Predicting the future location of a General Aviation aircraft

SESAR WP-E Research: ProGA

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Abstract—To date, scheduled, business and military aviation are well represented in the SESAR Concept. Low-end light GA is currently taken into account and integrated into SESAR to a far lesser extent. SESAR WP-E project ProGA aims to bridge this gap and has as objective to study the feasibility of a system that can continually and automatically predict the future GA aircraft’s flight corridor or its volume of operation. This paper describes the foreseen system’s input, the approach to the prediction process and to the way the system can interact with air traffic management. An important input for the prediction process is a statistic of historical flight paths acquired by the system. The compiled flight path information can be used to describe standard GA behaviour and to predict the likely future flight corridor or volume of operation. This information can be used by ATC as it gives additional data about aircraft approaching controlled airspace and it triggers an alert in case of risks of airspace infringements.

General aviation, flight corridor predictions, volume of operation predictions, SESAR.

I. INTRODUCTION

This paper describes the SESAR WP-E research project ProGA (Probabilistic 4D trajectories of light General Aviation operations) and the results obtained so far. To date, scheduled, business and military aviation are well represented in the SESAR Concept [1] and the deployment of SESAR technology will focus on these. The higher-end of general aviation (GA), flying technologically advanced aircraft, will be able to comply to some extent with the SESAR concepts of operation. Low-end light GA is currently taken into account and integrated into SESAR to a far lesser extent [2] (it is noted that the SESAR Conops at a Glance [3], and some SESAR work packages have addressed specific GA issues). Low-end light GA includes non-commercial operations of other-than-complex motor-powered aeroplanes (wording from [5]) and gliders. This type of GA covers single pilot flights under visual flight rules.

II. IDEA AND CONTEXT

A. The ProGA idea

The foreseen ProGA system is composed of airborne equipment and ground equipment to perform two main tasks: flight path monitoring and prediction. The airborne equipment consists of transceivers that broadcast the aircraft position to other aircraft and to the ground. The ground equipment consists of receivers, which get the messages broadcast by the GA aircraft, and processing units that compile the information received. The compiled flight path information can be used to

SESAR’s idea behind 4D trajectories is to reduce uncertainty [3] and therefore increase safety and capacity. Two of the key performance targets of the SESAR work programme are to improve the ATM safety performance by a factor of ten, and enable a three-fold increase in capacity [3]. A prime need for GA is continued or improved access to airspace, whilst maintaining or increasing safety levels appropriately [4]. The challenge taken up by ProGA is to research and develop cost-effective technology to support the GA community integration into the SESAR concept without losing access to airspace. This is done while safeguarding the key characteristics of GA: the requirement for affordable equipment, limited complexity of procedures and freedom of flight. In that light the key objective of ProGA is to study the feasibility of an affordable system that can continually and automatically predict the future GA aircraft’s flight corridor or its volume of operation.

The paper is organized as follows: in Section II the reference context is described and the scope of the ProGA project is outlined; in Section III the target categories of flights are analysed; in Section IV a preliminary overview of the system input is provided; in Section V the approach to the prediction process is described; in Section VI some preliminary results are presented; finally, in Section VII conclusions are drawn.
describe standard GA behaviour and make iterated inferences on the future airspace occupancy of an aircraft (the prediction).

Two main types of predictions for future locations of aircraft are defined:

- The first type predicts a near-future **4D flight corridor**. The corridor is characterized by a flight path, made of linear segments lasting several minutes, with some uncertainty;
- The second type predicts the position of an aircraft flying in a constricted area. The idea is to determine **4D volumes of operation** that are occupied by the aircraft during its flight. These volumes could allow the definition of zones where leisure powered aircraft flights and/or glider activities are taking place.

**B. Context and foreseen benefits**

Low-end GA aircraft usually fly in uncontrolled airspace at low altitude (airspace class G). In Europe uncontrolled airspace is common in nearly all countries in the lower layers outside TMAs, CTAs, and airways.

