

Preliminary Investigation of Impact of Technological Impairment on Trajectory-Based Operations

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The Next Generation Air Transportation System (NextGen) incorporates collaborative air traffic management and Trajectory-Based Operations (TBO) in order to significantly increase the capacity, efficiency, and predictability of operations in the National Airspace System (NAS), without decreasing safety. This is enabled by airspace users and service providers sharing knowledge about operations that allows prediction of the complete 4D flight trajectory with as little uncertainty as possible. Additionally, new software and hardware technology is critical to reaching NextGen goals, especially with regard to TBO. What if the technologies that are critical for TBO were to be impaired or fail completely? Should there be a malfunction of a piece of the technology, it must be ensured that the whole system does not break down completely or suffer severe impairment. Instead, operations need to be maintained proportionally to the problem and safety needs to be ensured (graceful degradation). This paper proposes a systematic framework to investigate the vulnerability of TBO to technology disruption, and determine the impact of technological impairment on TBO. Two representative technologies are chosen for detailed investigation and the impact of their impairment on the degradation of TBO is illustrated using a weather-related scenario.

I. Introduction

The National Airspace System (NAS) consists of a variety of entities including people, facilities, and technology, along with the rules and regulations that are needed to protect persons and properties on the ground, and to provide a safe and efficient airspace environment for civil, commercial, and military aviation.¹ As a result of the efforts of a number of national and international organizations conducting regular risk assessments, establishing standards, enacting rules and regulations, auditing for compliance, providing education, and improving technology for aircraft, avionics, and air traffic control, the NAS has reached a very high level of safety.^{1,2} Nonetheless, the Joint Planning and Development Office (JPDO) states that the US air transportation system is under significant stress³ caused by the considerable amount of effort needed to maintain the aforementioned level of safety under ever-increasing air traffic demand. NAS operations are forecast to increase, due both to increases in commercial flying and the integration

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of Unmanned Aerial Systems (UAS) and other new entrants into the NAS.¹ As a result of concerns that the current air transportation system might not be able to accommodate forecasted growth, a significant amount of effort has been invested in the development of the Next-Generation Air Transportation System (NextGen).³

A Concept of Operations (ConOps)³ for NextGen lists the various capabilities that need to be an integral part of NextGen. Existing technologies can support some of the needed functionalities and capabilities, but new technology development and new processes are required to support increased capacity and efficiency. The availability and correct functioning of technology is extremely critical to NextGen, and in fact, the entire US air transportation system. Should there be a malfunction of a piece of the technology, it must be ensured that the whole air transportation system does not break down completely or suffer severe impairment. Instead, operations need to be maintained proportionally to the problem and safety needs to be ensured, thus facilitating a graceful degradation (as opposed to an abrupt breakdown).

This paper analyzes the dependence of NextGen air traffic management operations on different types of technology. In particular, this paper focuses on Trajectory-Based Operations (TBO), which is key to the NextGen Air Transportation System. The goals of this paper are to (i) qualitatively examine the impact of breakdown of different technologies on TBO, and (ii) determine whether graceful degradation to a particular technology breakdown is feasible. While it is also important to analyze the extent of TBO impairment under technological disruption, such quantitative analysis is out of the scope of this paper.

Besides the hardware needed for TBO operations (such as radars and ADS-B (Automatic Dependence Surveillance - Broadcast)), this paper also considers software required for a variety of activities, such as separation management, trajectory negotiation and management, and so on. Most of the hardware components and software components are closely interconnected with each other. Over the past two decades, researchers have investigated the failure of both hardware and software components.⁴⁻⁶ While in some cases, built-in redundancies may reduce the impact of such failures, in other situations, there may be a significant amount of risk associated with these failures.

In order to investigate whether TBO will degrade gracefully, it is important to understand how to measure its performance. This can be achieved, for example, by assessing several key performance indicators,⁷ as defined by the Federal Aviation Administration. An impairment in technology affects one or more of these performance indicators, with a decrease in one indicator possibly causing a decrease in another indicator. For example, when efficiency is reduced, it may be necessary to continue operations at a reduced capacity. However, these performance indicators may not be equally critical, e.g., safety is much more critical than efficiency, so it may be reasonable to compromise efficiency to maintain safety at acceptable levels.

Based on the changes to the key performance indicators, it is then possible to understand whether degradation of TBO is abrupt or graceful. Specifically, a significant, sudden drop of a critical performance indicator can be associated with abrupt degradation. Similarly, a graceful degradation is said to occur when a critical performance indicator decreases gradually, in such a way that there is sufficient time left until which the most crucial operations can continue while the impairment is being corrected. In the presence of graceful degradation, airline operators, air traffic controllers, and automation software can compensate for the change such that critical performance indicators stay within acceptable levels (or recover to acceptable levels).

The goal of this paper is to explore the topic of degradation of TBO in detail and to answer the following four questions:

1. What is the impact of impairment of technology on the NextGen Air Transportation System and Trajectory-based Operations?
2. In case of an impairment, does TBO degrade gracefully?
3. How does this impairment impact the performance of Trajectory-Based Operations?
4. Is it possible to ensure a graceful degradation of Trajectory-Based Operations functionality in the presence of technological impairment?

