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Validation of the use of GBAS precision approaches for improved runway throughput in poor weather conditions

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Abstract— **In current low visibility operations at an airport while normally using Instrument Landing System (ILS), extra spacing margins between aircraft have to be provided in order to protect the ILS critical and sensitive areas. This results in a decrease of runway throughput during low visibility conditions. The benefit of the use of Ground-Based Augmentation System (GBAS) instead of ILS in low visibility conditions is that there is no sensitive or critical area that has to be protected. The GBAS Local Object Consideration Areas (LOCA) are also much smaller and usually located outside aircraft movement areas. This leads to an immediate improvement in runway throughput in adverse weather conditions. To validate this anticipated benefit a real-time simulation was conducted in the frame of the SESAR 06.08.05 GBAS operational implementation project. The results of this real-time simulation show that when using GBAS precision approach in LVP operations for segregated runways, the expected runway throughput benefit is materialised without negatively impacting safety and human performance. However, GBAS in LVP operations for mixed mode runway operations might not bring any significant gain in runway throughput since the results indicate that the spacing cannot be reduced as much as expected.**

***Keywords-** GBAS;ILS; low visibility procedures (LVP); runway throughput; safety; human performance; airport; separation; spacing; ESCAPE; EDEP; HMI; ATC; SESAR*

I. INTRODUCTION

Today busy European airports operate near their maximum capacity in good weather conditions, but the landing rate is decreased during low visibility conditions experienced in bad weather. When visibility drops below the required minimum, air traffic control establishes low visibility procedures (LVP). These ensure safe operations, which regulate the ground movements and protect the Instrument Landing System (ILS) signal used by approach and landing aircraft.

The ILS system is installed in the runway area and is subject to multi-path effects. These place restrictions on building development and also on aircraft movements in the airport. In low visibility conditions the flight crew is required to use on-board automation (i.e. autoland) for approach and landing, which are highly dependable on the ILS signal. These aircraft operations are called Category II and III (CAT II/ III). Due to the technical nature of the ILS signal, ILS protection areas become larger in low visibility. Aircraft entering the runway areas are required to hold on CAT III holding points as opposed to CAT I holding points, which are closer to the runway and used in good visibility. This results in restricted ground movements and greater spacing margins between aircraft in order to accommodate the subsequently longer runway occupancy times (ROT). The consequence is a significant decrease of runway throughput during low visibility conditions. To increase capacity on a runway, navigation aids are being introduced with smaller sensitive areas [1]. One proposed navigation aid is the Ground Based Augmentation System (GBAS). The GBAS operational implementation study proposes optimised low visibility operations based on the use of GBAS for approach and landing.

II. "OPTIMISED LOW VISIBILITY OPERATIONS USING GBAS" CONCEPT DESCRIPTION

A GBAS station is implemented locally at an airport and augments the existing Global Positioning System (GPS) (and potentially any other constellation in the future) so as to provide enhanced level of service supporting all phases of approach and landing in all weather conditions. One GBAS station can provide the approach service for all runway ends at an airport.

GBAS offers flexibility near the airfield as the station can be located further away from the runway. Certain siting and signal protection area requirements must still be met; the GBAS protection area is named Local Object Consideration Area (LOCA). GBAS is much less likely to be prone to interference than ILS as the station is usually located outside the aircraft movement areas and the radio signal is used differently [2].

The optimised low visibility operations using GBAS are based on the removal of ILS runway protection areas and the provision of a later landing clearance to the pilots from ATC at 1NM. Today with ILS the landing clearance is provided at 2 NM before threshold at the latest. A landing clearance line is defined, replacing the current ILS CAT III holding points. This clearance line determines the point that an aircraft or vehicle vacating the runway must have reached before the controller can issue landing clearance to an approaching aircraft [1].

The determination of the landing clearance line (see Fig.1) takes into account (a) the need to protect the runway area, called Obstacle Free Zone (OFZ) in low visibility operations (regardless of whether the navigation aid ILS or GBAS is used for landing); (b) the aircraft wingtip clearance from touchdown to the end of the roll out along the runway; (c) the collision risk during the landing and balked landing [3].

