L1/L5 SBAS MOPS to Support Multiple Constellations

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ABSTRACT

This paper proposes a message structure for the L5 GEO data signal that can support more than 90 simultaneous L1/L5 satellite corrections. The proposal is similar to the existing L1 structure with 250 bit messages sent at one Hertz. It eliminates the need for fast clock corrections. It creates a new integrity information message capable of updating the status for 91 satellites in a single message. Further, it simplifies the satellite corrections by gathering all of the required information for each satellite into a single message. This structure has excellent flexibility as a service provider that wishes to correct fewer satellites (e.g. a single constellation) may update the satellite corrections more often for improved accuracy. The paper also examines optimal scheduling strategies and the handling of alerts. The proposed structure addresses many of the shortcomings of the current L1 structure while remaining very similar in nature. Thus, this proposal leverages the most successful aspects of the L1 Minimum Operational Performance Standards (MOPS) while adapting it to meet the goals set forth for dual-frequency multi-constellation use.

INTRODUCTION

GPS has launched its first two L5 capable satellites and intends to achieve its L5 Full Operational Capability (FOC) in the 2019 (or later) time frame [1]. GLONASS has returned to a full constellation of 24 operational satellites and has plans to offer CDMA signals at both the L1 and L5 frequencies [2]. Europe and China are each building their own constellations (Galileo [3] and Compass [4] respectively) with intent to broadcast in the L1 and L5 bands. Thus, it is possible that in the next decade, there could be four constellations suitable for use by aviation with signals at L1 and L5. RTCA is developing an update to the Satellite Based Augmentation System (SBAS) Minimum Operational Performance Standards (MOPS) to include the use of GPS L5. EUROCAE is similarly developing dual frequency MOPS for Galileo. The intent is that these efforts will be merged into a single MOPS.
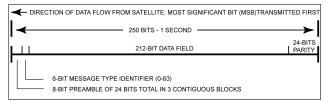
The different SBAS service providers have formed an Interoperability Working Group (IWG) to ensure that their respective systems remain compatible and to plan for future enhancements. This group has set a goal of having the L5 MOPS support all four constellations. Further, the L5 MOPS should ideally allow a service provider to correct all of the GNSS satellites in view of their network. Therefore, the IWG set a goal of having the L5 MOPS support up to 90 simultaneously corrected satellites.

L5 MOPS ARCHITECTURE

The current L1 MOPS [5] supports the use of the GPS L1/CA signals. The existing SBAS signals are broadcast from a geostationary satellite using the L1 frequency and are very similar in design to the GPS L1/CA signals. This legacy service will be maintained for the foreseeable future. It is possible that additional messages will be added to the L1 SBAS signal to expand the L1-only service to include additional satellites. Such an expansion would be implemented in a manner to maintain the existing service levels for legacy L1-only, GPS-only receivers. However, the addition of new messages and new services on L1 is not the topic of this paper. Instead, this paper focuses on an entirely new service on the L5 frequency.

Future SBAS satellites will also broadcast a service on the L5 frequency using a signal similar in design to the L5 civil signal provided by GPS [6] [7]. This new L5 signal will provide an additional service that makes use of the civil signals at the L1 and L5 frequencies. The L1-only and L1/L5 services can coexist and not interfere with each other. Thus, the legacy service will not be interrupted or reduced in any way as the new service is developed and implemented.

The messages on the SBAS L5 frequency will specifically correct the ionosphere-free combination of the L1 and L5 signals from the core constellations [8] [9] [10]. As such,

Figure 1. *An overview of the SBAS message format. It contains 14 header bits, and 24 parity bits leaving 212 bits for the actual message content.*

there is no need to broadcast ionospheric corrections as is done on the SBAS L1 signal. It is possible that some service providers will want to provide a reversionary L5-only service. Such a service may allow for improved operational capability in environments where the L1 frequency is experiencing interference. This paper does not develop ionospheric corrections to support enhanced L5-only capability. Receiver Autonomous Integrity Monitoring (RAIM) will support horizontal guidance in regions where L5 is clearly received, but L1 is not. Reversionary L5-only RAIM will allow the aircraft to navigate out of regions with interference.

LIMITATIONS IN EXISTING L1-ONLY MOPS

The current L1-only MOPS [5] do a very good job of supporting horizontal and vertical guidance given the limited available information bandwidth (250 bits per second). Therefore the proposed L5 MOPS will follow the existing structure and format closely. However, there are some issues with the L1 messages that can be improved with a new MOPS. Some major issues addressed in this paper are:

- GPS is the only fully specified constellation
- Only 51 active corrections are supported
- Corrections are spread across many messages
- SBAS satellites limited to geostationary orbits
- Poor identification of Service Provider ID
- Reduced accuracy due to quantization

These issues are further described in the paragraphs below.

