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Agenda Item 3: SARPs for GNSS elements and signals (GBAS)

Alternative Architecture for Dual Frequency Multi-Constellation GBAS

(Presented by Tim Murphy)

SUMMARY

This paper describes a proposed alternative architecture for Dual Frequency Multi-Constellation (DFMC) GBAS. The proposal builds off of the good work done over the last 10 years by the SESAR program. However, the proposal is designed to enable more optimal airborne processing that should enable better performance and higher availability for DFMC GBAS globally.

This proposal is being put on the table for consideration as GWG converges on standards for DFMC GBAS. There is still much work to do to flesh out this proposal. However, much of the work is common to validating any DFMC GBAS architecture.

1. INTRODUCTION

1.1 This paper describes a proposed alternative architecture for DFMC GBAS. The proposal can be succinctly describes as follows. Pseudorange (PR) and carrier phase (CP) measurements are uplinked to the airborne users rather than carrier phase corrections. Then the airborne processes the PR and CP measurements to produce carrier smoothed PR measurements using multiple different types of smoothing. Both Divergence Free (DFree) and Iono Free (IFree) smoothing is performed in parallel. The airborne user creates differential corrections using the uplinked measurements in the same way that the ground station would produce differential corrections for MT 1 and MT 11. (See the SARPs [1]) By moving the computation of differential corrections to the airborne the use of a much longer carrier smoothing time constant is enabled. Also the of DFree smoothing with longer smoothing intervals is enabled because the airborne can ensure that smoothing of airborne and ground measurements are matched. By combining these two things, it allows the airborne receiver to directly estimate the ionospheric gradient between the airborne receiver and the ground station without having the smoothing filter buildup due to the iono gradient confound the observation. When the observed gradient for any given satellite is above some threshold, the airborne will switch from using the DFree smoothed pseudoranges for that satellite to the IFree smoothed pseudoranges. In this way, the effect of the high gradient is removed completely albeit with some penalty on the noise for that measurement. Since the increase in noise is known, the satellite can be de-weighted in the solution as appropriate.

1.2 The primary mode for positioning uses corrected pseudoranges DFree smoothed with a long time constant (e.g. 600 seconds). Since the airborne is computing the smoothing for both the ground and airborne monitoring, the smoothing time can be matched as appropriate. An IFree combination of the DFree pseudoranges is formed by the user and differential corrections are computed using the ground reference station location given in MT 2. Subtracting these IFree differential corrections from the ground pseudorange correction for L1 obtains an estimate of the ionospheric delay observed by the ground station at L1 in the same manner as suggested in NSP 5 WP 41 [2]. The main difference is that by using DFree smoothing before forming the IFree combinations to form the differential corrections, the estimate of the ionospheric delay seen by the ground station has no filter build-up component due to the smoothing time. This technique provides low noise effectively long baseline airborne iono gradient monitoring. This allows the airborne to determine whether switching to the IFree smoothed measurements is necessary and it allows DFree measurements (with much lower noise) to be used for most of the satellites. Consequently the accuracy of this type of solution is much better than the accuracy of a solution based on all IFree measurements. The longer smoothing times also contribute to higher accuracy of the solution. The combination of primarily using L1 DFree smoothed pseudoranges and long interval smoothing results in a higher accuracy position solution than achieved with either the nominal GAST C or GAST D services. Adding the effect of multi-constellation will even further improve the accuracy. However, with this proposal, the availability of service should be relatively robust to the loss of an entire constellation.

1.3 In addition to the basic positioning mode described above, (L1 DFree long interval smoothing), up-linking measurements instead of corrections enables the use of pure carrier phase position solutions such as Real Time Kinematic (RTK) Carrier Phase (CP) based solutions. Such solutions are used extensively by other industries for very precise positioning at the centimetre level. However, ensuring the integrity of this type of solution is still an open question and an active area of research. Researchers in other industries are also trying to solve this issue (e.g. self-driving cars, unmanned aerial vehicles etc.). So it is likely that a solution will be found and that sub-decimeter performance with protection levels on the order of 2 to 3 meters will be possible. By adopting this alternative architecture now the use of these very precise positions solutions is potentially enabled in the future.

2. DISCUSSION

2.1 The proposed architecture is envisioned to support a new level of GBAS approach service. For now, this GBAS Approach Service will be referred to as GAST X. It is envisioned as a natural exstension of GAST C and GAST D. In addition, the proposal borrows heavily in many respects from the SESAR proposal for GAST F [2]. GAST X will be used to differentiate this proposal until some concensus is reached on the architecture for DFMC GBAS.

2.2 This proposed alternative architecture is based on up-linking unsmoothed PR and CP measurements rather than smoothed pseudorange corrections (PRCs). By providing unsmoothed measurements, it allows flexibility in how the airborne receiver applies smoothing. The airborne can in fact smooth with different time constants and use both IFree and DFree smoothing in parallel. The nominal positioning mode would use L1 (or L5) DFree smoothed pseudoranges. The ground measurements are translated to the GBAS reference position (given in MT 2). The airborne receiver can compute a differential correction for each satellite using the reference position given in MT2 and the satellite location as computed by the airborne receiver. Note that since the airborne receiver is doing the computation of the differential correction, it is not necessary to align which ephemeris the ground station may be currently using for computing satellite positions. It is only necessary that the airborne receiver use a consistent satellite position for the computation of the differential position and when doing the position solution.

2.3 Figure 1 shows the processing for the primary mode of GAST X. The ground subsystem sends up one or more MT 23 messages (see section 3) containing unsmoothed measurements for pseudorange and carrier phase. The airborne receiver applies divergence free smoothing, as described in reference [3] to all the satellite measurements for both ground and air. Then the airborne receiver uses the results to form IFree combinations for all the pseudoranges. The airborne computes differential corrections using both the DFree PR's and the IFree PR's. Those corrections are averaged and B-values are computed in the same way that a gound station would do those computations. Finally, the IFree differential corrections are used by on iono gradient monitor to detect if a iono gradient greater than some threshold exists between the user and the ground station. The iono gradient monitoring results are used to determine which satellites in the position solution will use the IFree corrected pseudorange, vs. the DFree corrected PR. The position solution and the Iono Gradient both use sigma_pr_ground from MT 11 (or MT 1 if GAST D is not supported) as an input. The value of sigma_pr_ground is scaled appropriately to account for the difference in smoothing time constants and the number of reference receivers used etc. in order to obtain a representative sigma for the pseudoranges as smoothed and averaged in the air.

