

Fuel-Efficient Safe and Secure Formation Flying in Commercial Air Traffic: Procedures, Sensor Fusion, and Communication Strategies

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Abstract—Civil aviation has a significant impact on climate change, and reducing greenhouse gas emissions from this sector is a critical goal. One promising approach to mitigating emissions is the use of wake vortex uplift in formation flying. Initial tests by test pilots have demonstrated the general feasibility of this maneuver. However, for the execution of formation flying, the current safety separation distances between aircraft, as defined by ICAO, must be temporarily suspended. The current separation distances are designed for collision avoidance and specifically to mitigate risks associated with wake turbulence, which can pose significant dangers to aircraft, crew, and passengers. To integrate formation flying into routine civil aviation operations, new procedures are required. These procedures must ensure the efficient utilization of wake vortex effects in formation flying while maintaining current safety standards. Currently, no such procedures exist.

We propose a six-phase procedure to address the absence of such protocols and identify key challenges that must be overcome to enable the safe and efficient use of wake vortices in formation flying. The proposed procedure requires only minimal modifications to existing ICAO regulations, making it feasible for rapid integration into current air traffic management systems. Our solution involves several key components: sharing and negotiating adjusted flight plans, utilizing and fusing multiple types of sensors during the flight, and sharing the data collected by these sensors. For effective communication of flight plans, a high-throughput air-to-ground datalink is necessary. Additionally, for using and real-time sharing sensor data, a secure, low-latency air-to-air data link between formation partners is required, a technology that is currently unavailable.

We define specific requirements for these datalink systems at various stages of the proposed procedure using heuristic values to guide the design of the communication infrastructure. By combining the proposed formation flying phases, sensor fusion strategies, and the necessary data link requirements, we present a novel framework for integrating formation flying into civil aviation operations.

Index Terms—Wake Vortex Riding, Formation Flying, Fuel Saving, Civil Aviation Procedures, Sensor Fusion, Aeronautical Communications

I. INTRODUCTION

Saving fuel in aviation is not only a major goal for operational economics, but it is also contributing significantly to any efforts to green our planet. A very promising but hardly-researched method for this is formation flying, where

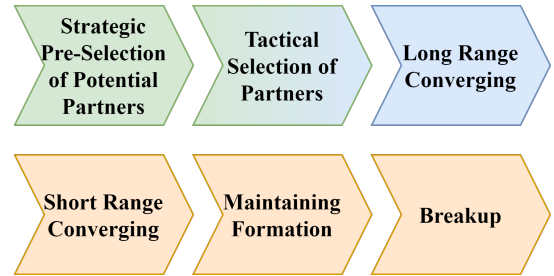


Fig. 1: The six-phase formation flying procedure divided into the three communication strategies **Preparation**, **Enroute**, and **Formation**.

uplifting air from the wake vortex is used by a following aircraft. Although the principle has been tested in practice with flight trials, there is, to the best of our knowledge, no method proposed to integrate this procedure into regular passenger air traffic.

To do this, existing safety standards have to be reshaped, as aircraft are currently not allowed to fly within a short distance after each other because of, next to collision avoidance, exactly those wake vortices. Their turbulence could severely disrupt airflow and therefore harm the structure as well as any people inside the aircraft. To integrate the whole process into commercial air traffic, precise procedures need to be defined which also involve novel sensor and communication techniques to maintain safety and security.

In this paper, we shed light on procedural aspects of integrating wake vortex riding as part of regular commercial air traffic, with a focus on adopting communication links suiting the needs of the respective phase of the flight.

Our work lays the groundwork for the smooth integration of formation flying into commercial air traffic. For this, we propose a well-structured procedure in three main phases with six sub-phases and derive from these the requirements for sensor usage and Air-to-Ground (A/G) as well as Air-to-Air (A/A) network data communication.

In Section II we introduce wake vortices, formation flying, and avionic communication systems. We explain how we

deduct phases and requirements from the envisioned application and necessary safety boundaries in Section III. In Section IV we explain the phases of formation flying in detail, which lead to the requirements to the communication channel calculated in Section V.

II. BACKGROUND

To perform a formation flight and use the wake vortices their exact location has to be known to the follower aircraft, safety must be upheld, and high-throughput communication links are needed. In this Section, we describe the state of the art with regards to modeling and detecting wake vortices (Section II-A), safety, economic, and procedural considerations for formation flying (Section II-B), and current (digital) communication systems (Section II-C).

A. Wake Vortices

Wake vortices, long-lived counter-rotating turbulence, exist in two phases: the diffusion phase and the rapid decay phase [1]. Holzäpfel et al. [1] predict the evolution of such wake vortices with a Probabilistic Two-Phase (P2P) model. It combines experimental and numerical wake vortex research. The model is built to include vortex strength and vortex evolution and consider the variability and uncertainty evolving from environmental conditions. Because of the nature of turbulence, vortices are deformed and transported in a stochastic manner, resulting in deterministic wake vortex predictions being infeasible for operational use, thus creating the need for a probabilistic model, according to Holzäpfel et al. [1].

