A Practical Way Forward for Aviation Multi-Constellation Service Provision Based on the ICAO GNSS Charter

Gerhard E. Berz
EUROCONTROL
Brussels, BELGIUM
E-mails: gerhard.berz@eurocontrol.int

Federico Bergamasco
University of Luxemburg
Luxemburg, LUXEMBURG
E-mail: federico.bergamasco@uni.lu

ABSTRACT

Aviation wishes to take advantage of signals from multiple GNSS core constellations[1] in order to provide a robust, high-performing and continuous service to aircraft. This goal requires that each State accepts signals from at least one or more foreign constellation providers in its Air Navigation Service (ANS) provision. While GPS has already been introduced in aviation for many years, it has evolved from a supplemental means service to an essential ingredient for Performance Based Navigation (PBN) and a host of other Communications, Navigation and Surveillance (CNS) applications. Non-core constellation provider States have in some cases struggled with the legal implications of allowing the use of navigation signals from a foreign entity in their airspaces. This has led to the establishment of a "Charter on Rights and Obligations of States Relating to GNSS Services" by ICAO in 1998, still in force as Assembly Resolution 32-19 [1]. The charter contains only very high level principles relating mainly to safety and cooperation – but practical implementation details are missing. With the development of multi-constellation GNSS, some concerns resurface and remain unaddressed while others evolve in the sense that multi-constellation GNSS may actually provide solutions.

Very little legal work has been done on the subject since the publication of the Charter and almost no case law is available on GNSS legal issues or any related domain – which is actually a credit to the high quality service provided by GPS that aviation has benefitted from for many years. The paper, which is intended for a non-legal expert audience, will summarize the current legal mechanisms and address challenges such as sovereignty, liability and the legal consequences of approving GNSS elements[2] in a State's airspace in the context of multi-constellation GNSS. Furthermore, it will propose practical mitigations to those challenges, essentially based on the established practice with current GPS L1-based operations[3] and a more detailed interpretation of the GNSS Charter principles. A particular topic of technical interest will be the evaluation of the need for and benefits of introducing a State-specific receiver selection capability of individual GNSS elements based on a geographic database. Such a capability is one element of the GNSS concept of operations (CONOPS) currently being developed by ICAO [2].

The goal of the paper is to support the implementation of multi-constellation GNSS for aviation by addressing legal concerns and providing guidance on the need and functionality of any associated technical functionalities.

INTRODUCTION

Moving from the current widespread use of single frequency GPS to multi-constellation GNSS is expected to significantly mitigate current GNSS vulnerabilities, such as constellation weakness, the impact of solar activity on propagation through the ionosphere, and unintentional, single-frequency radio interference. While this is highly desirable from an overall aviation system point of view, such benefits are difficult to quantify to aircraft operators who are already enjoying very reliable service with current GPS. Due to this small cost-benefit

---

[1] A core constellation is providing a set of global orbiting satellites which enable the calculation of a position solution, such as GPS, GLONASS, Galileo or Beidou. The term "core" constellation differentiates from other satellites used to provide augmentation services (QZSS, WAAS, EGNOS, other commercial services).

[2] GNSS as defined by aviation includes both core constellation services and their augmentation, which is either aircraft, space or ground-based. A GNSS "element" can consequently be either a core constellation or an augmentation service.

[3] The civil GPS L1 C/A code signal on 1575.42 MHz as used by the large majority of aviation receivers today.

trade space and the overall safety-motivated desire to keep receiver functionalities as simple as possible, equipment manufacturers wish to apply a performance-based approach to GNSS element selection, where the receiver independently decides which signals are best suited to achieve the required level of navigation performance. While the performance-based principle is also well established in the International Civil Aviation Organization, ICAO [3], it directly clashes with the desire of States to approve which navigation signals are used in their airspace. This desire stems from justified concerns over sovereignty and legal issues, equally based on ICAO principles.

The objective of this paper is to provide satisfactory arguments to resolve and mitigate these concerns, such that future multi-constellation GNSS receivers can continue to provide cost-efficient positioning and navigation services to support future airspace improvements.

CURRENT GNSS STATE APPROVAL STATUS

ICAO Annex 15 [4] and other materials [5] oblige States to publish in their official Aeronautical Information Publications (AIP) which GNSS elements (core constellations and associated augmentation services) are approved for use in their airspace. Currently, only 9 out of 41 EUROCONTROL member States make such statements in their AIP [6]; the situation is expected to be similar globally. Among the remaining States, some have approved procedures permitting or even requiring the use of GPS. Due to uncertainty of the legal implications of such an AIP entry, and the general struggle to formally approve GPS (in Europe, this is also linked to single European sky service provision regulations), they have chosen to leave the matter in ambiguity. Meanwhile, it is generally well understood that aircraft operators will use their equipment capabilities everywhere, regardless of a State's individual GNSS approval declaration. This is in line with the approvals obtained in their State of registry. In the case of PBN specifications allowing the use of multiple navigation sensors, such States will often formally base their procedures on terrestrial navigation aids (DME/DME and VOR/DME Area Navigation), while the standard use of GPS remains a "supplemental-use" choice by aircraft operators. While not having been the case for any aeronautical navigation system in the past, the currently ongoing standardization process now envisions the implementation of geo-referenced tuning of GNSS elements, automatically respecting the State approved elements even in en-route and terminal area navigation. Such a feature is thought to be necessary to mitigate State concerns over sovereignty and liability of GNSS.

