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Benefits for Greek Regional Airports Through Innovative Approach Technology using an LPV to GLS Converter

A Case Study for Corfu and Thessaloniki

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Abstract—**Required Navigation Performance procedures are a cost effective and accurate solution for aircraft instrument approaches, especially when combined with a final approach segment utilizing satellite based augmentation. However, transport category aircraft are currently not equipped with the satellite based augmentation for precision guidance. An existing converter technology can provide this final approach segment to aircraft equipped with the GPS landing system. Then, as an added bonus, an automatic landing at pilots discretion is possible after the presented approach. Here, we study Thessaloniki and Corfu airports, both accommodating a large number of transport category aircraft, with many ground infrastructure constraints. Both were recently equipped by the Hellenic air navigation service provider with RNP approaches. We successfully flight tested the satellite based augmentation to GPS landing system converter and show that both airports could benefit from a permanent installation of such a system by having fewer diversions.**

Keywords- instrument approach procedures, GNSS, LPV, Augmentation Systems, GBAS, GLS, SBAS

I. INTRODUCTION

During the recent past, aviation navigation has slowly changed from having a ground based infrastructure to the utilization of Global Navigation Satellite Systems (GNSS). Navigation using satellite signals is based on signal propagation time measurements from the satellite to the receiver, knowledge of the satellite position, and subsequent triangulation [1]. ICAO harmonized the need for comparable standards in satellite navigation within the Performance Based Navigation (PBN) concept [2]. Here, navigation system performance requirements are specified for on-board navigation capability with a high level of accuracy and integrity.

For the approach to airports, ICAO is differentiating between Non-Precision Approaches (without vertical guidance) and Precision Approaches (with vertical guidance). Precision Approaches with three-dimensional guidance to a dedicated runway can either be achieved by traditional ground based landing aids (i.e. ILS, MLS) or by GNSS based approaches. However, due to atmospheric interference and noise in the horizontal direction, a position resolution is only possible with an accuracy (95%) of several meters, depending on satellite geometry, and in the vertical direction it is even more diluted due to the absence of signals originating below the receiver. For this reason, the GNSS signals need to be augmented to be used for Precision Approaches to airports.

Generally, two different augmentation systems exist to improve the lateral and especially the vertical navigation integrity, accuracy, continuity and availability. These are based on ground stations at fixed and surveyed locations. For the Ground Based Augmentation System (GBAS, [3]) these reference sites are located at the respective airport. Correction and integrity data is provided via a VHF aeronautical data link. For the second system, the Satellite Based Augmentation System (SBAS) [4], [5], reference sites are distributed over a country to continental sized service region and the data is provided via satellite downlink. Both systems use Final Approach Segment (FAS) data blocks to describe the approach funnel used by aircraft to approach the runway. This data block contains all the necessary information for the avionics to compute virtual localizer and glide path information. Using GBAS, the system is called GNSS Landing System GLS and the FAS data block is provided at the airport by the VHF data broadcast. Using SBAS, the procedure is called Localizer Performance with Vertical guidance (LPV). The LPV procedure is typically available as lowest minimum on an RNP approach procedure [6], and the FAS data block is provided by the navigation data base of the flight management system. Correction information and FAS data are largely identical for both systems (GLS and SBAS). Both systems enable a decision height as low as 200ft above the aerodrome and a minimum Runway Visual Range (RVR) of 550 meters.

At present, automated landings can only be carried out with precision guidance systems such as the Instrument Landing System ILS [7], the Microwave Landing System MLS, or the GBAS landing system GLS [8]. The common feature of all these systems is the routing of guidance signals directly from the receiving device to the autopilot. Based on these signals the autopilot controls the aircraft during landing phase. The receivers for these three systems are often combined in a multimode receiver (MMR). From the GLS FAS data block the MMR calculates angular deviations from the target path and transmits these directly to the autopilot.

Regarding the equipment rate of aircraft used for commercial transport service, most of the recent Boeing models (B 737-800 and newer, B 787, B747-800) have a GLS capable multi-mode receiver as a standard equipment. For most of the new generation Airbus types, the GLS capability of a multi-mode receiver is either available as an option or it is already installed by default and can be activated for a service fee. In contrast to this, almost no medium-size aircraft in service with European airlines (A 320, B 737 families) is equipped with avionics capable of using the SBAS system for final approach LPV type guidance [9]. This lack of equipage with SBAS capable avionics in combination with the economic aspect of the high procurement and installation costs for a GBAS ground station presently prevents the use of GNSS based Precision Approaches at regional airports.

