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A 4D ATM Trajectory Concept Integrating GNSS and FMS?

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NextGen and SESAR have now been under development for several years, but have increasingly complex engineering and operational specifications. A variant Air Traffic Management (ATM) concept is sketched for generating fuel-efficient, very accurate and air-ground synchronized 4D-trajectories by using flight segment groundspeed profiles and linking Global Navigation Satellite Systems (GNSS) data to the aircraft Flight Management Systems (FMS) with feedback control. Is this a flawed concept or a feasible and operationally practical proposition?

KEY WORDS

1. SESAR. 2. NextGen. 3. Air Safety. 4. GNSS. 5. FMS. 6. ATC.

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1. INTRODUCTION. There are currently very large programmes of work in place to develop future Air Traffic Management (ATM) systems. NextGen (Next Generation Air Transportation System) and Single European Sky ATM Research (SESAR) have now been under development for several years (e.g. see http://www.jpdo.gov/index.asp and http://www.sesarju.eu/about). The following outline analysis arose from concerns about their increasingly complex engineering and operational specifications. The goal is to try to construct the simplest four-dimensional air traffic management (4D ATM) trajectory-based system that would work in practice and be a good investment decision. The emphasis here is on basic design elements for commercial flights in controlled airspace.

2. BACKGROUND. For present purposes, the following assumptions describe the features of currently foreseeable future ATM systems:

- There are no major new inventions. Global Navigation Satellite Systems (GNSS) operate generally as they do now. Aircraft Flight Management Systems (FMS) incorporating autopilots are roughly the same as now, with effective RTA (Required Time of Arrival) facilities and no database size or processing issues (Walter, 2001; Herndon, 2012).

- Controllers continue to have all their current safety responsibilities. There is no general delegation of their tasks to pilots. Pilots continue to have all their current safety responsibilities. Significant changes to these responsibilities might happen in certain operational circumstances, but there would have to be a near-absolute assurance of no adverse effects on ATM safety performance.
- Automatic safety aids for conflict detection and collision avoidance develop from their existing forms, but do not take "responsibility" for safety decisions in normal operations. Thus, they provide accurate information about conflicts but do not implement actions to resolve them. They might offer resolution suggestions to the pilot/controller. An exception might be the Traffic Alert and Collision Avoidance System II (TCAS), where corrective Resolution Advisories (RA) could link to the auto-pilot/flight-director to initiate the required manoeuvre.
- Air Traffic Control (ATC) displays must provide very accurate pictures of aircraft positions. If cooperative satellite-based surveillance is the prime tool, e.g., Automatic Dependent Surveillance (ADS)-Broadcast and/or ADS-Addressed, there is where possible back-up by (e.g.) independent Secondary Surveillance Radar (SSR) or multilaterating passive surveillance. Purely procedural ATC would be used only in special circumstances.
- Flight Data Processing Systems (FDPS) and digital communication systems perform sufficiently well to ensure that they are not the safety critical weak points.
- Weather forecasting performance continues to improve, but there would not be perfectly accurate forecasts of the winds etc encountered during aircraft flights.
- There are no game-changing Human Factors innovations – people are still good at some tasks and poor at others (e.g. long-term vigilance).

There is of course considerable debate about the nature of longer-term systems; in particular the degree/nature of automation they would need to involve. HALA! (2012) and Casado (2012) provide a good picture of the issues and recent research work.

3. 4D ATM TRAJECTORY SYSTEMS.

With hindsight, most people would view the historical goals of 4D ATM systems development as rather weird. The early workers were almost totally focused on using FMS to navigate fuel-efficient paths, e.g., Garteur (Garteur, 1990), PHARE (van Gool and Schröter, 1999). They did not worry too much about ATC costs or the computational aspects of multi-airport scheduling of these flights. NextGen and SESAR take much more of a "system" viewpoint.

There are several distinct and largely non-overlapping goals and objectives one might prioritize:

- Ensuring safe and fuel-efficient airport A to airport B flightpaths. These need to be easily renegotiable if new constraints arise.
- Effective use of airports, e.g., safely cutting the times allowed for safety buffers and timing variations of landing sequences. This produces huge capacity gains for mixed mode airports, but very little for segregated operations (Brooker, 2012).

