Satellite-Unmanned Airborne Systems cooperative approaches for the improvement of all-weather day and night operations

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Executive Summary

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Abstract

The feasibility study of a novel navigation system for Unmanned Airborne System (UAS) based on bistatic Synthetic Aperture Radar (SAR) is presented. The innovative bistatic configuration builds on spaceborne radar transmitters and airborne receivers, the latter mounted in a forward-looking geometry. Such approach, impossible or extremely demanding with a monostatic approach, allows one to achieve dual information with two different radar working modes: imaging capability can be in fact coupled with the possibility of moving target indication. The study is particularly suited on one of the most common UAS platforms: a close range, medium takeoff weight, with an endurance of roughly 7 hours and cruise speed of about 50m/s, whose requirements have been identified. The feasibility analysis is conducted through a very detailed performance analysis, a wide state-of-the-art research, and the identification of the key technological issues. The possibility to re-use, also partially, existing or under development systems has been considered from the point of view of the constellation (LEO/MEO), the radar transmitter (SAR, TELECOM, GNSS), and radar receiver. The finalization of the study is achieved by the definition of a strawman system concept with different approaches. Four options are identified, with different performance and system complications/challenges. A newly ad-hoc developed option have been introduced, based on a MEO constellation with more than 40 satellites all equipped with a radar able to radiate 2-3kW on small multiple beams, in order to have a term of reference for the other two less demanding systems, which are all based on the use with (medium to low) modifications of GALILEO constellation/satellites. A fourth option has been also introduced to propose a validation experimental campaign which can be based on existing SAR satellites and existing, but modified to introduce a forward looking geometry, airborne SARs.

Introduction

Navigation of Unmanned Airborne Systems (UAS) is mainly performed with satellite navigation systems (e.g. GPS, Galileo). They offer accurate and reliable navigation data in terms of UAS position and velocity, but no information about the surrounding environment. This limitation could be in principle overcome by using on board recorded information about the areas along the route (e.g. digital elevation models, classification maps, etc.). Besides the impact on the mass memory and on-board computer of the UAS, it must be noted that this approach is not suitable when flying over unknown or partially known areas. In addition, this approach does not offer any capability in the case of scenario modification, which could be severe in low altitude flight phases (e.g. approach and landing or terrain following).

As a consequence, a vision-based navigation system can greatly improve UAS autonomy with an additional beneficial impact on obstacle avoidance capability. In order to be applicable in all possible UAS missions and flight phases, such system must be capable of working in both day and night conditions, independently from weather conditions, thus calling for microwave instruments. Synthetic Aperture Radars offer great capabilities and have been already experienced on-board aircrafts of different classes. Nevertheless, such sensors have been only used as experimental remote sensing payloads in side-looking geometry. For navigation purposes a forward looking geometry is preferable, but it has been rarely experienced due to major limitations (imaging geometry) which can by only partially mitigated at the cost of strong complexities. Bistatic Synthetic Aperture Radar, i.e. a radar system where the radar transmitter is separated by the receiver, have beneficial effect on an imaging radar for navigation purposes. First of all, forward-looking geometric limitations are overcome thanks to the different paths of electromagnetic waves in transmission and reception. In addition, if the transmitter is no longer on board the aircraft, the airborne receiver can be much more compact and lightweight, with a reduced power request.

In the following, a navigation system based on bistatic SARs relying on spaceborne transmitters and airborne receivers is comprehensively analyzed to obtain a preliminary feasibility assessment and a first overall figure. In particular, the first part of the study consists in the study and identification of requirements. Then, the system feasibility study is carried out by first assessing the state-of-the-art for the different technologies and then by analyzing the performance and identifying the key technical issues. Finally, the study was finalized and synthesized in the definition of four strawman system and operation concepts with an analysis of their capability to fulfill the identified requirements. An analysis of the possibility of using the system for natural disasters monitoring and with a HALE UAS as a transmitter platform closes the study.

The study herein described was carried out under ESA contract 22449/09/F/MOS “Satellite-unmanned airborne systems cooperative approaches for the improvement of all-weather day and night operations”.

Requirement Analysis

UASs can be categorized in different ways. The most common classification is based on the type of mission, i.e. tactical, combat or strategic. Other common classifications refer to altitude/endurance/range and maximum take-off weight (MTOW). Further minor UASs classifications can be based on the type of propulsion, number of engines, type of lift system (fixed wing or rotor) and so on. If the possibility of a feasible future technological demonstration is in high priority, a close range, MTOW Class 1 vehicle is the best choice for case studies. Many UASs of this class are available and are used for reconnaissance, surveillance, target acquisition. Vehicle selection also establishes a set of missions that it is able to perform. Main characteristics of the reference UAS are: altitude <5000m; MTOW<500kg; endurance7 hours; range 60km; max velocity 70m/s; cruise velocity 52m/s. A typical flight profile for such vehicle accounts for:

- Take-off starts on the runway and includes climb-out to initial climb altitude. It may also include (depending on GNC strategy) the initial maneuver to align with the first leg of the flight plan.
- Climb starts with the transient maneuver to achieve steady rate of climb and includes the transition to level flight. It may include alignment to the first leg of the flight plan (if not included in take-off).
- Mission Maneuvering/Execution can be required to achieve mission objectives (e.g. keep a sensor in the proper direction or to follow objects on air/on ground).
- Descent, similar to climb phase, consists of a transition to steady descent rate and to level flight.
- Approach: the aircraft follows the given standard terminal arrival route to the initial approach fix and proceeds from there to the alignment of the respective runway.
- Holding: aircrafts fly in a holding pattern (racetrack), stacked on top of each other, to provide altitude separation when the traffic flow exceeds the airport capacity.
- Diversion: if the conditions at landing location airport are not satisfactory, for safety reasons a diversion to a different land site can be executed.
- Landing, the final phase starting when the vehicle intercept the right glide slope, includes touchdown, rollout, and braking to taxiing speed.

Depending on mission and UASs capabilities, mission phases can be totally or partially automated with complexities of relevant GNC algorithms depending on the a-priori knowledge of the operational environment. Such automation may typically require some operative needs, such as:

1. Sense and avoid allows a safe cooperated (or non-cooperated) flight with the other scenario participants. Sensors used are classical inertial sensors (with/without GPS) and radars.
2. Navigation aid in case of in totally or partially obscured communication can be useful in applications such as recognition & surveillance, information collection, etc. In any case such technology would improve mission safety and fault tolerance levels.
3. On air or on ground target tracking is particularly useful during Mission Maneuvering/Execution. Sensors used are infrared/optical imaging sensors and tracking radars with limitations arising depending on weather conditions, stealth targets, etc.
4. Identification of landing site and of ground obstacles. Automatic landing capability has already been demonstrated. For civilian UASs, landing on instrumented runways is performed by using the classical localizer and glide slope signals, as well as GPS and optical sensors. Military scenarios can instead evolve in a partially or totally unknown environment. Furthermore, such capability would become critical on not instrumented runways.

An alternative technology overcoming main limitations of currently used systems can be implemented using a Bistatic Synthetic Aperture Radar system that illuminates the target (the intruder for the sensing and avoid, the area in front of the UAS itself for the GPS-less navigation, an on ground or on air target to follow, and the landing site where the UAS decides to land). The analysis of needed functionalities and requirements has been performed (Tab. 1) and the results utilized to derive the impact on the functionalities of the bistatic radar system (Tab. 2). R (target range), ϑ (elevation) and ψ (azimuth) are defined in a UAS-fixed reference frame. For the variables reported in Tab. 2 refer to Fig. 1.

