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Permanent Link to Innovation: Ground-Based Augmentation
2021/06/13
Combining Galileo with GPS and GLONASS By Mirko Stanisak, Mark Bitter, and Thomas Feuerle INNOVATION INSIGHTS by Richard Langley GPS = SAFER FLIGHT. While reviewing material for an article celebrating the 25th anniversary of the launch in February 1989 of the first Block II or operational GPS satellite, I was yet again annoyed by many articles on the Web stating that GPS only became available for civil use after the launch of this satellite. Some sources get closer to the truth when they say that GPS was opened for civil use in 1983, following the shoot-down of the Korean Airlines Flight 007. In fact, GPS was designed to serve the needs of both the military and civil communities from the outset. A government memo from April 1973 clearly states: “Civil user needs should be considered in the design of the spaceborne equipment.” One of the first demonstrations of the use of GPS for aircraft navigation occurred in July 1983, when a Sabreliner business jet was flown in stages from Cedar Rapids, Iowa, to the Paris Air Show, flying only when a sufficient number of the experimental or Block I satellites were in view. The first standalone GPS receivers certified for aviation use (with Receiver Autonomous Integrity Monitoring or RAIM) became available by the mid-1990s. But already the Federal Aviation Administration had been looking into the development of a system to provide higher accuracies and better integrity than that afforded by standalone receivers. In 1994, the FAA announced the development of the Wide Area Augmentation System, its brand of a system generically known as satellite-based augmentation. Geostationary satellites transmit corrections and integrity information to GPS receivers, permitting GPS use for en route navigation all the way down to traditional Category I approach and landing. CAT I approaches can be flown down to a decision height of 61 meters (200 feet). WAAS was declared operational on July 10, 2003, but enhancements to the system continue. Japan, Europe, and India also have operational SBAS based on GPS. Ground-based GPS augmentation was first developed for maritime applications with the U.S. Coast Guard’s low-frequency system coming on line in the mid-1990s. Also in the mid-1990s, the FAA began the development of the Local Area Augmentation System, generically known as a ground-based augmentation system (GBAS), to provide aircraft with approach and landing capabilities from CAT I down through

CAT II (30-meter or 100-foot decision height) and CAT III (no decision height but certain visual range minima) using a VHF datalink. Initial CAT I systems are being operated at Bremen, Germany, and at Newark Liberty International Airport and Houston George Bush Intercontinental Airport. While a GPS-based GBAS will definitely offer improved navigation services for aircraft, might these services be even better if the systems were to use satellites from other constellations besides GPS? In this month’s column, we look at a straw-man concept for modifying the GBAS protocols to accommodate multiple constellations and the results of preliminary tests using GPS, GLONASS, and Galileo simultaneously. “Innovation” is a regular feature that discusses advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering, University of New Brunswick. He welcomes comments and topic ideas. Write to him at lang @ unb.ca. Ever since the declaration of Full Operational Capability (FOC) of the U.S. Global Positioning System in April 1995, GPS has dominated satellite navigation, especially in aviation applications. By contrast, the Russian GLONASS system cannot be used in western aviation because no approval guidelines exist for GLONASS equipment. Thus GPS has been the de-facto standard in aviation for years. However, within the last few years, major changes have evolved in the field of GNSS, providing a wide variety of useable satellite navigation systems. The European Union launched its Galileo project, which will provide global multi-frequency services in the near future. China is upgrading its BeiDou system (formerly called Compass) to provide global coverage with more medium-Earth-orbit (MEO) satellites. The operators of GPS and GLONASS have started modernization programs that will enable multi-frequency operations in the future, too. Therefore, a large number of usable satellites and signals from multiple systems will soon be available. In aviation, almost all phases of flight can be assisted by satellite navigation systems nowadays. The most challenging phase of flight with respect to accuracy, continuity, availability, and integrity is the approach and landing phase. The Ground Based Augmentation System (see FIGURE 1; courtesy of the European Organization for Civil Aviation Equipment) allows precision approaches to be performed using satellite navigation. It uses a VHF data link to broadcast differential GNSS corrections, integrity information, and approach definitions to approaching aircraft. These aircraft combine the differential corrections with their own GNSS measurements, calculate a GBAS-corrected position solution, and determine path deviations based on the selected approach. FIGURE 1. GBAS principle. (Source: EUROCAE WG 28, ED-114) From a technical perspective, GBAS can use either GPS or GLONASS for differential corrections. For this, the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) include GPS and GLONASS side by side. On the other hand, some standardization documents (for example, those from RTCA) are limited to GPS only, effectively excluding GLONASS from being used in the western world. Nevertheless, Russian GBAS systems provide differential corrections for GPS and GLONASS, and are expected to be certified in Russia in the near future. Additional GNSS such as Galileo or BeiDou are not yet included within these documents, as these systems are not approved for aviation