



Project:

**Feasibility Study on Satellite-Unmanned
Airborne Systems Cooperative
Approaches for the Improvement of all-
Weather Day and Night Operations**

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Study Objective and Scope

1 Study Objective and Scope

Monostatic forward-looking Synthetic Aperture Radars currently employed by high-end autonomous and remotely piloted vehicles can - due to the observation geometry and the resulting limited Doppler bandwidth - only offer a limited resolution. This is clearly reducing the use of remote sensing data gathered by these means, and it has a decisive impact on the capability of a UAS to perform autonomous sense & avoid maneuvers.

To overcome the above mentioned limitation of currently existing forward looking systems, a combination of satellites as a microwave transmitter, and unmanned aerial systems (UAS) as the microwave receiver in a bistatic configuration may be the solution. The feasibility of such satellite - UAS cooperative approaches with respect to the requirements imposed by both the remote sensing and sense & avoid functions of the UAS will be determined within this study. The system configuration needed to fulfil the requirements will be evaluated, including existing or firmly planned satellite constellations, and entirely new constellations designed in a manner to provide a good solution for the task to be performed.

In agreement with the SoW, this study will analyze the following fundamental elements:

- **techniques and technologies needed** to significantly improve the performance of the forward-looking airborne sensor
- **parameters of the satellite constellation** required to offer the necessary coverage to a certain number of areas of operation,
- **spaceborne illuminator payload characteristics** and performance

The work proposed herein is consisting of a study, which comprises three parts as required in the agency's statement of work. In the first part of the study (WP 2000) the system-level requirements will be derived from the user requirements in terms of a remote sensing payload for a dual-use mission, and a forward-looking radar for autonomous "sense and avoid" navigation functions.

In the second part of the study (WP 3000), based on the system-level requirements derived in WP 2000, the system feasibility will be analyzed. Here, a survey and analysis of suitable spaceborne or high altitude illuminators and airborne microwave detectors will be performed. The performance parameters achievable by such a configuration in terms of e.g. SNR will be derived, and a comparison with non-bistatic configurations will be performed.

Based on the instrument-related parameters and the requirements, a system-level concept including satellite constellation-, timing-, and information flow-related issues will be performed in the third part of the study (WP 4000).

Derivation of Preliminary System-Level Requirements

2 Derivation of Preliminary System-Level Requirements

2.1 Introduction

The requirements for the UAS to be examined in the course of this study are driven by two separate functions. The first is the surveillance function of the UAS. The requirements for this can be derived based on the specific surveillance mission. The necessary resolutions can be derived from widely accepted standards (see below). The more challenging part in the definition of the requirements is the second function, autonomous sense & avoid. At first, it has to be analyzed what requirements to that functionality are defined in international regulations such as the "EUROCONTROL Specifications for the use of military unmanned aerial vehicles as operational air traffic outside segregated airspace" [RD1]. In essence, unmanned aerial systems are required to provide the same level of reliability with respect to airspace interactions as manned systems could provide. The respective requirements for the detection ("see") function of the standard human process "see-understand-decide-act" will be derived in this work package.

The requirements will be used to evaluate the benefit of satellite - UAS bi-static configurations with respect to normal UAS forward-looking radar configurations in the course of WP 4100. They will also be the basis for the definitions of the sensor concept to be performed in WP 3200.

2.2 UAV Specifications

In this chapter, the UAV specifications that will be assumed in the course of the study are defined. The specifications represent currently existing unmanned air systems that could potentially be capable of supporting the configurations to be examined in the course of the study. The typical values for velocity, altitude, wingspan, and maximum take-off weight are given in two classes, one for the Predator-type MALE (medium altitude, long endurance) UAVs, and one for the Global Hawk-type HALE (high altitude, long endurance) UAVs.

The requirements include flight performance Specifications and physical specifications for the UAVs.

2.3 Requirements for Remote Sensing

Satellite-UAV cooperative missions for remote sensing can be beneficial for a number of reasons. The prominent advantages are on the one hand the possibly better resolution, on the other hand the bi-static scenario would enable an UAV that does not transmit any signals and can thus be detected more difficultly, increasing its military utility and its survivability.

The requirements for remote sensing in terms of timeliness are closely linked to the mission to be performed by the UAS. Needed spatial resolutions are defined in documents such as the "National Image Interpretability Rating Scales" [RD24], "STANAG 7194 JINT - NATO Imagery Interpretability Rating Scale (NIIRS)" [RD25], "STANAG 3769 - Minimum Resolved Object Sizes and Scales for Imagery Interpretation" [RD26].

In the first part of that work package, different types of observations that shall be performed by the UAS are defined. For each of those types of observations, requirements in terms of spatial resolution are determined based on [RD24], [RD25], and [RD26].

Derivation of Preliminary System-Level Requirements

2.3.1 Spatial Resolution Requirements

Different NIIRS levels and their associated resolutions will serve as a guideline to derive a set of remote sensing performance requirements that target different performance levels.

NIIRS specifies 10 resolution levels (0 to 9) based on the sufficiency of the image information to detect, distinguish between, or to identify certain types of objects. NIIRS level 0 would mean that the image cannot provide any information due to obscuration, degradation, or very poor spatial resolution [RD 24].

NIIRS rating levels are available for different kinds of sensors, including visible, radar, infrared, and multispectral ones. For the activities within this study, the criteria for radar sensors will be used.

In this study, three NIIRS-levels will be examined, NIIRS-3 (ca. 3.5 m GRD), NIIRS-5 (ca. 1.0 m GRD), and NIIRS 7 (ca. 0.3 m GRD).

2.3.2 Product Requirements

For remote sensing, scene sizes of 2 km x 2 km are assumed. The NESZ (noise equivalent sigma zero) shall be better than -20 dB throughout the scene.

2.3.3 Temporal and Coverage Requirements

In the next step, different sets of requirements will be defined that cover essentially the availability of the bi-static observation geometries with respect to time and place.

The chosen parameters represent different philosophies with respect to the use of remote sensing data acquired using bi-static satellite-UAV cooperative observations. As far as the temporal requirements are concerned, different levels of persistency are assumed here.

The next set of requirements deals with the coverage - or place-dependent availability - of satellite-UAV cooperative observation opportunities. Here, three assumptions with respect to the area of regard have been made.

2.4 Requirements for Sense & Avoid

As the full integration of Unmanned Aerial Systems requires a system capable of flying autonomously in an unstructured environment, it is necessary that the classic human process "see - understand - decide - act" can be replicated at the same or a higher level of reliability. That high level of reliability has to be ensured throughout the entire process to achieve the required results. The detection of possible obstacles such as other flying vehicles crossing the flight path, or forests, or man-made structures is at the very beginning of the process. In this work package, the requirements for the "see" part of the process with respect to object sizes, accuracy of the determined position, and probability of detection will be derived.

A number of items listed in the EUROCONTROL Specifications for the use of military unmanned aerial vehicles as operational air traffic outside segregated airspace [AD1] have to be considered when deriving the requirements for sense & avoid navigation functions:

In **Specification UAV5** it is mentioned that "...additional provision should be made for collision avoidance against unknown aircraft." The result of that specification with respect to the "see" function in the process is that the system has to be capable of detecting all aircraft possible interacting with the

Derivation of Preliminary System-Level Requirements

UAV flight path.

A similar requirement can be derived from **Specification UAV6** stating that a "...automatic system should provide collision avoidance in the event of failure of separation provision."

Specification UAV7 then states that "The S&A system should achieve an equivalent level of safety to a manned aircraft." The implications with respect to the "see" part of the process will be discussed in WP2200.

Specification UAV8 is again stating that "A UAV S&A system should notify the UAV pilot-in-command when another aircraft flight is projected to pass within a specified minimum distance. Moreover, it should do so in sufficient time for the UAV pilot-in-command to manoeuvre the UAV to avoid the conflicting traffic by at least that distance or, exceptionally, for the onboard system to manoeuvre the UAV autonomously to miss the conflicting traffic." From this specification, a number of requirements pertaining e.g. to the detection range, and the timeliness, can be derived.