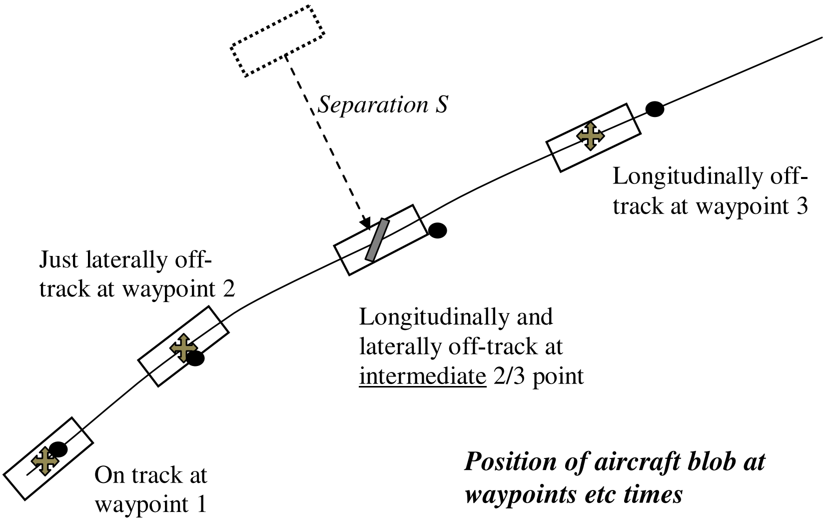

Figure 1. Contract boxes on Controller's Display. Not to scale, but note the display could show magnified scale boxes/aircraft positions in a local region.

- Removal of airspace "capacity barriers", the thrust being that controller workload is an un-breakable constraint on sector capacities, and hence airspace throughput. The "un-breakability" might not be true, as non-aircraft-linked computer assistance may help to increase sector capacities by large amounts.
- Hugely reduced ATC costs: FDPS, communications etc cost more, but many staff-related costs could be much less, if task times can be reduced or even disappear. PHARE and later Eurocontrol work led to similar ATC staff workload costs to those in the existing system, but some recent USA work suggests large reductions in these costs for particular future automation scenarios (Prevot et al., 2012).
- The core 4D-trajectory concept is in essence a plan view picture of an aircraft flight across controllers' screens. This might not be the kind of display used, but it does allow controllers to "see" times of passing, etc.

There has been extensive work on 4D-trajectory issues in ATM systems in the last two decades. Examples of current critical reviews are Jackson et al. (2013), and Mondoloni and Kirk (2013).

4. CONTRACT BOXES.

Figure 1 illustrates some potential features of a NextGen/SESAR 4D-trajectory as seen by a controller. Aircraft navigation errors mean that the predicted position of the aircraft flying the 4D-trajectory is the symbol centred in a "contract box". The aircraft is "contracted" to fly within this moving box. As an example, a PHARE box – the "Contract Tube" – is symmetrical about the trajectory, and was chosen to have limits of the order of one nautical mile (Nm) laterally, 200 feet vertically and 10 seconds longitudinally, each on either side of the contracted 4D-trajectory position (Wilson, 1996). Those dimensions were not

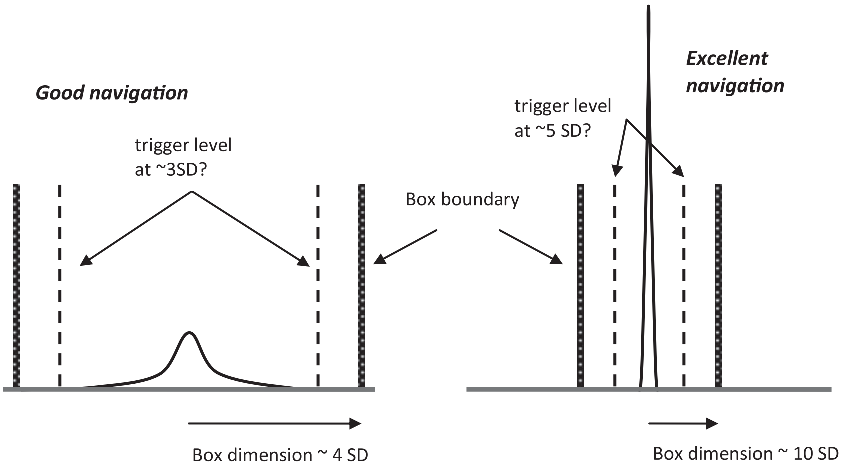

Figure 2. Contract box quality – not to any scale.

formally linked to navigational performance requirements. The actual aircraft position is shown here as a blob. The box is of course three-dimensional, so one option is that flashing symbols would signal all non-conforming – outside the box – blobs to the controller, including deviations above or below the contract box. Some kind of Decision Support Tool (DST), akin to existing Short Term Conflict Alert systems (which essentially perform simple extrapolations of recent surveillance tracks), could be used by the controller to explore options for handling non-conforming blobs.

The Figure shows different situations at three waypoints and at an intermediate position between two waypoints. Intermediate points are actually as important as waypoints, because the contracted 4D-trajectory is the *whole* trajectory, not just the waypoint locations. Note that the blobs show the position at the time of arrival at the waypoint etc. The dashed outline is the predicted position of a nearby aircraft, set at minimum separation S from the contract aircraft box. The separation here is measured between box boundaries. This ensures that separation minima infringement would not occur when aircraft were navigating normally and "within contract". The value of S might well be not much less than present minima, because it would be equivalent to the time for pilots to receive and react acceptably to "last ditch collision avoidance", e.g., TCAS RAs (e.g. see Brooker, 2011).

