COMMUNICATION LATENCY AND LOSS FOR INTEGRATED IFR-RPAS MOVEMENTS IN THE TMA

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Abstract

In recent years, innovative technology emerged enabling unmanned flight and putting a strain on airspace as a resource. It is expected that the number of remotely piloted aircraft (RPA) will increase significantly in the near future. In 2021 Royal NLR performed real-time simulations for the SESAR Exploratory Research Project INVIRCAT addressing some of the consequences of that development. The INVIRCAT project investigates the safe and efficient integration of the movements of RPAs under instrument flight rules into current-day operations at and around smaller but significant airports with a variable mix of traffic. NLR activities focused on Rotterdam The Hague Airport (ICAO: EHRD).

The NLR simulation set-up included a high-fidelity tower and approach simulation environment (NARSIM Tower and NARSIM Radar) and a connected simulation platform for a generic Remotely Piloted Aircraft System (RPAS) Ground Control Station facility (called Multi Unmanned Aircraft Supervision Testbed, MUST). Experienced former air traffic controllers guided all aircraft in the traffic mix including the drone traffic. A military pilot was responsible for control of the RPAS and so-called pseudo-pilots controlled the remaining visual (VFR) and instrument (IFR) traffic in the Terminal Manoeuvring Area (TMA) and at the airport.

The present paper focusses on the results of the real-time simulations that are related to latency in radio communication between RPAS pilot and Air Traffic Control (ATC) as well as procedural issues regarding loss of voice communication.

Latency was suspected to have an immediate impact on the work of air traffic controllers as it would slow down both pilot readbacks and pilot flight control responses to ATC instructions. Different radio delay parameters were tested in abovementioned environment and controller and pilot reactions were studied.

Loss of voice communication was also assessed in all flight phases applicable to approach and departure operations in the TMA. Both pilot and ATC feedback on the procedures was collected leading to surprising results that may trigger a re-evaluation of our notions of voice communication loss with remote pilots. One of the most notable results was that both pilots and controllers were adamant that the IFR RPAS should follow the same procedures defined for manned IFR traffic.

Introduction

The military and State use of Unmanned Aerial Systems (UAS) for reconnaissance and combat missions has developed rapidly since the early 1990s. Most of these drones can be armed, are typically much larger than commercial drones, and weigh over 1,000 pounds. They generally operate beyond the visual line-of-sight, but very often use a radio line-of-sight (RLOS) architecture for command and control (C2) and for ATC communication. These drones have a fixed-wing structure and are categorized as either medium-altitude long-endurance (MALE) or high-altitude long-endurance (HALE) drones that can be used for gathering intelligence, but also for battlefield support [1].

A MALE or HALE drone is often referred to as Remotely Piloted Aircraft System (RPAS) and consists of an airborne segment and a ground segment. The airborne segment is the remotely piloted aircraft itself. Some of the RPAs resemble conventional aircraft in both appearance and performance, and the pilot on board is simply replaced with a Remote Pilot (RPIL). The RPAS ground segment consists of a Remote Pilot Station (RPS), sometimes also called Ground Control Station (GCS). It encompasses all systems for control and monitoring of the RPAS flight and is connected to the RPA via abovementioned C2 link.

Given the fact that MALE drones efficiently carry heavy and large cargo across a wider range, it is expected that development of commercial drones with comparable performance will also increase in the years to come, addressing the need for both large area surveillance (e.g. border control, sensitive infrastructure inspection, environmental protection) and transport missions (e.g. disaster relief). As a consequence, airspace would become a valuable resource [2]. This would particularly be true around those airports in Europe that currently strive to broaden their customer base by attracting commercial drone activities. Eventually, the MALE drones would need to be fully integrated into visual and instrument flight rule traffic patterns around these airports to efficiently accommodate all commercial traffic. Thus, in order to make use of the economic advantages of MALE RPAS, operational concepts for their integration into the current controlled airspace structures are needed that consider the technological and functional differences to manned aircraft.

Being the leading ATM research activity in Europe, the SESAR Joint Undertaking understood this challenge and outlined a roadmap for the integration of RPAS in the European ATM Master Plan of 2020. The Master Plan outlines a three-step approach that is meant to contribute to one of the key missions of the SESAR programme, which is the safe and efficient integration of all aerial vehicles into both controlled and uncontrolled airspace. The goal is to ensure that all drone operations are managed as routine operations by 2035 and that the so-called U-space services for drones are fully integrated with ATM in the years thereafter [3].

INVIRCAT Project

In 2020 a project called Investigation of IFR RPAS Control at Airports and in the TMA (INVIRCAT) was initiated by the SESAR Joint Undertaking and is currently still being carried out by a consortium including three ATM research organizations in Italy (CIRA), Germany (DLR) and in the Netherlands (Royal NLR). As the name suggests, the aim of the project is to provide means for a safe and efficient integration of RPAS into the existing ATC procedures and infrastructures within TMAs under instrument flight rules in airspace classes A to C. It thereby addresses the first step in the EATM roadmap. The INVIRCAT project focuses exclusively on the TMA operations and the related work of approach controllers as well as the work of tower controllers at airports who are in charge of runway operations. High fidelity taxiway operations were not considered in the project and therefore have not been simulated.

One of the main achievements of the INVIRCAT project so far, has been the creation of a State-of-the-Art document, based on earlier research and regulation material [4], and a concept of operations (CONOPS) for IFR RPAS integration in the TMA [5] with pertaining operational use cases [6]. In order to obtain a first indication of the viability of the concept and to receive feedback from operational experts on the defined operational and technical requirements [7], simulations were planned and carried out at the three different research institutions at the end of 2021 [8]. The results of these simulations are expected to eventually lead to a set of recommendations for rule makers and standardization bodies with respect to:

- Operational options and applied procedures for all phases of flight in the TMA
- RPAS architecture considerations and related latency issues
- Several non-nominal use cases, such as C2 link and communication loss

The present paper will focus entirely on the simulations carried out at NLR and the relevant concept elements considered for validation of initial requirements and suggested procedures. The simulations at NLR concentrated on the latency issues encountered when different RPAS control and communication architectures are applied and on the special case of R/T failure of the RPAS in all phases of flight inside the TMA.

INVIRCAT Concept of Operations

Basic Assumptions and Conditions

The goal of the INVIRCAT CONOPS is to define adequate systems and operations for the full integration of RPAS in TMA airspace classes A to C around airports with the RPAS flying IFR traffic patterns. It builds on earlier SESAR research and has been established in line with the rules and guidelines of international associations such as ICAO, JARUS, and EUROCAE [5]. Several key assumptions were made in order to clearly define the scope of the concept and the elements investigated in the simulation activities. One of the basic assumptions is that the RPAS vehicle is defined as being of UAS traffic class VI in accordance with the EUROCONTROL definition [9]. In short, it means that the RPAS is expected to be capable of flying SIDs and STARs as designed for manned operations. Such RPAS can be manned transport aircraft that are converted to fly unmanned and have similar capabilities as the manned version. However, they can also be entirely new types that are able to meet the relevant performance requirements. This choice already implies that it is expected that the chosen vehicle will have minimum impact on other airspace users, airports, and ATC, as its performance in terms of speeds and vertical movement rates should be similar to the present IFR traffic.