In additionally to the potential emission saving by using the wake vortex upwind, formation flying is also better for the climate because two aircraft flying close behind each other generate in total less contrail [2].

A method to measure wake vortices is by the use of Light Detection and Ranging (LiDAR). Stephan et al. [3] combine the use of Pulsed Coherent Doppler LiDARs (PCDLs) with a computer vision deep neural network and a regression convolutional neural network to detect wake vortices individually with high accuracy.

B. Formation Flying

Airbus performed test flights during its project Fello'Fly validating the general feasibility of formation flying and showing the possibility to save up to 10% of fuel [4]. As a follow-up, SESAR project GEESE aims to further develop the implementation of formation flight procedures in the Atlantic and continental airspace [5].

Ewert et al. [4] review the safety and security implications for formation flying. The optimal position of the follower aircraft relative to a leading commercial aircraft such as an A340 or a B777 over the Atlantic is estimated [4] to be as follows:

- vertical: 50 - 100 ft below;
- lateral: 20 - 30 meters to the outside;
- longitudinal: 1.5 - 2.0 NM behind.

The optimal relative position, the so-called *sweet spot* [6], depends on various factors such as the wingspan, the speed of the aircraft relative to the air, and others.

To perform a formation flight procedure, aircraft involved in the formation need to meet enroute. Therefore, it is likely that a potentially longer route has to be flown by at least one of the two participating aircraft to be able to perform formation flying on a large portion of the route. Escarré et al. [7] model the fuel consumption for different approaches for two aircraft to meet in the air. They conclude that the most fuel savings can be achieved if not one aircraft flies towards the other while it keeps its original route, but both aircraft meet 'in the middle'. They estimate that 5-6% of flights in continental Europe could be used to conduct formation flights [8].

A higher percentage can be expected in oceanic airspaces, particularly over the North Atlantic, where more than 730,000 flights operate annually despite the absence of consistent radar or VHF voice coverage. To ensure safe and efficient air traffic management, procedures such as the North Atlantic Organised Track System (NAT-OTS) have been implemented, providing daily optimized routes for aircraft to follow. With the adoption of new technology standards, such as Performance Based Communication and Surveillance (PBCS) or Advanced Surveillance-Enhanced Procedural Separation (ASEPS), aircraft separation was significantly reduced, from 2,000 ft vertically, 60 NM laterally, and 10 minutes longitudinally to just 1,000 ft, 19 NM, and 14 NM respectively. While this increases airspace capacity, the utilized Communication, Navigation and Surveillance (CNS) systems, including ADS-B, remain vulnerable to cyber security threats [4].

C. Current Communication Systems

The main communication system in civil aviation remains voice communication over VHF [9]. Current digital air-to-ground communication alternatives include VHF Data Link Mode 2 (VDL-M2), which is used by Controller-Pilot Data Link Communications (CPDLC) [10]. However, VDL-M2 has a very low bandwidth and therefore low data throughput. Additionally, CPDLC has a very high latency in the order of 10 to 20 seconds [10]. As a modern alternative, the high-bandwidth air-to-ground communication system L-band Digital Aeronautical Communications System (LDACS) A/G is currently in its standardization phase at the International Civil Aviation Organization (ICAO) [11]. However, for its air-to-air pendant only proposals for OSI Layer 1 and 2 exist [12].

The current default for broadcasting aircraft's positions is Automatic Dependent Surveillance-Broadcast (ADS-B) [13]. Although this provides for situational awareness, it is known to be vulnerable with regards to its data integrity [4]. A type of communication that is completely missing is a high-throughput low-latency A/A communication method for setting up self-managed ad-hoc networks.

III. METHODOLOGY

The characteristics of wake vortices are well-documented in the literature, and their applications in formation flying for fuel conservation are widely recognized. In this study, we investigate the gap between the successful completion of flight tests utilizing wake vortices for fuel saving and the integration of formation flying into commercial aviation. Our analysis indicates that for wake vortex utilization, or formation flying, to be adopted in regular civil aviation, appropriate regulatory frameworks and operational procedures must be developed as these are currently nonexistent.

We propose a procedure consisting of six phases for implementing formation flying into commercial aviation. The six phases are as follows.

- A) Strategic Pre-Selection of Potential Partners
- B) Tactical Selection of Partner
- C) Long-Range Converging
- D) Short-Range Converging
- E) Maintaining Formation
- F) Separation

The procedure is tailored such that only minimal changes to ICAO safety regulations are needed whilst upholding the current safety standards. The individual phases are elaborated in Section IV. Each phase has specific environmental requirements, such as the need for data availability and robust communication links with predefined bandwidth and latency constraints. In particular, for Phases D and E, which represent the core formation flying stages, we recommend using a combination of multiple sensors integrated with a high-throughput, low-latency air-to-air data link. This datalink would facilitate the exchange of crucial data, including aircraft positions, steering control, and intended flight paths. The combined use of multiple sensors and an air-to-air datalink are further described in Section IV-E.

