The underlying arguments for this are presented in D4.1 and D5.1.
SYS	SYS.ER.1		Has the potential impact of the concept/idea on the target architecture been identified and described?	Achieved	D4.1 presents technologies investigated within NAVISAS in detail, i.e. It provides concepts/architectures. D5.1 is the assessment report that evaluates the performance of investigated technologies and assesses their applicability to target platforms nowadays and in the future (RPAS, GA...)
SYS	SYS.ER.2		Have automation needs e.g. tools required to support the concept/idea been identified and described?	Not Applicable	
SYS	SYS.ER.3		Have initial functional requirements been documented?	Achieved	Functional requirements have been documented in D2.1.
PER	PER.ER.1		Has a feasibility study been performed to confirm the potential feasibility and usefulness of the new concept / idea / Technology being identified?	Achieved	We believe the work reported under D4.1 and D5.1 provides evidence on the feasibility and potential usefulness. Furthermore, D6.4 and D5.3 describe the way ahead towards maturing the NAVISAS technology and testing it under appropriate conditions through the Exploitation Plan and Business Plan for NAVISAS.

PER	PER.ER.2		Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence Factors?	Partial - Non Blocking	Final conclusions for NAVISAS investigated technologies (cost, SWaP, performance) were provided in D5.1. However, a specific cost analysis did not take place as this was not foreseen in the contract. At the current level of maturity, a clear and precise identification of the costs mechanisms may be harder than expected.
PER	PER.ER.3		Has an initial cost / benefit assessment been produced?	Achieved	Initial CBA has been performed in D5.3.
PER	PER.ER.4		Have the conceptual safety benefits and risks been identified?	Partial - Non Blocking	D5.1 presents an assessment in safety, performance, reliability of small airborne vehicles, impact on the flight safety regulations of the NAVISAS concept and technology. This looks at impacts of NAVISAS on the operations and current regulations for operating drones in particular.
PER	PER.ER.5		Have the conceptual security risks and benefits been identified?	Partial - Non Blocking	The project investigated GNSS and INS coupling and inclusion of MAC. Although the consortium did not carry a complete security risk assessment, NAVISAS' relevance to spoofing has been analyzed in D4.1.
PER	PER.ER.6		Have the conceptual environmental impacts been identified?	Not Applicable	
PER	PER.ER.7		Have the conceptual Human Performance aspects been identified?	Not Applicable	
VAL	VAL.ER.1		Are the relevant R&D needs identified and documented? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution once Exploratory	Achieved	The consortium identified the future work and recommendations for R&D in the Final Publishable Report and the proposed APNT roadmap of D5.2

			Research activities have been completed, and the definition of validation exercises and validation objectives in following maturity phases.		
TRA	TRA.ER.1		Are there recommendations proposed for completing V1 (TRL-2)?	Not Applicable	

4 Conclusion and Lessons Learned

4.1 Conclusions

NAVISAS tried to address the performance of emerging and future technologies to be used in still to-be-defined APNT concept for light aircraft and RPAS. The project studied three possible alternative navigation capabilities:

- Atomic gyros have been extensively studied by CSEM and TRL3 was achieved on this technology in the course of the project. While there is still a long way to go before a mature and affordable technology is available, the envisioned performances are promising and could challenge the state of-the-art laser ring gyros.
- Hybridization of multi-constellation and multi-frequency receivers with inertial systems based on atomic gyros was studied. No real benefit could be seen from the use of multi-frequency receivers when compared GPS L1 signal, nevertheless they are a good backup mean in case of unintentional interference on one GNSS frequency. Tightly-coupled multi-constellation navigation is expected to bring improvements, particularly for scenarios with low satellite visibility such as navigation in urban canyons. The change from conventional crystal oscillator to a miniature atomic clock (MAC) in GNSS receiver would bring numerous advantages to GNSS performance such as faster recovery from signal outages or improved robustness in spoofing detection, but at the moment there is no GNSS receiver in the market that supports external clock source and copes with NAVISAS requirements (small, low-power, affordable).
- Vision-based navigation, initially not in the scope of the project, was considered of major interest and has been added to the perimeter of the study. This technology is particularly interesting for RPAS navigation and showed good performance for light aircraft as well. Limitations of such a system have been identified.