We hereafter make the reasonable assumption that, whatever SESAR brings to the structure and categorization of controlled airspace, uncontrolled (or unmanaged) airspace will still remain in many areas of Europe. Within this type of airspace pilots have been using “free flight” for more than a century, and they do not expect any change in the future.

However, GA pilots have to deal with interfaces with controlled airspace, as far as possible, without introducing undesirable constraints. In this sense the ProGA system could well represent a solution to bring safety benefits to all parties; a better situational awareness to GA pilots (touted in [3] as the essence of the use of shared trajectory data), and the provision of additional information to ATC about traffic of interest for the safety of operations in managed airspace.

It is expected that local peculiarities - related to flight rules, procedures, and operating methods - will remain when SESAR plans are implemented. As a consequence, ProGA algorithms will have to be adapted to the local situations, until harmonization for VFR operations happens.

**III. FLIGHT PATH EXAMPLES**

In ProGA multiple flight paths have been studied [6] to provide a first overview of types of general aviation flights and practices: flight preparation and execution, navigation methods used and relevant external influences. This section gives examples of flight paths and the knowledge relevant for the ProGA project obtained from studying these flight paths. Two types of flights are considered: flights with fixed-wing aircraft and gliding flights.

**A. Fixed-wing flights**

Fig. 1 shows the flight path of a cross-country flight. The flight departed from Saint-Cyr (east) and is bound to Dreux (west). The flight is made in class G airspace and is kept under the applicable VFR maximum altitudes. Specific flight segments characterize the flight, namely: a departure procedure, turns to avoid a populated area, and a straight leg towards the final destination. The populated area needs to be bypassed because it has to be overflown at a minimum altitude higher than the flight’s altitude, which is in itself limited by the maximal permitted altitude in that airspace class. To improve predictability of flight paths the ProGA system could use information on population density and minimal altitudes as inputs.

A typical flight path of a basic training flight of a powered GA aircraft is illustrated in Fig. 2. The aircraft flies from the departure airfield (LFPZ) to a remote location, there the pilot performs the exercises and flies back to the airfield of origin.

Whereas the flight path from and to the airfield is quite smooth, the prediction of the flight path at the location of the exercises does not appear feasible. However, it might be possible to predict the volume of operation in which the exercises take place, as indicated in Fig. 2. The volume of operation is a certain volume of airspace in which the aircraft is estimated to reside for a certain time horizon. Although there are no official training zones, some parts of the airspace are dedicated to this type of flight, making such estimation feasible if these zones are known by the system, for example from historical flight data. In this example, the volume is an elliptical cylinder having a length of about 15 km, a width of 10 km and a vertical extension from 500 ft. AGL to 3500 ft. QNH.

**B. Gliding flights**

Gliding is flying a plane without an engine, able to climb from a lower to a higher level by the action of air currents. Glider flights may be classified in three broad categories: training flights, leisure flights and competition flights. There are three ways for a glider to remain airborne: hill lift, thermal
lift (see Figure 3) and mountain wave lift. These lift conditions are influenced by specific meteorological conditions, by terrain and by geographical characteristics. The flight of a glider is therefore heavily dependent on weather conditions, terrain characteristics and geography. The influence of hills or mountains is significant on the flight and vertical wind conditions.

The increase in altitude of glider flight paths is often far greater than for powered aircraft flights. Unlike a powered aircraft that has a range limited by the quantity of fuel that it can carry, the capability of a glider to extend the range of its flight depends on its altitude, the higher it can get, the farther it can fly. The continuous need for gaining altitude to remain airborne, and the need for the right weather conditions to climb, makes it challenging to predict glider aircraft’s behaviour.