Further requirements will arise from military specifications, such as those listed in "STANAG 4671: UAV Systems Airworthiness Requirements (USAR) for North Atlantic Treaty Organization (NATO) Military UAV Systems" [RD28].

2.4.1 The Sense & Avoid Process

The Sense (or "See") Function of the Sense & Avoid process can be subdivided into three primary functions:

- Object Detection: The capability to detect the presence of an object whose flight path might be conflicting with the own flight path.
- Object Tracking: The capability to continuously update information on the flight path of the object(s) under consideration.
- Object Identification: The capability to identify properties of an object (such as type).

All the above functions may potentially be supported by forward-looking radar in the configurations to be examined in this study. However, for most of the above points, solutions already exist, or they are currently in the loop-

The Avoid function of the Sense & Avoid process consists of:

- State Propagation: Computation of future states based on the available information
- Identification of a close encounter
- Implementation of an avoid manoeuvre

2.4.2 Sensitivity and Timeliness Requirements

The sensitivity requirements are driven by the parameters of the smallest objects to be detected in order to gain a level of situational awareness that is equal to or better than that which can be achieved in manned flight.

Derivation of Preliminary System-Level Requirements

The Safety Integrity Requirements in [AD1] can serve as a guideline to determine a proper lower limit for the object sizes detectable. Two Safety Integrity Requirements are of special interest here:

SIR-11 states that: "The frequency of occurrence with which a UAV Pilot-in-command loses situational awareness shall be equivalent, and preferably lower, to that of manned aircraft."

SIR-14 states that: "The probability of a UAV false collision avoidance or other false alerts shall be equivalent to that for manned aircraft."

The human eye is capable to provide a maximum angular resolution of 0.5 - 1.0 arcminutes. At a distance of 1 km, such a resolution would equal to the capability of seeing an object with 0.14 m diameter, assuming proper illumination. At a distance of 10 km, this would equal to the capability of seeing a 1.4 m diameter object at proper illumination, assuming the theoretical maximum capability of the human eye which is rarely reachable.

Assuming a VFR situation where the brightness of the target is in the same order as that of the background, the above method is a good rough approach to determine the needed resolution. Should it not be the case (brightness of the target much larger than that of the background), even smaller objects would be detectable (similar to point light sources (distant stars) on a telescope) to the human eye.

The question to be answered now is the distance at which conflicting objects have to be detected. It can be answered by applying similar criteria to those used within TCAS to trigger either traffic (TA) or resolution advisory (RA) messages. Traffic advisory messages are just indicating incoming traffic with an aural voice such as "traffic, traffic". Its purpose is to draw the attention of the pilot-in-command to this issue. In case the more stringent requirements for resolution advisory are met (only available in TCAS II), instructions are triggered that target at avoiding a collision, such as "Climb, Climb, Climb!", or "Descend, crossing, descend!" In case of a successful separation, the message "clear of conflict" is triggered.

The criteria for those messages are listed below. It is assumed that in order to start a collision avoidance manoeuvre, no matter what sensor or instrument provides the information of incoming air traffic, the timeliness requirements are similar to those for TCAS. Tau is the time until the closest point of approach (CPA).

The most stringent requirements as far as the timeliness of the collision warning is concerned can be derived from the Tau Criteria for traffic advisory at high altitudes. The worst case as far as the required detection range is concerned, is a head-on approach of the two aircraft. Assuming that both aircraft travel at a speed of no more than 300 m/s (hypersonic aircraft excluded) the 45 s time to closest approach would mean a required detection range of 27 km.

At that distance, the human eye would be capable of seeing a faint object as big as about 4 m in diameter. The UAV7 suggestion in [AD 1] is stating: "The S&A system should achieve an equivalent level of safety (ELOS) compared to a manned aircraft." Based on that and the above, some requirements can be derived. At first, the sensor has to be capable of detecting and tracking incoming air traffic at a range of 27 km and below.

Derivation of Preliminary System-Level Requirements

2.4.3 Reliability Requirements

The FAR 91.113 specification states that "When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules (IFR) or visual flight rules (VFR), vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft."

In [AD 1], UAV7 states that: "The S&A system should achieve an equivalent level of safety to a manned aircraft." In order to determine what that equivalent level of safety (ELOS) is, the probability for near mid-air collisions (in that sense, the probability of failure of the human sense & avoid process, in absence of existing sense & avoid systems) has to be determined. According to the AOPA (Aircrafts Owners and Pilots Association), an average of 13 collisions occur in general aviation (where collision avoidance systems are rarely implemented) in the United States. The number of near mid air collisions is at about 210 per year. Using the total number of 25 Million flight hours, the probability of failure of the human sense & avoid system is at 8.36×10^{-6} . This equals to a reliability of 99.9992 %.

System Feasibility Study

3 System Feasibility Study

Bistatic radars offer several advantages when compared to their monostatic counterparts. In addition to increased performance, sensitivity, coverage and revisit times, all of them parameters which are mainly dependent on their spatial configuration, bistatic radars offer the additional advantage of being more robust to jamming, since the receiver operates as a mere passive system. The proposed system consists of a spaceborne-based transmitter illuminating an area of interest and one or several receivers mounted on a UAV to perform a two-goal mission: a) help autonomous navigation of the UAV, and b) perform surveillance of the overflown area using remote sensing techniques. Although the requirements for these significantly different tasks might seem distant, the fact of having a spaceborne transmitter ensures that the coverage needed for both purposes is achieved. If such a system is successful, autonomous UAV flight allows significant cost reductions with respect to conventional manned airborne vehicles.

3.1 Remote sensing performance analysis

In the present section, the main performance parameters of the remote sensing system, geometrical resolution and sensitivity, are analysed. The purpose of the section, rather than to analyse a specific system example, is to describe the dependences of these parameters as a function of system or configuration parameters of the radar.

3.1.1 Geometrical configuration

Imaging radars achieve good geometrical resolution by exploiting range and Doppler properties of the system. Good image resolution requires then orthogonality between time and frequency measures. This means that, in order to maximise the utility of the Doppler information of the imaged scene, this should be acquired orthogonally to the range information, which is radial (roughly boresight). This is the reason why imaging radars, or synthetic aperture radars (SAR), operate in side-looking configurations. The satellite flight with respect to the imaged scene is assumed to be arbitrary (it makes no sense to impose a study only about parallel or perpendicular nadir track to the UAV), since the UAV is assumed to be able to change its trajectory much easily than the satellite overflies the desired scene in a side-looking mode. The best azimuth resolution can only be achieved if the synthetic aperture is built using a side-looking antenna of the UAV, and this is the only assumption of the system. The satellite can be flying arbitrarily, with its nadir track forming any possible angle with the nadir of the UAV. Figure 3-1 shows a plot of the bistatic configuration used for deriving the remote sensing performance of the system. In the plot, the incident angles (θ), the operating heights (h), the speeds (v), the slant ranges (r), the bistatic angle (β), and the baseline vector (b) for transmitter (Tx), receiver (Rx) and target (P) are shown