The obvious first question is how big ought the contract box to be? If the box has large dimensions, then this effectively implies a large separation between aircraft positions, and hence a tendency for more complex searches for safe routeings if a trajectory has to change. A lateral box dimension relates to the Required Navigation Performance (RNP – ICAO (2008)) value. The RNP number is set at the 95% navigational performance, so a 2 x RNP value – the RNP "safe containment area" – would be roughly a 4 standard deviation (SD) level, i.e. ~99·99%. [NB: lateral deviations are conventionally assumed to be Gaussian distributed.]

Setting a box dimension at (say) 4 SD (Figure 2) causes problems with changes to trajectories if the SD and box are both of large dimension. It means that monitoring routinely detects 2 SD and 3 SD deviations. A sizable deviation will trigger some kind of response, indicating to the controller that this *might* be the onset of a much larger deviation (shown by "trigger levels"). Thus, there would be a workload implication. If, in contrast, navigation were excellent rather than just good, then the box dimension could be very much smaller while still being set at several SDs. Thus in Figure 2 the right hand side shows a much narrower distribution and a much smaller contract box, but at a large SD setting. The corresponding trigger levels would still be several SDs wide, so would generate "Gaussian extreme" alerts extremely infrequently. The "quality" of the box for conformance monitoring and deviation warning – and hence controller workload – would thus be much better.

How big do safety/navigation researchers believe that boxes should be? Unfortunately, this demonstrates a weakness in NextGen/SESAR. There are lateral dimensions – which are rather large – but no well-argued vertical or longitudinal baseline dimensions (the JPDO Study Team Report JPDO (2011) is a useful source). Laterally: if flying an "RNP 1" *en route*, the total safety containment area would be two Nm on either side of the prescribed flight track – so the contract box is four Nm wide.

There are no ICAO recognized longitudinal equivalents of RNP. The Study Team suggests some "notional" Required Time Performance (RTP) values – RTP being a "concept that requires development" and "a placeholder for the acceptable time variability at a point in space". JPDO (2011. P.23) offers some values for different operations and airspaces. For example, the Study Team asserts appropriate criteria for "High-Density Airports" figures:

Cruise: 2–5 minutes,
Top of Descent: 1 minute,
Metering Fix: 12–18 seconds,
3-mile Final: 3–4 seconds,
Landing Threshold: 3–4 seconds.

Taking 60 seconds as an illustrative figure for an aircraft at ~500 knots produces roughly 8 Nm RTP. However, wind-forecasting uncertainties inherently affect the box dimension derived from airport performance/FMS considerations. [NB: wind forecast inaccuracy is shorthand here for all atmospheric and technical elements in estimating airspeed, including temperature, pressure, wind forecast updates/interpolation, pitot tube measurements, etc.] To take account of wind forecasts that are markedly in error, an even bigger box is needed, i.e. including "Separation Buffers" (Lee et al., 2009). The bigger the box, the more airspace is "blocked" by existing flights; the more difficult it generally is to re-plan a 4D-trajectory; and the more likely fuel penalties become, given the cruise and cruise-climb altitudes are usually in fairly narrow height bands.

The time criteria used at airports are critical parameters in determining runway capacity. ATC planners have to allow some "safety buffer time" when interleaving departures and arrivals, and to allow for statistical variations in landing inter-arrival times (e.g. see Brooker, 2009: Figure 1). If ATC had a high degree of confidence in aircraft navigation and performance, then this would permit the safe reduction of such buffers and allowances, thus leading to major airport capacity gains (e.g. Wichman et al., 2003). The figure of 3–4 seconds at the Landing Threshold noted above is not an operationally small variability – it is only a 95%, i.e. 2SD (with an approximately

Gaussian distribution, containment time, rather than any kind of tight statistical bound. There would be major capacity benefits if it were <1 second.

Neither is there a vertical analogy of RNP – a notional RVP. This is not because altimetry is inaccurate – there are tight ICAO standards in force and good evidence that the SD in cruise is much less than the 1000 feet separation standard (e.g. Reynolds and Hansman, 2003). The problem is path definition in climb/descent. To quote Nakamura (2009): "vertically, there are some parts of the flight profile where a defined path (trajectory) does not exist. Profile paths are not always a fixed trajectory (e.g. aircraft are flying by rate of climb)".

Returning to Figure 1, a key element is *Trajectory Synchronization*. The two trajectory-based automation systems – the aircraft's FMS and the ground-based contract box plus associated DSTs must be coordinated throughout the whole flight. The two need to operate continuously, and be based on exactly – or at least to a strict tolerance – the same predicted trajectory. In loose terms, what the aircraft 'thinks' will happen must match what the ground ATM system 'thinks' will happen. This trajectory synchronization ensures that when the controller perceives a marked deviation from the predicted trajectory it genuinely represents a potential problem with the flight, and is not merely a failure of air and ground systems to keep in step. Thus, for operational purposes, they must represent the same 4D trajectory at all points in the flight.

