Trajectory Uncertainty and the Impact on Sector Complexity and Workload

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Abstract*—Complexity metrics are tools to quantify the perceived workload felt by the controller in various traffic situations. Previous complexity measures have focused on traffic density and the geometry of interacting flights. These metrics can be useful for evaluating sector and airspace design, distributing workload, benchmarking cost and productivity. These measures do not, however, address the *improvements* in trajectory uncertainty related to controller workload. Data from the DFS VAFORIT system clearly identifies the relationship between trajectory uncertainty and complexity. Climbing and descending aircraft are the biggest contributors to workload, due more to uncertainty around trajectory predictions than to trajectory geometry. Current complexity measures will have limited value assessing the improvements in trajectory information through the implementation of air to ground datalink. Data communication is seen as a key transformational technology in ATC. The authors believe that a new complexity component can help to quantify the extent that controller workload is reduced with Datalink and new procedures designed to reduce trajectory uncertainty. Within this paper we will propose a metric framework, where the quality of trajectory information available to the controller is included in the complexity value. This will support a mechanism for evaluating reductions in complexity and workload, as technologies and procedures associated with advanced data comm improve trajectory prediction. Our intent is to incentivize the industry to implement key data link functions. Additionally, this enables two more interesting applications: the assessment of individual complexity contribution by individual aircraft, and the mapping of sector complexity as a function of the number of Data Link equipped aircraft.

I. Introduction

Today approximately 5% of all flights in Europe are held on the ground to manage en route congestion (see [1], page 57). To meet future traffic demands airspace capacity must be increased. Therefore, reducing controller workload through automation is a key component of both SESAR (*Single European Sky ATM Research*) and NextGen strategies to increase airspace capacity.

For today's working environment, controller workload has been approximated by measures of airspace/sector complexity. Airspace complexities have been calculated in numerous research including Eurocontrol Performance Review Unit's study titled *Complexity Metrics for ANSP Benchmarking Analysis*, [1], NASA studies on *Airspace Complexity and its Application in Air Traffic Management*, [2], FAA report on the *Relationship of Sector Activity and Sector Complexity to Air Traffic Controller Taskload*, [3]. The SESAR Joint Undertaking workgroup on airspace complexity (project *4.7.1 Complexity Management in En-Route*) has summarized much of the research on complexity in their recent report titled *Consolidation of Previous* (Complexity) *Studies*, [4]. These works focus on traffic characteristics as a proxy for complexity and controller workload. Sample traffic characteristics include the number of aircraft, aircraft density, number of climbing and descending flights, speed variation and the proximity of projected trajectories.

Previous studies have not focused specifically on uncertainty in the trajectory as a key driver of complexity and workload. This paper focuses on the role of trajectory uncertainty in controller workload and proposes a new approach to measuring complexity. The motivation for this focus on uncertainty is driven by data from DFS in the recent implementation of the medium term conflict detection (MTCD) at Karlsruhe Center. The MTCD is a component of the VAFORIT deployment. A clear finding during VAFORIT deployment is that conflict detection is directly related to trajectory uncertainty. Additionally, Karlsruhe UAC controllers have made it clear that trajectory uncertainty drives their workload even if they end up taking no measurable action. Data from the work to implement the MTCD at Karlsruhe are used in this paper to show the clear correlation between trajectory uncertainty and sector complexity.

Key applications of this new complexity framework include better understanding workload reductions from improvements in trajectory predictability associated with better use of *data comm*. For the purpose of this paper, the term *data comm* refers to both the link and the trajectory information shared between aircraft and ground system. As trajectories become better defined through coordination between the ground automation and the FMS, the accuracy of MTCDs will increase enabling Air Traffic Control to handle more aircraft.

It must be noted that beyond the tactical timeframe, great uncertainties in trajectories will continue to be driven by departure times. Currently flights target a window from 5 minutes early to 10 minutes late. This 15 minutes window could amount to 100nm of change in lateral space when projecting forward. Clearly, for strategic planning there needs to be huge focus on departure times. For this paper we are focused on the value of removing tactical uncertainty where aircraft are airborne and within a 20 to 30 minute look ahead.