C. Initial assessment of predictability

The flight path examples discussed in sections III.A and III.B offer clues of the predictability of flights. In [6] more flight paths are analysed. From this analysis it is expected that predictions of fixed-wing aircraft flight corridors will be feasible for:

- Local flights (i.e. taking-off and landing at the same airfield) performed for leisure purpose such as sightseeing or by pilots to maintain currency and proficiency in the basics of flight;
- Traffic pattern flights, performing various types of take-offs, approaches and landings, in case the patterns are published and known to the system;
- Parts of flights following specific departure or arrival procedures;
- Flights using a specific kind of navigational means, for example VOR;
- Flights between known landmarks, and;
- Descents to avoid TMAs. The ProGA flight path prediction could be used in this case by ATC to predict a possible airspace infringement if the pilot starts the descent too late.

It is expected that volume of operation predictions will be feasible for:

- Local basic training flights to acquire basic flying skills through a number of exercises such as straight-and-level flight, level turns, climbs and climbing turns, various types of straight climbs, descents and descending turns and various types of straight descents, and;
- Local flights for additional training to acquire skills for non-nominal situations such as recognition and recovery of stalls, and even spins or basic aerobatic manoeuvres.

The continuous need for gaining altitude to remain airborne, and the need for weather conditions to climb, makes it difficult for glider pilots to fly in a predictive way. Consequently, glider flight paths depending on weather conditions are more difficult to predict than those of powered aircraft, both in the horizontal dimension and in the vertical dimension. In the horizontal dimension, gliders need freedom to move to areas where lift can be found whereas in the vertical dimension, the higher it can get the better will be its situation to continue its flight. The predictability of glider flight paths, although limited, is however possible in some cases:

- For local flights, with known weather conditions and geographical features, it is possible to predict the volume of operation of glider flights from a former observation of what usually happens with these conditions;
- During larger cross-country flights the path might be approximated by corridors linking specific turnpoints that can be stored in a database. However the flight path will always be interrupted by periods of circling and turning when height gain is needed and possible.

IV. PROGA SYSTEM INPUTS

The foreseen ProGA system is composed of airborne equipment and ground equipment to perform two main tasks: flight path monitoring and flight corridor/volume of operation prediction. The monitoring concept relies on aircraft equipage with transceivers and receivers placed on the ground, which are able to gather the information broadcast by the airborne transceivers. The prediction system makes use of four inputs:

- The past and real-time location of the aircraft for which the prediction is made;
- A statistic of historical GA flight paths plus associated data, e.g. type of flight;
- Data such as weather conditions that influences possible flight paths, and;
- Additional inputs given to the system by the pilot or ATC.
A. **Statistic of historical GA flights**

One of the main components of the ProGA system is a statistic of observed flight paths. It is foreseen that the ProGA system will be able to collect, when fully deployed, flight records and populate a database. From this database it is possible to obtain a statistic of historical GA flight paths, i.e., the distribution of GA flight paths for a specific area. The flight path distribution should be considered the ‘standard’ historical behaviour of a GA flight. By comparing the real-time location of an aircraft with the distributions a prediction of its likely future flight corridor or volume of operation can be made. This idea is detailed in Section VI.

B. **Data that influences possible flight paths**

The predictability of future flight paths can be improved by providing various inputs to the system. A list of possible inputs is:

- Information on population density in the flight’s surroundings;
- Airspace design including minimum and maximum altitudes for VFR flights, and prescribed Visual Meteorological Conditions;
- Arrival and departure procedures, and, for gliders, off-field landing locations;
- Infrastructural characteristics of the flight’s surroundings, e.g., the location of motorways, and easy-to-identify landmarks;
- Geography and terrain, e.g., mountains and waters;
- Weather conditions and forecasts, including (vertical) wind data.

C. **Inputs from pilot and ATC**

Two types of pilot input are foreseen: pre-flight and in-flight. Pre-flight the pilot could input into the system its intention with regard to the type of flight, its destination and the intended navigational means. The type of aircraft could also be given as input to the system. Nowadays, many pilots use tablets and specific software to prepare and execute their flights. It then appears obvious that if the information about the legs to be followed is transmitted to the ProGA system on the ground, prior to the flight, and then if any change of plan can be transmitted to the ground in-flight, the prediction will be made easier.

