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2.2: Addressing safety risks related to evolving aviation technologies

MODE N – RESILIENCE AND SPECTRUM EFFICIENCY FOR FUTURE NAVIGATION

(Presented by Germany)

EXECUTIVE SUMMARY

This paper presents information on progress made by Germany regarding an effective Alternative Positioning, Navigation and Timing (A-PNT) system concept developed with the goal of maintaining services to aircraft in the event of a global navigation satellite systems (GNSS) signal loss, improving radio spectrum efficiency and discouraging intentional interference attempts by reducing the operational impact of interference.

The Mode N, or Mode Navigation, concept as detailed in this paper is the result of a joint civil-military aviation program.[1] By combining backward compatibility with conventional systems, easy transition to a new system without a fixed sunset date, simple exchange of avionics and improved spectrum efficiency, Mode N qualifies as a promising A-PNT candidate. It has the potential to complement and, in future, replace the currently used distance measuring equipment (DME). This paper provides a description of the motivations to develop Mode N, the system concept and expected benefits. It additionally discusses the participation of international partners in finding a shared path ahead.

1. INTRODUCTION

1.1 The introduction of performance-based navigation (PBN) procedures in Germany is a key enabler for increasing efficiency, reducing environmental impact, increasing capacity, and improving airport access. The operational use of these procedures relies on the global navigation satellite system (GNSS) as the primary source for positioning, navigation and timing services.

1.2 GNSS signals are vulnerable to certain interference threats. This can be due to radio frequency interference (RFI) or certain natural phenomena. RFI can be unintentional (equipment failure or operator error) or intentional (jamming or spoofing), caused by a variety of actors from governmental organizations in the context of military or security operations (c.f. ITU Resolution 676 (WRC-23)) to individuals aiming for privacy. To mitigate the risk of service loss, there is a need for alternatives when

[1] Supported by German air navigation service provider (DFS), the Bundeswehr Technical Center for Aircraft and Aeronautical Equipment (WTD61), and an engineering partner Interdisciplinary Engineering Consultants Madritsch (IECM). [Bundeswehr: German Armed Forces]

GNSS cannot be used to provide positioning for PBN. Thus, to ensure safe and secure operations for both civil and military airspace users, the availability of a robust and resilient A-PNT system to backup GNSS in case of jamming, spoofing or technical failure, is essential.

1.3 Current PBN transition activities in Europe following Commission Implementing Regulation (EU) 2018/1048 rely on DME/DME multilateration as a terrestrial A-PNT solution. According to recent decisions made by the North Atlantic Treaty Organization (NATO), the terrestrial navigation solution for military air traffic is still formed by the Tactical Air Navigation (TACAN) system. The radio spectrum is a scarce resource with finite capacity limits. In the core area of Europe, the frequency band 960 - 1215 MHz is heavily congested and the demand of DME and TACAN channels exceeds the available resources. Rolling out additional DME facilities to ensure sufficient DME/DME coverage, especially for RNAV-1 operations in terminal airspace, is becoming more and more challenging. Therefore, technological solutions for the provision of A-PNT services beyond DME/DME are being discussed (e.g., eLORAN and LDACS-Nav). By combining improved spectrum efficiency, backward compatibility with legacy systems, easy transition to a new system without a fixed sunset date and simple exchange of avionics, Mode N qualifies as one of the most promising A-PNT candidates.

1.4 The band 960 - 1215 MHz (L-band) is a primary aeronautical frequency band and is used intensively to support a number of systems for civil and military purposes. The use of this band by aeronautical systems is based on primary allocations agreed within the International Telecommunication Union (ITU) to the Aeronautical Radio Navigation Service (ARNS, e.g., used by DME, TACAN, SSR, potentially for Mode N), and the Aeronautical Mobile Route Service (AM(R)S, used potentially for the L-band Digital Aeronautical Communications System (LDACS)). Moreover, the sub-band 1164 - 1215 MHz is also allocated to the Radio Navigation Satellite Service (RNSS, e.g., used by GPS L5, GALILEO E5).

