# USES OF A CLOUD-BASED FLIGHT MANAGEMENT SYSTEM TO ENHANCE AIRSPACE EFFICIENCY

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## Abstract

This paper qualitatively explores a Cloud-based Flight Management System, which is a digital twin of an FMS. The Cloud FMS (CFMS) is a type of digital twin that is hosted on a cloud computing environment. Because the CFMS has access to the state of the aircraft on which the FMS is running, it contains a wealth of information not normally available to ground-based aviation systems. In addition, the CFMS can access large amounts of compute power that is unavailable to the flight-deck based FMS. Therefore, the CMFS is in a unique position to compute quantities that were impractical in the past. This paper begins by discussing the CFMS concept some use cases. It ends by discussing additional quantities—such as wake vortex and noise footprints—that can be computed by the CFMS and may lead to enhanced NAS efficiency.

## Introduction—What is Cloud FMS?

The CFMS concept has been previously published [1]. To set the context for the remainder of this paper, we summarize some of that previously published work in this section. The Cloud FMS concept requires that some of the functions of an on-board FMS be duplicated in the cloud environment. A preliminary assessment indicates that non-safety-critical functions are candidates for duplication. Such functions involve flight planning, trajectory prediction, aircraft performance, and some navigation data. Functions associated with controlling the aircraft remain with the onboard FMS and are inaccessible from the cloud environment.

The Cloud FMS concept could benefit several areas of commercial aircraft operation, such as trajectory synchronization, trajectory negotiation, and time-based operations. Urban Air Mobility (UAM) operations could benefit from CFMS in the areas of trajectory negotiation, exchange of rerouting information between the Provider of Services for UAM (PSU) and the UAM operator, exchange of urban wind information, and during unplanned entry into controlled airspace.

Trajectory negotiation for commercial carriers is a component of Trajectory-Based Operations [2]. The need for trajectory negotiation may be driven by airspace constraints (e.g., en route or arrival congestion), by weather constraints (e.g., unforeseen severe thunderstorms), or by other factors (e.g., airline business considerations).

In this use case, the flight crew uses a Trajectory Negotiation application residing on its EFB that communicates with the Cloud FMS to identify and consider alternate routes with respect to the current flight plan. The Cloud obtains the current flight plan from its Airline Operations Center (AOC) via the IP datalink. Using the EFB, the flight crew sends ranked alternatives to the Cloud, which analyzes the alternatives based on a variety of criteria (e.g., flight time, distance to destination, forecasted weather) and provides viable trajectory options to ATC, as well as both the flight crew and its FOC. The flight crew and FOC review the options and coordinate via the Cloud to agree upon the option that best meets the overall business objectives of the flight. After a decision has been made, the flight crew reviews the updated flight plan, acknowledges the flight plan with a CPDLC message, and autoloads the flight plan into the FMS.

## Benefits of Cloud FMS

The CFMS concept specifies that there is one CFMS instance per flight, but only some of the flights have a CFMS instance. The concept does not assume that all aircraft have the CFMS digital twin. Nevertheless, for those aircraft that do possess the CFMS, there are some benefits.

The CFMS is immersed in a unique environment. It has access to most of the quantities from the onboard FMS. It has access to almost unlimited compute power and memory storage on the ground. It has access to web-based services supplied by the Federal Aviation Administration (FAA). And finally, it has access to the airline's operations center, which can provide business constraints to CFMS.

Although the CFMS has access to some sensitive variables in the cockpit (such as the aircraft's weight), only a subset of these variables is exposed to other web-based processes. Therefore, a CFMS instance representing one flight from one airline cannot access sensitive variables from a CFMS instance from another flight by a different airline. Non-sensitive variables, such as position, heading, trajectory intent, and so forth, will be accessible from processes outside a given CFMS instance.

Cybersecurity is a looming issue with the CFMS concept. As far as this paper is concerned, we are assuming that cybersecurity has been "solved" and that CFMS instances are secure from cyberattacks. We assert this claim so that we continue investigating the benefits and uses of CFMS, without specifying *how* such cyber protections will be implemented.

Given this background, the main benefit of the CFMS concept is that it has a ubiquitous view of the current traffic situation, access to the current state of the "ownship," and nearly infinite computing resources. To be more specific, here is a partial list of the quantities that CFMS has access to:

- The Cloud FMS has the most up-to-date current and forecasted weather information which it can upload to the pilot's EFB when needed.
- The Cloud FMS also has access to expanded, more detailed weather information that simply cannot be stored in the flight deck FMS component.
- The CFMS has access to current air traffic control restrictions and status information.
- The Cloud FMS has access to all current flight positions, velocity vectors, and intent information that it can use to identify conflict-free alternative routes.
- The Cloud FMS trajectory negotiation module can be updated as often as necessary, as opposed to updating dozens or hundreds of FMS trajectory negotiation modules were they to reside onboard aircraft.
- Important algorithms, such as trajectory prediction, can be common to all instances of CFMS. These common algorithms avoid problems in cross-coordinating different versions of an algorithm that may otherwise reside aboard diverse aircraft. Multiple versions of an algorithm can cause problems when, for example, different algorithms provide different answers for computations such as conflict probe, conflict resolution, monitor alert predictions, and so forth.
- The interface between CFMS and the flight deck can be "thin," whereas the interface with other CFMS instances can be "thick." Computations that involve a lot of data exchange can be performed among the CFMS instances, with just the result being transmitted to the cockpit. This results in efficiency of communication channel usage without sacrificing aeronautical computations.

