# Satellite-Based Augmentation Systems: The Need for International Standards

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This paper discusses the technical, administrative and certification compatibility issues associated with satellite augmentation of GPS/GLONASS. It indicates that the Signal-in-Space specifications are central to compatibility and interoperability. ICAO Standards and Recommended Practices are a key mechanism for interoperability. The paper recommends that one standard be implemented worldwide. It also urges a mechanism for the co-ordination and management of augmentation services.

1. icao and standards. The International Civil Aviation Organisation (ICAO) is certainly one of the more successful of the UN bodies. When a pilot tunes in his ILS receiver he knows he will have a system that provides him with the same indications regardless of whether he is approaching London Heathrow or Santiago Chile. Equally, when he looks up at decision height, he will see the same pattern of approach and runway lights, and can expect the same phraseology from the air traffic controllers. Aviation is covered by the ICAO Annexes which provide Standards and Recommended Practices (SARPs) for States implementing international aviation facilities.

ICAO Annex 10 is the document that provides SARPs for international Aeronautical Radio Communication and Navigation Systems. Up to now, the standards related to what has conveniently been called the 'Signal in Space' (SIS). As long as the signal in space had the specified properties, it mattered little how it got there. Certain guidance material was provided in Green Pages to guide States, particularly the less developed ones, in implementing their navigation and communication systems, but compliance with this guidance material was not mandatory. Any changes to the Annexes have to be agreed by States – a very lengthy process and not suitable for modern systems that depend on computer software for their operation.

For station-based aids, how the signals were generated, etc., was decided by States. Many different ways are utilized to provide ILS and VOR signals, but the end result, as far as the aircraft receiver is concerned, is identical. However, when the navigation signal is regional or international, as with satellite augmentation, a wider mechanism for standardisation becomes necessary. With the introduction of satellite communications systems, ICAO found its 100-page Annex 10 suddenly expanded to almost 500 pages. A lot of the material means very little to most of the aviation community and



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certainly would not be amenable to elaborate international co-ordination procedures to facilitate necessary and often urgent changes, many of them minor. A somewhat different approach was obviously needed to deal with global satellite navigation systems, and the augmentations thereto.

The ICAO GNSS Panel realized that the material they were preparing was totally different in concept to existing 'point source' (station-based) radio navigation standards. To facilitate the inclusion of the material in ICAO Annex 10, it has been decided to develop different levels of SARPs, only the top level needing international agreement for changes. Included in the top level SARPs would be fundamental parameters such as radio frequency and power levels, not likely to require a change. The more detailed technical specifications would be contained in technical appendices. These appendices could be changed without the necessity for formal international co-ordination.

## 2. satellite-based augmentation system (sbas) elements.

Full operational provision of a satellite augmentation service involves the following elements:

- (i) A Service Provider, who operates and manages the GNSS monitoring network and the central processing facility to generate the SBAS data and control the provision of a particular SBAS.
- (ii) An Operator of a Navigation Land Earth Station (NLES), which supports the satellite uplink signal generation.
- (iii) A navigation transponder on a geostationary satellite platform. Inmarsat is currently the only provider of such capacity.
- (iv) The 'Signal in Space' which is transmitted to, and relayed by, the navigation transponder. This signal carries the SBAS data. The signal and data format should meet the appropriate international standard(s). The SIS is received by the user equipment (receiver).
- (v) The user equipment, which may be either a stand-alone GNSS receiver or a navigation sensor within an integrated aircraft (or other vehicle/vessel) navigation system. Equipment requirements are specified in the Minimum Operational Performance Specifications (MOPS) from RTCA and Eurocae, the ICAO SARPs, and specific directives issued by appropriate authorities (e.g. TSOs from the US FAA).

The SIS thus sits at the heart of the system: in one way or another, all of the above elements must comply with the SIS specifications. The Service Provider must generate suitable data. The NLES Operator must meet Inmarsat's System Definition Manual (SDM). Inmarsat's satellite transponder specifications and performance are consistent with the SIS specifications. For example, the signal standard requires a certain signal power, bandwidth, and stability. The user equipment must process the various signal structures and messages of the SIS. It is thus no accident that the specifications have been incorporated, directly or by reference, within the System Specifications for WAAS and EGNOS, within the about-to-be-issued ICAO SARPS for SBAS, within Inmarsat's System Definition Manual (SDM) for the Navigation Overlay Service, and within the receiver MOPS documents.