use themselves. This article will focus on how a multi-constellation GBAS with GPS, GLONASS, and Galileo could work. GBAS installations can provide multiple services for different kinds of operation, based on GNSS L1 corrections only. On the one hand, the differentially corrected positioning service (DCPS) is intended to be a generic service for high accuracy positioning. On the other hand, two different GBAS approach services have been defined. GBAS Approach Service Type C (GAST-C) allows Category I (CAT I) procedures and is already in operation. GAST-D is still under development and will enable precision approaches and landings down to CAT II/III minima once certified. To mitigate all possible hazards, GAST-D will require some additional broadcast messages. VHF Data Broadcast The VHF Data Broadcast (VDB) is used to communicate binary GBAS messages to approaching aircraft. It operates in the VHF band (108.025 – 117.975 MHz) and uses time-division multiple access (TDMA) to allow the operation of multiple GBAS ground stations on a single frequency. As shown in FIGURE 2, VDB uses UTC time to have a common time frame. Two frames are transmitted each second, lasting 0.5 seconds each. Within each frame, eight slots with durations of 62.5 milliseconds can be used for transmission. Binary application data is encoded using a differentially encoded eight-phase-shift-keying modulation (D8PSK) and a symbol rate of 10,500 symbols per second. With three bits transmitted per symbol, up to 31,500 bits per second can be transmitted. Each slot can contain up to 222 bytes of binary application data. Usually, only a subset of slots is allocated to a particular ground facility. This way, multiple GBAS ground facilities can share a common VDB frequency. FIGURE 2. VDB timing structure. (Source: RTCA SC-159, DO-246D) Within each slot, multiple VDB messages can be transmitted as application data. The coding of information in VDB messages is defined in the RTCA’s GNSS-Based Precision Approach Local Area Augmentation System (LAAS) Signal-in-Space Interface Control Document (ICD) and depends on the VDB message type. (LAAS is the U.S. GBAS.) Currently, message types (MT) 1, 2, 3, 4 and 11 are defined. Figure 2 is derived from this document. Message Type 1 – MT1. Within VDB Message Type 1, differential corrections based on 100-second smoothing are transmitted. These corrections are required by all GBAS approach services (GAST-C and GAST-D). Aside from the differential corrections, additional information for the first broadcast satellite is transmitted. This includes an ephemeris cyclic redundancy check (CRC), mitigating the effects of wrongly received GNSS navigation data, and the Issue of Data (IOD) flag, indicating the time of applicability for the ephemeris data to be used. To transmit this information for all satellites, the satellite for which differential corrections are transmitted first has to be alternated continuously. Each MT1 message can contain up to 18 pseudorange- and range-rate corrections for individual satellites. Nevertheless, it is possible to link two consecutive MT1 messages using the Additional Message Flag (AMF). The value of this parameter indicates whether this is a single message (0), or the first (1) or second (3) part of a linked MT1 message. Up to 36 differential corrections can be transmitted using two consecutive VDB time slots with 18 corrections each. All MT1 measurement blocks must be transmitted at least once per frame. The maximum transmission rate is once per slot for all measurement blocks. Message Type 2 – MT2. VDB Message Type 2 contains station and integrity parameters such as the coordinates of the reference point to which all differential corrections refer. MT2 messages can include (next to a “core” MT2 message) multiple Additional Data Blocks (ADBs) to transmit information required for different GBAS services. At the moment, the Additional Data Blocks 1, 3, and 4 are defined. ADB1 contains the maximum distance to the reference point at which the corrections may be used (Dmax) as well as parameters to calculate the remaining risk of incorrect GNSS ephemeris data (Kmd,e). Within ADB3, additional information required for GAST-D is transmitted. ADB4 implements the VDB authentication feature. If this ADB is broadcast by a ground facility, MT2 messages must be transmitted first and contain additional indications about which VDB slots are allocated to the ground facility. MT2 messages must be transmitted at least each 20th frame, but may be repeated up to once per frame. Message Type 3 – MT3. The VDB Message Type 3 is a fill message, which is only used in conjunction with the GBAS authentication feature (MT2, ADB4). Among other things, this feature requires a minimum slot occupancy of at least 95 percent. Thus, MT3 messages are broadcast only by ground facilities that support the authentication feature and are completely ignored by airborne GBAS receivers. Message Type 4 – MT4. With VDB Message Type 4, approach information can be broadcast to approaching aircraft. A pilot can select a specific approach by simply tuning to a given channel number. Currently, GBAS only uses Instrument Landing System look-alike straight-in approaches called Final Approach Segments (FAS). Each FAS represents one approach. This way, a single GBAS ground facility can provide multiple approaches for all runways of an airport. All approaches must be broadcast at least once per 20 consecutive frames. Message Type 11 – MT11. The VDB Message Type 11 provides differential corrections in a way very similar to MT1 messages. The main difference is that MT11 corrections are based on 30-second smoothing, which is required for GAST-D service. As for MT1, all MT11 measurement blocks must be transmitted at least once per frame. Enhancements for GBAS with Galileo At the moment, the GBAS standardization documents include information on GPS, GLONASS, and SBAS ranging sources. No information on Galileo or other constellations