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Authors of the document

Name/Beneficiary	Position/Title	Date
Pavel Klang / HI sro	Project member	22/08/2018
Jan Cigánek/HI sro	Project member	11/09/2018
Petr Cásek/HI sro	Project coordinator	

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date
Elena Simona Lohan/TUT	Project member/Assoc. Prof at TUT	13/10/2018
Jukka Talvitie/TUT	Project member	16/10/2018
Luboš Korenčiak/HI sro	Project member	16/10/2018
Václav Mareš/HI sro	Project member	17/10/2018

Approved for submission to the SJU By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date
Petr Casek/HI sro	Project coordinator	26/10/2018

Rejected By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

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EMPHASIS

EMPOWERING HETEROGENEOUS AVIATION THROUGH CELLULAR SIGNALS

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Abstract

The key objective of the project EMPHASIS (EMPowering Heterogenuous Aviation through cellular SIgnalS) is to increase the safety, the reliability, and the interoperability of General Aviation/Rotorcrafts (GA/R) operations both with commercial aviation and with emerging drones' operations. These aspects are foreseen as critical elements to secure and improve airspace access for GA/R users in future airspace environment and to improve operational safety of their operations. This document investigates the operation needs for low-cost cooperative surveillance for different airspace users and discusses properties of this surveillance.

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1 Introduction

The key objective of the project EMPHASIS (EMPowering Heterogenuous Aviation through cellular SIgnalS) is to increase safety, reliability and interoperability of General Aviation/Rotorcrafts (GA/R) operations taking into account interoperability both with commercial aviation and with emerging drone operations. These aspects are foreseen as critical elements to secure and improve airspace access for GA/R users in future airspace environment and improve operational safety of operations in such environment.

Although the applicability and benefits of technological research conducted within the project EMPHASIS is expected to be broader, there are three main use cases driving the research activities:

- GA/R aircraft flying in airspace G focusing primarily on the risk of mid-air collisions among GA aircraft and in the future also with unmanned aircraft.
- Rotorcrafts flying bellow 500ft are facing typically challenges resulting from possible degradation of GNSS navigation as well as from potential conflicts with emerging drone operations (U-space).
- GA/R aircraft flying in terminal area focusing on risk of mid-air collisions with commercial aviation.

The purpose of the WP6 in EMPHASIS project is to investigate the surveillance functions addressing operational challenges of the above use cases, in particular risks of mid- air collisions with different types of airspace users and detection of various type of obstacles. This document concludes a first step describing state-of-the art as a starting point of WP6 and the initial concept with planned next steps.

1.1 Glossary of terms

- **Separation:** Maintaining a specific minimum distance between an aircraft and another aircraft or terrain to avoid collisions, normally by requiring aircraft to fly at set levels or level bands, on set routes or in certain directions, or by controlling an aircraft's speed.
- **Clearance:** Permission given by ATC for an aircraft to proceed under certain conditions contained within the clearance.
- **Type of flight:** Aircraft can operate under visual flight rules (VFR) or instrument flight rules (IFR). There is also an intermediate form, special visual flight rules (SVFR).
- **Air traffic control service:** A service provided for purpose of preventing collisions between aircraft, and on the manoeuvring area between aircraft and obstructions; and expediting and maintaining an orderly flow of air traffic.
- **Traffic avoidance advice:** Advice provided by an air traffic services unit specifying manoeuvres to assist a pilot to avoid a collision.
- **Traffic Information:** Information given by ATC on the position and, if known, on the intentions of other aircraft likely to pose a hazard to flight.

- **Air traffic advisory service:** A service provided within advisory airspace to ensure separation, in so far as practical, between aircraft which are operating on IFR flight plans.
- **Flight information service:** A service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights.
- **Wake vortex (turbulence):** A turbulence which is generated by the passage of an aircraft in flight. It will be generated from the point when the nose landing gear of an aircraft leaves the ground on take off and will cease to be generated when the nose landing gear touches the ground during landing (definition adopted from Skybrary).

1.2 List of Acronyms

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
ATC	Air Traffic Control
CAA	Civil Aviation Authority
CAT	Commercial Air Transport
COTS	Commercial off-the-shelf
EC	Electronic Conspicuity
EASA	European Aviation Safety Agency
ELS	Elementary Surveillance (Mode S)
(E)GPWS	(Enhanced) Ground Proximity Warning System
EHS	Enhanced Surveillance (Mode S)
FIS-B	Flight Information Service – Broadcast
FL	Flight Level
GA	General Aviation
GA/R	General Aviation/Rotorcraft
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization

IFR	Instrumental Flight Rules
MTOM	Maximum Take-Off Mass
RC	Radio Communications
SSR	Secondary Surveillance Radar
SVFR	Special Visual Flight Rules
TAS	Traffic Advisory System
TAWS	Terrain Awareness and Warning System
TCAS	Traffic alert and Collision Avoidance System
TIS-B	Traffic Information Service – Broadcast
TSAA	Traffic Situational Awareness with Alerts
UAT	Universal Access Transceiver
UAV	Unmanned Aerial Vehicle
UTM	UAV Traffic Management
VFR	Visual Flight Rules
VHF	Very High Frequency

1.3 Background: Automatic Dependent Surveillance – Broadcast

Automatic dependent surveillance broadcast (ADS–B) is a surveillance technology in which an aircraft broadcasts periodically its position and other information. No external stimulus is required (that's why it is automatic), but it relies on on-board navigation sources (GNSS) and on-board broadcast transmitting subsystems (that's why it is dependent) in order to provide surveillance information to other users. There are several frequencies which can be used to transmit ADS-B messages (1090 MHz for mode S extended squitter, 978 MHz for UAT, and/or some VHF frequencies (117.975–137 MHZ). We focus on European airspace where only 1090 MHz extended squitter is used and therefore the remaining of this section is inspired by the related standard RTCA DO-260B [5].

ADS-B system includes two main components: message generation/transmission by the source aircraft and message reception/report assembling by the user. The ADS-B system does not include the sources of the data to be sent by the source subsystem, neither does it include the client applications which use the information received by the ADS-B user subsystem. We call the transmit functionality as ADS-B Out and the receive functionality as ADS-B In.

1.3.1 ADS-B Out system

The ADS-B Out system consist of a message generation function and a transmitting message exchange function. It takes position, velocity, time, status, and intent inputs as well as data quality indicators from other on-board systems and transmits this information on the 1090 MHz frequency as Mode S extended squitter messages. The ADS-B Out system includes the input interface, message assembly, encoding functions, the radio modulator/transmitter, and 1090 MHz transmitting antenna. It may be implemented either using Mode S secondary surveillance radar transponder (in that case the squitters use Downlink Format 17 – DF=17), or using Non-Transponder-Based 1090 MHz transmitting equipment (the squitters use DF=18, so the ADS-B In system will know that the message comes from equipment that cannot be interrogated).

1.3.2 ADS-B In system

ADS-B In system consists of a receiver function and a report assembly function. It takes ADS-B Mode S extended squitter messages, processes them, and outputs information to other systems. It includes the 1090 MHz receiving antenna and radio receiver/demodulator.

1.3.3 ADS-B message

ADS-B message contains 112 bits of which 56 bits contain the various navigation, intent, and other data comprising the ADS-B information. The remaining 56 bits contain the aircraft address as well as required forward error correcting parity information.

There are several message types with different broadcast rate (see Table 1). The highest rate of 2 Hz is for Airborne position and velocity messages. The exact content of the messages is defined in sections 2.2.3.2.3 and following ones in [5].

There are three key ADS-B messages used for traffic surveillance:

- airborne position message: altitude, latitude, longitude, and quality indicators describing accuracy and integrity of the reported position information (NIC, NACp)

- airborne velocity message: E/W and N/S velocity and its direction, vertical rate and its sign, and quality indicator describing accuracy of the reported velocity (NACv), and
- aircraft identification and category message: emitter category and call sign.

1090ES ADS-B Message	Broadcast Rate		
	On-the-Ground, not moving	**On-the-Ground and moving**	**Airborne**
Airborne Position	N/A	N/A	2 / 1 second (0.4 – 0.6 sec)
Surface Position	LOW RATE 1 / 5 seconds (4.8 – 5.2 sec)	HIGH RATE 2 / 1 second (0.4 – 0.6 sec)	N/A
Aircraft Identification and Category	LOW RATE 1 / 10 seconds (9.8 – 10.2 sec)	HIGH RATE 1 / 5 seconds (4.8 – 5.2 sec)	HIGH RATE 1 / 5 seconds (4.8 – 5.2 sec)
Airborne Velocity	N/A	N/A	2 / 1 second (0.4 – 0.6 sec)
Aircraft Status (Emergency/Priority Status, Subtype=1) (TCAS RA Broadcast, Subtype=2)	TCAS RA or Mode A Code Change 0.7 – 0.9 seconds		
	No TCAS RA, No Mode A Change 4.8 – 5.2 seconds		
	No TCAS RA, No Mode A Change, No Emergency, Mode A Code set to 1000_8 No Transmission		
Target State and Status (TSS)	N/A	N/A	1.2 – 1.3 seconds
Aircraft Operational Status	4.8 – 5.2 seconds	No change NIC_{SUPP}/NAC/SIL 2.4 – 2.6 seconds	TSS being broadcast or not No change TCAS/NAC/SIL/NIC_{SUPP} 2.4 – 2.6 seconds
		Change in NIC_{SUPP}/NAC/SIL 0.7 – 0.9 seconds	TSS being broadcast Change in TCAS/NAC/SIL/NIC_{SUPP} 2.4 – 2.6 seconds
			TSS not broadcast [2] Change in TCAS/NAC/SIL/NIC_{SUPP} 0.7 – 0.9 seconds

Table 1: ADS-B Messages broadcast rates (part of table 2-79 in [5])

ADS-B Report refers to standardized consolidation of ADS-B Messages data received from a 1090MHz broadcast into various reports that can be used directly by other on-board application. Four reports are defined: State Vector (SV), Mode Status (MS), Target State Report (TSR), and Air Referenced Velocity (ARV) Report.

1.3.3.1 State Vector Report

The State Vector (SV) Report contains information about an aircraft current kinematic state as well as a measure of the accuracy of the SV. The SV data is the most dynamic of the four ADS-B reports. Hence the applications require frequent updates to meet the required accuracy for the operational dynamics of the typical flying aircraft.

1.3.3.2 Mode Status Report

The Mode Status (MS) Report contains current operational information about transmitting participants (e.g., call sign or address) that may be needed at lower update rate than information in SV.

1.3.3.3 Target State Report

The Target State (TS) Report contains information that will be broadcast when current Target State information is available.

1.3.3.4 Air Referenced Velocity Report

The Air Referenced Velocity Report contains velocity information that may be broadcasted by certain classes of ADS-B equipped aircraft.

1.3.4 Equipage Class Categories

ADS-B equipment is categorized into aircraft system equipage classes as defined in Table 2-1 of RTCA DO-260B [5] and ADS-B message coverage for Class A Transmitter Equipment in Table 2 (a copy of Table 2-3 from [5]).