One of the four key areas of research in the SESAR Program is the “High Performing Airport Operations” which is also reflected in the European ATM Masterplan and the SESAR Deployment Programme (https://www.atmmasterplan.eu/). In 2018, the EUROCONTROL study European Aviation in 2040 – Challenges of Growth [10] has forecasted a steady and continuous growth of IFR movements in Europe stating that *“geographically, there has been particularly strong growth in arrival and departing flights* *for Greece and Iberia, including the Canary Islands, as tourism preferences continued to change*”. Whilst most of the solutions provided by the SESAR programme are focused on managing the operations at larger (hub-) airports, in the future the stability and quality of service at the smaller regional airports will also play a growing role in the European network. If feeder flights to the hubs are cancelled or delayed due to poor meteorological conditions at the regional airports this will also have a major impact on the punctuality and service quality for the hubs and hence for the entire air traffic network.

As a cost-efficient solution mainly for regional airports, [11] we describe a system that enables aircraft equipped with a GLS capable MMR to receive correction data as generated by a SBAS system via the GLS data broadcast system. The system is called GLASS and schematically illustrated in Figure 1. It receives the correction information generated by an SBAS, assembles them to a GBAS conformal structure and applies correction factors to account for the differences between the two systems. GLASS is intended to bring together the advantages of both augmentation systems. It combines an SBAS-capable GNSS receiver with a database and a GLS-compatible data link. The correction and integrity data received from the SBAS satellite are automatically translated into GLS-compatible structures and sent to the multi-mode receiver including the FAS data block. The device can be installed on the ground as well as in the aircraft. An extended version generates ad-hoc FAS data blocks via a user interface by putting in basic data such as approach trajectory and glide angle, enabling faster set-up and commissioning. For both, airport operators and air navigation service providers, the RNP approach is easy and cost-efficient to implement, since it does not require any additional installation of navigation aids on the ground. An LPV to GLS converter could enable aircraft, which is already equipped with an appropriate MMR, to utilize those lower minima and even – at pilot’s discretion – perform automatic landings.

The GLASS system can enable improved access to airports, which operate under location constraints and adverse weather conditions. More specifically, such an airport, is the Greek regional airport at Corfu island (ICAO identifier LGKR) which is built on an embankment into the Mediterranean Sea and a large part of the RWY is surrounded by water; the approach end of runway 34 is surrounded on the one side by a lagoon and on the other side by the Mediterranean Sea and the approach end of runway 16 is bordered by the city of Kerkira. Consequently, due to the limited airside area, the installation of a conventional instrument landing system (ILS) or GLS is not feasible. Hence, until today LGKR airport is served only by non-precision approaches.

A second airport, worth examining it, is Thessaloniki Airport (ICAO Identifier LGTS) , the 2nd largest airport in Greece, with a significant annual number of aircraft movements. The airport has a complex infrastructure with 2 crossing RWYs, both extending into the sea (Thresholds 16 and 10), with constraints to both North and North West ends. Both RWYs are equipped with a Precision Approach system to the 2 of the 4 RWY ends. The significant constraint of LGTS airport is the great number of diversions due to low ceiling. Aeronautical charts for both airports can be found at https://www.ead.eurocontrol.int/.

II. OPERATIONAL CONCEPT

Since the GLASS system does not need to receive any navigation data directly from the GPS satellite and only needs the information channel from the SBAS satellite, it can be installed almost anywhere at the airport. Multipath considerations as in GBAS are not necessary. The only requirement is a clear view of one (or for redundancy reasons better two) of the EGNOS satellites. To cover the approach area, one needs to take care that zero points of the electromagnetic field are not at critical locations on the approach path. This is covered by GBAS VDB siting instruction [12].

Charting of the procedure does prove a bit more difficult. A straightforward way would be to amend the RNP approach chart with a supplemental GLS channel number. It should also indicate that the LPV final approach is rebroadcast as GLS. The reference path identifier could be named SBAS or S26A instead of the usual notation “G26A” (or similar). In this notation, the G stands for GPS, 26 for the approach runway, A for the first GLS approach in sequence for that particular runway end. If such a charting option would be approved, the pilot would have to manually enter the channel number into the FMS and switch the autopilot/flight director to landing system mode.

Another option would be to issue a GLS approach chart identical to the RNP approach chart. This chart would need to have the restriction “LPV Only” in order to make it known to the pilot that he is flying an LPV approach. In this case, no manual entry of the channel number is required since this number is already stored in the navigation data base.

III. CURRENT STITUTATION IN GREECE - CORFU AND THESSALOKINI AIRPORTS

In line with the forecast from the “Challenges of Growth” study by EUROCONTROL [10] many regional airports in Greece have pre-Corona experienced a strong traffic growth. But many of these airports are currently not equipped with ground based landing aids, i.e. ILS, either because it is geographically not feasible or because of economic considerations. At some of the Greek regional airports, Non Precision Approach procedures with relatively high minimum decision heights are the only alternative. In situations of poor weather and especially at low cloud base, these procedures can lead to diversions or cancellations for airlines.