The first question helps in explicitly understanding how TBO depends on various technologies, and how the impairment of technologies will affect NextGen and TBO. If one or more technologies were to fail, it is possible to identify what aspects/functionalities of TBO will be affected. The second question focuses on identifying whether and how TBO will degrade under technological impairment; a graceful degradation is preferable because it may be possible to maintain critical operations at decreased efficiency, and more over, a graceful degradation may provide sufficient time to perform corrective maintenance actions to restore nominal operation of technologies. The third question aims to quantify how the performance of TBO changes when technology is impaired; this is achieved by identifying a few key performance metrics that can assess the performance of TBO. Finally, the fourth question analyzes what types of technological impairment may lead to a graceful degradation and what types may not. Collectively, the above questions aid in understanding the dependence of TBO technologies and helps in identifying how trajectory-based operations may be degraded (particularly focusing on determining whether the degradation is graceful or not) when different types of technology are impaired.

The rest of the paper is organized as follows. Section II describes the overall approach for the investigation of the impact of technological impairment on the degradation of TBO; a few performance metrics are discussed and two illustrative examples of technological impairment are explained in detail. Section III presents a small-scale realistic weather-related scenario where the degradation of TBO under the aforementioned two examples are discussed with reference to the context of this scenario. Section IV concludes this paper and suggests possible directions for future work.

II. Investigation of Degradation of TBO

This section develops a systematic approach to investigate the TBO performance degradation under technology impairment. This approach is briefly summarized in Fig. 1.

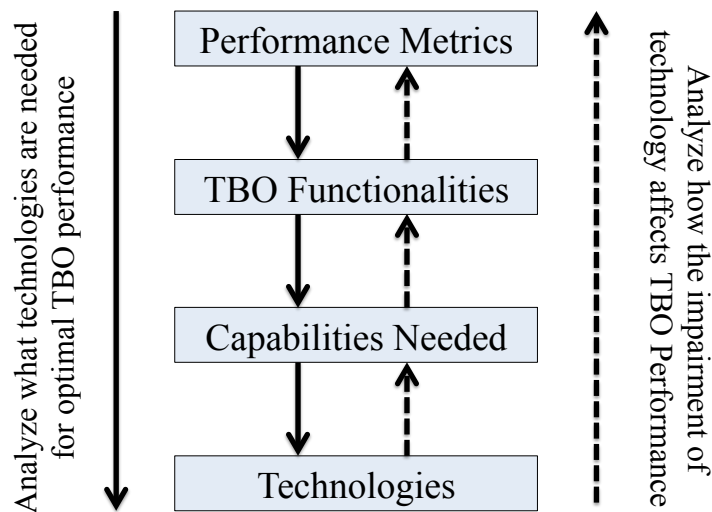


Figure 1: Proposed Approach as Flowchart

As seen from Fig. 1, the approach is a two-step procedure. The first step (indicated by solid lines in Fig. 1) involves the analysis of capabilities and technologies that are required for optimal performance of TBO. This is accomplished through the following steps:

- Identification of key performance indicators (KPIs) that measure the performance of airspace operations. The KPIs will ultimately indicate whether the degradation is graceful.

- Understanding how the various functionalities of TBO are interconnected with the aforementioned KPIs.
- Identification of the various capabilities that are needed to enable the aforementioned functionalities.
- Identification of various technologies that facilitate the aforementioned capabilities.

The second step (indicated by dotted lines in Fig. 1) involves the investigation impairment of technology and its impact on TBO performance. This step is exactly the reverse of the first step. Given a technology is wholly or partially impaired, this procedure involves:

- Understanding what capabilities of TBO will be affected.
- Understanding what functionalities of TBO will be affected.
- Identifying which KPIs will be affected and how.

Thus, the proposed approach provides the fundamental framework to understand how technologies affect the TBO performance metrics. The following sections further explain the various steps of the proposed approach in greater detail.

II.A. TBO Performance Indicators

The Federal Aviation Administration (FAA) lists more than 20 key performance indicators.⁷ For the sake of illustration, this paper focuses on the following four key performance indicators:

1. **Safety:** *Airspace safety* deals with the prevention of occurrence of safety hazards, and Roychoudhury et al.² have discussed the assessment and monitoring of safety in airspace systems.
2. **Predictability:** *Predictability* is one the main features of the planned TBO. It refers to being able to accurately predict the position of any aircraft regarding its planned trajectory. It is envisioned that there would be very little uncertainty regarding these positions. (Note that the focus here is on trajectory predictability and not on the predictability of operations.)
3. **Capacity:** *Capacity* measures the number of aircraft/operations that can be operated by the Air Navigation Service Provider (ANSP, which is the Federal Aviation Administration in the United States of America) in a specific time-frame (daily capacity, hourly capacity, etc.).
4. **Efficiency:** *Efficiency* is a generic term that measures how minimum resources can be used to meet the requirements of the national airspace system.

While the above four performance indicators were selected primarily for the purpose of illustration, they are also important factors for NextGen. It is anticipated that the capacity will be increased and 4-D trajectories will be accurately available for future aviation. Hence, the uncertainty in predictions needs to be reduced while simultaneously maintaining a desired level of safety. Operations also need to be performed in an efficient manner, without compromising the other three factors. Thus, these four factors are chosen for investigation in this paper. Future work may consider the inclusion of other important factors such as delays, fuel burn rates, etc.

It is of interest to understand how the impairment of technology affects the above performance metrics, and answer questions, such as, “How does each performance indicator get influenced by the TBO technology impairment?”, “Does the performance metric drops down abruptly or gracefully if the technology is impaired?”, and so on.