The use of landing clearance line by ATC and the possibility for later provision of landing clearance to flight crew provide the controllers with a means to reduce final approach spacing thus improving landing rates in low visibility conditions. The amount of gain depends on other local airport factors such as airfield design, traffic mix, traffic demand, etc.

Other capacity limiting factors in low visibility such as slower taxi speeds leading to an increase of runway occupancy time are outside the scope of this study.

The main objective of the presented GBAS in LVP study was to validate the increased runway capacity in poor weather conditions brought about by the use of GBAS CATII/III for precision approaches.

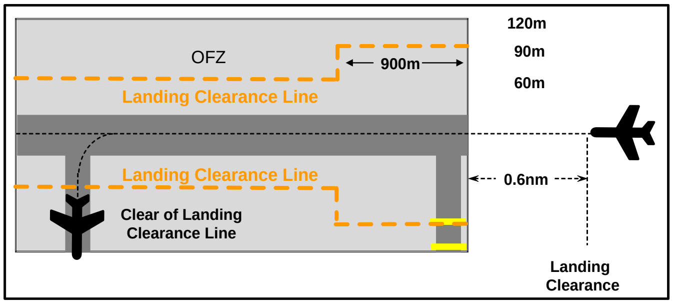

Figure 1. Illustration of landing clearance line [4]

III. VALIDATION APPROACH AND SETTING THE SCENE

In line with the European Operational Concept Validation Methodology (E-OCVM) this project was classified as being in the life cycle phase V3 pre-industrial development and integration. The objective of this phase is threefold: firstly to further develop and refine operational concepts and supporting enablers to prepare their transition from research to an operational environment; secondly, to validate that all concurrently developed concepts and supporting enablers (procedures, technology and human performance aspects) can work coherently together and are capable of delivering the required benefits; thirdly, to establish that the concurrent packages can be integrated into the target ATM system. The main type of validation exercise conducted in this phase is thus concerned with the integration, and establishing that the performance benefits predicted for individual concept elements in V2 can be realised collectively [5]. A real time simulation was used for this purpose.

A. Real Time Simulation

The real-time simulation was conducted from September 29 to October 3, 2014 in the Eurocontrol Experimental Centre (EEC) in Brétigny-sur-Orge, France. The simulation uses the ESCAPE (EUROCONTROL Simulation Capability and Platform for Experimentation) platform, a real-time air traffic control simulator for en-route, TMA and approach. This was linked to the eDEP/ITWP (Early Demonstration and Evaluation Platform/Integrated Tower working position) – a real-time tower control simulator with advanced capabilities, and the MCS - Multi Cockpit simulator [6]. For the purpose of this exercise these platforms were used to simulate three controller working positions: (a) feeder and final approach controller generated by ESCAPE/Approach only; (b) tower runway controller generated by eDEP/ITWP; (c) pilots using the MCS.

The final approach and tower controller working positions were measured. The feeder controller working position was not measured. Departing traffic was not part of the approach or feeder controller task and was automated and assumed to be handled by other sectors. The ground movements, i.e. taxiways were not part of the tower runway controller task and were automated.

1) The simulated operational environment and scenarios

The simulated operational environment was Paris Charles de Gaulle (CDG) airport. However, only runway 27L was simulated. During the exercises, runway 27L was used for arrivals in the segregated runway mode and in mixed mode for the arrivals and departures. This runway is not used in mixed mode in today’s CDG airport operations. The objective was to create scenarios applicable to a variety of airports including those with only one runway. In order to obtain an as generic environment as possible the setup of the simulation was stripped of some local specificity.

Traffic samples were created to represent peak traffic in a capacity demanding airport.

The simulation scenarios represented various runway configurations and mixed ILS/GBAS landings as below:

- ILS arrivals only (reference scenario).
- ILS arrivals/departures (reference scenario).
- GBAS arrivals only.
- GBAS arrivals/departures.
- GBAS/ILS arrivals only.
- GBAS/ILS arrivals/departures.