1.5 These aeronautical systems in the band utilize a primary allocation because they provide Safety of Life Services and harmful interference to them must be avoided. In addition to the legacy systems in the L-band, other systems to be introduced to the band need a thorough assessment of compatibility with existing aeronautical systems in the band. Although the aeronautical L-band is already congested in many regions, new systems which are projected to use this band are under standardization. They will increase spectrum load and radio frequency congestion even further. Under these conditions, the interoperability of systems must be ensured, and all potential incompatibility issues must be resolved before new systems can be brought into operation.

1.6 New systems intended for operation in the L-band are meant not only to improve the performance of legacy services but also to provide functions to reduce the spectrum load generated by onboard and ground-based installations, and with a long-term view to enable spectrum access for future aviation use. When introducing new systems and applications, it is essential to provide a seamless transition to the new environment while providing support for the legacy system that will be replaced. The timeline for standardization and implementation effort needs to be considered, changes to avionics should be minimized and allow gradual implementation. Figure 1 illustrates the current usage of the L-band. Future systems, such as Mode N and LDACS, are already included to complete the picture.

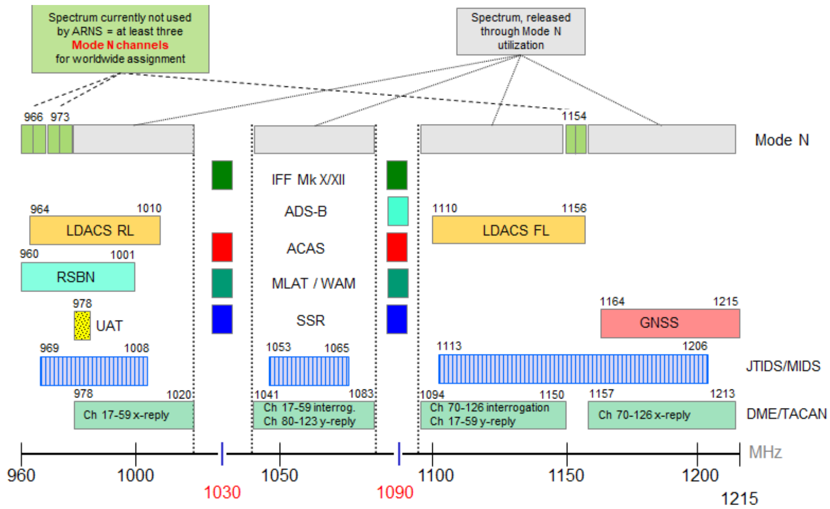

Figure 1. Overview of utilization of the aeronautical L-band

1.7 The assessment of the spectrum efficiency of an aeronautical communications, navigation and surveillance (CNS) system is complex. The spectrum efficiency of a pure communication system is often judged by the raw amount of data that is transferred per unit of time for a given bandwidth. On the other hand, the spectrum efficiency of navigation and surveillance systems is to be judged by the range and/or azimuth accuracy to be achieved with a signal for a given bandwidth. The aeronautical navigation systems DME and TACAN are the least efficient systems in the L-band since they occupy a wide part of the band, but only achieve a coarse range accuracy (in the case of TACAN also bearing accuracy).

1.8 Since secondary surveillance radar (SSR)/Mode S-based systems transmit significantly more information in a compressed form requiring much less bandwidth, they can achieve a much better ranging accuracy than DME and TACAN.

2. DISCUSSION

2.1 Mode N is a new concept for a terrestrial system to provide navigation service by substituting DME with a system based on SSR/Mode S signal formats while retaining legacy DME functionality. Since Mode N is designed to operate on a single frequency and employs error detection and correction algorithms, it enhances sharing possibilities with other L-band systems. The electromagnetic compatibility of Mode N onboard aircraft is supported by utilizing L-band frequencies 960 - 977 MHz and 1151 - 1156 MHz, which allow for the provision of a meaningful frequency separation to other aeronautical systems operating in the band. Further studies on radio-regulatory and detailed technical aspects of frequency assignment planning have to demonstrate that Mode N can be accommodated in existing allocations to the aeronautical mobile and radionavigation services. Significant spectrum benefit can be gained when Mode N fully substitutes DME in the long term.