Transmitter Class	Minimum Transmit Power (at Antenna Port)	MASPS Requirement (RTCA DO-242A)	Minimum Message Capability Required (From Table 2-2)
A0 (Minimum)	70 W	SV MS	Airborne Position A/C Identification & Category Airborne Velocity A/C Operational Status Extended Squitter A/C Status
		SV MS	Surface Position A/C Identification & Category A/C Operational Status Extended Squitter A/C Status
A1S/A1 (Basic)	125 W	SV MS	Airborne Position A/C Identification & Category Airborne Velocity A/C Operational Status Extended Squitter A/C Status
		SV MS	Surface Position A/C Identification & Category A/C Operational Status Extended Squitter A/C Status
A2 (Enhanced)	125 W	SV MS TS TC+0	Airborne Position A/C Identification & Category Airborne Velocity A/C Operational Status Extended Squitter A/C Status Target State and Status Reserved for TC Message
		SV MS	Surface Position A/C Identification & Category A/C Operational Status Extended Squitter A/C Status
A3 (Extended)	200 W	SV MS TS TC+n	Airborne Position A/C Identification & Category Airborne Velocity A/C Operational Status Extended Squitter A/C Status Target State and Status Reserved for TC Message
		SV MS	Surface Position A/C Identification & Category A/C Operational Status Extended Squitter A/C Status

Table 2: ADS-B Class A Transmitter Equipment To Message Coverage – table 2-3 from [5]

1.3.5 Regulation

ADS-B Out provides large benefits for ATM environment and other users, and it is therefore mandated in several regions. For US, all aircraft flying above FL100 are required to be equipped with ADS-B Out after December 31, 2019. In Europe, ADS-B Out is mandated for all aircraft (IFR flights, Maximum Take-Off Weight (MTOW) greater than 2700kg or max cruising speed above 250kt) with certificate of airworthiness issued on or after January 8, 2015. The mandate is valid from June 7, 2020 for older aircraft.

In general, the mandate does not apply to most GA/R users in Europe. The fact that ADS-B Out capability is not required for all users represents an important limitation both for modernisation of ground surveillance infrastructure and for on-board safety systems.

The technology is used in commercial aviation and it is expected to be used even more in near future. Deployment of a compatible technology outside the mandate would be therefore very beneficial. Unfortunately, certified ADS-B Out solutions are not suitable to some segments of GA community which limits voluntary installations, key limitations being:

- Affordability: the price of the certified ADS-B Out solution is not affordable for most of the GA users.
- Power consumption: for some users the device should be able to operate on batteries.
- Portability: for some users it needs to be small and lightweight, portable from one aircraft to another one with no regulatory barrier.

Another potential issue for the future airspace environment is related to possible spectrum congestion: if all small airspace users are equipped with high power ADS-B Out it may lead to 1090 MHz spectrum congestions.

1.4 Background: Obstacle Detection

The operational risk of collision with ground based obstacles is for GA considerably reduced through application of Rules of the Air [32]. According to the latter, the GA aircraft is not allowed (outside of airport or terminal area) to fly below 500 ft, in many countries this limit being even higher. The typical hazard associated with the ground (common for GA and rotorcrafts) is then represented by a Controlled Flight Into Terrain (CFIT) mostly during descent and take off.

For rotorcrafts, the situation is considerably different due to their operational versatility. This is due to the fact that their operations are ranging from relatively safe helipad-to-helipad operations to demanding and dangerous operations, which include low level manoeuvring, landings and take-offs in urban and/or space restricted areas. Intentional or accidental very low-level operations obviously introduce considerable risks of collision with low and small obstacles (e.g., wires) or terrain.

Finally, the emerging drone market results in an increasing risk of mid-air collision with these new airspace users below 500 ft. Due to the procedural limitations described above this risk is reduced for GA but very relevant for rotorcraft operations.

1.4.1 Existing Surveillance Solutions

The main mitigation mean for CFIT in todays' aviation is Terrain Avoidance and Warning System (TAWS). This on-board equipment is designed as a safety net providing pilot with alerts in case of potentially dangerous proximity of terrain. Originally, it was used only for information from radar altimeter, but the system was progressively evolving and after the introduction of Enhanced Ground Proximity Warning System (EGPWS) as an implementation of TAWS by Honeywell in 1997, it started to commonly use GPS position, a regularly updated terrain database, and radar altimeter data[1] for providing the standardized set of alerting functions. Currently there are two classes (A and B) of TAWS where class A (mandated for large aircraft) includes display and has larger set of alerting functions.

TAWS is not mandated for aircraft with Maximum Take Off Weight (MTOM) less than 5700kg and less than 9 passengers. TAWS Class B is mandated for helicopters operating under Instrumental Flight Rules (IFR) with MTOM greater than 3175kg and more than 9 passengers. For smaller aircraft/helicopters TAWS (Class B) is only recommended.

As described above TAWS is primarily intended to protect against CFIT during common aircraft operations. It means that it focuses on the area around the airports where the database resolution is higher than in remote areas. In this context, it provides only limited support for low-altitude rotorcraft operations.

Considering smaller, mobile/flying obstacles, or non-cooperative aircraft, there is not any commonly used solution in today's civil aviation of this risk, except pilot's eyes and see-and-avoid principle. The

[1] On top of this there are some additional information such as airplane configuration or ILS deviations used as well in the alerting logic

existing mitigations are typically procedural, e.g., flying only above 500 ft, or segregating different types of traffic. These mitigations are well applicable for GA/R in normal situation but are not effective in cases of intentional or accidental operations below 500 ft which are not rare for rotorcrafts.

2 Low cost ADS-B

2.1 Introduction – State of Art

A wide deployment of ADS-B surveillance has the potential to bring many benefits to all airspace users. The largest disadvantages of the certified ADS-B Out systems for GA users are cost, power consumption, and size.

In the context of possible cooperative surveillance for GA it is important to mention the extensive work about Electronic Conspicuity devices done by the UK Civil Aviation Authority (document CAP 1391) which covers many interesting elements. Electronic Conspicuity (EC) is an umbrella term for a range of technologies that can help airspace users to be more aware of other aircraft in the same airspace. It includes transponders and radios. At the most basic level, the aircraft equipped with an EC device effectively signal their presence to other airspace users, turning the 'see-and-avoid' concept into 'see, BE SEEN, and avoid.' Many EC devices also receive the signals from others. This then alerts pilots of the presence of other aircraft which may assist the pilots to visually acquire and avoid other aircraft as necessary.

2.1.1 Use of COTS Components

Cost reduction may be potentially achieved through the use of COTS (Commercial Off-The-Shelf) components, e.g., for GNSS receiver. COTS use would need to be reflected in quality indicators provided in ADS-B messages.

Within EC device it is not necessary to use a certified position source but in case of COTS (Commercial Off-The-Shelf) position source, the reported quality indicators NIC (Navigation Integrity Category), NACv (Navigation Accuracy Category - Velocity), SIL (Surveillance Integrity Level), SDA (System Design Assurance) should be set to 0, NACp (Navigation Accuracy Category - Position) could be set to 0 or according to the HFOM (Horizontal Figure of Merit).

A specified surveillance system (providing ADS-B Out function) which allows use of COTS position source (with some additional requirements) is the Traffic Awareness Beacon System (TABS) class B. In case of TABS class B position source, NIC could be set to the value up to 6, NACp depending on HFOM, NACv to 1, SIL to 1, and SDA to 0.

	COTS	TABS B
NACp	0/HFOM	HFOM
NACv	0	1
SIL	0	1
NIC	0	up to 6
SDA	0	0

Table 3: EC quality indicators depend on position source (COTS vs TABS B)

Data quality indicators are an effective way to influence how the broadcasted data will be used. Each ADS-B IN application has typically a set of minimal eligibility criteria which needs to be satisfied in order that the received ADS-B data are used in the application. For reference, the list of minimal requirements for different application as defined in RTCA DO-317B, table 2-4 is provided below:

	ATSA-AIRB/TSAA	ATSA-SURF	VSA	ITP	CAVS	ACAS Xa*
NACp	7,5	5,6,7,9	6	5	7	7
NACv	1	2	1	1	1	1
SIL	N/A	N/A	1	2	3	3
NIC	N/A	N/A	6	5	6	6
SDA	1	1	1	1	2	N/A

Table 4: Minimal requirements for quality indicators needed for standardizes ADS-B IN applications: Air Traffic Situation Awareness during flight operations (ATSA-AIRB) and on the airport surface (ATSA-SURF), enhanced Visual Separation on Approach (VSA), In-Trail Procedure (ITP) or CDTI (Cockpit Display of Traffic Information) Assisted Visual Separation (CAVS). ACAS Xa is the next generation airborne collision avoidance system.

A CAP 1391 compatible device also uses messages downlink format DF=18 (instead of DF=17 used by transponders), which ensures that ADS-B In system will know that the message comes from equipment which cannot reply to interrogations.

2.1.2 Transmission Characteristics

The specified transmit power for low cost ADS-B device should consider three aspects:

- power consumption – ideally the device should be suitable for light aircraft/parachutes with limited power supply or without possibility to use external power. Fewer messages and/or lower power results in longer endurance.
- detectability – higher power enables longer detection range. But it is not usually necessary for GA aircraft or drones to be visible at large distances.
- 1090MHz congestion – higher power results in the additional messages impacting a larger area. A higher number of broadcasted messages represents a stronger impact on frequency load.

According to the standard DO-260B, the minimum RF peak output power shall be 18.5 dBW (70 W) for smaller aircraft or 21 dBW (125 W) for larger aircraft. For the EC device, the maximum RF peak output power of each pulse of each transmitted message at the antenna terminals of the EC device shall not exceed 16 dBW (40W). The EC device could be an ADS-B out like system which cannot be certified according the DO-260B as it transmits with less power than required.

Concerning detectability, the range where the power level drops below TCAS Minimum Triggering Level (MTL) of -74dBm[2] is about 16NM for 70W transmitter, 12NM for 40W transmitter, and 2NM for 1W transmitter.

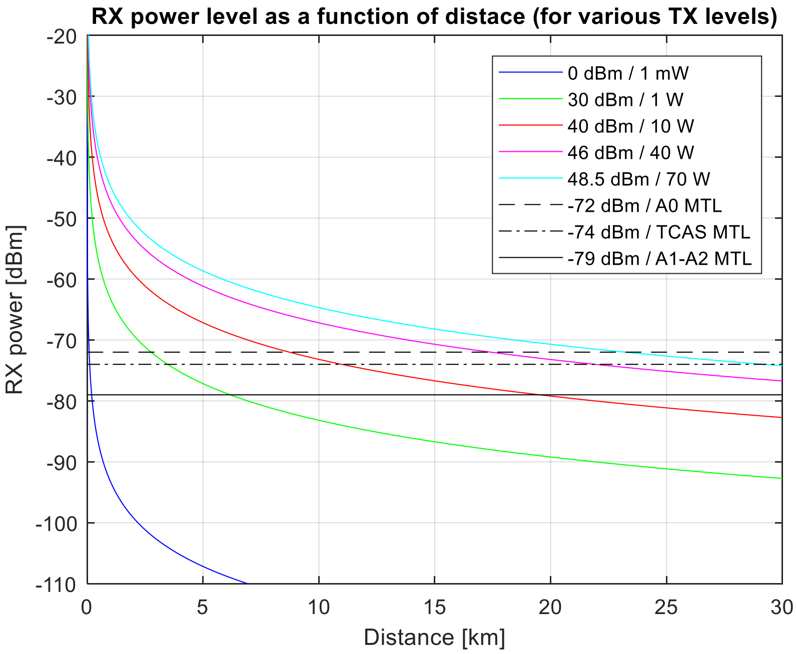

Figure 1: Received power level as a function of distance (for various transmitted power levels and various receiver classes).

When addressing the risk of spectrum congestion there are three complementary mitigations that can be considered:

- Transmit at lower power – we expect that small GA/R/drones would need to transmit less power to be visible at the appropriate range than much faster air transportation.
- Reduce the number of message types – for instance it may not be necessary to broadcast the velocities for vehicles which either move very slowly (balloons) or which change the velocity quite often (multicopters).
- Reduce the number of messages per second – especially in situations, where there is no other vehicle in the vicinity, it may not be necessary to broadcast the position messages at nominal 2Hz. It could be sufficient to reduce it for instance ten times to one position message every 5 second (same as reduced mode of Mode S surveillance standardized in DO-185 [4]). On the other hand, a big reduction in the broadcast rate could lead to inability for some systems to maintain tracking of the aircraft with infrequent messages. In any case, the maximum ADS-B

[2] Many existing systems have in reality MTL -79 dBm or better which would allow to further reduce power requirements.

message transmission rate shall not exceed 6.2 transmitted messages per second. You can find the broadcast rate for different 1090MHz ADS-B messages in table 2-79 in DO-260B [5].