has been added yet. Thus, to include Galileo for GBAS, some Galileo-specific experimental additions to the standards are necessary. These proposed modifications have been made in such a way as to keep as close to the other system standards as possible to preserve consistency. This way, hardly any new functionality is added, but additional satellites can be used. The additional Galileo signals (E5a, E5b, E6) are not used at the moment; however, they might be highly beneficial for multi-frequency applications in the future. All modifications presented here are purely experimental and will most probably not be exactly the same as those in future standards documents. Nevertheless, they provide a way to test Galileo together with GPS and GLONASS for GBAS on an experimental basis. Ranging Source ID. The Ranging Source ID uniquely addresses a single satellite. It is used in MT1 and MT11 to transmit the differential corrections and other information for each ranging source. In ICAO Annex 10, Standards and Recommended Practices, the Ranging Source ID is defined for GPS, GLONASS, and SBAS only. To provide Galileo corrections as well, an experimental mapping for Galileo satellites was added; see TABLE 1. TABLE 1. GBAS Ranging Source IDs. In this way, up to 36 Galileo satellites can be addressed. Navigation Data. Galileo provides two different sets of navigation data. The I/NAV data corresponds to the Safety-of-Life (SoL) service and is broadcast on E1 and E5b. The F/NAV data corresponds to the Open Service (OS) and is broadcast on E5a. In order to remain as close as possible to the legacy navigation systems, we selected the I/NAV navigation data for use, as it is broadcast on the E1 frequency and can thus be received with an L1-only GNSS receiver. The navigation data is primarily used in VDB MT1. For the first transmitted correction in this message, the ephemeris set that shall be used in the aircraft is identified via the Issue of Data (IOD) field. To be consistent with the GPS ephemeris, we used Galileo's IODnav parameter. Together with the identification of the navigation data, a CRC parameter is transmitted in MT1 for the first satellite within the differential corrections. This parameter ensures that the receiver as well as the ground facility use identical navigation data for all calculations. The CRC algorithm uses the raw navigation data to generate a distinct CRC value. For GPS and GLONASS, two ephemeris masks are defined. These masks ensure that only information relevant for GBAS processing are covered by the CRC. For Galileo, a similar mask had to be designed. Additional Data Blocks in MT2. Within VDB MT2, station parameters and integrity information are transmitted. Some parameters for the over-bounding of possible ephemeris errors are specific to each satellite navigation system. To extend MT2 to Galileo, parameters for the DCPS, GAST-C, and GAST-D must be added for Galileo. For downward compatibility, these parameters cannot be included in the existing Additional Data Blocks beside the existing parameters. Thus, a new Additional Data Block (ADB5) was defined on an experimental basis. This Additional Data Block is dedicated to Galileo and is structured as shown in TABLE 2. The coding of all values corresponds to the coding of the parameters for the existing systems. TABLE 2. Additional Data Block 5 in Message Type 2 for Galileo parameters. Optimized VDB Transmission Scheme Having available a large number of ranging sources for differential corrections, the VHF VDB is a bottleneck for the transmission of this data. To demonstrate this, we first consider the number of visible satellites that there will be in the future. This leads to construction rules for an optimal VDB transmission scheme, which allows transmitting the maximum number of differential corrections. Number of Satellites Available. To demonstrate the number of differential corrections enabled by the different systems in the future, we computed the number of visible satellites over a day for a stationary GNSS receiver in Braunschweig, Germany. Even though only four Galileo satellites were in orbit at that time, up to 26 different satellites (GPS, GLONASS, and Galileo) were in view simultaneously. Keeping in mind the preliminary Galileo constellation, it is obvious that more than 30 satellites will be available simultaneously in the future — considering only GPS, GLONASS, and Galileo. Adding BeiDou satellites for GBAS would further boost these numbers. The broadcast of such a large number of differential corrections is limited by the capacity of the VDB and thus by the number of slots assigned to a GBAS ground facility. The number of assigned slots for a facility should be limited as far as possible to be able to use the same frequency for other GBAS ground facilities. Thus, the available capacity must be used as effectively as possible. Number of Bytes Required. Each VDB message is framed by a message block header (6 bytes) and the message block CRC (4 bytes). The length of each message depends on the message type and the amount of information to be transmitted. The resulting length for a message of each type is given in TABLE 3. TABLE 3. Size of different VDB message types (including message block header and CRC). Variable length message types are dependent on the number of corrections, N. VDB Constraints. A GBAS ground facility must transmit the VDB data following some constraints. These are: MT2 messages (including all Additional Data Blocks required) must be transmitted at least each 20th frame (that is, every 10 seconds). If authentication is required, each MT2 message must be transmitted in the first slot assigned to the GBAS ground facility. All differential corrections (both MT1 and MT11) must be transmitted at least once in each frame. However, it is possible to split the differential corrections into two adjacent slots using the Additional Message Flags in MT1 and MT11 messages. Within each MT1 message, the ephemeris