2.2 Mode N is based on the multilateration (MLAT) principle to measure the time difference of arrival (TDOA) of signals transmitted by Mode N ground stations which are received by the aircraft Mode N system. The frequency-agile multimode Mode N aircraft system can also selectively interrogate Mode N ground stations if additionally two-way slant range measurements are necessary. Mode N could one-to-one replace the existing aircraft DME interrogator. Thus, there is no requirement for additional space or an additional antenna to be integrated into an aircraft. Mode N uses existing SSR/Mode S signal and data transmission specifications already globally defined in ICAO Standards. This shortens standardization and design time compared to the standardization and implementation of a completely new system.

2.3 Mode N can not only be used in commercial and general aviation but also flexibly and/or spatially limited for special applications where a terrestrial GNSS backup is a prerequisite for operation and to ensure safety and security. An example would be urban areas or airspaces that will be used by uncrewed aircraft.

2.4 **System Concept**

2.4.1 The technical functionality of Mode N is sometimes called “reversed MLAT”. In the following it is explained what the commonality with MLAT is and what is reversed.

2.4.2 In ground-based MLAT systems, several ground stations, synchronized in time, receive a signal from an aircraft. Due to the different ranges from the aircraft to the ground stations, the signal arrives at different times at the individual ground stations. The time differences between signal arrivals and pseudo-ranges respectively are used to calculate the position of the aircraft. Mode N reverses this method. Several ground stations, synchronized in time, broadcast signals to aircraft. The aircraft’s onboard receiver measures the time differences between signal arrivals and calculates its own airborne position.

2.5 **Time Synchronization**

2.5.1 All Mode N ground stations are synchronized in time. The time synchronization source is a local high precision clock at each ground station which is disciplined to reference stations within the Mode N network. Although it is not necessary for the navigation function of Mode N, the ground stations also provide time that is synchronized to UTC realized by a connection to timing systems, such as terrestrial long-wave radio clocks or time distribution networks (e.g., fiber optic) or satellites. If GNSS is available, it can also be used for this purpose. Time synchronization information Is distributed via Mode N ground stations radio frequency (RF) interlinks. The Mode N ground stations are organized in a tree structure with a reference ground station on top of the tree, see Figure 2. It is possible to have multiple reference stations in the ground station network.

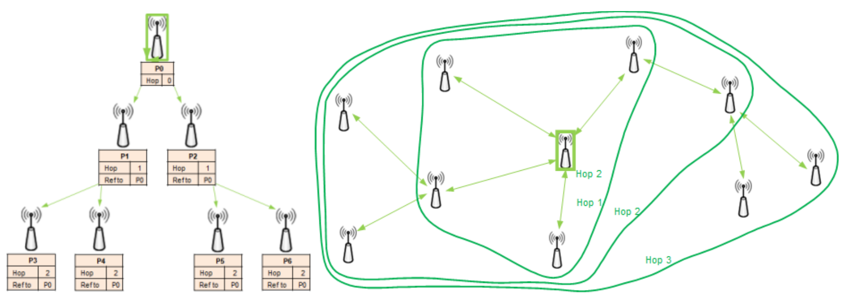

Figure 2. Principle of the Mode N time synchronization network

2.6 **Signal Characteristics**

2.6.1 Mode N utilizes a Time Division Multiple Access (TDMA) method known as slotted ALOHA protocol [1] to synchronize its ground station network and send Mode N Squitter to the aircraft. As a prerequisite for position calculation onboard the aircraft, the ground stations broadcast the following information in the Mode N Squitter:

a) ground station’s antenna location in WGS-84 coordinates;

b) antenna’s geometric height;

c) time of transmission;

d) a unique ground station identifier (ID) that allows the aircraft system to identify the received ground station and retrieve ground station specific data from an onboard navigation database, if available; and

e) the operational status of the ground station.