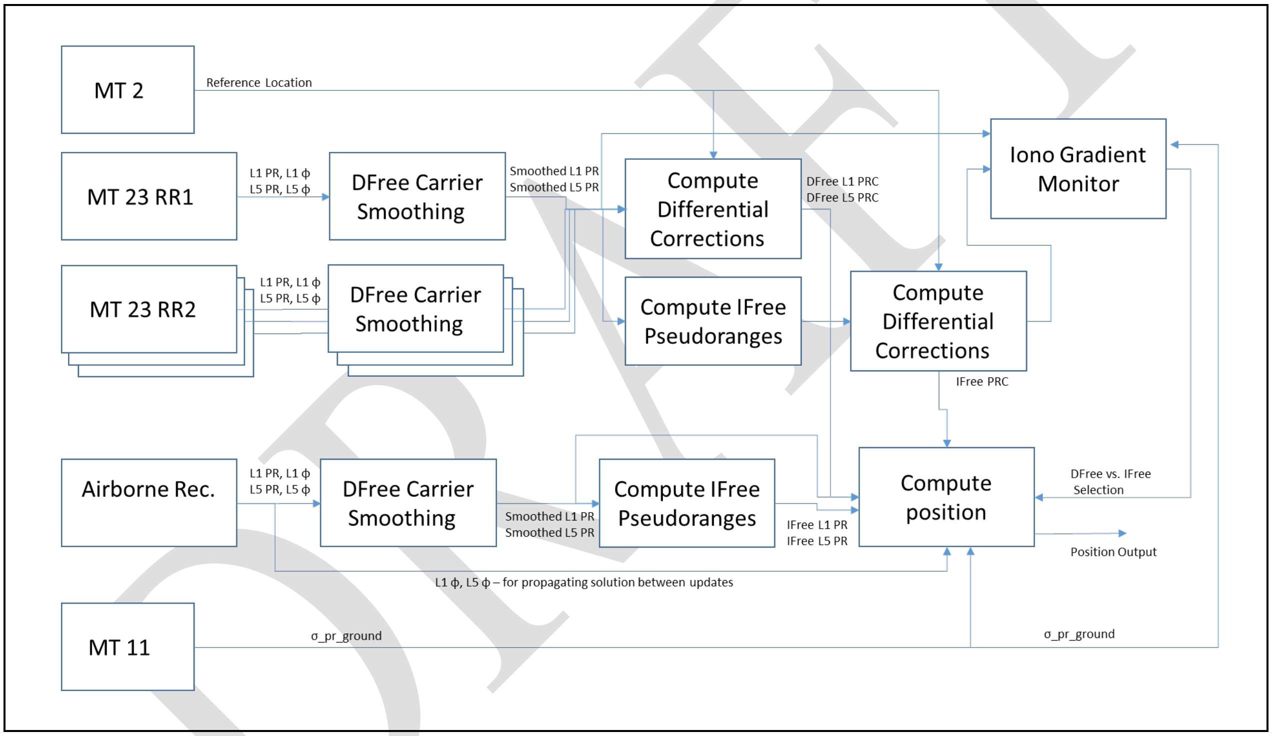


Figure 1 Processing for Primary Positioning mode

2.4 The GAST X proposal leverages paramters that are already sent to the airborne in MT 11. (Should the discussions of the proposal for GAST D to be optional but recommended conclude that GAST D can in fact be optional, then the necessary parameters could be obtained from MT 1. However, the parameters from MT 11 are more appropriate as sigma_pr_gnd should have no inflation to cover ionospheric effects. The computations for the protection levels in GAST X are the same for GAST C and D with the exception that sigma_pr_gnd should be scaled to account for the different smoothing time constant and for the number of receivers used in averaging the corrections in the airborne. The airborne will also compute $B_{i,j}$ values for each pseudorange correction (PRC) computed in the air by taking the difference between the computed averaged PRC and the PRC obtained by excluding the jth reference receiver measurement from an average for the i^{th} ranging source. This is exactly the same calculation that would be done by the ground station for MT 1 or MT 11. Repeating this calculation in the air allows for a different (longer) smoothing time constant to be use.

2.5 As discussed above, the primary positioning method is L1 DFree Carrier-Smoothed-Code phase position solution. Consequently the basic form of the general-least-squares given in section 3.6.5.5.1.1.2 of the SARPs will be the same. The difference will be in the weighting and use of the parameters provided by the ground system. The weighting matrix in section 3.6.5.5.1.1.2 has the following terms on the diagonal:

$$\sigma^2_{W,i} = \sigma^2_{pr\_gnd,i} + \sigma^2_{tropo,i} + \sigma^2_{pr\_air,i} + \sigma^2_{iono,i}$$

For a GAST X system, the weighting should be modified to accound for the longer smoothing time constants.

$$\sigma^2_{W,i} = SF_{gnd,i}\sigma^2_{pr\_gnd,i} + \sigma^2_{tropo,i} + SF_{air,i}\sigma^2_{pr\_air,i} + \sigma^2_{iono,i}$$

Where:

$\sigma^2_{pr_{gnd},i}$ = $\sigma^2_{pr_{\_gnd\_30},i}$ for the ith ranging source in the most recent Type 11 message.

$\sigma^2_{pr_{air},i}$ = the standard deviation of the aircraft contribution to the corrected pseudo-range error for the ith rangin source.

$\sigma^2_{tropo,i}$ = the residual tropospheric uncertainty for the ith ranging source (see section 3.6.5.3 of the SARPs). Because this parameter is not dependent on frequency this term should not need to be scaled relative to the GAST D.

$\sigma^2_{iono,i}$ = the residual ionospheric delay (due to spatial decorrelation) uncertainty for the ith ranging source (3.6.5.4). Because DFree smoothing is used for GAST X, the term broadcast for GAST D should be conservative for GAST X and no scaling should be necessary.

$SF_{gnd,i} = \frac{100 \cdot M_{gnd,i}}{T_{smoothing\_air} \cdot M_{air,i}}$ - Assumes Sigma_PR_gnd_D is used from MT 11.

$SF_{air,i} = \frac{100}{T_{smoothing\_air}}$

$M_{gnd,i}$ = the number of reference receiver measurements averaged on the ground to produce the PRC in MT 11 for the ith satellite.