decorrelation parameter (Peph), the Issue of Data (IOD), and the ephemeris CRC is transmitted for the first satellite in the message. Thus, the first satellite must be alternated in order to broadcast the ephemeris information for all satellites. Approach definitions are transmitted in MT4 messages. All MT4 messages must be transmitted within at least each 20th slot. Based on these constraints, a VDB encoding scheme has been developed, which allows us to fulfill all the requirements listed above while optimizing the number of differential corrections that can be transmitted. Even though it is optimized for GAST-D-like services (including authentication parameters, MT11 messages, and experimental Galileo extensions), it can be used for legacy GAST-C systems, too. Rules for Optimal VDB Transmission. To fulfill the requirement for the MT2 message to be transmitted first, a complete MT2 message must be transmitted each 20th frame at the beginning of the first slot assigned. If no MT2 message has to be transmitted, an MT4 message is transmitted instead. Thus, all messages are arranged in proper order by three simple rules: MT2 (each 20th frame) or MT4 (otherwise) MT11 (all corrections; can be split into two messages) MT1 (all corrections; can be split into two messages). Additionally, two more rules must be fulfilled. On the one hand, if supporting the authentication feature, each slot in which the ground facility may transmit VDB data must be filled to at least 95 percent. For this, MT3 null messages may be used to ensure that each slot is filled sufficiently. On the other hand, an additional rule for MT1 messages is necessary if more than three slots are assigned to the GBAS ground facility. In this case, to maximize the number of differential corrections the MT1 messages may be transmitted in the last two assigned slots only. This rule is necessary because the Additional Message Flag is limited to two slots for differential corrections. Using this transmission scheme, the number of differential corrections is maximized while fulfilling the minimum requirements on the VDB data. Even in case of the maximum number of differential corrections, MT4 approach definitions can still be broadcast. However, in this case, the number of transmittable FAS segments is limited to 19. If more approaches (or different approach types such as Terminal Area Paths (TAPs)) have to be transmitted, the VDB generation scheme must be adapted. Number of Transmittable Corrections. Using the optimized transmission scheme explained earlier, the number of transmittable corrections can be calculated easily for different numbers of assigned slots for GAST-C as well as for GAST-D services (see TABLE 4). TABLE 4. Number of differential corrections that can be broadcast. The exact distribution of VDB messages for the maximum number of differential corrections (18) is shown in FIGURE 3 for an MT1/MT11 configuration and two assigned slots. FIGURE 3. VDB messages for two slots and 18 satellites (MT1 and MT11). Experimental Realization of Multi-Constellation GBAS The experimental GBAS multi-constellation extensions described earlier have been implemented in software for further testing. As these enhancements are purely experimental and might change in the future, we have ensured that these definitions can be changed easily. Navigation Software. The Institute of Flight Guidance at Technische Universität Braunschweig has been developing an experimental navigation framework for many years. This software, called TriPos, can handle and combine different navigation technologies. TriPos can be used for simulations, post-processing of recorded data, and even for live (online) processing. It is written in C++ and supports various platforms. The navigation framework can be extended easily. Originally, only GPS was supported within the software, but support for GLONASS and Galileo as well as augmentation systems like SBAS and GBAS were added over the past few years. Additionally, the software handles GNSS data of multiple frequencies internally and can thus be used for multi-constellation and multi-frequency applications. TriPos includes decoders for the binary protocols of most GNSS receivers currently available. For GBAS research, two components can be simulated using the software. On the one hand, the Ground Facility simulation calculates the differential corrections and provides simulated VDB data. On the other hand, the GBAS receiver simulation emulates the behavior of an airborne GBAS receiver and uses VDB data and GNSS measurements to calculate a GBAS solution. Both simulations can use either recorded data in post-processing or live data for online-processing. This allows complete simulation of GBAS. Multi-Constellation GBAS Ground Facility Simulation. The GBAS ground facility simulation uses raw binary data from multiple stationary GNSS receivers to calculate binary VDB data. The simulation can be freely configured to process either live or pre-recorded GNSS data. Even though it features all algorithms required by the standards, it does not contain additional monitor algorithms at the moment. Nevertheless, it can provide a valid VDB signal-in-space (SIS), which can be used by GBAS receivers and simulation tools (such as Eurocontrol's PEGASUS tool). The ground facility simulation supports legacy GBAS CAT-I (GAST-C) as well as GAST-D (including all additional VDB information required) using GPS and GLONASS. Support for Galileo has been added according to the experimental definitions described earlier. In addition to FAS data blocks, the ground facility simulation is also capable of providing curved approaches using TAP data blocks. Multi-Constellation Airborne GBAS Receiver Simulation. The GBAS receiver simulation has been used for various GBAS-related projects. It supports GAST-C as well as GAST-D and can be configured flexibly to use GPS, GLONASS, and/or Galileo (using the experimental enhancements as described earlier). For GAST-D, all airborne