One of the main research challenges addressed in this document is to determine the required transmit power. The required supported surveillance range must be defined. This required range will differ for different aircraft pairs and will mainly depend on the aircraft speed.

2.2 Use cases

The main use cases addressed by the project Emphasis are described in Initial Concept (D2.1):

- GA/R aircraft flying in Airspace G (above 500ft (~150m)) focused primarily on the risk of mid-air collisions among GA aircraft.
- Rotorcraft flying bellow 500ft facing challenges resulting from possible degradation of GNSS navigation and potential conflicts with emerging drone operations (U-space).
- GA/R aircraft flying in terminal area focusing on risk of mid-air collisions with commercial aviation.

These three use-cases are described in more detail in D2.1. The characteristics of GA and commercial aviation operations are known which is not the case for emerging drone operations and therefore the next chapter aims to provide some information about them.

2.2.1 Unmanned Aircraft Operations – Relevant Concept Elements

There are a lot of activities connected with emerging drone market and creating rules for drone operations in non-segregated airspace.

CORUS - Concept of Operations for U-space [1] expects all drones to emit an “e-Identification” that includes the current 3D position of the drone. The “e-identification” includes type, model, serial number of the aircraft, and identity of the operator.

CORUS assumes there will be separation minima for any pair of drones, as well as for drones vs. manned aircraft, drones vs. people, drones vs. crowds, drones vs. obstacles or structures (buildings) and drones vs. the ground (section 4.3 in [1]). However, contrary to the current definition of separation minima, CORUS considers that in the future, separation minima should depend on the properties and capabilities of the involved aircraft. Each aircraft will have a “bubble” around it and touching of these bubbles defines separation minima. The size and shape of each bubble will then depend on various factors such as the size, speed, and manoeuvrability of the vehicle, its detect-and-avoid capabilities, the risk associated with its payload, and so on.

Such pair approach is in an agreement with DLR study [2] addressing urban mobility. It also considers that UAS separation needs to be based on several aspects, not only the wake vortex classes as applied in manned aviation. New airspace users such as UAS (e.g., multicopter, helicopters, gyrocopters, fixed wing drones) and Urban Air Taxis (mostly Vertical-Take-Off-and-Landing (VTOL) or hybrid systems) differ significantly in their technical capabilities, size, manoeuvrability, and performance. Thus they require new means of modelling the safety distances required to enable safe traffic operations in a joint airspace respecting these individual airspace user characteristics.

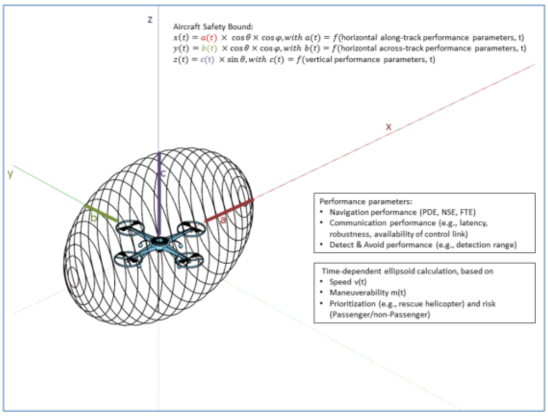

Figure 3: Aircraft Safety Bound

Figure 2: Safety bubble definition from [2]

As it can be seen from this concept the size of the safety bubble depends not only on the type of both aircraft (analogically to current situation in manned aviation, mainly dependent on the wake vortex categories) but also on the equipage of both own-ship and intruder. When the intruder is equipped with high accuracy collaborative surveillance, the separation could be smaller and at the same safety level as larger separation from non-collaborative intruder.

There are 3 axes of the safety bubble – along the track axis, perpendicular axis, and vertical axis. The length of the bubble along the first axis (i.e., along the track axis) depends on the actual speed and on the ability of changing this speed with the extreme situation to have zero speed. The other axis is connected to manoeuvrability – how quickly the aircraft can change heading/track. And the last one depends on the current vertical rate, maximum climb rate, etc.

2.3 Surveillance Range Considerations

The aim of this section is to propose performance requirements on the surveillance (detectability) range based on simplified analysis of operational needs. For purpose of this analysis, the following assumptions were adopted:

- The minimum operational requirement is that low-cost ADS-B Out capability enables collision avoidance function on-board surrounding aircraft.
- For a successful collision avoidance an aircraft must be able to avoid NMAC (Near Mid Air Collision) region which is a disk with 500ft radius and +-100ft height. In the analysis we considered a box shaped avoidance region with 1000ft horizontal and 200ft vertical side to simplify the calculations.
- Vertical avoidance manoeuvres are usually faster than the horizontal ones, partially also because NMAC region is 5 times larger in horizontal plane than in the vertical one (500ft vs 100ft). In this context the minimal detection range needed for horizontal avoidance manoeuvres are calculated in the following as they are expected to be larger than for vertical avoidance.

- Fixed-wing aircraft have worse horizontal manoeuvrability than rotorcrafts, so by estimating the time needed to avoid collision by fixed-wing aircraft we are on the safe side. We assume 20° bank angle for avoidance manoeuvers of fixed-wing aircraft.
- The worst scenario in terms of detectability requirement is head-on encounter.

For purpose of the analysis it was decided to categorize users of intended airspace (airspace G and D, with speed restriction of 250kt) based on their speed:

The proposed groups are:

- Very slow airspace users – this group contains aircraft (e.g., balloons) with maximum speed below 10kt.
- Slow aircraft – at the very low altitude (VLL airspace) it is expected that the speed usually won't exceed 100kt. In this category airspace users such as gliders or slow rotorcrafts can be found.
- Fast aircraft– vehicles with quite high maximal speed (up to 250kt limit of G-space), e.g., Cessna 172, Airbus A320, Boeing B737, etc.

The objective of the analysis is to determine minimum distance from which a conflicting aircraft needs to see own ship to be able to perform an avoidance manoeuver without any help from own aircraft.

The analysis is based on the following steps:

Step 1: Aircraft is flying against an infinite wall (static)

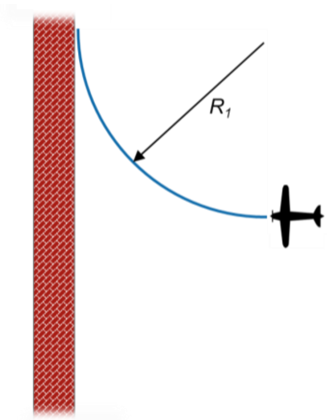

Figure 3: Aircraft flying against an infinite wall

Aircraft has to make 90° turn to avoid collision with the wall. The turn radius for fixed-wing aircraft depends on the speed and bank angle and in this way the turn radius R_1 is calculated. The aircraft has to start the turn when it is more than the radius before the wall.

Step 2: The wall is 1000ft wide (500ft to the left and 500ft to the right, still static)

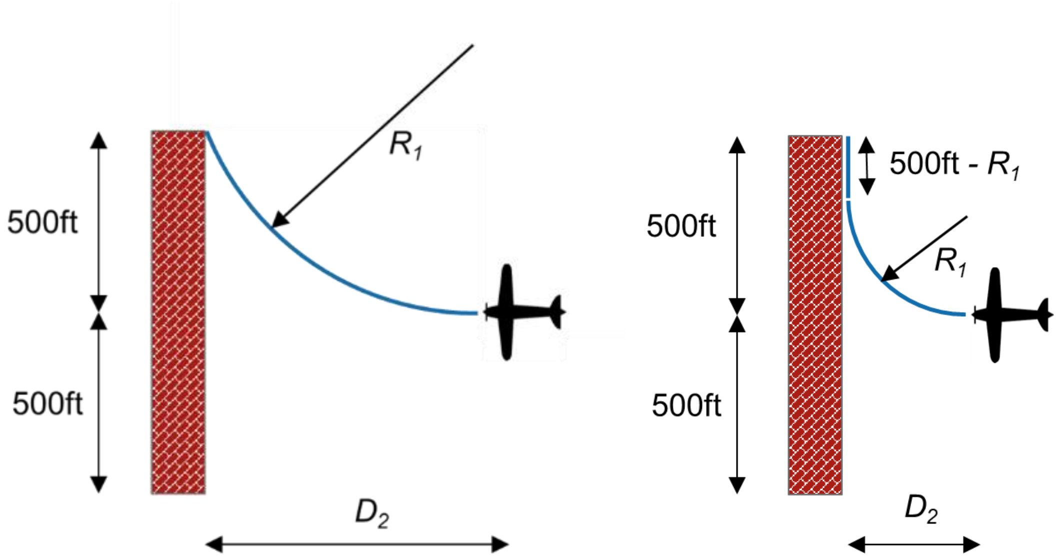

Figure 4: Aircraft flying against 1000ft wide wall

An aircraft having turn radius R_1 larger than 500ft don't need to make whole 90° turn to avoid the wall – it just needs to move 500ft off the central line. An aircraft having a smaller radius needs to continue moving forward after the 90° turn and fly distance R_1-500ft to avoid the wall. In this way the distance D_2 in front of the wall, where the aircraft has to start the turn and time t_2 it needs to avoid the wall are determined.

Step 3: The 1000ft wide obstacle (emulating NMAC zone) is moving against own-ship

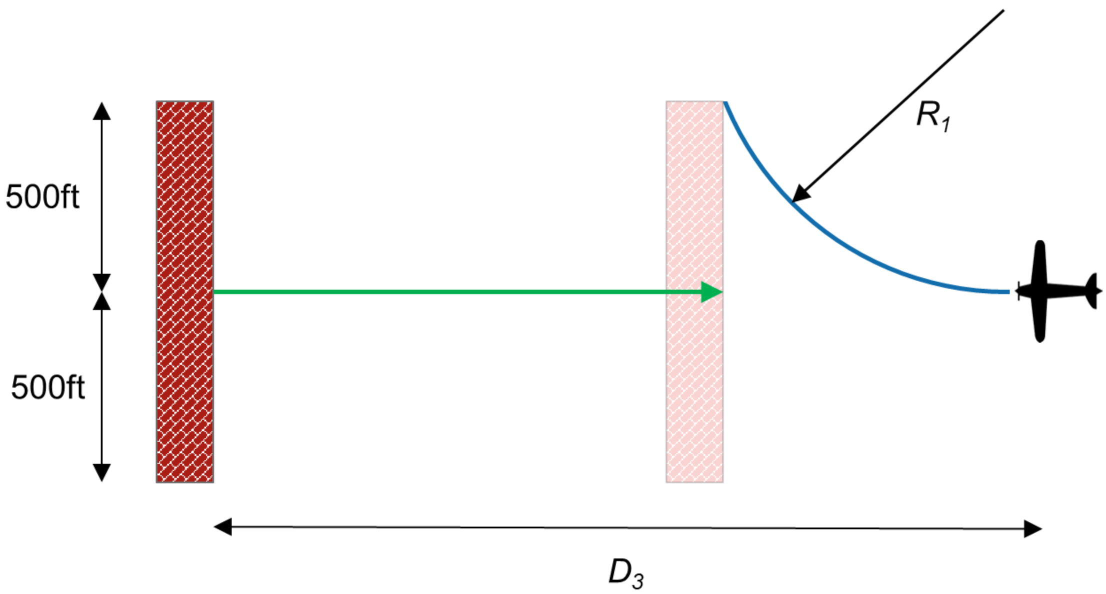

Figure 5: Aircraft flying against 1000ft wide moving wall

This scenario models a square no-entry-zone of another aircraft that is flying against own aircraft. From step 2 we know the time and distance the aircraft needs to start the turn in case of static wall. When the wall is moving, the aircraft needs to start turning at larger distance, let's call it D_3, to avoid the moving wall. The distance D_3 is larger than D_2 by the path the wall moved during time t_2.