II.B. Capabilities, Technologies, and Impairment of Technologies

It is important to address the above questions in order to identify the capabilities that are essential in enabling TBO. Within TBO, in addition to monitoring the states of each aircraft in the airspace system (i.e., velocity, position, heading, and remaining fuel), it is also important to obtain knowledge to the largest degree possible regarding the trajectory of an aircraft (including the complete 4-dimensional trajectory, the underlying metering way-points, possible conflicts, etc.). To enable these capabilities within TBO, many different technologies and systems need to be developed. Some of the technologies have already been developed and deployed in the aircraft and ground stations, and some are still under development. The next step is to understand the benefit mechanism behind how a given capability improves and enhances TBO. Then, it is possible to associate such capabilities with the aforementioned performance metrics. Thus, when a given capability is missing, it is possible to recognize how the system will be disrupted, how will the loss of such capability affect the TBO operations, and which performance metric might get affected.

A preliminary listing of various TBO-related technologies is provided in Fig. 2, which provides inter-relationships between the technologies, capabilities, benefit mechanisms, and performance metrics. These interrelationships are constructed based on the following analysis:

1. **Understanding how Trajectory-Based Operations (TBO) works within the NextGen:** It is important to understand the differences between today's Clearance-Based Operations (CBO)^{3,8} and the proposed TBO, focusing on specific operational procedures in order to determine additional technologies/capabilities that are required for the implementation of TBO.
2. **Identifying the major technologies already deployed or under development to enable the new characteristics in TBO:** It is important to understand how each technology works, how it contributes to TBO in enabling new capabilities and functionalities and what the benefits of each technology are.
3. **Building the relationships between technologies and capabilities:** The construction of functional mapping between technologies and capabilities enables us to answer the following questions:
 - (a) What capability each technology is able to provide for the system?
 - (b) Is this technology the only one within TBO to enable such capability?
 - (c) Is there any overlap among different technologies in enabling the same capability?
4. **Investigating the benefits enabled by each capability:** An important problem is to evaluate how the TBO stakeholders (airline operation center, airspace user, or air traffic controller, etc.) are going to benefit from these new capabilities, how the new capabilities are going to advance the airspace operations, and what is the specific benefit mechanism in advancing the system.
5. **Studying the relationship between the benefit mechanisms and the system performance metrics:** Considering a particular specific benefit mechanism enabled by each capability, it is possible to identify which system performance metric would be improved.

Using the flowchart in Fig. 2, it is possible to facilitate both the steps of the proposed two-step procedure (Fig. 1), i.e., first, understand what technologies are necessary to enable the desired functionalities, and second, understand how the impairment of a particular technology affects TBO and the performance of TBO. If a particular technology were to fail, it is possible to identify what capabilities would be affected by such a failure. In particular, if a given capability can be enabled only through that particular technology, then such failure would be deemed as critical. Once the affected capabilities are identified, it is possible to further down-select the performance metrics relevant to this capability. If alternate technologies are still available to provide the system that specific capability, it is important to identify the differences in the various technologies in enabling that capability (in many cases, an alternate technology may not be as efficient as the original technology) and recognize the system performance metrics that may be adversely affected.