Through this, we identify the technical requirements for such an air-to-air data link. Our findings suggest that no current datalink solution meets these specifications, indicating the need for the development of a new communication system tailored to the demands of formation flying in civil aviation. The calculations that form the basis for the identified requirements for the air-to-air datalink are further described in Section V.

IV. FORMATION FLYING PHASES

In this Section, we introduce the six phases of our proposed formation flying procedure. Per phase, we describe its characteristics from which we deduce challenges and requirements to the environment and communication links that we then propose solutions to.

A. Strategic Pre-Selection of Potential Partners

The initiation of the formation flying procedure requires the identification of suitable partner aircraft. This process involves the analysis of flight plans to determine candidate flights that are expected to operate concurrently on the same route, at the

same altitude, and in the same direction, thereby maximizing the duration of the potential formation flight.

A prerequisite for this step is the exchange of flight plan data among participating airlines. Such data sharing enables the identification of optimal pairings based on temporal and spatial alignment. However, one significant issue to be addressed is the impact of delayed departures, which can substantially disrupt pre-planned formations and reduce the feasibility of coordinated flights. Additionally, the partner selection must account not only for route and timing compatibility but also for cost-benefit analyses, potentially placing high demands on computational resources.

Our proposed solution focuses on maximizing the fuel-saving potential of formation flying by targeting long-haul flights, where the benefits outweigh the associated operational overhead. In contrast, for short-haul or continental flights, the additional complexity and limited formation duration may render the approach economically unviable. Consequently, we propose implementing formation flying primarily along the North Atlantic Tracks (NATs), also known as NAT-OTS, which are well-suited to this concept due to their structured nature and well-defined entry and exit points, calculated daily. These fixed points can serve as initiation and termination points for the formation flying procedure.

Given that many transatlantic flights operate on regular schedules, often recurring daily or weekly at similar times, most cost-benefit analyses need to be conducted only once per route pairing. Subsequent calculations are required only for newly added or modified flights, significantly reducing the computational burden.

To further enhance operational robustness and mitigate the impact of in-flight delays, we propose the pre-selection of multiple formation partners across a range of delay scenarios. This multi-scenario planning ensures that, even in the presence of deviations from the expected schedule, viable alternative formation pairings remain available, thereby maintaining the feasibility and efficiency of the procedure.

B. Tactical Selection of Partner

Building upon the previous phase and the now-completed takeoff, the real-time trajectory of each aircraft becomes predictable within a defined accuracy margin. This updated positional and temporal information enables the identification of the most suitable partner for formation flying, initiating the agreement and coordination process for that specific aircraft pairing.

To support a dynamic partner selection between aircraft (potentially) still far apart from each other, a secure high-throughput A/G communication link is required. This link must facilitate the continuous exchange of up-to-date flight data from all potential partners identified in the pre-selection phase. As pre-flight planning data may quickly become outdated due to operational variations, reliance on real-time information is critical. The volume and frequency of data exchange, including not only positional information (e.g. via ADS-B) but also updated flight trajectories and intent, requires

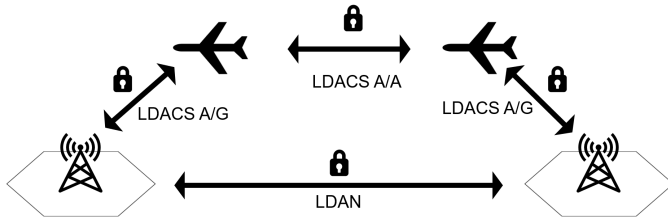


Fig. 2: Schematic LDACS A/G and A/A infrastructure.

a robust communication infrastructure capable of handling high data rates securely and reliably.

While optimal partner selection algorithms can be executed on ground-based infrastructure during the continental flight phase, the transition to oceanic airspace introduces additional challenges. Beyond the range of terrestrial communication networks, data exchange must be maintained through alternative means. This can be achieved either via Satellite Communication (SATCOM) or through the establishment of ad-hoc A/A networks between aircraft. These communication channels must meet tight requirements for latency, bandwidth, and security as well as range to support the time-critical coordination necessary for safe and efficient formation flying. For instance, ADS-B has a range limit of about 250 nautical miles.

The timely selection of a suitable formation flying partner requires that all candidate aircraft continuously update their operational status. While position data broadcast via ADS-B provides a foundational layer for situational awareness, it is insufficient on its own for precise and reliable partner selection. At this stage of the procedure, at least one aircraft is already airborne, requiring the transmission of a wide range of dynamically changing data, including real-time trajectory updates, speed adjustments, and flight intent, between the ground infrastructure and multiple aircraft. To support this high-volume, time-sensitive data exchange about a potentially large list of selection candidates, we propose the use of LDACS A/G as it offers the necessary throughput and latency characteristics to accommodate the dynamic data demands of this phase.