2.6.2 The messages used for information distribution are based on the Mode S signal structure as depicted in Figure 3. The message content is Mode N specific. Figure 4 shows the Mode N Squitter as an example. All messages are defined in detail in the "Mode N Basic Design Document" [2].

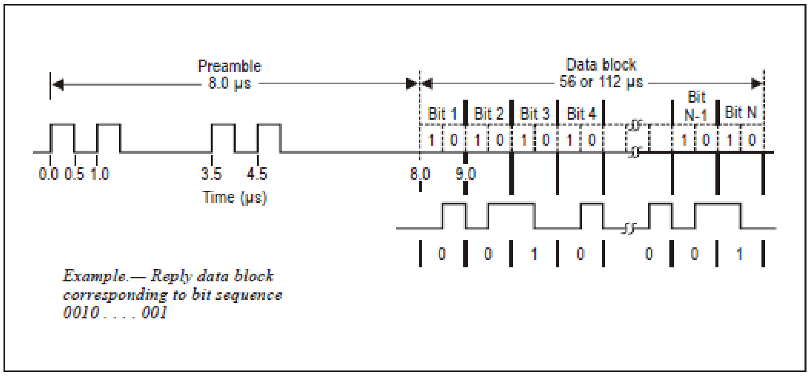

Figure 3. Mode N signal structure derived from SSR/Mode S, standardized in ICAO Annex 10, Volume IV

Format **0**	Station ID	Time Offset	LAT	LON	Height (HAE)	Sync	CRC
3 bit	15 bit	7 bit	25 bit	25 bit	12 bit	1 bit	24 bit

Figure 4. Mode N Squitter message (112 μs Data block)

2.7 **Passive and Active Operation**

2.7.1 The aircraft's position determination is carried out completely passively by receiving Mode N Squitter and without any need for active interrogations by the aircraft. Obviously, this mode of operation offers some advantages especially for military applications.

2.7.2 As a complement to passive position determination, an active mode is also possible. The Mode N aircraft system uses the ground station ID to selectively interrogate the desired ground station with a ranging request. The addressed ground station replies with a ranging reply. Both formats together are used in such an interrogation-reply sequence to:

a) induce more Mode N Squitter from the ground to accomplish the TDOA measurements - integrity enhancement;

b) precisely synchronize the aircraft's Mode N system clock with the ground station clock and enable the time of arrival (TOA) measurements - accuracy enhancement;

c) mitigate a ground station synchronization loss - safety enhancement;

d) verify the ground station's position in case of reasoned doubts about the correctness - security/integrity enhancement; and

e) determine the aircraft's position with a two-way ranging method, using slant ranges instead of TDOA; This could mitigate an insufficient number of available ground stations for passive operation in low altitudes (e.g., approach and landing phase).

2.8 **Accuracy**

2.8.1 The Mode N position accuracy is dependent on the TDOA accuracy, the geometry of the spatial distribution of ground stations and the position of the aircraft to the ground stations. The dilution of precision (DOP) is an indicator of the system's performance and must be considered for the complete intended Mode N coverage area and ground station topology versus the required performance. However, the achievable position accuracy is proven by wide area multilateration systems (WAM) for ATC operations, which use the same principle as Mode N and provide a spatial accuracy of 30 to 50 meters.

2.9 **Integrity Considerations**

2.9.1 The integrity of the data content exchanged in Mode N messages is ensured by error detection and correction methods as already defined in the relevant standardization documents of ICAO [3] and the standardization bodies of the aviation industry [4].