Specifying Other Constellations
Although there is partial support for GLONASS in the existing MOPS, the details of including this constellation are not fully developed. Although, the details are not fully developed in this paper either, the messages are constructed to allow for satellites from any constellation to be included, provided they meet certain minimum requirements.

Limited Number of Corrections
The limit on the number of correctable satellites comes specifically from the design of the existing alert message (Message Type 6 or MT 6). Each message is limited to 212 data bits (see Figure 1). The integrity alert information for each satellite on L1 is broadcast via a 4 bit value called User Differential Range Error (UDRE). Therefore, the alert message can only update 51 satellites in a single message (another eight bits are used for synchronizing the message to other correction information).

Distributed Corrections
The L1-only corrections include fast clock corrections, slow or long-term satellite clock and ephemeris corrections, and ionospheric corrections. Each of these correction types is sent in a different message and it requires several messages to assemble the full correction element. This adds to the overall complexity of the L1-only MOPS.

Geostationary Orbits
The L1-only MOPS have a limited dynamic range to specify the location of the SBAS satellite. Currently, they are restricted to geostationary or nearly geostationary orbits. The inclination angle of these satellites must be below nine degrees. This restriction can prevent the use of other satellites for SBAS service provision and limit the useful lifetime of existing satellites

Identification of Service Provider ID
The airborne user is required to match the service provider ID of their intended approach procedure with the ID of the SBAS service that they are using. However, the L1-only MOPS has a two-step process for identifying the service provider ID. The service providers uniquely identify the location of their own SBAS satellite. The ID, however, is contained within an almanac message that may come from any SBAS satellite from any service provider (although the ID should be determined from messages from the same service provider). The airborne receiver must then match the locations of the two messages to confirm that the SBAS satellite that they are using is indeed associated with the correct provider.

Quantization Penalty on Accuracy
The L1-only MOPS was originally developed to work in the presence of Selective Availability (SA) [ref]. It therefore required clock corrections to have a large dynamic range and, consequently, a quantization level set at 12.5 cm. This is a significant source of inaccuracy for SBAS service.

L5 PRN Slot	Satellite Assignment	Current L1 Slots
1-37	GPS	1-37
38-74	GLONASS	38-61
75-111	Galileo	-
112-119	Reserved	62-119
120-158	SBAS	120-138
159-173	Reserved	139-210
174-210	Compass	-

Table 1. *Proposed L5 satellite mask*

Parameter	No. of bits	Scale Factor (LSB)	Effective Range
IODP	2	1	0 to 3
For each of 91 satellites			-
DFRECI	2	1	0 to 3
For each of up to 7 SVs			-
DFREI	4	1	0 to 15

Table 2. *Proposed L5 satellite alert message structure to support L1/L5 users.*

L5 SATELLITE MASK

The satellites used by the system are specified in the satellite mask. For L1-only this is specified in Message Type 1. It defines GPS, GLONASS, and SBAS satellites. The new L5 mask will need to also include Galileo and Compass satellites. Previous work has already specified 39 L5 SBAS PRN values [11] that we also include in our proposed mask. Further, the L1-only MOPS specified 37 GPS PRNs and 24 GLONASS PRNs. For the L5 satellite mask we propose 37 PRNs for each core constellation.

Table 1 shows the proposed L5 satellite mask contents and how it aligns with the existing satellite mask. All that is required are to define previously reserved bits. No previously specified bits are changed. Thus, it is fully backwards compatible. The structure of the new satellite mask message is identical to the existing MT 1 structure. All that has changed is that more of the possible bits have been defined. A 0 at a particular location indicates that the satellite is not being used by the service provider and a 1 indicates that the satellite is being used by the SBAS. Under the current proposal the new mask is only used by the new alert message. That is, the mask allows the user to determine which alert information corresponds to which satellite. No other messages require the satellite mask to determine against which satellite to apply the information.

THE ALERT MESSAGE

In order to alert more than 51 satellites within the required Time-To-Alert (TTA), either a new alerting methodology is required or we must reduce the required number of alert bits down from four. We have chosen the latter approach in this paper. We recommend using two bits to alert the satellite status, however this does require a small change to the alerting strategy. Instead of being able to update all satellite integrity states to any acceptable value within a single message we can only alert some satellites to any

state and the majority of the satellites have a more limited set of update values.
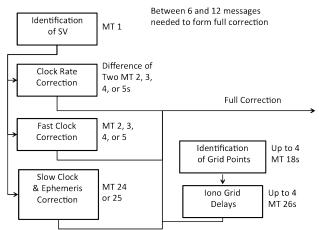
The two bits are used to indicate one of the following states:
- Unchanged   (0 0)
- Changed   (0 1)
- Not Monitored   (1 0)
- Do Not Use   (1 1)

The most common state for this message should be unchanged. That is, the full state was provided earlier with the full correction and it has not changed since that time. The next most common state would likely be Not Monitored (NM). That is, the satellite is not in view or not sufficiently viewed by the SBAS to provide a valid correction. Relatively infrequently, the SBAS may elect to change the integrity state from one numerical value to another with this alert message. If it chooses to do so, there is space for seven full four-bit integrity state values. We will call these Dual Frequency Residual Errors (DFREs) to distinguish them from the L1-only integrity state values. Very rarely, the system may need to indicate that one or more satellites has an integrity problem and should not be used for navigation.