monitoring algorithms required are present. Thus, the aircraft-specific parameters (for example for the airborne geometry screening) can be configured together with the other parameters. Flight Trials The practicability of the multi-constellation GBAS approach has been tested in flight trials. To ensure that all four Galileo satellites were in view and capable of providing valid data during our trials, an orbit prediction tool and the Notice Advisory to Galileo Users (NAGU) service of the European GNSS Service Center (GSC) were used prior to the flight. The data processing configuration is shown in FIGURE 4 and includes the GBAS simulation components explained earlier. All processing is done in real time while recording all data for later post processing. FIGURE 4. Schematic data processing for the flight experiments (ground components in orange, airborne components in blue). Ground Processing. On the ground, two Septentrio AsteRx3 GNSS receivers connected to two roof-top antennas were used. The GNSS receivers were connected to the GBAS ground facility simulation via a network and provided binary GPS, GLONASS, and Galileo raw measurements with an update rate of 2 Hz as well as navigation data. Using this data, the ground facility simulation generated binary VDB data. The GBAS ground facility simulation was configured to generate multi-constellation GAST-D VDB data for a three-slot configuration. All required messages (MT1, MT2 including all required ADBs, MT3, MT4 and MT11) were generated and sent to the telemetry facility via the network. Telemetry. Official VHF data broadcasts operate in a frequency band between 108 and 118 MHz, which is reserved for authorized aviation applications. However, for our experimental system, an alternative data link was used. The Institute of Flight Guidance operates a full-duplex telemetry system to share data between ground and aircraft. Even though the operating frequencies are different, the telemetry system allows the generated binary VDB data to be transmitted to research aircraft. The airborne telemetry receiver outputs data as if it were a VDB receiver to allow us to switch between a real VDB receiver and the telemetry receiver easily. Research Aircraft. The Institute of Flight Guidance operates the research aircraft of the Technische Universität Braunschweig. The Dornier Do 128-6 with the call sign D-IBUF (see FIGURE 5) is a twin-engine turboprop aircraft without a pressurized cabin and has been used multiple times for GBAS-related research over the years. FIGURE 5. Research aircraft D-IBUF (Dornier Do 128-6). The research aircraft allows us to flexibly integrate experimental equipment for specific flight trials. For the multi-constellation GBAS flights, a JAVAD Delta GNSS receiver (capable of multiple constellations and frequencies), a telemetry receiver, and an experimental cockpit display were installed temporarily. Airborne Processing. The online GBAS receiver simulator uses GNSS data from the JAVAD Delta GNSS receiver together with the VDB data received via telemetry. The receiver was configured to output raw GPS, GLONASS, and Galileo measurements with an update rate of 10 Hz. The simulator was configured to use this data to calculate a multi-constellation GAST-D solution. Based on the selected approach definition, the resulting information (deviations, distance to threshold, and so on) was displayed in the cockpit using an experimental cockpit display. Results. The flight test was conducted in the evening of November 6, 2013 (16:52 – 17:58 UTC), at Research Airport Braunschweig (EDVE). We performed five approaches with a 10 nautical mile final segment. The flight path as calculated by the GBAS receiver subsystem is shown in FIGURE 6. FIGURE 6. Flight trial trajectory. (Map data © OpenStreetMap contributors) FIGURE 7 shows the number of satellites used for the GBAS receiver simulation, and distinguishes between the different satellite navigation systems used. Up to 22 satellites have been used simultaneously for GBAS processing, including up to 10 GPS satellites, eight GLONASS satellites, and four Galileo satellites. FIGURE 7. Number of satellites used by the multi-constellation GBAS receiver simulation. Even though no certified GBAS equipment was used for the flight trials, FIGURE 8 shows the resulting vertical and lateral protection levels (VPL and LPL) of the online multi-constellation GBAS receiver simulation. Both values fluctuate due to the differences between 100- and 30-second smoothing position solutions, which have to be added to the protection levels for GAST-D. Nevertheless, both sets of values remain clearly below the corresponding Alert Limits (FAS Lateral Alarm Limit (FASLAL): 40 meters, FAS Vertical Alarm Limit (FASVAL): 10 meters). A valid GAST-D service was achieved continuously. FIGURE 8. Vertical and lateral protection levels (VPL and LPL). FIGURE 9 shows a vertical integrity diagram, commonly known as a Stanford plot, for the integrity of the multi-constellation GBAS simulation. This plot shows the Vertical Protection Level (VPL) as determined by the GBAS receiver simulation against the actual Vertical Position Error (VPE). The Vertical Position Error is a direct measure for the Vertical Navigation System Error (V-NSE). This has been determined using a precise point positioning reference trajectory. Both values are normalized by the current VAL as these values change during the approaches. During the flight, the GBAS online processing ran at a rate of 10 Hz, resulting in 43,670 GAST-D epochs and an availability of 100 percent. FIGURE 9. Normalized vertical Stanford plot of flight trials (GAST-D using GPS, GLONASS, and Galileo). Color scale indicates number of occurrences. Of course, these results must not be misinterpreted as a multi-constellation GBAS performance assessment. The ground facility simulation was highly experimental and lacked any kind of long-term analysis. Even the GNSS antennas used do not meet formal