Within this paper we will show the strong link between trajectory uncertainty and workload, and progress a new complexity measure that addresses the improvements in trajectory predictions. This approach can then be used to clarify a specific benefit case for data comm implementation from a new perspective, namely the impact of trajectory predictability on controller workload.

In section II we will first outline the current approach to complexity as used by today's state of the art metrics. Here we will show why current metrics do not explicitly account for uncertainty in trajectory predictability. We will outline the reasons and effects of trajectory uncertainty in section III.
In section IV we will propose a new framework for complexity measurement that will incorperate uncertainty, and introduce its possible applications in section V. While the importance of analyzing trajectory uncertainty as a major component of complexity and workload is explained in example formulations, specific results are not presented and are encouraged for future research.

II. Complexity Metrics in Air Traffic Control

Complexity Metrics are important tools used in the air traffic management field to quantify the perceived workload felt by the controller in various traffic situations. Current complexity metrics are used to measure the level of workload in an observed airspace — usually a sector or ACC-wide area. Typically, a complexity value is calculated and compared to a limit in order to project and recognize potential workload overload so that changes in airspace structure or real time traffic flows can be made.

The authors have identified three general purposes of complexity metrics:

- **Workload Management**
  Projecting future workload in a short-term horizon, i.e. in situations when trajectories are changed (conflict resolution and so on), or for supporting a supervisor in ATFCM.

- **Airspace and Route Design**
  Sector design considering workload and traffic complexity, aiming for an increase in capacity.

- **Benchmarking**
  Complexity metrics also deliver contextual (exogenous) information for benchmarking performance.

These purposes are normally associated with different time frames. Workload management can use complexity measures to project sector workload from 20 minutes to hours ahead in order to alert the need for distribution of workload or flow control procedures. On a more strategic scale, complexity measures can be used in airspace design to distribute workload. Additionally complexity measures can support a management function in benchmarking airspace performance.

One example of a complexity tool in use today is Crystal by SkyGuide, [5], that could play an important role in the future complexity approach within SESAR. Basically, Crystal uses three geometric traffic information to compute a complexity score:

- number of flights,
- number of vertical flights, and
- number of flights close to sector boundary.

Their approach is based on Eurocontrol CAPAN studies and its workload model, [6]. Crystal is focused on measuring the distribution of workload as opposed to capturing future factors like improved trajectory predictions that will actually reduce workload. Why is this uncertainty important?
As new technologies and procedures like data comm or ADS-B, which improve trajectory information, are implemented, the weights used in the complexity model for the geometric indicators mentioned above have to be adapted. In the case of Crystal, this has been done twice during its one year deployment. Applying the same Crystal release version to an identical traffic situation now and several years ahead, it will yield the same complexity score for both cases.

In [7], Meckiff et all also have contributed key work related to Complexity and Workload. They address complexity differences driven by FMS capabilities thereby already assuming the data comm transfer of ground automation and FMS is already in place. In fact, the aviation community has yet to agree upon a schedule for full data comm implementation. Real time trials by both Eurocontrol and Mitre have shown workload reductions related to a data comm environment, [7] and [8]. The results have not specifically addressed the workload reduction factors contributing to additional sector capacity.

Currently, benefit cases for data comm have focused on the reduction in controller workload for moving the execution of tasks from voice to data. Little analysis has been done how controller workload is impacted by the improvements in the accuracy of automation tools like the MTCD.

As we move to an environment where information is passed between ground automation systems and the aircraft FMS, the predictability of trajectories will greatly enhance controller automation tools like medium term conflict detection, hence reducing workload. These trajectory improvements are major components of NextGen and SESAR ([9], [10]).