Step 4: Aircraft with 1000ft square no-entry zone is flying against own-ship

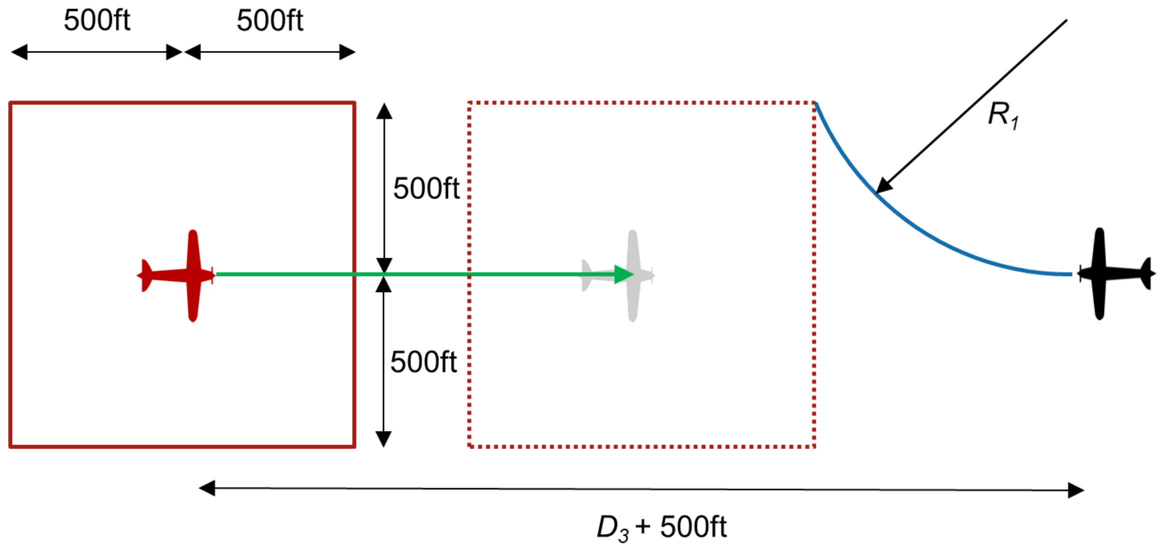

Figure 6: Head-on scenario

We need to add 500ft to the distance D_3 as the aircraft is flying 500ft behind the wall – inside the box.

In addition to the above geometrical considerations, in real life it is necessary to count with a reaction time of pilots and system on top of the time needed for avoidance manoeuver itself. In case of TCAS, a pilot reaction time of 5s is considered for initiating a requested vertical manoeuver. For GA/R operations it is considered that on-board system may not be directive and also the training of GA pilots may be different – hence we added another 5s for the pilot reaction time.

In addition, the surveillance system needs several seconds (it needs to receive few messages) to start tracking of nearby vehicles that use ADS-B Out. Altogether we considered additional 15s before an avoidance manoeuvre really starts, and the distance flown by an aircraft fly during these 15 seconds was added to D_3.

The above estimation of needed detectability distance was performed considering possible conflict between all groups of aircraft and Table 5 shows the resulting requirements on detectability range.

NM		--> Speed -->		
	Category	Very slow	Slow	Fast
	max. speed	10	100	250
<-- Speed <--	Very slow 10	0.21	1.35	3.24
	Slow 100	0.39	1.00	2.02
	Fast 250	0.79	1.39	2.40
Minimal visibility		0.8	1.4	3.3

Table 5: Detectability range (in nautical miles) for different airspace user (using their maximal operational speed in knots) pairs. Aircraft in the left column represent avoiding aircraft while groups in the top raw represent endangered (avoided aircraft).

As described above, these ranges are the minimal visibility distance needed for collision avoidance manoeuvres. Therefore these ranges do not consider needs of separation management or strategic planning. The analysis also does not consider any operational priority rules and as you can see the worst case is represented by very slow aircraft avoiding a fast aircraft (which may be equipped with a certified ADS-B anyway).

It should be mentioned than in real environment, visual acquisition of an aircraft such as Cessna from the cockpit at the distance larger than 3NM is quite challenging, so the calculated ranges seem to be comparable with visibility limits.

2.4 Recommendations and Next Steps

Our concept of affordable ADS-B transceiver for broad spectrum of airspace users (not considered in the current Implementing Regulation) is based on the following design objectives:

- The requirements on affordable ADS-B must represent a balance between operational usability of the broadcasted information and system requirements including installation complexity reflecting suitability for targeted users.
- The system requirements should be scalable taking into account targeted operational environment (and relevant risk-based analysis) and the type of aircraft as well as the potential intruders in the considered operational environment. Currently 2-3 categories of the ADS-B transceiver are envisioned.
- ADS-B for some type of users needs to be able to operate on battery and potentially in proximity of human body.
- **The minimum operational requirement is that broadcasted ADS-B information allows avoidance of NMAC on-board the conflicting aircraft** with conservative assumptions about pilot/aircraft performance.
- Broadcasted messages may not contain all elements/reports included in RTCA DO-260B compliant systems but should be compatible with DO-260B. At the same time, the reports shall be clearly distinguishable from data sent by DO-260B compliant systems. *The objective is that the messages can be easily received and decoded on-board of commercial aviation aircraft using their ADS-S B In system. The operational use of such information then needs to be controlled via eligibility criteria which allows to exclude them from the applications for which they are not intended.*
- 1090 MHz frequency needs to be used when needed for interoperability with commercial aviation but the system may use additional communication links, for instance to ensure higher integrity of broadcasted information or to handle non-nominal situations.
- Broadcasting parameters (power, update rate, number of messages) may be adapted (comparing to DO-260B) to reduce spectrum congestion taking into account traffic characteristics of the targeted operational environment.

Based on the considerations and concept presented in the previous sections, the following steps will be taken within the design phase:

- Based on Table 5 and **Figure 1** the (transmission) power of ADS-B Out transceiver for each user group will be defined aiming to consider the lowest feasible power to spare the 1090 band.
- The content and number of the messages as well as their minimum update rate needed for safe NMAC avoidance by the various types of conflicting aircraft will be defined.
- The probability of reception and 1090 MHz load will be modelled for a set of possible operational environments taking into account forecasts of low altitude traffic.

- Use of additional communication links (in particular LTE/5G) will be incorporated taking into account alternative certification concept (WP3) as well as result of overall safety analysis.

Some of the open questions to be investigated along the above steps are listed below:

- How does power consumption of the ADS-B In receiver depend on its sensitivity?
- Antenna gain for small drones?
- What sensitivity of ADS-B In receiver is the best to use? The criteria to be considered include: power consumption, ability to receive needed messages, ability to avoid signals/messages from traffic too far away, etc. Is it better to use less sensitive receiver and stronger transceiver or the opposite?
- How many airspace users of each group are acceptable in certain airspace volume to avoid collisions (NMACs) and congestion of 1090 band?
- How to ensure that data from low cost ADS-B Out device can be used for better situation awareness (e.g., to be displayed on CDTI-like displays or used for TSAA application) but they are not used for other ADS-B In application (e.g., for FIM or CAVS) where the required quality of data is higher. We can achieve this goal by reporting ADS-B out data quality parameters below the minimum level required by these ADS-B In applications.
- How much can we decrease the transmitting power? How much can we decrease the number of messages per second? These questions are already mentioned in Section 2.1.

3 Low-Cost Obstacle Detection

3.1 Introduction

Radars used in todays' civil aviation are typically X-band radars for detection of weather hazards. Although there are trends to extend capabilities of these systems also to other hazards, their Size, Weight and Power as well as Costs (SWaP-C) practically exclude their use for majority of General Aviation. The only additional airborne radar system with wider deployment in civil aviation is then radar altimeter used for measuring altitude above terrain. Data from this system are used among others for TAWS/EGPWS system discussed in Section 1.4.1.

Beyond the systems mentioned above there are new promising technologies such as various LIDAR (Light Detection And Ranging) systems, however, their costs are typically still too high for large part of GA if they should be used only for obstacle detection.

EMPHASIS concept for affordable obstacle detection is based on exploring possibility to use industrial sensors widely deployed in other industrial areas and potentially combine them with some already existing aerospace approaches.

The primary use case considered in WP6 for obstacle detection are low-altitude operations of rotorcraft with a particular focus on landing in unfamiliar area.

The secondary objective is to investigate a possible detection of non-cooperative flying objects. However, it should be clearly stated that EMPHASIS concept assumes that a primary mean for detection of surrounding traffic should be an affordable cooperative surveillance, potential obstacle detection being considered only as a safety backup for non-nominal situations.

Millimeter wave radars used commonly in automotive industry were selected as a top candidate technology to be considered for the purposes described above. In the rest of this chapter a detailed description of two selected sensors from Texas Instrument (TI) representing state-of-the-art in this area are provided.

3.2 mmWave FMCW radar

Millimeter wave (mmWave) is a special class of radar technology that uses short wavelength electromagnetic waves [6].

A complete mmWave radar system includes:

- transmit (TX) and receive (RX) radio frequency (RF) components;
- analog components such as clocking;
- digital components such as analog-to-digital converters (ADCs), microcontrollers (MCUs) and digital signal processors (DSPs).

FMCW (frequency-modulated continuous wave) radars transmit a frequency-modulated signal continuously in order to measure range, velocity, and bearing (angle) of the target.

In the signal used in FMCW radars, the frequency increases linearly with time. This type of signal is also called a chirp. [6]

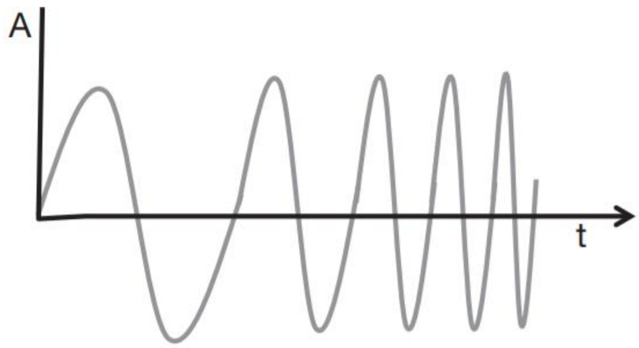

Figure 7: Chirp signal, with amplitude as a function of time [6]

An FMCW radar system transmits a chirp signal and captures the signals reflected by objects in its path. [6]

FMCW radar can be used in various applications. In automotive applications radar is used as short-range radar, long-range radar, in-cabin driver detection, parking sensors, etc.

Radar can be used in industrial applications such as drones, robotics, traffic monitoring, level sensing, etc.

3.3 IWR1642 and IWR1443 Single-Chip 76- to 81-GHz mmWave Sensor

This paragraph describes two industrial mmWave sensors IWR1642 and IWR1443. These chips are highly accurate intelligent mmWave sensors for detecting range, velocity, and angle [8][9].

Figure 8: IWR1642 and IWR1443 Single-Chips.