	Application	**SAR BASED Sensor Preliminary Requirements**			
		FOV / Image size	Resolution / Accuracy	Minimun Update Frequency	Maximum Latency Time
MTI Mode	On Air Target Detection	R: 500ft..5Nmi θ: [-10..10]deg Ψ: [-60..60]deg	R, θ, Ψ: [10m, 1.3deg, 1.4deg] $\dot{R}$, $\dot{\theta}$, $\dot{\psi}$: [3m/s, 0.2deg/s, 0.2deg/s]	10Hz (target) 1Hz (acceptable)	0.1s (target) 0.5s (Acceptable)
	On Ground Target Detection	R>3.8Nmi θ: [-15..15]deg Ψ: [-60..60]deg		0.3Hz	0.1s
Image Mode	Map based Navigation	Minimum distance from UAV: Don't Care Size: as large as possible	Landing: Horiz. 1m Mid-Air Horiz. 10m, Vert. 15m	1Hz (landing) 10min (mid-air)	0.1s (landing) 5min (mid-air)
	On Ground Obstacle and Runway Detection	(runway always in view) R: 0..3.8km Θ, Ψ: ±20deg	Resolutions: Transversal to UAV motion: 2m Direction of motion: 10m Obstacle size: 80cm	One shot is acceptable. Target : more than one shot	Latency shall be accurately known
	3D Synthetic Vision for RPV	(runway always in view) R: 0..3km Θ : ±40deg Ψ: ±50deg	Horiz. Accuracy Landing: 1m Mid-Air: 10m	10Hz	0.1s (normal) 0.3s (degraded)

Table 1 Summary of SAR Sensor Required Performance.

Tracking Mode	<u>Detection Range and Resolution</u>	<u>Observation Geometry and Clutter</u>	<u>Timing & Synchronization</u>
	1. Detection Range defined by SNR Processing Gain 2. Range resolution depending on system bandwidth and bistatic angle 3. Doppler resolution depends on coherent integration time and bistatic angle 4. Angle discrimination achieved by phase interferometry of echoes received on two separated channels	1. Forbidden Geometry – Target on the baseline – Target moving on the bisector of bistatic angle 2. Relative Geometries leading to poor resolutions to avoid 3. For AMTI, ground clutter limited by antenna pattern and Doppler frequency diversity 4. For GMTI, ground clutter limited by relative space-airborne configurations	1. Bistatic receiver shall be provided with: – Instant of transmission of pulse – Transmitted signal phase
Imaging Mode	<u>Resolution</u>	<u>Observation Geometry</u>	<u>Timing & Synchronization</u>
	1. Geometric Resolution defined by: – Pixel area – Ω-angle 2. Resolution Requirements: – Ω : [30, 150] deg – NESZ : [-30, -20] dB - TBC – γ : [0.5, 3.5] dB - TBC	1. Requirements: – Θ_{Tx} : [0, 60] deg – Θ_{Rx} : [40, 75] deg – Φ: [0, 360] deg 2. Forbidden Geometry – $\Theta_{Tx} = \Theta_{Rx}$ & $\Phi = 180°$ 3. Relative Geometries leading to poor resolutions to avoid	1. Bistatic receiver shall be provided with: – Instant of transmission of pulse – Transmitted signal phase 2. Constant offset of carrier frequency shall be removed from the received signal

Table 2 Bistatic radar preliminary requirements.

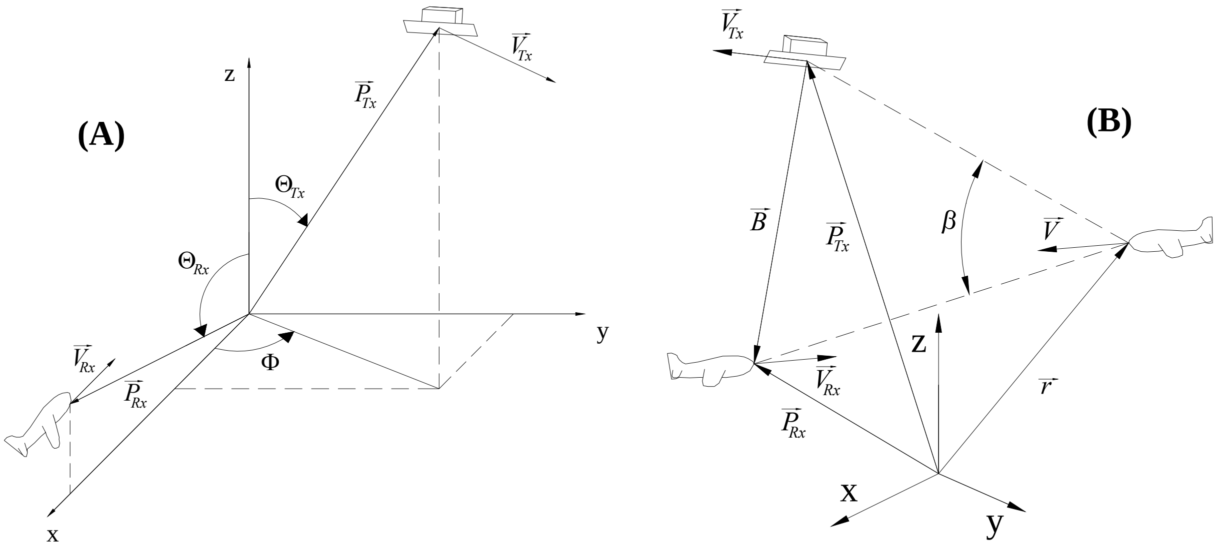

Figure 1 Bistatic SAR observation geometry in imaging (A) and MTI (B) modes.

Feasibility Study

State-of-the-art

Existing airborne SARs cover the whole radar spectrum from P-band to W-band. In addition, multi-frequency, multi or full polarization capabilities are widespread with some documented interferometric capabilities. Thus, the experience on these sensors is well assessed, at least in Tx/Rx working modes. The only forward looking system is SIREV which utilizes a multi antenna system to achieve the synthetic antenna. Apart from PAMIR, which has GMTI capabilities (but in such case it does not work as a SAR), airborne SARs have never been developed or utilized for aiding or supporting aircraft navigation. As a consequence, such “remote sensing-oriented” sensors lack in some peculiarities helpful in air navigation: (a) real-time SAR processing in high resolution is very limited; (b) only a few systems are designed for a compact and lightweight envelope (but they do not include the processing hardware).

From the point of view of existing or planned spaceborne SARs, they all orbit in sunsynchronous low earth orbits, with most of them being down dusk (6am-6pm ascending-descending node local time). The typical mass of modern SAR satellites, with no other heavy or large power consuming payloads, is approximately in the range 1-2 tons with a mission lifetime designed at 5 years. Carrier frequencies range from X-band (high resolution) to L-band (wide area). Transmitted peak power varies from 1 to 5 kW and system bandwidth of the order of 100 MHz or higher. Most of the present generation SAR systems are able to implement ScanSAR and spotlight modes, thus being able to steer the antenna main lobe both in elevation and in azimuth and to tune the PRF to sample different Doppler bandwidths.