III. Uncertainty and Complexity in Air Traffic Control

When asking controllers for their perception of complexity, they usually agree that most level flights contribute less to workload than flights climbing and descending. This is reflected by common controller procedures to prefer horizontal vectoring over level changes for level flights, see [11]. This finding is supported by many current complexity measures which have separate factors for climbing and descending flights. Experience from the implementation of VAFORIT at DFS further suggests that complexity is less driven by geometry and more by the uncertainties in the trajectories. Non-level flights are more complex to handle because they have much less predictable trajectories. Controllers are not able to make firm judgements as to whether an aircraft will reach a desired requested altitude. Additionally, automation systems do not have key data on aircraft weight, thrust, and configuration to support accurate medium term conflict detection to assist controllers. In discussions with controllers at Karlsruhe Center (Karlsruhe UAC) in Germany it is clear that in non-level flight, the controllers often can do better than the automation systems, which use algorithms based on average aircraft performance. Controllers know airline tendencies and have day to day experience of flights on the same routes.

In fact, in sectors where aircraft are climbing out of a series of airports and descending down into those same airports (like the *TANGO* sector in Karlsruhe, [12]), controllers may wait to gain more information before solving the potential conflict. Solving potential conflicts too early can both add to workload for moving aircraft that did not need to be moved and reduce the fuel efficiency of both aircraft involved. Nevertheless, controllers have to keep monitoring the flights involved — which will drive up their workload — more than if they had better trajectory information to start with.

Uncertainty in trajectories increases when a controller requests change in altitude or vector for conflict. In today's environment neither the controller nor the automation system knows exactly when the turn or change in altitude will be made. Inaccuracies or uncertainty around the accuracy of trajectory predictions is a function of the quality/detail of the input data and the trajectory model itself. In today's automation systems, trajectory models do not include detailed data available to the FMS (like aircraft weight, thrust, and wind configuration). Current automation systems usually feature a trajectory prediction that will compute the aircraft position ahead in time so that possible conflicts and/or complexity/workload violations might be detected and identified. In order to maximize the usefullness of these tools, they must yield more accurate trajectory predictions. The key drivers of trajectory uncertainty can include:

- **Trajectory Data Quality**,
  i.e. the accuracy and availability of raw data (aircraft state, including weights, controls or weather),
- **Model Quality**,
  i.e. the models ability to capture and to process all necessary information,
- **Operational Procedures**,
  i.e. the procedures that determine aircraft trajectories via clearances assigned by traffic controllers.

A. Trajectory Data Quality

In their work *Tactical and Post-Tactical Air Traffic Control Methods*, [13], Omer and Chaboud have pointed out how increased data reliability will enhance the efficiency of future automated support tools. This can be understood when one observes that every trajectory prediction is based on a certain variable vector $\vec{p} \in \mathbb{R}^d$. These variables include fundamental parameters like aircraft weight, its velocity, thrust, flap settings or exact heading. In current automation processes, most of these data is not available in an accurate way. In reality, the prediction of aircraft trajectories is based on an estimate

$$\vec{p} \approx \vec{p}_0,$$

where $\vec{p}_0$ are the true aircraft parameters. This estimation of parameters $\vec{p}$ is usually obtained by data fitment and is then inserted into a generic aircraft performance (BADA) that is used to compute a trajectory prediction. Figure (1) shows varying trajectories for different take-off weights (TOW). Due to the inaccuracy of parameters, the resulting

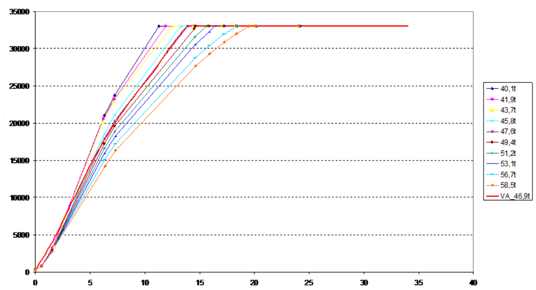

Fig. 1. Flight profile variation for B737-800 aircraft with different TOWs, compared to VAFORIT prediction (VA curve).

trajectories are highly uncertain and often mis-match with actual flight trajectores. This is addressed by studies like *Lateral Intent Error's Impact on Aircraft Prediction*, [14]. In reality, controllers often achieve better trajectory predictions inside their minds because they rather use their knowledge and experience from working with the same aircraft on the same routes on a daily basis. Controllers know which aircraft related to individual airlines are *good climbers* beyond the data considered in the trajectory model. Ground automation is continually improving — often based on controller input. These issues regarding current automation processes have been addressed in several recent studies, including [15], [16], [17] and [18].