requirements. However, aside from a quantitative judgment, these results show the practicability of this multi-constellation GBAS approach on an experimental basis. Conclusion and Outlook In this article, experimental extensions to GBAS have been developed to support GPS, GLONASS, and Galileo simultaneously. Based on these extensions, an optimized VDB transmission scheme has been created. In this way, the number of transmittable differential corrections could be maximized. Using flight trials, the multi-constellation GBAS concept has successfully been verified. The experimental airborne GBAS subsystem was able to calculate a valid GBAS solution including GPS, GLONASS, and Galileo satellites continuously. It has been shown that multi-constellation GBAS is possible from a purely technical perspective. On the other hand, neither operational nor approval aspects for satellite navigation systems other than GPS have been addressed yet. Additionally, further testing would be necessary to ensure the compatibility with legacy GPS-only GBAS equipment. However, in theory, all modifications for Galileo are backward compatible. Nevertheless, it has to be assured that certified GBAS multi-mode receivers only use the GPS part of the VDB data and are not disturbed by additional VDB messages or additional ranging sources, for example. The required tests are planned for the future. The operational benefit of multi-constellation GBAS systems cannot be foreseen yet. A certification for this will take several years and could only be addressed by the GBAS community after the completion of the GAST-D certification. Most probably, the use of GNSS signals on multiple frequencies could provide a highly improved GBAS service and will allow much more operational benefit. Many of the satellite navigation systems have already introduced additional frequencies, including signals in the protected L5 aviation band. The use of multiple frequencies for satellite navigation in aviation can remove most ionospheric errors effectively and mitigate a major source of uncertainty. Thus, multi-constellation GBAS can just be seen as a preliminary step on the way towards multi-frequency GBAS. The concepts and infrastructure described in this article will serve as a basis for more research in this area. Acknowledgments Most of our work on multi-constellation GBAS was done within the research project "Bürgernahes Flugzeug," which was established in 2009 and is partly funded by the German federal state of Lower Saxony. This is gratefully acknowledged by the authors. Additionally, the authors would like to thank all colleagues involved for constructive discussions and their support. This article is based on the paper "Mulitple Satellite Navigation for the Ground Based Augmentation System" presented at ITM 2014, The Institute of Navigation 2014 International Technical Meeting, held in San Diego, California, January 27-29, 2014. MIRKO STANISAK is a research assistant at the Institute of

Flight Guidance (IFF) at the Technische Universität (TU) Braunschweig in Germany. He received his diploma in mechanical engineering (Dipl.-Ing.) in 2009 from TU Braunschweig. MARK BITTER holds a Dipl.-Ing. in mechanical engineering from TU Braunschweig and has been employed as a research engineer at TU Braunschweig IFF since 2003. THOMAS FEUERLE received his Dipl.-Ing. in mechanical engineering in 1997 from TU Braunschweig. He joined the TU Braunschweig IFF in May 1997. Since 2005, he has been the leader of the Air Traffic Management Team at the IFF. In April 2010, he completed his Ph.D. dissertation at TU Braunschweig. FURTHER READING • Authors' Conference Paper "Multiple Satellite Navigation Systems for the Ground Based Augmentation System," by M. Stanisak, M. Bitter, and T. Feuerle in Proceedings of ITM 2014, the 2014 International Technical Meeting of The Institute of Navigation, San Diego, California, January 27–29, 2014, pp. 254–264. • Standards Documents Aeronautical Communications, Vol. 1, Radio Navigation Aids, Annex 10 to the Convention on International Civil Aviation, International Standards and Recommended Practices, International Civil Aviation Organization, Montreal, Draft Version, May 2010. GNSS-Based Precision Approach Local Area Augmentation System (LAAS) Signal-In Space Interface Control Document (ICD), DO-246D, RTCA Special Committee 159, Global Positioning Systems, RTCA Inc. Washington, D.C., December 2008. Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment, DO-253C, RTCA Special Committee 159, Global Positioning Systems, RTCA Inc. Washington, D.C., December 2008. Minimum Operational Performance Specification for Global Navigation Satellite Ground Based Augmentation System Ground Equipment to Support Category I Operations, ED-114, EUROCAE Working Group 28 on Global Navigation Satellite System, European Organisation for Civil Aviation Equipment, Malakoff, France, September 2003. • GBAS Research and Development "Conception, Implementation and Validation of a GAST-D Capable Airborne Receiver Simulation" by M. Stanisak, R. Schork, M. Kujawska, T. Feuerle, and P. Hecker in Proceedings of ION GNSS 2012, the 25th International Technical Meeting of the Satellite Division of The Institute of Navigation, Nashville, Tennessee, September 17–21, 2012, pp. 250–257. "Making the Case for GBAS: Experimental Aircraft Approaches in Germany," by U. Bestmann, P.M. Schachtebeck, T. Feuerle, and P. Hecker in Inside GNSS, Vol. 1, No. 7, October 2006, pp. 42–45. "Initial GBAS Experiences in Europe" by A. Lipp, A. Quiles, M. Reche, W. Dunkel, and S. Grand-Perret in Proceedings of ION GNSS 2005, the 18th International Technical Meeting of the Satellite Division of The Institute of Navigation, Long Beach, California, September 13–16, 2005, pp. 2911–2922. • GPS Use in Aviation "Aircraft Landings: The GPS Approach," by G. Dewar in GPS World, Vol. 10, No. 6, June 1999, pp. 68–74. "GPS in Civil Aviation" by K.D. McDonald in GPS World, Vol. 2, No. 8, September 1991, pp. 52–59.