2.9.2 The Mode N navigation integrity concept consists of several methods to check the continuous and error-free functioning of the system and thus guarantees a reliable navigation solution, including reporting capability. The following methods used between aircraft (Air) and ground station (Gnd), onboard the aircraft and between ground stations, as well as their combination, make the Mode N system reliable against malfunctions within the system and interferences from outside:

a) Authentication (Gnd-Air);

b) Autonomous Integrity Monitoring (Air);

c) Status Reports (Gnd-Air);

d) Active Probing (Air-Gnd); and optional

e) Database Comparison (Air).

2.10 **Implementation Options - Airborne Component**

2.10.1 A new development allows some freedom in the design of the system. Instead of having separate devices installed onboard an aircraft (e.g., SSR/Mode S transponder, DME, the airborne collision avoidance system ACAS, and LDACS), it is possible to combine such L-band systems in one box, see Figure 5.

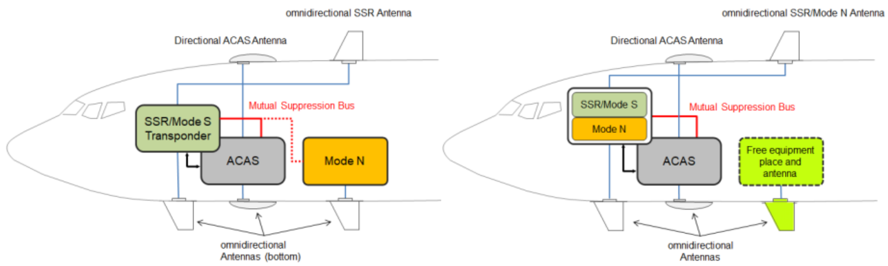

Figure 5. DME substitution by an external (left) or internal (right) Mode N box

2.10.2 Mode N operates on frequencies supporting the provision of a larger frequency separation to SSR/Mode S compared to other legacy systems (c.f. Figure 1). This provides for the ability to function satisfactorily in an electromagnetic environment onboard an aircraft resulting in a reduced need for onboard mutual suppression. Furthermore, SSR transponder availability can be improved because SSR/Mode S and Mode N can operate in parallel. In addition, a single box design will save installation space. Mode N can co-exist with a ground DME infrastructure, once the Mode N frequency is selected either regionally or worldwide. In terms of transition its use is flexible and not bound by a fixed date for its introduction.

2.11 Implementation Options - Ground Component

2.11.1 The installation and distribution of ground stations can be based on existing ground installations (e.g., CNS sites). Results of a preliminary study show that current DME sites in Germany can be used for Mode N installations providing gap-free navigation coverage at 5 000 ft and above. However, in this case, additional ground stations or time beacon sites are needed to close gaps in a RF-based time synchronization network. In a recent study, the Mode N ground station network was remodeled and optimized. That study demonstrated that a ground station network of 35 stations in Germany is sufficient to provide RF time synchronization and a navigation coverage at FL100 and above. Time beacons are not required for this type of network, see Figure 6.