Like the L1-only UDRE Indicator (UDREI), the four-bit DFRE Indicator (DFREI) identifies one of sixteen possible states. Fourteen are numerical and will be described later and the last two correspond to Not Monitored (NM) and Do Not Use (DNU).

Table 2 provides the message format for this alert message. The last seven full DFREI correspond in order to previously identified changed values. That is, the first DFRECI to indicate a change will have its full DFREI in the first full slot at the end of the message. The second DFRECI to indicate a change will have its full DFREI in the second full slot, and so on. Thus, no more than seven DFREIs may be changed from one numerical value to another in between satellite updates. When a DFRECI

Figure 2. *A high-level schematic of the messages and components required to correct a single satellite under the current L1 SBAS MOPS.*

Figure 3. *The corresponding schematic of the proposed message structure for the L5 SBAS MOPS. All corrections are contained in a single message.*
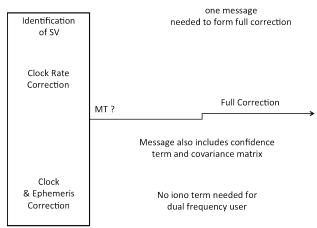
indicates a change it must continue to do so until the correction message(s) with the invalid DFREI has timed out (or the confidence value is sufficiently increased by degradation terms).

Any satellite may be changed to NM or DNU at any time. Such a change does not require a full DFREI update and therefore does not end up filling one of the slots at the end of the message. If there is any danger of needing more than seven slots within the update period, the service provider should send a larger initial value with the full message, increase the message degradation parameters (discussed later), or set some satellites to NM that otherwise could have had valid numerical values.

In test mode when a satellite is being evaluated but has not yet been approved for aviation use, the alert message may also serve the role of indicating the satellite is not to be used for aviation. As the L1 MOPS specifies MT 0 for this role, the alert message could assume a different message type number, but otherwise contain identical contents. WAAS used this approach for testing, replacing its MT 2 with an MT 0 that had all the contents of MT 2. In this way, the system can be tested in a safe manner in essentially the identical information bandwidth usage as the future operational system.

SATELLITE CORRECTION MESSAGE

The components of the satellite corrections are spread across many messages in the L1 SBAS MOPS. As shown in Figure 2, it requires between 6 and 12 messages to receive the full correction for any individual satellite. The MOPS is designed to be loss tolerant, so the user should be able to operate even if they are missing any individual

message, thus there are many possible valid corrections in use depending on which messages an aircraft has received or lost. At least three additional messages are required to calculate the integrity bound for the satellite correction. Again this leads to multiple conceivable valid bounds in use. Accounting for all these variations leads to additional complexity both in the aircraft and for the service provider.

We propose to reduce this complexity by combining all of the required corrections for an individual satellite into a single message as shown in Figure 3. This message also includes more of the integrity information, so that it may be more closely connected to the correction. This approach significantly lowers the number of possible active corrections to two: either the current message, or the one before (for en route flight three chances are provided, so for this mode there is a third possible active correction).

Table 3 shows the full contents of this message. Note that it includes the full PRN value for the satellite. Therefore it is not necessary to use the satellite mask to determine to which satellite this information applies. The IODE, which is used to match this correction with the broadcast data from the GNSS satellite, has an extra couple of bits associated with it. This is to allow better matching between these two data sources. We are still evaluating the best method to fill these bits. We could use the full IODC for GPS, or we could create a 10-bit hash of the broadcast data or some combination of the two approaches.

The clock/ephemeris and clock/ephemeris rate values have reduced dynamic range and quantization level values compared to the L1 corrections. When the L1 SBAS