HCAA has recognized the issue and has developed RNP procedures for many locations to improve the stability of service at the regional airports. As of the AIRAC cycle 1019 (effective 12 Sep 2019), Corfu (LGKR) airport is equipped with one RNP approach to runway 34, with an LNAV only minimum line and an Obstacle Clearance Height (OCH) of 764ft above aerodrome level (AAL) for all approaching aircraft. Thessaloniki (LGTS) airport has a RNP Y approach for runway 34 with LPV minimum only and a decision height of 973ft AAL for approach category C and a RNP Z with LNAV/VNAV obstacle clearance altitudes of 882ft AAL for an approach category C. Most likely, the minimum for the LPV approach is higher due to incomplete obstacle data, as the LPV obstacle assessment surface is slightly wider than the one for LNAV/VNAV [13].

Since both airports have relatively high OCHs it is very likely that during bad weather conditions, diversions are necessary. Records of diversions by the airport operator Fraport Greece show that for Corfu Airport, 19 flights in total were affected during year 2019, 29 flights during 2018 and 17 flights during 2017. The months, which were affected, were almost all during the winter and early summer. The number of days affected during 2019 was 9, 14 days during 2018 and 11 days during 2017 (Table 1).

Korfu Thessaloniki	Total Movements	GLS Equipped	Potentially Retrofittable with GLS	Diversions due to weather
2017	21860	8656	9589	17
	44545	11627	25567	121
2018	26595	10960	12194	29
	56186	16017	34423	209
2019	18822	7406	8340	19
	38673	11463	23443	109

Table 1 Movement statistics for Corfu and Thessaloniki airports, extracted from the Eurocontrol CNS Dashboad (https://www.eurocontrol.int/dashboard/communication-navigation-and-surveillance-dashboard). Only 8 Months of 2019 are considered

For Thessaloniki Airport, 109 flights in total were affected during year 2019, 209 flights during 2018 and 121 flights during 2017. During 2019 and 2018, the months which were mostly affected by the weather conditions and specifically by the low ceiling were January and February, with some minor diversions beginning of March. However, during 2017, months mostly affected were November and December with some minor diversions at the beginning of December. The number of days affected during 2019 were 17, during 2018 21 days and during 2017 19 days. According to the Eurocontrol CNS Dashboard (https://www.eurocontrol.int/dashboard/communication-navigation-and-surveillance-dashboard), both Corfu and Thessaloniki Airports have already traffic with aircraft equipped with GLS. Specifically at Corfu Airport, the number of movements with GLS equipped aircraft reached the number of 8.656 movements during 2017, increased during 2018 with 10.960 movements and for 2019 , since early January and until August (where the available data ends) the movements of 7.406. Extrapolation to 12 months yields approximately 11000 movements .

Regarding Thessaloniki Airport, the movements of GLS equipped aircraft were 11.627 during 2017, with an increasing number of 16.017 movements during 2018. During 2019, from January to August, the movements of these aircrafts have reached already the 11.463 movements (Table 1). Extrapolation to 12 months yields approximately 17000 movements

If the aircraft that could potentially be retrofitted with GLS are taken into account, the aircraft movements at Corfu for the time period 2017-2019 were 9.589 during 2017, 12.194 during 2018 and 8.340 during 2019 (counting only the first 8 months- January to August for 2019). If the aircraft that could potentially be retrofitted with GLS are taken into account, the aircraft movements at Thessaloniki airport for the time period 2017-2019 were 25.567 during 2017, 34.423 movements during 2018 and 23.443 during 2019 from January to August. From this data, it can be assumed that a significant number of flights can benefit from the GLASS system in poor visibility conditions, it can enhance safety for Corfu Airport and can provide further assistance and guidance for pilots to Thessaloniki Airport, having also in mind the great increase of the accessibility and thus of the performance of both airports (Table 1).

IV. GROUND MEASUREMENT CAMPAIGN

In order to ascertain the feasibility of an installation of the GLASS converter system at LGKR and LGTS, we recorded 24h GPS and EGNOS data at each of the two airports. The campaign at Corfu took place from August 29th to 30th 2019 and the one at Thessaloniki from September 3rd to September 4th 2019. In both cases, a Septentrio AsterRx receiver was installed and connected to a Talysman multi-frequency GNSS antenna on the roof of the terminal building of each airport. Then, the availability of the system with protection level inflation and without was assessed. In [11], the inflation introduced in the protection level calculation was described, in order to fully reproduce SBAS protection level in the converter system. However, since GBAS actually only "cares" about the cross track component in the horizontal, plus a percentage of the along track component mapped to the vertical due to the glide path, this inflation is strictly not necessary for safety considerations.