A VFR flight is often composed of legs that are not flown in the same type of airspace. A flight can start in a controlled airspace, proceed in uncontrolled airspace, enter and exit controlled airspace en-route and finally terminates in uncontrolled airspace. Fig. 4 shows such a flight. This flight exemplifies the added value of ATC input and is therefore concisely narrated next.

The aircraft leaves the controlled Saint-Cyr aerodrome informing ATC that the destination of the flight is Amiens. The pilot has to fly west to avoid class A Paris TMA or over-flying population (the yellow zone). The ProGA system, knowing the destination of the aircraft through Saint-Cyr ATC, knowing the location of class A airspace and knowing the location of populated areas could derive a prediction of the future flight corridor. After having bypassed the yellow zone, the pilot has to contact Pontoise ATC before entering the class D CTR, the ProGA system can be updated with this new information provided by ATC. Overhead Pontoise VOR, the pilot turns towards Beauvais and contacts Beauvais ATC, saying that he is bound to BVS VOR (near Beauvais). Then he leaves Beauvais CTR giving his intention to Beauvais ATC, i.e., flying to its final destination Amiens. For such a flight, ATC inputs to the system are very valuable and make predictions easier and more accurate.

V. **ProGA Prediction Concept**

A. **Regarding statistical prediction**

Predicting the value of an observable is an important problem in statistics. Past observations can in fact be effectively used to make inferences on the next outcome of an experiment; the interested reader is referred to [7] for a comprehensive review.

Speaking of statistical inference, one often distinguishes between Bayesian and non-Bayesian inference methods. A valuable aspect of Bayesian prediction is the possibility to dynamically update the estimate on the observable as soon as new measurements become available, see [8] and [9]. The general scheme of Bayesian inference is in fact the following: a guess (the so-called “prior”) on the probability distribution of the value taken on by the observable is initially made; this guess is successively updated using Bayes rule and a measurement of the observable (the updated distribution obtained this way is known as “posterior”).

The Bayesian updating scheme just described can be used as well for time-dependent observables; an example of a time-dependent observable is the state of a moving target (e.g., position and speed of an aircraft). Here the idea is to set up an iterative estimation scheme using the current posterior as the...
prior of the next estimation; this idea is the core of the so-called Kalman Filter (KF).

Kalman filtering requires the fulfilment of some tight properties by the models describing either the motion of the target and the outcome of a measurement [11]. For this reason many approximated methods have been devised, such as the Extended Kalman Filter (EKF) [10] or the Particle Filter (PF) [12]. Usually, KFs and all related methods are referred to as Stochastic Filters (SFs).

In the case of manoeuvring targets like the aircraft analysed in ProGA, it is often convenient to use a single, simple dynamic model for each different manoeuvre that the aircraft is assumed able to perform; this approach give rise to a number of algorithms, the most renown being the so-called Interacting Multiple Model (IMM) [10].

There are several examples of the use of SF techniques in ATM contexts, the interested reader is referred to [13] and [14]. However, very little literature is dedicated to the case of GA aircraft. To the best of our knowledge, the state of the art for GA-specific trajectory prediction is [15], where an IMM algorithm based on EKF is presented.

B. Short-term vs. long-term prediction

Short- and long-term predictions require the answer to radically different questions. The main challenge in short-term predictions is to estimate with high accuracy the position and the speed of the aircraft, as well as the kind of manoeuvre it is performing and the probability to execute a manoeuvre over another. On the contrary, a prediction over a long time scale is affected by such a level of uncertainty that it is possible to safely neglect many aspects of the actual motion, e.g. potential inaccuracies in the execution of a manoeuvre by the pilot or the presence of a light to moderate breeze.