As the aircraft are still expected to be operating within continental airspace at this point, A/G communication via LDACS should remain available. However, if direct A/G connectivity is degraded or unavailable, e.g. when approaching oceanic regions such as the entry to the NATs, alternative communication methods must be used. These may include extending LDACS coverage via airborne relay using A/A networking (see Figure 2) or transitioning to SATCOM, provided that the chosen system satisfies the data throughput and reliability requirements.

The final selection of a formation flying partner may be computationally demanding, as it requires the evaluation of multiple dynamic parameters, including updated trajectories, aircraft performance, and cost-benefit considerations. To manage this computational demand effectively, we propose offloading the partner selection process to dedicated ground-based

infrastructure if possible. This infrastructure can aggregate and process real-time data from multiple aircraft, subsequently communicating the optimal pairing recommendations to the relevant participants via a high-throughput A/G communication link.

In scenarios where ground-based infrastructure is no longer available, such as during extended oceanic operations where A/G connectivity is inaccessible, partner selection must be conducted locally onboard the aircraft. However, in such cases, the computational complexity is probably significantly reduced, as only a limited number of aircraft are expected to be within the communication range of an ad-hoc A/A network. Consequently, the number of potential formation partners is smaller, simplifying the decision-making process.

This phase also includes the negotiation process between the selected aircraft pair. During this negotiation, the aircraft agree on the specific parameters of the formation flight, including the designated entry and exit points, the assignment of roles (i.e. leader and follower), and, if operated by different airlines, the terms of economic compensation to ensure mutual benefit. This compensation accounts for the asymmetry in fuel savings, as only the trailing aircraft benefits from the reduced drag.

C. Long-Range Converging

In cases where two aircraft selected for formation flying share a substantial portion of their planned route but originate from different departure airports, at least the following aircraft must perform a coordinated maneuver to position itself behind the designated lead aircraft. This convergence maneuver is conducted such that the trailing aircraft positions itself near the lead aircraft to a proximity close to the minimum separation distance currently permitted under ICAO regulations.

A prerequisite for this maneuver is the prior agreement on a common entry point during the negotiation in the previous phase. Both aircraft must be capable of proceeding toward this predefined point and be authorized by Air Traffic Control (ATC) to do so. Although it would suffice for the entry point to be on the lead aircraft's original route, optimal fuel saving can be achieved if both aircraft deviate from their original route, as described in Section II-B. Throughout this phase, all coordination and navigational instructions continue to be managed via standard ATC communication protocols, ensuring compliance with existing Air Traffic Management (ATM) procedures and maintaining flight safety.

Unanticipated deviations in takeoff times can only be compensated to a limited extent by adjusting airspeeds enroute. As a result, even after a carefully planned and agreed-upon partner selection, the conditions required for formation flying may no longer be achievable. Furthermore, the success of this phase is heavily dependent on the cooperation and operational flexibility of ATC. If ATC, for any reason, such as traffic flow optimization or airspace restrictions, chooses to reroute one or both aircraft in a way that prevents spatial and temporal convergence, the feasibility of formation flying is compromised, and the procedure may have to be aborted. For this reason, it is highly advisable that ATC knows the intention of formation

flying at a later stage through an indication in the already filed flight plan.

Once a formation partner has been selected, ATC needs to be immediately notified of the decision. ATC is then responsible for facilitating the coordinated guidance of both aircraft toward the predefined entry point, ensuring that they arrive within a sufficiently narrow time window to enable the formation flying procedure. Beyond the environmental benefit of reduced fuel consumption and emissions, an additional incentive structure could be considered to encourage ATC participation. Specifically, Air Navigation Service Providers (ANSPs) could receive a portion of the economic savings resulting from successful formation flights, thereby aligning operational priorities with broader sustainability goals.

D. Short-Range Converging

At the beginning of this phase, the two participating aircraft establish a dedicated A/A communication link. This connection is a critical safety component of the formation flying procedure, as it enables the exchange of real-time flight data and control commands. To enable continued convergence, this A/A link will be used in subsequent phases to transmit not only planned routing and ATC clearance limits, but also continuous positional and precise maneuvering input, including vertical, lateral, and speed adjustments from the lead aircraft to the follower. These transmissions allow the trailing aircraft to automatically and promptly respond to changes in the lead aircraft's trajectory, ensuring both synchronized and safe operation within the reduced separation distances and aerodynamic efficiency.

To meet the safety and performance requirements, the A/A communication link must support high-throughput data exchange (5 kbit/s per aircraft pairing) and low latency (≤ 100 ms) as described in Section V-B. Additionally, robust security features, including authentication and integrity verification, must be an integrated part of the communication link to safeguard against data corruption or unauthorized interference, without compromising the earlier-mentioned performance requirements.