System Feasibility Study

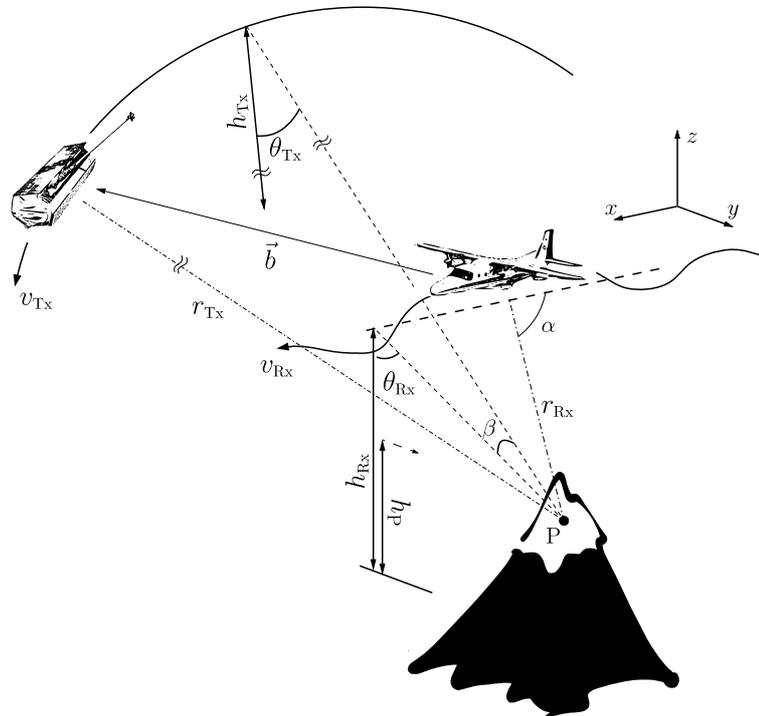


Figure 3-1 Bistatic radar geometry for remote sensing applications

The analysed orbits for the satellite are comprised between LEO and GEO and correspond to mean heights above the Earth between 200 km and 35800 km, respectively. For these orbits, not all off-nadir angles are possible, since the desired targets must necessarily lie on the Earth surface. Since the off-nadir angles are important in the computation of essential performance parameters such as resolution, the computation of the total off-nadir range angle as a function of the orbit height is a valuable input for the resolution and sensitivity analysis.

3.1.2 Selection of the carrier frequency

Due to the high resolutions aimed for the remote sensing system, a high carrier frequency is suggested. Limitations such as atmospheric attenuation and transmitted powers or antenna dimensions have to be taken into account for the carrier definition. As a basic design parameter, C and X bands are selected as possible bands for the system. They have the advantages of allowing high resolution imaging and detection, moderate antenna sizes and tolerable propagation attenuation. Moreover, these frequency bands have shown to be mature in radar remote sensing applications (experience of several spaceborne radar missions like ERS, ASAR-ENVISAT, SIR-C/X, TerraSAR-X).

3.1.3 Range resolution analysis

Instantaneous range resolution projected on a flat ground can be shown to be a function of the incident angles of transmitter and receiver, as well as inversely proportional to the transmitted bandwidth of the radar signal. Using these functional dependences, the required bandwidths to obtain a ground range resolution of 0.3 m can be seen in Figure 3-2 as a function of UAV and satellite incident angles. The UAV incident angle is shown for a flat ground and the possible look angles of the

System Feasibility Study

UAV (as assumed in the system specification). The satellite incident angle range coincides with that of a low-height LEO case undoubtedly a best case as far as satellite component is considered, and remains almost constant during the illumination of a scene. The best possible scenario, clearly not achievable in most of the cases requires a transmitted bandwidth of over 500 MHz. More typical cases, the only possible for higher orbits, require transmitted bandwidths of up to 1 GHz. Even the 500 MHz bandwidth is a challenge to present civilian spaceborne and airborne systems (TerraSAR-X has an experimental mode with 300 MHz, for instance), and are therefore considered as too expensive. Systems with such a high bandwidth also produce a high amount of data, and require a high data rate link if the acquired data need to be transferred.

Figure 3-3 shows an analogous plot for a ground range resolution of 1 m. Since resolution and transmitted bandwidth have an inverse relation, the results are scaled roughly by a factor 3, and this resolution (1 m) is achievable for typical transmitted bandwidths of around 300 MHz. This bandwidth is still high for present SAR systems, but is nonetheless reasonable as a design parameter.

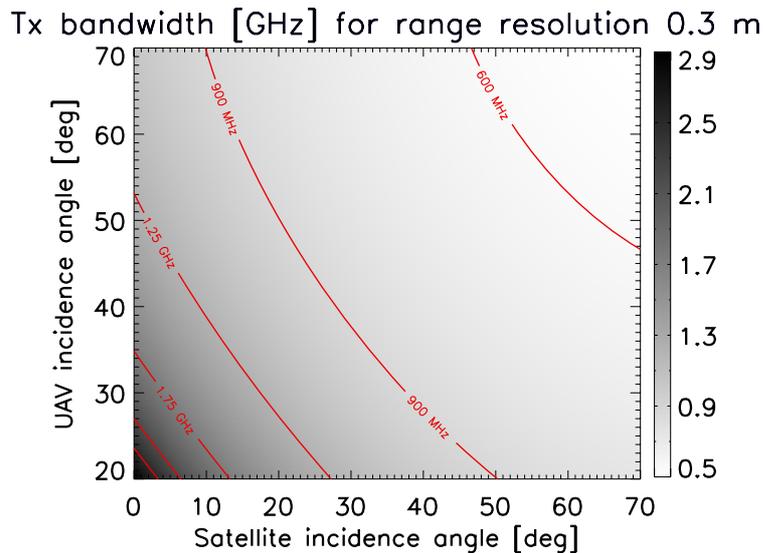


Figure 3-2 Transmitted bandwidth required for a ground range resolution of 0.3 m as a function of the satellite and UAV incident angles

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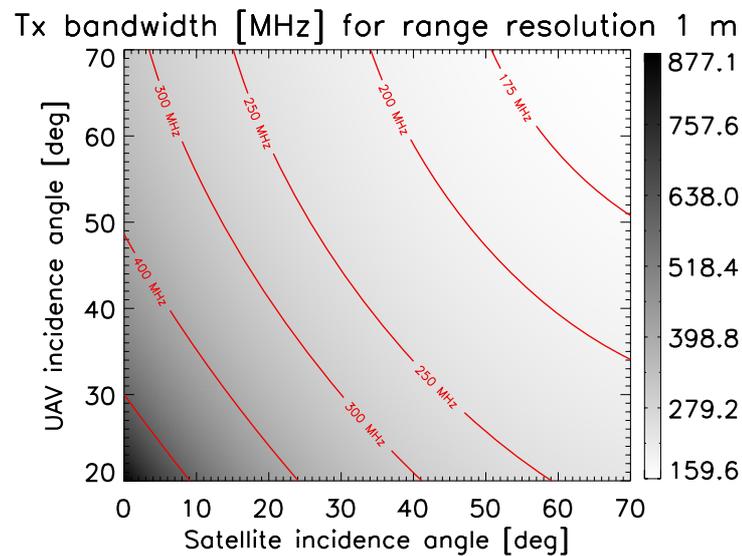


Figure 3-3 Transmitted bandwidth required for a ground range resolution of 1 m as a function of the satellite and UAV incident angles

3.1.4 Azimuth resolution analysis

Azimuth resolution is gained via Doppler filtering. Due to the difficulty in the evaluation of instantaneous Doppler, its estimation is done with a spectral analysis performed over the integration time. So, the main parameter to analyse in this section is the integration time required for a given resolution requirement. The integration time of the system can be used for computing antenna dimensions and the antenna steering requirements. Azimuth resolution improves with decreasing wavelengths and increasing integration times.

The illumination of the scene by the satellite footprint lasts longer for higher orbits, unless an antenna steering is implemented. Current LEO radar satellites achieve illumination times of around 5 seconds, which would require a maximum UAV height of around 6 km so that this 1 m resolution is guaranteed. In the following subsections, the satellite will be assumed to be contributing to the azimuth resolution, and the dependence of the required integration time with respect to: a) resolution, b) carrier frequency, and c) UAV speed are analyzed.