As we have briefly mentioned in section V.A, any SF works as a two-stage estimation scheme; here we give more details and discuss the possibility to use this methodology for long-term predictions. During the first stage, the prediction phase, the prior is propagated one step ahead in time using the dynamical model of the target. The predicted probability distribution obtained in this way is successively updated using a measurement model and an observation of the target; by Bayes’ theorem the posterior is then computed. Finally, the last computed posterior is taken as the prior and another iteration starts over.

A SF is in principle capable to characterize the state of the target arbitrarily far in the future by using a suitably large time step in the prediction phase. The quality of that prediction, though, is likely to degrade very rapidly with the time-step size. The point is that a GA flight is not committed to issue a flight plan, and its manoeuvres present a high degree of freedom. Therefore, if as in [15] we assume that the motion of the aircraft is described by a simple, second order linear dynamical model, then the uncertainty on the state of the target will soon grow so large that any inference is hardly possible.

Although GA aircraft can fly with a very large amount of freedom, it is possible to outline a heterogeneous knowledge base (KB) that contains all those notions exploited for the VFR navigation. The contents of this KB range from the structure of the airspace to the overflight constraints induced by populated areas, from the choice of landmarks useful to navigation to their geographic position, from the limits of areas fitting for pilots’ training to the location of landscape elements interesting for sightseeing.

Shifting from a short-term prediction to a long-term one, it is then necessary to address different problems than state (e.g. position and speed) prediction; long-term predictions, in fact, aim at estimating only high-level features of the flight, like the final destination, the intermediate points used for navigation, or the likelihood of airspace infringements. Clearly, the KB mentioned above must be of an empirical nature. It also has a strong local character as the elements involved in the navigation vary from area to area, even within the same country. Nevertheless, embedding these notions into the prediction concept leads to a GA-tailored description of the aircraft behaviour.

All in all, the set-up of a local, GA-specific model seems a well thought idea to keep at bay the increase of the uncertainty levels and go beyond the aforesaid limits to the prediction time-step size.

C. Statistic of recorded flights as a surrogate for the KB

The construction of the KB mentioned in section V.B is in general a laborious task. It involves carrying out surveys among local GA communities as well as a crosschecking of collected data. A viable approach to lighten such a great workload is to try and infer as many aspects as possible of the KB from the analysis of a sufficiently number of recorded flight paths. This analysis will result in a statistic of flight paths.

Looking at a statistic of flight paths we expect to see one or more emerging behaviours, leading to the definition of flight corridors and/or volume of operations. Figure 5 displays a Kernel Density Estimation (KDE) of the distribution of GA aircraft flying between Saint-Cyr-l’Ecole (LFPZ) and Bernay (LFPD); the two airfields are located in correspondence of the lowest and the highest peak, respectively. Figure 5 also shows a dominant behaviour in the way of flying between LFPZ and LFPD. The interpretation of the KDE and the subsequent characterization of flight corridors and volume of operation will be detailed in Section VI.

![Figure 5. Kernel density estimation of the airspace occupancy based on a dataset of flight paths between LFPZ and LFPD.](image-url)
Summarizing, the idea is the following:

1. record and collect flight data (this includes many information such as weather conditions of the day) into a global database (DB);

2. set up a business intelligence (BI) able to
   a. aggregate data from the DB in the area of interest for the target flight to create a statistic of flight paths in the form of a KDE;
   b. define a set of rules for evaluating flight corridors and volumes of operations from the KDEs of the airspace occupancy returned by the BI.

The resulting prediction workflow and system architecture are depicted in Figure 6 and Figure 7, respectively. In Figure 6, the two time-scales discussed in Section V.B coexist and cooperate to the trajectory prediction. The state estimate is used to determine the position and the velocity of the target aircraft; the target state estimate is then compared with the KDE returned by the BI: if the expected behaviour, i.e. the estimated airspace occupancy, is consistent with the actual one, then the future flight corridors and/or volume of operations are evaluated; on the contrary, if the target aircraft behaviour do not match with the known statistic, i.e. it is an outlier, then the system may raise a warning (e.g. to ATC) and continue to monitor the target by a secondary flight path prediction. This could be either a short-term only prediction or a prediction based on a small KB obtained from operative, expert considerations. We will return to this point in Section VI.