They show that there is a large variation in performance, especially concerning climb and descent flight phases. For that matter, we would like to point out the most significant results in *Aircraft Performance Modelling for Air Traffic Management Applications* by Suchkov, Swierstra and Nuic, [17], where it is shown that there is a dramatic dependency of climb rate with respect to aircraft mass — a parameter, that is not and will (most probably) not be known in the future.

All these factors are based on the unavailability and inaccuracy of data regarding the airspace user as well as environmental factors, and lead to uncertainty in the trajectory prediction within current automation systems. As stated previously, data comm, ADS-B and a system-wide information exchange (SWIM) will improve the performance of ground automation. In [19], it was shown how FANS can improve aircraft derived data for better trajectory prediction. A desired complexity metric will therefore incorperate expected changes to these aspects and relate perceived complexity to data quality.

Note that the authors are aware that some system characteristics fit both to data and model quality. This is the case for e.g. wind and weather information. The authors have discussed that the division is made so that all information that is used as input is considered to be relevant to data quality. If there is no weather model included in the algorithms, it is an issue of model quality — if it is indeed part of the algorithms but the input is only an estimate — it becomes an issue of data quality.

B. Model Quality

This group of issues regarding uncertainty addresses the quality of models and their validation. Even with perfect data quality concerning all involved parameters, most models will not achieve perfect predictions. This is due to the fact that for deriving dynamic models, certain assumptions and approximations have to be made. Furthermore, there are many environmental features that are very hard to model. While some of them might be incorporated into very sophisticated models once computational power has improved (e.g. aerodynamics), others will most probably never be fully modelled, e.g. weather and wind. This is due to the literal nature of the environment.

Nevertheless these factors highly contribute to unpredictable aircraft states ahead in time. In the foreseeable future we will not be able to predict these wind events — especially when looking out an hour or more ahead. Hence, we will always have a level of uncertainty in trajectories moving forward. The nearer term goal is with technologies like data link to be able to bring the accuracy of the FMS to the ground automation.

Current automation systems use sophisticated models like the BADA model trying to incorporate as many information as possible in order to obtain a more accurate trajectory prediction. Nevertheless data on weight, thrust, etc. are not passed on to the ground automation. Analysis as in *Advanced Aircraft Performance Modelling for ATM: Analysis of BADA Model Capabilities*, [16], or in a DFS study regarding VAFORIT performance, have shown that the capability of current automation systems has its limits.

Experiences with the DFS VAFORIT system show that even with carefully designed algorithms, errors and inaccuracies in the model will cause uncertainties in trajectory prediction. Figure (2) shows an inaccurate trajectory prediction from the original VAFORIT Trajectory Predictor. This is also

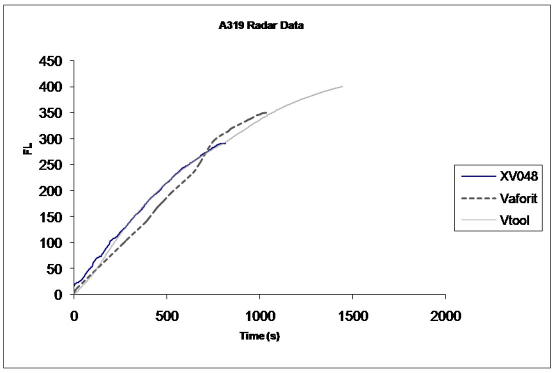

Fig. 2. Previous and current trajectory prediction by the VAFORIT system.

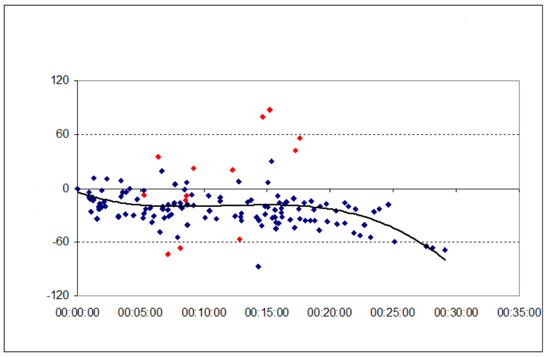

Fig. 3. Relative deviation of actual flights to VAFORIT prediction.

demonstrated by figure (3). It shows the relative deviation of real aircraft data (B737-800) compared to VAFORIT prediction. The straight line is a data fitting curve, while the red points indicate Top of Climb.