The previous results were computed for a system with a negligible satellite contribution to the azimuth resolution. Consider a system where this is no longer the case, and the satellite contributes as much as it can to the azimuth resolution. This is achieved by setting low incident angles and parallel nadir tracks to the imaged scene. The contribution of the satellite is more noticeable for lower orbits, and becomes less and less significant for higher orbits. The integration times required for an azimuth resolution of 1 m are shown in Figure 3-4 and Figure 3-5.

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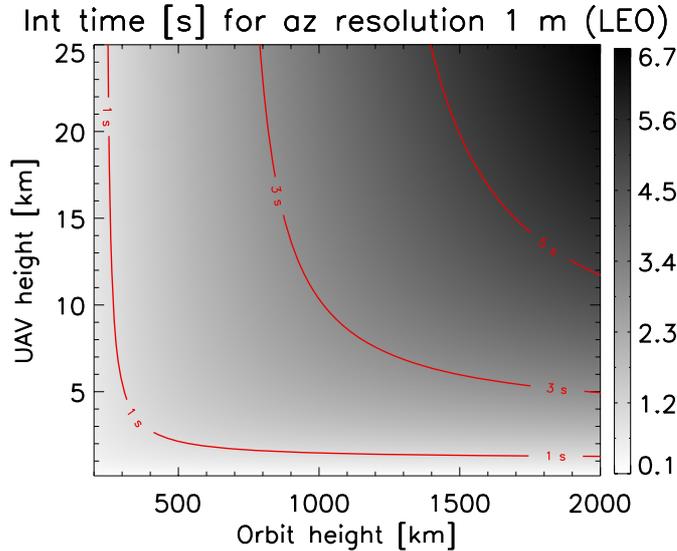


Figure 3-4 Integration time required for an azimuth resolution of 1 m (LEO case), with UAV speed 100 m/s and a carrier frequency of 10 GHz (satellite contribution)

Both plots are equivalent to the two previous. The decreasing impact with increasing orbit heights can be noticed in the figures through the more similar integration times. The system, which is used in the following as reference for the azimuth resolution analysis, corresponds to a UAV speed of 100 m/s and a carrier frequency of 10 GHz. Results for MEO-GEO satellites require longer integration times, which are also more likely due to the expected larger antenna footprints and lower satellite velocities.

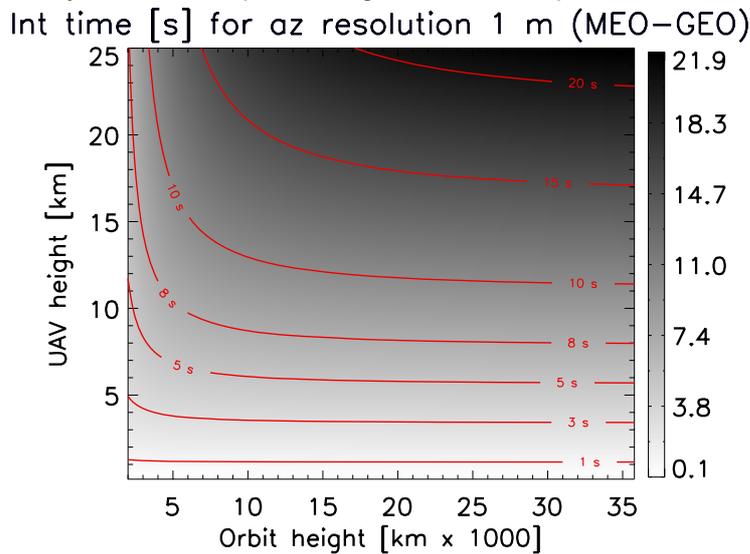


Figure 3-5 Integration time required for an azimuth resolution of 1 m (LEO case), with UAV speed 100 m/s and a carrier frequency of 10 GHz (satellite contribution)

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3.2 Sense and avoid performance analysis

The structure of this section is analogous to that of Section 3, and aims at a general description of the crucial parameters of the radar to perform sense & avoid. Once again, no specific system example is analysed, and the results are shown to understand the critical system parameters to take into account once the system is to be designed.

3.2.1 Selection of the carrier frequency

The targets are placed at a maximum range of 27 km, which roughly requires a PRF below 11 kHz for unambiguous range estimation.

The unambiguous target velocity range of $[-1d3, 1d3]$ km/h requires a PRF above $1.85 \cdot (f_0 [\text{GHz}])$ kHz.

Conclusion: the carrier frequency must be lower than 5.94 GHz (C-band).

3.2.2 Range resolution analysis

Targets in the sense & avoid applications are clearly point targets. The range resolution required for airplane detection (in the order of 2-5 m are largely enough) is significantly less demanding than the range resolution required for remote sensing purposes. In general, targets placed not near the baseline vector of the bistatic radar are seen with good range resolution, since range resolution can be expressed as a function of the bistatic angle. Figure 3-6 shows the maximum tolerable bistatic angle as a function of desired range resolution and transmitted bandwidth.

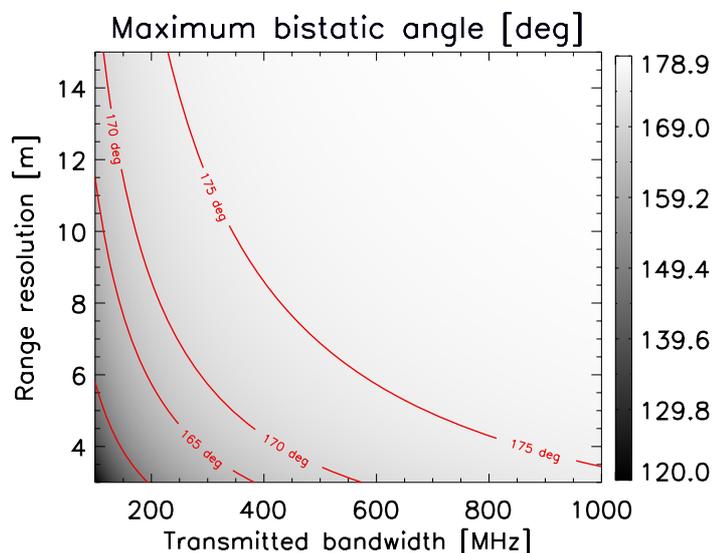


Figure 3-6 Maximum bistatic angle tolerable as a function of required range resolution and transmitted bandwidth

The way of interpreting the previous plot is the following: given a transmitted bandwidth of the system and a desired resolution, the plot shows the maximum bistatic angle allowing the desired performance. For a 300 MHz system and a range resolution requirement of 5 m allows a bistatic angle up to 170 deg. This means that (almost) only targets reaching the UAV through the baseline vector are seen

System Feasibility Study

with worse range resolution. Even in this improbable case, due to the fast variation of the baseline vector, targets might be detected using azimuth angular or Doppler resolution.

3.2.3 Sensitivity analysis

Sensitivity is computed using the bistatic radar equation, with which values for the SNR of a received target can be computed. The reference system used for the analysis assumes a carrier frequency of 5 GHz, a transmitted power of 5 kW, satellite antenna gain of 45 dBi, UAV antenna gain of 20.8 dBi, and a transmitted bandwidth of 100 MHz; the target RCS is 1 m². Figure 3-7 and Figure 3-8 show the one-pulse video SNR of the bistatic radar as a function of satellite off-nadir angle and orbit height for LEO and MEO-GEO cases, respectively. Note the saturation of the curves for decreasing off-nadir angles obtained at increasing orbit heights, as already explained in Section 3.