Parameter	No. of bits	Scale Factor (LSB)	Effective Range	Units
PRN	8	1	1 to 210	-
IODE	10	1	0 to 1023	-
δx (ECEF)	11*	0.03	±30	meters
δy (ECEF)	11*	0.03	±30	meters
δz (ECEF)	11*	0.03	±30	meters
δB (ECEF)	12*	0.03	±60	meters
δx_dot (ECEF)	8*	2^{-12}	±0.0313	meters/sec
δy_dot (ECEF)	8*	2^{-12}	±0.0313	meters/sec
δz_dot (ECEF)	8*	2^{-12}	±0.0313	meters/sec
δB_dot (ECEF)	9*	2^{-13}	±0.0313	meters/sec
Time of day, t_0	13	16	0 to 86,384	seconds
Scale exponent	3	1	0 to 7	-
$E_{1,1}$	9	1	0 to 511	-
$E_{2,2}$	9	1	0 to 511	-
$E_{3,3}$	9	1	0 to 511	-
$E_{4,4}$	9	1	0 to 511	-
$E_{1,2}$	10*	1	±512	-
$E_{1,3}$	10*	1	±512	-
$E_{1,4}$	10*	1	±512	-
$E_{2,3}$	10*	1	±512	-
$E_{2,4}$	10*	1	±512	-
$E_{3,4}$	10*	1	±512	-
DFREI	4	1	0 to 15	-

* signed value coded as two's compliment

Table 3 . *The L5 satellite correction message*

MOPS were created, selective availability was in use to dither the GPS satellite clocks. Further, there was discussion of possibly dithering the ephemerides as well. However, the removal of selective availability, the absence of ephemeris dithering, and the continual improvement in performance mean that we can significantly reduce the dynamic range needed to correct the core GNSS constellations. Instead the quantization steps may be decreased leading to smaller errors in the corrections. As can be seen in the table, the dynamic range is reduced to 30 m and the quantization error is reduced to 3 cm. The rate of change corrections have also had their quantization levels reduced.

The equivalent of the L1 MT 28 clock-ephemeris covariance matrix parameters [12] are in the back half of the message. These will be formed and used in the same manner as they are for the L1-only integrity bounding. Finally, the full DFREI is included at the end. These values combine to provide the basis for the confidence bound. As in the L1 SBAS MOPS there are additional degradation terms that can increase the overall confidence bound. These will be discussed in a later section.

In order to be able to send up to 91 satellite correction messages within 150 seconds, we recommend eliminating the fast correction entirely. For the current WAAS L1 system, approximately one half of the available bandwidth is taken up by the fast corrections and UDREs in MT 2, 3, and 4. Although the L1 MOPS has provisions for sending the fast corrections less frequently, there is no longer any need to send separate fast corrections at all. Instead, the full clock and clock rate corrections are described by the *δB* and *δB_dot* terms listed in Table 3. In fact, everything needed to determine the L1/L5 SBAS correction for an individual satellite is contained within this message.

SBAS SATELLITE ORBIT AND ALMANAC MESSAGES

The GNSS satellite correction message provides a correction on top of the ephemeris messages broadcast from the GNSS satellite themselves. SBAS also needs to provide full orbital information for the satellites from which it broadcasts its messages. In the L1 SBAS MOPS these are referred to as geostationary satellites or GEOs. However, in our proposal we intend to allow any type of orbit to be used for broadcasting the SBAS L5 messages.

In order to use the SBAS satellite for ranging, in addition to message broadcast, we need to be able to accurately specify its position. Here again we target 3 cm for the accuracy level. In order to accommodate a greater variety of orbit types we switch away from the position, velocity and acceleration as the broadcast elements and instead use Keplerian elements with some additional terms.

Unfortunately, it is not possible to describe all possible orbits to with 3 cm using a single message. Instead, we will send the orbit information in two messages the contents of which are shown in Table 4. Here again we have the full PRN value that can be used to ensure that we are tracking the intended satellite, and are not cross-correlating on another PRN code. We have a 4-bit IODG in each of the messages to link the two halves together. The health and status of the SBAS satellite are indicated with 3 bits as they are defined in the L1 SBAS MOPS.

Also included are the service provider ID bits to match against the approach plate as needed.

Next the six Keplerian elements are provided: semi-major axis, eccentricity, inclination, argument of perigee (ω), longitude of ascending node (Ω_0), and mean anomaly at reference time (M_0). Three more elements are added to improve the orbital accuracy: the amplitudes of the cosine and sine harmonic correction terms to the argument of latitude (Cuc and Cus respectively), and the rate of change of the inclination angle (IDOT). The clock and clock rate correction terms: a_{Gf0} and a_{Gf1}, and the time of epoch are also included. Because these terms are a subset of the parameters broadcast for the ephemeris by the GPS satellites, the same process that GPS specifies for converting these elements to the current position may be used [13].

Finally the clock-ephemeris covariance matrix parameters and the DFREI for the SBAS satellite are included in the message. Although the bits are spread across two messages, the IODG ensures that the two parts are combined to form one unique message. One may not combine two halves with different IODG values.

The SBAS satellite will only send this message pair to describe its own orbit. If other SBAS satellites are used, the user must get the ephemeris messages from those other SBAS satellites. The SBAS satellite supplying the correction stream will broadcast satellite correction messages for the other SBAS satellites even if they come from the same service provider. No satellite correction message is needed for the ephemeris corresponding to the SBAS satellite providing the correction stream, that is, an SBAS satellite will not provide a satellite correction message for itself. It does not need to correct its own ephemeris information.