With reference to bistatic SAR experiments with SAR illuminators, they have been performed or planned in side-looking geometry with parallel tracks. Such demonstrative experiments have shown that spaceborne SAR orbital dynamics poses severe limitations: very short acquisition time spans (a few seconds) and very limited imaged area (a few tens of kilometers). Synchronization between Tx and Rx have been solved by either (a) continuous signal reception and filtering during processing or (b) receipt of direct signal for Rx PRF set up. If on the one hand bistatic SAR experiments using non-SAR (telecom or GNSS) satellites have shown that continuous multiple coverage simplifies the identification of a good bistatic couple, on the other hand Tx signal limitations (transmitted power and bandwidth) strongly limit achievable resolutions.

Finally, the analysis of existing or firmly planned constellations has shown that SAR constellations integrate a very limited number of satellites (a few: 2-5) flying in LEO equipped with payloads with a limited beam-width (a few degrees) but capable of steering the beam within a much wider angular range (tens of degrees). Navigation constellations integrate tens of satellites in MEO and with payloads transmitting within a very wide angular span. In addition, some of the TELECOM constellations integrate tens of satellites in LEO.

System performance

The adoption of a spacecraft constellation for providing future UASs with real-time, all-weather all-time, high-resolution forward-looking imaging capability for supporting autonomous navigation has been analyzed. The derived analytical tools show that the main limitations of monostatic forward-looking operation due to range/Doppler ambiguity can be overcome provided that specific requirements on the acquisition geometry are satisfied. For LEO transmitters greater and more complex constraints are established on allowed relative configurations, that is for any given illuminator position only a limited range of velocity are allowed. On the contrary, for GEO/MEO illuminators performance depends solely on position. Figure 2 shows this different behavior, whereas the effect of transmitter-target-receiver relative geometry on range/Doppler directions is highlighted in Fig. 3.

On the basis of these considerations it is possible to state that for keeping low the number of illuminators and for simplifying the design of a constellation of satellite illuminators, MEO altitude could be a good choice, since no constraints are established on the orientation of the illuminator velocity. In such a case, satisfactory observation geometries can be resumed as follows:

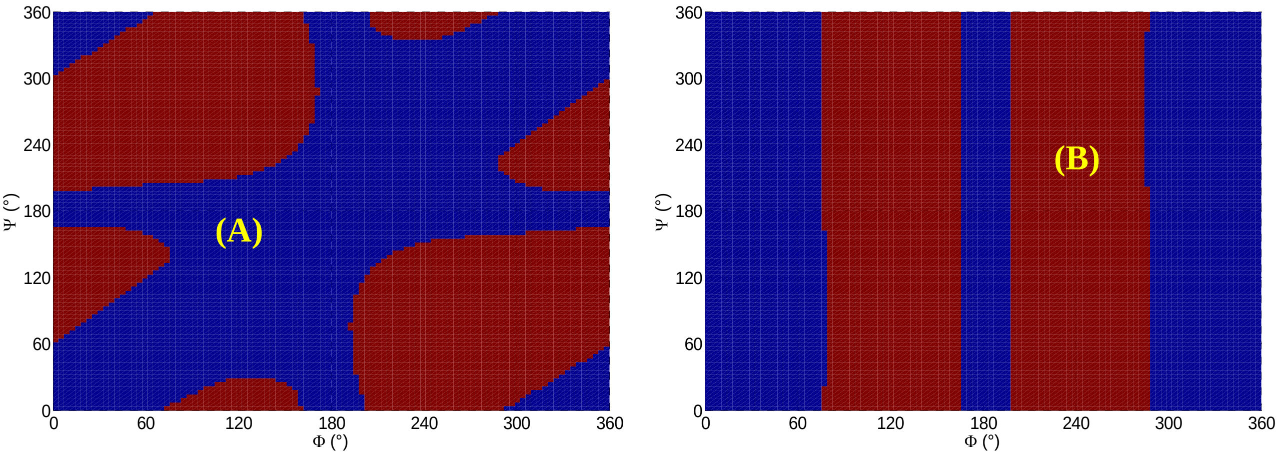

Figure 2 Allowed illuminator position and velocity (red) for an airborne receiver and LEO (A) or MEO (B) illuminators (assumed performance: 4 m^2 pixel area and 30° <Ω< 150°)

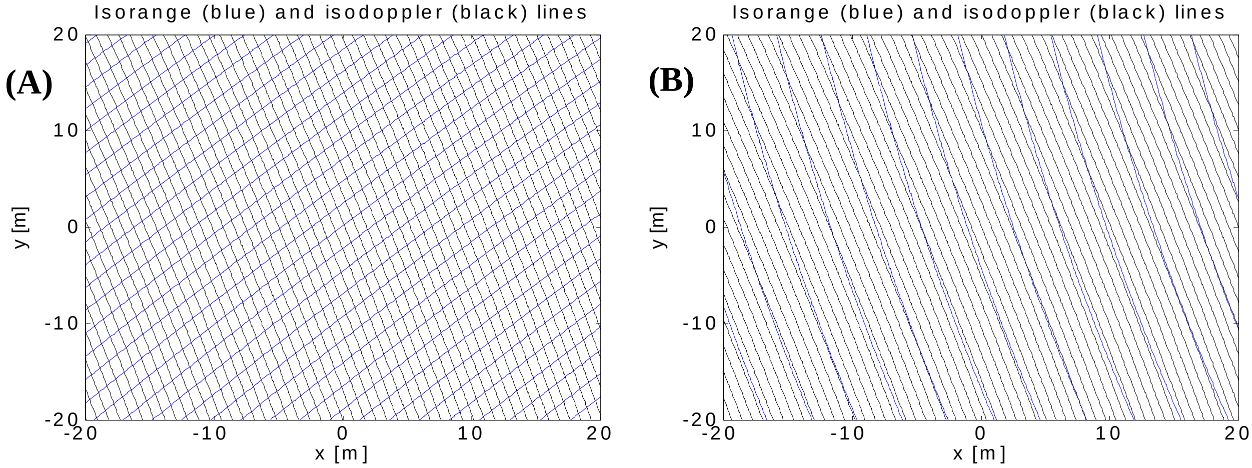

Figure 3 Performance of good (A) and poor (B) observation geometries. In the first (latter) case, transmitter out-of-plane angle is 220° (160°), velocity out-of-plane angle is 100° (90°), ground range and Doppler resolutions are 1.6m (3.5m) and 0.8m (0.75m), Ω is 105° (177°), pixel area is 1.5 m^2 (52m^2).

- Imaging mode – transmitter incidence angle ranging from 25 to 55 degrees, and transmitter out-of-plane angle ranging from 90 to 150 degrees or from 210 to 270 degrees.
- Tracking mode – transmitter incidence angle lower than 60 degrees.