The topic of synchronization has been the subject of considerable past and current research. HALA! (2012) and Casado (2012) are useful starting points for the literature. Major contributors include the REACT Consortium (2008) and Eurocontrol/FAA Cooperation through "Action Plan 16" (e.g. see Mondoloni and Swierstra, 2005). Mondoloni and Kirk (2013) have recently produced a very valuable bibliographical literature review and analysis of European and USA trajectory prediction studies. Vivona et al. (2011) introduce an interesting conceptualized model to analyse synchronization issues. However, even after a decade's work, there is still a need for harmonization of NextGen and SESAR technical definitions and detailed operating concepts. Most of the operational changes necessary require extensive use of available and emerging FMS guidance capabilities (seldom exploited by current ATC practices), such as RNP RNAV (e.g. see CASA Australia, 2010) and RTA. The NextGen/SESAR 4D system to ensure synchronization is inherently complex, e.g., to quote from the REACT Consortium (2008):

> "The objective of the predicted trajectory-based approach is that the ground-based automation system continuously operates on the basis of the trajectory as predicted by the FMS. To that aim, the aircraft must periodically downlink the FMS's predicted trajectory (output of the FMS's trajectory prediction process) to the ground system… In general, a 4D point comprises of latitude, longitude, altitude and time coordinates (other aspects of the predicted trajectory, such as turn radius, speed, etc, may also be included as part of the FMS's predicted trajectory)… the ground system will uplink constraints to the FMS. In response to the uplinked constraints, which may be in the form of speed and/or altitude restrictions at a waypoint, a required time over a waypoint, a geometric path, etc, the FMS would amend its predicted trajectory so that it complies with the constraints."

5. POSSIBLE WAY FORWARD.

One of the questions that non-aviation people find difficult to understand is why, given that GNSS is incredibly accurate,

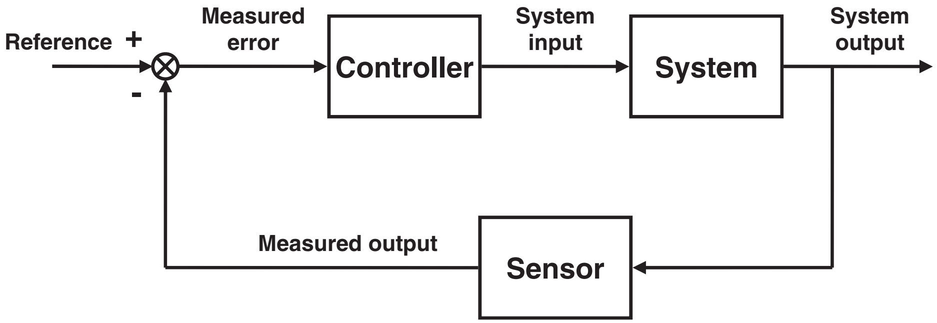

Figure 3. ’Classic’ closed-loop feedback control system.

aircraft do not fly on equally incredibly accurate flightpaths. The dissonance is simply because “Position” ≠ “Navigation”, e.g., knowing where one is now is not the same as being able to travel accurately to other places. The obvious technical question: could it somehow be feasible for aircraft navigation *and* ground ATM to be GNSS-position based while still using current FMS? Could such ideas help with Trajectory Synchronization? Could it be made more straightforward? Could it be largely eliminated?

How might an integrated GNSS/FMS 4D-trajectory system work? The core idea here is that GNSS information modifies FMS speed control settings so that the aircraft adheres to the explicit and implicit times set down in the agreed 4D-trajectory. The starting point is to recognise that FMS segments between waypoints and other trajectory change positions have very specific position and speed regimes. Examining the descriptions in Walter (2001. Figures 15·4 and 15·5) shows that the speed changes in flightpath segments are predictable and deterministic. Two speed profile examples are acceleration at constant altitude as fuel weight reduces, and speed remaining constant (e.g. in a cruise climb). The FMS ensures that the engine thrust setting and aircraft configuration deliver the required altitude and speed evolution.

Take the simple case of a constant speed “straight line” segment, say a cruise climb. The aircraft uses the best environmental information available – the critical parameters being the predicted wind vectors – but these may not be accurate. For this speed regime, each elapsed second (in general terms, each programmed time instant) would produce the same distance D travelled. But there is likely to be an error after each second, so that measurement of the GNSS position distance is $D + e_1$, $D + e_2$, etc. If the errors occur because of a consistently under-forecast head wind, the e_i values would be expected to increase roughly linearly.

But this is exactly the kind of problem that feedback controls handle (e.g. Åström and Murray, 2013). Figure 3 is the ‘classic’ error-actuated system that maintains a desired or reference speed, e.g., adaptive cruise control for automobiles. Here, the System is the aircraft; the System output is the $D + e_1$, etc; the Measured errors are e_1 etc; and the Controller acts by inputting a wind correction to the FMS speed control functions. It might use some variety of the common Proportional-Integral-Differential (PID) Feedback Controller to ensure that the aircraft flightpath has (statistically) progressively smaller e_i values. The contracted speed regime could obviously be more complex, e.g., a level segment cruise at constant thrust etc, with the aircraft weight reducing as fuel is used. The succession of distances D_i travelled would be an exactly known (or reasonably interpolated) set of values dependent on the aircraft weight, configuration etc; and observed values would be $D_1 + e_1$, $D_2 + e_2$, etc.