$M_{gnd,i}$ = the number of reference receivers used to create the averaged PRC in the airborne computations.

$T_{smoothing\_air}$ = the smoothing time for the airborne DFree carrier smoothing.

2.6 Figure 2 shows a comparison of the pseudorange accuracy for the proposed GAST X service compared to a GAST D service and a full IFree solution (denoted GAST F). All the cases in the figure are based on the assumption of reference receiver accuracies commensurate of a GAD C4 ground facility. In addition the airborne receiver is assumed to be characterized by Airborne Accuracy Designator B (AAD B). The standard airborne multipath models are used. For simplicity's sake sigma_tropo is assumed to be 0.1 meters. Sigma_vig is ignored beacause it is assumed to be negliglble for GAST D. It should be essentially zero for GAST X because DFree smoothing is used for both the ground and air. From Figure 2 it can be seen that a IFree combination results in a substantial increase in the noise. Also the figure shows that GAST X will actually provide psedurange accuracy better than GAST D. For this example, GAST X is assumed to have DFree smoothing with a 600 second time constant. Four curves are shown for

GAST X, two which assume measurments are uplinked for only two reference receivers and another two based on the assumption that measurements are uplinked for all 4 reference receivers. There is little difference between the two GAST X curves with 2 versus 4 reference receivers used as Airborne noise and multipath begin to dominate such that the averaging over 4 ground measurements instead of 2 doesn't change the total significantly. The cases labelled "GAST X IFree" assume that and IFree combination is formed with the DFree smoothed L1 and L5 PRs. Recall, that this will only be done for satellites where an iono gradient above some threshold is detected. While the accuracy for these GAST X IFree cases is significantly worse than the nominal GAST X DFree cases, it is still better than the GAST F IFree case because the GAST X takes advantage of the longer smoothing interval (assumed to be 600 seconds in this example).

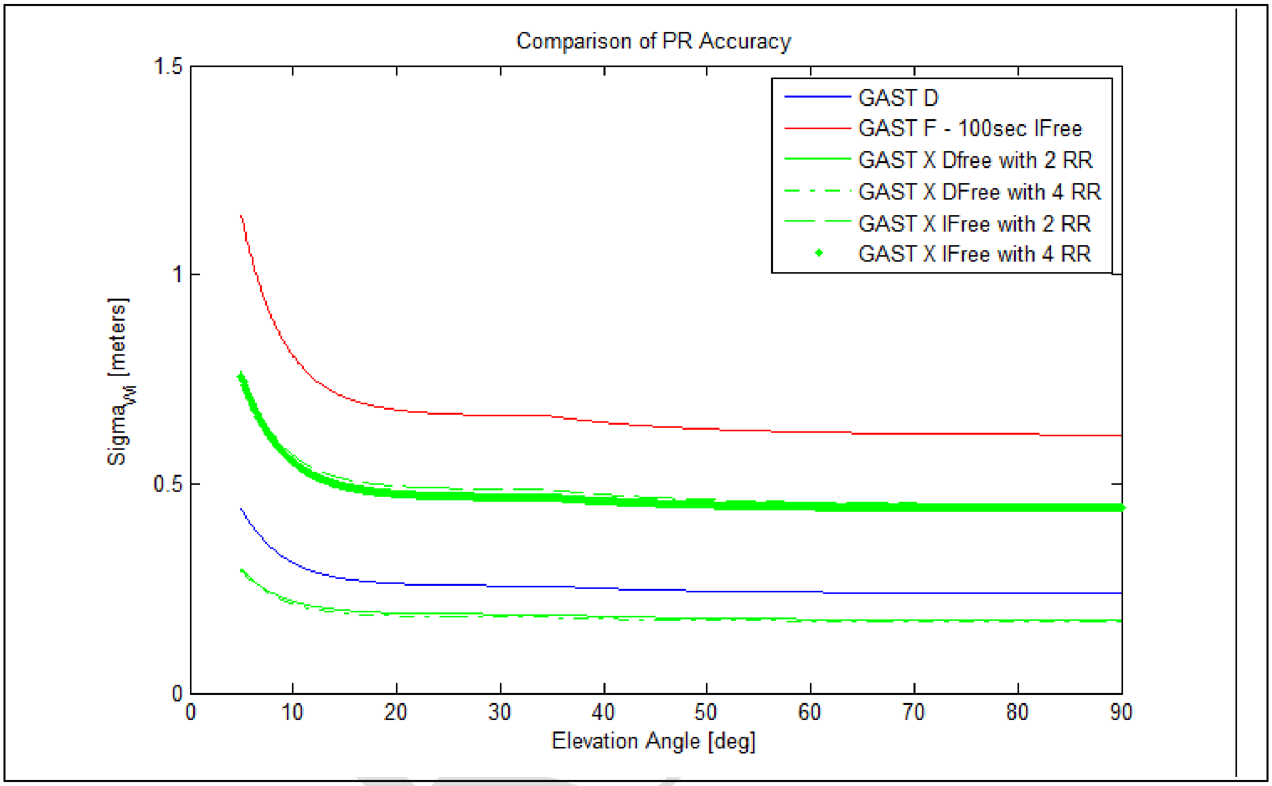


Figure 2 Comparison of Corrected Pseudorange Noise for GAST D, GAST F and GAST X.

2.7 Figure 2 well illustrates the potential versatility of GAST X. It is possible that GAST X with DFree extended smoothing intervals would provide better accuracy than any of the other service types. Note that the curves for GAST DFree are either L1 or L5 only which suggests that GAST X can support an L5/E5 only fallback mode The figure seems to indicate that the performance is roughly equivalent whether measurements are sent up from two reference receivers or all 4. However, it is probable that the size of the protection levels will prove to be a discriminating factor in that regard. A full availability study will be required in order to fully understand the benefits of how many reference receivers will need to be used in the GAST X solution. It does at this point appear to be possible to use only 2 reference receivers which means that a full 1 second update rate could be supported with only one slot per frame.