The GBAS standards [3] provide for alert limit scaling as the aircraft gets closer to the landing threshold. According to [3], the vertical alert limit is scaled with height Hp above the threshold as

Vertical Alert Limit	Height above Threshold Hp
FASVAL	Hp<60.96m
0.095965Hp+FASVAL-5.85m	60.96m< Hp< 408.432m
FASVAL+33.35m	Hp>408.4432m

Any GBAS airborne system following this equation will only apply the Final Aproach Segment Vertical Alert Limit (FASVAL) from below 200ft (60.96m) Above Ground Level (AGL). Since the GLASS approach will terminate the latest at 250ft according to

[6] or at the published OCH if higher, we chose to assess the integrity at the lowest possible height for each published approach procedure. For the RNP approach to LGKR's runway 34, this altitude is 764ft AGL and for the RNP approach with LPV final to LGTS's runway 34, this altitude is 973ft.

With the final approach segment vertical alarm limit limited to 25.4m instead of the maximum of 35m, an increased availability will arise if no inflation is used

In Figure 2 we depict the results for Corfu Airport in a Stanford integrity diagram. In =[14]=[14] we provided a brief description of what is depicted in such an integrity plot: *"In order to evaluate integrity and continuity of an SBAS system, actual navigation performance and protection levels are plotted as a 3D histogram in an integrity plot. ….The integrity plot can be divided into four areas: For normal operations, the position error is smaller than the protection level which is in turn smaller than the alert limit (white area). The system is available and overbounding the actual position error correctly. If the protection level is larger than the alert limit the system is unavailable for use (yellow area). Should the position error exceed the protection level, misleading information (MI) is given by the system (red/pink area). In case the navigation system error is larger than the alert limit, this misleading information becomes hazardous (HMI) to the aircraft (red area) since no guarantee for it to be within the protected area can be given."*

In Figure 2 (top) we show that a 99.88% availability can be achieved with the GLASS system running in the uninflated mode. In Figure 2 (bottom) we can see that using the inflator reduces the availability to 97.2%. In no case misleading or hazardously misleading information occurred. Here we considered the Vertical Alert Limit (VAL) of 41.9m as calculated by an airborne GLS receiver at 764ft above aerodrome level, where the missed approach point is reached. Figure 3 follows the same analysis for Thessaloniki. In Figure 3 (top) we show an uninflated availability of 99.95% and using the inflation method, it drops to 98.34% shown in in Figure 3 (bottom). Equally, no misleading or hazardously misleading information occurred at any time. We considered the VAL of 48m at 973ft above aerodrome level, where the missed approach for the existing procedure must be initiated.

V. EXPERIMENTAL FLIGHT TESTING

On 14 February 2020, we flew DLR's Advanced Technology Research Aircraft (ATRA) to Thessaloniki Airport to conduct GLASS flight tests.

The ATRA is equipped with the current Thales Flight Management System (FMS) version 2 and a basic Flight Test Instrumentation (FTI). The FTI provides ARINC 429 [15] data acquisition from the aircraft's basic avionics system, as well as additional sensors such as precise high-quality GNSS receivers, data storage and real time visualization of this data to the flight test engineer. The FTI consists of six CRONOS data acquisition units by IMC [(http://www.imc-berlin.com/applications/aerospace/)], three controlling computers and seven display screens for two engineer workstations. From the FTI, a custom data stream can be provided to further experimental stations if needed.

Unfortunately, the VHF frequency transmission permission was not yet available ,thus we were forced to collect data for post processing only and we were not able to transmit a live GLS signal from the ground. We recorded GNSS data including SBAS using a Septentrio PolaRx3 receiver at 10Hz from an experimental GNSS L1/L2/L5 multiband antenna installed on top of the aircraft's fuselage.

At 09:56 UTC the aircraft began to conduct three RNP Z approaches to Runway 34 at Thessaloniki. The ground track, waypoints and terrain are shown in Figure 4. The approach began from the west, at the initial approach fix waypoint APZOC with a minimum altitude of 5000ft MSL. Next, the aircraft passes the intermediate fix CEFEB at 4000ft MSL or above. The final approach commences at 3500ft MSL at the waypoint TS626, from which the aircraft descents on a 3.8 degree path towards the runway for landing. The final approach is rather steep and follows the terrain contour of a hill located south of Thessaloniki airport. During the first two approaches, the pilots initiated a missed approach at the decision altitude followed by radar vectoring to APZOC as provided by the air traffic controllers. The last approach was concluded with a successful landing on runway 34.