Some aspects of the SIS definition, particularly some of the Message Types, are essential to interoperability and compatibility. Strictly speaking, however, these specifications are only *enabling*, not mandating. In particular, the Service Provider is

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not required to provide all of the defined message types, nor required to meet performance requirements to any particular level outside his self-defined service region.

3. satellite-based augmentation systems under construction. Amongst the standards being developed by the GNSS Panel are those for satellite-based augmentation systems. Currently there are three such systems being implemented. Already the signal (satellite footprint) coverages of these systems under construction overlap. A number of States are considering either their own systems or getting benefits from systems provided by other States. Compatibility and interoperability issues are therefore prominent, and cannot be resolved by unilateral or even bilateral measures.

3.1. *The USA Wide Area Augmentation System* (*WAAS*). The WAAS is a safety-critical navigation system that will provide a quality of positioning information never before available to the aviation community. It is what the name implies – a geographically expansive augmentation to the basic GPS service. The WAAS improves the accuracy, integrity, and availability of the basic GPS signals. This system will allow GPS to be used as a primary means of navigation for en-route operations and non-precision approaches, as well as Category 1 approaches to selected airports throughout the coverage area. The wide area of coverage for this system includes the entire United States, Alaska, Hawaii and some other outlying areas (see Figure 1; Kinal, 1997). Canada is also co-operating in this project and will

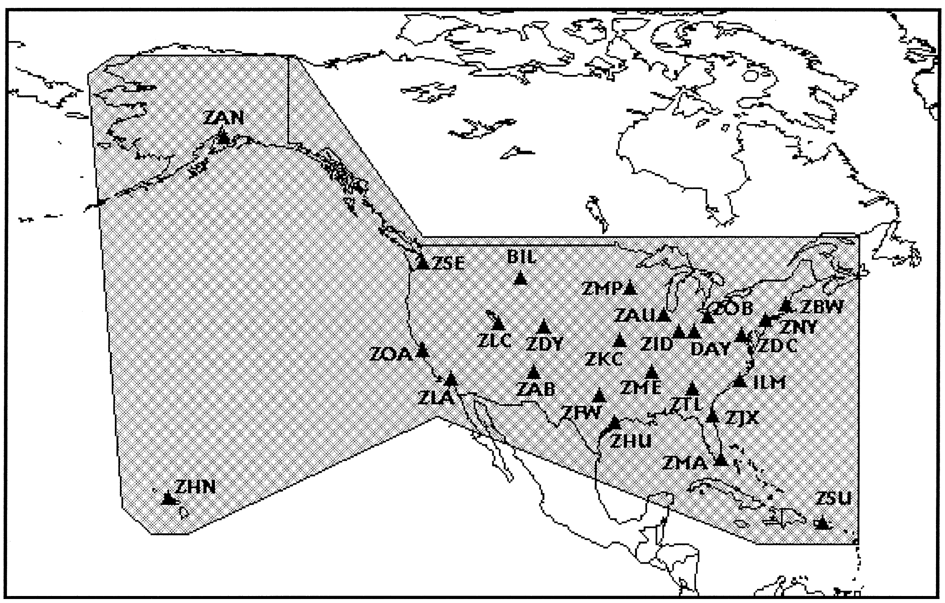

Figure 1. WAAS service area and US reference stations.

implement its own monitoring network. In WAAS precision approach flight trials at thirteen Canadian airports, Category 1 accuracy standards were exceeded, even though some of the airports were almost 500 nm from the nearest reference station.

The WAAS is based on a network of ground reference stations. Signals from GPS satellites are received by aircraft receivers as well as by ground reference stations.

Each of these reference stations is precisely surveyed, enabling each to determine any error in the GPS signals being received at its own location. This information is then passed to a wide area master station. The master station calculates correction algorithms and assesses the integrity of the system. This data is then put into the SBAS message format and sent to a Navigation Land Earth Station for uplink to the Inmarsat geostationary communications satellite. The SBAS signal transmitted by the satellite's navigation transponder at 1575·42 MHz is received by the aircraft receiver, which decodes the GPS integrity and correction data. The SBAS signals, from the Inmarsat-3 AOR-W (55° W) and POR (180° E) also function as additional navigation ranging signals for the position and velocity determination.