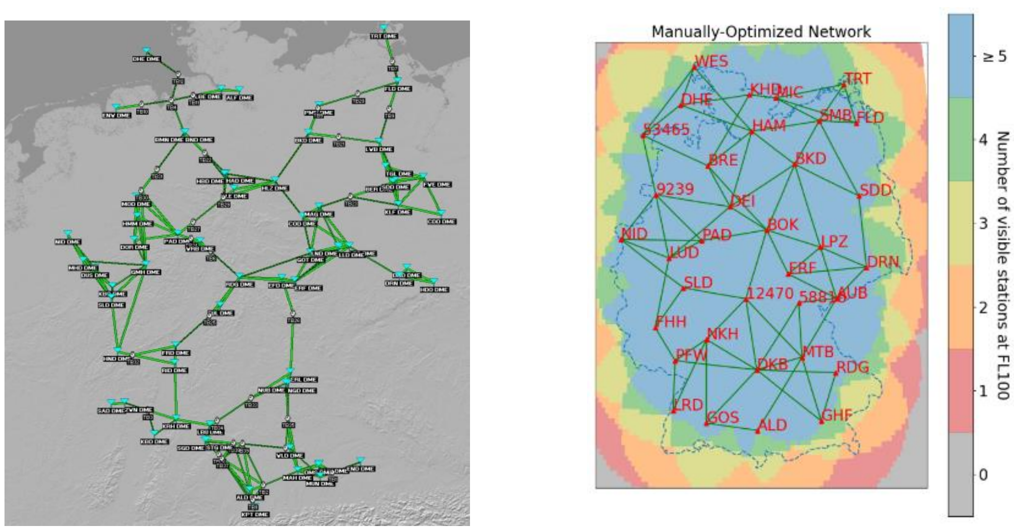

Figure 6. Potential German Mode N network using existing DME sites and time beacons (left) vs. a model-based optimized distribution (right)

2.12 Applications beyond A-PNT: Uncrewed Aircraft

2.12.1 In addition to being used for global navigation and as an A-PNT for commercial and military aviation, Mode N is also capable of providing navigation for other user groups such as general aviation, air taxis and uncrewed aircraft (UA). Air taxis and delivery drones are planned to be operated in urban areas where interruption of satellite service for navigation will have a significant safety and/or security impact. Mode N as GNSS backup can resolve this problem. The idea is to create a navigation environment specifically for this dedicated user group. The application case for uncrewed aircraft would be a “spatially (and possibly temporally) flexible” Mode N system that is specially developed for the target airspace at low altitudes. Recent technical developments show that software defined radio (SDR)-based Mode N devices are so small and lightweight that they can be carried on small drones or even become integrated as a chip.

2.13 Applications beyond A-PNT: Mode N as Surveillance Backup

2.13.1 Mode N can also be used as an ADS-B backup since Mode N-equipped aircraft provide position information independent of GNSS availability. The advantages are (1) the Mode N position can be used as a redundant onboard position source for ADS B data and transmitted via an ADS-B link (e.g., 1090ES, UAT), and (2) the Mode N position derived onboard can be directly transmitted from the aircraft through the Mode N ground station network as redundant surveillance information. As it is synchronized in time, the Mode N ground station network can provide position information from active Mode N aircraft systems by multilateration in the same way as conventional MLAT systems. For the transfer of surveillance data from Mode N ground stations to the user, a suitable ground communication network must be available.

2.14 Expected Benefits

2.14.1 The advantages of Mode N are not limited to navigation. The Mode N design combines the benefits, technical parameters, and functionality of Mode N, DME, ADS-B and MLAT in one system. It offers a variety of benefits with respect to efficient spectrum use, the transition from legacy to the new system, and new applications, such as A-PNT. It provides the opportunity to introduce new and reassign legacy systems within the L-band without frequency/channel competition or limitations due to legacy systems. Mode N is a system concept that opens the opportunity to be used globally in civil and military applications in the future. The benefits of a Mode N system are:

a) continuous operation of CNS systems relying on GNSS, e.g., ADS-B while GNSS is not available;

b) common civil and military utilization without any restrictions and provision of common ATC procedures, e.g., PBN;

c) introduction of new systems providing more capacity and safety/security due to removal of legacy systems’ bandwidth limitations;

d) single channel operation on unused L-band frequencies provide system-inherent frequency compatibility to legacy L-band systems. This could:

    1) gradually release a significant number of DME channels,

    2) decrease the demand and reduce the RF load on 1030/1090 MHz by reassigning of legacy services, including military ones,

    3) allow additional channels to be established for new CNS systems (system enabler).