2) *Setup of the real-time simulation*

The real time simulation was composed of 12 exercise runs in two measured positions. Three ENAV (Italy) air traffic controllers participated during the entire week and three active airline pilots participated for two days each. Although the controllers were not from the Charles de Gaulle airport, it was chosen for the simulation for practical reasons. Before the simulation the controllers participated in a three-day training session that included theoretical training on the proposed GBAS procedures as well as the practical training which meant familiarisation with and adaptation to the environment, maps, traffic sample and the HMI. The 12 runs meant that each scenario was repeated once leading to a total of two exercises per six scenarios. The validation run and the controller rotation were designed in such a way that the data from all scenarios with segregated mode runway can be compared, and the scenarios with mixed mode runway respectively. Additionally three exercises with specific safety scenarios were performed. During these safety scenarios (a) a technical failure of the GBAS station on ground (b) a technical GBAS failure on board the aircraft and (c) a misunderstanding in the pilot / controller communication were simulated.

Due to the small number of repetitions only descriptive statistics with mean values were calculated for the quantitative data. Those quantitative data included the number of landings, loss of separation, go-arounds and runway incursions, among others.

Different questionnaires on workload, situational awareness, usability and acceptability were distributed. The results were supported by observation (in each position an observer was sitting throughout the entire simulation week) and by debriefing data. Qualitative feedback was collected on the safety scenarios.

B. *Stakeholder workshop*

Before the simulation, a stakeholder workshop including controllers and pilots was conducted. One of the purposes of this workshop was to decide on the procedures used in the real-time simulation. The ATC procedures developed for the purpose of the simulation were based on London Heathrow optimised microwave landing system (MLS) low visibility procedures [7], since they are very similar to what is proposed for GBAS.

The concept of the optimised GBAS CAT III low visibility procedures relies on:

- The definition of a landing clearance line (instead of ILS CAT III holding points) for determining when an aircraft vacates the runway in case of a GBAS landing.
- The provision of late landing clearance to the flight crew of an approaching GBAS aircraft (1 NM before threshold).

ATC procedures were developed for both segregated and mixed mode runways as related to the provision of landing clearance, and are described below.

In segregated runways the landing clearance was given at the latest at 2 NM before threshold for ILS approaching aircraft and 1 NM before threshold for GBAS approaching aircraft provided that preceding aircraft has vacated the runway (passed the landing clearance line for GBAS).

In mixed mode runways the landing clearance was given at the latest at 2 NM before threshold for ILS approaching aircraft and 1 NM before threshold for GBAS approaching aircraft provided that the preceding aircraft has vacated the runway or as soon as the preceding aircraft is airborne in case of departures. The simulated procedure related to departures might be different if compared to today’s operations. In most airports, depending on the position of the localiser, the landing clearance is given to approaching aircraft when the departing aircraft has overflown the localiser. This difference between the simulated and current procedures is noted and taken into account when interpreting the validation results.

Tables I and II were used to provide the controllers with clear recommendations regarding the minimum spacing they should apply.

Table I SPACING PROPOSAL FOR MIXED MODE RUNWAY SCENARIOS

	ILS only	**GBAS 60%** **(60% GBAS / 40%ILS)**	**GBAS 100%** **(GBAS only)**
Mixed mode runway	Reference scenario 2* (RS2) - 10 NM	Solution scenario 2* (SS2) • ILS 10 NM • GLS 8 NM	Solution scenario 2A* (SS2A) - 8 NM

Table II SPACING PROPOSAL FOR SEGREGATED RUNWAY SCENARIOS

	ILS only	**GBAS 60%** (60% GBAS / 40% ILS)	**GBAS100%** (GBAS only)
Segregated runway	Reference scenario 1* (RS 1) -7 NM -8 NM behind H	Solution scenario 1* (SS1) - ILS: -7 NM -8 NM behind H - GLS: -5 NM -6 NM behind H	Solution scenario 1A* (SS1A) -5 NM -6 NM behind H

C. *Human Performance & Safety Assessment Process*

As the role of the human is central in the concept validation itself and in the real-time simulation, human factors (HF) are systematically addressed and considered in the system design and development process. This is ensured by applying the SESAR HP Reference Material. If human factors are not adequately considered, the proposed system performance benefits in terms of safety, capacity and efficiency may not be achieved. It is therefore essential that the standardised SESAR human performance assessment methodology is applied [8].