According to the EUROCONTROL CONOPS it further implies that the RPAS will file a flight plan including the following information [9]:

- Type of RPAS
- Contingency procedure
- Planned operation (route, level etc.)
- Contact phone number

Other requirements mentioned in the CONOPS document of EUROCONTROL [9] are:

- RPAS meets CNS airspace requirements
- RPAS is capable to establish two-way communication with ATC
- RPAS operator is able to contact ATC in contingency situations, such as:
    - Data link loss
    - Emergency
    - Controlled termination of flight
- RPAS has DAA capability compatible and cooperative with existing ACAS systems

Additional Concept Considerations

On top of these requirements, the INVIRCAT project formulated some further conditions [5]. These conditions specify that the RPAS is required to have the following characteristics:

- RPAS has a fixed-wing structure
- RPAS has an airworthiness certificate and, consequently, a type certificate
- The C2 link may also be used for relaying voice communications (R/T) to ATC
- The Automatic Take-off and Landing (ATOL) system can be operated in compliance with the same rules and procedures that other airspace users follow, without disruption of the current operations and without assistance of the RPIL by visual aids (to prevent handling problems, such as pilot-induced oscillations in situations with high signal latency, in line with [10])
- RPAS can conduct taxi operations on their own power (with the exception of pushback) and without the support of ground vehicles (such as follow-me cars) in order to limit the impact on throughput and capacity of the airport

Furthermore, a number of requirements also address the abilities of the RPIL [5]:

- RPILs must be adequately trained and certified on IFR RPAS procedures
- RPILs must not use visual aids for flight-critical operations (such as the landing),
- RPILs must always fly under IFR, without requesting or accepting visual in-flight procedures
- RPILs must always monitor the flight (except in the case of system failures) and is responsible for the highly automated (but not autonomous) RPAS at all times

The INVIRCAT CONOPS requires ATC to be able to contact the RPIL, if required, i.e. in case of contingencies that do not allow for continuation of the nominal operation. It does not make any assumptions regarding the number of flight crew members required to control an IFR RPA in non-segregated airspace, meaning that the term RPIL is used in a generic sense. Datalink connections in the TMA have not been considered (due to low responsiveness and restrictions in message size). The operational concept covers all phases of flight within the TMA, with ground operations, take-off and departure operations along the SIDs, and approach operations using the defined STARs up until final approach and landing. It puts a special focus on the impact of C2 link latency and voice communication latency on ATC. Special attention is also given to the procedures related to the use of ATOL systems and the handover of the RPA between different RPIL ground control stations. To that end, flight and communication procedures were defined (if not available) and evaluated in the simulations.

Control and Communication Architectures

Different C2 link and communication architectures were defined and eventually set up in the simulation environments in order to compare their impact on the operation. In order to better understand the different architectures for command and control (C2) of a Remotely Piloted Aircraft System, it is important to know about the system components and the tasks of the RPIL in the system. Figure 1 shows the different INVIRCAT system interfaces in accordance with their description in the ICAO CONOPS [11].

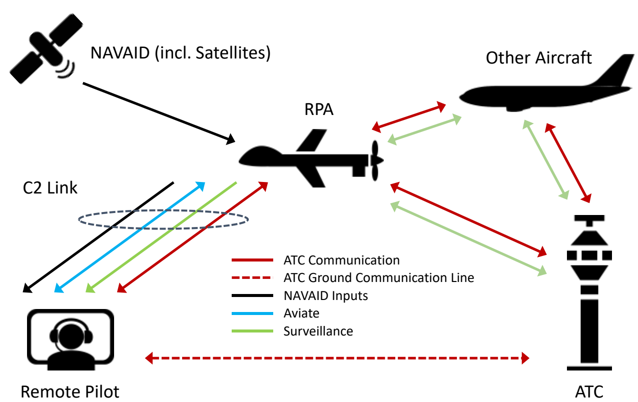

Figure 1. Overview of System Interfaces

As mentioned before, the RPAS consists of an airborne segment and a ground segment.

The airborne segment is the RPA itself. Some of these RPAs resemble conventional aircraft in both appearance and performance, and the pilot on board is simply replaced by a Remote Pilot (RPIL) on the ground. However, due to the fact that life supporting systems and equipment are not required, such airborne systems might result in drastically different designs as well.

The RPAS ground segment consists of the RPS that encompasses all systems for control and monitoring of the RPAS flight. The ground stations differ in set-ups and designs, but they all have in common that a single RPA can only be controlled by a single RPS at a given time. The RPIL is in control of the systems via the C2 link. The systems are divided into critical (with regards to carrying out flight operations) and non-critical systems (e.g. to monitor and control payload).

The C2 link architectures supporting RPAS operations are usually classified as Radio Line-of-Sight (RLOS) and Beyond Radio Line-of-Sight (BRLOS) and are described in the ICAO RPAS Manual [12].

In RLOS, transmitters and receivers are within mutual radio link coverage and thus able to communicate directly. The transmitting and receiving unit on the ground may be in direct proximity to the RPS or at a remote location and part of a network with negligible signal delay.

BRLOS refers to a configuration where transmitters and receivers are not within mutual radio link coverage. Thus, the link must be established via a satellite system (SATCOM) or any other system where an RPS communicates with one or more ground stations via a terrestrial network, but where complete transmissions cannot be realized in a timeframe comparable to that of an RLOS system (see also Figure 2).

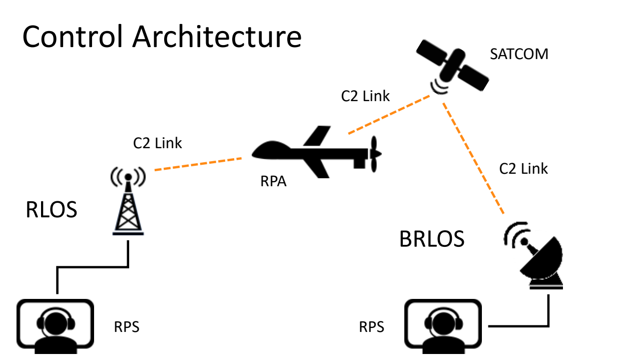

Figure 2. Control Architecture showing Difference between RLOS and BRLOS

This means that latency is always higher during BRLOS than during RLOS. The ICAO RPAS Manual [12] also mentions that any system must meet the required communication performance parameters for latency and availability established for the airspace and operation. As a consequence, in the

INVIRCAT CONOPS, it was decided that RLOS should be used for take-off and landing if possible, even if BRLOS is used for en-route operations. Nonetheless, it is also noted that all flight phases can be controlled via BRLOS if necessary and that the performance requirements need to be adequate to safely fly the RPA and also support other airspace performance requirements, such as Required Communication Performance (RCP) and Performance Based Navigation (PBN), which are globally agreed upon [5].