3.2. *European Geostationary Navigation Overlay Service* (*EGNOS*). The EGNOS is similar in concept to the WAAS. The manager of this project is the European Tripartite Group comprising the European Community (EC), European Space Agency (ESA) and Eurocontrol. The geostationary satellites used are the Inmarsat-3s, IOR (65° E) and AOR-E (15·5° W). The planned coverage area is for the (ECAC) States (Figure 2), but consideration is also being given to service provision

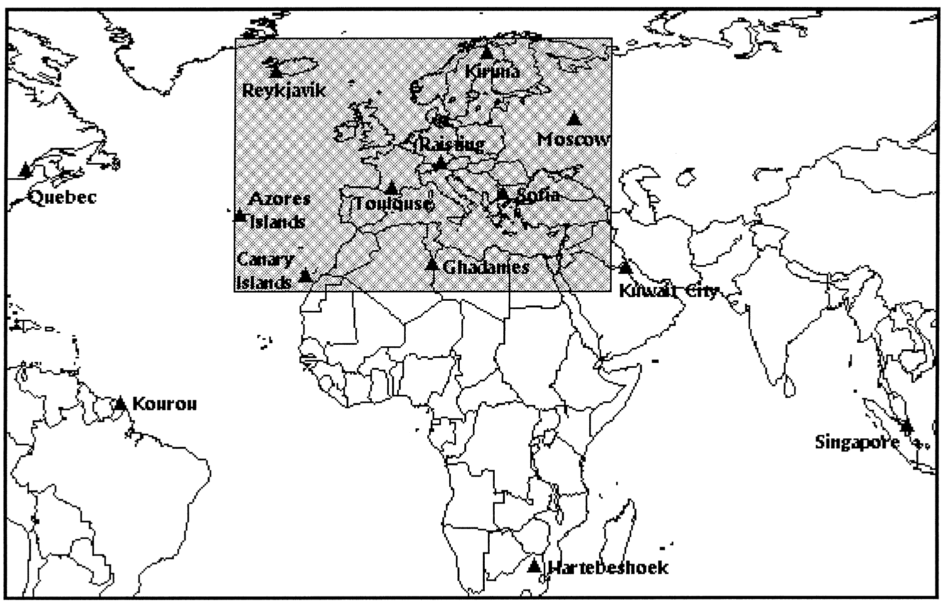


Figure 2. EGNOS reference integrity monitoring stations.

in a number of States within the footprints of the satellites including South America, Africa and India.

Europe plans to implement this system in three stages: ranging, integrity and wide area differential, with the fully operational system becoming available around the year 2002.

3.3. *MTSAT Augmentation System* (*MSAS*). The Japan Civil Aviation Bureau (JCAB) and the Federal Aviation Administration (FAA) have had several meetings to confirm that multi-function transport satellites (MTSATs) will offer a WAAS compatible wide-area augmentation system, MSAS, in the Asia-Pacific region. The first MTSAT satellite is scheduled for launch in 1999.

## 4. COMPATIBILITY AND INTEROPERABILITY.

The following separate, but related, issues must be considered:

(i) Technical (Signal in Space) co-ordination and compatibility
(ii) Administrative and certification compatibility.

4.1. *Technical or Signal Compatibility*. As with any system or service used by international civil aviation, it is highly desirable to achieve standardization. As pointed out earlier, this requirement has successfully been met by the application of ICAO SARPS for existing ground-based navigation systems. So that aircraft can navigate anywhere in the world using GNSS, a common signal standard for all augmentation systems is needed. It is the role of ICAO, with the assistance of its GNSS Panel (GNSSP) to achieve this standardization for implementation by its member States.

Since all SBASs will work on a common frequency – that is, 1575·42 MHz (GPS L1) – each individual satellite transmission must use a different Pseudo Random Noise (PRN) code. Each PRN code (19 have been designated) has been assigned a specific reference number. When the augmentation signal specifies that integrity information is being provided for PRN 120, the user receiver knows that this information applies to a particular geostationary SBAS satellite which is transmitting a particular PRN code. This information structure, the standard message format and the meaning of each message, are being established by the GNSS Panel. A procedure or mechanism must be established for choosing or assigning PRN code and satellite numbers to all augmentation system providers. Inmarsat has already made designations for primary and alternate assignments for the satellites serving its current four ocean regions (and its spare F-5 satellite).