The aim of the HP assessment process is to iteratively demonstrate that (a) the role of the human actors in the proposed ATM system is consistent with human capabilities and characteristics; and (b) the contribution of the human within the ATM system supports the expected system performance and behaviour. The HP assessment process informs the design and development of an operational concept through the identification of recommendations and/or requirements. These may be necessary to prevent or mitigate any potential negative impacts a concept may have on human performance.

In close cooperation with the human performance approach the SESAR safety approach was applied. The SESAR safety assessment process considers safety from two perspectives. Firstly, from a ’success approach’ angle, which assesses how effective the new concepts and technologies would be when they are working as intended, i.e. by how much the pre-existing risks that are already in aviation will be reduced by the ATM changes. Secondly, from a ’failure approach’ angle, which assesses the ATM system generated risks, i.e. risks that are induced by the ATM changes failing. The adoption of a ’success’ and ’failure’ approach to safety in SESAR means that the safety assessment must now consider not only the functionality and performance of the system under degraded modes of operation but also the functionality and performance of the system under normal and abnormal conditions [9].

The aim of the SESAR safety assessment for the GBAS in LVP concept was to demonstrate that the levels of safety are at least as good, if not better than in current LVP operations. In order to do this, evidence had to be provided to ensure that: (a) The GBAS in LVP concept has sufficient safety functionality and performance and can perform safely under normal, abnormal and degraded modes of operation and; (b) the proposed safety requirements are realistic and achievable [10] [12].

IV. RESULT OF THE REAL – TIME SIMULATION

A. *Capacity*

With the introduction of GBAS in LVP, it was expected that more or the same number of landings would take place in the GBAS scenarios compared to the reference scenarios. Fig. 2 depicts the number of landings for both environments: the segregated runway (arrival only) and the mixed mode runway (arrival and departure).

The expected benefit was observed in the segregated runway scenario, where more landings took place in the GBAS scenarios compared to the reference scenario. In the mixed mode runway scenarios, only a slight increase was recorded in the ‘GBAS 100%’ while in the ‘GBAS 60%’ the same number of landings as in the reference scenario was recorded.

B. *Safety*

1) *Radar separation*

Results presented in Fig. 3 consider only wake turbulence pairs, meaning that the following aircraft in the aircraft pair had to respect the distance required according to the ICAO wake turbulence category.

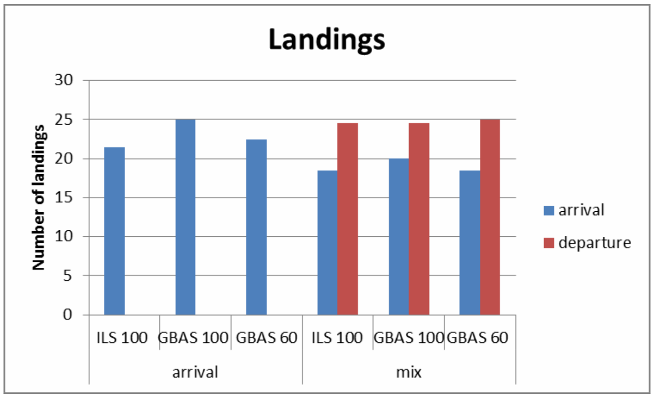

Figure 2. Aircraft landing rate per hour

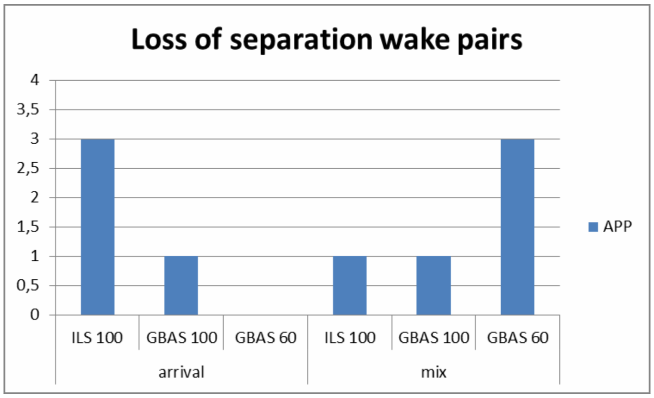

Figure 3. Loss of wake separation – wake pairs

The graph shows that for segregated runways – marked as arrival – more separation infringements were recorded in the scenarios with 100% ILS equipped aircraft than in GBAS scenarios. This, however, does not hold for the scenarios with mixed mode runway operations (arrival and departure). In the mixed mode scenarios more or at least the same number of separation infringements were recorded as in the reference scenario ILS 100%.