The table below summarizes the findings of the consortium regarding the different technologies being investigated and developed within the scope of NAVISAS.

Technology	TRL	Benefits wrt currently used technologies	Limitations	Contribution to operational concepts proposed in D3.1
Atomic gyro	3	RPAS rely heavily on GNSS receivers. The loss of GNSS in manned aircraft, even in VFR, is likely to have a significant Human Factor. INS based on atomic gyros could provide coasting, assuring the RPAS platform (and hence RPAS operator) navigation capabilities. For the pilot of manned aircraft atomic gyro would provide time and comfort to revert to other navigation mean and divert to the	The limitation of the technology at the moment is its low TRL.	Atomic gyros will bring benefits to all operational scenarios defined in D3.1. In particular: - “buy time” and coasting solution when flying en-route until GNSS signals are reacquired for VFR and

		nearest airport if needed. Experiments of purely inertial performance (without using any GNSS receiver) presented in D4.1 have shown that atomic gyros will not only reach RNP accuracy requirements, but could challenge the expensive state-of-the-art laser ring gyros (2Nm/h). Probably will be smaller and lighter than current inertial systems.		IFR pilots (although IFR pilots are trained to revert to VOR/NDB beacons in case of GNSS signal loss) - Navigation capability until GNSS recovery or capability to carry out emergency procedures for RPAS - Navigation capability relying solely on INS for specific RPAS missions (short in time, for instance with time duration 1 hour)
Atomic gyros hybridized with multi-constellation GNSS	3	Main benefit coming from usage of hybridized solution will be demonstrated in scenarios with degraded satellite visibility. Multi-constellation approach and receiver coupling with INS improves signal availability and decreases signal recovery time. In the long-run, upon the GNSS loss, IMU quality will dominate the navigation accuracy and expected performances of atomic gyroscope could challenge the state-of-the-art laser ring gyros (2Nm/h).	GNSS&INS coupling techniques are used already in commercial aviation; hence the main NAVISAS limitation lies in the low TRL of the atomic gyro. Useful mainly in low satellite visibility scenarios.	GNSS hybridized with INS will have strong impact on operations in environments where GNSS availability is limited such as RPAS operations in urban canyons. Hybridization could make the satellite recovery process faster.
Miniature Atomic Clock	5-6	Small aircraft, just like other GNSS users, are vulnerable to GNSS outages or deliberate attacks on their navigation systems. In general, MAC improves the solution availability and accuracy when compared to crystal oscillator clocks. It could reduce the signal recovery time upon GNSS outage, allows clock to be coasted in critical situations of satellite visibility and provides better protection against spoofing (better spoofing detection).	At the moment, there is no GNSS receiver on the market that supports external clock source and copes with NAVISAS requirements (small, low-power, affordable).	MAC could be used to detect spoofing – this is applicable to all flight phases, all flight rules (IFR, VFR) and relevant for both manned and unmanned small aircraft.
Vision-based	2	The flight tests of the prototype have proven the usefulness of the concept,	The technology is useful only in	Vision-based navigation could be used in scenarios

Navigation		only 1 – 2 % drift was demonstrated. This is very cheap alternative navigation method when compared to any other relevant system.	VMC flights. It does not reach satisfying performance in monochromatic environment, e.g. flight above open water or clouds. Other limitations: cruise speed, flight altitude.	of RPAS manoeuvring in urban environment or flights (manned or unmanned) performed under VFR on relatively low altitudes in VMC.

Table 9: Summary on NAVISAS elements.

4.2 Technical Lessons Learned

4.2.1 Atomic gyroscope and miniature atomic clock

The driver for the future market success of an atomic gyroscope in applications for UAV and ULA will be its price. We find several technological solutions at system and subsystems levels allowing us to reduce the price of future gyroscope.

4.2.2 Navigation performance based on inertial and hybridized system

GNSS-INS coupling

Several concepts for GNSS-INS coupling were investigated and proposed. Tight coupling was identified as the approach to follow.

Multi-constellation multi-frequency receivers

The interest and limitation of stand-alone multi constellation / multi frequency receivers for A-PNT are well known and are no longer a challenge.