4.2. *Administrative Co-ordination and Certification*. While it is possible to make designations in advance for the correspondence of PRN codes and the satellite identification numbers in the GIC messages, this does not solve the administrative questions. A receiver may be *physically capable* (by virtue of its design and location) of receiving an augmentation signal, but this does not guarantee either that the State responsible for managing air traffic in the airspace is ready to permit that signal to be used for navigation, or that every receivable signal actually contains data which are valid and certifiable for use in that airspace. Unless the State is willing to permit users to take advantage of any receivable signal, it will have to consider both the administrative question of deciding which signals are and which are not authorized for use *and* the practical matter of how user receivers will be controlled. Most desirable would be an automatic method of control, so that receivers would use only those signals which are authorized, without any manual selection or intervention.

In the longer term, however, the ideal situation would be that *all* signals which are available in an area are valid for *at least* en-route use. This ideal situation may not be achievable globally for some years. However, at a minimum, service providers whose augmentation signals and service areas overlap should consider co-operation and co-ordination on a reciprocal basis. This would mean, for example, that Japan and the USA negotiate an agreement so that the WAAS signal is certified for use in Japanese air space, and the MSAS signal is certified for use in US airspace, etc. This does not mean that each signal is the *best* one outside its designated service region, only that it is certified for use for specified operations. The receiver can then be programmed to choose the best augmentation signals which are available at any time in any location. An SBAS will not, normally, provide the necessary ionospheric data to enable *precision* approach capability outside of its own service area, so the option of using WAAS in Japanese airspace, or *vice versa*, does not apply to precision approach but could apply to en-route and non-precision approach. However, this goal of using the best augmentation signals is not as easily achieved as it would seem.

Interoperability has been treated in several earlier references, and it is worthwhile reviewing these in the light of subsequent developments. Fernow *et al*. (1997) provided an extensive list of possible interpretations of the question 'What is SBAS Interoperability?' From these, we single out two which are most relevant:

(i) The signals from *any* SBAS can be used by all avionics (that is, *any* user equipment) complying with suitable standards (such as ICAO SARPS).
(ii) The broadcast navigation data from an SBAS can be used safely in airspace outside that SBAS Service Provider's service volume, for any phase of flight except precision approach.

These two interpretations are virtually identical. To put tangible meaning to the discussion, performance and service possibilities in South America were examined (see Figures 3–5; Fernow, 1997). South America, like western Africa, is an excellent example case. It is covered by the AOR-West satellite's WAAS signal as well as the AOR-E EGNOS signal. If the WAAS and EGNOS monitoring networks exchange no information between themselves, so that each SBAS's performance depends only on its own data collection and measurement resources, normalized User Range Errors (UREs) apply (Table 1). The normalized URE is the geometric degradation

Table 1. Normalized User Range Errors (URE)

| | WAAS monitors only | EGNOS monitors only |
|---|---|---|
| Caracas | $< 10$ | 90–100 |
| Rio | 40–50 | 90–100 |
| Santiago | 70–80 | $> 100$ |
| Recife | 20–30 | 70–80 |
| Buenos Aires | 70–80 | $> 100$ |

factor which relates the measurement accuracy of the SBAS monitors, expected to be a fraction of one metre, to the possible range error which would occur if the corrections broadcast by the SBAS are applied at the user's position. The UREs *within* the Service Provider's region will typically be around 1. UREs below about 20 will result in an improvement over uncorrected GPS signals with Selective Availability.

Now, if monitors are installed *within South America* and connected to either one of the SBAS, and their data incorporated within that SBAS's broadcast, this is equivalent to extending the service region, and the URE will fall to a small number, certainly less than ten and possibly less than five, depending on the actual monitor deployment. In fact, evidence of this is already present in that WAAS's monitor in Puerto Rico enables a URE less than ten in parts of Central America and northern Venezuela.

But alternatively, if the WAAS and EGNOS systems shared *and incorporated* each other's monitoring data, the URE would be less than eight everywhere in South

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America *without any monitor at all in South America*. In practice, some combination of WAAS-EGNOS data exchange and a few monitors in South America providing data to both systems would provide excellent performance, the reliability of two Service Providers, and a suitable level of regional integrity monitoring.