They are based on FMCW radar technology capable of operation in the 76- to 81-GHz band with up to 4 GHz continuous chirp. The device is built with TI's low-power 45-nm RFCMOS process, and this solution enables unprecedented levels of integration in an extremely small form factor. [8] [9]

These sensors are an ideal solution for low-power, self-monitored, ultra-accurate radar systems in industrial applications such as building automation, factory automation, drones, material handling, traffic monitoring, and surveillance. [8] [9]

The IWR1642 device is a self-contained, single-chip solution that simplifies the implementation of mmWave sensors in the band of 76 to 81 GHz. [8]

IWR1642 includes a monolithic implementation of a 2TX, 4RX system with built-in PLL and A2D converters. IWR1443 includes 2Tx and 4RX system. [8]

IWR1642 also integrates a DSP subsystem, which contains TI's high-performance C674x DSP for the radar signal processing. [8]

The IWR1443 includes fully configurable hardware accelerator that supports complex FFT and CFAR detection. [9]

The devices include an ARM R4F-based processor subsystem, which is responsible for front-end configuration, control, and calibration. Simple programming model changes can enable a wide variety of sensor implementation with the possibility of dynamic reconfiguration for implementing a multimode sensor. [8]

Additionally, the devices are provided as a complete platform solution including reference hardware design, software drivers, sample configurations, API guide, training, and user documentation. [8] [9]

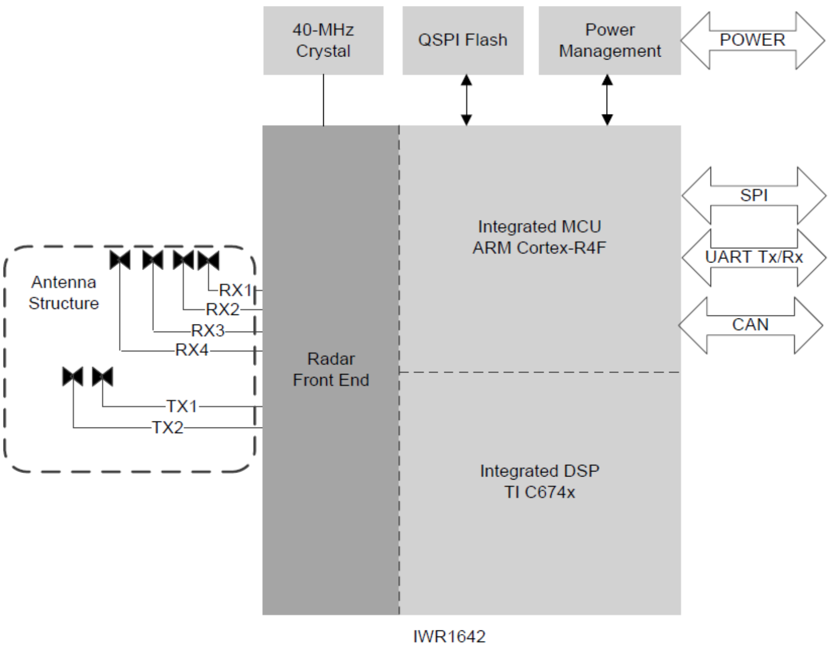

Figure 9: Autonomous Radar Sensor for Industrial Applications [8]

IWR is primary targeted for industrial applications. TI produces also three other sensors AWR intended mainly for automotive applications:

- AWR1642 [11]
- AWR1443 [12]
- AWR1243 [10]

The differences between IWR sensors and AWR sensors are:

- AWR1xxx devices support a wider junction temperature range, -40C to 125C. IWR versions support -40C to 105C.
- AWR1xxx devices are qualified for automotive applications as they are AECQ100 qualified and ASIL-B capable. This is not the case for IWR variants.
- Specific to the 1642, AWR1642 has 2 CAN interfaces, one of them being CAN-FD. IWR1642 only has one CAN interface (no CAN-FD).
- In term of RF alone there is no difference between IWR and AWR.
- AWR1642 and AWR1443 are similar as IWR1642 and IWR1443.

Function	AWR1243	AWR1443	AWR1642
Number of receivers	4	4	4
Number of transmitters	3	3	2
On-chip memory	-	576KB	1.5MB
Max real sampling rate (Msps)	37.5	37.5	12.5
Max complex sampling rate (Msps)	18.75	18.75	6.25
Max Intermediate Frequency (MHz)	15	15	5
Processor			
MCU (R4F)	-	Yes	Yes
DSP (C674x)	-	-	Yes

Table 6: Device features comparison [10]

The biggest advantage of AWR1243 is that it enables to cascade these sensors together [17]. Multiple AWR1243 chips may be cascaded on PCB to improve target detection and resolution (Figure 10) [28].

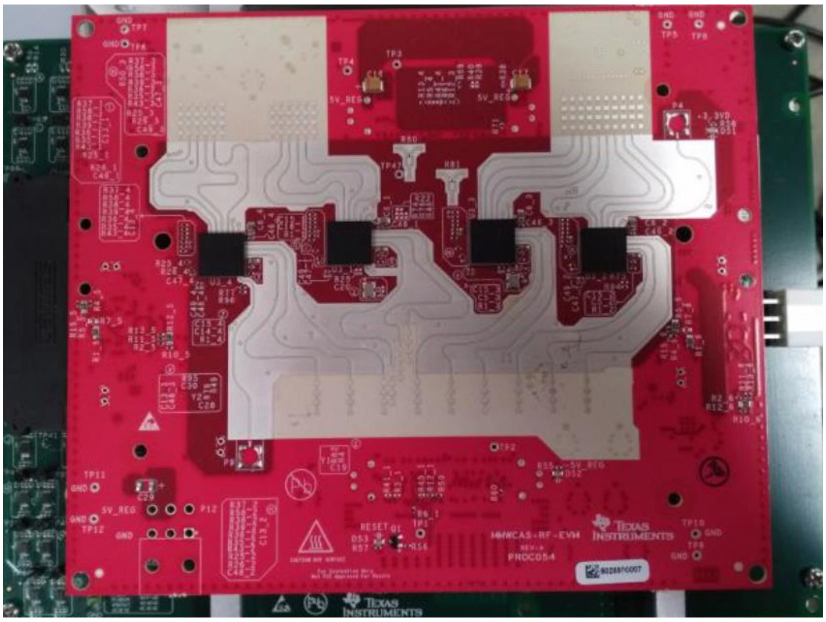

Figure 10: IWR1243 cascade

Several of these chips are cascaded and operated in synchronism. Each AWR1243 chip supports up to four receive and three transmit antennas. Cascading multiple such chips allows the radar system to operate with more receive and transmit antennas, thereby improving target detection and resolution in comparison with a single AWR1243 radar chip based system. [17]

3.4 IWR1x Evaluation Modules (IWR1xBOOST)

The IWR1642 BoosterPack (EVM) and IWR1443 BoosterPack (EVM) from Texas Instruments are easy-to-use evaluation boards for the IWR1642 and IWR1443 mmWave sensing devices, with direct connectivity to the TI MCU LaunchPad Development Kit [13][14].

The BoosterPack contains everything required to start developing software for on-chip C67x DSP core and low-power ARM R4F controllers, including onboard emulation for programming and debugging as well as onboard buttons and LEDs for quick integration of a simple user interface. [14]

Figure 11 shows the front view of IWR1642 EVM.

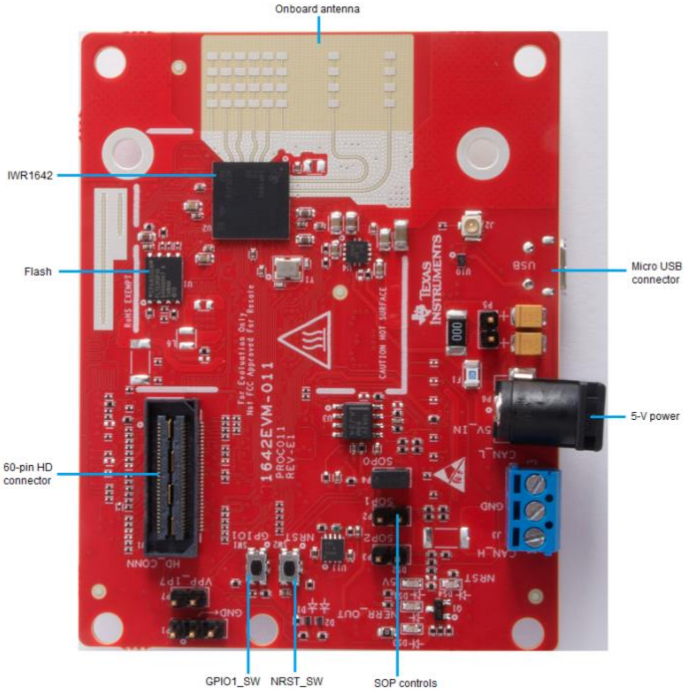

Figure 11: EVM (Front) [14]

Figure 12 shows the Rear view of IWR1642 EVM.

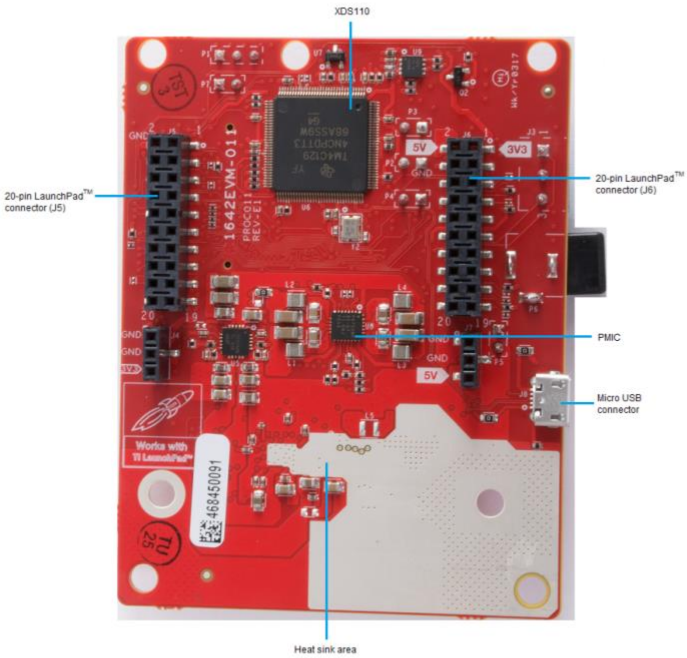

Figure 12: EVM (Rear) [14

3.5 Antennas

The BoosterPack includes onboard-etched antennas for the four receivers and two transmitters that enable tracking multiple objects with their distance and angle information. This antenna design enables estimation of distance and elevation angle that enables object detection in a two-dimensional plane. Figure 13 and Figure 14 show the PCB antennas [22].

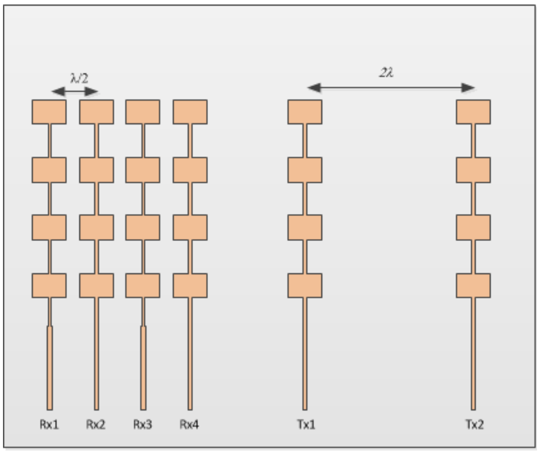

Figure 13: Antenna of IWR1642 EVM [22]

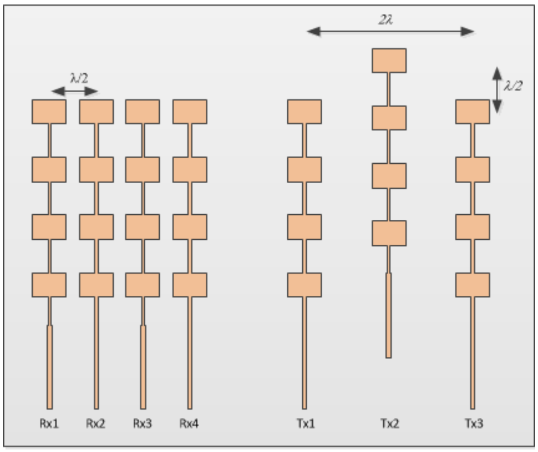

Figure 14: Antenna of IWR1443 EVM [22]

This radar configuration enables to use radars as MIMO system. IWR1642 EVM enables MIMO in horizontal plane. IWR1443 EVM enables 2D MIMO (Azimuth and Elevation estimation).

Increasing the number of antennas results in an FFT with a sharper peak, thus, improving the accuracy of angle estimation and enhancing the angle resolution.