As regards non-dedicated systems, navigation constellations offer global, continuous, multiple coverage whereas remote sensing constellations only offers strict repetitivity capabilities: i.e. the possibility to fly over the same Earth location at regular time interval, often at the same local time. In addition, TELECOM constellations offer zonal or global, continuous, single coverage. From this point of view, SAR constellations can be characterized by time interval between successive observations of the same Earth target also accounting for beam steering capabilities. The best result can be obtained by synergic use of COSMO/SkyMed, SAOCOM, and Sentinel-1 satellites (all flying on down-dusk orbits), which leads to an estimated mean revisit time of 10 hours (Fig. 4). A reduction of such time to about 7 hours could be obtained only by placing additional satellites with a different ascending node local time (noon-midnight orbits), which is unfortunately not foreseen in the next years. Existing SAR satellites can be considered very interesting to carry out proof of concept experiments of all the analyzed bistatic acquisition options since they can allow the bistatic radar to achieve very good geometric and radiometric resolutions, but only for very short time spans, a few seconds at most, and only if specific relative acquisition geometries are established. On the contrary the radar performance achievable by existing non-SAR illuminator is poor because of the limited transmitted signal power level and the bandwidth.

Referring to newly designed constellations, high altitudes allows for a reduction of required transmitters. Two design cases have been considered at roughly 10000km and 20000km altitude. For the first altitude the best result is offered by the Walker constellation 34/17/12 at an inclination of 66° and an altitude of 10554km, whereas Walker constellation 8/2/1 gives the best result at an altitude of 20200 km and an inclination of 47° (Fig. 5). When satellite position limitations for radar imaging mode are taken into account, we get an estimation on the number of satellites which is larger than 170 (10000km) and 40 (20000km).

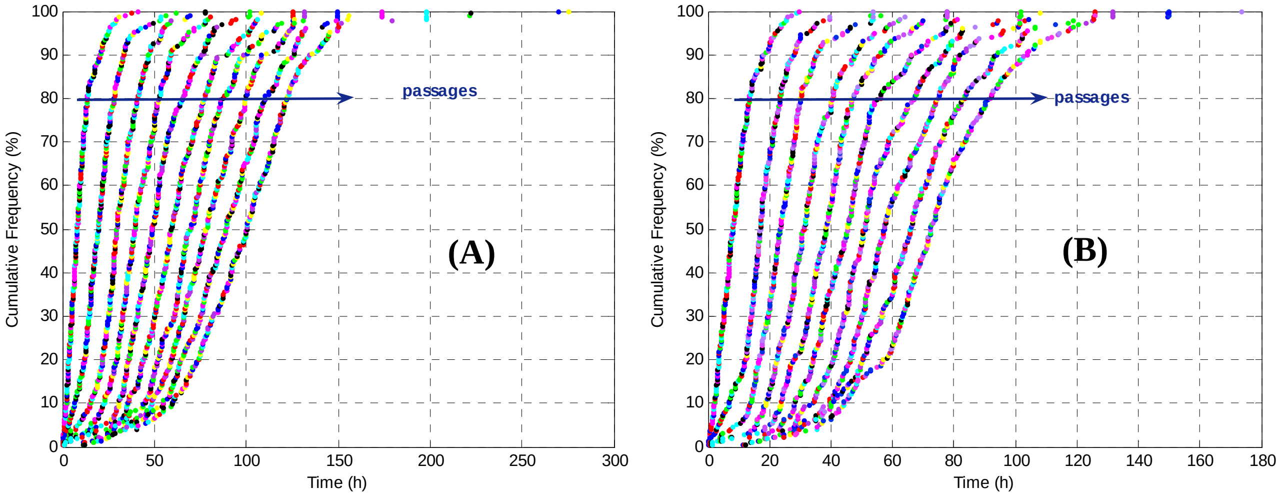

Figure 4 Observation time statics for SAR constellations: synergic use of SIASGE and Sentinel-1 (A) with 4 additional satellites with 90° shift in ascending node right ascension (B).

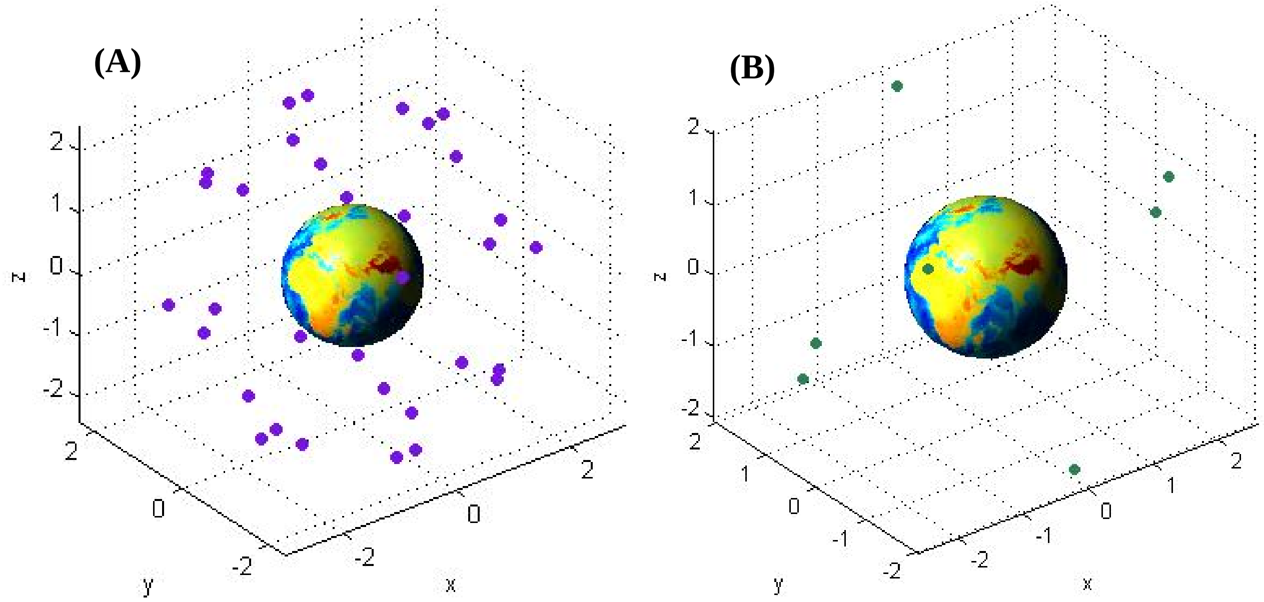

Figure 5 Constellation design results at an altitude of 10554km, Walker pattern 34/17/12 (A), and at an altitude of 20200km, Walker pattern 8/2/1 (B).

Technical Issues

Dedicated satellite constellation

A MEO constellation seems the best choice to keep low the number of satellite illuminators and to simplify constellation design. Indeed, if the orbital altitude is higher than 10000-15000 km geometric resolution in imaging mode will only depend on illuminator position with no effect of illuminator velocity. The achieved performance can be satisfactory, but the following key technical issues still remain:

- High transmitted peak power (>2kW) and large transmitting antenna dimension (5-18m diameter) to achieve: (a) good SNR in imaging mode; (b) required detection range in tracking mode; (c) concentration of transmitted energy on one/few small spots (50-250 km diameter).
- New constellation of satellites (>40) to guarantee: (a) continuous global coverage; (b) relative positioning requirements to fully enable MTI and imaging modes.