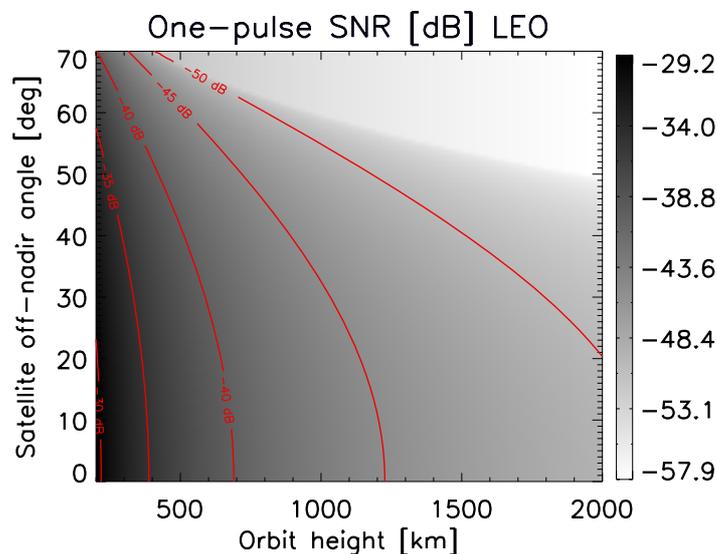


Figure 3-7 One-pulse video SNR for reference system (LEO case), carrier 5 GHz, power of 5 kW, satellite antenna gain of 45 dBi, UAV antenna gain of 20.8 dBi, bandwidth of 100 MHz; RCS 1 m²

The resulting values are very low. However, it has to be noted that range compression gain (essential in point target detection) is not included. For the obtained values, SNR increases in 80 dB and becomes independent of bandwidth. The pulse duration has to be accounted for too. It is usually expressed in microseconds, and takes values of a couple of tenths of microseconds for typical spaceborne radars. A pulse duration of 20 μ s corresponds to a subtraction of 47 dB. As a result, the range compressed signal shows at peak SNR values 33 dB better than the plotted curves. Doppler integration is not considered in the analysis, but an integration time of 0.01 s improves the SNR values in 20 dB further. These values, all of them conservative, make the system usable for almost every LEO configuration. However, the usability in MEO-GEO systems requires additional sensitivity of the system, probably achievable using longer integration times or higher gain antennas.

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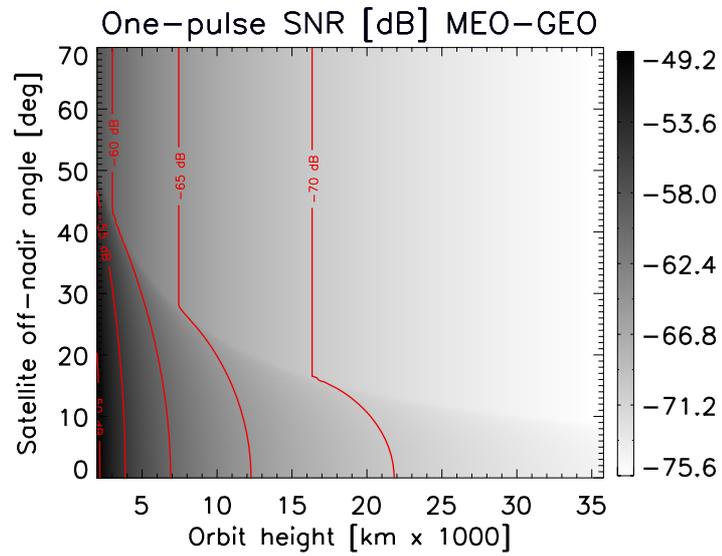


Figure 3-8 One-pulse video SNR for reference system (MEO-GEO case), carrier 5 GHz, power of 5 kW, satellite antenna gain of 45 dBi, UAV antenna gain of 20.8 dBi, bandwidth of 100 MHz; RCS 1 m²

System and Operational Concept

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4.1 Operational Concept

In the beginning, this chapter will show what satellite constellation would be needed for global persistent coverage, taking into account that the incidence angle (with respect to the local zenith) of the satellite beam on the ground is nowhere larger than 60 degrees. That requirement can also be translated into the following one: the satellite constellation has to be designed in a manner that for any given point on Earth, on any given time, there is always at least one satellite of the constellation at an elevation of 30 degrees or higher.

4.1.1 Satellite constellations for global persistent coverage

The constellations that will be shown in this chapter will consist of a very large number of satellites, especially when considering only satellites in LEO. For evaluations of questions as asked above - for global persistent coverage, constellations designed using Walker Delta Patterns will be used. The purpose of the following descriptions is to show feasibility limitations, especially when considering persistent, global coverage.

4.1.1.1 LEO Satellite Constellation

All satellites in this constellation have a semimajor axis of 7.100 km, and an inclination of 86.4 degrees. The analyses showed that a Walker Delta Pattern of 86.4°:450/15/1 would be able to fulfil all the requirements described above and provide a global persistent coverage. The constellation would consist of 450 satellites, 30 satellites per plane.

4.1.1.2 MEO Satellite Constellation

When examining the option to use a MEO constellation for global persistent coverage, the possibility to place the radar transmitters as a secondary payload on a possible next generation Galileo constellation was taken into account. Using all satellites of the Galileo constellation to carry that secondary payload would clearly be an overshoot. It was found that it would be sufficient to have 5 satellites (out of 9) per orbit plane equipped with radar transmitters. Therefore, in total there would be 15 satellites which would be sufficient for global persistent coverage. The constellation, which is basically the Galileo constellation with 4 satellites per plane removed, is shown in **Error! Reference source not found.**

4.1.2 Satellite Constellation for Persistent Coverage in Polar Regions

In order to cover the north and south Polar Regions completely, and considering the limitations concerning the ground incidence angle, 5 MEO satellites at polar inclination and at an altitude of at least 13,300 km would be needed. As higher altitudes mean better coverage they can also be used, especially to avoid the radiation belts. Basically the altitude chosen will be a trade off between the adverse effect of raising the altitude (i.e. in terms of required transmit power) and the proximity to the radiation belts.

4.1.3 Temporal Parameters of Existing Satellites providing on-demand service

For the determination of the temporal parameters (revisit time) of existing satellites providing on-demand service it is assumed that these satellites would illuminate the flight path of the UAS within the

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required parameters described above. As these requirements differ (especially the incidence angle limitations for taking monostatic SAR images from the satellites are different), the following performance figures only pertain to the use of the respective satellite for illuminating the flight path. They also do not reflect any potential limitations of the satellite itself.

Illuminator constellation consisting of some currently existing radar satellites

The figures below show the revisit statistics for a constellation consisting of TerraSAR-X, the COSMO Skymed Constellation, Radarsat 2, ERS-2, and Envisat. They represent the capability achievable in case the satellites are available at specific times.

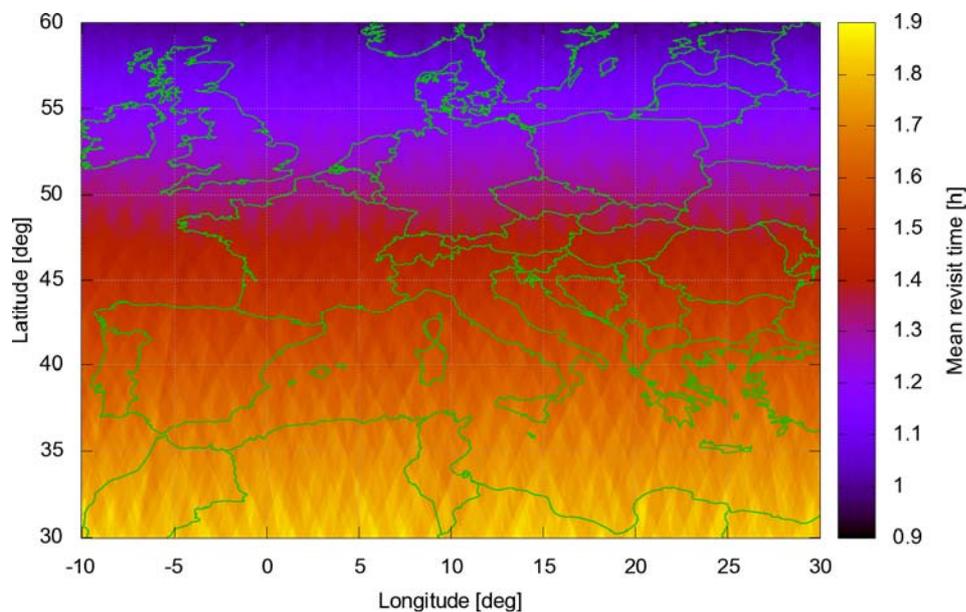


Figure 4-1: Mean Revisit Time for an on-demand flight path illumination performed by the heterogenic illuminator constellation