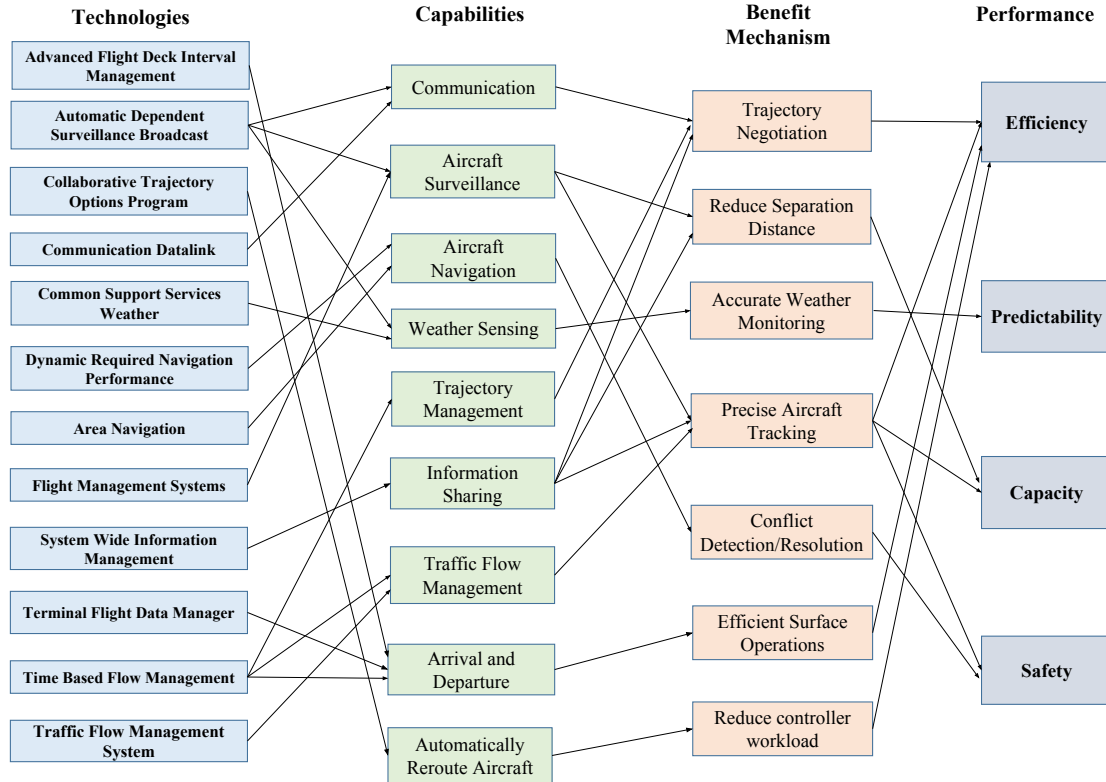


Figure 2: Relationships between Technologies and TBO Performance

Note that the list of technologies in Fig. 2 is meant to be only representative, not exhaustive. Two of those technologies – Automatic Dependence Surveillance Broadcast (ADS-B) and System-Wide Information Management (SWIM) – are chosen in this paper for further detailed discussion. A brief summary of the other technologies is provided in the Appendix, at the end of this paper.

II.C. Technology: Automatic Dependence Surveillance - Broadcast (ADS-B)

ADS-B is a surveillance technology in which an aircraft determines its position via satellite navigation and periodically broadcasts it to ground stations and nearby aircraft, enabling live tracking. To track the airplane, active participation by the aircraft through its onboard ADS-B transponder is required. The tracking information can be received by air traffic control ground stations as a replacement for secondary radar. It can also be received by other aircraft to provide situational awareness and allow self separation. ADS-B is ‘automatic’ since it requires no pilot or external input. It is ‘dependent’ since it depends on data from the aircraft’s navigation system. ADS-B provides a large number of information to both pilots and ATC, such as traffic information about surrounding aircraft provided those aircraft are equipped with ADS-B out. ADS-B enabled aircraft will also be able to receive weather reports, if they are equipped with universal access transceiver (UAT). Finally, the flight information service-broadcast (FIS-B) also transmits readable flight information such as temporary flight restrictions (TFRs) and Notice to Airmen (NOTAMs) to aircraft equipped with UAT in the US.⁹ The Automatic Dependent Surveillance-Broadcast (ADS-B) is a technology that uses GPS satellite signals and aircraft avionics systems to broadcast the aircraft information, e.g, location, speed, altitude, and over 40 other parameters, continuously to air traffic controllers and other participating aircraft.

ADS-B uses the global Low Earth Orbiting (LEO) satellites to cover the oceanic and remote regions so

as to keep tracking and reporting the aircraft positions more accurately and frequently (twice per minute). Compared to traditional methods, ADS-B enables real-time aircraft surveillance by tracking the aircraft more accurately, reporting its location more frequently, as well as covering the surface more thoroughly, as indicated by “Aircraft Surveillance” in the second column of Fig. 2. The precise aircraft surveillance enables a reduction of the aircraft separation minima. Hence, the advent of satellite based surveillance would allow us to boost capacity and accommodate more aircraft than before while maintaining the same safety level. On the other hand, ADS-B also strengthens the situation awareness ability by automatically broadcasting the meteorological information sensed by each aircraft to its nearby airplanes, as represented by the weather sensing capability in Fig. 2. The collaborative and crowd-sourcing weather sensing and sharing capabilities greatly cut down the uncertainty in whether prediction, thus enhancing the predictability on the system evolution. The above analysis shows the process in building the relationships between the ADS-B technology, TBO functionalities and capabilities, and the chosen performance metrics. This technology is immensely important for Aircraft, the Air Navigation Service Provider (ANSP, which is equivalent to the FAA, in the United States) and the Airlines Flight Operation Center (AFOC).

What happens when ADS-B is impaired?

Given that the FAA is planning to gradually phase out the radars, ground stations will increasingly rely on ADS-B for getting information regarding aircraft in flight. Failure in AD-B may be of varying degrees ranging from minor hardware issues (more noise in the measurements than usual, intermittent connection issues, unusual lag between transmission and reception) to major failures where ADS-B is completely unavailable for operational purposes. The rest of this section focuses on the latter issue where ADS-B is subject to complete failure.

When there is an impairment of ADS-B out, an aircraft is unable to automatically broadcast its own position and related information to the external agents. As a result, it may resort to alternative methods of communication such as voice, radio, etc. From the point of view of the ANSP and AFOC, the predictability of the location and the future trajectory of this aircraft may not be directly reduced, because the aircraft still receives GPS information but it is simply not able to broadcast it. However, the efficiency in broadcasting this information is abruptly reduced, when switching over to alternative methods of communication that are less efficient. As a result, the automation involved in TBO suffers because it may be necessary to use more manpower to handle this situation. Therefore, if a greater number flights suffer from the impairment of ADS-B out capabilities, the overall efficiency will abruptly drop down. Further, safety will also be affected gradually.

When there is an impairment of ADS-B in, (*i*) an aircraft fails to receive automated information regarding itself from satellites; and/or (*ii*) an aircraft fails to receive automated information regarding other aircraft in the vicinity. The former leads to predictability issues, there is an increase in the uncertainty in the position of that particular aircraft; in fact, it may not be possible for the ANSP/AFOC to closely track that aircraft along its entire trajectory. Such an abrupt decrease in predictability will be followed by gradual decrease in safety levels since the likelihood of hazards may increase beyond acceptable levels. Further, the efficiency of operation will also suffer because of lack of predictability.