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lansing eudf+15050-2600 ac adapter 5vdc 2.6a -(+) used 2x5.toshiba pa8727u 18vdc 1.7a 2.2a ac adapter laptop power supply,creative a9700 ac adapter9vdc 700ma used -(+)- 2x5.5mm 120vac.compaq series 2862a ac adapter 16.5vdc 2.6a -(+) 2x5.5mm 100-240,d-link smp-t1178 ac adapter 5vdc 2.5a -(+) 2x5.5mm 120vac power,i've had the circuit below in my collection of electronics schematics for quite some time,all mobile phones will indicate no network incoming calls are blocked as if the mobile phone were off.aps ad-555-1240 ac adapter 24vdc 2.3a used -(+)- 2.5x5.5mm power.50/60 hz transmitting to 24 vdcdimensions.nerve block can have a beneficial wound-healing effect in this regard.cobra swd120010021u ac adapter 12vdc 100ma used 2 audio pin,delta 57-30-500d ac adapter 30vdc 500ma class 2 power supply,ault inc mw128bra1265n01 ac adapter 12vdc 2.5a used shield cut w,ihomeu150150d51 ac adapter 15vdc 1500ma -(+) 2.1x5.5x10mm roun.anti jammer bluetooth wireless earpiece unlimited range.one is the light intensity of the room.li shin lse0107a1230 ac adapter 12vdc 2.5a used -(+) 2.1x5.5mm m.canon k30287 ac adapter 16vdc 2a used 1 x 4.5 x 6 x 9.6 mm.a cellphone jammer is pretty simple.liteon ppp009l ac adapter 18.5v dc 3.5a 65w laptop hp compaq,nec adp52 ac adapter 19vdc 2.4a 3pin new 100-240vac genuine pow,li shin lse9802a2060 ac adapter 20vdc 3a 60w used -(+) 2.1x5.5mm,anoma electric aec-t5713a ac adapter 13.5vdc 1.5a power supply.dv-1220dc ac adapter 9v 300ma power supply.delta electronics, inc. adp-15gh b ac dc adapter 5v 3a power sup,this project uses arduino for controlling the devices,this was done with the aid of the multi meter,2 w output power3g 2010 – 2170 mhz,finecom azs9039 aa-060b-2 ac adapter 12vac 5a 2pin din ~[o |]~,h.r.s global ad16v ac adapter 16vac 500ma used90 degree right,aironet ad1280-7-544 ac adapter 12vdc 800ma power supply for med,briefs and team apparel with our online design studio.