Since we could not use the installed Collins GLU-925 multi-mode receiver (MMR) to receive a live signal in space due to the absence of the frequency transmission permission, we post processed the Septentrio data with corrections generated by the GLASS system algorithms and a multi-mode receiver software. Figure 5 shows the result of this post-processing. The top panel of Figure 5 shows the vertical integrity data calculated by the MMR in GBAS mode as described in [3] and [16]. As the vertical component is always the more restrictive one and the horizontal and lateral does not give additional information, we show here only the data pertaining to the vertical component.

The top panel of Figure 5 depicts the different Vertical Protection Levels (VPL) and the alert limit during the flight test. The green line shows the vertical alert limit. It scales from 58.75m down to the final approach segment vertical alert limit (FASVAL) of 25.4m. We can already notice that this value is only achieved at the very end of the trial for a very brief period of time when the aircraft is below a height of 60.96m (or 200ft) above ground for the final landing. During the two previous approaches, the alert limit scales down to 39.4m during the go-around. This is in accordance with our argumentation in the previous section, where we conclude that the VAL at the decision height is the limiting factor and not the FASVAL.

Protection Levels (PLs) estimate the position uncertainty at the allocated integrity risk bound at any measurement epoch. This calculation is a requirement for any airborne GNSS receiver (details can be found in [4], [11] and the references therein). The red line is the standard SBAS VPL as computed by a pure SBAS receiver certified according to [4]. The yellow line shows the VPL computed by the airborne receiver using the GLASS ground system without any inflation and the purple line is the VPL computed by GLASS ground system including inflation. The sawtooth pattern in the protection levels is typical for SBAS and takes into account the degradation of the correction validity over time.

In this snapshot, we can observe that the protection levels behave as expected from [11]. The VPL obtained by the uninflated GLASS system is slightly larger than the pure SBAS VPL due to addition of the along track error component to the vertical error estimate, caused by the aircraft descending on an angled glide path and the larger K multiplier required by GBAS. Lastly, of course, the inflated GLASS is the largest. When the aircraft is in a turn (at 10:05, 10:17 and 10:29), tracking to some low elevation GPS satellites is lost and the protection levels increase.

The middle panel shows both localizer (blue) and glide slope (red) deviations in degrees calculated from the FAS data block in angular units. The deviation calculation is stopped at full scale deviation, which is determined by taking 0.25 times the glide path angle for glide slope deviation and the course width at threshold from the FAS data block. Arrows indicate the respective value in the panel.

Lastly, on the bottom panel we can see the aircraft altitude above the WGS84 ellipsoid. Whenever the aircraft was in the precision approach region defined by [3] we shaded the plots with gray background color.

Figure 6 shows a magnified view of the last approach. In the top panel the zig-zag pattern of the protection levels is now clearly visible. Contrary to Figure 5we show the localizer and glide slope deviations in Figure 6, bottom panel, as rectangular deviations in meters, in order to depict the actual displacement in an easy to visualize manner.

VI. CONCLUSIONS

Both ground and flight tests yielded results as expected with a good availability (>97%) and integrity (no violations). Only a small percentage of availability is lost even in the inflated case. When evaluating the simulated yielded MMR data from the flight test, system behavior was as expected.

As shown in section III, a total of 65 flights were affected by the current approach minimum at Corfu airport from 2017-2019. In the same time span a total of 530 flights were affected in Thessaloniki. This means that with a pessimistic availability estimation of the GLASS system by97%, a total of 577 flights could have benefited from a lower minimum at those two airports. This would increase the airport performance significantly assuming that all relevant aircraft would be GBAS equipped.

In order to gain operational experience and in preparation of an upcoming certification, we plan to install and test several systems at Corfu and Thessaloniki airports based on the positive results from our measurement campaign. We will use already existing LPV final approach segments and dedicated airline partners to gather data over a longer period. Involvement of the Hellenic CAA is crucial to jointly define operational procedures for the trial period. For the forthcoming certification process of such a system like GLASS we will firstly rely on the existing approval of the two main augmentation systems SBAS and GBAS. Some of the basic functions of GLASS are derived from these systems like the SBAS message decoder as well as the GBAS data broadcast. Industrialization of the system is envisaged in the proximate future.