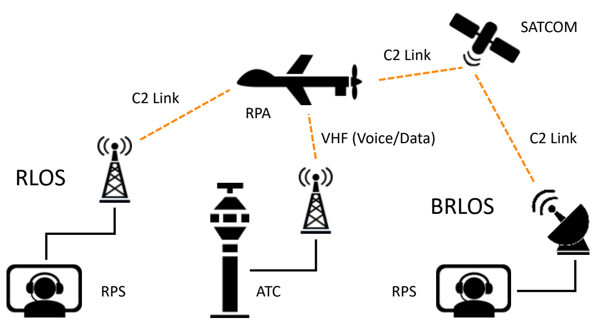

Figure 3. Communication Architecture with RPA Relay showing RLOS vs. BRLOS

For the voice communication functions, there are two possibilities, namely a relay via the RPA and communication to ATC not involving the RPA.

When using the RPA as relay station for R/T communication between the RPIL and ATC, standard Very High Frequency (VHF) equipment needs to be available on the RPA. Such a relay can occur under both RLOS and BRLOS configurations (Figure 3). Again the expectation is that BRLOS communication will add some latency. While no significant changes to ATC procedures are expected for RLOS operations, the additional BRLOS latency can potentially affect operations. It should be noted that, in oceanic or remote area operations, the ATC link may also be established via SATCOM.

When there is no relay via the RPA, R/T communication between RPIL and ATC will have to occur via a direct link that could be established via either VHF, a (commercial) SATCOM or ground network, or a dedicated ground communication line (see Figure 4). While the VHF connection will certainly work for short range operations or when a nearby network of VHF antennas is available, ATC communication at a remote location will face more difficulties, as either a satellite connection is required, or there must be a connection to a commercial or dedicated ground network.

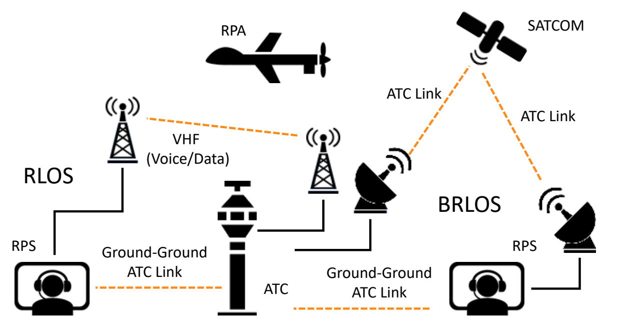

Figure 4. Communication Architecture without RPA Relay showing RLOS vs. BRLOS

The dedicated ground network is the most reliable option and will only lead to low signal latency values allowing the RPA to operate in the full range covered by the ATS unit. When such a dedicated line is not available, it seems to be a straightforward solution to use a simple phone line with a handheld receiver. However, this may not be acceptable as primary communication means between RPS and ATC. Furthermore, any of the direct lines must be connected to the relevant ATC frequency to allow for sufficient situational awareness for all involved actors. A particular solution to this problem is the multi-link system that is currently investigated by the EECNS project in the SESAR 2020 programme [5].

Signal Latency Considerations

The INVIRCAT project considered the different control and communication architectures as input for the simulation scenarios and made a distinction between different values of signal latency for the three cases of RLOS, BRLOS and Ground Relay. The latter meant that there was a dedicated ground communication line between RPS and ATC and the C2 link was accomplished via ground relay to a station in RLOS.

Based on a literature review consulting sources from EUROCAE, RTCA, ITU, ESA and TNO, rough estimates for the maximum latencies to be expected for each architecture were determined [5]. The numbers are based on the assumption that the RPS is either located sufficiently close to the TMA that the RPA is connected via RLOS, or that there are intra-regional distances between RPS and RPA resulting in a single-hop connection for SATCOM (BRLOS). For the Ground Relay case, the assumption is that the RPA has a C2 link connection to a ground station in RLOS, which again is connected to the RPS via a dedicated ground line. Communication with ATC is expected to be achieved via a dedicated ground line.

Accordingly, abovementioned numbers have been applied to the INVIRCAT simulation activities:

Table 1. Expected Maximum Signal Latencies

C2 Round Trip	RLOS	BRLOS	RLOS via Relay
	1 s	2 s	1.5 s

Voice One Way	RLOS	BRLOS	Ground-Ground
	290 ms	700 ms	150 ms

NLR Simulation Activities

Simulation Environment

The NLR simulation facilities that were used for the INVIRCAT simulation activities are the Multi-UAV Simulation Testbed (MUST), and the NLR ATC Research Simulator (NARSIM) environment for Radar and Tower control.

Figure 5. Royal Netherlands Air Force Pilot behind MUST RPS

MUST was developed by NLR as a generic UAS research simulation facility (Figure 5). For INVIRCAT it was configured in such a way that it allowed the RPIL to fly the RPA from a working position that simulated the necessary RPS equipment of the RPAS in a realistic manner.

NARSIM Tower and NARSIM Radar, the two other NLR facilities that were deployed in the INVIRCAT project, accounted for a highly realistic simulation of the complete ATC environment. The NARSIM middleware controls the simulation of all air traffic required for the different scenarios, including additional ground movements of airport traffic, if necessary.

Figure 6. NARSIM Approach and Tower Controllers

Different types of controller working positions can be added to the simulation in a plug-and-play fashion in order to provide realistic front-ends for each of the ATCO roles defined in the scenarios (Figure 6). For the INVIRCAT project, this meant that a complete tower simulation of a smaller airport with significant IFR and VFR traffic was simulated. In addition, the TMA was controlled by an Approach controller in a realistic radar control environment.

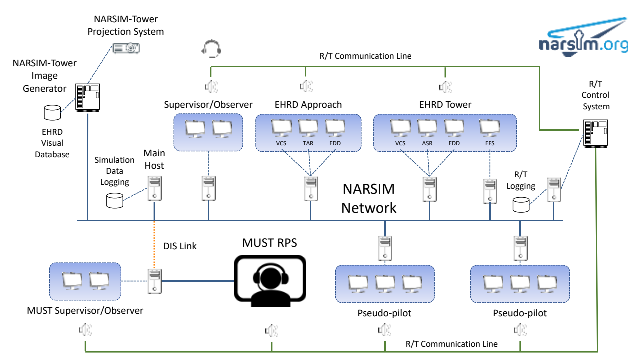

Figure 7. NARSIM-MUST Simulation Architecture

The MUST platform was connected to NARSIM via a DIS link (Figure 7). DIS is an IEEE standard that is used for connecting real-time simulation platforms. The link sent aircraft status information from MUST to NARSIM so that the RPA was visible as one of the flights in the ATC simulation. In the same way, NARSIM was sending information back to MUST to make all traffic from the ATC simulation visible for the RPIL [13].