2.14.2 The Mode N aircraft system:

a) provides, beside Mode N, also DME and TACAN interrogator functionality for legacy navigation support in areas without Mode N ground infrastructure;

b) allows a flexible use of the system in a diverse ground environment (DME-only, DME/Mode N mixed, pure Mode N) and therefore offers a smooth transition from a DME to a Mode N infrastructure without a “fixed sunset date”;

c) operates passively but can also interrogate ground stations of interest with adjustable power needed for a safe link, offering an additional reduction of spectrum impact;

d) is intended to replace the existing onboard DME or TACAN interrogator. Neither additional space nor an additional antenna is needed to install Mode N on an aircraft; and

e) reduces onboard interference and mutual suppressions by the ability to operate also during SSR/Mode S transmissions and hence improve transponder availability.

2.14.3 Mode N ground station hardware is as easy to deploy as DME or ADS-B ground systems, for example. Mode N can utilize existing CNS sites and infrastructure as necessary, including onsite hardware such as DME antenna, communication and power supply infrastructure, and cabling. Mode N uses existing ICAO standards and specifications for SSR/Mode S signals and data transmission. This significantly shortens standardization and design time compared to the standardization and implementation of a completely new system. Mode N is an A-PNT system for a terrestrial GNSS backup that may enable a significant release of spectrum within the L-band.

2.15 **Current Development Status**

2.15.1 In 2012, the Mode N idea was published in the research magazine of DFS Deutsche Flugsicherung (DFS) the first time and was updated in 2017 including new developments [5]. The development of the “Mode N Basic Design Document” [4] started in 2014, which was further developed in the Single European Sky ATM Research (SESAR) program in 2015 [6]. As a result, Mode N has been set as a long-term solution for an A-PNT system in the EUROCONTROL Civil-Military CNS Interoperability Roadmap [7]. In 2015, the detailed work started on signal formats, time synchronization, and system design. Signal generation and reception was successfully tested with software defined radios (SDR) [8]. The layout of a Mode N ground station system, the detection of gaps in the navigation coverage and the development of a time synchronization network were topics in a study, which ended with positive results in early 2017 [9].

2.15.2 In 2018, the four-year national aviation research project FUTURE / NexT CNS started, where DFS together with industry partners developed a Mode N testbed for performance tests based on Adalm-Pluto SDRs from National Instruments, see Figure. 7 and Figure 8.

