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Statistical characterization of deviations from planned flight trajectories in air traffic management

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ABSTRACT

Understanding the relation between planned and realized flight trajectories and the determinants of flight deviations is of great importance in air traffic management. In this paper we perform an in-depth investigation of the statistical properties of planned and realized air traffic on the German airspace during a 28 day periods, corresponding to an AIRAC cycle. We find that realized trajectories are on average shorter than planned ones and this effect is stronger during night-time than day-time. Flights are more frequently deviated close to the departure airport and at a relatively large angle-to-destination. Moreover, the probability of a deviation is higher in low traffic phases. All these evidences indicate that deviations are mostly used by controllers to give directs to flights when traffic conditions allow it. Finally we introduce a new metric, termed di-fork, which is able to characterize navigation points according to the likelihood that a deviation occurs there. Di-fork allows to identify in a statistically rigorous way navigation point pairs where deviations are more (less) frequent than expected under a null hypothesis of randomness that takes into account the heterogeneity of the navigation points. Such pairs can therefore be seen as sources of flexibility (stability) of controllers traffic management while conjugating safety and efficiency.

1. Introduction

In the recent literature it is possible to find many examples where network science has been applied to the air transportation system (for a review, see (Zanin and Lillo, 2013; Cook and Rivas, 2016)). Many studies have focused on the topological aspect of the airport network (Wang et al., 2001; Li-Ping et al., 2003; Barrat et al., 2004; Chi and Cai, 2004; Li and Cai, 2004; Guimerà et al., 2005; Colizza et al., 2006; Guida and Maria, 2007; Bagler, 2008; Xu and Harriss, 2008; Cardillo et al., 2013a; Gomes et al., 2014), but network science techniques can also be used to study topics more related to air traffic management (Malighetti et al., 2008; Lacasa et al., 2009; Ben Amor and Bui, 2012; Cai et al., 2012; Cook et al., 2013; Fleurquin et al., 2013; Pyrgiotis et al., 2013; Cardillo et al., 2013b; Campanelli et al., 2014; Zanin, 2014; Blom et al., 2015). In particular, one can consider different elements of the airspace like sectors and navigation points and build networks which are informative about the air traffic management (Gurtner et al., 2014). In fact, differently than the airport network, navigation point networks are more related to air traffic management problems and to safety issues.

Here we present a study of the air traffic management procedures controlling the flow of flights occurring on top of the navigation point network. Navigation points are fixed two dimensional points in the airspace specified by latitude and longitude. The airlines must use this grid to plan each flight trajectory from departure to destination. Navigation points are also of reference for air traffic controllers who use them to solve conflicts and problems originated by unforeseen events and to rationalize and decrease the complexity of the aircraft flow. The navigation points can be viewed as a guide for airlines, but also as a burden, because flights cannot fly straight and have to find a path on this predefined grid. In fact, it is foreseen by the SESAR project (SESAR, 2012) that navigation

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points will slowly disappear to allow smooth trajectories, the so-called "business" trajectories. However, in the present air transportation system they are crucial for air traffic controllers. In the present work we will focus on a quantitative assessment of their role in the air traffic management.

In our study we investigate how the planned flight trajectories are modified by controllers in relationship with unforeseen events or pilots' requests. Our study is based on a metric called directional-fork, or *di-fork*, comparing planned flight trajectories with deviated flight trajectories. By using this metric we obtain a quantitative description of the deviations of planned flight trajectories called by air traffic controllers at the level of single navigation point pairs. The activity of air traffic controllers usually concerns two main aspects: on one side they are responsible for avoiding safety events and for making the aircraft trajectories conflict-free. On the other side, whenever possible, they can issue directs that (*i*) shorten trajectories, thus allowing for lower fuel consumption, and (*ii*) can improve the predictability of the system. In our investigations we show that directs are the main determinants for the probability of flight trajectory deviations.

We perform a statistical validation of the navigations point pairs by comparing the observed values of the di-fork metric with the values expected under a null hypothesis of deviations occurring at randomly distributed navigation point pairs. In other words, we investigate how the different navigation points present in a given airspace are used by air traffic controllers over the day. Specifically, we detect navigation point pairs where trajectories (*i*) are most likely to be deviated with respect to the planned ones, thus providing a "destabilization" of the planned trajectory, or (*ii*) are most likely not to be deviated with respect to the planned ones, thus providing a "stabilization" of the planned trajectory.

The paper is organized as follows: in section 2 we describe the database used in our investigation. Section 3 deals with the statistical investigation of planned flight trajectories. Section 4 focuses on the statistical properties of flight deviations observed from the planned flight trajectories. Section 5 introduces the di-fork and the statistical validation method used to detect a set of over-expressed and under-expressed navigation point pairs. Finally, in section 6 we draw our conclusions.

