

Regional Navigation System Using Geosynchronous Satellites and Stratospheric Airships

Chang-Hee Won

University of North Dakota

ABSTRACT

This paper proposes a methodology to design a regional navigation system using geosynchronous satellites and stratospheric airships. One important factor in designing a navigation system is dilution of precision. We design a regional navigation system based on the simulations of the system's dilution of precision. The system would consist of geosynchronous orbit satellites and stratospheric airships for the urban areas. In the beginning stage, the system would augment the existing GPS constellation, and in the later stage with sufficient satellites and airships, we could achieve an independent alternative navigation system.

I. INTRODUCTION

Since earliest of time, mankind was interested in knowing where he or she is at. Now the Global Positioning System (GPS) provides the ultimate solution to the problem of navigation. GPS is a space based navigation system designed and operated by the US military. In May of 2000, selective availability was discontinued and the user range error was reduced to about 1.7 meters [1]. Europe also has realized the importance of a global navigation system for many years [2], and it has been proceeding with global navigation satellite system (GNSS) [3,4,5,6,7] and the Galileo projects [8]. The Asian region is also responding, albeit slowly, to the need for a reliable global navigation system. For example, Japan is proceeding with the Multifunctional Transport Satellite-based Augmentation System (MSAS) program to augment the existing GPS constellation

[9]. Japan has also performed a differential positioning experiment using two geostationary satellites [10].

For a smaller country such as Korea, with limited resources, realizing a global navigation system is a gigantic task, which may be impossible to realize. Nevertheless, participating in this exciting new development is possible. Because there already exists a fully functional global positioning system (i.e., GPS), we propose to use the existing system, start augmenting it with geosynchronous orbit satellites, and later with stratospheric airships. As the hybrid augmented system grows in number, we may even be able to perform regional navigation using just this augmented system without the aid of the existing global positioning system.

The idea is to first create an augmentation system to the existing global navigation system, and if for whatever reason, this system becomes unavailable, we propose to use the augmented system as an independent regional navigation system. Moreover, if other countries follow suit, forming similar systems, the regional coverage may extend to a global coverage. The idea of regional to global satellite based navigation system is not new, see [11] for example, but we shall study the possibility of using a small number of satellites or airships both as an augmentation system and an independent backup navigation system, which appears to be a new idea.

Another reason for augmenting the existing global positioning system is to increase the availability and integrity of the system. GPS by itself cannot meet the integrity requirements for the nonprecision approach used in operational air navigation systems [12]. The availability of GPS with receiver autonomous integrity monitoring (RAIM) is 94.7%, and the availability increases to 99.0% with barometric altimeter aiding. Both of these numbers are below the availability of transmitted Loran-C signals, which exceeds 99.7%. The availability of GPS signals in urban canyons is much lower. In one test, the availability went down to 60% in downtown areas [13]. Thus there is a need for increased availability of navigation signals.

We consider hybrid GPS, geosynchronous orbit satellites (GSO), and airship systems.

First we perform the stand-alone GPS simulation to provide the basis for the comparison. Then we determine the dilution of precision (DOP) for the various GPS, GSO, and airship combinations. DOP values are a measure of how well the satellite/airships are geometrically located in space to give good positioning performance. Assuming a time-of-arrival navigation system with passive receivers, we can determine the DOP values for various combinations of GPS, geosynchronous orbit satellites, and airships.

We shall determine the effects of using GPS and a geostationary satellite or an airship to improve the positioning accuracy. We shall determine DOP of the proposed GPS augmentation system. For the system with GPS and new augmented navigation system, the simulation will show that the average visibility increases and DOP decreases. Furthermore, we propose to use only the augmented set of satellites or stratospheric airships without GPS, naturally with reduced accuracy, as an alternative satellite navigation system if GPS become unavailable for some economical or political reasons.

As an independent alternative navigation system, four, five, and six geosynchronous satellites are simulated to provide navigation systems in the Asia-Pacific region. A stratospheric communications system is in the preliminary design phase in Korea. Therefore, we consider stratospheric airships as another possible independent alternative navigation platform. To increase the availability of the navigation signals over major cities, we have determined the required number of airships to give “good” DOP values based on line of sight calculations. We found that we require about six to ten airships in each region. Naturally, if these airships were used with other GSOs and GPS, the DOP values would be much better. In [14], it is shown that about sixty-four stratospheric airships are required for the communication needs of Korea. We have performed the DOP calculations, assuming that this system of airships is in place.