Currently, there is no communication system established that satisfies these combined requirements for A/A links in civil aviation. Furthermore, frequency allocation poses a significant challenge, as the available spectrum for such communications varies across regions. Due to the strict latency constraints, any required handover or frequency transition during active formation flight could introduce unacceptable delays or interruptions, potentially compromising the safety of the maneuver. As such, careful consideration must be given to the design of both the communication architecture and its global regulatory framework to ensure reliable and consistent performance throughout the formation flying procedure.

At present, no secure A/A communication datalink exists that fully meets the requirements identified in Section V. To address this critical gap, we propose the adoption and further development of LDACS A/A. As it is currently under development, it presents itself as a unique opportunity to

be tailored to the specific demands of formation flying. By integrating formation flight support into the ongoing design and standardization of LDACS A/A, it is possible to ensure that the system can deliver the required throughput, low latency, and security features necessary for safe and efficient operation of this novel flight concept.

The radio frequency spectrum is a limited and highly regulated resource, with different frequency bands allocated and utilized variably across global regions. Consequently, the availability of suitable frequencies for an A/A datalink may vary depending on geographic location, presenting a potential challenge for the implementation of a globally consistent formation flying procedure. However, the primary intended area for formation flying over the Atlantic Ocean offers a favorable environment for spectrum allocation. Compared to densely trafficked continental airspaces, the radio frequency usage over oceanic regions is significantly lower. This creates an opportunity to implement a dedicated frequency band for LDACS A/A in this area.

We propose a frequency allocation strategy in which existing and planned LDACS A/G resources are utilized within continental airspace, while a separate, dedicated frequency band is reserved for LDACS A/A in oceanic airspace. This dedicated frequency would be activated upon exiting continental airspace and used throughout the entire formation flight segment. This approach implies that the critical Short-Range Convergence maneuver must be executed within the oceanic region. This constraint arises from the requirement for a secure, high-throughput, low-latency A/A datalink for operating at reduced separation distances.

After establishing a secured short-range communication link between the two aircraft involved in the formation, the aircraft are allowed to converge to separation distances aiming for the sweet spot, which are below the current minimum standards prescribed by ICAO. To ensure safety while entering close proximity, the follower aircraft must execute a controlled and deliberate approach toward the lead aircraft. As wake vortices are known to descend at an average rate of approximately 500 ft/min and gradually increase in size over time, the safest trajectory for this maneuver is from above or the same level, behind, and offset laterally.

Throughout this maneuver, the reliability of the A/A communication link is essential as it enables the continuous exchange of real-time steering and intent data between the aircraft, allowing the follower to precisely mirror the lead aircraft's trajectory. In the event of a short-term communication disruption, the follower must be able to rely on the lead aircraft to maintain a stable course and heading. Any unanticipated deviation during such a failure could expose the follower to wake turbulence and pose a significant safety hazard.

To enable precise and safe proximity during formation flight, accurate prediction of the wake vortex location is essential. We propose a three-step hybrid approach that combines wake vortex models, such as those developed by Holzäpfel et al. [6] with real-time air measurements. In the first step, the model is used in combination with the received location

data to predict the region where the wake vortices are most likely located. While closing into this predicted zone, onboard LiDAR can be employed in a second step to directly detect and track the wake vortices. During this phase and subsequent phases, LiDAR measurements are complemented in the third step by airflow sensors to provide additional data on local aerodynamic disturbances. These sensor modules are discussed in greater detail in Section IV-E.

Throughout the Short-Range Converging phase, the A/A communication link plays a central role in ensuring safety by enabling the continuous exchange of positioning, velocity, and steering commands between the lead and following aircraft. In the event of a temporary failure of the A/A link, a predefined fallback mode must be activated to preserve safe separation. In this fallback mode, the lead aircraft is required to maintain a constant heading and flight path for a predetermined time interval, calculated based on the estimated distance to the trailing aircraft. This stability allows the follower aircraft to initiate a controlled retreat to restore a safe separation margin. Given that the follower is typically approaching from behind, offset laterally, and potentially from a higher altitude, the retreat maneuver should be executed by slightly reducing airspeed and ascending. This path mirrors the approach trajectory in reverse, minimizing the risk of wake encounters. If the A/A communication link is reestablished, the approach may either resume from the current state or be restarted from a safer distance, depending on the operational context.

E. Maintaining Formation

After achieving the formation flight configuration, the relative position of the trailing aircraft with respect to the wake vortex of the lead aircraft must be accurately maintained, which is critical, particularly in the lateral and vertical axes. While the longitudinal separation, i.e., the distance between the lead and following aircraft, allows for relatively large tolerances on the order of several hundred feet, the lateral displacement and altitude must be controlled within a margin of only a few feet. Deviations beyond these tight tolerances can result in the trailing aircraft encountering significant wake turbulence, potentially compromising flight stability and safety. Therefore, for this phase higher-precision measurement techniques are required. We propose a sensing fusion approach based on a combination of LiDAR and dedicated airflow measurement modules to achieve the necessary spatial resolution for safe and stable formation flight.

Using LiDAR, the trailing aircraft can detect and precisely locate the wake vortex. LiDAR also facilitates continuous monitoring of vortex dynamics, including positional shifts over time.