Figure. 7. Adalm-Pluto SDR with added time synchronization board

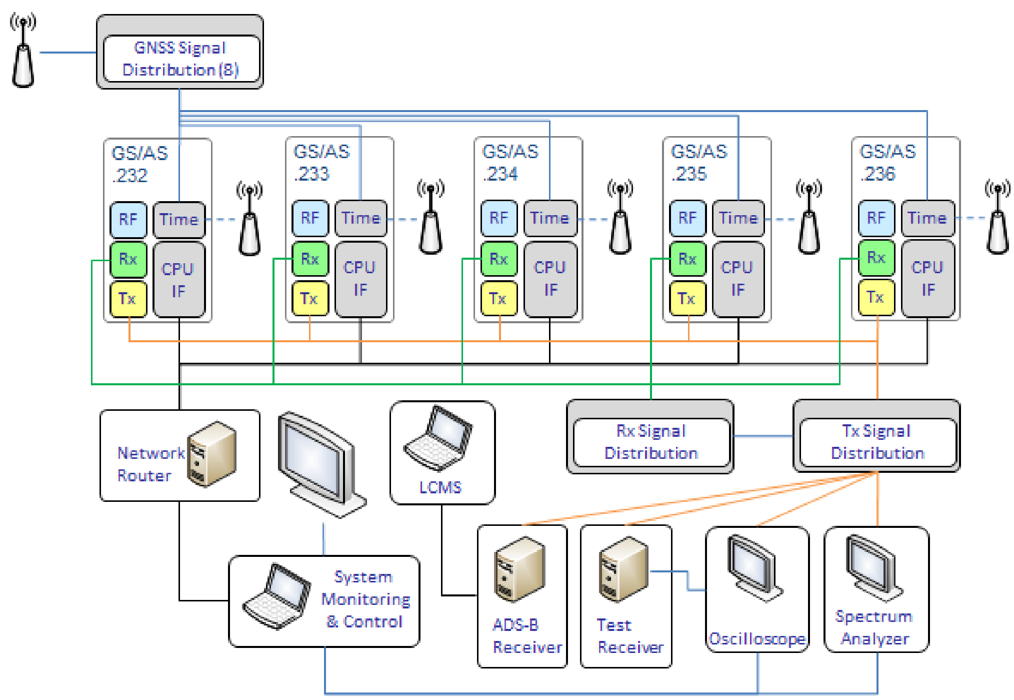

Figure 8. Schematic diagram of the Mode N testbed

2.15.3 In parallel and in cooperation with DFS, the German Aerospace Center (DLR) conducted performance analyses and optimization of the ground station network [10]. Tests have been executed on spectrum conformance, signal generation and reception, time synchronization accuracy, time stamping, and positioning. All testbed results and simulations show a very good match with the predictions and prove the feasibility of Mode N with good performance [11]. The result achieved by the testbed is a position accuracy of 20 meters for a static target using the Bancroft 85 algorithm for positioning, see Figure 9. Simulations show a predicted 95 per cent accuracy of 26 meters, see Figure 10.

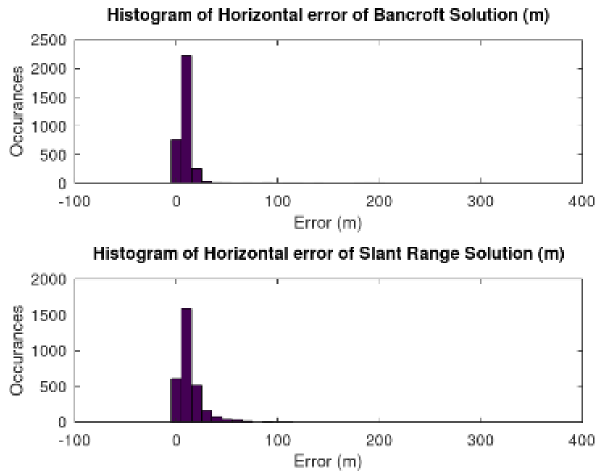

Figure 9. Position accuracy derived by testbed measurements

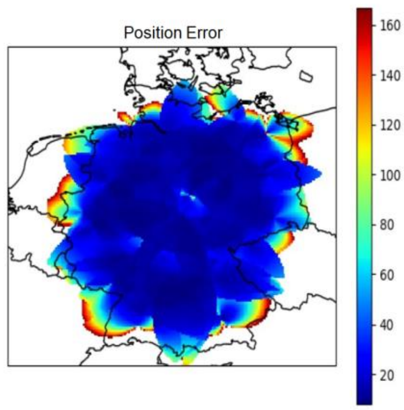

Figure 10. Position accuracy for Germany derived from simulations

2.15.4 Purpose-built Mode N devices have a high potential for significantly better performance since they are not bound by the limitations of the hardware and software used for testing.

2.15.5 In parallel to the civil activities, the Bundeswehr Technical Center for Aircraft and Aeronautical Equipment (WTD 61) in cooperation with DFS is also developing a Mode N demonstrator, focusing on specific military aspects. Studies have been performed to assess requirements, such as passive operation, selective availability, and authentication to incorporate them into the system specification at an early stage. WTD 61 established an "SDR Laboratory" and small and medium distance test-ranges for Mode N ground and flight tests.

2.15.6 Currently, four Mode N ground stations are operational and precision synchronization protocols and algorithms are being evaluated. First results show a ranging accuracy below five meters. A long-range reception test was recently conducted with promising results. A radiated power of 300 W and two dipole antennas were sufficient to reliably receive the Mode N signal over a distance of 125 km (67 nautical miles).

2.15.7 Up to now, Mode N has been developed within a purely national framework in Germany. Clearly, the further deployment of such a technology cannot be fostered at a national level. Therefore, aviation organizations, airspace users, service providers and industry are invited to join the further discussion and development.

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