SOVEREIGNTY, GNSS AND ANS PROVISION

ANS provision is a State responsibility under article 28 of the Chicago Convention (CC) on international civil aviation [7], where "each contracting State undertakes… to provide in its territory… radio services… to facilitate international air navigation[4]". States view this provision as an exercise of a sovereign function in accordance with article 1 CC which establishes sovereignty of States as the foremost principle of the Convention. Despite the territorial link in article 28, it is established practice to delegate a State's ANS provision (such as to a private national entity), including foreign entities. The typical case for delegation of ANS to foreign entities is to neighboring States where an airport is located close to the State border. In the interest of safety and efficiency, this prevents aircraft operators having to switch between State ANS providers while performing approaches to or departures from such an airport. In most cases where the airspace in an adjacent State is joined to the ANS provision of such an airport, delegation agreements are in force. This allows the delegating State to exercise a certain amount of control (clear rights and obligations, performance targets, certification process, system surveillance). The stipulation of such an agreement can be seen as ensuring a respect of State sovereignty.

When applying this ANS delegation practice to GNSS, it is generally accepted that operators of core constellations will not enter into such agreements with potentially all the ANS providers around the globe. The absence of such agreements can be interpreted as an infringement of State sovereignty in ANS provision while at the same time implying a waiver of liability by the core constellation operator. This topic was the subject of intense debate over several years, leading up to the setting up of a ICAO Legal and Technical Expert Panel (LTEP) from 1995 to 1998 [A1]. The main agreement resulting from the LTEP was the GNSS Charter [8], which establishes high level principles relating to the use of GNSS in ANS provision. The final LTEP report [9] further considers that "GNSS core constellation services… are not an ANS under article 28 CC" but rather an external ingredient which "provides navigation aid signals for use in aircraft positioning". Because GNSS systems are generally not specifically designed to directly meet aviation requirements, they are all subject to augmentation systems which ensure the accuracy, integrity, continuity and availability needed to support the intended operation. Thus, the aircraft, ground- or space-based augmentation service (ABAS, GBAS, SBAS) is what makes GNSS an ANS and is consequently the service which is subject to standard aviation safety oversight. It is then the responsibility of the augmentation

[4] Air Navigation Services include all services required to conduct flight operations under instrument flight rules, including Air Traffic Control, Communications, Navigation and Surveillance, Aeronautical Information and Meteorological Services, etc (thus not at all limited to navigation only, even if this is the focus of this paper).

service and system design to ensure that critical core constellation performance assumptions are maintained. The distinction between core constellation and augmentation services is used to justify that the use of foreign-controlled GNSS signals by aviation does not infringe sovereignty. While the associated assembly resolution to conduct further work to resolve legal issues associated with GNSS remains in force [10], it has been downgraded in priority in 2012 and States have accepted that no amendments to the Chicago Convention are deemed necessary to accommodate the use of GNSS in ANS provision [11].

NEW ARGUMENTS TO ADDRESS SOVEREIGNTY IN RELATION TO GNSS-BASED ANS PROVISION

While the distinction between core constellation and augmentation system services is useful, it can be seen as a rather academic distinction. Without core constellation signals, no augmentation service will be able to meet its performance requirements, i.e., it will not work at all. It is consequently useful to evaluate the actual concerns behind the sovereignty principle. One sovereignty concern is the intrusion of a foreign State into domestic issues of another State. In the case of GNSS however, the core constellation State is only providing an offer, based on established standards in ICAO Annex 10 [12], which will facilitate the provision of ANS, and from which the other State directly benefits. It is up to each State receiving GNSS signals to accept them as part of their navigation services. In terms of intrusion into airspace, GNSS only provides positioning, allowing a determination in which State an aircraft is located. It does not navigate the aircraft – this is done by the pilot in cooperation with the avionics. If anything, GNSS can be helpful in avoiding airspace infringements. The use of GNSS by aircraft has no influence on the decision by any State to grant access to its airspace or not. In comparison with other sovereignty issues such as the use of earth observation satellites to gather intelligence of another States' activities[5], this intrusion does seem rather minor.

In terms of dependence on a foreign entity, there is of course valid concern over giving a foreign State significant control over another State's ANS provision, which has a significant role in the economic well-being of a State in supporting, for example, tourism revenues and business relationships. From that point of view, it is understandable that a State may consider that the letters of commitment to ICAO [13], the supporting standards and documents, as well as the 6 year advance notice requirement [12, section 2.1.4.1] in case a core constellation provider State would decide to significantly alter or terminate its service, can be seen as insufficient. After all, it may be difficult for a State to react quickly to any such changes, while the evolution of world politics and economics is difficult to predict. Furthermore, most if not all GNSS core constellations are subject to national defense interests.

There are two main arguments that mitigate this very pertinent concern. The first is that each State is at liberty and actually advised to maintain an alternate terrestrial infrastructure, based on current terrestrial navigation aids, in particular VOR and DME [12, Attachment H]. While operational aviation efficiency may still be impacted in the event of a significant GNSS service change, this impact and the associated dependence can be reduced significantly. The second argument is that if foreign dependence is really the concern, then as many GNSS core constellations as possible should be approved! After all, this is what motivated the European Union and the Peoples Republic of China to build their own, independent satellite navigation systems alongside the USA and the Russian Federation. One main issue in the discussions of the LTEP on sovereignty was that the US at the time held a global monopoly with GPS – something which is now changing.