We are also in the process of defining the SBAS satellite almanac message. We have a goal of having it be accurate to within one degree over the longer term (many days or weeks). We also hope to be able to fit two SBAS satellites into a single almanac message. The almanac message serves two purposes: to let the user know about other SBAS satellites; and to allow the user to determine which SBAS satellites are likely in view at some point in the future.

DEGRADATION PARAMETERS

In the L1 MOPS, MT 7 and MT 10 contain time-out information and parameters to increase the sigma values

Parameter	No. of bits	Scale Factor (LSB)	Effective Range	Units
PRN	8	1	1 to 210	-
IODG x 2	8	1	0 to 16	-
Health & Status	3	-	-	unitless
Provider ID	4	-	-	unitless
Semi-major axis	32	0.01	0 to 4.9×10^7	meters
Eccentricity	31	2^{-31}	0 to 1	dimension-less
Inclination	34	$\pi \times 2^{-34}$	0 to $\pi/2$	radians
ω	34*	$\pi \times 2^{-33}$	$\pm\pi$	radians
Ω_0	34*	$\pi \times 2^{-33}$	$\pm\pi$	radians
M_0	34*	$\pi \times 2^{-33}$	$\pm\pi$	radians
Cuc	21*	1.3×10^{-9}	± 0.0014	radians
Cus	21*	1.3×10^{-9}	± 0.0014	radians
IDOT	22*	8.5×10^{-14}	$\pm 1.78 \times 10^{-7}$	rad/sec
Time of day, t_0	13	16	0 to 86,384	seconds
a_{Gf0}	12*	.02	± 40.96	meters
a_{GF1}	10*	5×10^{-5}	± 0.0256	meters/sec
Scale exponent	3	1	0 to 7	-
$E_{1,1}$	9	1	0 to 511	-
$E_{2,2}$	9	1	0 to 511	-
$E_{3,3}$	9	1	0 to 511	-
$E_{4,4}$	9	1	0 to 511	-
$E_{1,2}$	10*	1	± 512	-
$E_{1,3}$	10*	1	± 512	-
$E_{1,4}$	10*	1	± 512	-
$E_{2,3}$	10*	1	± 512	-
$E_{2,4}$	10*	1	± 512	-
$E_{3,4}$	10*	1	± 512	-
DFREI	4	1	0 to 15	-

* signed value coded as two's compliment

Table 4. *The L5 SBAS satellite ephemeris messages.*

over time or when missing messages. Similar parameters are still needed for the L5 SBAS MOPS, although with the simplified satellite correction message, there are fewer cases that need to be covered. Rather than having individual terms for each satellite as in MT 7 we propose terms to cover all satellites. Future modifications may propose different values for different core constellations, but currently we believe that a single value for all satellites is adequate.

The message is described in Table 5 and includes the time-out interval for the satellite correction and SBAS ephemeris messages. This parameter allows for a broad

Parameter	No. of bits	Scale Factor (LSB)	Effective Range	Units
Time Out Interval	6	6	60 to 432	seconds
Update Interval: I_{corr}	5	6	30 to 216	seconds
C_{corr}	8	0.01	0 to 2.55	meters
R_{corr}	8	0.2	0 to 51	mm/sec
A_{corr}	8	0.02	0 to 5.1	mm/sec^2
RSS_{dfc}	1	-	0 to 1	unitless
C_{er}	6	0.5	0 to 31.5	meters
$C_{covariance}$	7	0.1	0 to 12.7	unitless
DFRE Table	84		See below	
σ_{DFRE}: DFREI = 0	4	0.0625	0.125 to 1.0625	meters
σ_{DFRE}: DFREI = 1	4	0.125	0.25 to 2.125	meters
σ_{DFRE}: DFREI = 2	4	0.125	0.375 to 2.375	meters
σ_{DFRE}: DFREI = 3	4	0.125	0.5 to 2.5	meters
σ_{DFRE}: DFREI = 4	4	0.125	0.625 to 2.625	meters
σ_{DFRE}: DFREI = 5	4	0.25	0.75 to 4.75	meters
σ_{DFRE}: DFREI = 6	4	0.25	1 to 5	meters
σ_{DFRE}: DFREI = 7	4	0.25	1.25 to 5.25	meters
σ_{DFRE}: DFREI = 8	4	0.25	1.5 to 5.5	meters
σ_{DFRE}: DFREI = 9	4	0.25	1.75 to 5.75	meters
σ_{DFRE}: DFREI = 10	4	0.5	2 to 10	meters
σ_{DFRE}: DFREI = 11	4	0.5	2.5 to 10.5	meters
σ_{DFRE}: DFREI = 12	4	1	3 to 19	meters
σ_{DFRE}: DFREI = 13	4	3	4 to 52	meters
Spare	79	-	-	-

Table 5. *The L5 degradation parameter message.*

range of options because the number of corrected satellites may vary from below 20 to more than 90. A separate entry specifies the update interval, I_{corr}. This is a separate entry to allow more flexibility in how many active messages a service provider may choose to allow. This parameter specifies the targeted time interval between the satellite correction and ephemeris messages.