The airport selected for simulation in INVIRCAT was Rotterdam The Hague Airport (ICAO code: EHRD) as it is a small but important airport serving one of the larger metropolitan areas in the Netherlands. It also ranks as one of the larger airports in the Netherlands behind Amsterdam Airport Schiphol. According to the numbers known to NLR, Rotterdam The Hague Airport served between 1 and 2 million passengers and about 50,000 flight movements annually between 2010 and 2019. For the INVIRCAT simulations it was necessary to find an environment that would fit a reasonable scope in terms of airspace layout complexity and traffic mix. Rotterdam has one runway (Figure 8) and a less segregated traffic structure than a larger airport, such as Schiphol, with a mix of IFR and VFR operations. This meant that integrating new users at this airport had an immediate impact on the nominal operation.

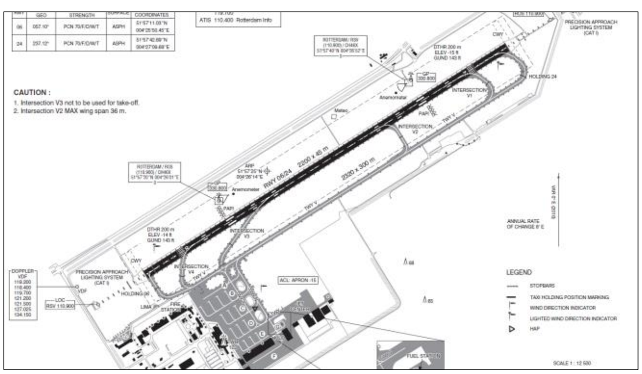

Figure 8. AIP EHRD Aerodrome Chart

In the simulations, the airport was used in southwesterly direction (RWY 24) with traffic on all SIDs and STARs defined for that operation (as can be found in the AIP of the Netherlands [14]). The ATCOs were former EHRD controllers and the pseudo-pilots were real Dutch pilots. Both ATCOs and pseudo-pilots were very familiar with the airport environment.

The RPA chosen for the NLR simulations was the General Atomics MQ-9 Reaper. There were several reasons for NLR to select this RPA. First of all, it was available in NARSIM as part of the EUROCONTROL Base of Aircraft Data (BADA) which is used as performance model for aircraft in the ATC simulation. This meant that NARSIM was also able to add several instances of the RPA as an additional aircraft type to reference simulations, which was necessary to find answers to research questions involving more than one RPA. The BADA model also helped finding some of the flight parameters necessary to create a more realistic MUST simulation inside NARSIM, as a very detailed model was not available for MUST. Secondly, the RPILs supporting the NLR simulations were military drone pilots who were experienced in flying this type of RPA. They also gave indications of how to improve the performance model of the RPA.

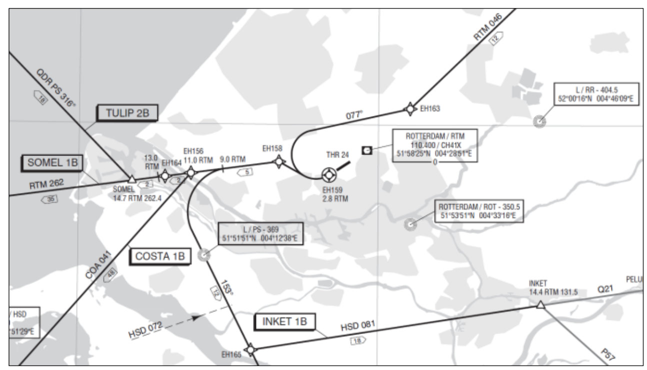

Figure 9. AIP EHRD Standard Departure Chart (AD 2.EHRD-SID-24, 23-May-2019)

In a typical scenario, the flight of an RPA controlled by the RPIL working in MUST, departed from the airport and left the approach area via SID COSTA 1B towards Belgium (Figure 9). Minutes later, another instance of the RPA simulation would be generated outside the TMA and enter the TMA to land at the airport via STAR PUTTY 2R.

Standard RWY 24 ILS approaches from the IAF (ROT) were taken as a basis for all IFR traffic approaches (Figure 10). Additional VFR traffic in circuits around the airport was also considered and integrated into the landing sequence. Pseudo-pilots managed all other IFR and VFR movements at and around the airport, following the instructions of the approach and tower controllers.

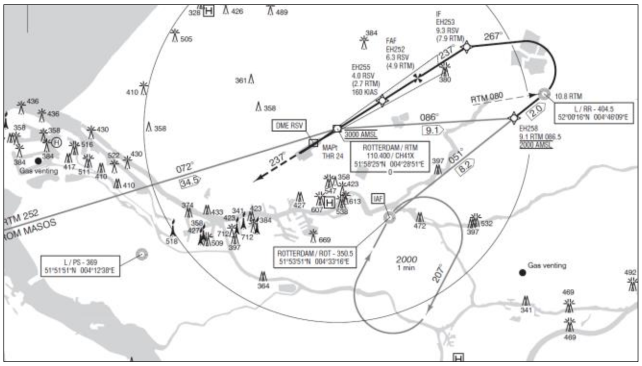

Figure 10. AIP EHRD Instrument Approach Chart (AD 2.EHRD-IAC-24.1, 23-May-2019)

Validation Objectives

The validation objectives of the INVIRCAT project were described in a Validation Plan document [15] and they addressed operational acceptability and operational safety of the integration of IFR RPAS movements in the TMA in terms of the defined concept and procedures [6] in both nominal and contingency situations. Apart from that, several indicators for human performance with respect to the defined operations were suggested for further investigation. Measurable results were expected for runway throughput and equity of operations. While the latter were investigated by NLR, their results are not published in this paper, but will appear later this year (in the summer of 2022) as part of the consolidated INVIRCAT project documentation.

The common plan for the simulations at research institutes CIRA, DLR and NLR also mentioned ATOL procedures and the procedures for a handover of the RPA between different RPS as additional concept elements to be assessed. For the contingency operations, specific conflict situations between manned and unmanned traffic were defined as well as situations in which a complete loss of either C2 link or voice communication functionality would occur. While CIRA looked at the ATOL system for different architectures and DLR focused on contingencies due to conflicts and C2 link loss, the NLR investigations specifically addressed signal latency caused by the different architectures in nominal flight operations as well as R/T failure procedures. Simulations for the RPS handover were also planned by DLR and NLR, and eventually carried out by NLR in November 2021, but the results of this activity will also appear later this year.