VI. FLIGHT CORRIDORS AND VOLUMES OF OPERATIONS

In this section the KDE discussed in Section V.C is interpreted in terms of flight corridors and volumes of operation. KDE is a nonparametric technique for the estimation of probability density functions; roughly speaking, KDEs are closely related to histograms, but differ from the latter as they are smooth and regular if a suitable kernel is used.

KDEs are tuned by varying a free, smoothing parameter called bandwidth, see [16]. The optimal bandwidth selection is a widely studied problem in inferential statistics, see e.g. [17] and [18]. The choice of a particular bandwidth can strongly influence the resulting estimate: small values may result in undersmoothing and undesirable artefacts, whereas too large values may lead to oversmoothing and loss of information.

Figure 8 shows the contour lines of the KDE illustrated in Figure 5 on a map; points lying on the same curve are given the same value. The nature of the KDE and the effects due to the bandwidth may help to better understanding Figure 5 and Figure 8. One would intuitively expect to recognize standard GA behaviours between LFPZ and LFPD as lines of nearly equiprobable points; in other words, one would expect to recognize ideal routes representing the more frequently flown paths as ridges connecting points with the same, maximal value. Unfortunately, the bandwidth choice that leads to such a picture results in an oversmoothed and non-significant estimate. Selecting the bandwidth by following the Scott’s rule [19], the surface in Figure 5 exhibits instead three maxima and several saddle points.

The highest and lowest peaks correspond to LFPZ and LFPD, respectively; the discrepancy in peaks height is due to the procedures for approaching and leaving the airfields (shape and wideness of the circuit), i.e. there exists a substantial difference in the number of points recorded per path by the GPS near LFPZ and LFPD. The presence of the middle peak can be understood by examining more in detail the dataset from which the KDE was computed: the GPS paths present quite an amount of scattering south of the town of Orgeval, see Figure 9 and Figure 10; the configuration of the samples and the nature of the kernel used (Gaussian) lead to the peak.
Moreover, the paths are close to each other before and after this peak, therefore leading to the formation of two saddles, see Figure 8 and Figure 11.

It then seems reasonable to reconstruct the standard behaviour of GA traffic from the KDE surface using shortest lines that touch a sequence of maxima and saddles, i.e. paths that are orthogonal to the contours. From the discussion of Figure 9 and Figure 10 it also emerges that those paths may be split in flight corridors (located around saddles, where the paths are close to each other and only small fluctuations happen) and volume of operations (located around maxima, where the paths are more scattered and a higher uncertainty occurs), see Figure 11.

Therefore, it should be possible to create a set of rules for the automated recognition and dimensioning of flight paths, corridors and volumes of operation from recorded traffic data. It is expected that those rules will be evaluated, revised, and continually updated with the aid of operative experts.

VII. CONCLUSIONS

An analysis of GA flight tracks has shown that although these flights are very much “free flights”, there are very often specific characteristics that make predictions of future flight corridors and volumes of operation feasible for both fixed-wing and glider flights.

An important input for the prediction process is a statistic of historical flight paths acquired by the foreseen ProGA system. The compiled flight path information can be used to describe standard GA behaviour and to predict the likely future flight corridor or volume of operation.

A first analysis has shown that it should be possible to create a set of rules for the automated recognition and dimensioning of flight paths, corridors and volumes of operation from recorded traffic data. It is expected that those rules will be evaluated, revised, and continually updated with the aid of operative experts. For that purpose a workshop will be organized with operative experts in a later stage of the project.

DISCLAIMER

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