More importantly, it allows for an automatic bump in the confidence value to older messages. The magnitude of the bump is specified by C_{corr}. Parameters to specify correction rate and acceleration uncertainty are also provided (R_{corr} and A_{corr} respectively). These are combined to form a correction degradation term ε_{corr}:

$$\varepsilon_{corr} = \left\lfloor \frac{t - t_{corr}}{I_{corr}} \right\rfloor \cdot C_{corr} + \left(t - t_{corr}\right) \cdot R_{corr} + \frac{1}{2}\left(t - t_{corr}\right)^2 \cdot A_{corr} \quad (1)$$
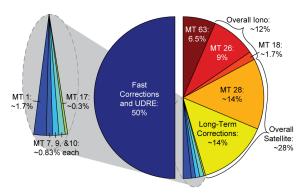
where, $\lfloor x \rfloor$, denote greatest integer less than or equal to x, t is the current time and t_{corr} is time of arrival of correction message for all satellites except for the SBAS satellite providing the correction stream. For this satellite it is the t_0 in the SBAS ephemeris message.

The message also includes an RSS_{dfc} bit that determines how the elements of the bounding of the dual frequency correction are combined. There is an en route degradation parameter that is applied if corrections older than the time-out interval are applied (en route users may continue to use corrections for an additional update interval beyond the time out interval). Finally there is covariance term that is used with the MT28 parameters exactly as it is in the L1 SBAS MOPS and therefore becomes part of $\delta DFRE$. These are combined to form the dual frequency correction variance overbound:

$$\sigma_{dfc}^2 = \begin{cases} \left[\left(\sigma_{DFRE}\right)\cdot\left(\delta DFRE\right)+\varepsilon_{corr}+\varepsilon_{er}\right]^2, & if \; RSS_{dfc}=0 \\ \left[\left(\sigma_{DFRE}\right)\cdot\left(\delta DFRE\right)\right]^2+\varepsilon_{corr}^2+\varepsilon_{er}^2, & if \; RSS_{dfc}=1 \end{cases} \quad (2)$$

Finally, this message also includes the ability to fully specify the numerical values for σ_{DFRE}. This allows the values to be optimized for the service provider's capability and minimize the quantization penalty inherent in only having 14 numerical values. Currently WAAS is unable to utilize more than half of the UDRE values as they fall below its minimum achievable level. The L5 MOPS need to be determined before the final achievable DFRE values will be known. This flexibility allows the values to be optimized later and also allows optimization to occur at the service provider level.

Until the user has received this message from the service provider they should assume that the DFRE values are at the maximum value for each index. One should be very careful about changing these values during operation. Either, the system has to assure the lower of the two active values or the system should have a planned interruption in service to allow the old message to time

Figure 4. *The approximate relative occurance of messages currently broadcast by WAAS.*

out before generating DFREIs associated with the new message.

TIMING

The two most significant concerns surrounding sending 90+ corrections are being able to alert the active corrections and having enough bandwidth to send all of the corrections. Figure 4 shows the approximate utilization of messages for WAAS today. Fifty percent of all messages are fast corrections and UDREI values. Nearly half of the bits in these messages are unneeded as the satellites are not visible or not defined in the mask. Removing the fast corrections and eliminating the dependence of corrections on the mask, allow us to only send messages and bits that are really needed.

0	Mask	Integrity	SV#1	SV#2	SV#3	SV#4
6	Empty	Integrity	SV#5	SV#6	SV#7	SV#8
12	SV#20	Integrity	SV#9	SV#10	SV#11	SV#12
18	SV#21	Integrity	SV#13	SV#14	SV#15	Ephem1
24	Ephem2	Integrity	SV#16	SV#17	SV#18	SV#19
30	Degrad.	Integrity	SV#1	SV#2	SV#3	SV#4
36	Empty	Integrity	SV#5	SV#6	SV#7	SV#8
42	SV#20	Integrity	SV#9	SV#10	SV#11	SV#12
48	SV#21	Integrity	SV#13	SV#14	SV#15	Ephem1
54	Ephem2	Integrity	SV#16	SV#17	SV#18	SV#19
60	Almanac1	Integrity	SV#1	SV#2	SV#3	SV#4
66	Empty	Integrity	SV#5	SV#6	SV#7	SV#8
72	SV#20	Integrity	SV#9	SV#10	SV#11	SV#12
78	SV#21	Integrity	SV#13	SV#14	SV#15	Ephem1
84	Ephem2	Integrity	SV#16	SV#17	SV#18	SV#19
90	Almanac2	Integrity	SV#1	SV#2	SV#3	SV#4
96	Empty	Integrity	SV#5	SV#6	SV#7	SV#8
102	SV#20	Integrity	SV#9	SV#10	SV#11	SV#12
108	SV#21	Integrity	SV#13	SV#14	SV#15	Ephem1
114	Ephem2	Integrity	SV#16	SV#17	SV#18	SV#19
120	Mask	Integrity	SV#1	SV#2	SV#3	SV#4