As a consequence controllers had to turn off the conflict detection based on altitude feature in the previous VAFORIT release. Before shut-down, this feature did actually increase controller workload as they were questioning the automation system.

Even though the problem is now considered to be solved (observe the new VTool trajectory in figure (2)), the necessary process of updating VAFORIT still shows evidence of typical drivers of unpredictability based on the quality of models used in automated systems.

Additionally, airline practices, individual flight goals and pilot behaviour are not captured. Both NextGen and SESAR will include more information in flight planning related to business goals (CDM) for each flight — data that could be possibly used to improve trajectory prediction.

C. Operational Procedures

An additional area or trajectory uncertainty comes from the execution of operational instructions (*clearances*). One of the majors factors in this group is the timing of execution of controller requested changes in heading or flight level. As of current procedural regulations, a controller will not know when exactly an aircraft will start its climb to a new altitude or its turn towards a new heading. Both aspects are increasing the perceived complexity dramatically, since in both cases, a huge area of possible aircraft positions at a given instant of time ahead is created. Currently, controllers try to compensate for this by assigning boundaries to instructions (*climb before*) in order to achieve a higher level of trajectory certainty.

Figure (4) shows three different climb profiles, exaggerated for the purpose of visibility. It is easily observed that by not knowing when an aircraft will start its climb, and how quickly it will climb, a controller has to reserve and to monitor much more space than actually necessary. An actual

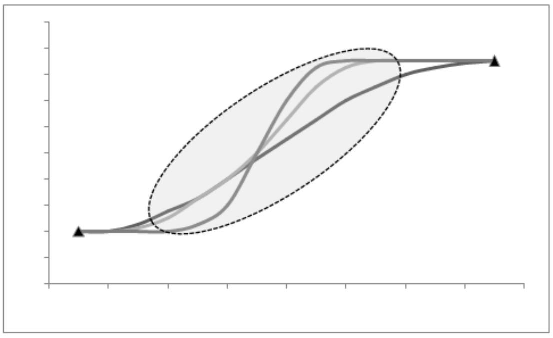

Fig. 4. Various climb trajectories (flight level to time). Ellipse shows the area of uncertainty.

climb profile is shown in (5). Investigating this figure shows evidence of the significant difference between predicted trajectory and actual position at 09:43:12 of more than 1000ft. Possible improvements in trajectory prediction with regard to operational procedures and the soundness of how instructions are followed are addressed in *Controller and Pilot Evaluation of a Datalink-enabled Trajectory-based Operations Concept*, [20].

Figure (6) shows an additional problem with ground

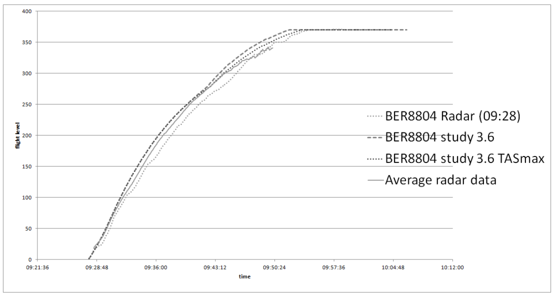

Fig. 5. Actual flight profile of flight BER8804, A320 aircraft.