As a result, in the case impairment of ADS-B in/out, in order to ensure a graceful degradation and guarantee safety, it may be necessary to operate at decreasing capacity levels and/or ground certain critical aircraft. The presence of radars may be helpful in avoiding abrupt disruption of activities, but if radars have become phased out, then ADS-B will be of paramount importance.

II.D. Technology: System-Wide Information Management (SWIM)

Another important technology, the System-Wide Information Management (SWIM) can also be analyzed using the framework described above. SWIM is the data-sharing backbone of NextGen, which aims to improve FAA’s capability in delivering the important information (e.g., flight data, weather information, airport operational status, aeronautic information, and special use airspace status) to the right stakeholders (e.g., pilots, controllers, dispatchers, and Flight Operation Center) at the right time.¹⁰ SWIM facilitates the

data sharing requirements for NextGen, providing the digital data-sharing backbone of NextGen. SWIM enables increased common situational awareness and improved NAS agility to deliver the right information to the right people at the right time. This information-sharing platform offers a single point of access for aviation data, with producers of data publishing it once and users accessing the information they need through a single connection. SWIM is a technology enabler that provides the IT standards, infrastructure and governance necessary for NAS systems to share information, improve interoperability, and reuse information and services. SWIM was designed to implement a set of information technology principles in the NAS and to provide users with relevant and understandable information, such as flight data, weather information, airport operational status, surveillance information, and special use airspace status. SWIM is the NAS data sharing backbone of NextGen enabling the transition from a point-to-point communication model to a net-centric communication. SWIM provides users access to the NAS database via publication and subscription.¹⁰

SWIM is operated over an inter-operable infrastructure: the ground/ground communication is implemented over IP-based network, and the air/ground communication is transmitted by data link. In this way, the data and information is distributed to relevant stakeholders. At present, the Federal Telecommunication Infrastructure (FTI) is the primary means for FAA's telecommunication services.¹¹ The goal of SWIM is to consolidate the telecommunication services for more than 5,000 facilities and 30,000 circuits in the national airspace system. SWIM provides a unified interface for all the stakeholders to access to the system-wide information they need, including more reliable information about the future state of the ATM system and its environment, via publication and subscription in a secure and timely manner. The sharing of system-wide information enables increased airspace safety through improving common situational awareness by allowing more decision makers to access the same information.¹² SWIM also improves the cost efficiency mostly thanks to the timely sharing of system-wide information, each pilot and ground controllers are capable of making more optimal decisions than before. By taking advantage the accurate meteorological information collected from heterogeneous data sources, e.g., ground radar, aircraft sensors, and satellites, the stakeholders is able to identify fuel saving route by taking advantage of the wind speed. On the other hand, in the presence of convective weather or disruptions, the relevant stakeholders can make more appropriate decisions with the consideration of its effect on the subsequent air traffic because they have the complete observation on the system status.

What happens when SWIM is impaired?

In general, if SWIM does not change the underlying present day operations (either in terms of the traffic density or coordination of strategic traffic flow management), then the SWIM information is for situation awareness only for the different operators to make better decisions but its failure does not have significant implications. It may be possible to maintain operations at a slightly decreased efficiency level. However, if future operations leverages SWIM to automatically exchange traffic and weather information between different automations to allow more data-centric, coordinated strategic traffic management, then its failure will have a much larger impact.

Depending on the impairment causes, it may affect the SWIM performance in different ways and to varied extents. If the satellite communication is down, the current system needs to revert back to the legacy to transmit the data between the air and the ground. Even if the legacy system is able to accommodate the communication, the safety and efficiency is heavily compromised. A traditional legacy system may not have the same efficiency as the satellite-based communication in many aspects. For example, the information from multiple data sources cannot be synchronized in a timely manner, and the surveillance of the flight status is severely influenced. The loss of such capabilities heavily influence the efficiency and the safety of the national airspace system, which in turn weakens the situational awareness of the pilots and the ground controllers. Therefore, it is almost impossible to facilitate a graceful system degradation due to the significant role that SWIM plays in TBO.

If some transmitters or receivers (or data cables) were to fail, the related communication between air and ground controllers is affected. However, since there are other alternative methods to handle the communication originally processed by transmitters and receivers, e.g., vocal communication (when the amount of

data is not significantly large), the traffic controller would be able to handle the such amount of workload through vocal communication with the pilot. Even if the traffic controllers are unable to handle such data, they can seek help from other controllers to handle the affected air traffic provided they know which aircraft is influenced. In such specific scenarios that may be considered small-scale or local, it may be possible to ensure a graceful degradation of operations.

If there are technological problems at the data centers, the data from these data centers will not be available to the stakeholders in order to acquire the information about the system operation status. Under this circumstance, it may be necessary to make decisions without complete system-level information. As a consequence, the decisions are not optimal from the perspective of efficiency or safety. During this process, it is risky to plan for any additional aircraft operations (e.g., re-routing aircraft, landing, taking off, or en route operations). Considering that these issues arise from the missing data, the system degradation may not be graceful. It may be necessary to ground flights in order to assure minimum safety, and therefore, this may adversely affect the overall operations.