The antenna peak gain is > 9 dBi across the operating frequency band of 76 to 81 GHz. The peak output power with the antenna gain is < 55 dBm EIRP, as required by the European regulations. The radiation pattern of the antenna in the horizontal plane (H-plane Phi = 0 degrees) and elevation plane (E-plane Phi = 90 degrees) is shown by Figure 15. [14]

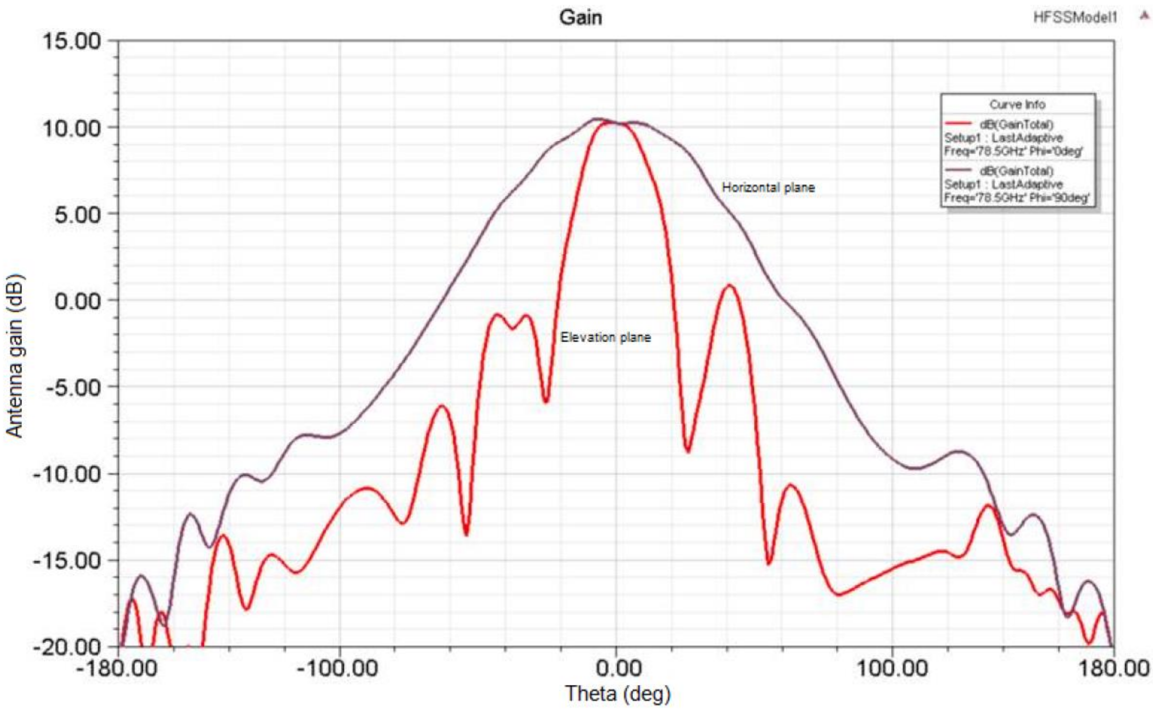

Figure 15: Antenna pattern of IWR1642 EVM [17]

3.6 Chirp Configuration

The TI radar devices allow you to control the parameters of chirps in a frame by defining chirp profiles, and variations on top of these profiles through a chirp configuration RAM. [15]

Chirp profiles are basic chirp timing templates, useful in defining chirp variants with significant differences in one or more defining parameters (start frequency, slope, idle time, etc.). [15]

The radar devices allow you to program four different chirp profiles. In addition, up to 512 unique chirps can be pre-programmed and stored in the chirp configuration RAM. Each chirp definition entry in the RAM can belong to one of the four profiles, and can optionally differ from their parent profile by small dithers in some of the parameter values. [15]

A frame would then consist of a sequence of chirps from a start index to an end index in the chirp configuration RAM which can be looped over up to 255 times [15].

The parameters that are controllable [24]:

- Start Frequency
- Frequency Slope
- Idle Time
- Tx Start Time

- ADC Start Time
- ADC Samples
- Sample Rate
- Ramp End Time
- R_X Gain
- Number of R_X
- Number of T_X
- No of Chirp Loops
- Periodicity
- MIMO (TDM or BPM)

How to set these parameters will be explained in the following chapters. Figure 16 illustrates a single chirp and its parameters - Start Frequency, Frequency Slope, Idle Time, Tx Start Time, ADC Start Time, and Ramp End Time. ADC Samples is number of samples in one chirp.

The rest of parameters have the following meaning. Rx gain is amplifying the signal that is being received. Number of R_X and T_X are number of received and transmit antennas. No of Chirp Loops is number of chirps in one frame. Periodicity defines the time of one frame. MIMO (TDM or BPM) is MIMO system [7].

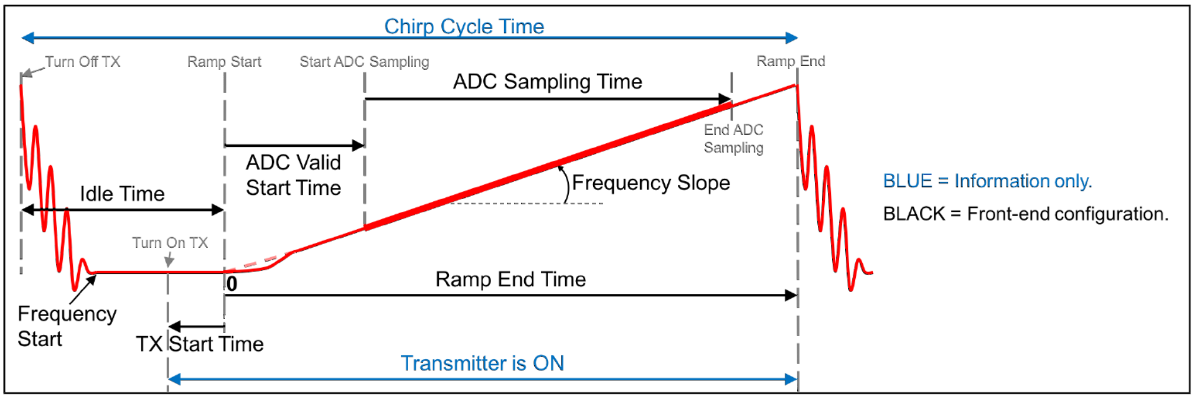

Figure 16: The chirp related parameters [15]

Note that for correct functionality of sensor, the optimal time setting is essential.

3.7 Programming Chirp Parameters in TI Radar Devices

The system requirements and care-abouts in each application could be very different. Range requirement, range resolution, max velocity requirement, sensor field of view, data memory, processor MIPS, and so forth are some of the aspects that need to be analyzed based on the end application [15].

TI's mmWave radar devices provide large flexibility in configuring chirp parameters and allow multiple chirp configurations in a single frame. The timing parameters are accurately controlled by the digital timing engine and a built-in radio processor without heavy real-time software interference.

3.7.1 Maximum range

Detecting a far-off object can be limited by either the SNR of the received signal or the IF bandwidth supported by the Radar device [15] [7].

There is no single maximum range for a radar sensor. It depends on all quantities:

- Tx output power, 12 dBm for IWR
- Tx antenna gain, 9dBi for EVM; Depends on Azimuth and Elevation field of view
- RCS of the target, 0.1 m^2 – 50 m^2; -10dBsm to 17 dBsm (Pedestrian vs. Truck)
- Rx antenna gain, 9dBi for EVM; Depends on Azimuth and Elevation field of view
- Noise figure, 15-16 dB for IWR, Implementation dependent
- Active frame time2 ms – 20 ms, Implementation dependent
- Detection SNR, 10 dB – 18 dB, Implementation dependent

The important aspect that limits the max range is the signal to noise ratio (SNR) of signal received by the receiver. SNR depends on:

- RF performance metric of the Radar device, such as TX output power, RX noise figure, as well as chirp parameters like chirp duration and number of chirps in the frame.
- Antenna parameters such as the TX and RX antenna gain in the direction of interest.
- Object characteristics such as Radar Cross Section (RCS). RCS is a measure of the amount of energy the object reflects back. This determines how detectable the object is with a radar sensor.
- Minimum SNR required by the detection algorithm to detect an object.

The maximum range based on SNR can be determined based on the following radar range equation [15]:

$$R_{MAX} = \sqrt[4]{\frac{Pt \times G_{RX} \times G_{TX} \times c^2 \times \sigma \times N \times T_r}{f_c^2 \times (4\pi)^2 \times kT \times NF \times SRN_{det}}}$$

Where:

- *Pt* → The transmitted output power, incident to the antenna in Watts.

- *GRx, GTx* → RX and TX Antenna gain, unit-less.
- *c* → Speed of light in free-space in meters/second.
- *σ* → The radar cross section (RCS), which is a unit-less gain factor relating incident power to reflected power of a target object.
- *N* → Number of chirps in a chirp frame
- *Tr* → Chirp ramp time in seconds
- *NF* → Noise figure of the receiver
- SNR_{det} → Minimum SNR required by the algorithm to detect an object
- *k* → Boltzmann constant – 1.38 x 10-23 J/K
- *Tdet* → Temperature in Kelvin
- *Fc* → Means frequency of the chirp ramp in Hz.

Number of chirps multiplied by Chirp ramp time is called integration time. In IWRx chip is calculated as:

$$Integration\ time = \frac{ADC\_samples}{F_s} \times N$$

- *ADC_samples* → Number of Samples in one chirp
- *Fs* → Sampling rate
- *N* → Number of chirps in a chirp frame

Minimum SNR is a trade-off between probability of missed detections and probability of false alarms. Typical numbers are in the 15 dB – 20 dB range.

The radar cross section (RCS) for typical objects are in Table 7 [29][30]. RCS for majority of objects are not available and cannot be easily establish without measurement.

Target	RCS [m^2]
Bird	0.01
Man	1
Automobile	5
Truck	50

Table 7: Radar Cross Sections (RCS) of typical objects

Maximum range as a function of Integration Time for different SNR with RCS = 5 m^2 is depicted in **Error! Reference source not found.**Figure 17. Maximum range as a function of Integration Time for different SNR with RCS = 10 m^2 is depicted in Figure 18.

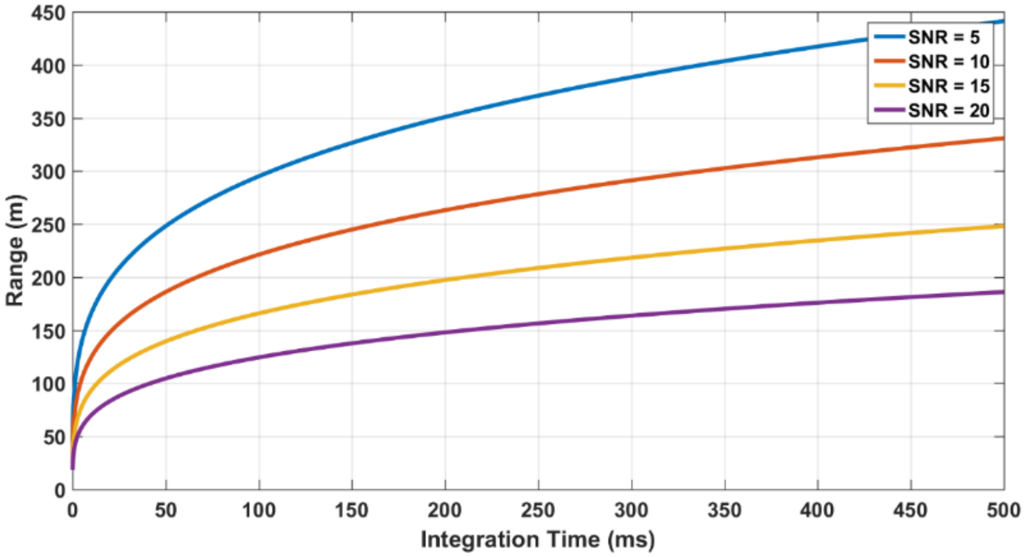

Figure 17: Max range in dependency of Integration Time for RCS = $5\ \mathrm{m}^2$