We further propose to integrate dedicated airflow sensors mounted on the wings of the trailing aircraft. These sensors are capable of measuring directional wind speeds, thereby allowing for the precise determination of the aircraft's relative position within the wake vortex. Figure 3 illustrates a possible configuration of the sensor array. The red arrows symbolize the directional sensors and the blue lines and arrows symbolize

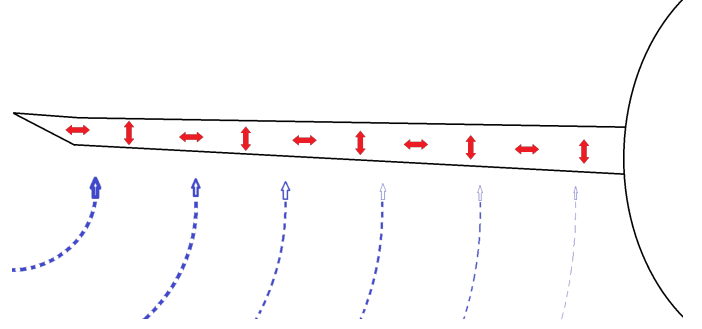


Fig. 3: Airflow sensors on the wing to measure the position within the wake vortex.

the moving air from the wake vortex. This setup is designed to precisely capture the local airflow over the wing and thereby calculate the aircraft's position with respect to the wake vortex. This enables the trailing aircraft to optimally exploit the aerodynamic upwash generated by the wake vortex, leading to substantial fuel savings.

While each option is expected to be effective on its own, the combined application of both LiDAR and airflow sensors is anticipated to yield improved robustness and positioning accuracy and therefore increased safety and fuel savings.

F. Separation

Once the exit point is reached or operational constraints require it, the active formation flight procedure must be safely terminated. Under nominal conditions, the trailing aircraft exits the formation by increasing the separation distance from the lead aircraft, typically through a controlled reduction in airspeed of the trailing aircraft, allowing it to fall behind to a safe distance. However, in time-critical scenarios such as e.g. emergencies involving either aircraft, this standard procedure may not provide a safe exit strategy. In particular, relying solely on deceleration could be hazardous if the lead aircraft is forced to unexpectedly reduce its airspeed or climb, potentially resulting in insufficient separation. In such cases, alternative exit maneuvers that ensure rapid and safe disengagement from the wake region may be required to maintain flight safety.

The termination of the formation flight procedure can occur via two modes: planned separation and unplanned separation.

1) *Planned Separation*: upon reaching the predefined exit point, planned separation is initiated. This exit point is determined and agreed upon during the tactical selection phase as described in Section IV-B. Since the maneuver into formation is typically achieved through lateral convergence, the separation maneuver is performed in reverse. By slightly reducing its airspeed, the trailing aircraft gradually increases its longitudinal distance from the lead aircraft, thereby restoring standard separation minima and ensuring compliance with established safety margins. If cleared, the trailing aircraft may additionally increase its altitude to switch to another cruising level or deviate laterally. Alternatively, and by instruction of ATC, the lead could be ordered to descend by at least 1,000 ft to another

flight level, which is considered a safe vertical separation in ordinary ATC procedures.

2) *Unplanned Separation*: in contrast to planned separation, unplanned separation is more complex and highly context-dependent. Such a maneuver may be necessary because of, e.g., a prolonged loss of A/A connectivity or an emergency involving either aircraft. In these situations, it is critical that the trailing aircraft exits the wake vortex region rapidly yet in a controlled manner to avoid hazardous turbulence. A suitable escape maneuver for the following aircraft involves climbing vertically to a higher flight level (typically 1,000 feet above the current altitude) and/or laterally deviating away from the lead aircraft's flight path. This maneuver must be performed without infringing on adjacent airways, thereby maintaining airspace integrity and traffic separation.

An additional risk that must be considered is the potential deviation by the lead aircraft, accidental or intentional, from the agreed-upon flight plan. Since the formation flight procedure relies on the trailing aircraft autonomously maintaining its position relative to the lead aircraft, such a deviation could inadvertently lead the trailing aircraft into restricted or unauthorized airspace. To mitigate this risk, the trailing aircraft must continuously monitor its geographic position and heading, as well as those of the lead aircraft. These real-time measurements should be cross-referenced with the pre-defined flight plan to perform continuous plausibility checks. This ensures that any significant divergence from the planned route can be detected promptly, allowing for corrective action to maintain regulatory compliance and operational safety. This also mandates a secured communication A/A link, ensuring proper authentication mechanisms before relying on the data as input for the flight controls.

V. ANALYSIS

We identify three communication strategies for the six formation flying phases. These are shown in Figure 1 and can be summarized as follows.

- 1) Preparation (Phases A-B);
- 2) Enroute (Phases B-C);
- 3) Formation (Phase D-F).