Is there an analogous process for lateral deviations? Yes – it essentially exists already. On board automation – in particular the feedback controls embedded in the aircraft autopilot – flies the aircraft in FMS in both lateral and vertical navigation. Lateral Navigation (LNAV) and Vertical Navigation (VNAV) compute guidance commands based on the agreed 4D-trajectory. The performance of this kind of operation was investigated by Airservices Australia and partners (Paglione et al., 2010), gathering data by Automatic Dependent Surveillance Contract (ADS-C). The lateral SD for stable-trajectory in-service aircraft operations was 0·026 Nm (48 m) (see also Reynolds and Hansman (2003. P.32). The fact that the lateral performance through feedback control is very good provides encouragement for believing that the longitudinal performance could also be of high quality.

Obviously most trajectories will not be straight lines. Paielli (2005) provides some clear ideas for a standard trajectory specification language using a series of parametric segments. Thus, for example, the long-track position is specified by a low-order polynomial function of time, i.e. consistent with the above longitudinal time regime. The paper goes into detail about the need to use a global earth-fixed coordinate system and several other key aspects relevant here.

In contrast, GNSS feedback does not specify the vertical dimension of the contract box. Current altimetry being barometric rather than geometric makes this a very difficult proposition. However, as the longitudinal and lateral dimensions would be small, so would be the box volume, even with extremely cautious assumptions for the vertical dimension.

6. CONCEPT AND BENEFITS.

Figure 4 is a simplified sketch of the system concept outlined above – a “GNSS/FMS Feedback Concept”. It is based around the kind of 4D-trajectory approach envisaged in NextGen/SESAR, so the following discussion focuses on this variant’s differences from them. A NextGen operational concept is set out very clearly in Chapter 5 of JPDO (2011). Here, “pilot” is shorthand for the aircrew plus the aircraft operator’s Flight Operations Centre etc. Pilot and ATC agree the 4D-trajectory in the way envisaged by NextGen/SESAR: an iterative process finding a near-optimal routeing that is compliant with ATM/airport constraints. That trajectory is based on specific wind forecasts. The initial decisions and any subsequent re-plans needed are made by the pilot and ATC, supported by FMS planning tools and DSTs (HALA! (2012) and Casado (2012) provide simple descriptions and discuss DSTs).

The new ingredient is that the aircraft FMS is committed to fly the agreed trajectory’s groundspeed profile segments. In reality, actual wind will be different from forecast wind, so to ensure the groundspeed profile is maintained, there need to be appropriate compensating wind inputs so that the FMS can make thrust and aircraft configuration corrections. This is achieved both longitudinally and laterally by feedback control from GNSS positional data to compare planned and actual positions at each programmed time instant, *thus covering the whole of the 4D–trajectory*. ATC monitors the flight by a display of a contract box, which represents plan-view positional uncertainty plus a cautious allowance for vertical deviations. The box