With reference to the exploitation of existing system, the best choice is GNSS constellation although upgrades are likely requested from the payload point of view (see above).
Synchronization issue must certainly be tackled. In case of performed experiments (side-looking geometry), the issue was solved by using the direct signal, from the transmitter to the receiver, together with critical status information about the location and condition of the transmitter. This means that if the airborne receiver is provided with an adequate heterodyne channel, synchronization has not to be considered a key issue for the hybrid space-airborne bistatic forward-looking SAR. For proof of concept experiments continuous sampling can be performed by the receiving chain, thus simplifying HW/SW to be embarked.
Computing effort onboard UAS must be also considered. Real-time processing onboard UAS is needed to make use of bistatic data for aiding UAS navigation. By making explicit assumptions on the collection geometry and the nature of the collected phase history data, monostatic SAR system can use fast algorithms (polar format, range migration, chirp scaling). Bistatic SARs, in contrast, have experienced much less development with back projection algorithm or matched filtering. The latter one is well suited for image formation, as it works as a maximum likelihood estimator for the reflectivity of scatterers in the scene and therefore can be selected as a reference to measure the needed real-time computational expense. Matched filtering is characterized by $O(N^4)$ time complexity (N^2= number of pixels), i.e. $O(10^7)$ time complexity is achieved for 100 m x 100 m image and 4 m^2 pixel area.

Strawman System Analysis

Strawman system identification

On the basis of previous analysis, four strawman system configurations, characterized by different performance levels and complexities, can be envisaged:

Configuration #1: a full-operational system concept based on a dedicated satellite constellation integrating more than 40 satellites needed to guarantee continuous global illumination. Each satellite embarks an X-band transmitter able to work with large signal bandwidth (up to 400 MHz), power level (up to 2-3 kW) and antenna dimension (5-10 m diameter). The airborne receiver can rely on a compact, small receiving antenna (0.1-0.2 m^2 area) that can work with short integration times both in imaging mode and in tracking mode.

Configuration #2: Galileo constellation is the starting point to define the satellite illumination system. The illuminator is an L-Band system working with a carrier wavelength of 0.252 m from a satellite altitude of 23222 km. The remaining illuminator parameters are selected so that the following conflicting requirements can be fulfilled: (a) limited impact on Galileo platform (power consumption, antenna dimension, signal bandwidth, etc.); (b) proper performance achieved in imaging and in tracking mode.

Configuration #3: Galileo system is considered as illuminating constellation and the lowest level of modification, namely the exploitation of an additional transmitting antenna, is envisaged to improve the achievable performance both imaging mode and in tracking mode. 50 MHz signal bandwidth is considered for this system as achievable by the jointly exploitation of nominal E5a and E5b bands respectively.

Configuration #4 The last configuration is an outline for a series of proof of concept experiments. The best illuminating system in this case is an existing SAR satellite: the present generation spaceborne SAR system will be considered in the following because of its capability of large bandwidth, high power signals.

In the case of GALILEO system some considerations are required with reference to capability of fulfilling geometric constrains on transmitter-target-receiver area. In fact, for existing or already planned constellation, satellite distribution requirements are different from the ones arose from this study. Thus, a verification strategy has been assessed as follows:

- Definition of a number of target areas.
- Simulation of existing constellation in time.
- Definition of satellites coordinates in the topocentric reference frame of target areas (function of time).
- Verification of MTI capabilities for all target areas: available if at least one satellite meets the minimum elevation angle requirement (El>30°). Availability of MTI function as a function of time.
- Verification of imaging capabilities for all target areas: (a) definition of satellites meeting the elevation angle requirement (30°<El<65°); (b) depending on the satellite azimuth angles, identification of each satellite "bistatic coverage" as the two 60°-wide (in azimuth) "slices" with one border on the direction perpendicular to the satellite-target area projection in xy plane of the topocentric reference frame; (c) determination of the overall bistatic coverage merging all satellite "bistatic coverage" and identification of the percentage imaging service as the ratio between the overall covered azimuth intervals and 360° (i.e. percentage of routes to target area which are covered with imaging capabilities).
- Derivation of statistics on service availability (geometry-only) for both MTI & IMG

Targets area have been selected over Europe (Fig. 6): 24 areas from 37°N to 52°N and from 6°W to 19°E with a 5° step in both latitude and longitude. Then, a GALILEO simulator software has been developed, which propagates GALILEO satellites positions in the Geocentric Inertial Reference Frame (GIFR) and accordingly rotates the Earth-Fixed Reference Frame (EFRF). Then, for each target area the Topocentric Reference Frame (TRF) is defined and rotation matrix (GIRF to TRF) determined. Thus, at any time positions of all GALILEO satellites can be referred to the EFRF and elevation and azimuth coordinates can be consequently determined. Finally, the simulation software verifies for each satellite and for each time step if the geometric requirements in terms of elevation angle are met for both the imaging and the MTI radar working modes. Thus, it is possible to identify as a function of time the number of satellites above horizon, the number of satellites which meet the MTI elevation requirement and the number of satellites which meet the imaging elevation requirement. A simulation has been run for two GALILEO orbit period.

Considering simulations over all target areas, it can be stated that for all targets MTI capabilities is verified at anytime, with the additional advantage to have more than 1 satellite (at least 6 satellites) in a useful geometry which allows for selection of the one which offer better performance. On the contrary, although imaging capabilities is guaranteed for any target and any time, the number of useful satellites is not so large (>2) and their azimuth angles must be analyzed to verify how the “enabled regions” combine. A limitation can be foreseen for any region and at any time (slowly variable with time) from the routes which can be covered with imaging service capabilities.

To the end of roughly quantifying such performance, an additional analysis has been carried out. For any target and at any time, all satellites meeting the imaging elevation requirement have been selected and their azimuth angle recorded. On the basis of such angles, the enabled region of each satellites have been identified and then merged to determine the overall azimuth range where imaging service is offered, which is then quantified in percentage of the overall 360°-wide azimuth range. For the sake of brevity, results at 14°E longitude are only reported (Fig. 7A): data show that an oscillation exists in time, related to satellite orbital motion, and that latitude and longitude do not sensibly affect the attained performance (taken into account the limited variation of geographic coordinates considered in the study, i.e. central Europe).

In order to have a better and more synthetic interpretation of the results, for each target the mean value and the standard deviation of the imaging service capability have been derived (averaging over time). The variability of the mean value (Fig. 7B) (standard deviation) with geographic coordinates is limited to 5% (3%) around approximately 78.5% (9.5%). Different statistics have been then obtained at any time by averaging over all the targets (Fig. 8) which show that the mean value oscillates around approximately 80%. In conclusion:

- MTI capability is guaranteed at any time for any target with multiple satellites (at least 6);
- image capability is guaranteed at any time for any target over 78.6% of the routes towards any target.