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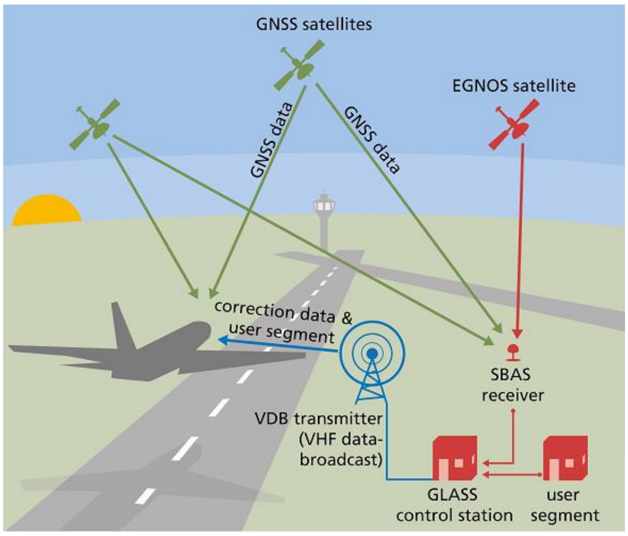

Figure 1 Set-up and function of the GLASS Systems (GLS approaches based on SBAS)

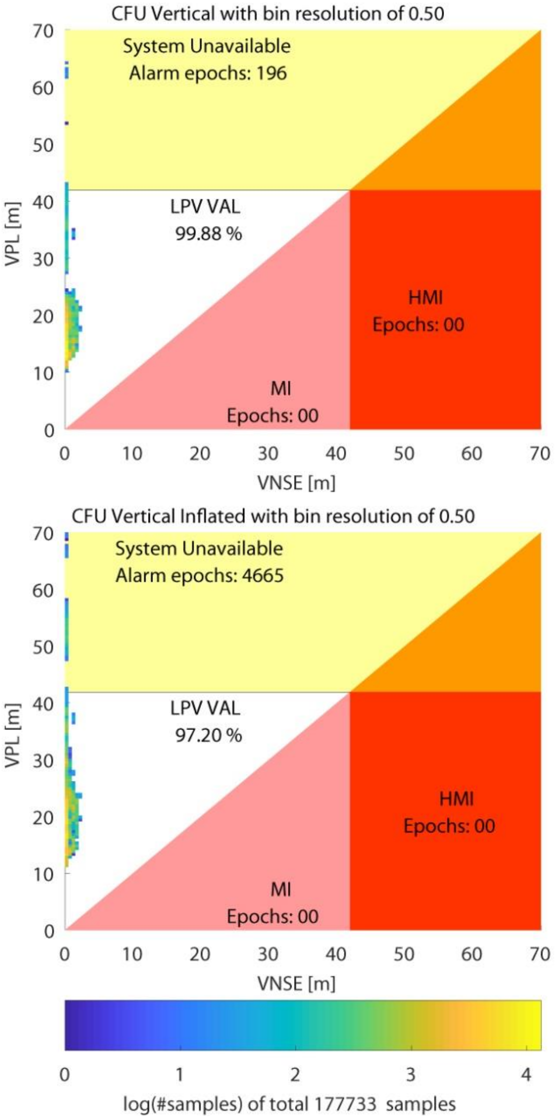

Figure 2 Measurement Campaign Data obtained on 29/30 August at Corfu (top) No inflation (bottom) with protection level inflation. The Vertical Alert Limit (VAL) of 41.9m is considered at 764ft above aerodrome level