## CFMS Architecture

A reference architecture for the CFMS concept is shown in Figure 1.

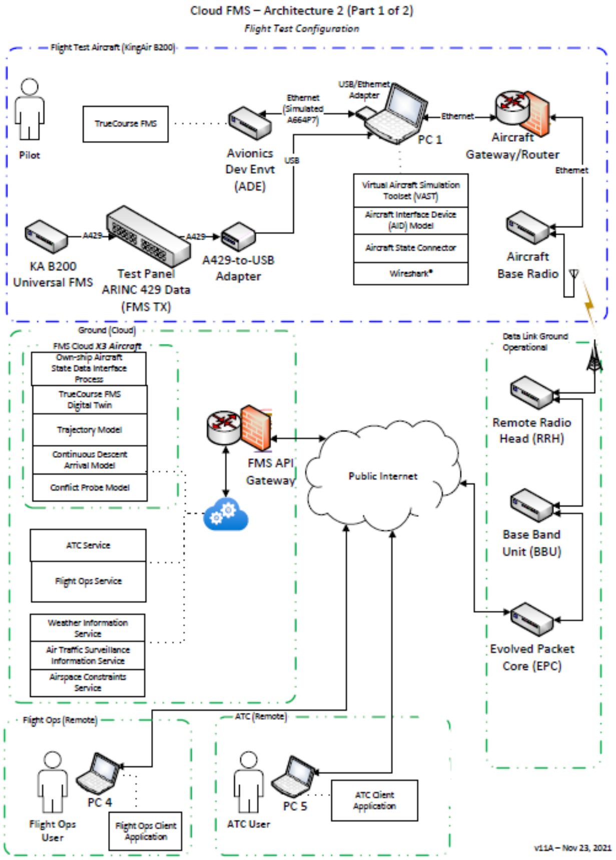

**Figure 1. Cloud FMS Reference Architecture**

In Figure 1, the top part represents the flight deck. The middle-left sequence (left of the "public internet") represents the CFMS digital twin. Right of the "public internet" represents the communication link from the aircraft to the CFMS instance. The very bottom of the diagram represents two other connections, one connecting the CFMS to an airline operations center (“flight ops” in the diagram) and another connection the CFMS to ATC.

Implicitly shown in the figure is the CFMS connection to the public internet. Through that connection, CFMS can access voluminous data about flights. These data include surveillance information, weather information, National Airspace System (NAS) status information, and so forth.

## Uses of CFMS to Increase NAS Efficiency

One of the intriguing questions surround the CFMS concept is whether it can be used to enhance operations in the NAS. In other words, besides improving current NAS operational procedures, can it add new capabilities to the NAS that it currently lacks? We will explore the answer to this question in this section.

Most surely the CFMS concept can bring new capabilities to the NAS, because it is an entirely new way of organizing flight information such that proprietary safeguards are in place while allowing greater participation in critical computations.

One possibility is the computation of the ownship’s wake turbulence. Per the FAA’s wake turbulend definition, “Every aircraft generates wake turbulence while in flight. Wake turbulence is a function of an aircraft producing lift, resulting in the formation of two counter-rotating vortices trailing behind the aircraft” [3]. The strength of the vortices is directly related to the weight of the aircraft. For heavier aircraft, more lift is needed, which generates stronger vortices than lighter aircraft. But the strength of the wake vortex is also affected by the speed, wingspan, and shape of the ownship’s wing.

These variables—the ownship’s weight, its speed, and its overall geometry (wingspan and shape) are all known to the CFMS instance assigned to that aircraft. In contrast, the ownship’s weight is unknown to other processes and is currently absent from any downlinked data from the aircraft (although there are proposals to add weight to data linked messages). The CFMS can be instantiated with the aircraft’s wingspan and shape from engineering diagrams created by the manufacturer. These variables—weight and aircraft geometry—can be kept private within each CFMS instance if the data are considered proprietary or sensitive.

In addition, the CFMS has access to wind data. The wind speed is computed by the onboard FMS and can be part of the state duplicated by the CFMS. But the CFMS also has access to the wind data computed by surrounding, nearby aircraft, and therefore can construct a wind field in the vicinity of the ownship. This wind field is likely to be very accurate and detailed. The wind field determines how quickly wake turbulence will fade into the atmospheric background, and whether it will rise, or fall, or stay level as the aircraft travels. While wake turbulence is affected by gravity and will drift downward, under certain atmospheric conditions it can stay aloft longer than expected and, although unusual, it can rise as well.