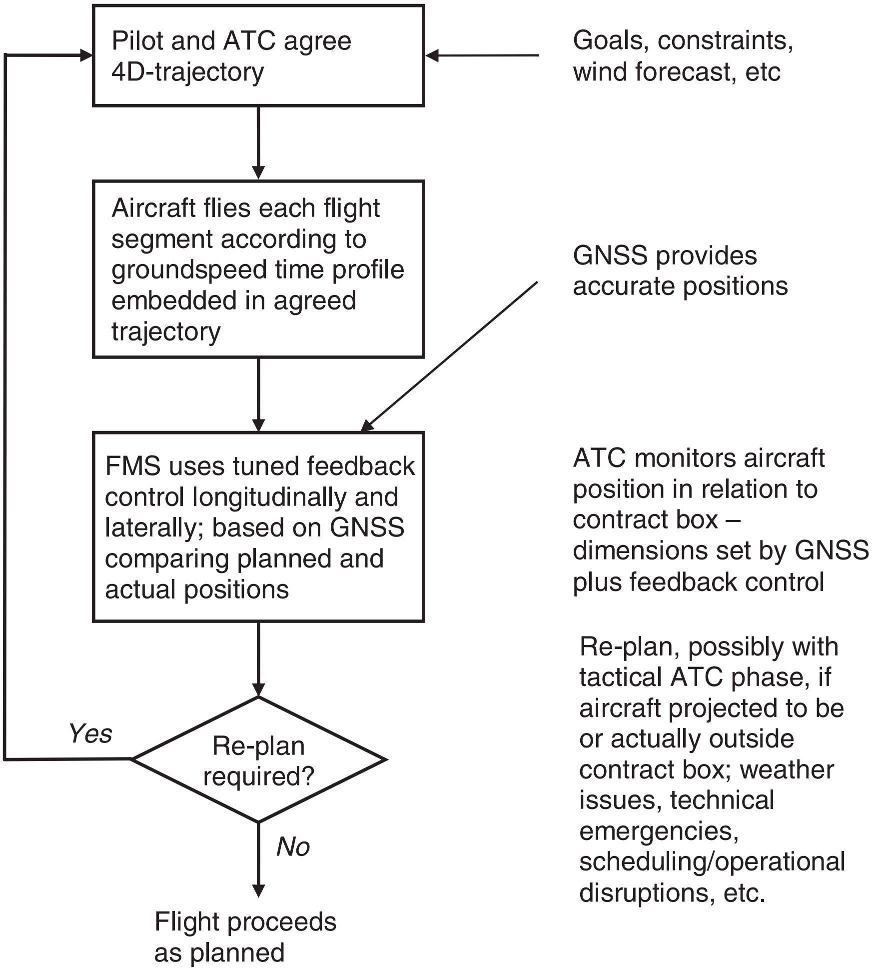

Figure 4. Sketch of GNSS/FMS Feedback Concept.

is small, but its size covers several SDs of normal navigation, as its plan-view dimensions are set by the positional accuracy of GNSS plus feedback control.

The Concept meets key design goals and has several worthwhile qualities:

(i) All the projected safety and operational 4D-trajectory benefits of NextGen/SESAR are achievable.

(ii) There is assured trajectory synchronization from take-off and throughout the flight, without the need for complex ground-based trajectory prediction models (e.g. see Eurocontrol (2013). There is only one 4D-trajectory once it has been contracted between air/ground systems.

(iii) There are large reductions in the need for either air or ground systems to re-compute estimated 4D-trajectories or to re-negotiate agreed trajectories simply because of inaccurate wind forecasts.

(iv) It is not necessary to datalink detailed wind etc data between air and ground in normal operation.

(v) Flights make maximum use of the very high position accuracy delivered by GNSS.

(vi) Small volume contract boxes make it much easier to construct optimal 4D-trajectories *and* to change them when required. This is very important in the context of operational disruptions – see Subsection 7.3.

(vii) An excellent navigation performance – the right hand side of Figure 2 – would permit a high-quality box, ensuring very low false alarm rate conformance alerts, highly effective DSTs (because of reduced uncertainties in 4D positions), and hence much lower controller workload required for monitoring tasks.

(viii) There is no requirement for changes of safety responsibility between air and ground operations.

If these benefits were achievable, then automated data processing of trajectory data plus computer assistance through DSTs should enable reductions in controller workload per aircraft handled. How this would translate into ATC provider cost reductions through increased productivity has to be speculation at present. The problem is that the operational 4D concept has to be sufficiently detailed to support estimates of controller task components and execution times, rather than relying on a variety of assumptions, e.g., see Welch et al. (2007).

Points (iii) and (iv) need some comment. The focus is on the groundspeed profile in flight segments. The aircraft's absolute position is the key variable here. Trajectory waypoints are absolute positions (and times), and the controller's screen displays absolute positions. Flights travel from one absolute position to the next according to the groundspeed profile. True airspeed, i.e. relative to the atmosphere, is important to the aerodynamics and performance of the flight, but estimates of the actual trajectory require concurrent wind vector forecasts to convert to estimated groundspeed. In the concept sketched here, the wind forecasts for the evolving flight are in effect being "fine-tuned" by a GNSS positional feedback correction, i.e. adjusting the forecast wind vector input to the FMS so that it matches reality. Statistically, longitudinal errors are reduced in magnitude and do not accumulate.

7. ISSUES (NOT IN ANY PARTICULAR ORDER).

7.1. *Is the error signal that generates feedback large enough to compensate for measurement noise?* Some rough numbers help to indicate that they should be. Feedback stability depends on the ratio of signals to the noise in the environment. Take as an example the speed of an aircraft flying *en route* as 250 m/s (i.e. ~ 500 knots). Suppose there is a sudden un-forecast headwind error of 5 m/s (~ 10 knots). Taking the current GPS (Global Positioning System) SPS (Standard Positioning Service) Performance Standard (http://www.gps.gov/systems/gps/performance/accuracy/) as a cautious GNSS estimate, the GPS signals have a "worst case" pseudorange 2SD accuracy of 7·8 m. Thus, in a 2-second period, the aircraft will plan to fly 500 m and actually fly about 490 m – but the distance error of 10 m will be greater than the GNSS error 2SD. Hence, even in two seconds of flight the feedback trigger would exceed 2SDs of measurement noise – a time error of a fraction of a second.

The rough sum indicates how quickly the feedback could start to have an effect, preventing cumulative wind error effects. For wind forecasts differing from reality by a roughly constant vector, the aircraft would soon be operating with an FMS wind input that is close to the actual wind encountered. A constant vector assumption would be appropriate for the stratosphere, which has high velocity – but not generally gusty – winds. The effects of gusts at lower altitudes might need feedback control to prevent undesirable oscillatory behaviour.