Kinal (1997) also used South America, with the WAAS and EGNOS, as an example, but rather than treating the URE, this reference showed the change in availability of monitored, as opposed to unmonitored, GPS satellites that occurs if the user receiver can use data from both SBASs, rather than just from WAAS. This reference, unlike the previous, *did* take account of EGNOS's monitor in French Guiana, thus indicating the improvements possible with incorporation of data from monitors in South America within the 'scope' of either WAAS or EGNOS.

The presentation in Loh *et al.* (1997) addressed similar issues, but from the administrative aspects. In particular, the various levels of participation in an SBAS by an 'independent' nation – i.e. one not already involved in implementing its own SBAS – were discussed. A set of priority rules for selection of the most suitable SBAS signal, where more than one is available, was recommended (Table 2).

Table 2. SBAS Signal selection priorities

| SIS priority | Priority implementation |
|---|---|
| 1 | The CAA requires use of a specific SBAS in its FIR |
| 2 | A primary and a secondary SBAS are defined for the FIR |
| 3 | An SBAS that contains ionospheric data is selected over one that does not |
| 4 | An elevation angle criterion is applied (e.g., $> 10°$) |

This paper then analysed a flight from Los Angeles *westbound* to London. This (future) flight passes through WAAS-only, WAAS+MSAS, WAAS+MSAS+EGNOS, MSAS+EGNOS, MSAS+EGNOS, and EGNOS+WAAS coverage regimes. It should be noted that while Priority Rule 3 would ensure that the WAAS, MSAS and EGNOS each are selected in favour of another SBAS within the respective service volumes of the three Service Providers, ionospheric corrections are not required for en-route navigation. Thus, application of this rule deprives the user of possibly additional useful information from the de-selected SBAS(s); in particular, EGNOS will provide augmentation data for GLONASS, unlike WAAS and MSAS. Furthermore, in the portions of the flight outside any defined service volume, especially much of Asia, there is no clear definition of which SBAS should be used. Figure 3 shows the areas of the world illuminated by one, two or all three of the current three SBAS service providers' augmentation satellites (*not* the number of illuminating satellite signals).

A very recent change to the MOPS being developed by RTCA SC-159 (expected to be issued shortly as Change 3 to RTCA DO-229 [1996]) describes quite well the quandary that is created if China, for example, were to be forced to choose between approving use of EGNOS and/or MSAS, or not, in its controlled airspace; the text (below) has been slightly abbreviated from the original:

1.3.3. *International Compatibility*

The operational concept for GNSS and space-based augmentation systems (SBAS) is predicated on the combination of the different GNSS elements without pilot intervention.

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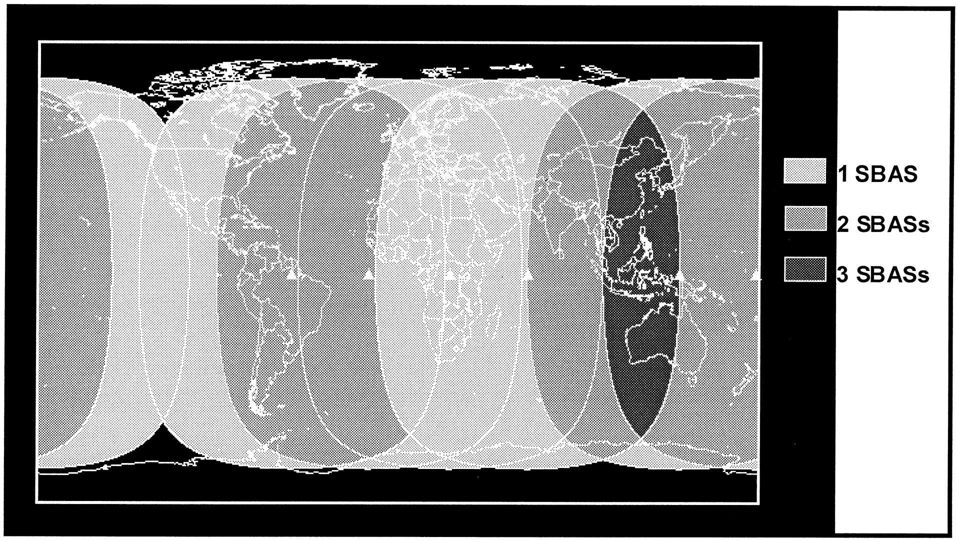


Figure 3. Areas of the world covered by 1, 2 or 3 SBASs. (Inmarsat-3, F5 is also shown although it is not currently allocated to any service provider.).