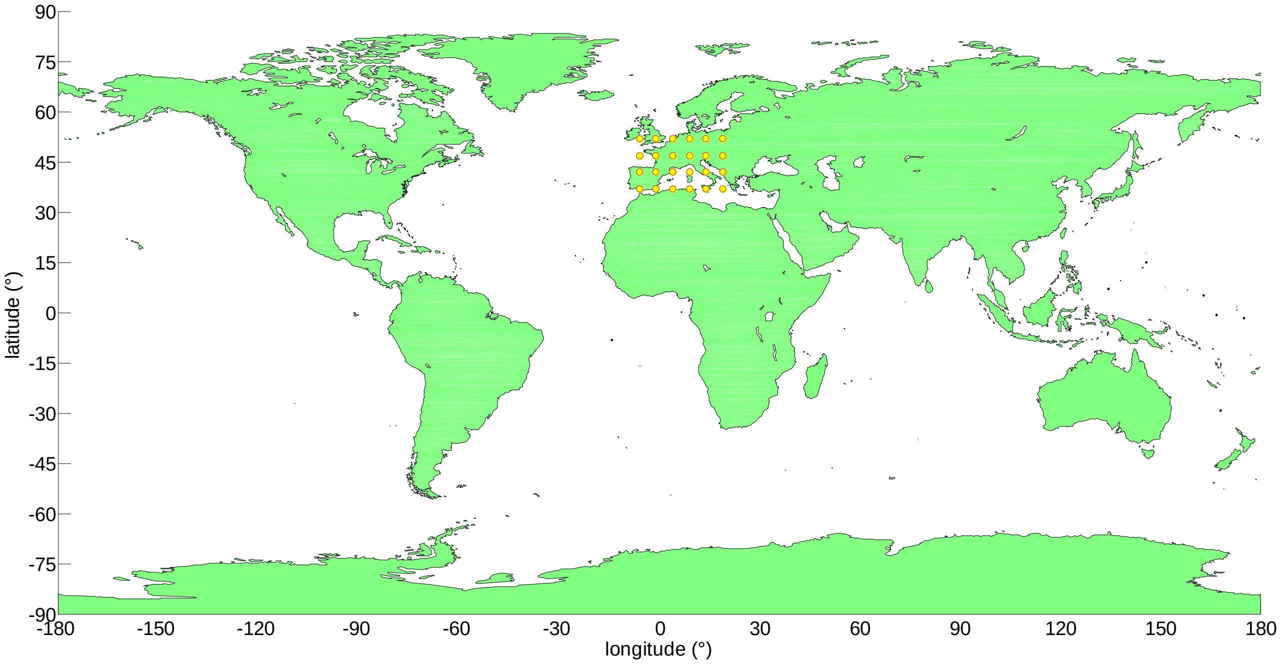

Figure 6 Selected target areas for analysis of GALILEO potential.

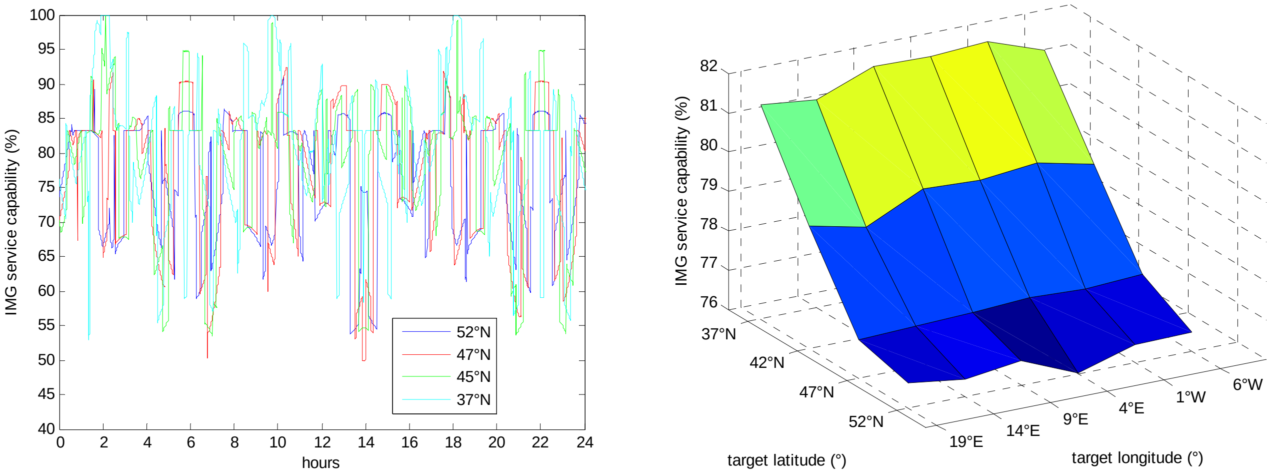

Figure 7 GALILEO IMG capability over 1 day for the targets at 14°E longitude (A) and for different target areas (B, mean value over 24h).

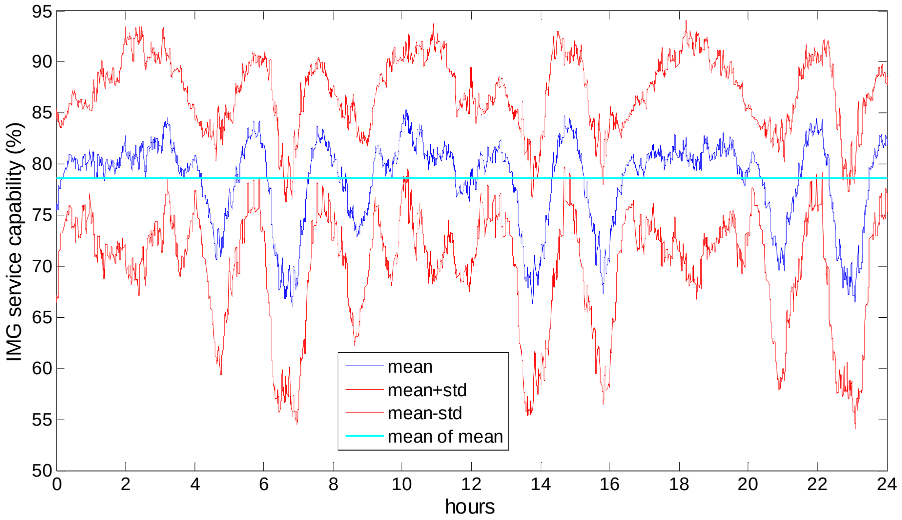

Figure 5.38 GALILEO average IMG capability over all target areas and over time.

Finally, strawman system parameters have been derived for configurations #1-#3 for both receiver (Tab. 3) and transmitter (Tab. 4). X-band systems enables a reduction of receiving antenna dimension, but fixed-pointed receiving antenna is too narrow to be compatible with sense-and-avoid FOV requirements. Therefore, receiving antenna is supposed to steer its beam both in azimuth and in elevation when in tracking mode. However, as in X-band shorter integration times (up to a factor 10) are needed than in L-band, a limited update frequency degradation is expected.

Achieved performance for tracking (Tab. 5) and imaging (Tab. 6) modes are derived. The update frequency for all configurations and modes is limited by the coherent integration time, and, for X-band systems, by the need to steer the receiving antenna beam for widening the instantaneous file-of-view when working in tracking mode. It should be noted that update frequency in IMG mode refers to the possibility to get a new data set, partially overlapped to the previous one if required or convenient, but not to the update of the same data set. Hence, reported minimum values refer to the possibility to get a new data set adjacent to the previous one. The expected maximum latency time, instead, is mainly depended on the necessity to process the received raw data signals to generate a product that can be utilized for UAS navigation.

	Configuration #1	**Configuration #2**	**Configuration #3**
Altitude	up to 3000m		
Velocity	up to 100 m/s		
Antenna dimension	0.5 m x 0.25 m (1)	1 m x 0.5 m (1)	1 m x 0.5 m (1)
Antenna Pointing	– fixed in imaging mode – steered in tracking mode	fixed	fixed
Reception Scheme	Continuous sampling		
Direct signal antenna dimension	< 0.01 m^2		
Quantization level (I/Q)	8+8 bits	from 5+5 to 8+8 bits	from 5+5 to 8+8 bits

(1) two receiving antennas are needed for interferometric angle determination when working in tracking mode

Table 3 Receiver parameters for each selected system configuration.