When evaluating the issue of foreign ANS dependence, a further argument can be identified, which is risk-based. What is the actual risk that for example, the United States of America would disable GPS? Aviation has incurred considerable complexity from the fact that GNSS is a multi-modal, multi-user system. It necessitates augmentation systems and makes aviation subject to radio frequency interference which is typically not directed at aviation. While this is the downside, one should not forget the upside: this dependence by many economic sectors (not to mention military forces!) on GPS provides clear justification in that risk being extremely small due to the dramatic consequences this would have on nearly all aspects of modern human activity, not only abroad [14], but also in the United States [15]. At least judging by the experience of the last two decades, GPS is providing significant economic advantage to the U.S. and its industry, such that it becomes rather difficult to hypothesize cases of why the U.S. would modify negatively its GPS service. It must also be remembered in this context that satellite orbits are bound to the physics of Keplerian orbits, thus making the possibility for any local performance optimizations at the expense of other global regions quite minimal [16]. The resulting domestic policy statements by the U.S. [17, 18] are a clear recognition of the economic value of GPS and its intention to maintain the system for the foreseeable future.

As a final argument on the matter of sovereignty, where the lack of a binding agreement may be seen as an obstacle, it must be considered what the content of such an agreement would be. Using the example of GPS, it can be observed that for the most part, the U.S. is already providing what would likely be key aspects of such an

[5] Sovereignty concerns relating to earth observation were mitigated primarily by assuring that the observed State can derive benefits from the other State's activity, i.e., obtain access to the data. The benefit is very clear in the case of GNSS.

agreement. This would include user support and quick notifications in case there are problems with the system performance, provided by the U.S. Coast Guard GPS Navigation Center. It would also include system performance standards [19] and interface control documents [20], subject to a public review process when changes or updates are considered. In the case of the few system malfunctions that have been encountered over the years (such as the SVN49 issue, [21]), transparent analysis and information has been provided to public forums, such as the Civil GPS Service Interface Committee (CGSIC) or through the U.N. International Committee on GNSS (UN ICG). The only aspect that could be seen as missing would be more explicit obligations towards aviation stipulated through ICAO. For this reason, it has been proposed [22] to provide further details of how the ICAO GNSS Charter provisions are to be interpreted, by providing a description of the practice that has been established by GPS, making it a benchmark for other constellations. Current developments in the ICAO Navigation Systems Panel are supporting this proposal [23].

Based on the arguments above, it seems that apart from a States' right to accept or not the use of a GNSS element in its airspace, concerns over sovereignty can be sufficiently mitigated. It could even be argued that States have implicitly accepted this by not filing differences[6] to the core constellation standards in Annex 10. However, such an argument does not weigh up against the justified concern of any State over foreign dependence (where the nature of GNSS constellation systems is such that most States cannot afford this). The most relevant argument remains that if a State is concerned about foreign dependence, all available GNSS signals should be authorized for aviation use. Any associated effort to do so will surely pale against the cost of actually providing such services independently.

Finally, while a right of a State to approve or not the use of a GNSS element in its airspace can be derived from the principle of sovereignty, one must still ask what the purpose could be of not allowing the use of such GNSS elements, especially if other States have approved them. Here, safety is the only concern and justification. If a GNSS core constellation system is not supporting safe operations in a given airspace, then of course it is understandable that a State would not approve its use. However, a State would also have to be a lot more vigorous in insisting that such elements be disabled when entering its airspace, since it would need to establish that this constitutes a clear threat to safe operations. The current practice of leaving the situation ambiguous does not really support the idea of a valid safety concern. Instead of a somewhat philosophical discussion of the interpretations of articles 1 and 28 of the Chicago Convention, the need for States to approve GNSS elements should instead be based on article 12 CC: rules of the air. It states that "every aircraft flying over or manoeuvring within its territory… shall comply with the rules and regulations… there in force". Rules of the air have a much more direct safety focus and are also subject to further conditioning by CC articles 11 (non-discrimination), 33 (mutual recognition of certificates) and 37 (uniformity of regulation). While it will be difficult to make a legal case, it seems that if State A has approved an aircraft of its registry to use a GNSS element which is meeting all ICAO and certification standards, it would be a clear act of discrimination for State B to forbid the operation of such an aircraft in its airspace due to using a non-approved GNSS element. The mutual recognition of certificates is also directly linked to an equivalent safety level in accordance with the corresponding standards. The role of standards is clearly to prevent discrimination and enable mutual recognition.

THE MEANING OF STATE APPROVALS

The principles of sovereignty and safety support that a State should have a say in what signals are approved[7] for use by aircraft in its airspace. However, what does it actually mean in terms of State responsibility if a State approves a GNSS element? Does a State then accept a liability which is largely beyond its control? This concern appears to be a main reason for why so many States hesitate to make explicit statements in their AIP's mentioned earlier. Paradoxically, the insistence of a State to approve a GNSS element clashes with the associated responsibility to do so. There has been no effort so far to clarify the meaning of such approvals. It is equally understandable that a core constellation provider State does not want to sign up for any explicit acceptance of liability for providing a global service free of direct user charges as it is for a receiving State to not sign up to any explicit statement of acceptance of liability of matters that are outside of its control.