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Canon ca-590 compact power adapter 8.4vdc 0.6a used mini usb pow.the inputs given to this are the power source and load torque,huawei hw-050100u2w ac adapter travel charger 5vdc 1a used usb p,delta adp-180hb b ac adapter 19v dc 9.5a 180w switching power su.download the seminar report for cell phone jammer,sil vd090030d ac adapter 9vdc 300ma power supply transformer,hi capacity ea1050a-190 ac adapter 19vdc 3.16a used 5 x 6 x 11.please pay special attention here.mascot 9940 ac adapter 29.5vdc 1.3a used terminal battery char,a low-cost sewerage monitoring system that can detect blockages in the sewers is proposed in this paper,griffin itrip car adapter used fm transmitter portable mp3 playe,dve dsa-31s fus 5050 ac adapter+5v dc 0.5a new -(+) 1.4x3.4x9.,tenergy oh-1048a4001500u-t ac adapter 30vdc 1/1.5a used univers.mastercraft maximum dc14us21-60a battery charger 18.8vdc 2a used,lenovo 42t4426 ac adapter 20v dc 4.5a 90w used 1x5.3x7.9x11.3mm.delta adp-65mh b ac adapter 19vdc 3.42a used 1.8 x 5.5 x 12mm,iluv dys062-090080w-1 ac adapter 9vdc 800ma used -(+) 2x5.5x9.7m,sony ac-l 200d ac adapter 8.4vdc 1.5a 4x6mm used for digital cam.sony ac-lm5a ac dc adapter 4.2vdc 1.5a used camera camcorder cha,gamestop 5v wii remote conteroller charging dock,it captures those signals and boosts their power with a signal booster.hi capacity ac-c10 le 9702a 06 ac adapter 19vdc 3.79a 3.79a 72w,t4 spa t4-2mt used jettub switch power supply 120v 15amp 1hp 12,vertex nc-77c two way radio charger with kw-1207 ac adapter 12v.the pki 6025 is a camouflaged jammer designed for wall installation,austin adp-bk ac adapter 19v dc 1.6a used 2.5x5.5x12.6mm,fld0710-5.0v2.00a ac adapter 5vdc 2a used -(+) 1.3x3.5mm ite pow.aps aps61es-30 ac adapter +5v +12v -12v 5a 1.5a 0.5a 50w power s,delta adp-150cb b ac adapter 19v 7.9a power supply,find here mobile phone jammer.ad-1200500dv ac adapter 12vdc 0.5a transformer power supply 220v.netgear ad810f20 ac adapter 12v dc 1a used -(+)- 2x5.4x9.5mm ite.cisco adp-20gb ac adapter 5vdc 3a 34-0853-02 8pin din power supp.wifi gps l1 all in one jammer high-capacity (usa version) us$282,5v 400ma ac adapter travel cellphone charger used mini usb 100-2,new bright a519201194 ac dc adapter 7v 150ma charger.astec da2-3101us-l ac adapter 5vdc 0.4a power supply,fj-sw1202000u ac adapter 12vdc 2000ma used -(+) 2x5.5x11mm round.

Sima sup-60lx ac adapter 12-15vdc used -(+) 1.7x4mm ultimate cha,pa-1650-02h replacement ac adapter 18.5v 3.5a for hp laptop powe,radioshack 15-1838 ac adapter dc 12v 100ma wallmount direct plug.consumerware d9100 ac adapter9vdc 100ma -(+) used 2 x 5.4 x 11.24vac-40va ac adapter 24vac 1670ma shilded wire used power suppl.black & decker mod 4 ac adapter dc 6v used power supply 120v,fuji fujifilm cp-fxa10 picture cradle for finepix a310 a210 a205.acbel api3ad05 ac adapter 19vdc 4.74a replacement power supply f.hipro hp-ok065b13 ac adapter 18.5vdc 3.5a 65w used -(+) 2x5.5x9.,modeling of the three-phase induction motor using simulink.radioshack 23-240b ac adapter 9.6vdc 60ma used 2-pin connector,2 w output powerwifi 2400 – 2485 mhz.cui eua-101w-05 ac adapter 5vdc 2a -(+)- 2.5x5.5mm thumb nut 100,apple m5849 ac adapter 28vdc 8.125a 4pin 10mm 120vac used 205w p,the present circuit employs a 555 timer,fellowes 1482-12-1700d ac adapter 12vdc 1.7a used 90° -(+) 2.5x5,35-9-300c ac adapter 9vdc 300ma toshiba phone system used -(+).the first circuit shows a variable power supply of range 1.lind pa1540-201 g automobile power adapter15v 4.0a used 12-16v,cellet tcnok6101x ac adapter 4.5-9.5v 0.8a max used,5% to 90%modeling of the three-phase induction motor using simulink.toshiba pa2484u ac adapter 15vdc 2.7a ite power supply,li shin 0405b20220ac adapter 20vdc 11a -(+) used 5x7.4mm tip i,global am-121000a ac adapter 12vac 1000ma used -(+) 1.5x4.7x9.2m,sony ac-l25a ac dc adapter 8.4v 1.5a power supply 02-3273-2000,this paper describes different methods for detecting the defects in railway tracks and methods for maintaining the track are also proposed.insignia u090070d30 ac adapter 9vdc 700ma used +(-)+ 2x5.5mm rou..

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Adp-90ah b ac adapter c8023 19.5v 4.62a replacement power supply,hp ppp0016h ac adapter 18.5v dc 6.5a 120w used 2.5x5.5x12.7mm.it should be noted that operating or even owing a cell phone jammer is illegal in most municipalities and specifically so in the united states,merkury f550 1 hour sony f550 rapid lithium ion battery charger,we – in close cooperation with our customers – work out a complete and fully automatic system for their specific demands.braun 3 709 ac adapter dc 1.3w class 2 power supply plug in char.digipos retail blade psu2000 power supply 24vdc 8.33a ac adapter,.
Email:MPU_8nfBr@gmx.com
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Anoma electric aec-t5713a ac adapter 13.5vdc 1.5a power supply,digipower tc-3000 1 hour universal battery charger,dv-751a5 ac dc adapter 7.5vdc 1.5a used -(+) 2x5.5x9mm round bar,.
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