As GNSS is a global system, there should be no flight crew interaction based on airspace, so that the flight crew should not be involved in the selection of different SBAS (e.g., WAAS, EGNOS, MSAS).

In order to support the designation of a particular SBAS service provider for a precision approach, the FAS data block contains an SBAS-service provider ID that can be confirmed against the ID broadcast in a Type 17 message.

For operations other than precision approach, it is expected that States will approve all combinations of GNSS elements, to include SBAS services provided by another State. If a State decides to approve a subset of GNSS elements, there could be serious operational restrictions depending on the capability of the equipment. These restrictions depend upon the capability of the user equipment. For example, if the US FAA were to approve WAAS operations, but not EGNOS operations:

(a) Equipment with de-selection capability: Equipment which provides this optional capability could deselect EGNOS in US airspace. Potential implementations of this capability could be realized through parameters stored in the updatable navigation database, software modifications, or pilot interface. A pilot interface provides the most flexibility to accommodate operational needs, but requires training and is contrary to the basic operational concept for GNSS.

(b) Equipment that is designed to use only WAAS: For equipment intended to be used only in the US NAS, operational restrictions can be avoided by using WAAS alone. However, this equipment could not be used where WAAS is not approved.

(c) Equipment that is designed to use all SBAS providers could suffer severe restrictions in the event that a State does not approve the use of a service. Users of this equipment would be forced to revert to non-GNSS navigation, or VFR flight, in the event that EGNOS were not approved in the US.

A similar operational issue can arise for the approval of SBAS operations outside the airspace of the SBAS service provider. Throughout most of South America, WAAS equipment could use WAAS to support nonprecision approaches whenever WAAS is available. If a State chose to approve GPS operations, but not WAAS, then any equipment that did not provide de-selection capability would not be usable in that State's airspace.

It is implied in the above that the Service Provider identification in the Message Type 17 could be used, not only for precision approach but also other phases of flight, to identify and select authorized SBAS signals, in conjunction with the selection/de-selection capability. There is, however, no agreement about how such (de)selection is to be achieved, beyond a general distaste for manual (pilot-controlled) methods.

The SIS specification also provides for a message Type 27. This was originally intended to allow the Service Provider (perhaps acting in co-operation with the authorities responsible for navigation in a given area) to designate the performance or unsuitability of that SBAS in a given region. Thus, in the above example, China could request that MSAS transmit a Type 27 message making the MSAS unsuitable for non-precision approach (or even, en-route) in Chinese airspace. But notice that this requires the co-operation of the MSAS Service Provider, and to illustrate better this point, the FAA has chosen not to provide any Type 27 messages, so user receivers compliant with the MOPS will assume (absent a de-selection) that the WAAS data are valid everywhere within the coverage footprints of the WAAS satellites, i.e. Inmarsat's POR and AOR-W – a very wide region extending from Japan eastwards to Europe.

5. conclusions. The desirability of data exchange among the SBAS systems is understood and well accepted, but the necessary agreements are only at the earliest stages, and are proceeding on a bilateral basis.

There is no apparent agreement or documented specification regarding the permissible or preferred mechanisms for service provider selection/de-selection. Three possible techniques have been suggested:

(1) Single-region receivers (hard-wired for only one SBAS).
(2) Manual (de)selection (pilot interface).
(3) An automatic link to a database, thus assuming databases will contain the necessary information.

Strong inputs to this discussion are urgently needed from the non-SBAS States. Otherwise there is a risk that the bilateral discussions among the three SBAS operators will result only in a 'lowest common denominator' solution; that is, SBASs usable only within the defined service volumes.

While multilateral and bilateral agreements may be sufficient for Service Providers' areas, the problems for a third party, such as Australia, South America, or Africa, who may wish to benefit from systems operated by other States, must also be taken into consideration. It may therefore be appropriate to begin thinking about how an internationally agreed institution of some kind might be authorized to manage the co-ordination and synchronisation of augmentation services.

The number of Service Providers catered for in the Type 17 message, currently 16, is more than sufficient under the current definition of SBAS, but could in fact become inadequate if regionalised variants of SBAS are introduced in the future.

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## key words

1. Satellites. 2. Augmentation systems. 3. Standards.