Table 7. *Potential L5 message schedule with up to 19 GPS and 3 SBAS satellites in view.*

Data	Maximum Update Interval (seconds)	En Route, Terminal, LNAV Time-Out (seconds)	LNAV/VNAV, LP, LPV, Approach Time-Out (seconds)
Don't Use for Safety Applications	6	N/A (Note 1)	N/A (Note 1)
PRN Mask	120 (Note 2)	600	600
Integrity	6	18	12
SV Corrections	See Table 5	See Table 5	See Table 5
SBAS Ephemeris	See Table 5	See Table 5	See Table 5
Degradation Parameters	120	600	600
SBAS Almanac	120	None	None

Note 1: For safety applications, reception of a Type 0 message results in cessation of use and discarding of any ranging, correction, and integrity data obtained from that L5 SBAS signal (PRN code).
Note 2: When the PRN mask is changed, it should be repeated several times before the new masks are used. This will ensure that all users receive the new mask before it is applied, maintaining high continuity.

Table 6. *Message content broadcast update and time-out intervals.*

The message update intervals and time-out intervals are shown in Table 6. Note that this corresponds very closely with the existing L1 SBAS MOPS intervals. There are fewer overall message types and greater flexibility given the variable correction intervals.

Without ionospheric corrections or the need for ionospheric alerts, it becomes easier to broadcast messages according to a rigid pre-planned schedule. Currently, WAAS uses an adaptive message scheduler, which tries to meet all of the message time-out requirements while getting out the most urgent updates most quickly. This is a very complicated process. A rigid scheduler, on the other hand, uses a fixed schedule and once determined is very simple. We will provide two examples here: a single constellation version of WAAS; and a four constellation maximum number of corrections version.

For the GPS only case we will use the current WAAS conditions: 32 GPS satellite and 3 SBAS satellites. The number of GPS satellites in view varies between 12 and 19. In a 120 second interval we need to broadcast one each of the PRN mask and degradation parameters, and

two SBAS almanac parameter messages. We will also need to broadcast an integrity message every six seconds, for a total of 20 such messages in 120 seconds. This leaves 96 available slots for the satellite corrections and SBAS ephemeris messages. Using an update rate for the satellite corrections of 30 seconds means that we will broadcast four corrections for each satellite within 120 seconds. We have up to 19 GPS satellite plus 2 other SBAS satellites to correct for a total of 84 satellite corrections to broadcast in this period. We also have to repeat the SBAS ephemeris messages four times for our own satellite. This information takes up two message slots for a total of 8 more required slots in the 120 second period. Thus, we have a grand total of 116 message to broadcast in the 120 second interval.

This is possible if each message has a predefined slot. The PRN mask could take the first position (slot 0) followed by an integrity message (these will in fact get every slot where time modulo 6 seconds = 1 second). Table 7 lists one option where each row in the table corresponds to a six message sequence. The first column indicates the slot number or relative time. Each cell indicates a message type. Degrad refers to the degradation parameter message, Ephem1 and Ephem2 to the two parts of the SBAS satellite ephemeris message, and SV# referring to a satellite correction message for particular satellites. SV#20 and SV#21 could be specifically for the other two SBAS satellites in the network. SV#13 -19 may be replaced by empty messages depending on how many satellites are in view at the moment.

As another example, consider the case with 91 active corrections (90 other satellites and the broadcasting SBAS satellite itself). In this example we will update the corrections every 120 seconds. We still need one each PRN mask and degradation parameter messages, 2 SBAS ephemeris messages, as well as 20 integrity messages. We will assume 4 SBAS almanac messages are required, leaving 92 available slots for 90 corrections. Again this is possible with rigid timing. Table 8 shows one possible solution.