Validation Scenarios

All validation scenarios were carried out with a comparatively high traffic load for EHRD. Traffic was tuned in consultation with operational experts in order to have a good balance between IFR and VFR traffic in both TMA and CTR. Similar scenarios were used when it was necessary to compare results. This meant that, in order to create a traffic sample that could be used with an RPA, one manned flight in the nominal situation had to be replaced with one RPA. The remaining traffic was not changed.

For the two research areas addressed in this paper, specific scenarios were elaborated (see also Ch. 4.4 in [8]) that allowed to validate operations with different levels of signal latency caused by the three different control and communication architectures described earlier, with relevant propagation delay values specified in Table 1. These scenarios could be compared to a nominal scenario, where the MUST RPA would fly without any additional latencies (on top of the inherent system latencies in the simulation system) being applied. In summary, this led to the following overview of the latency scenarios including some characteristics:

Table 2. Scenarios for Latency Impact Assessment

	Architecture		**Latency**	
	C2	R/T	C2	R/T
Nominal	RLOS	G-G	1 s	150 ms
Latency 1	RLOS	RLOS	1 s	290 ms
Latency 2	BRLOS	BRLOS	2 s	700 ms
Latency 3	RLOS*	G-G	1.5 s	150 ms

* this is RLOS via Relay as shown in Table 1

The latency scenarios were defined for all phases of flight, meaning that the RPA departed from RWY 24 of EHRD on SID COSTA 1B until leaving the TMA. Another RPA simulation then had to be started outside the TMA on STAR PUTTY 2R and the RPA would land from its intended spot in the arrival sequence with other IFR and VFR traffic on

RWY 24. Such a simulation run took between 30 to 45 minutes to complete.

For an assessment of the impact of voice communication loss between RPS and ATC, a scenario for each of the flight phases was defined as well. One of the critical design choices for the procedure was made when producing the use case definitions [6].

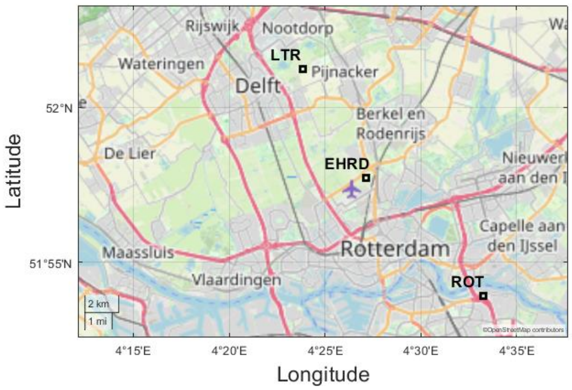

Figure 11. R/T Failure Loiter Point (LTR)

That choice was to determine that, in case of complete loss of all voice communication options (including backup communication methods), the RPIL had to turn the RPA towards a defined loiter waypoint (LTR) with a surrounding loiter area (at a distance of about 10 km to the Northwest, with sufficient radar separation from ILS and runway, and perpendicular to the runway, as shown in Figure 11). Furthermore, several scenarios were possible regarding the initiation of the backup communication call via an available phone line by either RPIL or ATCO and the termination of the R/T failure procedure by returning to base with either a regained R/T connection or a backup phone connection.

Validation scenarios were also split into different sections in order not to repeat similar situations for identical traffic patterns. Thus, most of the scenarios were only defined up to the point where the RPA reached the loiter area. Additional scenarios were devised where the RPA would start circling in the loiter area and needed to be integrated into the arrival sequence with either regained R/T connection or the backup phone as communication means in order to land at the airport. Not all possible combinations of scenarios could eventually be simulated. However, it was possible to combine all optional elements in such a way that ATCO and RPIL feedback could be received. Table 3 gives an overview of the R/T failure scenarios and their characteristics.

Table 3. Scenarios for Voice Communication Loss

	Flight Phase of Failure and Characteristics
Contingency 1	***Departure*** Failure restored in loiter area Departure is continued
Contingency 2a	***Arrival*** Backup call initiated by RPIL Ends when reaching loiter area
Contingency 2b	***Arrival*** Backup call initiated by ATCO Ends when reaching loiter area
Contingency 3	***Approach*** Ends when reaching loiter area
Contingency 4	***Landing*** Ends when reaching loiter area
Contingency 5	***Approach*** BRLOS conditions throughout Failure restored in loiter area Approach is continued
Loiter 1	***Arrival/Approach/Landing*** Failure restored Landing from loiter area
Loiter 2	***All phases*** Failure not restored Landing from loiter area
Loiter 3	***Arrival/Approach/Landing*** BRLOS conditions throughout Failure restored Landing from loiter area

It should be noted that the flight phases mentioned in Table 3 have the following definitions:

- Departure: after take-off and passing EH158 (as shown in Figure 9)
- Arrival: before reaching or around the IAF (as shown in Figure 10)

- Approach: after passing the IAF, before reaching the FAF (as shown in Figure 10)
- Landing: after passing the FAF

Another complexity of the R/T failure scenarios (which becomes apparent from the flight phase definitions above) was the timing of the failure. While the loss of communication and the time to realize the backup connection could be rather long without necessarily causing trouble around the IAF, it had to be almost instant during the approach and landing phases in proximity of the airport. This complexity was recognized by the simulation design team from the beginning, and it was decided to not prescribe a definite procedure in these cases, but leave it open to the participants to come up with an operational solution based on the situation at hand, which was difficult to predict in detail. This was also in line with the exploratory character of the INVIRCAT project.

Assessment Techniques

The NLR validation scenarios were defined in such a way that they would particularly address abovementioned research areas for signal latency and voice communication loss, with both the ATCO and RPIL roles in mind, leading to results for:

- Operational acceptability
- Perceived safety of operations
- Perceived workload levels
- Applied R/T phraseology
- Provision of information content (on HMI)
- Adequacy of expected human contribution
- General impact of latency on operation

Most of the performance indicators above were assessed using dedicated questionnaires developed together with all project partners under the lead of ISSNOVA. NLR customized the relevant questions for each of the developed scenarios and grouped them in accordance with the validation objectives formulated for each of the scenarios. Questions were mostly arranged for use with a six-point Likert scale with the highest value indicating strong agreement. In addition, standard questionnaires and assessment techniques were used to get a more detailed view on Situational Awareness (SA), workload and acceptability. After each of the validation runs a quick assessment of SA and workload of both ATCOs and RPIL was performed using a modified Bedford rating scale developed by ISSNOVA (and to be published in the final result report of INVIRCAT). In addition to very specific questions on the topic after each of the validation runs, acceptability of the general concept was assessed using a CARS rating scale [16] that was slightly adapted by NLR for use with novel operational procedures.