Fig. 4 depicts the data recorded for the non-wake aircraft pairs. This means in these aircraft pairs a loss of separation was recorded as soon as the following aircraft had a minimum separation of less than 3NM.

The results suggest the same effect as for the wake pairs. In the scenarios with the segregated runway marked as arrival – no separation infringements were recorded in the GBAS scenarios while one infringement was recorded in the ILS 100% scenario. This is not the case for the scenarios with mixed mode runway operations (arrival and departure). While in the ILS 100% and GBAS 60% one infringement event for each was recorded, five events were recorded in the tower position in the GBAS 100% scenario. The infringements in these cases were always between a departing and an arriving aircraft. It was mentioned by the controllers in the debriefing and in the questionnaires that the landing clearance at 1 NM for GBAS aircraft led to a loss of radar separation when the departing aircraft became airborne and the arriving aircraft was just about to land.

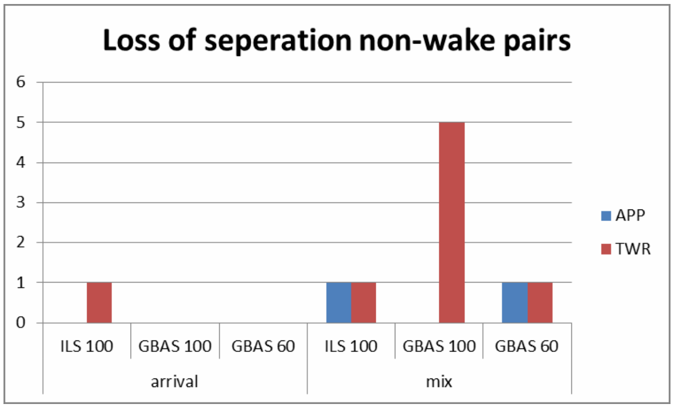

Figure 4. Loss of separation - non wake pairs

2) *Runway incursions*

Only one runway incursion was recorded during the entire simulation. This runway incursion happened in one of the GBAS 100 % mixed runway mode scenarios. Although a small number of runway incursions is the expected and desirable result it is very difficult to draw any firm conclusions regarding the impact of GBAS on the likelihood of runway incursions.

3) *Go-around*

One go-around was recorded in the reference scenario (ILS 100 %) with segregated runway and two go-arounds in the reference scenario (ILS 100 %) with mixed mode runway. No go-arounds were recorded in the GBAS 100 % with segregated runway and two go-arounds in the GBAS 100% with mixed mode.

C. *Human Performance*

Assessing the human performance of the ATCO during the validation exercise included measuring their situational awareness, the HMI usability, the acceptability of the procedures and phraseology and the ATCO workload. The data were combined with qualitative data from questionnaires and debriefings.

1) *Workload*

In the assessment of human performance, mental workload is of particular importance when implementing a new concept and/or new system. Workload is a fundamental parameter in determining acceptable levels of ATCO performance.

The workload of the ATCO was measured with the help of two different methodologies. The first is the Instantaneous Self-Assessment (ISA) tool. Every three minutes throughout the simulation run the controller had to rate the perceived mental workload on a scale from one (very low) to 5 (very high) at that moment.

The second tool was the Bedford workload scale, which provides a 10 point scale to rate the workload perceived during the last simulation run.

The graph of the Bedford workload scale (see Fig. 5) shows that the workload was ranging from very low to satisfactory in the tower runway position during the segregated runway scenarios where only arriving aircraft were simulated.