Another factor that must be taken into account when designing an augmentation system is the link budget. We discuss the link budget analysis for the inclined geosynchronous orbit satellite

(IGSO) and the stratospheric airship. To clarify terms, geosynchronous orbit satellites (GSO) are satellites with an orbiting period equal to the Earth's rotational period, which is 1,436 minutes. GEOs are GSOs with zero degrees inclination, and IGSOs are GSOs with nonzero inclination. We require the user minimum received power to be -160 dBW for both GSOs and airships, and find the appropriate transmitter power and transmit antenna gains.

In the next section, DOP simulations for GPS, GSO, and airship combinations are performed. In Section III the service coverage area for GSO and airships are discussed. Then in Section IV, the design methodology for a regional navigation system is presented. In Section V, the link budget is discussed for GSOs and for the stratospheric airships. Finally conclusions are given in Section VI.

II. HYBRID (GPS, GSO, AND AIRSHIP) SYSTEM DOP SIMULATION

The accuracy of the navigation solution depends on (1) the accuracy with which the receiver can measure the pseudorange to the appropriate satellite, and (2) the geometric positions of the satellites. Dilution of precision (DOP) provides a way to numerically measure how well the satellites are mutually positioned. Following the results of Axelrad and Brown, we have calculated the DOP values in the North-East-Down (NED) reference frame [15] for the GPS standalone, GPS & GSO, and GPS & airship cases.

The major advantage of using the satellites as a navigation system lies in the fact that the coverage area is large and we would require only a small number of satellites. The advantages of using stratospheric airships are that the airships would require less power than satellites because they are much closer to the receivers on the ground, and the signals from the airships would have no ionospheric delay (their altitude is around 22 km). Moreover, the airships can be brought down for maintenance and can be reused. On the other hand, the airship navigation system would require a ground infrastructure to provide real-time updating of airship location. This would require having

precise clocks on ground and synchronizing all the clocks on board the airships. Naturally the hybrid system of both airships and satellites would have both these advantages and disadvantages as well as the problem of interfacing with each other.

In order to provide a basis for comparison, we have performed a simulation of the GPS constellation using the MATLAB® Constellation Toolbox [16, 17]. We assumed a masking angle of 5° and an epoch of 22 March 1998 00:00:00. The user position is assumed to be at 127 °E longitude, 37 °N latitude, and 100m altitude. The observation was taken for one day with the interval of 10 minutes. The mean number of visible satellites was 8.486 with a standard deviation of 1.058. Table I(a) shows the average, standard deviation (Std.), and maximum (Max.) DOP values for the GPS constellation on 22 March 1998. For comparison purposes, here we assume that the user range error of GEO and airship are comparable to that from GPS.

TABLE I
DOP values of GPS, GEO, and Airship constellation

Cases		GDOP	PDOP	HDOP	VDOP	TDOP
(a) GPS	Mean	1.9969	1.7694	0.99706	1.4566	0.92185
	Std.	0.45342	0.36978	0.18290	0.34399	0.27550
	Max.	3.441	2.9126	1.8357	2.5090	1.8499
(b) GPS+GEO	Mean	1.8994	1.6755	0.92209	1.3953	0.89165
	Std.	0.37490	0.30214	0.12149	0.29422	0.23406
	Max.	3.2708	2.7543	1.3742	2.4336	1.7641
(c) GPS+Airship	Mean	1.8094	1.6147	0.88926	1.3446	0.81358
	Std.	0.33134	0.27308	0.10414	0.26896	0.20000
	Max.	3.1320	2.7422	1.1839	2.4734	1.5133
(d) GPS+GEO+Airship	Mean	1.7289	1.5343	0.845954	1.2778	0.7944
	Std.	0.26618	0.2127	0.087586	0.20821	0.17265
	Max.	2.5117	2.1830	1.1364	1.9368	1.2537

With the GPS constellation and parameters of the previous section, we now add a geostationary (GEO) satellite, Koreasat, to form an augmented system. Koreasat is a geostationary communications satellite located at 116 °E longitude. We assume that a navigation payload is onboard this satellite and perform the necessary DOP analysis. Naturally, the number of visible satellites increases by one to 9.49 and the standard deviation stays the same at 1.058.