2.8 GAST X is flexible because it supports a number of downgraded modes (e.g. an L5/E5 only mode) albeit at a lower level of performance (e.g. CAT I or GAST C equivalence only). This flexibility is futher illustrated in Figure 3. The nominal mode for GAST X is an extended DFree smoothing interval with iono gradient monitoring to determine if individual satellites should be switched to use IFree combinations. This nominal mode depends on measurements being available on both frequencies. If use of L5 is lost, either at the ground station or in the airborne, the GBAS airborne equipment can transition to GAST D (if available) and still maintain CAT III capability. If GAST D is not available, the system can transition to GAST C. Both these service levels and the transition between them is covered by the current SARPs and MOPS. If L1 is lost, then the airborne equipment can transition to a GAST X sub-mode that recreates a GAST D equivalent service on L5/E5 only. This is done by the airborne computing corrections from the ground station at both 30 second and 100 second smooting. The airborne will also performe Dsigma processing on L5 (i.e. compare the 30 second and 100 second smoothed pseudoranges to detect iono gradients). Finally, the airborne can do all the same processes required for GAST D using L5/E5 only. In this way, CAT III capability should be maintained. Should the L5/E5 GAST D equivalent mode be unavailable, then the airborne equipment can trasition to an L5/E5 GAST C equivalent sub-mode of operation. This would entail computing differential corrections (B values etc.) for 100 second smoothed pseudoranges and forming a position solution (and protection levels) commensurate with GAST C processing as defined in the SARPs. For these two sub-modes there is still some trade space to be explored in that because all the computations are done in the air, the extended smoothing times may be able to be exploited to improve the performance of both modes.

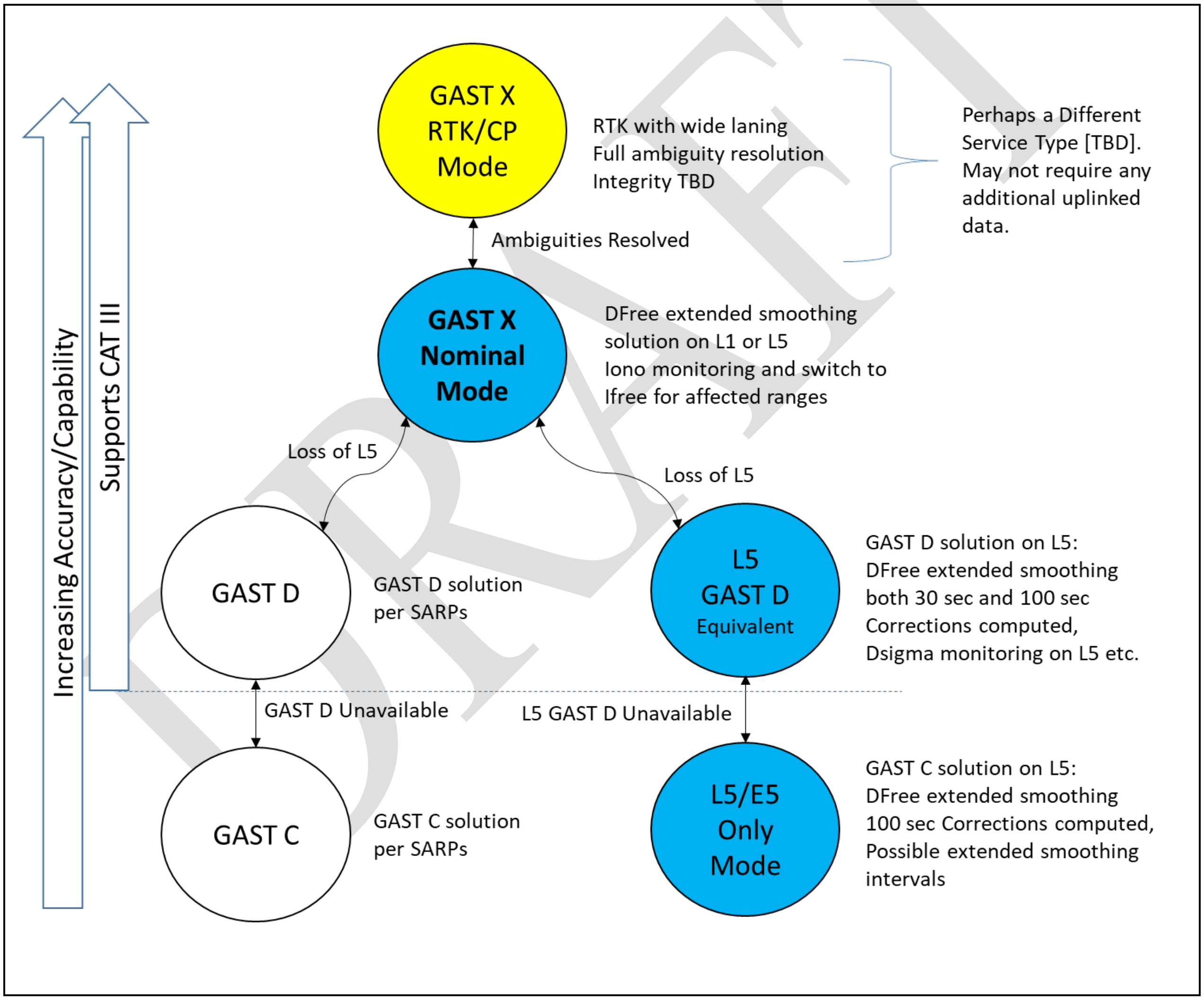
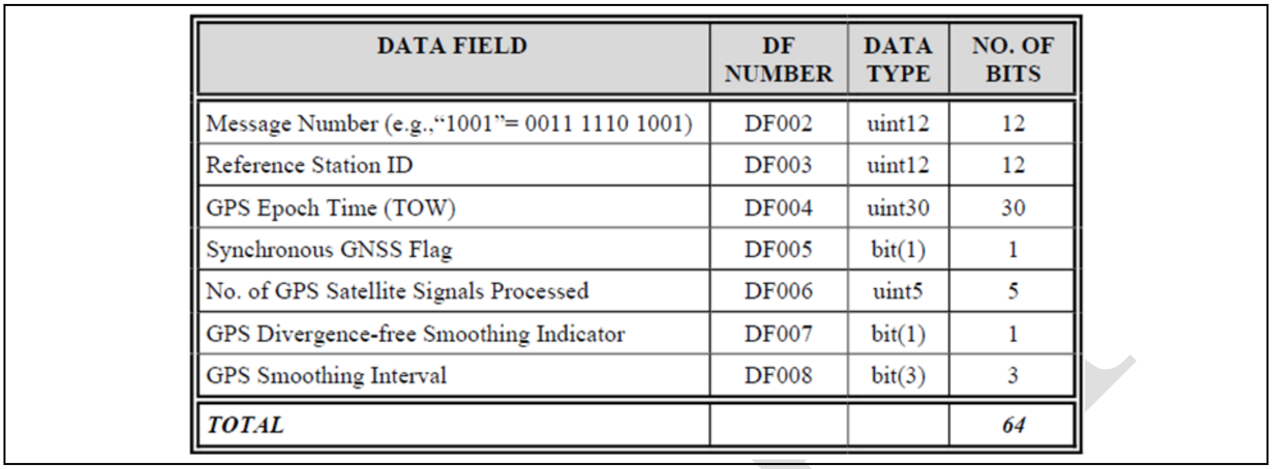