This paper proposes that a States' statement of approval of a GNSS element should also be limited to the matters that are under its jurisdiction. For this purpose, it is

[6] ICAO contracting States are obliged to "file differences", i.e., inform ICAO if they do not comply with any part of the standards in the Annexes which could have an impact on global safety and interoperability. Also, standards are agreed through a State Letter process where States can state their (justified) disagreements with the proposed standards. How differences are managed in the context of GNSS is subject to some interpretation apart from the expectation that for example the U.S.A. would file a difference to its own GPS standards if it would not meet them, as has been done on one minor item in the past.

[7] Several different terms are under discussion, such as "approved", "authorized", "certified", etc; for the purposes of this paper, only the term "approved" will be used.

instructive to consider the GPS performance standard [19, section 2.4.5]: it applies only in space, just where the signals are leaving the antennas of the space vehicles. Propagation issues due to solar activity or other factors in the local receiver environment are considered to be outside of the provider's control. Typical end-user performance is only indirectly indicated using representative error budgets. Although it is easy to accept that factors such as solar activity are also not under the control of the receiving State, they are subject to local variation and assessment and thus the interface of responsibility can be aligned with the performance standard. The following statements represent a proposed meaning of the act of State approval:

- A State safety oversight process is in place to verify that a core constellation provider is meeting its obligations as specified in Annex 10 (this role may of course be delegated, and some receiver States specifically encourage the provider States to self-declare such compliance [24][8].

- The impact of nominal atmospheric and solar disturbances (ionosphere, troposphere) has been assessed and found to be within error budgets agreed for particular levels of service [25].

- The radio interference environment has been assessed and measures are in place to ensure that aircraft can operate without being subject to undue interference (confirming adequacy of its radio regulatory environment as well as reactive capabilities in the case of interference events) [26, Appendix F].

- Contingency measures are in place to deal with non-nominal situations, such as reversionary terrestrial infrastructure, if considered necessary.

By performing these duties, which are in line with the GNSS Manual [26] and limited to things any individual State or group of States can assess and provide with reasonable effort, it could also be argued that a State is performing its duty of care, ensuring that operators can achieve the required service performance levels in their airspace. In other words, these proposed activities linked to a statement of approval could be seen as limiting liability rather than exposing a State to it. Having engaged in the activities listed above, it should be an easy argument to make that all has been done under its control to ensure safe operations, recognizing that in any complex technological system it is difficult to extrapolate to future performance based on historic analysis.

Another argument that could be made in the context of State approval would be to assert that a State should not prevent an aircraft to use navigation signals which can help ensure the safety of its operation. As has been seen in the case of KAL007 [27] and many others, correct awareness of position by pilots is a key factor in preventing accidents. While it is useful to recognize that unnecessarily withholding navigation signals which are in compliance with standards in Annex 10 is not in the interest of safety, this would be difficult to argue in a court of law. It can also be observed that liability issues could become rather complex as soon as aircraft GNSS receivers make use of multiple constellations. Therefore, the current status of GNSS liability and associated possible new arguments deserve further attention.

GNSS LIABILITY: AN UNSOLVABLE PROBLEM?

The ICAO LTEP ended in a gridlock between one side saying that existing legal provisions are sufficient, while others argued that they are not. A more recent review [28] provides a clear analysis that legal instruments (both at the international air and space law and the national tort law level) in case of an accident caused primarily by a malfunction of a GNSS core constellation signal would face an arduous uphill battle with little chances of success. Taking the example of a so-called Controlled Flight Into Terrain (CFIT) accident with significant loss of life due to erroneous aircraft guidance, the aircraft operator would be faced with liability from the families and relatives of the deceased passengers. This could be done easily under national tort law, where each passenger concluded a contract with the aircraft operator by purchasing a ticket. It would then be up to the aircraft operator to seek regress from those responsible for the provision of those navigation signals. This could involve a significant number of parties: the local ANS Provider, the regulator overseeing the ANS provider, the State which funds the GNSS core constellation system, the operator of the system itself, or also the aircraft and avionics manufacturers. In all these cases, it is not clear what the applicable legal framework, the specific tort law or even the appropriate court jurisdiction would be. Additionally, given that many of the involved entities are sovereign States, it is quite possible that such States would bring to bear a sovereign immunity defense. Given these uncertainties, in combination with the absence of case law in both the common law and the civil law context[9], such lawsuits would need to follow the applicable conflict of law rules. The outcome of such lawsuits would be highly unpredictable, thus likely requiring a lot of time and implying a lot of cost. But while there does exist quite clear argument that liability issues related to ANS provision using GNSS are

[8] A detailed discussion of GNSS safety oversight is outside the scope of this paper, but some basic principles are described in [26].

[9] In layman's terms, there are two basic law systems; civil law is more common in Continental Europe, common law in Anglo-Saxon countries, where case law has a more dominant role. The point here is that case law is also relevant under civil law, not only common law.

unsolved, the fact that the ICAO assembly resolution [10] tasking States to resolve them has not gotten any noteworthy attention over the course of many years with increasing use of GNSS, coupled with recent discussions in ICAO, it is also clear that States have very little appetite to restart such discussions. When faced with unsolvable problems, at least the possible reaction to them is simple: one can either accept the situation and live with the unsolvable problem, or something else needs to be done (in this case, stop using GNSS in aviation altogether – where current aircraft equipage makes this a rather preposterous proposition). So the subsequent question naturally becomes whether we can live with this unsolvable problem concerning GNSS liability? The following paragraphs will provide arguments as to why the answer to this question should be yes.