In this Section, we describe the characteristics of these communication strategies and the cybersecurity measures necessary to ensure the safe operation of formation flying throughout the procedure. From the strategies, we deduce the data properties needed in different phases and thereby define requirements for the different communication links, such as data throughput and latency.

A. Communication Strategies and Cybersecurity

1) *Preparation, Phases A-B*: there needs to be a detailed multi-party data exchange between ATC and all participating airline operators. This could be achieved with a dedicated database controlled by, e.g., European Organisation for the Safety of Air Navigation (EUROCONTROL) on top of the flight plan management system as currently deployed. As the preparation of formation flights can take place weeks

or even months before the actual flight, infrastructure-based communication systems can be used.

So far, the flight plans submitted by the airline operators do not have to be cryptographically signed for integrity, authentication, and non-repudiation purposes. However, this would be an additional benefit not only for formation flying but also for other means to establish trust and reliability in the data contained.

2) *Enroute, Phases B-C*: once an aircraft commences off-block, it needs to keep updating its situation to a centralized facility so that other aircraft can adjust their tactical selection based on this data, as well as the other way around the aircraft needs this data of other aircraft to perform its own tactical selection of a partner. Data to be sent may e.g. include currently assigned departure routes, clearance limits, airways, and altitude restrictions. The aircraft is either at the gate, taxiing, or airborne, and therefore digital aeronautical communication systems are needed. As a lot of data needs to be sent in both directions for the negotiation in the tactical selection, the datalink needs to be high-throughput. A promising candidate for this is LDACS A/G, as it will provide a secured high-throughput connection between the aircraft and ATC. Additionally, the certificates from LDACS A/G's Public Key Infrastructure (PKI) can further be used to later establish a secure A/A connection. A schematic of connections in an LDACS environment is shown in Figure 2. Using LDACS A/G, the integrity of authenticated data can already be verified. However, for establishing trust in the flight plans and ensuring non-repudiation, these need to be signed by both the airline operator and ATC.

To have both, lead and follower, benefit from formation flying to a maximum extent, both may have to divert from their initial filed plans to an agreeable extent as described in Section II-B, which requires active consent. However, a minimum agreement could be the indication of a potential lead to its willingness to act as a lead in its flight plan. For this procedure, no later active consent would be required, but restrictions in instantaneous maneuvers apply.

Once an agreement between two partners has been reached, the Long Range Converging will begin. For this phase, hardly more communication than currently already existing between the aircraft and ATC is to be expected. LDACS A/G will be available in continental regions, which will most likely suffice to successfully perform this phase. ATC will make sure both partners of the formation are brought together following classical ATC procedures close to the safety limits.

3) *Formation, Phases D-F*: at the beginning of the Short Range Converging phase, a secured high-throughput low-latency A/A datalink is to be established between the two aircraft. Its purpose is to directly exchange location data, steering control data, and flight path intent from the leading aircraft to the following aircraft. This data is being sent continuously with non-balanced resource usage (as the lead mainly transmits whereas the follower mainly receives) throughout the Short Range Converging and Maintaining Formation phases. In case of planned separation, also here the A/A datalink will be main-

tained until standard separation minima are restored. In phases D to F, it is of utmost importance for the safety of both aircraft that any data sent is authenticated and integrity checked within the low-latency requirements. It therefore needs to be signed by the sender, be it the lead or the follower. Otherwise, deliberately injected false information could directly lead to a fatal crash mid-air. However, currently, no datalink meeting these requirements exists.

As mentioned in Section IV-E, the most challenging part of positioning the follower in the sweet spot is lateral, not longitudinal. Being a few meters left or right of the sweet spot makes a huge difference. This is partly accounted for by the two different sensor systems used to measure the accurate uplift, but also the main reason for the short-range communication link to provide information about any change in steering input at the lead before it actually affects the steering controls of the aircraft, resulting in a change of the wake vortices. Reacting to change in relative position by differentiating the absolute position of both aircraft (e.g. determined by Global Navigation Satellite System (GNSS) and transmitted by ADS-B) is simply too slow.

B. Data Estimates and Requirements

1) *Air-to-Ground*: there are roughly 730.000 NAT flights per year, which are on average 83 per hour. As most aircraft fly westwards during the day and eastwards during the night, we consider that this and the filtering of aircraft flying in the same direction cancel each other out for this estimation. We consider a time window of 2 hours for potential candidates, consisting of 0.5 hours before and 1.5 hours after Calculated Take-Off Time (CTOT). The average size of a NAT flight plan is ca. 5000 Byte = 40 kbit. In Phase A, an aircraft needs thus to send an amount of 40 kbit, but receive potentially about $2 * 83 * 40 \text{ kbit} = 6.6 \text{ Mbit}$ if this phase is performed locally. These flight plans then form the basis for the next phase, the Selection of a Partner.