Figure 3 GAST X Fallback modes (blue) and Future Mode (yellow)

3. PROPOSED GAST X MESSAGES

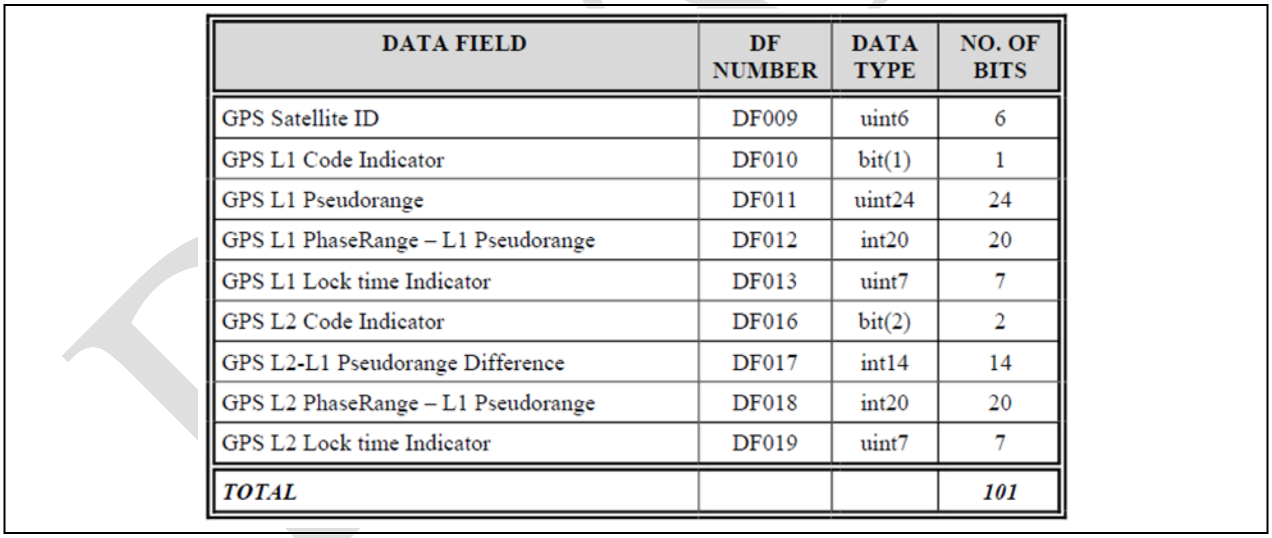
3.1 The unsmoothed PR and CP measurements are provided by a new message type which is modelled after RTCM 10403.2 standard Message Type 1003. As a reminder, the original message types for GBAS were derived from RTCM messages, so much similarity already exists in the message header and general structure. The following tables show the RTCM messages currently defined to support dissemination of GPS measurements to support RTK on L1 and L2.

Table 1 Contents of RTCM 10403.2 Message Header, Types 1001, 1002, 1003, 1004 : GPS RTK Messages



DATA FIELD	DF NUMBER	DATA TYPE	NO. OF BITS
Message Number (e.g.,“1001”= 0011 1110 1001)	DF002	uint12	12
Reference Station ID	DF003	uint12	12
GPS Epoch Time (TOW)	DF004	uint30	30
Synchronous GNSS Flag	DF005	bit(1)	1
No. of GPS Satellite Signals Processed	DF006	uint5	5
GPS Divergence-free Smoothing Indicator	DF007	bit(1)	1
GPS Smoothing Interval	DF008	bit(3)	3
TOTAL			***64***

Table 2 Contents of the Satellite-Specific Portion of a Type 1003 Message, Each Satellite – GPS Basic RTK, L1 & L2



DATA FIELD	DF NUMBER	DATA TYPE	NO. OF BITS
GPS Satellite ID	DF009	uint6	6
GPS L1 Code Indicator	DF010	bit(1)	1
GPS L1 Pseudorange	DF011	uint24	24
GPS L1 PhaseRange – L1 Pseudorange	DF012	int20	20
GPS L1 Lock time Indicator	DF013	uint7	7
GPS L2 Code Indicator	DF016	bit(2)	2
GPS L2-L1 Pseudorange Difference	DF017	int14	14
GPS L2 PhaseRange – L1 Pseudorange	DF018	int20	20
GPS L2 Lock time Indicator	DF019	uint7	7
TOTAL			***101***

3.2 Additional information about the coding and use of the parameters in Table 1 and Table 2 can be found in the RTCM 10403.2 specification.

3.3 Table 3 contains a proposal for a new message type, MT 23, intended to support DFMC GBAS. Note MT 23 is modelled after the RTCM message formats shown in Table 1 and Table 2. Notable is that the message header is modified to make it consistent with GBAS.

Table 3 Proposed MT 23 – DFMC GBAS Measurements

Data Content	Bits Used
Modified Z-Count	14
Additional Message Flag	2
Measurement Type	3
Reference Receiver ID	2
Number of Measurements (N)	5
For N Measurement Blocks:	
Ranging Source ID	8
L1 code indicator	1
L1 Pseudorange	24
L1 Phase Range – Pseudorange	20
L1 Lock Time Indicator	7
L5 Code Indicator	2
L5-L1Pseudorange Difference	14
L5 Phase Range – L1 Pseudorange	20
L5 Lock time Indicator	7

3.4 From Table 3 it can be seen that the length of a Message Type 23 is: 24 bits + N x 103 bits. Since a slot accommodates 222 bytes and the message header is 6 bytes, then the number of satellites that can be accommodated in a single slot is N=((222-6)*8-24)/103 = 16.54. So 16 satellites can be accommodated in a slot with about 56 bits to spare.