NLR Validation Results

ATCOs and RPILs described the simulation environment as very realistic and the traffic samples were considered adequate in traffic volume and typical for a busy day at EHRD with a mix of VFR and IFR traffic with different performance characteristics. ATCOs said that the aircraft performance of the MALE RPAS operating under IFR was similar to that of general aviation aircraft, and with lower speeds than manned IFR traffic. While it was challenging for them to have slower traffic on the SIDs and STARs and further on in approach, no additional separation buffers were applied between manned and unmanned aircraft.

Establishing an arrival sequence with RPAS and other IFR aircraft, flying at higher speeds, resulted in an increased experienced level of workload when compared to the simulation without RPAS in the sequence. Yet, the workload level was still rated as satisfactory.

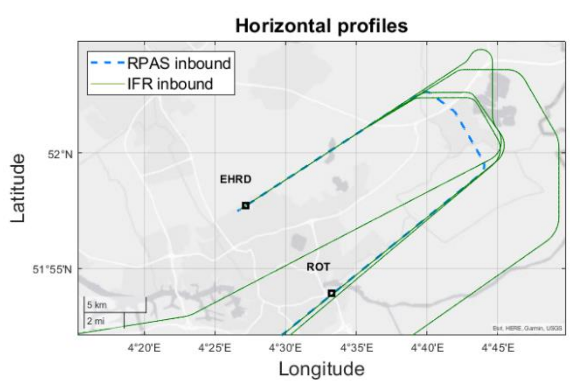

Figure 12. Ground Tracks of Inbound RPAS and IFR Flights during Nominal Operations

Regarding equity of operations, the RPAS was treated the same as other IFR traffic, although it was necessary to consider speed differences when building the landing sequence. As a consequence, manned IFR traffic incurred more delay than the RPAS, as can be observed in the ground track plot during nominal operation with a single inbound RPAS in Figure 12. Controllers tried to minimize delay whenever possible while adhering to the landing sequence. If necessary, the RPAS as well as the manned IFR traffic would receive radar vectors in order to maintain separation i.e. the RPAS was not given priority on purpose.

Voice Communication Latency

During nominal operations, ATCOs did not notice that different levels of voice communication latency were applied to outbound and inbound RPAS flights within the simulated environment. Therefore, they also did not change their ways of working with the different types of traffic They stated that a reason for not noticing any latency could have been that ATCOs were used to pilots in manned aircraft that do not immediately read back or respond to their instructions. The introduction of latency did not deteriorate the perceived situational awareness and experienced workload level of the controllers.

To evaluate the influence of a noticeable voice communication latency on the operation, an additional scenario (on top of what has been described in Table 2) was created. In that scenario the maximum one-way voice latency for BRLOS was multiplied by a factor of 2.5, increasing that latency to 1.75 s. Such extreme levels of latency may be observed in case of a BRLOS connection that is relayed via multiple satellite connections. Both ATCOs immediately noticed the voice latency and anticipated accordingly. The TWR controller could accept the latency level in the nominal condition as the number of calls to outbound and inbound RPAS was limited. The APP controller tried to minimize the frequency of communication exchanges with the RPIL. ATCOs felt that the additional waiting time resulted in inefficiencies for handling the manned traffic. In addition, they were irritated when they did not receive an immediate response to simple inquiries. They stated that, in distress situations or situations with a higher traffic load and with more voice communication exchanges between ATCOs and pilots, such extremely high latency levels could potentially cause more operational complications with overlapping or missed radio calls.

R/T Failure and Voice Communication Loss

For the simulation of VHF equipment failure onboard the RPA and the consequent voice communication loss, the voice communication system (VCS) interface of the RPIL for the currently used frequency could be disabled by simulation observers and transponder squawk code 7600 for radio communication loss was emitted by the RPAS. The squawk code was displayed and highlighted on the ATC radar displays. In such a case a (conventional) backup phone was used and the call could be initiated by either RPIL or ATCO using a list of available phone numbers. Once a connection was established, the line was kept open such that both RPIL and ATCO could communicate at any time. For practical reasons, the experiment did not foresee an ATSU contact person or a supervisor who would redirect the call. The RPIL would either call the last controller who was contacted on the frequency or the tower or approach controller would call the RPIL. In general, the controllers had an equally positive experience as in the nominal validation run.

Unlike loss of communication with manned aircraft, the availability of a backup phone connection between ATC and RPS when there is loss of communication with the RPA offers more possibilities and flexibility in finding an operational solution to the problem. Although not being as efficient as conventional R/T communication (not on the frequency or integrated in VCS interface), the direct communication via the backup phone resulted in the APP controller managing the RPAS as if there was no R/T failure. Instead of guiding the RPAS immediately towards the loiter waypoint, where the RPIL was expected to check and possibly restart the VHF component and restore the failure, the ATCO preferred to provide instructions to proceed with the planned operation. This operation could have been the landing or a continuation of the flight towards the final waypoint on the SID with transfer to the following sector. The same was true for the pilot. Instead of directly turning to the loiter area, the RPIL preferred to stay on the route given in the flight plan and to quickly access the backup option for further communication with ATC.

For inbound RPAS, the ATCO preferred to proceed with the arrival procedure because, at that point, a landing sequence had already been planned and established by the ATCO integrating the RPAS into the IFR traffic arrival flow. While the ATCO could have given instructions to the RPIL to steer the RPA towards the loiter waypoint, several reasons were mentioned why this was not the best solution:

1) the uncertainty if and when the failure will be resolved
2) the fact that the backup communication option worked very well
3) the additional effort to integrate the RPAS into the landing sequence again after the failure had been resolved

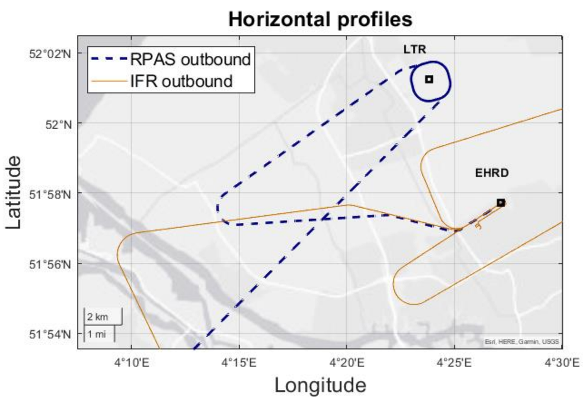

Figure 13. Ground Tracks of Outbound RPAS with Loss of Voice Communication

In order not to close the backup communication channel between the APP controller and the RPIL when transferring control to the TWR controller before the landing, the APP controller stayed connected and coordinated via intercom with the TWR controller to (indirectly) provide the landing clearance. In this way, the ATCO tried to mitigate the additional hazards that can occur when closing and opening a (backup) communication channel, i.e. when the phone of the TWR controller is not working, the RPIL cannot find the correct phone number or in any other case of communication service disruption.