One of the key "problems" in this context is that GNSS core constellation signals are provided for free, without direct user charges. Discussions of legal issues are for example non-existent in the domain of satellite communications, where the aircraft operators have to pay fees directly to the providers of such services. It is understandable and not uncommon that providers of free services do not want to sign up to liability commitments. It is useful to recall that aviation has also made explicit statements in this regard, declining any possible obligation to pay for core constellation GNSS services [29, 30]. Therefore, if aviation, as one GNSS-user segment among many, would press for a more satisfying resolution of liability then it would only be fair to also review the associated charging policy. It would be unfortunate if government-furnished services providing significant operational benefits at a high cost-efficiency for aviation would have to be given up for fully commercial services.

Moving on to a more detailed analysis of the associated liability risk, over 20 years of aviation use of GPS and many more decades of only very few accidents where navigation systems have played a role in civil aircraft accidents underline that the risk of such accidents leading to liabilities are small. Even if Annex 10 maintains requirements on legal recording for all navigation systems, CNS system experts are generally not among the first responder team for an accident investigation [31]. In the case of GNSS, aviation has designed augmentation systems which have been designed to the best ability of international teams of experts to cater to all known system faults. The resulting standards are being adhered to through avionics certification standards and careful system oversight. While some of the faults that have occurred over the years certainly had a potential to cause accidents, currently implemented safeguards especially by the core constellation signal providers have typically stopped the possible fault-sequence early on and within a limited amount of time. From this point of view, it can be said that it would be very difficult to prove any willful or wrongful negligence, that would likely end up in a stalemate where the courts would have to weigh one expert advisors opinion against the expert advice from the other party. When this is compared to cases where entire ATC systems have shut down in busy terminal areas [32], the case of GNSS faults would seem like a relatively small risk that should be well-covered by normal ANSP insurance[10].

EXPANDING ON THE ICAO GNSS CHARTER

Some main principles of the GNSS charter are:

- Safety as the paramount principle;
- Uniformity of regulation to the highest practicable degree;
- Effective arrangements to minimize operational impact of system malfunctions; and
- Conformance with ICAO standards and associated timely aeronautical information, if necessary.

The current state of GNSS implementation has demonstrated that for GPS, safety performance, arrangements to minimize impact of system malfunctions, conformance with ICAO standards and the provision of aeronautical information are satisfactory, and can be expected to continue in this manner. Already today this seems to be less true for uniformity of regulation, given the struggle of many States to declare their GNSS approval status. Current positions underlying the development of multi-constellation GNSS applications within the ICAO Navigation Systems Panel threaten to undermine this uniformity further. Since the days of Marconi [33], radio signals have brought people together. Radio signals do not respect State boundaries, following the imagination of John Lennon [34]. While admittedly aviation frequency assignment practices often take such boundaries into account for terrestrial navigation aids, current multi-sensor avionics use such signals wherever they can be received, leaving the responsibility to judge the goodness of the navigation signal for use to the avionics. Inherent in the design of terrestrial navigation aid signals is the notion that they are usable wherever they can be received (IDENT can only be decoded when the modulation components are stable[11]). This is also the basis of aviation's enthusiasm for GNSS as a seamless system for all phases of flight [35].

As mentioned earlier, more detailed interpretation of the GNSS charter based on currently established GPS

[10] Evaluating aircraft accident insurance issues was not done in support of this paper, and would deserve some further work.

[11] Pilots, with support from avionics, should always first "identify" the correct tuning of a radio navigation facility before using it. This is done through the broadcast of an audible morse code in conventional navigation systems.

practice as a best practices benchmark is being pursued further [2, 22, 23]. In summary, it is expected to include the following elements:

- Inclusion of core constellation system performance aspects in ICAO Annex 10. This makes it an aviation system, also for the purposes of establishing its recognition as a safety service under the ITU radio regulations [36][12];

- Provision of detailed system performance standards and interface control documents. What may still require some further work are detailed methods on how to demonstrate that the system is meeting requirements which are essential to the performance of augmentation services;

- Provision of user support and notices of satellite outages;

- Aviation receiver certification standards based on sufficient insight into the system failure modes (Failure Modes, Effects, and Criticality Analysis, FMECA);

- Transparent communication and remedial action in case of system malfunctions.

While the above are provider obligations, the "receiver obligations" (here in the form of the ANS provider taking advantage of the GNSS signals in its service provision to airspace users), the corresponding duties have been outlined in the section above on State approvals. This additional guidance material would then serve as a sort of a substitute intermediary, replacing the need for formal, direct contracts with all ICAO contracting States (currently 191). They would mitigate liability risk and be in line with principles of sovereignty, while more explicitly establishing methods to approve GNSS elements in a given airspace. Moreover, these best practices underline safety as the paramount principle. But how far can they go in achieving the highest practicable degree of uniformity of regulation?