4.2 System examples

4.2.1 Some observations on the proposed systems

The critical performance parameters of the system for remote sensing and sense & avoid applications have been presented in the system feasibility study in an intuitive, scalable manner. Two main conclusions on the system can be extracted from the performance values obtained in WP3000: a) as expected, using a LEO satellite as transmitter improves the overall performance (resolution and sensitivity) of the system, mainly because the transmitter is closer to the scene, and b) sense & avoid requires constant monitoring of the area where the UAV is flying, which mixed with LEO condition, results in a constellation with an enormous amount of satellites (see WP4000). If constant monitoring is desired, MEO orbit satellites are needed.

Achieving high resolution, high SNR radar images with a MEO constellation guaranteeing constant monitoring in C-band requires very expensive bandwidths and transmitted powers values. On the other hand, realistic configurations allowing high resolution and high SNR images (see example with TerraSAR-X) cannot guarantee constant monitoring. Since the MEO solution allows both sense &

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avoid and remote sensing (with moderate resolutions), whereas the LEO solution only allows remote sensing, we select as proposed system a MEO constellation guaranteeing global, constant monitoring. Assuming the technical feasibility of the complete system, it would provide a cheap and robust manner for enabling global UAV flight, while enabling continuous all-weather imaging capabilities of the UAV-overflown areas with fair resolution values.

Ideally, the system consists of a MEO satellite constellation illuminating with chirp pulses the interesting areas at a carrier frequency of around 5 GHz. These pulses are used for both purposes, and so no further intelligence on the transmitter part needs be included. Ideally too, the receiver is mounted on the UAV and is shared for remote sensing and sense & avoid (the ideally is to be understood as a “to be desired”). Since no timing analysis has been performed, this might not be feasible in a final system), and separate antennas are used for remote sensing and sense & avoid. A central unit is responsible for the time allocation of the receiver to the different subsystems. An integrated positioning unit (usually IMU + GPS) is essential for absolute location of the targets (both in remote sensing and sense & avoid).

Receiver remote sensing antennas have to be designed so that image NESZ is better than -20 dB, provided that transmitted power, pulse duration and transmitter antenna gain have been already optimized (and fixed) for the satellites. The antennas are side-looking, the only sensible solution for such a system, if acceptable resolution imaging is desired. If imaging of a given area is desired, the UAV shall flow side-looking to it.

Receiver sense & avoid antennas are distributed all around the UAV to guarantee 360 deg surveying of the airplane environment. A scanning on the azimuth plane of the antennas is proposed, and thus the azimuth beamwidth of the antennas is a function of the desired gain and of the properties of such a scanning. The elevation beamwidth depends on the desired gain and on the relative height coverage requirement of the system.

4.2.2 System example using Sentinel-1

The parameters used in the simulation of the system are listed in Table 4-1.

| | |
|---|--------------------|
| Orbit height | 710 km |
| Centre frequency | 5.405 GHz |
| Transmitted bandwidth | 100 MHz |
| Transmitted power | 4.5 kW |
| Duty cycle | < 15% |
| Off-nadir angle range | [20 deg, 45 deg] |
| Antenna size (el x az) | 0.821 m x 12.315 m |
| Azimuth beamwidth (one-way 3 dB) | 0.26 deg |
| Azimuth steering capability | ±0.75 deg |
| Satellite velocity | 7590 m/s |

Table 4-1 Useful parameters for Sentinel-1 platform simulation

The ground range footprint extends to 80 km, more than enough to cover a typical imaged scene (specified to 2 km) and to cover the 60 km needed in sense and avoid applications. Basic PRF is set to 10 kHz, which yields a pulse duration of up to 15 µs.

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Performance analysis for remote sensing (RS) operation

A similar look angle range as before is assumed for the UAV, [20, 70] deg. This requires very small dimensions in elevation for the receiver antenna. More realistic antennas might have significantly smaller elevation beams, thus limiting the imaged scene as function of the UAV height.

Taking a look at Figure 3-3 and scaling the bandwidth values to the 100 MHz available, for the whole elevation range of the receive antenna, the ground range resolution takes values between 4.5 m and 2.3 m. Scaling to the azimuth resolution and comparing the results of Figure 3-4, the required integration times for a resolution of 2.3 m vary from 0.15 s to 4.5 s from low to high altitudes of the UAV, the latter is feasible due to the steering characteristics of the antenna. Concerning geometrical resolution of the system, a state-of-the-art imaging radar with comparable performance to stripmap modes of present high-resolution spaceborne systems is achievable.

Accounting for the slightly inferior transmitter power, the slightly superior carrier frequency, the notably inferior pulse duration and the size of the resolution cell, NESZ varies between [-30, -10] dB for lower to higher altitudes of the UAV. The requirement of -20 dB is achieved up to flying heights of 9 km. For higher altitudes, an increase of receiver antenna gain is needed.

Performance analysis for sense & avoid (SA) operation

An SNR range for the 710 km orbit shown in Figure 4.4 is [22, 25] dB. These values have to be corrected with roughly 6 dB due to the aforementioned parameters, yielding a SNR range between 16 and 19 dB, respectively. These are the values for a target with a RCS of 1 m². These results can be scaled to any other RCS by adding the factor $10 \log(\text{RCS}[\text{m}^2])$.

4.2.3 System example using MEO constellation

This solution allows the operation of the system in its two desired modes: remote sensing and sense & avoid. The constellation is similar to that of Galileo (orbit height 25000 km, with very low eccentricity). Two interesting constellations are analyzed:

Global coverage (15 satellites)

Polar region coverage (5 satellites)

As a reference system, and for (easy) comparison purposes, we will select a Sentinel-1 placed on the selected orbit (cf. Table 5-1). Bad performance is expected on the first iteration, since it is a LEO satellite, but the necessary updates can be derived after the analysis. The remote sensing antennas of the UAV are selected with a gain of 21 dB throughout the analysis, a reasonable assumption. The sense & avoid antennas can easily have a higher gain, given that an azimuth scanning is foreseen, and so computing the sensitivity of the sense & avoid system with the gain of the remote sensing antennas can be understood as a worst case for the system. The objective of this subsection is to show that using reasonable radar satellites and airborne receivers, the resulting system can provide very good performance for both tasks.

4.2.3.1 MEO constellation with global coverage (15 satellites)

For a given instant, Figure 5-2 shows the number of satellites which are covering the different Earth regions: one satellite (red), two satellites (blue), three satellites (green), and four satellites (yellow).

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Performance analysis for remote sensing (RS) operation

For establishing the performance of the system, we can no longer focus on a single point. The analysis has to necessarily be focused on a worst/best case approach.

Range resolution

Since we cannot say anything on the incidence angle of the UAV, we will make the computations for a UAV incident angle of 45 deg, somewhere in the mid-range of the swath. Moreover, both backward (best) and forward (worst) scattering are considered. Figure 5-3 shows the histogram for the obtained resolutions in the backward (left) and forward (right) scattering cases.