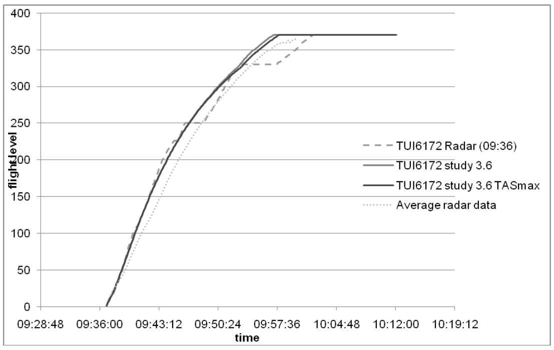

Fig. 6. Actual flight profile of flight TUI6172, B737-800 aircraft.

automation systems predicting trajectories. Here the flight profile for an actual B737-800 flight is mapped. One may observe that the trajectory did meet the prediction very well - untill operational procedures (step climb) took place that resulted in a deviation of approximately five minutes for flight level FL400. If trajectories are built on the average of actual trajectories (or a well-educated estimate) they may do better at the end of the climb, but they will miss early sections of the climb profile.

Figures (7) and (8) show the large variation of flight profiles and rate of climb and descend related to all three aspects above: trajectory data quality, model quality and operational procedures. These figures indicate possible results of inaccurate trajectory prediction and how they will affect sector complexity and workload to controllers.

IV. Proposed Complexity Metric Framework

The 4D trajectory concept of both NextGen and SESAR ([9], [10]) is clearly relying on increased trajectory certainty. In this future framework, controllers will manage non-conforming trajectories by exception. Assuming that the

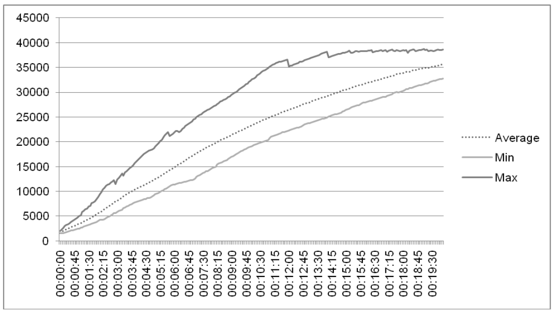

Fig. 7. Flight profile variation for B737-800 aircraft.

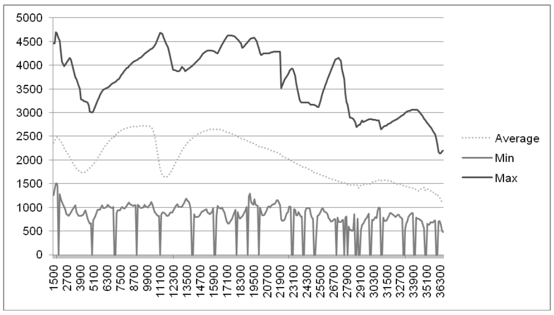

Fig. 8. ROCD with respect to flight level, variation for B737-800 aircraft.

controllers had perfect information about the aircrafts position on the considered time horizon, the same traffic situation would be perceived as much less complex as with uncertain information. In order to enhance the rationale for the deployment of data link technologies, this decrease in perceived complexity must be quantified.

Uncertainty can be captured with 3-dimensional ellipsoids, covering all possible aircraft positions at a specific instant of time ahead. The less uncertainty the smaller the ellipsoid needed when checking trajectories in MTCD. Large ellipsoids produce conflicts that do not need to be solved, hence occupying airspace that could be used by other traffic with the same amount of workload for the controller. Accurate trajectories and conflict detection is key to reducing controller workload.

When uncertainty is included, it becomes clear that the conflict counts will change depending on the predictability of the trajectory. Decreasing the volumes of individual ellipsoids will certainly decrease the number of overlapping ellipsoids, thus reducing the number of potential conflict counts.

Here we propose to assess trajectory uncertainty and its impact on sector complexity by using ellipsoids around predicted aircraft positions that are based on real statistical aircraft data. These ellipsoids can be obtained for any specific instant of time, by using the three-dimensional variance of previously tracked trajectories as the size of all three axes. The volume V of an ellipsoid is given by the size of his axes, i.e.

$$V = \frac{4}{3}\pi abc, \quad (1)$$

where we choose a to be the variance in altitude and b, c to be the variance in longitudinal and lateral dimension respectively.