UNIFORMITY OF REGULATION

The purpose of uniformity of regulation is again safety: if pilots have to change their procedures when they fly from one State to another, the chances of those procedures being applied correctly diminish. Pilots are admonished to respect such regulations since this essential to limit the extent of their liability [37]. Because liability limits could be waved when pilots do not respect a State's GNSS element approval status, inherently pilots wish to comply, even if current equipage functionality does not cater for that. Safety rules have to be as simple as possible. This also reduces overall system cost, and is one of the main reasons for establishing ICAO standards in all aspects of international civil aviation. If now a receiver specific function to comply with differences in regulation is implemented in avionics, it does appropriately reduce the burden of the pilots, however, it is not without technical safety risks. Databases can be out of date, and receivers are subject to potentially complex mode switching, especially when flying near boundaries with different approval status, requiring multiple re-initializations while in flight. Furthermore, the number of receiver interfaces is multiplied, and database storage requirements will increase significantly beyond the current state of the art [38]. Most importantly, the expected gain in system robustness from introducing multi-constellation GNSS will largely be nullified. It is impossible to make a convincing argument for safety reasons that a GNSS element considered safe in one region of the world should not be safe in another, since core constellation performance is largely uniform globally by nature (some differences do exist as a function of latitude). Of course what underlies this assessment is the assumption that appropriate compliance with standards has been verified. So rather than pursuing a clearly non-optimal technical solution, it is suggested that energy should instead be devoted towards ensuring this standards compliance in a cooperative manner. Maintaining a generous positive margin between claimed and achieved performance will remain important to ensure that such standards compliance does not become the subject of intense expert debate.

LINK TO PBN PRINCIPLES

It is widely recognized that the implementation of PBN has led to significant operational benefits, including more efficient routing and reduced environmental impact. GNSS based on single-frequency GPS L1 and Receiver Autonomous Integrity Monitoring (RAIM) is currently the principal enabler of all PBN specification, and also essential to Aircraft Dependent Surveillance – Broadcast (ADS-B). These receivers are still mostly based on a supplemental means certification standard [39], while it is clear that the role of GPS L1 is becoming a primary system, where conventional navigation aids provide a reversionary role instead of vice-versa. PBN remains for the most part a horizontal, en-route and terminal area navigation application, and has only recently started to expand into the approach domain. When it comes to approaches with vertical guidance in low visibility conditions, due to the associated increased criticality of operations, it is recognized that the enabling system safety standards need to be more prescriptive. But even there, the notion of XLS has been established, where the X stands for the corresponding technology (Instrument,

---

[12] GNSS is classified as a "Radio Navigation Satellite System", which is not considered to be a safety system with additional protection to guarantee interference-free operation. Only the aeronautical use of GNSS is considered a safety use for ITU purposes under the RNSS allocation.

Microwave or GNSS). While this is a more recent development, the concept of multi-sensor navigation for horizontal navigation has already a long history. A somewhat similar case to GNSS are DME's, or Distance Measuring Equipment, providing range measurements to aircraft, based on interrogating terrestrial transponders. PBN uses DME up to a maximum range of at least 160NM, where the individual facility Designated Operational Coverage (DOC) is often much smaller. The use of such ranging signals outside of the frequency protected range, while not without its own complexities, has been accepted, since there has been no mechanism for avionics to know what the official usable range is. To change this, a new, more appropriate facility information data field has been defined for ARINC 424 [40] (the aeronautical database message format definition), but never implemented – in part for sure because it has never been made a requirement through regulation. As a result, an avionics navigation solution based on multi-DME ranging will often contain sources from several different States, especially when operating at altitude. It can be speculated that this has been accepted because it normally involves only neighboring States, but nonetheless so far this has not raised a discussion on sovereignty and liability as has been the case for GNSS. While improving the connection between assured facility coverage and its operational use in avionics would certainly have merit, using signals where available remains a fundamental tenet of PBN to ensure seamless and continuous navigation around the globe without an excessive regulatory burden; that is the main motivation behind the effort to globally agree a limited set of navigation specifications to support PBN. Also from the point of view of efficient use of radio spectrum, it does not make sense to artificially limit the use of aeronautical navigation signals to an area that is significantly smaller than the coverage that is actually provided.

This discussion of established PBN principles is provided to make the point that certainly for the en-route and terminal area use of horizontal positioning, an unconstrained possibility to combine ranging sources has been key to its success. When it comes to final approach operations with their higher level of safety-criticality, there is always a need for the aircraft to receive a final approach path definition, whether this be through an aeronautical database (which has limits in the achievable integrity level[13]) or through the system itself (GBAS, ILS). Through that path definition it then also makes sense to specify the system which supports the operation. The available augmentation systems to support such operations when based on GNSS will automatically limit the available core constellations. For example, EGNOS (the European version of SBAS) today only provides corrections for GPS, consequently, the use of core constellation signals when flying an EGNOS approach will naturally be limited to GPS. If States wish to be more prescriptive on the use of core constellation signals on final approach with vertical path guidance, the problem will easily resolve itself through the corresponding approach chart publication. This is clearly not the case for horizontal-only navigation.

SUMMARY

This paper has revisited the link to sovereignty principles for the provision of ANS using multiple GNSS core constellations. It is argued that sovereignty concerns can be fully mitigated through the provision of terrestrial reversionary navigation infrastructure, while in the case of GNSS, it should motivate States to approve as many core constellation signals as possible, as long as it can be established that they comply with the appropriate standards. While the analysis agrees that States do retain the right to approve which signals are being used by aircraft operating within their airspace, it is argued that this stems primarily from the State's responsibility for safety (through article 12 CC) rather than to satisfy sovereignty. When it comes to liability, arguments have been provided which make the case that mitigation of this risk comes through ensuring compliance with standards as well, and that any residual risks are small and insurable, especially when considering the alternatives which would question the premise of aviation using core constellation signals free of direct user charges. An interpretation of the meaning of State approval of GNSS core constellation signals has also been provided, limiting this responsibility (and the corresponding interpretation of the extent of its liability) to things which can be assessed and controlled by the State itself.