3.5 Type 23 messages group measurements by reference receiver. Type 23 messages can be linked in the same manner as MT1 messages. In addition, multiple MT 23 messages can be sent with the same Modified Z-Count to provide measurements from multiple Reference Receivers. The Reference Receiver ID field indicates which reference receiver is the source of the measurments. However, all measurements are referenced to the GBAS reference location. This is possible because the location of each reference antenna is precisely know relative to the GBAS reference location.

4. DATA LINK CAPACITY CONSIDERATIONS

4.1 GAST X requires measurements uplinked from multiple reference receivers. Up to 16 satellites can be sent in a given slot. The minimum number of slots to support an update with 2 reference receivers is 2. With 4 reference receivers, 4 slots would be required. In a manner similar to that proposed for GAST F, the GAST X position solution can be computed at a lower rate and a pure carrier relative position can be used to propagate the solution between updates as necessary. How to insure indegrity between updates is an open question. However, something similar to the solution proposed for GAST F (i.e. MT 20 in []) should be feasible. A minimal solution could use 2 Hz update rates and only need 1 slot (per frame for 2 frames) for up to 16 satellites. This assumes that antenna diversity is not required for the GAST X service. If it is, then the update rate could be increased to once every 2 seconds and the same single slot would support a minimal solution. If the update interval is variable, we may need a parameter in the Type 2 message that lets the receiver know what to expect.

4.2 If an airport does not have coverage issues such that antenna diversity is needed, then a full GAST X solution should be able to be accommodated at a 2 Hz update rate for up to 16 satellites. If more than 2 constellations are to be augmented, then linked MT 23 many be employed. So, up to 32 satellites can be accommodated in 4 slots per update interval. If a minimal 2 RR system is employed, then 1 available slot per frame would support an update rate of once per 2 seconds.

4.3 If an airport is sufficiently difficult to serve with VDB from a single transmitter, consideration should be given to having the ground station transmit on multiple frequencies. This could be done in a way such that the receiver would not be required to receive signals on two frequencies at once. The ground station would duplicate all the MT 1, MT2, MT 11 messages on each frequency. Then MT 4 on each frequency would carry only those FAS data blocks for which the VDB has coverage at that frequency for the approach, landing and roll out.

4.4 It is a fact that GAST X requires more datalink bandwidth than GAST F as proposed in [2]. However the increased datalink use is more than offset by the improvement in performance and the fact that a fully CAT III capable L5/E5 only mode should be able to be supplied. In addition the potential growth to RTK (or other carrier phase based positioning) is an important factor that should not be overlooked. If we implement GAST F as envisioned and max out the datalink capacity, then there would be limited opportunity to evolve to support RTK without a major change in the datalink (e.g. higher order signalling) or use of multiple frequencies.

5. IONO GRADIENT MONITORING IN GAST F

5.1 With a full set of measurements from both the ground and air, the airborne can now monitor the entire threatspace for iono anomalies. In fact because the airplane can do this when it is relatively far from the ground station, it can do iono monitoring with much greater sensitivity than can be achieved by a ground station with reference receivers only separated by a few hundred meters. In essence, the system now has a long baseline monitoring capability that can detect the absolute gradient between the ground and the air. Furthermore, because divergence free smoothing can be applied to both the ground and airborne measurments, the true instantaneous Iono seen by the ground or the air can be determined. This means that the long smoothing filter build up due to iono will not confound the observation, possibly masking the ability to detect.

5.2 In reference [2] it is shown that IFree pseudorange corrections can be computed as:

$$PRC_{IFree} = \frac{f_{L1}^2 \cdot PRC_{L1} - f_{L5}^2 \cdot PRC_{L5}}{f_{L1}^2 - f_{L5}^2} \qquad \text{[Eq - 1]}$$

The reference notes that “Of course, this calculation only works if both corrections are calculated using an identical processing sequence with the same parameters.” In GAST X, both corrections are computed from raw measurements uplinked from the ground station and therefore the processing can be matched. That includes matching the carrier smoothing. For GAST X the ranges used to computed the differential corrections are smoothed using DFree smoothing with an extended integration interval (e.g. 600 seconds). Furthermore, the corrections are formed by averaging the measurements sent up from the ground.

5.3 Having computed the IFree differential correction for a given satellite, the ionosphereic delay seen by the ground station can be estimated by:

$$d_{iono,GF} = PRC_{L1} - PRC_{IFree} \qquad \text{[Eq - 2]}$$

Again, because this detection statistic is formed using DFree smooted observations, it has no filter build up error in it and the absolute instantaneous iono delay seen but the ground system is observed. However, this observation is confounded by the noise and other errors on the pseudoranges used to form the differential corrections. Characterizing that noise is somewhat complicated as PRC_{IFree} is a function of PRC_{L1}. So, rearranging:

$$d_{iono,GF} = PRC_{L1} - PRC_{IFree} = PRC_{L1} - \frac{f_{L1}^2 \cdot PRC_{L1} - f_{L5}^2 \cdot PRC_{L5}}{f_{L1}^2 - f_{L5}^2}$$

$$= \frac{PRC_{L1}(f_{L1}^2 - f_{L5}^2)}{f_{L1}^2 - f_{L5}^2} - \frac{f_{L1}^2 \cdot PRC_{L1} - f_{L5}^2 \cdot PRC_{L5}}{f_{L1}^2 - f_{L5}^2}$$

$$= \frac{f_{L1}^2 \cdot PRC_{L1} - f_{L5}^2 \cdot PRC_{L1} - f_{L1}^2 \cdot PRC_{L1} + f_{L5}^2 \cdot PRC_{L5}}{f_{L1}^2 - f_{L5}^2}$$

$$= \frac{f_{L5}^2 \cdot PRC_{L5} - f_{L5}^2 \cdot PRC_{L1}}{f_{L1}^2 - f_{L5}^2} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2}(PRC_{L5} - PRC_{L1}) \qquad \text{[Eq - 3]}$$

If the noise on PRC_{L1} is independent of the noise on PRC_{L5} then:

$$\sigma_{diono,GND} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2}\sqrt{\sigma_{gnd,L5}^2 + \sigma_{gnd,L5}^2} \qquad \text{[Eq - 4]}$$

5.4 In a directly analogous manner, the airborne can estimate the ionospheric delay:

$$d_{iono,Air} = PR_{L1} - PR_{IFree} = PR_{L1} - \frac{f_{L1}^2 \cdot PR_{L1} - f_{L5}^2 \cdot PR_{L5}}{f_{L1}^2 - f_{L5}^2} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2}(PR_{L5} - PR_{L1}) \qquad \text{[Eq - 5]}$$