During one of the validation runs, the RPAS experienced an R/T failure during the departure phase. The RPIL was instructed by the experiment leader to immediately head towards the loiter waypoint before initiating a call on the backup phone (as was described in the relevant use case). The ground track of this flight is presented in Figure 13. The controllers commented that…

1) …the situation was unpredictable because the RPAS changed heading towards the loiter waypoint without instructions from the controller,
2) …ATCOs would prefer to guide the RPAS towards the loiter waypoint via the backup phone
3) …instead of defining a dedicated loiter waypoint, the existing holding stack could be used as the RPAS was still controllable and there was a direct communication link.

During two of the validation runs with R/T failure, the RPIL was instructed by the experiment leader to call the ATCO and in one validation run the RPIL was requested to wait for the ATCO to initiate the call. In the other runs, ATCOs and RPIL could decide for themselves when to pick up the phone. It was expected that the ATCO would wait for the call of the RPIL as the ATCO was busy controlling the TMA traffic. However, in some situations, the ATCO had the impression that it was preferable to understand the intentions of the RPAS before instructing other traffic to perform avoiding maneuvers. This impression was supported by the fact that backup communication could easily be established.

In those runs where the RPAS used the loiter waypoint to restore voice communication via the VHF equipment, the APP controller several times suggested to the RPIL to use the existing backup phone connection to continue the flight and land at the airport. The ATCO stated that the main reason for doing this was the preference to get the aircraft to land as quickly as possible to clear the airspace. Furthermore, the ATCO said that, in some cases, he spotted a gap in the inbound traffic that would have allowed the RPIL to land the RPAS without delaying manned traffic or having to wait in the loiter area.

The TWR controller was contacted by the RPIL via the backup phone in case the R/T failure occurred when the RPAS was still under control of the tower controller, i.e. immediately after take-off and while on final approach before having received the landing clearance, which would lead to the initiation of a Missed Approach (MA) procedure. In both situations the RPAS would soon enter the airspace under control of the APP controller. Therefore, after coordination between TWR and APP controllers via the intercom, the RPIL was instructed by the TWR controller to call the APP controller on the backup phone. While the RPIL was contacting the APP controller, the backup phone connection with the TWR controller was closed.

Figure 14. Approach Controller in Contact with RPIL on the Backup Phone

For the APP controller to efficiently perform all duties, the backup phone was switched to speaker mode to allow the ATCO to use his hands (as presented in Figure 14). To avoid overlap between ATCO instructions to the RPIL via the backup phone and manned aircraft calling in on the frequency, the ATCO broadcast his instructions to the RPIL to all pilots by talking on the frequency. This reduced the possibility of the ATCO missing calls on the frequency and increased the situational awareness of all other pilots.

Failure of the Backup Communication

The validation run where also the backup phone would fail was not briefed to controllers beforehand. When the backup phone failed, the RPAS emitted emergency squawk 7700 and followed the radio communication loss procedure for conventional manned aircraft (i.e. without turning to a loiter point). The choice for squawk code 7700 was made by the RPIL as it was expected that the RPA would need to land without landing clearance and to indicate to controllers that the backup phone had failed.

Since the APP controller was not aware whether the RPAS indeed had an emergency or suffered a loss of backup communication, the squawk was interpreted such that emergency measures had to be taken. This meant that the APP controller expected the RPAS to either land without clearance or move towards an emergency waypoint (usually a loiter waypoint above an unpopulated area) where the RPAS could perform a CFIT procedure, as would be necessary if the RPAS became completely uncontrollable and initiated an automated emergency procedure. Accordingly, the APP controller cleared the entire airspace for the RPAS, instructing other traffic to enter the IAF holding. This resulted in a significant increase in workload.

The ATCOs commented that, instead of squawking 7700, the RPAS could have squawked 7600 and should have proceeded with the loss of communication procedure as defined for manned aircraft. Furthermore, they identified the need for an indication that communication via the backup phone was not possible. ATCOs might lose valuable time trying to reach the RPIL on the backup phone. In addition, an instant messaging service as a backup of the backup phone would have sufficed to communicate the intention of the RPIL, which again had made RPAS movements more predictable.

Following this validation run, the ATCOs felt the need to provide clearances to the RPAS earlier than usual fearing another failure of the back-up line.

Conclusions and Recommendations

Summary of Results and Conclusions

The delay times in voice communication were suspected to have an impact on the work of air traffic controllers as any delay in communication would slow down both pilot readbacks and pilot reactions to controller instructions. It was thought that this would force ATC to consider additional safety buffers between an RPA and surrounding traffic or when timing merge operations to establish an approach sequence. However, the applied latency values were not high enough and both controllers and pilots said that they did not notice any delays. Accordingly, working procedures were not changed and there were no differences in workload or SA level values.

When artificially increasing these values both controllers and pilots started noticing the delay. While the R/T latency was already rather high (1.75 seconds) and controllers started anticipating RPA movements (thus artificially adding a buffer) to be able to react more quickly, they stated that they could still work with such a constraint, as the traffic situation was still permitting to do so. They expected that this would be different in busier TMAs where the load on the frequency is higher.

In summary, controller and pilot debriefings showed that voice communication delay values below 1 s were considered acceptable given the specific situation assessed for EHRD, with one RPAS flight being integrated into an operation of about 20 IFR and 8 VFR flights per hour, while values above 1 s would lead to changes in working behavior (early anticipation of actions to take on the side of the APP controller) and an increased workload with reduced SA. However, according to the feedback obtained, when or how a delay value will lead to a change, very much depends on local conditions regarding airspace layout and availability as well as traffic load and type of traffic.

Loss of voice communication was also assessed in all flight phases in the TMA. Emergency procedures for other technical issues with RPAs (such as C2 link loss) were taken as a basis for defining an appropriate procedure for an R/T failure. This meant that a loitering waypoint was made available that RPAs can navigate to autonomously when they encounter technical difficulties. The NLR simulations came to the following basic conclusions regarding such procedures:

- Both pilots and controllers were adamant that the IFR RPA should follow the same procedures defined for manned IFR traffic. This means that IFR RPAs would need to continue to follow the flight plan and the last given clearance or any other procedure prescribed for manned aircraft in case of loss of communication (e.g. an MA procedure) until there is backup communication.
- If backup communication can be set up easily (e.g. by integration into the VCS panel or by automation and full integration into the control frequency), there would be no reason to follow an emergency procedure to a loiter point and normal operations could be resumed.

Recommendations

On the basis of the validation runs, a number of procedural challenges for voice communication latency and loss were identified by simulation participants and the NLR validation team. They must be seen as recommendations for further research.