In terms of practical implementation, to help States become comfortable with these arguments, the ICAO GNSS charter principles (in particular safety and uniformity of regulation) should be expanded by adding appropriate guidance spelling out the interpretation of these principles based on established best practice with GPS. This should serve as a benchmark for other constellations in providing services to aviation, hopefully enabling the future implementation of a fully robust, optimal GNSS without artificial limitations to the best use of navigation signals. It is hoped that this will be possible especially for horizontal positioning applications, avoiding the need to implement geo-referenced GNSS element tuning.

Further work should consequently focus on improving performance metrics for GNSS core constellations in supporting specific augmentation systems, as is being envisioned by Advanced RAIM developments to support future multi-constellation GNSS use. Emphasis is made there for example on demonstrating compliance of core constellations with the assumed ranging performance and

[13] Of course SBAS gets around this issue by means of the Cyclic Redundancy Check (CRC) algorithm. The point here is that with multiple interfaces across the avionics architecture, current database structures may not lend themselves easily to accommodating geo-tuning complexities.

satellite and constellation fault probabilities. To generate global agreement on such values, an approach similar to that used for Reduced Vertical Separation Minima (RVSM[14]), where regional organizations cooperate globally to ensure compliance to a Target Safety Level (TSL), could be used. Such mechanisms for GNSS should help to extend the Chicago Convention principles of non-discrimination (article 11 CC) and mutual recognition of certificates (article 33 CC) to GNSS core constellations in a manner that can be acceptable to all ICAO contracting States. Whatever the outcome in terms of future multi-constellation GNSS receiver functionalities and the preservation of the associated benefits, it is recommended that a practical and balanced view of all relevant ICAO principles must prevail. The current interim conclusion to require State-specific approval based receiver tuning does not seem to be based on such complete reasoning. This paper can hopefully make a first contribution towards such a balanced approach.

ACKNOWLEDGMENTS

This work has been performed in part under GSA GRANT Agreement No. 2 of GSA/GRANT/EGNOS/02/2014.

DISCLAIMER

This paper does not contain any official EUROCONTROL position or policy.

REFERENCES

[1] ICAO, date, Assembly Resolution 32-19, TBC, Montreal, Canada

[2] ICAO, June 2017, GNSS Concept of Operations (CONOPS), Working Paper 16, 2nd Joint Working Groups Meeting of the ICAO Navigation Systems Panel, Montreal, Canada

[3] ICAO, 2013, Performance Based Navigation Manual, DOC 9613, Fourth Edition, Montreal, Canada

[4] ICAO, July 2010, Aeronautical Information Services, Annex 15 to the Chicago Convention, 13th Edition, Montreal, Canada

[5] ICAO, 19-30 November 2012, Report of the Twelfth Air Navigation Conference, DOC 10007, Recommendation 6/6b, Montreal, Canada

[6] R. Farnworth, 12-14 September 2017, GNSS Information in AIP, Agenda Item 6.3a, Joint 25th EUROCONTROL Navigation Steering Group and 12th ICAO EUR Region PBN Task Force Meeting, Brussels, Belgium

[7] ICAO, 2006, Convention on International Civil Aviation, DOC 7300, 9th Edition, first signed at Chicago 7 December 1944, Montreal, Canada

[8] ICAO, 2007, Global Air Navigation Plan, 3rd Edition, DOC 9750, Appendix C, Montreal, Canada

[9] ICAO, July 1994, Report of the 29th Session of the Legal Committee, DOC 9630, Montreal, Canada

[10] ICAO, October 2013, Development and elaboration of an appropriate long term legal framework to govern the implementation of GNSS, Assembly Resolutions In Force, A32-20, DOC 10022, Montreal, Canada

[11] ICAO, October 2013, A Practical Way Forward on Legal and Institutional Aspects of CNS/ATM, Assembly Resolutions In Force, A35-3, DOC 10022, Montreal, Canada

[12] ICAO, July 1996, Radio Navigation Aids, International Standards and Recommended Practices, Annex 10 to the Convention on International Civil Aviation, Volume 1, 6th Edition, Montreal, Canada

[13] ICAO, 28 July 2004, Report on the Establishment of a legal framework with regard to CNS/ATM systems including GNSS, 35th Session of the Assembly, Working Paper 75, Montreal, Canada

[14] London Economics, April 2017, Economic Impact to the UK of a disruption to GNSS, available on https://www.gov.uk/government/publications, Innovate UK, London, UK

[15] Department of Homeland Security, June 2013, National Risk Estimate: Risks to U.S. Critical Infrastructure from Global Positioning System Disruptions, available on https://rntfnd.org, Unclassified Version, USA

[16] M. Scaramuzza, G. Berz, 6 October 2001, Does the US DoD alter the GPS Constellation for Optimized Performance in Theaters of War?, GPS Constellation Report, skyguide Swiss Air Navigation Services Ltd, Zurich Airport, Switzerland

[17] U.S. Presidential Decision Directive, December 2004, U.S. Space-Based Positioning, Navigation and Timing Policy, available on http://www.gps.gov/policy, Washington DC, USA

[18] U.S. Government, 28 June 2010, National Space Policy of the United States of America, available on https://obamawhitehouse.archives.gov, Washington DC, USA

[19] U.S. Department of Defense, September 2008, Global Positioning System Standard Positioning Service Performance Standard, GPS SPS PS, 4th Edition, available on http://www.gps.gov, USA

---

[14] RVSM reduces the vertical spacing of so-called flight levels from 2000ft to 1000ft increments, also at higher altitudes. Careful monitoring of barometric altimetry performance of aircraft is essential to RVSM.