	Configuration #1	**Configuration #2**	**Configuration #3**
Altitude	> 15000 km	23222 km	23222 km
Velocity	< 4 km /s	< 3 km/s	< 3 km/s
Number of satellites	> 40	27	27
Number of additional satellites wrt to the existing/planned ones	> 40	0	0
Antenna dimension (diameter)	5 m	10 m	2 m
Transmitted Power	2-3 kW	2 kW	50 W
Radar Wavelength	X-Band	L-Band	L-Band
Radar Bandwidth	400 MHz	250 MHz	50 MHz
Radar duty cycle	0.25	0.25	1
Area covered by a single spot beam	100-200 km	2500 km	6000 km
Number of simultaneous spot beams	6-8	2-4	1

Table 4 Transmitter constellation parameters for each selected system configuration.

	Configuration #1	**Configuration #2**	**Configuration #3**
FOV	$R \le \begin{cases} 4.5\,km & \sigma^b = 0.1 m^2 \\ 14\,km & \sigma^b = 1 m^2 \\ > 30\,km & \sigma^b = 10 m^2 \end{cases}$ $\theta \in [-6°,6°]$ $\Psi \in [-14°, 14°]$	$R \le \begin{cases} 1.2\,km & \sigma^b = 0.1 m^2 \\ 3.6\,km & \sigma^b = 1 m^2 \\ 11\,km & \sigma^b = 10 m^2 \end{cases}$ $\theta \in [-7°,7°]$ $\Psi \in [-14°, 14°]$	$R \le \begin{cases} 500\,m & \sigma^b = 0.1 m^2 \\ 1.5\,km & \sigma^b = 1 m^2 \\ 4.5\,km & \sigma^b = 10 m^2 \end{cases}$ $\theta \in [-7°,7°]$ $\Psi \in [-14°, 14°]$
Resolution	$range\ res. < 2.5\,m$ $velocity\ res. < 1\ {}^{m}/_{s}$ $angle\ res. = 0.2°$	$range\ res. < 7\,m$ $velocity\ res. < 1.5\,{}^{m}/_{s}$ $angle\ res. = 0.8°$	$range\ res. < 30\,m$ $velocity\ res. < 1.5\,{}^{m}/_{s}$ $angle\ res. = 0.8°$
Minimum Update frequency	1 Hz	1 Hz	1 Hz
Maximum Latency Time	0.1 s	0.1 s	0.1 s
Service Type	on demand	on demand	on demand
Coverage	anytime/anywhere	anytime/anywhere	anytime/anywhere

Table 5 Expected tracking mode performance.

	Configuration #1	**Configuration #2**	**Configuration #3**
Image size (cross-track x along-track)	$low\ alt.\quad 60m \times 155m$ $medium\ alt.\quad 122m \times 170m$ $high\ alt.\quad 370m \times 330m$	$low\ alt.\quad 600m \times 670m$ $medium\ alt.\quad 900m \times 700m$ $high\ alt.\quad 2150m \times 2900m$	$low\ alt.\quad 600m \times 670m$ $medium\ alt.\quad 900m \times 700m$ $high\ alt.\quad 2150m \times 2900m$
Resolution	$pixel\ area \le 2\ m^2$	$pixel\ area \le 10\ m^2$	$pixel\ area \le 324\ m^2$
Minimum update frequency	0.3 Hz	0.05 Hz	0.05 Hz
Maximum Latency Time	1 s	1 s	1 s
Service Type	on demand	on demand	on demand
Coverage	anytime/anywhere	anytime/anywhere but only on 80% of the routes	anytime/anywhere but only on 80% of the routes

Table 6 Expected imaging mode performance.

In tracking mode the ambiguity function has to be derived and the target (if present) has to be detected. The related computational load depends on the equivalent number of needed cross-correlations. However, also considering the possible application of decimation techniques to the correlation to reduce the number and size of the calculation, it is reasonable to expect a maximum latency time lower than 0.1 s. On the contrary, the processing in imaging mode is more demanding as, at least, an image projected on the ground plane (i.e. major image distortions related to bistatic acquisition geometry have to be removed) has to be derived after SAR focusing, and therefore the latency time could approach 1s. However, assumed values are quite conservative and consistent with the state-of-the-art, it can be foreseen a reduction within few years thanks to improved computing facilities and dedicated HW/SW configurations

With reference to the Experimental System Concept (Configuration #4), it shall be devoted to a series of proof of concept experiments. Spatial coverage, transmitting power level and signal bandwidth are the main technical issue to be faced in view of the implementation of a constellation of illuminating satellites. However, during the testing and validation phases all these problem can be knocked down if existing LEO SAR satellites are utilized as illuminators of opportunity, indeed:

- very high power density level is available near Earth surface (> - 70 dBW/m^2);
- SAR satellites transmit very large bandwidth signals (up to 400 MHz);
- spatial coverage issue can be solved if the aircraft mounting the experimental receiver setup is scheduled to fly along the best achievable flight paths for the selected spaceborne illuminator.

The validation of the hybrid space airborne forward-looking SAR concept shall involve the analysis and resolution of further issues that affect the system at different levels. On this basis it is reasonable to state that the first phase of the experimentation should be devoted to:

- validation of synchronization schemes based on the reception of the direct signal.
- development and test of novel algorithms to: (a) focus SAR data gathered in space-airborne bistatic forward-looking geometry; (b) to project processed data in adequate geographic coordinates; (c) validate the process with reference to simplified scenes (corner reflectors, test targets, test sites).
- development and test of novel algorithms for target detection and tracking, able to work in space-airborne bistatic forward-looking geometry and their validation on simplified environment (single intruder, known bistatic scattering behavior).

The second phase, instead, should involve real time validation of on-board real-time processing for both tracking and imaging mode and for inclusion of this information in GNC architectures. Finally, the third and last phase should be in charge of validating real-time all weather day night autonomous UAS navigation schemes based on bistatic forward-looking SAR/MTI data.

From an operational point of view, it must be pointed out that the service can be limited by the following aspects:

a) a large transmitted power can strongly impact satellite resources if continuous transmission is required;
b) a small field-of-view implies the need to periodically re-orient the beam to either following a UAS route or illuminating a different Earth area.

Thus, the service offered by Configuration #1, although with highest performance, can only be considered an on-demand service: i.e. the UAS asks for service availability over a given route and for a given time span. In principle, Configuration #1 is able to provide the service anytime/anywhere, with the only limitation being the number of multiple beams contemporaneously operated and the energy per orbit that each satellite can allocate to the payload. In the case of Configuration #2, the transmitted power is still large but the field-of-view is much wider. Thus, the system must still work on an on-demand base due to energetic reasons. Nevertheless, the serviced area by a single beam is wide, which limits the need for the illuminator to follow the UAS track, it must be rather pointed towards the predefined target area. In the case of Configuration #3, the transmitted power is the same of a single GALILEO channel and the field-of-view reaches its maximum extent. Therefore, the system could still work similarly to Configuration #2, but an additional working mode can be identified which is target-oriented rather than UAS oriented. The system continuously illuminates *n* target areas when flying over, which (considering their width) are probably interested by several flights, with no need for the UAS to ask for service switch-on. A rough estimate of the Earth serviceable area can be derived by the ratio of beam field-of-view and GALILEO field-of-view and results in a rough figure of 15-30%. Of course a combination of always/on-demand serviced areas could be also identified. Another point to be mentioned is related to imaging mode, which is limited to roughly 80% of the routes towards any access area for Configurations #2 and #3. For such cases, an operational station able to simulate imaging service capability over the programmed route or to suggest alternative routes must be envisaged.