Having access to all this data and having access to compute power that exists on the ground, the CFMS instance can accurately compute the ownship’s wake turbulence. There are many studies and publications, and software implementations, of wake turbulence computations. Traditionally the methods to compute it have been slow, but recently techniques to speedup the computation have been appearing in the literature (see, for example, [4]).

If the CFMS can accurately compute the ownship’s wake turbulence, and furthermore can compute the direction the turbulence will move (down, up, or stationary) and its decay rate, how can that help the NAS? Wake turbulence represents the ultimate limit in aircraft spacing. Aircraft spaced too close will encounter the leading aircraft’s wake. The most likely hazard will be an induced rolling moment that may exceed the control systems of the trailing aircraft. But the trailing aircraft usually does not remain within the wake vortices, instead, it is ejected outside where positive control can be regained.

But do such wake turbulence encounters occur? A search of NASA’s Aviation Safety Reporting System (asrs.arc.nasa.gov) shows that have been approximately 170 wake turbulence incidents since 2020. This number might appear large, but the number of flights over the same period exceeds 36 million. The probability that a flight will experience wake turbulence is therefore approximately 170/36,000,000 = 4.7 chance in a million.

The NAS currently contains standards for separation that include expected wake vortex encounters. These standards vary by aircraft size and weight. However, as noted in the ASRS reports, sometimes these standards are inadequate—in some atmospheric conditions, wake turbulence may decay very slowly and remain aloft longer than the standards assume. Additionally, it is suspected that the standards may be overly conservative in certain cases, leading to a larger spacing than necessary thus reducing the capacity of the NAS.

A CFMS instance can compute the wake turbulence behind the ownship dynamically and determine how fast it decays and in what direction it is headed. This information can be broadcast to the trailing aircraft. The flight crew and FMS on the trailing aircraft can use the information to maintain proper spacing with the leading aircraft. In some instances, the spacing might be less than the recommended FAA minimum. In other cases, the spacing might be more than needed. But using this technique, it is well within the capability to virtually eliminate all wake turbulence encounters, thus increasing the safety—and possibly efficiency—of the NAS simultaneously.

## Urban Air Mobility (UAM) Noise Modeling

Another possible use of the CFMS is in computing the noise footprint for UAM aircraft. UAM is a concept, currently unimplemented, in which electric vertical takeoff and landing vehicles (eVTOLs) are used to transport passengers from one area of a metroplex to another, bypassing the ground transportation system. An obvious use case is from an airport to a city center and back but transporting passengers from two parts of a conurbation is another use case.

One of the hindrances to UAM implementation is the possibility that the noise footprint on the ground might be too large for the population to handle. Already, ground noise footprints in urban areas is large, consisting of a superposition of trains, buses, cars, sirens, and other sources. If a UAM aircraft adds significant noise to this din, then the concept might be impractical to implement.

Like the wake turbulence use case mentioned earlier, the CFMS has all the information it needs to compute an aircraft's ground noise footprint. It also has the computational power to do so quickly. It can compute the noise footprint before or during flight (or both). The noise information can be used by traffic managers to "spread out" the UAM traffic so that each community experiences UAM noise that is acceptable.

## Quickly Implementing New NAS Concepts

Another method by which CFMS can increase the efficiency of the NAS is by allowing new concepts to be implemented more quickly than currently experienced. Currently, NAS improvements can take years—in some cases decades—to realize. The slow adaptation is due to the natural concern over flight safety. Any change to air-ground communication or protocol typically requires years of research, design, testing, and iteration until the concept is proven safe.

With CFMS, safety can be incorporated while inserting new concepts into the NAS. The interface between the CFMS and the cockpit, and its interface with the controller, can remain constant and unchanged while the CFMS itself incorporates new concepts. Both examples above—the computation of the ownship's wake turbulence and the computation of its own noise—do not require any changes to the NAS to implement. A controller can be informed of the ownship's wake vortex and can use that information to properly space the trailing aircraft. If on a visual approach, the trailing aircraft is responsible for its own separation and can use the computed wake turbulence to adjust its spacing. No changes to NAS protocol are needed, and thus the concept can be implemented more rapidly than otherwise required.

Other examples include interval management, or IM. IM can be implemented by coordinating multiple CFMS instances to computing the timing and location of the crossing of each critical waypoint. This information can be shared with the controllers and, if approved, a new trajectory can be uplinked to the ownship. Such a NAS change will require substantial software processing in the CFMS. Federal Aviation Regulations (FAR) rules changes will be unnecessary for this implementation, and thus concepts such as IM can be implemented faster than otherwise possible.

## Conclusions

In this brief paper we have reported on some benefits cases, subjectively, for Cloud FMS. The CFMS project is an ongoing effort at Mosaic ATM. In the future, quantification of some of these concepts will be possible through experimentation in a laboratory simulation as well as with live flight tests.

## Acknowledgements

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