[20] GPS Directorate, 9 December 2015, GPS Directorate Systems Engineering & Integration Interface Specification IS-GPS-200, IRN-IS-200H-003 (and others), available on http://www.gps.gov, USA

[21] T. Stansell, 22 September 2009, SVN-49 Signal Anomaly, 49th Meeting of the Civil GPS Service Interface Committee, Savannah GA, USA

[22] G. Berz, November 2013, GNSS/ABAS Service Provision Requirements in Multi-Constellation Context, ICAO Navigation Systems Panel Working Group of the Whole, Working Paper 36, Montreal, Canada

[23] F. Salabert, June 2017, Next Generation GNSS CONOPS: Open Issues Section 7, Service Provision and State Approvals of GNSS Elements, ICAO Navigation Systems Panel, 2nd Joint Working Group Meeting, Information Paper 20, Montreal, Canada

[24] FAA William J. Hughes Technical Center, July 2017, GPS SPS Performance Analysis Report, Report Number 98, WAAS T&E Team, Atlantic City NJ, USA

[25] ICAO, December 2006, Ionospheric Effects on GNSS Aviation Operations, Navigation Systems Panel, White Paper, Montreal, Canada

[26] ICAO, 2013, Global Navigation Satellite System (GNSS) Manual, Doc 9849, 2nd Edition

[27] Korean Air Lines Flight 007, see https://en.wikipedia.org/wiki/Korean_Air_Lines_Flight_007

[28] F. Bergamasco, November 2014, GNSS Liability: Current Legal Framework and Perspectives for the Future from the International Aviation Point of View, The European Air Law Association, EALA Prize Paper, 26th Annual Conference, Oslo, Norway

[29] ICAO, 2013, Manual on Air Navigation Services Economics, DOC 9161, Fifth Edition, Chapter 5, Part J, Montreal, Canada

[30] ICAO, 2007, Report on Financial and Related Organizational and Managerial Aspects of GNSS Provision and Operation, DOC 9660, Montreal, Canada

[31] ICAO, July 2016, Aircraft Accident and Incident Investigation, Annex 13 to the Convention on International Civil Aviation, Eleventh Edition, Montreal, Canada

[32] Reuters, 12 May 2014, Exclusive: Air Traffic System Failure Caused by Computer Memory Shortage, see https://www.reuters.com/article/us-airtraffic-bug-exclusive/exclusive-air-traffic-system-failure-caused-by-computer-memory-shortage-idUSBREA4B02320140512

[33] G. Marconi, see https://en.wikipedia.org/wiki/Guglielmo_Marconi

[34] John Lennon, Imagine, see https://en.wikipedia.org/wiki/Imagine_(John_Lennon_song)

[35] ICAO, 2014, 2013-2028 Global Air Navigation Capacity and Efficiency Plan, 4th 2014-2016 Triennium Edition, DOC 9750, Montreal, Canada

[36] International Telecommunications Union, 15 July 2010, Report of Activities of the Correspondence Group on RNSS Systems, ITU Doc 4/141E, ITU-R Study Group 4, Geneva, Switzerland

[37] Convention for the Unification of Certain Rules Relating to International Carriage by Air, Warsaw, 1929 and Convention for the Unification of Certain Rules for International Carriage by Air, Montreal, 1999

[38] G. Berz, October 2016, ARAIM and Geo-Selection: A First Look, Advanced RAIM Technical Subgroup, Working Group C, EU/US Cooperation on Next Generation GNSS, Stanford University, Palo Alto CA, USA

[39] FAA, 20 February 1996, TSO-C129a, Airborne Supplemental Navigation Equipment using the Global Positioning System (GPS), Technical Standard Order, Federal Aviation Administration, Aircraft Certification Service, Washington DC, USA

[40] ARINC, December 2011, Navigation System Database, ARINC Specification 424-20, DME – Operational Service Volume, AEEC, Aeronautical Radio, Inc, Annapolis MD, USA

ADDITIONAL (UNPUBLISHED) REFERENCES

[A1] F. Bergamasco, Historical Development of the GNSS Legal Framework for International Aviation and its Current Regulatory Issues, EUROCONTROL ATM/RDS/NAV, 2017 (note 1)

[A2] F. Bergamasco, The Impact of GNSS on State Sovereignty: Multi-Constellation GNSS as the Way Out from the Institutional Impasse, EUROCONTROL ATM/RDS/NAV, 2017 (note 1)

[A3] F. Bergamasco, The Authorization of GNSS System Elements, EUROCONTROL ATM/RDS/NAV, 2017 (note 1)

Note 1: These papers are available upon request from the authors (email addresses are on the title page of this paper). This applies also to some references in the main reference section where the material may not be generally accessible (but not to references which need to be purchased from ICAO).

30th International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+

Portland, OR, USA, 26-29 September 2017