2. Data

Our database contains information on all the flights that, even partly, cross the ECAC airspace. Data are collected by EUROCONTROL (http://www.eurocontrol.int), the European public institution that coordinates and plans air traffic control for all Europe and were obtained as part of the *SESAR Joint Undertaking* WP-E research project ELSA "Empirically grounded agent based model for the future ATM scenario". [1]

Data come from two different sources. First, we have access to the Demand Data Repository (DDR) (EUROCONTROL, 2010) database containing all the trajectories followed by any aircraft in the ECAC airspace during 15 months – from the 8^{th} of April 2010 to the 27^{th} of June 2011. Each 28 day time period is termed AIRAC cycle. A planned or realized trajectory is made by a sequence of navigation points crossed by the aircraft, together with altitudes and timestamps. The typical time between two navigation points lies between 1 and 10 min, giving a good time resolution for trajectories. In this paper we use the "last filed flight plans", i.e. the so-called M1 files, which are the planned trajectories – filed from 6 months to one or two hours before the real departure. We also use the real trajectories, i.e. the so-called M3 files, because we will compare planned and realized trajectories in order to investigate the air traffic controllers role.

In our study we are considering commercial flights. For this reason we have selected only scheduled flights – excluding, in particular, military flights – using land-plane aircraft, i.e. no helicopter, gyrocopter, etc. This gives, in first approximation, the full set of commercial flights. We also excluded all flights having a duration shorter than 10 min and a few other flights having obvious recording data errors.

The database includes all flights in the enlarged ECAC airspace [2] even if they departed and/or landed in airports external to the enlarged ECAC airspace.

The other source of information are the NEVAC files. NEVAC files (http://www.eurocontrol.int/eec/public/standard_page/NCD_nevac_home.html) contain all the elements allowing the definition (borders, altitude, relationships, time of opening and closing) of the elements of airspaces, namely airblocks, sectors, airspaces (including Flight Information Region, National Airspace, Area Control Center, etc.). The active elements at a given time constitute the configuration of the airspace at that time. Thus, they give the configuration of the airspaces for an entire AIRAC cycle. Here we only use the information on sectors, airspaces and configurations to rebuild the European airspace. Specifically, at each time we have the full three dimensional boundaries of each individual sector and airspace in Europe. All this information have been gathered in a unique database, using MySQL, in order to allow fast crossed queries.

Our investigations are mainly performed considering the flights relative to the AIRAC 334, i.e. the AIRAC starting on May 6, 2010 and ending on June 2, 2010. Data relative to other AIRACs are considered in order to check the stability of our results. We only consider flights that cross the German airspace, which is one of the European regions with the highest levels of air traffic. Specifically, we select from our database all airspace portions labeled with an ICAO code starting with ED. This would imply that small portions of the airspace of Belgium and Netherlands, mainly at high altitudes, are also included in our analyses. The boundaries of the considered airspace are shown in Fig. 9 below. Moreover, to focus our analysis on the en-route phase of each flight, we filter the trajectories retaining only the portion at an altitude higher than 240 FL. Time of the day is always expressed in UTC. Finally, data do not include Saturdays and Sundays in order to avoid weekly seasonality effects.

In the left panel of Fig. 1 we show the box plot of the daily number of active flights in the different hours of the day. An intraday pattern is clearly recognizable, with many flights during day-time and almost ten times less flights during the night. In the right panel of Fig. 1 we show the number of active navigation points in the planned trajectories at different hours of the day. A navigation point is active in a given time interval if at least one flight is scheduled to pass through it in that interval. Also in this case one can see that significantly less navigation points are used during the night.

[1] Data can be accessed by asking permission to the legitimate owner (EUROCONTROL). The owners reserve the right to grant/deny access to data.

[2] Countries in the enlarged ECAC space are: Iceland (BI), Kosovo (BK), Belgium (EB), Germany-civil (ED), Estonia (EE), Finland (EF), UK (EG), Netherlands (EH), Ireland (EI), Denmark (EK), Luxembourg (EL), Norway (EN), Poland (EP), Sweden (ES), Germany-military (ET), Latvia (EV), Lithuania (EY), Albania (LA), Bulgaria (LB), Cyprus (LC), Croatia (LD), Spain (LE), France (LF), Greece (LG), Hungary (LH), Italy (LI), Slovenia (LJ), Czech Republic (LK), Malta (LM), Monaco (LN), Austria (LO), Portugal (LP), Bosnia-Herzegovina (LQ), Romania (LR), Switzerland (LS), Turkey (LT), Moldova (LU), Macedonia (LW), Gibraltar (LX), Serbia-Montenegro (LY), Slovakia (LZ), Armenia (UD), Georgia (UG), Ukraine (UK).