III. Weather-Related Scenario for Illustration

This section presents a NAS-related scenario that demonstrates the impact of impairment of technology on Trajectory-Based Operations. In particular, the scenario deals with adverse weather conditions being encountered enroute. First, the nominal air traffic operation without any technological impairment is discussed. Then, two possible technological impairments (ADS-B and SWIM, as discussed in the previous section), respective loss of capabilities, and the impact on nominal operations are investigated in detail.

III.A. Scenario Description

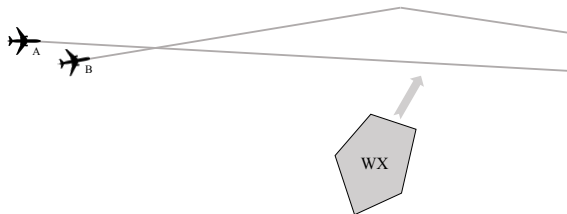


Figure 3: Description of WX Scenario

Consider a scenario where several aircraft that need to go around a region of adverse weather (labeled WX), as shown in Fig. 3^a. Each flight has its own predetermined trajectory, as shown by the solid line in Fig. 3. These trajectories had been successfully negotiated at an earlier stage, based on the information available regarding the intended destinations of the aircraft and the predicted movement of the weather. It had been predicted during initial trajectory negotiation that the original trajectories would not be conflicting with the weather at all.

For the sake of this example, consider a scenario where the weather movement is different from what had been predicted, and it ends up being in conflict some of the aircraft. Therefore, the trajectory of these aircraft need to be changed. Such a representative aircraft is denoted by A (referred to as ‘Type-A’, in the remainder of this section) in Fig. 3. It is also expected that the region of adverse weather WX may have some additional trailing weather zones.

While the trajectories of aircraft Type-A need to be changed, the resultant trajectories may cause conflict against other aircraft in the region. Other aircraft that are not in conflict with WX but would be in conflict

^aThis scenario is based on a similar scenario presented as a part of “Advanced 4-dimensional Prototype demonstration”, at NASA Langley Research Center, on July 14, 2016;¹³ the trajectory paths are very similar to what would happen in a practical weather situation. That original scenario had only two aircraft whereas the scenario in this section considers several aircraft; while some (these are called Type-A) need to be rerouted due to weather-conflict, others (referred to Type-B) may need to rerouted based on potential conflicts arising due to new trajectories of Type-A aircraft.

with the revised trajectory of Type-A aircraft are also considered in this analysis; a representative aircraft B (referred to as ‘Type-B’, in the remainder of this section) is also indicated in Fig. 3.

III.B. Scenario Under Nominal Conditions

To begin with, the onboard radars and weather-related equipment on the aircraft will be able to identify that the actual behavior of the weather is different from what had been anticipated. Hence, the aircraft along with the ANSP and their respective Airline Flight Operation Centers will recommence trajectory management, taking into account separation management, optimal trajectory generation, and adverse-weather avoidance. As a result, the trajectories of the aircraft change as indicated in Fig. 4. The change in trajectory, i.e., the new path of the aircraft is indicated in dotted lines.

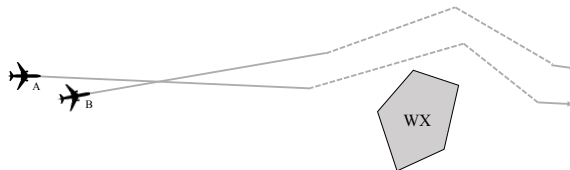


Figure 4: Description of WX Scenario: Nominal Operation

The procedure behind the negotiating new trajectories for the aircraft can be summarized as follows. First, the original trajectories of aircraft Type-A would be in conflict with the adverse weather region WX (identified through Onboard Weather Radars and Sensing System). So, the trajectory of this aircraft would have to be routed around the weather WX. It is more intuitive to route an aircraft behind the weather zone rather than in front of it. However in this scenario, of the possibility of trailing weather regions, some aircraft of Type-A may be rerouted far ahead of the weather zone WX, as shown in Fig. 4. Irrespective of whether a Type-A aircraft is being routed behind the weather or far ahead of the weather, this step requires weather information (Common Support Weather Services), information sharing (System-wide information management, enroute automation modernization) generating a set of option-trajectories (Collaborative Trajectory Operations Program), surveillance and broadcast (ADS-B), data communication (Communication datalinks), trajectory generation/management/negotiation systems, etc. This trajectory could either be generated by the AFOC or by the aircraft itself. An important feature of NextGen-TBO is that aircraft will be able to make mutual trajectory negotiations even without ground-support from ANSP/AFOC (Airborne Trajectory Management).

The fact that the trajectories of aircraft Type-A has been modified affects the other aircraft of Type-B, because the new trajectory of Type-A would be in conflict with the original trajectories of Type-B. The Traffic alert and Collision Avoidance System (TCAS) would indicate an impending collision between the newly planned trajectory of aircraft Type-A against the originally intended trajectory of aircraft Type-B. Hence, it would be necessary to use separation management and trajectory generation, and identify a new trajectory for aircraft Type-B that curves farther away from both the region of adverse weather WX and the aircraft Type-A, as shown in Fig. 4.

III.C. Capabilities and Technologies

The aforementioned successful trajectory re-negotiation and weather avoidance under the nominal scenario requires the following capabilities: Weather observations using onboard weather radars, 2-way communication with ATC, 2-way communication between any two aircraft, Self-knowledge of location and other related information, Conflict prediction and separation management, Trajectory management and negotiation, ANSP functionalities, and AFOC functionalities.