Requirement fulfillment analysis

The requirement fulfillment analysis has shown that

- Only ground target surveillance seems to be unfeasible for all three SAR configurations due to the expected wide clutter spectrum that will only allow detecting a small number of fast moving targets.
- Configuration #1 is compatible with all other applications with the exception of the ground obstacle and runway detection due to a too small image size. Furthermore, use of such sensor during landing for both GPS-less situations and for remote piloting shall be avoided due to the expected excessive latency time.
- Configuration #2 is compatible with all applications except ground target surveillance for the same reasons above. Also in this case, use of such sensor during landing for both GPS-less situations and for remote piloting shall be avoided due to the expected excessive latency time.
- Configuration #3 is compatible with all applications except ground target surveillance and ground obstacle and runway detection due to a too low accuracy with respect to what required. Same limitations of the other two configurations are applicable for the landing phase. Limitations exist for this configuration related to its use for sense & avoid application that need further studies.

Above conclusions only consider pure technical feasibility of using the envisaged forward looking SAR sensors for the selected applications. For each feasible application, hereafter some further considerations comparing the SAR based sensor with other solutions are reported:

- Sense&Avoid application seems to be very interesting and feasible with configuration #2 and #3, because it will increase the use of GALILEO (navigation and obstacle sensing) while dramatically reducing UAS on board requirements about weight and power with respect to current architectures.
- GPS-less navigation with configuration #2 and #3 does not make sense because it uses the same satellites that are used GPS navigation, thus it cannot be considered a valid alternative. Limiting the use of configuration #1 only for mid-air navigation, still seems to be not effective because of its cost and on-board added complexity with respect to other solutions that will only use camera or other sensors.
- Ground obstacle and runway detection is feasible only with configuration #2, thus it can be considered effective only if the same sensor is also used for Sense & Avoid, if compared with other solutions that can use cameras and other sensors.
- Finally, for RPV application, limiting the use of forward looking SAR only during mid-air flight is of little or no interest, because standard instrumental piloting during that phase is usually enough for UAS.

Additional option/potential

The analysis considered the possibility to use a High Altitude Long Endurance (HALE) aerial vehicle as transmitter in lieu of satellites and showed that the system can achieve high performance both in imaging and in tracking modes. As for satellite illuminators, imaging mode establishes tight constrains on acquisition geometry: a single HALE, loitering on a given area of interest, is not able to guarantee that all the possible flying direction of the bistatic platform will achieve good geometric resolutions. This could be a great limitation if the main application of the system is aircraft navigation in any flight condition, but, if application is well focused, such as landing on a specific airfield, HALE trajectory can be adequately selected to provide adequate service. For surveillance and remote sensing the receiver can be provided with the range of usable trajectory and therefore high performance can be attained.

With reference to application to natural disasters, the analysis showed that required resolutions are strongly dependent on application (tens of meters in case of drought, meters for other cases). The system can be able to satisfy the requirements of disaster monitoring, depending on disaster type and selected configuration.

Conclusions

A feasibility study was conducted of a novel navigation system for UAS based on a constellation of spaceborne radar transmitters and airborne receivers, which are mounted in a forward-looking geometry. The study started with the analysis of possible applications that can benefit by all-weather day-night forward-looking observations. Five main uses have been identified and related operational scenarios and required performance have been defined: sense & avoid, GPS-less navigation, target surveillance, autonomous landing and remote piloting. These operational scenarios involved the definition and study of two distinct working modes for the receiving radar, namely an imaging mode, that produces an image of the forward ground area and a tracking mode, able to indicate the location of airborne or ground moving targets.

The system feasibility study was carried out by first assessing the state-of-the-art for the different technologies involved in the system. Then, performance assessment was performed. It required the selection and the implementation of models and algorithms derived from literature as well as their extension to derive bistatic radar resolutions. As regards the imaging mode, the needs to deal with non-square image pixels forced to utilize the concept of pixel area and Ω-angle, together with classic range and Doppler resolution, in order to identify the behavior of geometric resolution completely. The derived analytical tools show that the main limitations of monostatic forward-looking operation due to range/Doppler ambiguity can be overcome provided that specific requirements on the acquisition geometry are satisfied. System performance has been evaluated with reference to a dedicated satellite constellation, but also considering existing SAR and non-SAR satellites. Contrary to LEO, if the illuminator is MEO or GEO performance depends solely on illuminator position and not on illuminator velocity. Moreover, considering that for a GEO illuminator only a fixed set of aircraft trajectories can be served, a MEO constellation has been identified as the best choice for a dedicated illumination system. With reference to non-dedicated systems, navigation constellations offer global, continuous, multiple coverage whereas remote sensing constellations offers strict repetitivity capabilities: i.e. the possibility to fly over the same Earth location at regular time interval, often at the same local time. In addition, TELECOM constellations offer zonal or global, continuous, single coverage. From this point of view, SAR constellation can be characterized by time interval between successive observations of the same Earth target also accounting for beam steering capabilities. The best result can be obtained by synergic use of COSMO/SkyMed, SAOCOM, and Sentinel-1 satellites (all flying on down-dusk orbits), which leads to an estimated mean revisit time of 10 hours. Existing SAR satellites can be considered very interesting to carry out proof of concept experiments of all the analyzed bistatic acquisition options since they can allow the bistatic radar to achieve very good geometric and radiometric resolutions, but only for very short time spans, a few seconds at most, and only if specific relative acquisition geometries are established. On the contrary the radar performance achievable by existing non-SAR illuminators is poor because of the limited transmitted signal power level and bandwidth.

The derived performance established the ground for the identification of three strawman system concepts, with different performance and system complications/challenges. A newly ad-hoc developed option have been introduced, based on a MEO constellation with more than 40 satellites all equipped with a radar able to radiate 2-3kW on small multiple beams, and two degraded systems, based on the use with (medium to low) modifications of GALILEO constellation/satellites. The first two systems have to be considered only on-demand services, whereas the third, even if characterized by worse performance, could be developed to continuously illuminate a set of given, thousands of kilometers wide, target areas. A fourth strawman system option has been also introduced to propose a validation experimental campaign which can be based on existing SAR satellites and existing, but modified to introduce a forward looking geometry, airborne SARs. Possible different experimental validation phases have been also outlined.

A final, qualifying step of the study has been a comparison between achievable performances with the proposed strawman configurations and the expected ones, set as baseline at the beginning of the study. Limitations and constraints relevant to the proposed options are put in evidence, gaining further insight into system peculiarities and stressing aspects that will need further investigations. However, it is demonstrated idea robustness, in fact several UAS navigation applications could be fulfilled at the required geo-radiometric accuracy and time schedule.