Alerts will come in either the form of an MT 0 like message that will shut down all service, or an integrity alert message that updates the status of all satellites. When an alert is required it will be sent in place of the rigidly scheduled message that otherwise would have been sent out. The message scheduler may then either send the previously intended message in the next empty slot (or replace a less valuable almanac message with the satellite correction) or it may opt to skip the message this cycle. As in the L1 SBAS MOPS an alert message is sent

0	Mask	Integrity	SV#1	SV#2	SV#3	SV#4
6	Almanac1	Integrity	SV#5	SV#6	SV#7	SV#8
12	SV#9	Integrity	SV#10	SV#11	SV#12	SV#13
18	SV#14	Integrity	SV#15	SV#16	SV#17	SV#18
24	SV#19	Integrity	SV#20	SV#21	SV#22	SV#23
30	Empty	Integrity	SV#24	SV#25	SV#26	SV#27
36	Almanac2	Integrity	SV#28	SV#29	SV#30	SV#31
42	SV#32	Integrity	SV#33	SV#34	SV#35	SV#36
48	SV#37	Integrity	SV#38	SV#39	SV#40	Ephem1
54	Ephem2	Integrity	SV#41	SV#42	SV#43	SV#44
60	Degrad.	Integrity	SV#45	SV#46	SV#47	SV#48
66	Almanac3	Integrity	SV#49	SV#50	SV#51	SV#52
72	SV#53	Integrity	SV#54	SV#55	SV#56	SV#57
78	SV#58	Integrity	SV#59	SV#60	SV#61	SV#62
84	SV#63	Integrity	SV#64	SV#65	SV#66	SV#67
90	Empty	Integrity	SV#68	SV#69	SV#70	SV#71
96	Almanac4	Integrity	SV#72	SV#73	SV#74	SV#75
102	SV#76	Integrity	SV#77	SV#78	SV#79	SV#80
108	SV#81	Integrity	SV#82	SV#83	SV#84	SV#85
114	SV#86	Integrity	SV#87	SV#88	SV#89	SV#90
120	Mask	Integrity	SV#1	SV#2	SV#3	SV#4

Table 8. *Potential L5 message schedule with up to 91 satellites in view.*

a total of four times in a row, so either three (if the alert overlaps a regularly scheduled integrity message) or four messages will be preempted.

The adaptive message scheduling currently in use, could not function with as little extra margin to recover from schedule upsets as in the examples provided here. Since three of the current L1 messages (Types 2, 3, and 4) each contain required information for roughly one third of the active corrections, a delay in any one of them can lead to a loss of availability. However, the message structure proposed here does not have the same vulnerability. Three message types have the ability to affect multiple satellites. Two of these (PRN mask and degradation parameters) have longer time-out intervals so that the user has five chances to receive them. They are extremely unlikely to be timed out by the user before a replacement message arrives. The other message is the integrity alert message itself, which will never be supplanted by another message. Every other message that affects the performance of a satellite affects one satellite only. If it gets pre-empted by an alert message it has much less impact on overall performance. Particularly when there are many satellites being corrected, the loss of any individual satellite message becomes less important. Even if message is not replaced, the user should still have a valid correction as the previous correction for that satellite will not have timed out. The service provider may opt to allow more than two chances to receive each correction under these circumstances.

FUTURE WORK

There is still much that needs to be done in the evaluation of this proposal and ultimate decision as to what to put into the L5 MOPS. We are still working on the almanac message to determine if we will be able to achieve our stated goals. There will need to be testing to ensure that the message contents can be practically generated, encoded, decoded, and applied. We also need to evaluate whether all of the necessary information is included and with adequate quantization values and dynamic ranges.

This paper only describes the message content and some of its use. The tracking requirements and many other details need to be determined for the different satellite signals. This work corresponds to Appendix A of the L1 MOPS, there are many more sections that need to have analogous work done to create a valid L1/L5 MOPS.

In this paper we have avoided assigning message numbers to our proposed messages. This is because even though some messages may be virtually identical in form (e.g. the PRN mask), their contents may be different from the L1 data stream to the L5 data stream. Therefore, we feel it is better if the L5 message numbers be completely different from the L1 message numbers. Until this principle is decided and our proposed messages are accepted, we feel that it is premature to start referring to the proposed messages by message type numbers.

SUMMARY

This paper has proposed a message structure for L1/L5 service to be broadcast on the L5 SBAS message stream independently from the existing L1 GPS SBAS service currently broadcast at L1 on existing SBAS satellites. This message structure is very similar to the existing structure, but it makes a few notable improvements. Most significantly it recommends eliminating the fast corrections and using a new alerting message that functions for up to 91 satellites at a time. It simplifies the correction messages so that only one message is needed per satellite. The proposal further improves accuracy by reducing quantization effects. It allows greater variety of satellites to be used to broadcast the corrections and improves upon the description of their orbits while allowing better specification of the service provider identity. It also includes flexibility in the specification of the DFRE bounding values.

These improvements meet the goals of allowing satellites from all four planned core constellations to be used at the service provider's discretion. At the same time we stay very close to the existing message structure in order to reduce significant changes from the L1-only mode of operation. We look forward to working with service providers, avionics manufacturers, airframe manufacturers, and users to continue to refine the L5 MOPS and ultimately chart the best course going forward.

ACKNOWLEDGMENTS

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