The above capabilities are enabled through the following technologies: (1) Onboard weather radars and sensing systems, (2) Airborne Trajectory Management (3) automatic Dependence Surveillance - Broadcast (ADS-B), (4) Data communication and datalinks, (5) Collaborative Trajectory Operations Program (CTOP),

(6) Traffic Alert and Collision Avoidance System (TCAS), (7) Common Support Services Weather (CSS), (8) System Wide Information Management (SWIM), and (9) Enroute Automation Modernization (ERAM).

Similar to Section II, the next subsection focuses on the two technologies - ADS-B and SWIM. The effect of impairment of these technologies on this scenario is evaluated and their qualitative impact on TBO is analyzed.

III.D. Scenario under Impaired Conditions

This section discusses what happens to this particular scenario when any of the above technologies are impaired.

- Impairment of Automatic Dependence Surveillance - Broadcast: The impairment of ADS-B means loss of one or more of the following functionalities: (i) the aircraft does not know GPS-related information about itself; (ii) the aircraft cannot automatically transmit its own information to the ANSP, AFOC or even other aircraft; (iii) the aircraft cannot receive information from other aircraft. If the position and other GPS-related information is unknown, there is an abrupt loss of predictability. Then, it would be necessary to increase separation to maintain the desired levels of safety, and this would lead to a decrease in capacity. Instead of automatically transmitting information, it would be necessary to resort to other means of manual communication such as voice, radio, and other similar two-way communication mechanisms that have been commonly used in clearance-based operations. Aircraft Type-A and Type-B would have to manually contact the ANSP and AFOC in order to with new trajectories. This may cause several errors during transmission, thus significantly reducing the efficiency. If predictability is intact, then alternate methods of communication can be used to ensure a graceful degradation. Otherwise, the ability to continue Trajectory-Based Operations may be lost, and it would be necessary to increase separation distances and resort to clearance-based operations to ensure safety. Other factors that affect degradation include surrounding traffic density (a larger density increases traffic complexity, reduces safety buffer and increases controller workload) and existing workload (if sufficient human resources are available, it is possible to maintain safety at decreased efficiency by resorting to voice-based operations).
- Impairment of System Wide Information Management: Under present day operations, Data Comm and ADS-B out should allow controllers and the flight deck to exchange trajectories without SWIM. However, future operations are expected to become much more efficient and strategically coordinated such that AFOC and Command Center negotiates and coordinates the flight plans. In such a scenario, SWIM will be at the heart of Trajectory-Based Operations, and its may pose serious threat to nominal operations. In this scenario, the planned trajectories of aircraft Type-A and Type-B will not be communicated through the satellites if SWIM is impaired. While surveillance of these flights may still be possible because of ADS-B, the surveillance-would not be distributed through the system. Therefore, it would be increasingly challenging for the ANSP and AFOC to guide the aircraft to avoid conflicts with one another and with weather. This results in an abrupt decrease in safety and predictability. Further, since there is increased workload for the ANSP and AFOC, the efficiency and the capacity would also gradually decrease. Thus, a graceful degradation is still possible but at the expense of efficiency

Note that the above scenario is relative a small-scale one, compared to overall airspace system. If such impairment were to occur in large-scale scenarios, then, the effect of impairment may be significantly greater. Future work needs to focus on developing such scenarios and investigating the effect of technological impairment on TBO.

IV. Conclusions

This paper investigated the effect of impairment of technology on Trajectory-based Operations, in the context of the NextGen Air Transportation System. A goal was to determine how operations may be impacted

in the presence of technological impairment. In order to achieve this goal, the various capabilities and functionalities required of TBO in the context of NextGen were identified, and then, the technologies necessary to enable these capabilities and functionalities were enumerated. In order to understand the performance of trajectory-based operations, four key performance indicators (safety, predictability, capacity and efficiency) were selected (out of several identified by the Federal Aviation Administration). A systematic approach was developed where it is possible to identify how each technology affects various TBO functionalities and capabilities and in turn, affects the metrics. Using this approach, it is possible to identify the effect of TBO technology impairment on TBO performance. While several possible technologies were possible candidates for discussion, 2 technologies (ADS-B and SWIM) were selected for detailed investigation. An illustrative weather-related scenario was discussed and the effect of impairment of these two technologies were studied. It should be noted that there are numerous root causes and symptoms for technology impairment that will manifest themselves in different ways, possibly leading to different impact on TBO operations. It should also be noted that this investigation here only considered a “hard failure” and not a case where technology is degraded only to some degree, resulting in degradation of signal or communications, for example. Finally, this study was carried out at a conceptual level only, that is, it was not validated in simulations or on real systems.

There are several possible directions of future work. We believe it is desirable to develop methods to quantitatively assess the impact of technological disruption on TBO and to have the simulation tools to validate the impact. The availability of prognostics and health management methods could be leveraged to predict technological failure/disruption, thus predicting how TBO will be affected, and possibly pro-actively mitigating the impact. It is important to develop large-scale scenarios where the effect of technological impairment is prominent, and identify methods to quantitatively assess the extent of TBO degradation. An important goal of such an investigation is the development of failure-resistant resilient trajectory-based operations. Resilience^{14, 15} is the property of a system to “bounce back” and resume at least a significant portion of its functionalities after degradation due to technological impairment(s). A systems resilience includes properties such as “buffering capacity” (quantifying disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in the systems structure), “flexibility” (ability to restructure itself in response to external changes or pressures), “margin” (how closely the system is currently operating relative to one or another kind of performance boundary), “tolerance” (whether the system gracefully degrades as stress/pressure increase, or collapses quickly when pressure exceeds adaptive capacity), etc. Future work needs to focus on quantifying and improving the resilience of TBO, and identifying resilient design solutions for aviation.