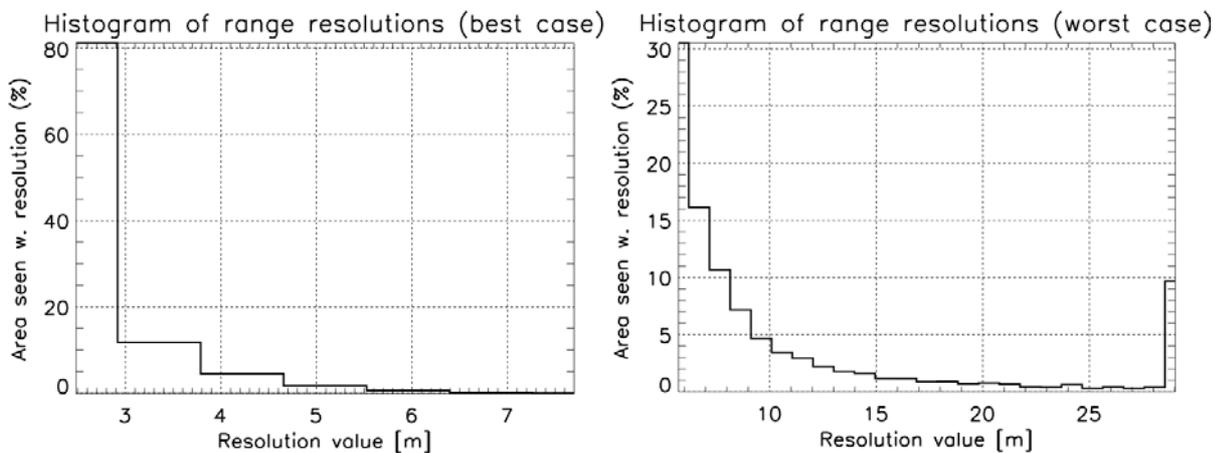


Figure 5-3 Range resolution histograms computed for backward (left) and forward (right) scattering cases. The histograms show the percentage of the covered area imaged with the corresponding range resolution.

The plots show the percentage of the Earth imaged with the corresponding range resolution. The last bin of the histogram has to be understood as that resolution or worse. We see that in both cases, (around 93% for the backward scattering case, around 50% for the forward scattering case), the majority of the Earth is imaged with the two best available range resolutions. Taking the reference of 10 m for the worst case of the range resolution, we see that values of 100% and 70% of the Earth for backward and forward cases, respectively, are attainable. Remember this figures correspond to a transmitted bandwidth of 100 MHz. Should this transmitted bandwidth be doubled, the corresponding range resolutions should be halved.

Synthetic resolution

Due to the orbit height, the synthetic resolution depends mainly on the UAV trajectory with respect to the scene: UAV height and integration time. In many cases, it will be impossible to record precise ancillary data of the UAV trajectory, and therefore the integration time will be limited. The differential clock errors can also limit the maximum integration time of the system. The bistatic image of Figure 5-1 was computed with an integration time of almost 3 seconds without the need of autofocus techniques. Therefore, an integration time of 5 seconds can be accepted as a valid reference for the system. In the worst case (UAV height of 25 km), this integration time yields a synthetic resolution of around 4 m (slightly worse than TerraSAR-X operating in stripmap mode, and significantly better than Sentinel-1 in the same mode).

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Sensitivity

With respect to Figure 3-18, the sensitivity analysis has to include the decrease in resolution of the final image, as well as the reduced duty cycle (pulse duration is set to 15 μ s). The NESZ value is 3 dB, 23 dB worse than what is expected for proper operation of the remote sensing system.

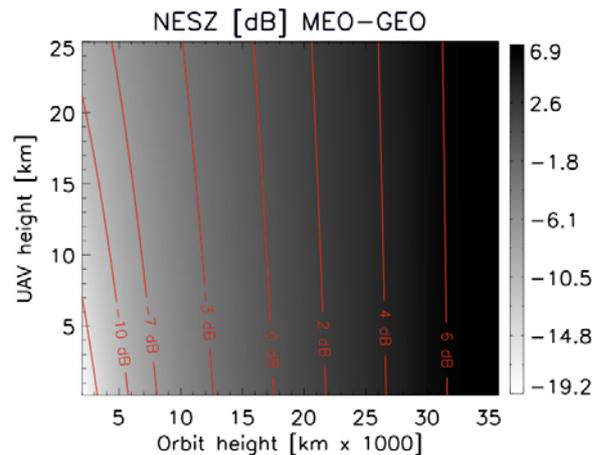


Figure 5-4 NESZ obtained for a Sentinel-1-like satellite placed on the MEO constellation proposed for the system. No parameter of Sentinel-1 has been changed, and the resolution has been worsened so that it matches the 5 m in range and 4 m in the synthetic direction. Pulse duration is set to 15 μ s.

The previous result should not be frightening, since it is what is expected from placing a LEO-designed satellite at a distance around 35 times higher from the target. The following parameters of Sentinel-1 can be changed:

- The utility of an active antenna (like Sentinel-1) is of much less use for a MEO satellite. Using a parabolic reflector with a diameter of 12 m (Sentinel-1 azimuth length), increases the transmit gain around +13 dB. A diameter of 15 m yields an improvement of about +17 dB.
- Increasing the duty cycle from 15% to 20% improves the NESZ in 1.3 dB.
- Transmitting 10 kW instead of 4.5 kW improves NESZ in around 3.5 dB.
- There exists the possibility of increasing the receiver antenna gain to match the requirement of -20 dB. An increase of gain of 6 dB is achieved using a 4 times larger antenna surface. The surface of an aperture of 26 dB gain is around 0.12 m². This solution corresponds to the use of a 12 m reflector without increasing the average power of Sentinel-1.

The previous values correspond to those of a pulsed radar. If a continuous-wave radar is used (swath width limitations should not be a problem for the foreseen applications), the transmit peak power could be dramatically reduced.

Performance analysis for sense & avoid (SA) operation

Range and Doppler resolutions

As we have seen in the system feasibility study, range and Doppler (velocity) resolutions do not pose a major problem in the performance of the system, and using the values of transmitted bandwidth and

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PRF derived for remote sensing (and unambiguous scanning of range swath and velocity range), sufficient values (cf. Figures 3-19, 3-20) are foreseen.

Sensitivity

Using the same values for which the standard NESZ was computed, and assuming an integration time of 0.1 s, enough for yielding an acceptable velocity resolution, the SNR of the detected echoes is shown in Figure 5-5.

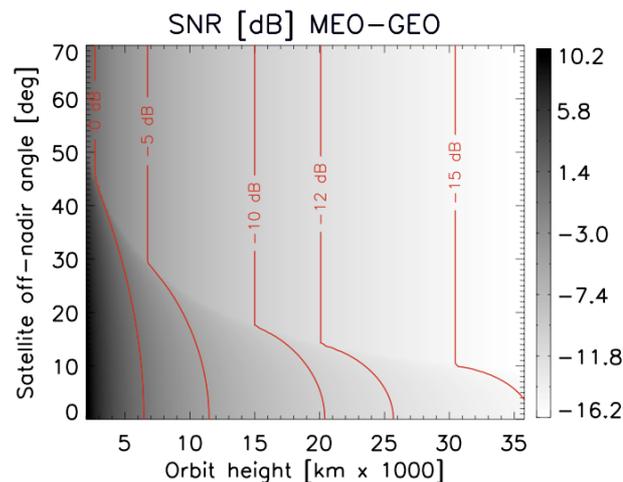


Figure 5-5 SNR of the detected echoes obtained for a Sentinel-1-like satellite placed on the MEO constellation proposed for the system. No parameter of Sentinel-1 has been changed. Doppler integration time of 0.1 s, and pulse duration is set to 15 μ s.

I remind that an SNR of -12 dB is not frightening, since we have just put Sentinel-1 on a MEO orbit, and thus the SNR decrease is expected. Moreover, the presented case is undoubtedly a worst case, because the sense & avoid antennas can easily have a higher gain than the remote sensing ones, as well as the integration time can be easily increased by a factor 2-to-3 without significant impact in performance. If the system is matched, so that the 23 dB for remote sensing are compensated, then the worst case scenario of a 1 m² RCS target at around 30 km would be detected with an SNR higher than 10 dB, largely sufficient for having a small constant false alarm rate.