Proper calculations of feedback effects would need detailed knowledge of the feedback control system. They would need to make allowance for intrinsic system lags, e.g., GNSS position latency, data processing time, response characteristics for control surface actuation, etc.

7.2. *Would rapid changes in horizontal wind gradient wreck the feedback process?* If the magnitude of wind-velocity forecast errors is small and/or slowly varying over flight segments then the feedback should be stable, and produce good positional accuracy. In cases where the meteorological forecasts change markedly during a flight, the revised forecast could of course be used to modify the agreed trajectory (see Subsection 7.5).

However, rapid changes in the horizontal wind gradient would occur at the boundaries of (e.g.) severe thunderstorms (there are many different weather related causes for rapid wind vector changes, e.g., Krozel (2011)). Severe weather is generally much more of a problem in the USA than in Europe. NextGen Weather Concept of Operations mentions severe thunderstorms several times (JPDO, 2005), mainly focused on the goal of better forecasting of their location to enable alternative routes to be constructed. However, the current advice to aviators – "keep 20 miles away" – seems to remain when NextGen/SESAR arrives. In the event that weather forecasting had poorly estimated the location of a major wind gradient error, e.g., the position of the gust front nose, the feedback tracking could provide warnings to the aircrew. If the aircraft continued on its flight, ATC (with DST) would quickly detect that an aircraft is, or soon would be, outside its contract box.

Another real-life situation in which the winds vary could occur for an aircraft flying along the edge of the jet stream. In these circumstances, the wind vector can vary greatly with time and position. If the flight GNSS/FMS feedback loop tries to keep it within the contract box, the FMS would probably have to make large throttle adjustments (if not subject to handling limits). Neither aircrew nor passengers might be very enthusiastic about these.

In these two examples of feedback instability because of un-forecast high variability in wind vectors, the aircraft might not be able to maintain its agreed trajectory. The next stage would be ATC "voiding the contract". ATC would then issue tactical vectoring instructions that ensure the aircraft moves away from the area of instability. When this is achieved, pilot and ATC would have to re-plan and negotiate a fresh 4D-contract, probably with a transitional flight segment subject to further ATC instructions. The process would be safe, because there would be positive ATC (as in the present system), the aircraft would start from at least the minimum separation from other aircraft, and protective air/ground collision detection/avoidance systems would be in place.

How any future ATM concept would respond to these kinds of pathological case is extremely important. The sketch above shows that safe revisions to the aircraft flightpath are potentially feasible. The same kinds of issues would arise with the current NextGen/SESAR concepts in similar pathological situations where the 4D-contract is being degraded. If the forecast wind errors were large and/or highly variable, then there would have to be the kind of trajectory re-negotiation and re-synchronization noted in Section 4 above. The GNSS/FMS Feedback Concept has the advantage that, with much smaller contract boxes, it is easier to determine revised trajectories for the affected aircraft.

7.3. *Are there problems in dealing with operational disruptions?* These disruptions are not the pathological cases sketched above, i.e. problems with the 4D-trajectory *per se*, but arise from the reality of aircraft/airport operations. These include airspace problems with unequipped flights, weather issues (particularly in the USA), technical emergencies and scheduling/operational disruptions (e.g. delayed departures because of passenger boarding issues, aborted approaches, runway changes, etc). Sherry et al. (2013) provide some graphic illustrations of "irregular operations", in particular aborted approaches. The TITAN (2010) project provides an informative overview of the predictability, cost efficiency and punctuality of the various operations involved in airline turnaround processes. The common feature at present is that flight schedules have to be adjusted tactically, implying that some aircraft have to suffer ground delays at the airport and others have to be vectored by ATC to hold in stacks, etc. In any NextGen/SESAR system there would need to be renegotiation of the affected aircraft's 4D-trajectories. Again, the GNSS/FMS Feedback Concept's advantage is that its much smaller contract boxes mean that it is easier to determine revised trajectories for the affected aircraft.

But there is an underlying problem requiring resolution for *any* strategically based ATM system, which means at present the operational feasibility of such systems is not fully proven. If airport operations were very tightly scheduled over long periods, then the bad effects on the airlines and airports of disruptions and irregular operations would be expected to persist for similarly long periods. There are certainly known ways of preventing system queuing overloads and instabilities. An obvious one is to require that airport schedulers do not persistently schedule up to the maximum runway throughput rate (e.g. Bubalo, 2011). The optimal system design for a strategically based ATM system has to take into account the frequency of irregular/disrupted operations, the costs to airlines and passengers of trajectory changes, and the opportunity costs of "un-squashed" scheduling.

7.4. *Is this kind of speed adjustment compatible with NextGen/SESAR?* There is an easy answer: Yes. This is because the ERASMUS (2009) project explored – for conflict reduction purposes – trajectory modification performed through minor speed adjustments. This was compliant with SESAR as the programme encompassed new separation modes such as "Trajectory Control by Speed Adjustment".