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Appendix

In this Appendix, a few technologies that were considered for investigation are tabulated below. Future work needs to delve into the impairment of these technologies in detail and develop realistic scenarios that focus on the degradation of TBO under the impairment of these technologies.

Table 1: TBO-Enabling Technologies

Technology	Brief Description	Impact of Impairment
Advanced Flight Deck Interval Management (AFIM)	AFIM is an ADS-B based concept developed to provide operational benefits through the management of spacing intervals between aircraft during arrivals and departure. ¹⁶	Complete impairment of AFIM may significantly affect the efficiency and capacity with respect to surface/terminal operations.

Table 1: TBO-Enabling Technologies

Technology	Brief Description	Impact of Impairment
Airborne Collision Avoidance System (ACAS)	ACAS is a type of Ground Collision Avoidance Technology (GCAT) that operates independently of ground-based equipment and air traffic control in warning pilots of the presence of other aircraft that may present a threat of collision. Several types of ACAS exist to prevent unintentional contact with other aircraft, obstacles, or the ground, such as: Airborne Radar, Traffic Collision Avoidance System (TCAS), Portable Collision Avoidance System, Ground Proximity Warning System (GPWS), and Terrain Awareness and Warning System (TAWS). ⁹	Failure of ACAS significantly decreases the safety, as it may fail to prevent airborne collisions.
Collaborative Trajectory Options Program (CTOP)	CTOP is a trajectory management initiative that automatically assigns delay and/or reroutes around one or more flow constrained areas in order to balance demand with available capacity. It is collaborative and allows operators to submit, well in advance of issuance of the program, a set of desired reroute options (known as Trajectory Options Set) that can be used to route around an FCA or constraint. ¹⁷	The impairment of CTOP would imply generating new trajectories for airborne aircraft will become substantially difficult and would require more human effort, thus adversely affecting the efficiency of operations.
Communication Datalink	The Controller-Pilot Data Link Communications (CPDLC) is a means of communication between controller and pilot, using data link for ATC communication. There are various implementations of datalink used by a variety of aircraft in different routes, as well as by different ground stations.	An impairment in communication data link will impact communication across the NAS, and hence pose a threat to both safety and efficiency.
Common Support Services Weather (CSS-Wx)	CSS-Wx is the single provider of weather data, products, and imagery within the NAS, using standards-based weather dissemination via SWIM. . ¹⁸	Weather sensing will be impacted if this technology is impaired, and hence accurate weather-related information will not be available. The predictability of trajectories will decrease and this also poses a threat to safety.
Area Navigation (RNAV) and Dynamic Required Navigation Performance (DRNP)	RNAV is a method of IFR navigation that allows an aircraft to fly on any desired flight path within a network of navigation beacons, rather than navigate directly to and from these beacons. DRNP is an Area Navigation method with the addition of onboard performance monitoring and alerting capability.	The impairment of these technology implies that navigation capabilities are affected, and this affects trajectory generation, efficient conflict detection/resolution, etc., thus compromising safety.
Flight Management System (FMS)	An FMS is a specialized computer system that automates a wide variety of in-flight tasks, reducing the workload on the flight crew to the point that modern civilian aircraft no longer carry flight engineers or navigators.	The impairment of FMS would be local, for that particular aircraft and would not have any NAS-level effect; however, that particular effect under consideration would be significantly affected. Airborne navigation would become challenging leading decrease in the safety of the aircraft as well as in the efficiency of operating the aircraft.
Terminal Data Flight Manager (TFDM)	TFDM is a surface management tool that streamlines the sequence of aircraft scheduled to depart while accounting for aircraft scheduled to arrive, in order to maximize airport efficiency and reduce delays. TFDM also uses surface surveillance and flow-management capabilities in its predictive modeling for improved departure management, ground movement, and flight coordination. ¹⁹	The impairment of TFDM adversely affects terminal/ground operations, and decreases the efficiency of arrival/departure planning/scheduling. While safety may not be affected, the airport/terminal capacity could be affected.
Time Based Flow Management (TBFM)	TBFM includes time-based metering capabilities and a trajectory modeler. This will enhance the efficiency and optimize demand and capacity, and also enable controllers to more accurately deliver aircraft to TRACON facility while providing the opportunity for aircraft to fly optimized descents. ²⁰	An impairment of TBFM will affect trajectory management capabilities and impair trajectory negotiation in addition to affect arrival/departure operations at terminal/ground level. Both of these factors may significantly affect efficiency of operations.

Table 1: TBO-Enabling Technologies

Technology	Brief Description	Impact of Impairment
Traffic Flow Management System (TFMS)	TFMS is a data exchange system for supporting the management and monitoring of national air traffic flow. TFMS processes all available data sources such as flight plan messages, flight plan amendment messages, and departure and arrival messages. ²¹	The impairment of TFMS may have significant consequences since it lead to the reduction of several benefits such as precise aircraft monitoring/tracking, communication, and poses threats to safety, efficiency, and predictability.

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