Purely inertial navigation

Although the performance levels of atomic gyros may reach the ones from current laser gyros, a lot remains to do to mature this technology and embed it into a certified operational inertial system.

4.2.3 Vision-based navigation

Vision based navigation is a promising emerging technology that will probably become a standard for UAV in the coming years. Although its interest for light aircraft is not clear at the moment it could become a low cost VMC navigation backup if GNSS outages become more and more frequent.

4.3 Recommendations for future R&D activities (Next steps)

Future activities should allow reaching the TRL4 of atomic gyroscope. A miniaturized design of the gyroscope system shall be achieved to allow for direct measurements of the gyro sensitivity to rotations. The dedicated control loop electronics shall be built, the bandwidth and SNR shall be measured to refine the gyro model and targeted gyro specifications.

Regarding, technologies hybridization, it has been shown that hybridization with dual frequency doesn't bring significant advantage compared to current GPS single frequency hybridizations. Further tests on tight coupling of GNSS and INS in adverse scenarios such as urban canyons are recommended.

At the moment there is no GNSS receiver on the market that supports external clock source and copes with NAVISAS requirements (small, low-power, affordable). As spoofing is a problem affecting all kinds of transportation systems, it would be interesting to pursue the concept of atomic clock powering GNSS as potential improvement to spoofing detection methods.

Flight tests conducted in the scope of the project provided a Proof-of-concept. Future work should aim at improving and optimising the image processing algorithms in order to provide a more accurate position while reducing the required CPU power. In next steps possible system architectures should be defined, several trade-offs (cost vs sensor grade; CPU load vs performance; performance in different flight conditions) and integrity of the solution needs to be investigated (safety analysis, sensor performance degradation due to meteorological conditions and others). Hybridization of the camera with other sensors is in an interesting idea as well.

Results achieved in the project paved the way to definition of A-PNT for small aircraft and project participants will seek for further development opportunities of NAVISAS technologies (presented in Table 9). End-users participating in the project expressed interested in this technologies, hence the consortium seeks for new financing opportunities enabling the operational validation of NAVISAS.

5 References

5.1 Project Deliverables

D2.1 D2.1 NAVISAS Requirements Document

D3.1 D3.1 Building Blocks for Small Aircraft APNT

D4.1 D4.1 NAVISAS APNT Concept

5.2 Project Publications

Boiko16 D.L. Boiko, *"Dual-Frequency (DF) Spin-Polarized Pumping"*, in Proc. of 30th European Frequency and Time Forum EFTF 2016, April 2016, York, UK (available: https://www.researchgate.net/publication/320402735_Dual_Frequency_Spin-Polarized_Pumping)

Karlen17 S. Karlen, G. Buchs, T. Overstolz, N. Torcheboeuf, E. Onillon, J. Haesler, D. Boiko, *"MEMS atomic vapor cells for gyroscope applications"*, in Proc. of 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC), July 2017, Besancon, France.

Buchs17 G. Buchs, S. Karlen, T. Overstolz, N. Torcheboeuf, E. Onillon, J. Haesler, D. Boiko, *„Nuclear spin decoherence time in MEMS atomic vapor cells for applications in quantum technologies"*, in Proc. of the Fourth International Conference on Quantum Technologies 2017, July 2017, Moscow, Russia.

5.3 Other

ICAO17 ICAO, Remotely Piloted Aircraft system (RPAS) Concept of Operations (CONOPS) for International IFR Operations, 2017.

SESAR17 SESAR JU, European ATM Master Plan: Roadmap for the safe integration of drones into all classes of airspace, 2017.

Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition
High-grade gyroscope	representative to the lower end of today-available airborne navigation-grade gyros and of the lower end of expected performances of the MAG	**D5.1**
Vey high-grade gyroscope	representative to the very upper end of today-available airborne navigation-grade gyros and of the upper end of expected performances of the MAG	**D5.1**

Table 10: Glossary

A.2 Acronyms and Terminology

Term	Definition
ATM	Air Traffic Management
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
MAC	Miniature Atomic Clock
MAG	Miniature Atomic Gyroscope
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SNR	Signal-to-Noise
SoA	State-of-the-Art
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WBS	Work Breakdown Structure

WP	Work Package

Table 11: Acronyms and technology