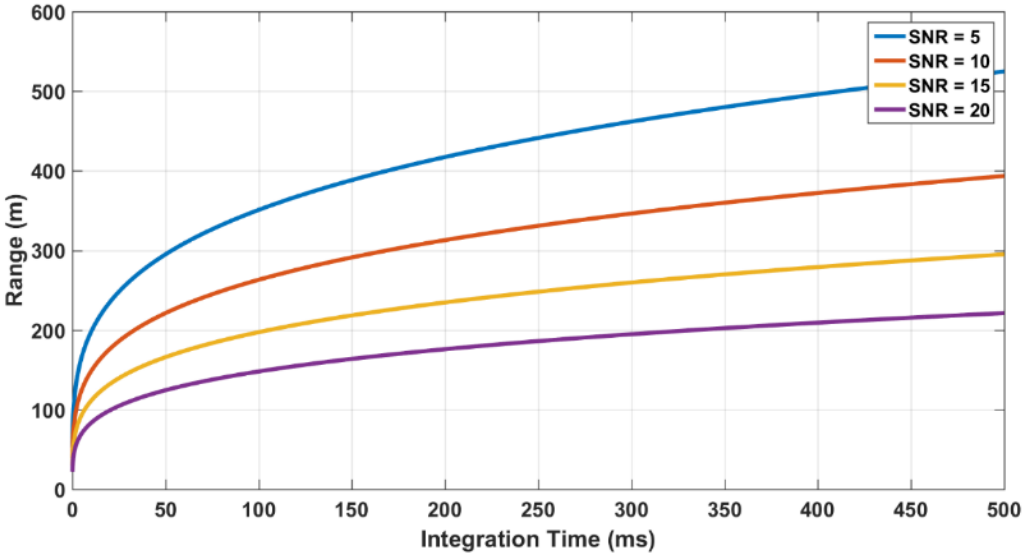

Figure 18: Max range in dependency of Integration Time for RCS = $10\ \mathrm{m}^2$

The maximum range relationship with the IF bandwidth is given by:

$$R_{max} = \frac{IF_{max} \times c}{2 \times S}$$

- IF_{max} → Maximum IF bandwidth supported
- c → Speed of light
- S → Slope of the transmitted chirp

A larger IF bandwidth, allowing more flexibility in the slope that can be used, which indirectly helps increase the max velocity [15].

Max IF (Intermediate Frequency)

- for IWR1443 is 15 MHz, and
- for IWR1642 is 5 MHz.

The IFmax is also dependent on the ADC sampling frequency (ADCsampling) used. In a complex 1x sampling mode, the IF bandwidth is limited to 0.8* (ADCsampling). In case of complex 2x and real sampling modes, the IF bandwidth is limited to 0.8* (ADCsampling)/2. The maximum ADC sampling frequency in the TI's radar devices is 37.5 Mhz [15]. There are some advantages for using complex mode [19].

Max Sampling rate of IWR1642

- (complex) is 6.25 MHz
- (real) is 12.5 MHz,

Max Sampling rate of IWR1443

- (complex) is 18.75 MHz
- (real) is 37.5 MHz.

3.7.2 Range resolution

The smallest distance between two objects that allows them to be detected as separate objects is referred to as range resolution. This primarily depends on the chirp sweep bandwidth that the radar sensor can provide. The larger the sweep bandwidth, the better the range resolution is [7].

$$\Delta R = \frac{c}{2B}$$

- c → Speed of light
- B → Sweep bandwidth of FMCW chirp

TI radar devices support a 4 GHz sweep bandwidth from 77 to 81 GHz and a 1 GHz sweep bandwidth from 76 to 77 GHz. The best range resolution (4 GHz bandwidth) can be as low as approximately 4 cm. [15]

Bandwidth (GHz)	Range Resolution (cm)
4	3.75
2	7.5
1	15
0.6	25
0.2	75

Table 8: Some typical numbers

Range resolution as a function of bandwidth is depicted in Figure 19.

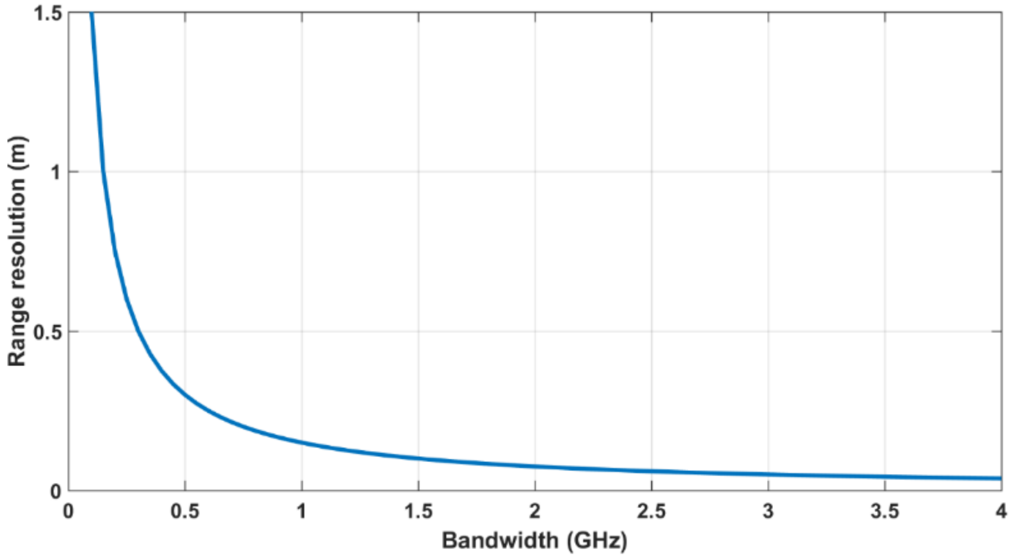

Figure 19: Range resolution in dependency of Bandwidth

3.7.3 Range accuracy

Accuracy of range measurement of one object depends on required SNR. The typically range accuracy is a small fraction of range resolution [7].

$$\sigma_R = \frac{c}{3.6 \times B\sqrt{2 \times SNR}}$$

- c → Speed of light
- B → Sweep bandwidth of FMCW chirp

Bandwidth (GHz)	Range Resolution (cm)	Range Accuracy (cm) for 10dB SRN
4	3.75	0.46
2	7.5	0.93
1	15	1.86
0.6	25	3.11
0.2	75	9.32

Table 9: Some typical numbers

3.7.4 Maximum velocity

The maximum measurable velocity in FMCW-modulated radars depends on the chirp cycle time, that is, the time difference between the start of two consecutive chirps. This in turn depends on how fast the frequency sweep can be performed and the minimum inter-chirp time allowed [15].

The faster the device can ramp the frequency, the higher the maximum unambiguous velocity. IWRx allows a fast ramp of 100 MHz/µs. Also the closed loop PLL is designed to support a very fast settling of the frequency ramp. Hence, the time taken for the VCO to jump from the end of the ramp frequency to restart the next ramp is very low and allows for a smaller idle time (as low as 2 µsec) [15].

The maximum velocity can be determined:

$$v_{max} = \frac{\lambda}{4T_M}$$

- T_M → Total Chirp time, which includes chirp time+idle time
- λ → Wavelength of the signal used

The maximum velocity as a function of chirp time is depicted in Figure 20. Some examples are inTable 10.

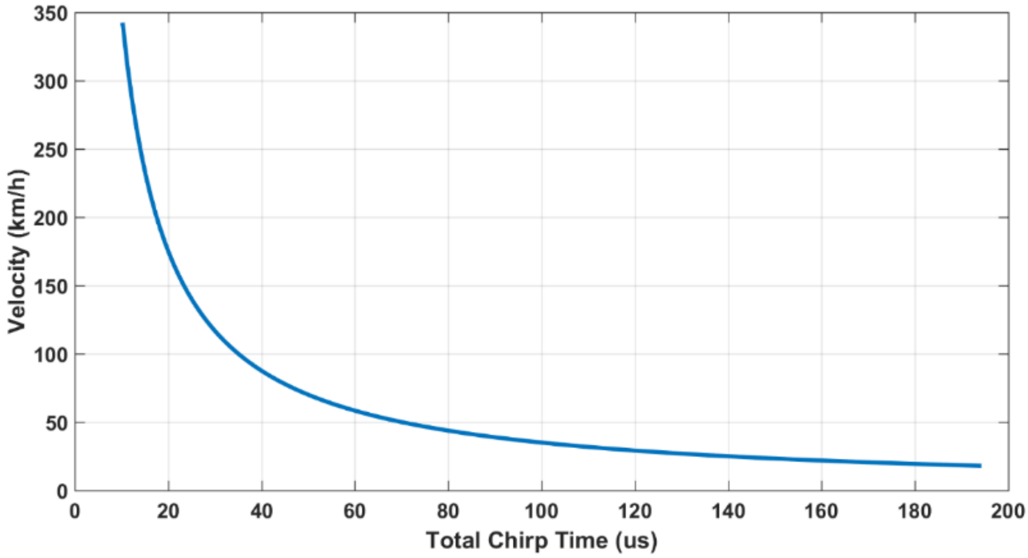

Figure 20: Maximum velocity

Note that chirp time includes some guard times that need to have some optimal time for correct sensor performance. For this reason, the Total Chirp Time in Figure 20 cannot be extremely small.

Total chirp duration (us)	Max unambiguity velocity (+/- kmph)
50	70
38	92
25	140

Table 10: Maximum unambiguous velocity

The max velocity can be extended beyond the unambiguous max velocity using higher level algorithm.

Note that TDM-MIMO and BPM-MIMO decrease the maximum velocity.

3.7.5 Velocity resolution

To separate objects with small velocity differences we need good velocity resolution. Velocity resolution mostly depends on the transmit frame duration, that is, increasing the number of chirps in a frame improves the velocity resolution [7].

$$\Delta v = \frac{\lambda}{2NT_M}$$

- N → number of chirps in a frame.
- T_M → Total Chirp time, which includes chirp time + idle time
- λ → Wavelength of the signal used

In standard configuration, the maximum number of chirps can be 255. It is possible to loop this group and increase the maximum number of chirps. The limit for maximum number is usually the memory on the chip for whole frame called radar cube memory. The largest size of this memory for IWR1642 is 768 KB and IWR1443 is 384 KB.

Radar cube memory stores data of whole frame which includes:

$$\text{Radar cube memory} = \#\text{Samples} \times \#\text{Chirps} \times \#\text{Rx} \times \#\text{Tx} \times 4\text{B}$$

- #Samples: number of samples in each chirp
- #Chirps: number of chirps in one frame
- #Rx: number of Rx antennas
- #Tx: number of Tx antennas
- 4B: Each sample (I and Q) 16 bits. Together 32 bits = 4B.

Velocity resolution as a function of Frame time is depicted in Figure 21. Some examples are in Table 11.