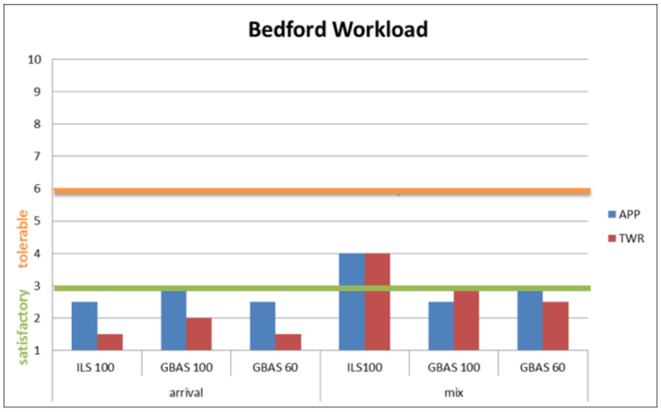

Figure 5. Bedford Workload scale rating

In the mixed mode runway scenarios a higher workload was recorded for the tower positions. Not much difference in the workload scale for the approach position was recorded. However, the highest workload was recorded for both approach and tower in the ILS 100% mixed mode runway scenario.

The ISA workload measurements (see Fig.6) revealed similar results with ratings in all scenarios being very low, low or fair. The highest ISA rating was recorded in the tower position in the ILS 100 % mixed mode runway scenario, where an average rating of 2.6 out of 5 was documented. The workload rating was considered as being acceptable. This was also confirmed in debriefings. The workload was never higher in the scenarios with GBAS than in the reference scenarios (ILS scenarios).

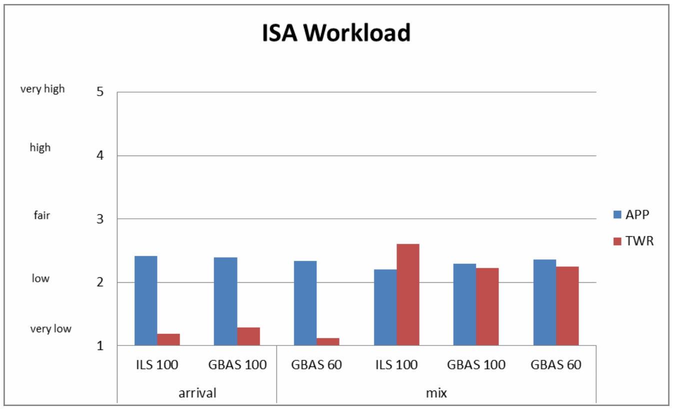

Figure 6. ISA Workload rating

2) *Situational awareness*

Situational awareness is defined as "acquiring and maintaining a mental picture of the traffic situation being managed and appreciating any unexpected progressions in this scenario"[1].

The situational awareness of the ATCO was assessed subjectively at the end of each simulation run by distributing the SASHA questionnaire to the controllers that were sitting on the measured positions. Situational awareness questions were based on the experience in the previous exercise run. SASHA scores range from 0 – 6, a score of 6 indicating a positive rating and hence high situational awareness.

As seen in Fig. 7, a higher or the same level of situational awareness was recorded in the GBAS scenarios compared to the reference scenarios. The lowest situational awareness score was recorded in the ILS 100% mixed mode runway scenario.

In the course of debriefings, controllers reported a deterioration in situational awareness when very long distances had to be applied as in the segregated ILS 100%.

With two or more aircraft already on the final approach it seems to be easier to judge when to initiate the last turn for the following aircraft to final.

These reports, coupled with the fact that the highest measures of workload and the lowest measures of situational awareness were recorded in ILS 100% mixed mode runway scenario, lead to the conclusion that the longer distances applied in the ILS 100 % make it more difficult for a controller to establish and keep a mental picture of the sequence of the aircraft as they are not on the same track. This seems to have decreased the controller's situational awareness.