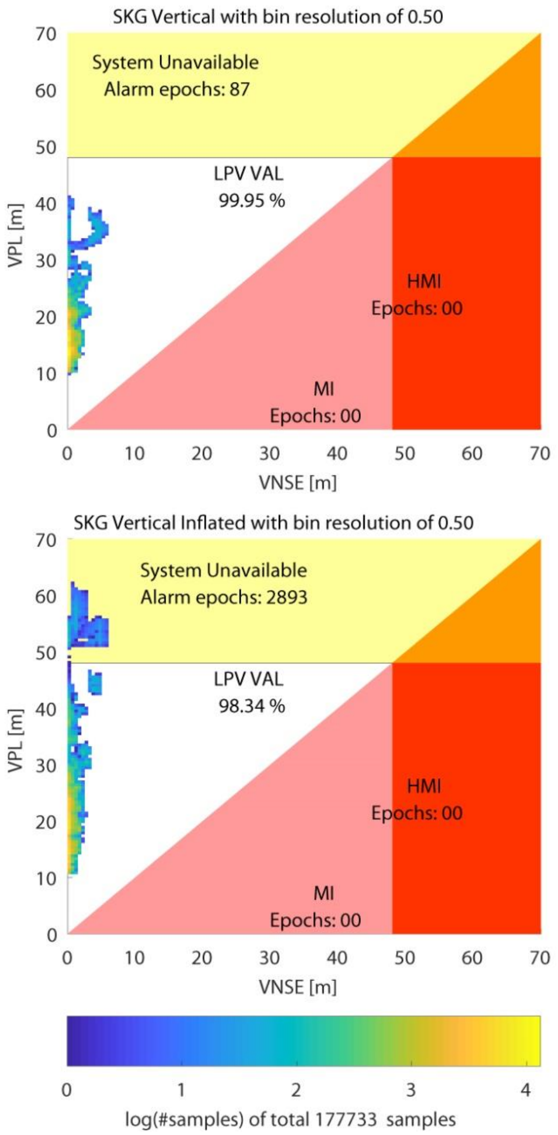

Figure 3 Measurement Campaign Data obtained on 3/4 September 2019 at LGTS. (top) No inflation (bottom) with protection level inflation. The Vertical Alert Limit (VAL) of 48m is considered at 973ft above aerodrome level

Figure 4 Ground track recorded during the flight trials on 14 February 2020

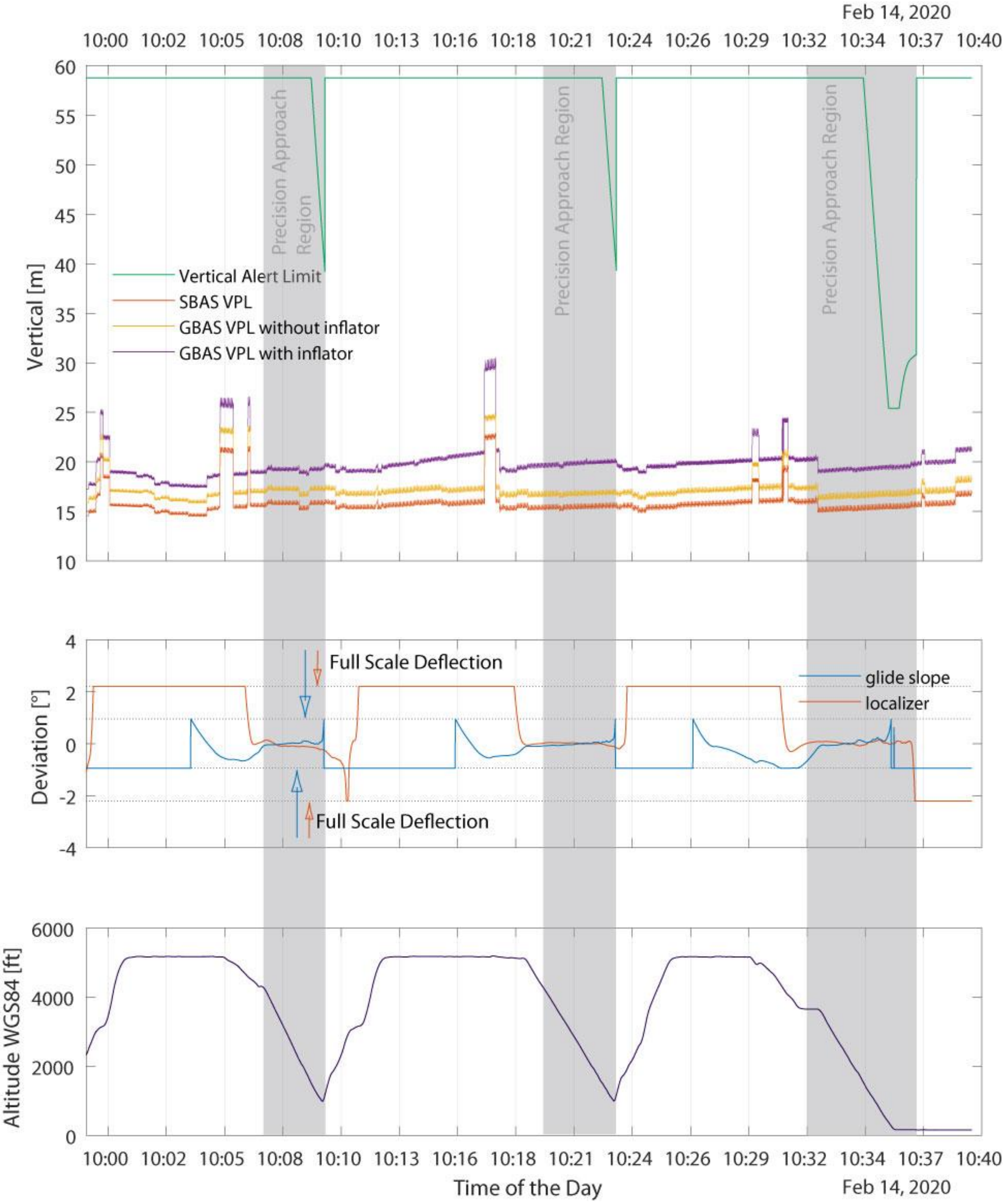

Figure 5 Multi mode receiver data from the approaches flown on 14 February 2020 in Thessaloniki. The gray shaded parts indicate that the aircraft was in the precision approach region. (top) Protection levels and alert limits (middle) Angular Deviations calculated my the GLS algorithms. The arrows indicate the maximum possible indication to the pilots (bottom) altitude above the WGS84 ellipsoid