Active Frame Duration (ms)	Velocity resolution (+/-km/h)
5	1.40
10	0.70
15	0.47
20	0.35

Table 11: Velocity resolution dependent on Frame time

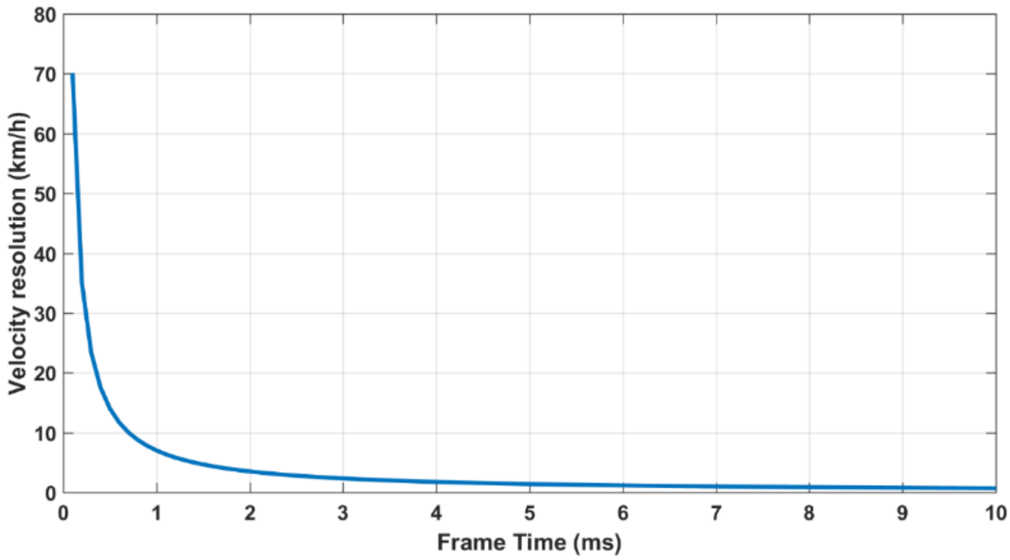

Figure 21: Velocity resolution

3.7.6 Velocity accuracy

Accuracy of velocity measurement of one object depends on required SNR and it is typically a fraction of velocity resolution [7]:

$$\sigma_v = \frac{\lambda}{3.6 \times NT_M \sqrt{SNR}}$$

Active Frame Duration (ms)	Velocity resolution (+/-kmph)	Velocity accuracy (kmph) for 10 dB SNR
5	1.40	0.25
10	0.70	0.12
15	0.47	0.08
20	0.35	0.06

Table 12: Velocity accuracy

3.7.7 Angular range

In order to locate the object in the 2D space, the angle of the object is also required along with the distance. In a radar system, the angle is estimated by receiving the reflected signal from the object using multiple receivers that are spaced apart with a distance 'd' [15].

The measurable unambiguous angular field of view from the radar depends on the spacing between the receivers (d).

$$\theta = \text{asin}(\frac{\lambda}{2d})$$

- *d* → Spacing between receiver antennas
- *ƛ* → Wavelength

IWRx EVM has d= ƛ/2. So for the widest angular field of view, the spacing of the receiver antenna should be ƛ/2, theoretically giving ±90° viewing range.

Apart from the antenna spacing, the measurable distance at different angles depend on the antenna gain pattern. Antennas used for IWRx have a peak gain at 0° angle (directly facing the front of the antenna) and then the gain is reduced as the angle increases. From Figure 15 is visible that the used antenna pattern has the gain at 90° angle is > 15 dB lower than what it is at 0° angle. [15]

For used antenna is ±50° viewing range for 6dB.

Note that the peak output power with the antenna gain is < 55 dBm EIRP, as required by the European regulations.

3.7.8 Angular resolution

Apart from the angular field of view, it might also be important to resolve two objects at close by angles, that is, have good angular resolution. In general, the angular resolution measurement depends on the number of receiver antennas available. The larger the number of antennas, the better the resolution is [15].

The angular resolution is also improved by using multiple transmitters. If there are multiple transmitters available, then the transmit antennas can be spaced in such a way that each of the transmitters paired with the set of receivers together create a virtual receive array. For example, if there are 3 TX and 4 RX, then a MIMO radar system can produce the equivalent angular resolution of 12 virtual channels. [15]

$$\theta_{RES} = \frac{\lambda}{d \times N_{RX} N_{TX} cos\theta} \times \frac{180}{\pi}$$

ϑ → Angle of interest, that is, the angle at which the objects are present

N_{RX} → Number of receiver antennas

N_{TX} → Number of transmit antennas

d → Spacing between receiver antennas

λ → Wavelength

The best resolution for Tx = 2, Rx = 4 and d = $\lambda/2$ is

$$\theta_{RES} = \frac{\lambda}{\lambda/2 \times 2 \times 4 \times 1} \times \frac{180}{\pi} = 14.32°$$

This is used for both configurations (IWR1642 and IWR1443) because of the antenna design.

NRX	NTX	Angular resolution [°]
4	3	15*
4	2	15
4	2	30
2	1	90
1	1	None

Table 13: Angular resolution

*The third NTX antenna is used for elevation, results for horizontal plane

If there are multiple transmitters available, then the transmit antennas can be spaced in such a way that each of the transmitters paired with the set of receivers together create a virtual receive array. For example, if there are 3 TX and 4 RX, then a MIMO radar system can produce the equivalent angular resolution of 12 virtual channels.

In case of d = $\lambda/2$ and θ is zero, angle resolution can be determined as:

$$\theta_{RES} = \frac{2}{\mathrm{N}}$$

3.7.9 Angle estimation

Angular resolution described in the previous paragraph is the spatial resolution. It depends only on the number of Tx and Rx antennas and is the minimum angle to separate two objects [22].

For 2 Tx and 4 Rx antennas there are only 8 samples for 3rd FFT and angle to separate two objects from each other is 15°. Example of the result of FFT with 8 samples is in Figure 22. Originally the object is on the angle of 7°. A sensor with this configuration cannot detect this angle with such precision.

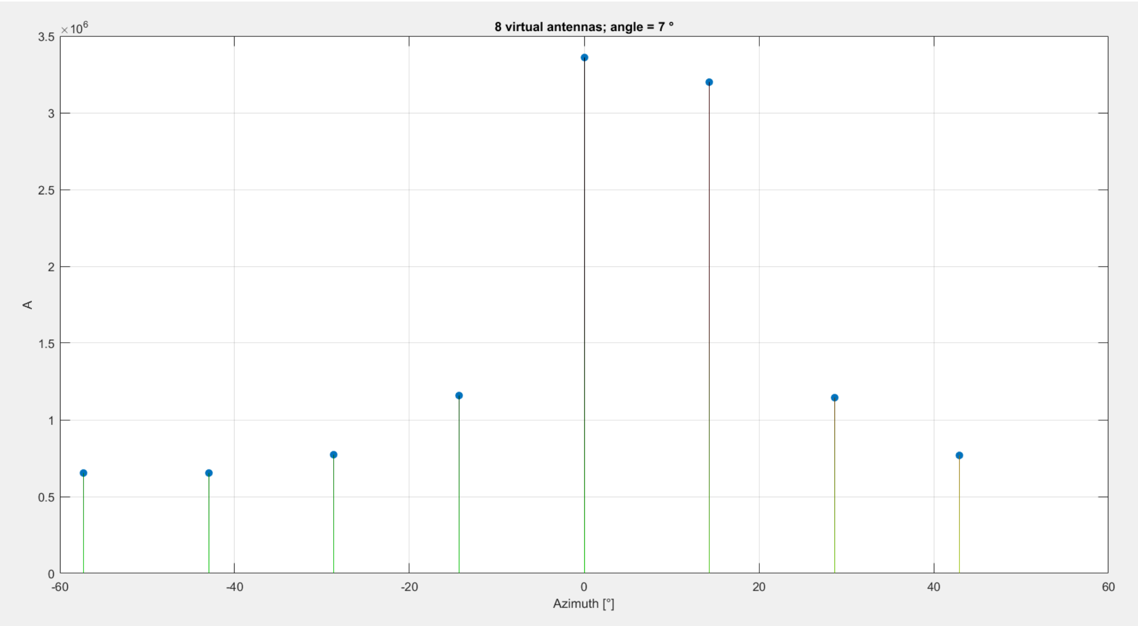

Figure 22: FFT with 8 samples

The length of FFT in the angular domain can be increased by interpolation. There are techniques as Zero-padding. If we use 64-point FFT to calculate the direction of arrival, originally interpolated from 8 samples, this will lead to the 2-degree frequency domain resolution (see, Figure 23). This technique only improves the angle of detected object. The minimum angle for separation of two objects is still 15°. The result is much closer to 7° than in previous example.

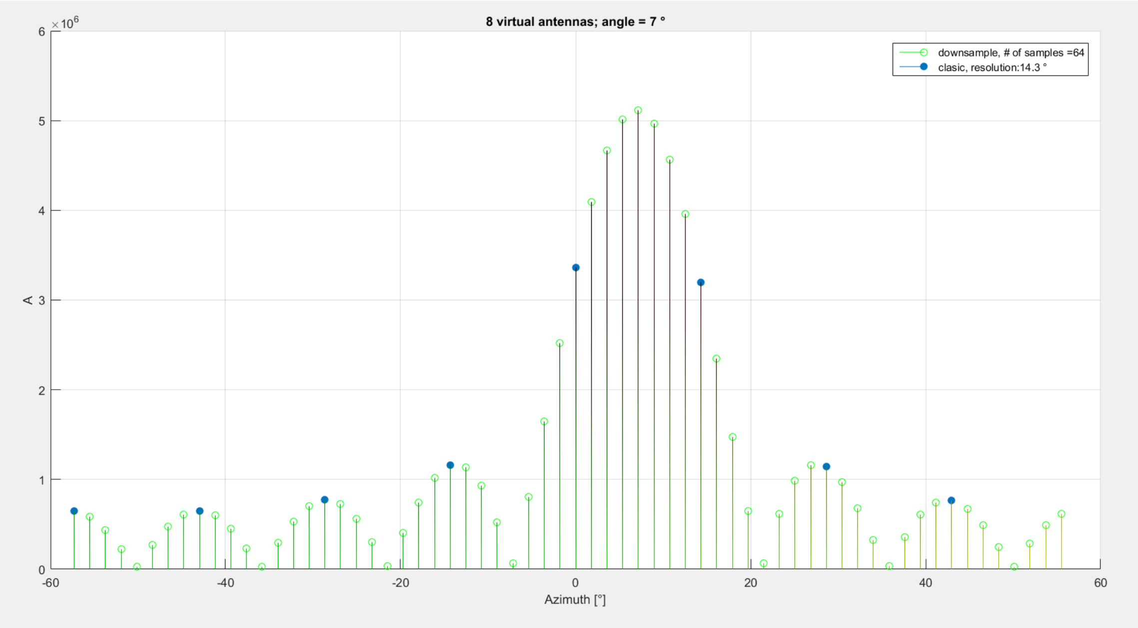

Figure 23: FFT with 64 samples - interpolation

3.8 Sensors Performance and Recommended Next Steps

Sensors performance in terms of maximum range for detecting various types of objects described by TI is listed in Table 14.

Object	EVM Measured Range (m)												
	1	5	10	20	30	40	60	80	100	120	140	160	199
Truck(1)	•	•	•	•	•	•	•	•	•	•	•	•	
Car(1)	•	•	•	•	•	•	•	•	•	•	•(2)	•(2)	•(2)
Motorbike(1)	•	•	•	•	•	•	•	•					
Bicycle with human(1)	•	•	•	•	•	•	•						
Human(3)	•	•	•	•	•	•							
Metal chair(3)	•	•	•	•	•								
Soda can(3)	•	•	•	•	•								
Wooden chair(3)	•	•	•	•									
Plastic chair(3)	•	•	•										
Cup of coffee(3)	•	•	•										
Large dog(3)	•	•	•										
Small dog(3)	•	•											
Coins (US quarters)(4)	•												

(1) xWR1443 using high RCS chirp configuration from object versus range.
(2) xWR1642 using long range chirp configuration from traffic monitoring.
(3) xWR1443 using low RCS chirp configuration from object versus range.
(4) xWR1443 using best range resolution chirp configuration from the out-of-box (OOB) demo.

Table 14: Sensors performance results provided by TI [25].

Our initial evaluation of the sensors (using evaluation boards with integrated antennas) in real environment showed slightly lower values (e.g., car detected from around 140 m) but as it was performed without any extensive optimization of chirp parameters and data processing it seems that value provided by TI are not unrealistic. The largest limitation of the sensors seems to be their sensitivity, i.e., their ability to detect smaller obstacles (smaller RCS).

The next steps will therefore focus on:

- possible methods how to increase sensitivity of the sensor(s),
- design of the hardware system addressing operational needs of targeted use case, and
- design of obstacle detection application potentially combining data from the sensors with other situation awareness functions.

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