4.2.3.2 MEO constellation with polar region coverage (5 satellites)

This configuration requires a smaller number of satellites, and guarantees a constant coverage of the polar regions. Analogously to the analysis of presented in 5.4.1, a snapshot of the density of satellites with which the covered area is covered is presented in the following Figure, where the color coding corresponds to: one satellite (red), two satellites (blue), not covered (white).

Performance analysis for remote sensing (RS) operation

An analogous analysis to that of the previous subsection is performed.

Range resolution

An analogous analysis to that of Figure 5-3 yields the results presented in Figure 5-5. The global behavior of the 15 satellites constellation is preserved, and the most of the covered area is imaged with the best available range resolution values. However, overall performance is worse for the 5

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satellites constellation due to the availability of fewer satellites (thus less possible incident angles) for choosing the best possible bistatic image configuration.

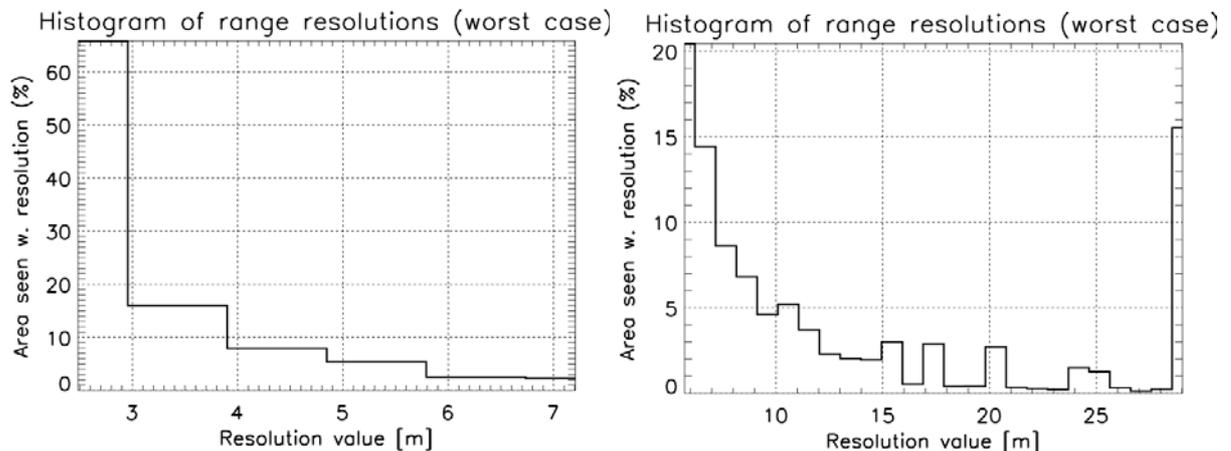


Figure 5-5 Range resolution histograms computed for backward (left) and forward (right) scattering cases (5 satellites constellation). The histograms show the percentage of the covered area imaged with the corresponding range resolution.

Synthetic resolution

The same reasoning and values than for the 15 satellites case apply.

Sensitivity

The same reasoning and values than for the 15 satellites case apply.

Performance analysis for sense & avoid (SA) operation

The same reasoning and values than for the 15 satellites case apply.

4.2.3.3 Proposed system using MEO constellation

Let me remind you that we have somehow gone an inverse reasoning for designing the system. We start from an existing LEO platform, put it on a MEO orbit at an altitude 35 times higher, and check what performance we get; then we redesign the system so that the desired performance is achieved using a dedicated MEO platform. Based on the sensitivity part of 5.4.1.1, we have selected the following modifications for the MEO system

- A parabolic reflector with diameter 14 m is mounted on the transmitter. The resulting NESZ by using this kind of antenna becomes -13 dB.
- The transmitted average power (either peak power or duty cycle) is increased by 2 dB. This results in transmitting 7 kW for the same duty cycle or increasing the duty cycle to 23% for the same transmitted power, as well as all the possible combinations of both factors.
- The receive antenna gain is increased by a factor of 5 dB, so resulting in a receive antenna gain of 26 dB, which corresponds to an antenna surface of 0.12 m².

The previous values allow the achievement of the -20 dB NESZ requirement. The parameters of the

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example MEO system are listed in Table 4-12.

| | |
|--------------------------------|--------------------------|
| Orbit height | 25000 km |
| Centre frequency | 5.405 GHz |
| Transmitted bandwidth | 100 MHz |
| Transmitted power | [4.5 – 7] kW |
| Duty cycle | < [23 – 15] % |
| Satellite incident angle range | [20 deg, 60 deg] |
| Antenna size (Tx) | 14 m parabolic reflector |
| Antenna size (Rx) | 0.12 m ² |
| Average power | 1.035 kW |

Table 4-2 Parameters of the MEO system example

Conclusion

5 Conclusion

We have presented the critical parameters affecting the performance of a dual-purpose system based on a bistatic radar with spaceborne illumination. The system is foreseen to provide sense & avoid information to flying UAVs and for allowing silent high-resolution imaging capabilities. As expected, two requirements oppose: a) constant coverage requires either an enormous amount of satellites or very high orbits, and b) good sensitivity requires either huge transmitted powers or close acquisitions. Resolution is considered as “what can be achieved”, once the trade-off is made.

Two different realistic systems have been analyzed:

- System for remote sensing only using an existing SAR LEO platform like Sentinel-1 or TanDEM-X. Results of actual campaigns performed by DLR have been shown.
- System for remote sensing and sense & avoid using a MEO (Galileo-like) constellation consisting of 15 satellites (global coverage) or of 5 satellites (partial coverage including continuous coverage of the polar regions). The imaging capabilities are compromised, but still yield performance values comparable to state-of-the-art spaceborne systems operated in stripmap modes. The use of a continuous-wave illuminator has to be considered as an option to reduce the transmitted peak power, which is anyway in the same order of magnitude to existing LEO radar satellites.



Annex A: Abbreviations

Annex A: Abbreviations

| | |
|--------|--|
| ACAS | Aircraft Collision and Avoidance System |
| ACQ | Acquisition Radar |
| ADS-B | Automatic Dependent Surveillance Broadcast |
| AOPA | Aircraft Owners and Pilots Organization |
| APC | Armored Personnel Carrier |
| ATCRBS | Air Traffic Control Radar Beacon System |
| CPA | Closest Point of Approach |
| ELOS | Equivalent Level of Safety |
| FAR | Federal Aviation Regulations |
| GCI | Ground-Controlled Intercept Radar |
| GPWS | Ground Proximity Warning System |
| HALE | High Altitude, Long Endurance |
| ICAO | International Civil Aviation Organization |
| ICBM | Intercontinental Ballistic Missile |
| IFR | Instrument Flight Rules |
| MALE | Medium Altitude, Long Endurance |
| MBT | Main Battle Tank |
| MSV | Missile Support Van |
| MTOW | Maximum Take-Off Weight |
| NESZ | Noise Equivalent Sigma Zero |
| NIIRS | NATO Imagery Interpretability Rating Scale |
| OCAS | Obstacle Collision Avoidance System |
| PCAS | Portable Collision Avoidance System |
| RA | Resolution Advisory |
| RTP | Rail Transfer Point |
| SAM | Surface to Air Missile |
| SS | Submarine |
| SSBN | Nuclear Ballistic Missile Submarine |
| SSN | Nuclear Submarine |
| TA | Traffic Advisory |
| TAWS | Terrain Awareness and Warning System |
| TCAS | Traffic Alert and Collision Avoidance System |
| TEL | Transporter Erector Launcher |
| VFR | Visual Flight Rules |

B

Annex B: Definitions

Annex B: Definitions

Annex C: References

Annex C: References

Applicable Documents

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