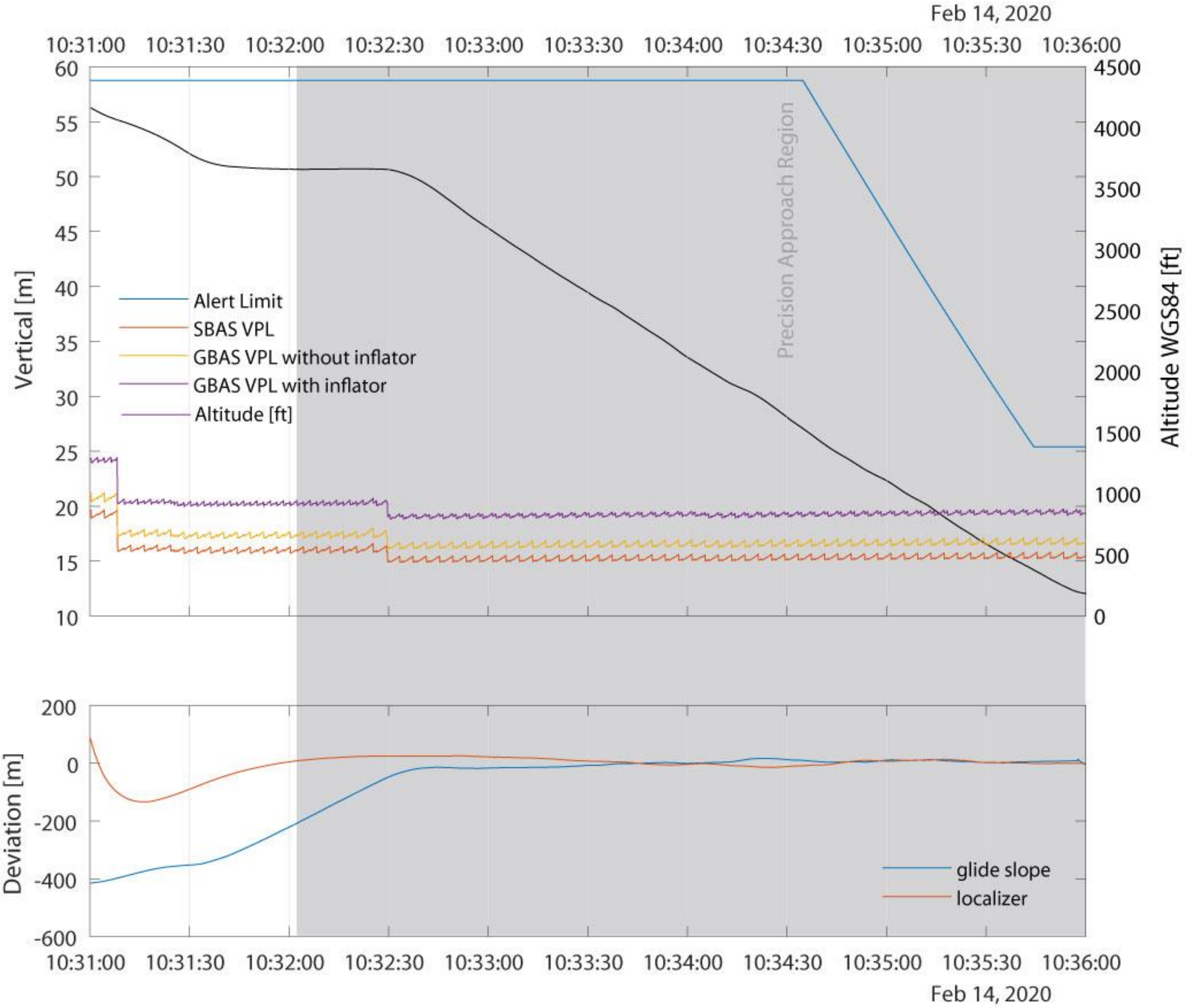

Figure 6 Close up data from the last approach. (top) Protection levels and alert limits during the approach. The black line with the scale on the right hand side shows the altitude above the WGS84 ellipsoid. (bottom) The rectilinear deviations from glide slope and localizer are shown.