Again, because this observation is formed using DFree smooted observations, it has no filter build up error in it and the absolute instantaneous iono delay seen but the airborne system is observed. The observation is confounded by the noise on the pseudorange and the error on the observation can be characterized by:

$$\sigma_{diono,Air} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2}\sqrt{\sigma_{air,L5}^2 + \sigma_{air,L5}^2} \qquad \text{[Eq - 6]}$$

5.5 Having computed the ionospheric error seen by the ground and air, the airborne can compute the difference:

$$d_{diff} = d_{iono,Air} - d_{iono,GF} \qquad \text{[Eq - 7]}$$

5.6 The noise on this observation can be characterized by:

$$\sigma_{diff} = \frac{f_{L5}^2}{(f_{L1}^2 - f_{L5}^2)}\sqrt{\sigma_{gnd,L5}^2 + \sigma_{gnd,L1}^2 + \sigma_{air,L5}^2 + \sigma_{air,L1}^2} \qquad \text{[Eq - 8]}$$

5.7 This difference divided by the baseline is an estimate of the gradient between the airborne and the ground station:

$$d_{gradient} = \frac{d_{iono,Air} - d_{iono,GF}}{D_{air-GF}} \qquad \text{[Eq - 9]}$$

Where

$d_{gradient}$ = estimate of the gradient between the airborne and ground
D_{air-GF} = Distance between the airborne antenna and ground facility reference point (from MT 2).

5.8 The noise on the $d_{gradient}$ observation is given by:

$$\sigma_{dgradient} = \frac{f_{L5}^2}{D_{air-GF}(f_{L1}^2 - f_{L5}^2)}\sqrt{\sigma_{gnd,L5}^2 + \sigma_{gnd,L1}^2 + \sigma_{air,L5}^2 + \sigma_{air,L1}^2} \qquad \text{[Eq - 10]}$$

5.9 Figure 4 shows a computation of σ_{diff} with all the same assumptions used in developing Figure 2 above. The ground reference receiver performance is characterized be GAD C4 and then scaled approapriately to account for whether 2 or 4 reference receviers are being used in the airborne computations. Similaly, the airborne noise is characterized by AAD B and the standard multipath model. For constrast the sigma that would result from use of 100 second smoothed PRs and an IFree combination on both air and ground is plotted (and denoted as "GAST F IFree"). As can be seen from the figure, use of the long smoothing intervals greatly improves the airborne equipmen't ability to reliably see large iono gradients.

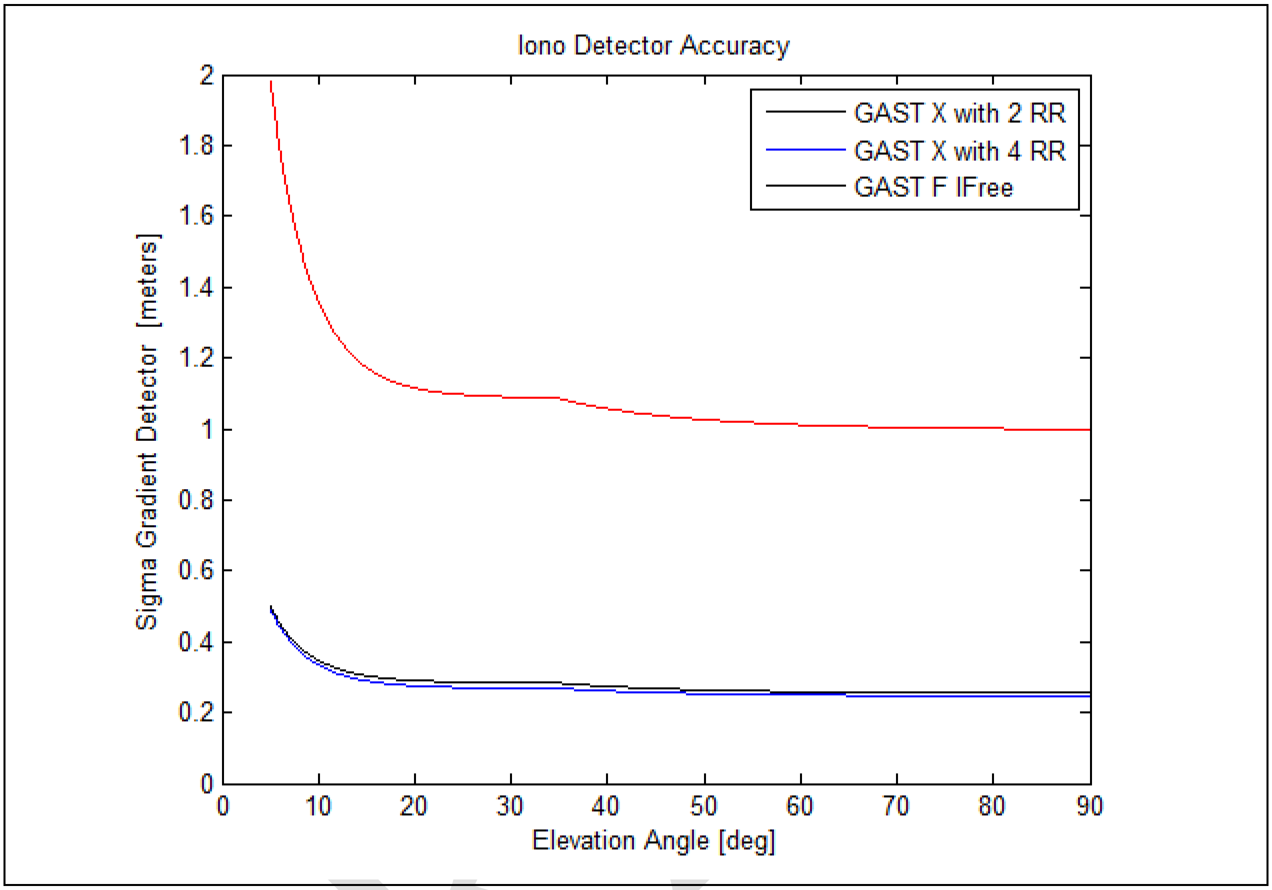


Figure 4 Sigma for Gradient Detector

5.10 Figure 5 shows a computation of the minimum detectable gradient based on the detector described in section 4.7 above. An assumed value for P_{fa} is 1e-3 and the assumed value for P_{md} is also 1e-3 for this example. The airborne equipment may detect on the absolute iono difference (section 4.5) or on the apparent gradient. In either case, the result of a detection would be that the receiver switches from using the DFree pseudoranges at L1 to the IFree combination. The weighting of the measurements would be adjusted appropriately.