7.5. *Are there issues with trajectory revision?* "Revision" of the trajectory in NextGen/SESAR (Mondoloni and Kirk, 2013) is a re-plan needed by pilot and ATC when an issue "further down the line" means that the present trajectory is no longer viable: for example, a sequencing problem at the destination airport. It would *not* cover cases where there were safety issues about the current flight (compare Subsection 7.2). The process to be followed would not differ from the kinds of operational sequences under analysis for NextGen/SESAR (JPDO, 2011). The additional ingredient would be the downlink of a detailed FMS ground trajectory, presumably to take effect at the next appropriate waypoint, but this would not be a safety-critical transfer requiring a high data rate/bandwidth. Would there be any significant extra loading on digital communications links, given the general reduction in synchronization datalinking? The datalink component of future aeronautical communications is the subject of much current R&D and "a lot of work remains to be done" (Fistas, 2011).

7.6. *Are there implications for PBN* (Performance Based Navigation)*, RNP RNAV, etc?* As envisaged at present, these would become redundant criteria, as GNSS accuracy and the feedback quality would set much tighter restrictions. The concept here is compliant with (e.g.) PBN "Radius to Fix" segments, quoting CASA Australia (2010):

> "Pilots are familiar with flying turns at a constant airspeed and angle of bank which enables a circular flight path to be flown *with reference to the air mass* and are trained to manually compensate for the presence of wind if necessary. Pilots now need to understand that the FMS will fly an exact circular flight path *over the ground* and the angle of bank will be adjusted by the flight control system to maintain that circular flight path."

7.7. *Could there be FMS restrictions that limit the effectiveness of the feedback mechanisms?* Two examples: for maximum climb profile segments, the FMS might not permit thrust adjustments, and there might be issues when the aircraft is near altitude ceilings or needs very large bank angles. This needs a detailed investigation – but again the key point is that similar issues would arise with the currently envisaged NextGen/SESAR concepts.

7.8. *What issues are there for FMS software etc?* Information on FMS costs are a commercial matter and hence generally not in the public domain. Patents protect much of the detailed work on FMS. Nevertheless, patent information does provide useful clues about the kinds of software development issues in the minds of manufacturers. For example, Honeywell International Inc. (2012) provides evidence of the importance of smooth transitions between waypoints. The FMS concept sketched here is a very simple one – it does not require novel algorithm developments. GNSS data is already available in the aircraft data systems and feedback systems are already basic FMS elements.

7.9. *Could more frequent changes to engine thrust, flaps etc cause failure or lifetime problems?* The GNSS feedback loop will not generate frequent and continuous changes when wind forecasts are very accurate or differ from reality by a roughly constant vector. A scan of the literature has not found obvious evidence that small frequent changes would have a major impact, in comparison with stress changes at operational envelope boundaries, but obviously specialist modelling might be required. Thus, engine life appears to be most affected by operational hours, exceedances of the registered engine speed, number of engine starts (i.e. cold-hot-cold cycles) and *sudden* changes of the engine speed. Modern fly-by-wire systems' "moving parts" are limited to power systems and actuators to move control surfaces.

7.10. *Would the concept make sense in terms of aircraft operating costs, in particular fuel usage?* Any assessment needs to be made against the best alternative NextGen/SESAR concept available. There is no immediately obvious reason why this GNSS/FMS Feedback Concept would consistently generate worse flightpaths in terms of fuel usage than the NextGen/SESAR 4D version. Delgado and Prats (2009) discuss under what conditions a speed reduction strategy does not penalise fuel consumption in terms of the selected Cost Index.

7.11. *Why would this be better than current NextGen/SESAR proposals?* A mature version of a "Full 4D concept" does not exist. Jackson et al. (2013) sketch key "Challenges" that need to be overcome even to make the initial steps: note that the paper's authors are from heavily involved organisations – Honeywell, MITRE and Boeing. If there are several options, including the idea here, then decision-makers have to conduct a variety of interconnected tests – technical feasibility (e.g. adequate datalink bandwidth), provability of safety, benefits versus costs, etc. The Concept discussed here might be better than other options *if* it could be shown that it passed those tests, *if* it had no deficiencies in any significant aspect compared with other variants, and *if* it offered larger reductions in operating – particularly staff – costs. In any event, there needs to be a compelling case for committing large NextGen/SESAR expenditures (Brooker, 2012). To put this into context, European ATM charges to users are running at about €8 billion per annum, with staff costs typically 60+% of the total costs.

8. THE QUESTION.

The text has sketched an ATM concept for generating safe, fuel-efficient, very accurate, and air-ground synchronized 4D-trajectories by using flight segment groundspeed profiles and linking GNSS data to the aircraft FMS with feedback control. Is it a better variant of existing NextGen/SESAR 4D-trajectory ideas? Are there intrinsic flaws? If not, would detailed work show this to be a feasible and operationally practical proposition?

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