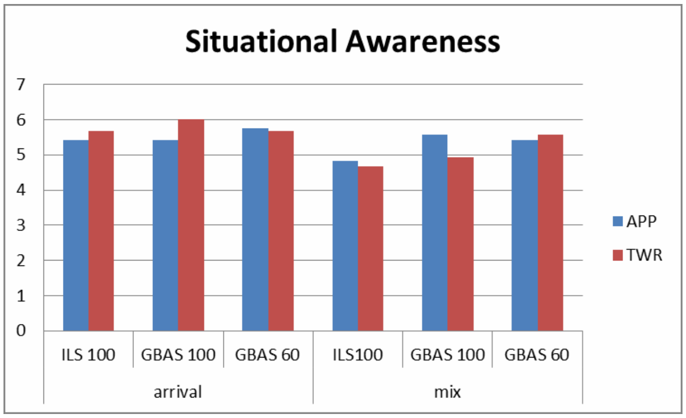

Figure 7. Situational Awareness

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[1] http://www.skybrary.aero

3) *HMI usability*

The HMI was very well received and accepted, especially the indication of a “G” for an aircraft performing a GBAS approach and landing and an “I” for an ILS approach in the label of the aircraft on the controller working position (see Fig. 8). The display of the letter on the HMI helped the controller to always know which aircraft performed a GBAS and which one an ILS landing. The landing clearance mark (displayed as a fine vertical line on the final approach at 1 NM, see Fig.9) was easy to see, and in debriefings it was confirmed that it was useful.

The landing clearance map on ground additional to the display of the ILS critical and sensitive area was rated as being clear, unambiguous and useful.

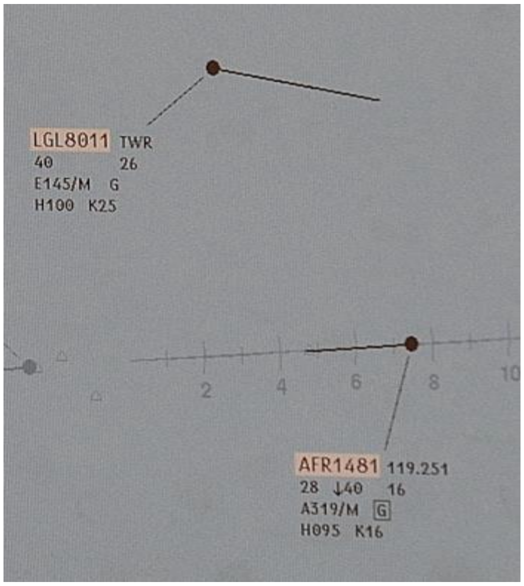

Figure 8. HMI in tower position, G in the label

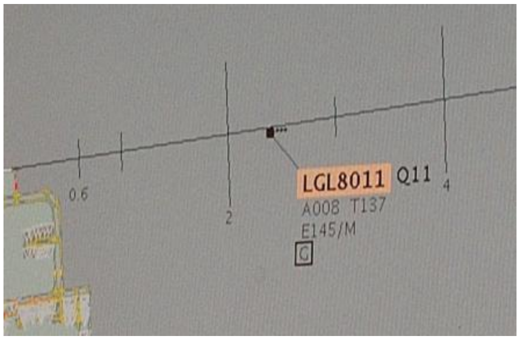

Figure 9. HMI, landing clearance mark

4) *Procedure usability/acceptability*

In a questionnaire the opinion of controllers regarding the procedures was asked. The questions checked for the clarity of the procedures and if the controllers felt comfortable applying them.

The questions were presented to the controllers after each GBAS exercise. The results show that the procedure of applying different spacing in front of a GBAS or an ILS aircraft was clear. However, it was not applied by everybody in the same way, and not all controllers felt comfortable applying the different spacing. Hence in the tower runway position they did not trust this procedure entirely, especially in the mixed mode runway scenario as a reduced spacing can lead to a loss of separation with the departing aircraft.

When asked if they used the 1 NM landing clearance for the GBAS aircraft, all three participating controllers replied affirmatively.

The fact that there were two different distances – 2 NM for ILS landing and 1 NM for GBAS landing – was not perceived as confusing.

Three active airline pilots participated in the simulation and provided their opinion in a questionnaire. In their view the 1 NM landing clearances is acceptable, as long as the flight crew is made aware that a late landing clearance is to be expected.

In the safety scenarios it was proposed that the pilot performs a go-around when the GBAS failure occurs with 10NM to threshold and switches to ILS in case of a GBAS failure when the aircraft is further than 10NM. While the procedures were acceptable for the ATCOs the participating active airline pilots objected to the procedures. The pilots voiced their concern that the 10 NM to threshold might not be the right criteria as it depends on the time it takes to switch from GBAS to ILS and the pilot’s concentration that is compromised.