In Phase B, assuming realistic Off-Block times of 0.5 hours earlier and 0.5 hours later than itself, we compare data of the 40 other aircraft with our own and start negotiating. The flight plans of other aircraft are now already known. However, real-time trajectory updates, speed adjustments, and entry and exit point negotiations need to be sent and received by the aircraft, resulting in roughly $40 * 40 \text{ kbit} = 1.6 \text{ Mbit}$ of data to be submitted in this phase. Although the delay of the data should remain as low as possible to enable a productive negotiation, it is not strictly time-critical. However, this data needs to be sent on top of any other regular A/G data such as weather, FMS input, or taxi data.

2) *Air-to-Air*: considering that a typical commercial aircraft such as a B777 is traveling at about 800 km/h performing a standard turn with a rate of 2 min. / 360 degree, that translates into 3 deg. per 222 m traveled, which is a lateral movement of 12 m in one second. If the distance between the peak uplift and the turning point in the vortices is about 3m, we derive the need to know any lateral change with at least 10 Hz and a delay limit of 100ms.

A potential approach to estimating the amount of data to be transmitted from the lead is to consider the ADS-B message format, thus 'ADS-B over LDACS' as a basis. The part of an ADS-B message that holds the information on the whereabouts of an aircraft, also known as Airborne Position Message or Extended Squitter, has a length of 56 bit [13]. ADS-B needs two subsequent messages to get decoded, i.e. 112 bit. Therefore, for an update rate of 10 Hz, such messages would result in $10 * 112 \text{ bit} = 1.1 \text{ kbit/s}$. However, due to the nature of encoding in ADS-B messages, the altitude is always rounded to a multiple of 25 ft (7.62 m), which is thereby the precision. Although this is precise enough for Phases A to C, it is not precise enough for the actual formation flying Phases D and E. Although ADS-B over LDACS as such may be a good idea for different purposes, it will not suffice for the formation flying procedure.

To encode latitude and longitude in degrees with both sub-meter precision, we need 25 bit and 26 bit respectively. Assuming that altitude is sent in feet, which is thereby its precision, we can allocate 20 bit for it, which results in a maximum encodable altitude of 1048576 ft or 319606 m. Airspeed and GNSS-speed can both be encoded in kt with 12 bit each. This gives a total message size of $25 + 26 + 20 + 12 + 12 = 95 \text{ bit}$. Now we add an estimated 33 bit to properly encode the steering angle for bank, pitch, and roll. This sums up the actual flight data message size to 128 bit. However, for operational and security constraints, a timestamp with sub-second precision (+4 bit) and longer support (roughly 1000 years, thus +4 bit) shall be added to each message for enforced freshness: $32 + 4 + 4 = 40 \text{ bit}$. Then a cryptographic signature is added, e.g. 128 bit or 256 bit, depending on the desired security level. This results in $128 + 40 + 128 = 296 \text{ bit}$ or $128 + 40 + 256 = 424 \text{ bit}$ per message respectively. With an update rate of 10 Hz, this results in a minimum requirement of $\lceil 296 \text{ bit} * 10 \text{ hz} \rceil = 3 \text{ kbit/s}$ and $\lceil 424 \text{ bit} * 10 \text{ hz} \rceil = 5 \text{ kbit/s}$, respectively to the A/A communication link for each aircraft pairing. To scale this procedure to multiple concurrent pairings, different frequency channels should be used. According to Bellido et al. [12] usually over 60 different frequency channels are available when using LDACS A/A, thus supporting at least 60 concurrent aircraft pairings in one region.

VI. CONCLUSION

We proposed a six-phase protocol for safe and efficient formation flying procedures to be applied in civil commercial aviation. We discussed challenges that may arise that could potentially inflict upon the safety of the procedure and proposed solutions using a combination of multiple sensors and secure high-throughput low-latency digital communication links. By using estimations based on already existing systems, we calculated realistic requirements for a potential future A/A communication link that include security, throughput, and latency.

Future work may further investigate separate formation flying phases in-depth and further define the A/A link needed for safe and secure formation flying procedures.

ACRONYMS

A/A	Air-to-Air
A/G	Air-to-Ground
ADS-B	Automatic Dependent Surveillance-Broadcast
ANSP	Air Navigation Service Provider
ASEPS	Advanced Surveillance-Enhanced Procedural Separation
ATC	Air Traffic Control
ATM	Air Traffic Management
CNS	Communication, Navigation and Surveillance
CPDLC	Controller–Pilot Data Link Communications
CTOT	Calculated Take-Off Time
EUROCONTROL	European Organisation for the Safety of Air Navigation
GNSS	Global Navigation Satellite System
ICAO	International Civil Aviation Organization
LDACS	L-band Digital Aeronautical Communications System
LiDAR	Light Detection and Ranging
NAT	North Atlantic Track
NAT-OTS	North Atlantic Organised Track System
OSI	Open Systems Interconnection
P2P	Probabilistic Two-Phase
PBCS	Performance Based Communication and Surveillance
PCDL	Pulsed Coherent Doppler LiDAR
PKI	Public Key Infrastructure
SATCOM	Satellite Communication
VDL-M2	VHF Data Link Mode 2

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