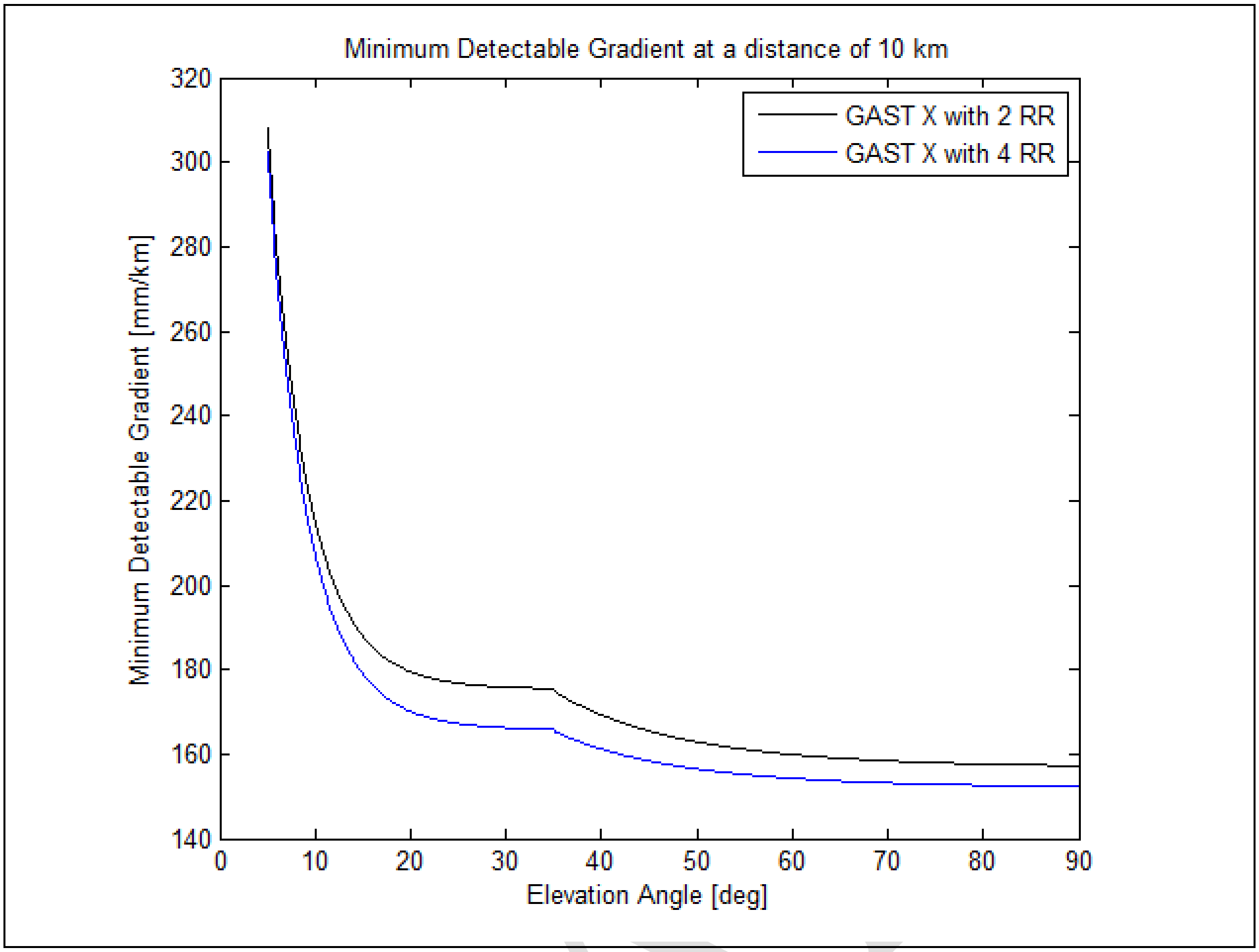


Figure 5 Minimum Detectable Iono Gradient for P_{fa}=1e-3 and P_{md}=1e-3 at 10 km from the Ground Reference Point.

6. PROTECTION LEVEL BOUNDING FOR GAST X

6.1 For GAST X in the primary mode protection level computations will have essentially the same form of the computations for GAST C and D. The B value paramters used in the xPL_h1 computations will be computed by the airborne equipment. As for the sigmas provided by the ground station, the intent is to reuse the sigma_pr_gnd_D uplinked in the MT 11 message. Some work will be required to ensure that this uplinked sigma can be scaled appropriately to compensate for longer smoothing intervals and for any differences between the number of reference receiver measurmements used by the ground and the number used by the air for computing averaged PRCs. This is an area that needs more work. Eventually a full availability study will need to be done as well as simulations to look at the impact of correlated errors between reference receivers (e.g. multipath correlated between L1 and L5 on the same satellite).

7. CONCLUSION

7.1 A basic alternative architecture for DFMC GBAS has been described in this paper. There are many unanswered questions about this proposal. However, many of those questions are common with the GAST F proposal in [2]. This is because the GAST X proposal essentially encompases all the capabilities of the GAST F proposal but allows for more flexibility. Further study is required to quantify the benefits in terms of availability and robustness. On the surface the proposal seems very attractive as it provides a service which is much more accurate and should have smaller protection levels the GAST C or GAST D. Also, the proposal appears to enable an L5/E5 only mode that can support CAT III as well as a downgraded version that would support only CAT I. Finally, the proposal opens the door for use of pure carrier phase based position solutions which would be an important improvement for surface operations and other new operations. The GAST X proposal should be included in the trade space currently being considered for DFMC GBAS.

8. RECOMMENDATIONS

8.1 NSP GWG is invited to note this proposal and discuss its inclusion in the architectural trade space for DFMC GBAS.

— END —

References

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[1] Annex 10 to the Convention on Intenational Civil Aviation – Volume 1, Seventh Edition (including amendment 91).
[2] NSP 5 WP 41 – DFMC GBAS Conceptual Framework – SESAR Joint Undertaking
[3] McGraw, G. "Generalized Divergence-Free Carrier Smoothing with Applications to Dual Frequency Differential GPS". ION Journal of Navigation, summer of 2009.