5) *Phraseology usability/acceptability*

For the simulation it was recommended to use the term “GLS” in the phraseology when requesting or giving a clearance for a GBAS landing and/or approach. This was chosen to be in accordance with ICAO and current GBAS good visibility operations implementation [11]. The results indicate that the recommended phraseology was not applied homogeneously throughout the simulation by all controllers. These results were backed up by debriefing results: When using the term “GLS” controllers did not agree on its acceptability, in fact they were in favour of the “GBAS” term.

The three active airline pilots were asked if they could imagine using the proposed phraseology, two answered with a “yes” however, they would prefer a more distinct difference to the term “ILS” than “GLS”. One of the pilots even answered that it is unimaginable to use “GLS”, with the same reasoning and mentioned the MLS example from Heathrow, where the phraseology says “Microwave” and not “MLS”.

In the safety scenarios, pseudo pilots were instructed to read back incorrectly to the controller. For example, when they were given a GBAS approach the pilot would read back ILS approach. The controller did not always pick up the approach type announced by the pilot as there was another indication in the label (e.g., the “G” for a GBAS approach). These events occurred both for the GLS and the GBAS phraseology, indicating that the controller sometimes read the “G” in the label and expected a request for GBAS (GLS) approach not catching that the pilot asked for an ILS approach. A possible means of mitigation to such a misunderstanding would be the usage of data link. This would imply that the approach clearance is communicated to the aircraft automatically and not transmitted verbally via radio.

V. DISCUSSION AND CONCLUSIONS

At first it has to be mentioned that the fact that Italian controllers were working in the CDG environment for the purpose of the simulation did not have a negative impact on the results of simulation as (a) they were trained beforehand and (b) these controllers worked in both the GBAS scenarios and the reference scenarios therefore their performance was compared.

No negative impact on the capacity was recorded for GBAS in LVP. In all scenarios an increase or the same amount of landings was recorded in the GBAS scenarios compared to the reference scenario. In the scenario with segregated runways the effect was more visible than in the scenario with mixed mode runway operation. These findings combined with the workload and situational awareness results suggest that an increased throughput can be reached with the implementation of GBAS in LVP. The results referring to safety are not fully conclusive and have therefore to be split according to the simulated environment. In the scenarios with segregated runways the level of safety could be maintained and no major issues were raised. In the scenarios with the mixed mode runway the level of safety was decreased. A higher number of losses of separation was recorded. In this context it was mentioned that the procedure of 1 NM for the landing clearance for a GBAS aircraft in combination with a closer spacing in front of a GBAS aircraft contributed to the loss of radar separation with the departure aircraft. The proposed spacing was acceptable for the scenarios with segregated runway, but the used spacing in the simulation can only be considered as spacing proposed for the special environment of this specific simulation. The procedures for the failure mode simulated in the safety scenarios were accepted by the controllers. The participating active airline pilots on the other hand objected that the time that it takes to switch to ILS if they have been already established on GBAS could be the cut-off criteria for a go-around.

The recorded workload values lead to the conclusion that the implementation would not lead to an unacceptable increase in workload. All workload values ranked from tolerable to satisfactory and from very low to fair. Within this range the highest workload was recorded in the ILS 100% mixed mode runway scenario (most similar to current LVP operations), which goes in line with the situational awareness results. The features implemented in the HMI especially for the GBAS environment enabled as well a good situational awareness. Especially the indication of “G” or “I” in the label, dependent on the performed approach type (GBAS or ILS), was highly appreciated. The landing clearance line at 1 NM, indicating to the controller when to give the landing clearance to the GBAS aircraft at the latest, as well as the landing clearance map on the A-SMGCS runway map, was perceived as being useful.

The proposed phraseology was discussed deeply in the debriefings both by controllers and pilots. The result of this discussion reveals that the difference between the terms “GLS” and “ILS” is too subtle. Therefore a more distinct difference in phraseology would be appreciated in order to avoid misunderstandings.

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