This ellipsoid would represent a possible position of the aircraft for a future instant of time, indicating the uncertainty of a particular trajectory. This approach is demonstrated in

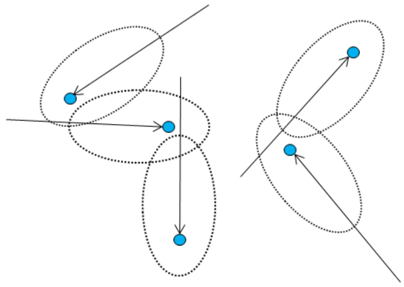

Fig. 9. Top view on 2D ellipsoids for individual trajectories.

figure (9) as a 2-dimensional simplification, where complexity is driven up more severely by crossing or overlapping ellipses.

The total volume consumed by aircraft in a sector could then be used as a complexity indicator that assesses not only conventional complexity drivers (i.e. traffic geometry), but also the impact of trajectory uncertainty on controller workload. More importantly, the volume of overlapping ellipsoids can be used as a further complexity indicator to assess the possibility of a conflict. When both indicators are combined to obtain a single factor for complexity based on trajectory uncertainty, the volume of overlapping ellipsoids must be indeed assigned to a much higher weight in correspondance to its signifiance.

Regarding conflict detection, the main difference to conventional assessment is achieved by using ellipsoids that are based on real statistical trajectory information that directly depend on the certainty of trajectories. Therefore, the uncertainty is inherently incorperated in the metric function instead of being accounted for by overly sensitive proximity measures. By using our approach, we will be able to quantify how data comm technologies will decrease the possibility of conflicts and increase the feasibility of conflict situations.

A related approach was proposed by Meckiff et all [7], by considering overlaps in 3-D control tubes. This approach could also be appropriate for the calculation above. Our focus is to show the strong relationship to complexity reduction as the sizes of uncertainty zones are decreased with better trajectory information in the ground automation.

Initially, the key element in trajectory uncertainty will be the ability to uplink trajectories from the ground system to the aircraft. A similar and possibly larger improvement will occur when we have enabled the transmission of data in the other direction — i.e. from the aircraft to the ground.

Once we have achieved the transition to an exchange of 4D trajectory constraints, see [21], aircraft flight paths will become more predictable and controller will be able to rely on the automation to predict and resolve conflicts with higher conflidence. Figure (10) gives a visualization of improvements

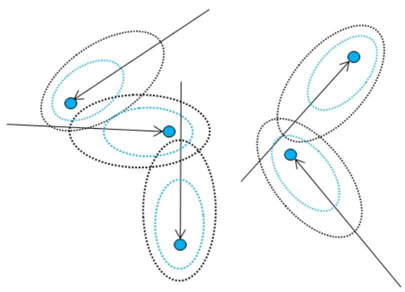

Fig. 10. Improvements in trajectory uncertainty visualized by ellipsoids.

in regard of trajectory uncertainty and corresponding ellipse size. The dotted line represents uncertainty of trajectory prediction with current data synchronization and prediction algorithms. One may observe that there are several possible conflicts between aircraft on the left side. The blue dashed line represents possible improvements in trajectory prediction that will yield much smaller ellipses — no conflicts are indicated, hence reducing perception of complexity and workload.

Interviews with controllers (and trials performed by the MITRE Corporation, see [8]) have shown that this will greatly decrease task load. More detailed information about wind and weather will also further increase the accuracy of trajectory prediction.

As we have mentioned above the emphasis here is on quantifying the impact of increased trajectory prediction on sector complexity and workload. The actual implementation of that new complexity model could be performed as follows. Assume that $F(\mathscr{T})$ is the conservative complexity score of a certain traffic situation $\mathscr{T}$ today, obtained by applying a conventional metric as it is used in Crystal or a comparable tool. Let $V(\mathscr{T})$ be the total volume of all ellipsoids within a sector. Now we may define a new complexity function

$$C(\mathscr{T}) := F(\mathscr{T}) + V(\mathscr{T}) - K, \tag{2}$$

where K is constant that must be calibrated, so that $V(\mathscr{T}_0) = K$, for $\mathscr{T}_0 = \mathscr{T}(t_0)$, where t_0 is today. Applying function (2) to the same traffic situation $\mathscr{T}_*$ with enhanced data link technologies deployed, we will observe a smaller volume of ellipsoids, i.e.

$$V(\mathscr{T}_*) < V(\mathscr{T}_0),$$

hence we obtain

$$C(\mathscr{T}_*) < C(\mathscr{T}_0), \tag{3}$$

even though $F(\mathscr{T}_*) = F(\mathscr{T}_0)$ still holds. This way we obtain a measure that quantifies the improvement made by data link to show its improvements in terms of sector complexity and ultimately sector capacity.