- The voice communication latency level during critical phases of flight (departure and arrival) should be minimized taking precautionary measures, such as having the RPIL (RPS) stationed in the vicinity of the airport. This should guarantee a low latency level.
- Generally, in order to find out when or how a communication delay value will lead to undesired changes in controller working behavior with increased workload and reduced SA, studies regarding the required communication performance (RCP) of a particular operation should be carried out. The ICAO Performance-based Communication and Surveillance (PBCS) Manual [17] describes the studies necessary for development of an appropriate (RCP) specification indicating required values for communication transaction time, continuity, availability, and integrity, and should be consulted to that end. Applied architectures and technologies will eventually need to comply with such a specification.
- R/T failure and loss of voice communication of an RPAS is not as critical as a loss of communication with manned aircraft since there are various backup means for recovery. Instead of defining an RPAS specific loss of communication procedure, the RPAS can follow the loss of communication procedure of manned aircraft until instructions are received via the communication link (either via the backup line or by resolving the failure). A dedicated loiter waypoint for R/T failure should not be defined.
- The backup communication link should be a direct voice communication line via a conventional phone line, however, an (additional) instant messaging function could also be investigated. While this option may cause too much workload for the APP controller, the RPIL could use it as a last resort for communication with a supervisor or assistant. The backup link should be secure and only accessible for authenticated users. The connection should be stable and reliable, meaning that the right ATCO or RPIL will be contacted, that there will be no conflict when both parties try to contact each

simultaneously and that multiple loss of communication situations will be accommodated.

- The RPAS squawked 7600 for R/T failure. It should be investigated whether the squawk should be changed at all when communication via the backup link is available, meaning that the RPAS only squawks code 7600 when it is following the loss of voice communication procedure. Alternatively, the ATCO position could be provided with an indication whether the backup link is lost so that the ATCO knows that the RPAS is indeed following the loss of voice communication procedure when code 7600 is squawked.
- Information in the flight plan regarding the RPS should always be up-to-date and clearly stating which station or pilot is in control (e.g. in case of handovers).
- ANSPs should define internal procedures with appropriate roles and tasks (or automated procedures and systems) such that backup communication between RPIL and ATCO is established as quickly as possible.
- The backup communication equipment should be part of the standard equipment for an RPS.
- Additional workload for the controller should be minimized when using backup communication. It should therefore be investigated how the backup communication can be integrated seamlessly into the CWP environment. This includes the integration of the backup communication into the control frequency to avoid overlapping calls.
- Communication via a dedicated ground-to-ground connection, if more reliable than VHF or SATCOM connections, could become the standard communication means for RPAS, with the VHF radio on the RPA functioning as the possible backup.
- Similar experiments could be carried out in busier airspace in terms of traffic or frequency load. This should be airspace that can practically be used for RPAS operations (i.e. not necessarily a hub operation).
- The number of simultaneous RPAS flights in the simulations should be increased (or varied) to further analyze the impact on ATC.

Future Activities

The NLR simulations have shown that it is possible to find out about the operational acceptance of typical latency values in human-in-the-loop simulations. However, these simulations must be seen as only one of the instruments to determine the required communication performance of an operation and to establish an RCP specification that all architectures must comply with.

The simulations have also shown that unmanned aircraft should be treated the same as manned aircraft when there is loss of voice communication, meaning that loiter points are not required. The availability of backup communication makes it easier to resume normal operations and continue the flight. In operationally complex areas, such as TMAs and airports, the most reliable and direct communication source is preferred, yet there always needs to be a compromise between reliability and mobility.

Results of the NLR simulations will be further analyzed and reported as part of the final validation report of the INVIRCAT project. Except for voice communication latency and loss, the report will also contain the results of an analysis of specific TMA conflicts between the RPA and manned traffic and an evaluation of different procedures for carrying out handover operations from one RPS to the next with a focus on the impact on ATC.

The next step in the European ATM Master Plan roadmap foresees operations in airspace classes A to G with DAA capabilities and an appropriate communication architecture addressing the relevant integrity and security requirements. While INVIRCAT has been a first step in indicating the impact of different architectures on ATC operations in airspace classes A to C, more complex operations are expected in classes D to G where there is less or almost no service provision. In the future, such airspace may also offer U-space services or may be considered as ATM U-space Shared Airspace (AUSA), which calls for even more integrated operations and complex studies for operational concept validation.

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Appendix I

Abbreviation List

ACAS	Airborne Collision Avoidance System
ADC	Aerodrome Chart
AIP	Aeronautical Information Publication
APP	Approach
ASR	Aerodrome Surveillance Radar
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOL	Automatic Take-off and Landing
AUSA	ATM U-space Shared Airspace
C2	Command and Control
CFIT	Controlled Flight Into Terrain
CIRA	Italian Aerospace Research Center
CNS	Communication, Navigation and Surveillance
CONOPS	Concept of Operations
DAA	Detect and Avoid
DIS	Distributed Interactive Simulation
DLR	German Aerospace Center
EDD	Electronic Data Display
ENAV	The Italian Company for Air Navigation Services
ESA	European Space Agency
EUROCAE	European Organisation for Civil Aviation Equipment
FAF	Final Approach Fix
G-G	Ground to Ground
GCS	Ground Control Station
HALE	High Altitude, Long Endurance
HMI	Human-Machine Interface

IAF	Initial Approach Fix
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INVIRCAT	Investigation of IFR RPAS Control at Airports and in the TMA
ITU	International Telecommunication Union
JARUS	Joint Authorities for Rule-making on Unmanned Systems
MA	Missed Approach
MALE	Medium Altitude, Long Endurance
MUST	Multi-UA Supervision Testbed
NARSIM	NLR ATC Research Simulator
NLR	Netherlands Aerospace Centre
NM	Nautical Miles
PBCS	Performance-based Communication and Surveillance
PBN	Performance-based Navigation
R/T	Radio Telephony
RCP	Required Communication Performance
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPIL	Remote Pilot
RPS	Remote Pilot Station
RTCA	Radio Technical Commission for Aeronautics
RWY	Runway
SA	Situational Awareness
SATCOM	Satellite Communication
SATI	SHAPE Automation Trust Index
SESAR	Single European Sky ATM Research
SHAPE	Solutions for Human Automation Partnership in European ATM
SID	Standard Instrument Departure
SJU	SESAR Joint Undertaking
STAR	Standard Terminal Arrival Route
SUS	System Usability Scale
TAR	Terminal Approach Radar
TMA	Terminal Manoeuvring Area
TNO	Netherlands Organisation for Applied Scientific Research
TSD	Traffic Situation Display
TWR	Tower
TWY	Taxiway
UAS	Unmanned Aerial System
VCS	Voice Communication System
VFR	Visual Flight Rules
VHF	Very High Frequency

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