V. Outlook & Applications

In the previous sections we have pointed out how uncertainty of trajectory prediction impacts the perceived sector complexity and controller workload. Therefore, a metric incorperating information about trajectory predictability will yield a better understanding of complexity in a particular sector, hence enabling more efficient resolution strategies.

The main point of this paper however is to highlight that additional benefits for data comm can be captured through improvements in uncertainty. This improvement may be quantified by assessing the volume saved by reducing the size of ellispoids. Smaller ellipsoids represent one major aspect of workload improved by data comm. Other improvements by data comm include workload reduction for transferring controller functions away from voice, [22]. These have been the primary focus of data comm benefit cases like [23] or [24].

Note that both these workload reductions associated with data comm are not addressable in current complexity measures — and to be fair, they were most likely not intending to work with transforming technologies and procedures.

Furthermore, our framework focuses and for the first time enables two more interesting applications: first the architecture of this approach enables the identification of the individual complexity contribution by single aircraft a_i. By inspecting the array of aircraft

$$A = [a_i, V_i]_{i=1,\dots,N},$$

where V_i is the volume of a single aircrafts ellipsoid overlapping the ones of other aircraft, and using a simple sorting algorithm, one obtains a sequence of aircraft

$$a_{i_1}, a_{i_2}, \dots, a_{i_N},$$

ordered by their corresponding ellipsoid size and, possibly, the volume of intersections with other ellipsoids. Interpretating the size of these individual volumes as a measure of individual complexity then gives us information about which aircraft contributes most to perceived sector complexity. This aircraft may then be re-directed, depending on its course and destination, so that sector complexity is decreased.

Therefore, this approach not only helps to detect sector complexity by summing up the total volume of all involved ellipsoids, it also helps to identify single or multiple aircraft that contribute most to sector complexity. This not only enables a better understanding of complexity, but also offers a better way of complexity resolution as certain aircraft may be addressed individually for a better overall performance.

A second application is to investigate the relation between sector complexity and the number of aircraft that are equipped with a more advanced level of data comm technology. The question is how controllers perception of complexity change with the implementation of future data comm technologies? In figure 11, three possible mappings for this relation are displayed (percentage of equipped aircraft to complexity score). It is considered to be an interesting application of our proposed metric to further investigate this relation and determine an actual coherence between complexity and equipage of aircraft.

More specific insight into this relationship would stress

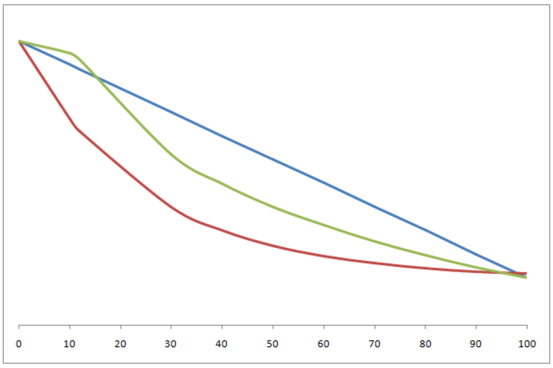

Fig. 11. Some possible functions describing the benefit of data link to sector complexity. Mapping is complexity on % of equipped aircraft.

the importance of data link technologies and would help to understand the benefits of it. As conventional metrics do not assess the effect of trajectory predictability to complexity, this is certainly a unique feature of our approach.

Further research and real-time simulations are needed for specific calculations of the impact on uncertainty driving workload compared to controller functions like transferring communications voice to data. A focus on complexity driven by trajectory uncertainty addresses the cognitive thinking needed to process the traffic situation. This paper offers a potential framework for future work.

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