The DOP results are shown in Table I(b). The mean and maximum GDOP value decreased by 4.9% compared to the stand-alone GPS case. Note also that the variation (standard deviation) also decreased for all DOP values.

A new way to augment the GPS system is to use a stratospheric airship. Assuming an airship at 127.4 °E longitude, 36.4 °N latitude, and 22 km altitude, we have calculated the DOP values. We have assumed the same user location as the GEO satellite augmentation case. The mean number of visible satellite/airship was again 9.49 with the standard deviation of 1.058. Here we assumed the elevation angle of the airship relative to the user as 90°. The improvement compared to GEO is probably related to this value. Thus, this should not be taken as a general result. Table I(c) shows the mean, standard deviation, and maximum DOP values. The average GDOP value decreased by about 10% compared to the stand-alone GPS. More interestingly, the mean GDOP is smaller by 0.1 than the GPS and GEO augmentation system. In fact all the mean and standard deviation values are smaller than the GPS and GEO case.

The disadvantage of using an airship comes from reduced coverage area. Nevertheless if an airship constellation is in place for some other purposes such as communications, then it is advantageous to use the airships to augment the GPS.

The last augmentation system we consider is a hybrid satellite/airship system. We assume the same location as before for the GEO satellite and airship. The epoch and user location is assumed the same as the previous simulations. The DOP results are shown in Table I(d). The mean GDOP values decreased by 13.4% relative to the stand-alone GPS, 9.0% relative to one geostationary

augmentation system, and 4.4% relative to the one airship augmentation system.

This augmentation system has smaller maximum GDOP, for example GDOP is 2.5117 compared to 3.2708 (GPS+GEO) and 3.132 (GPS+Airship) in Table I. Also the variation of the DOP values is less compared to first two cases.

III. Visibility

The minimum coverage area should be defined for a particular country in consideration. For example, we assume minimum coverage of 124°E to 132°E longitude and 33°N to 39°N latitude to cover Korea. This is the minimum requirement. As for using GSOs, we note that we can obtain much larger coverage area. We find out that as long as all GSOs are in between 80°E and 170°E the minimum requirement would be satisfied. Thus we have designed the GSO constellation within these boundaries. Here we show the approximate coverage area of five satellites, two geostationary satellites (GEOs) and three inclined geosynchronous satellites (IGSOs), as an example. The approximate coverage area is shown by the bold dashed line between 95°E and 160°E longitude in Fig. 1. Note that it includes all of Korean peninsula as well as most Southeast Asia and Australia, which is much larger than the design requirement.

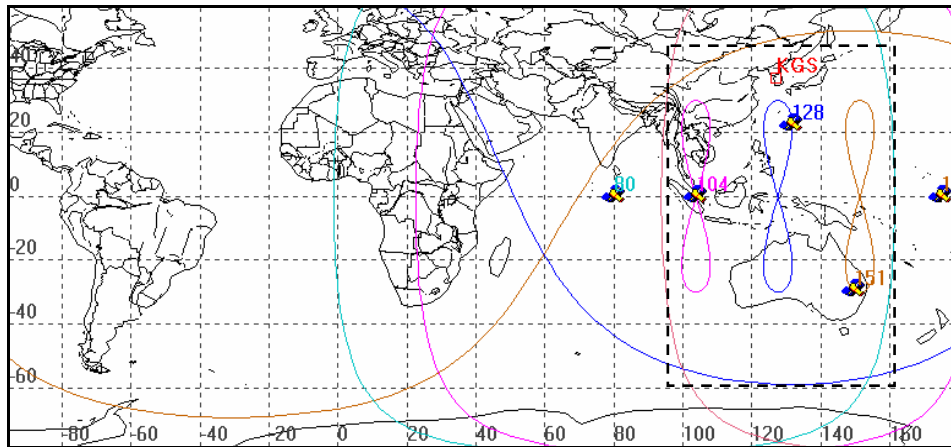


Fig. 1. Service Coverage Area of Five Geosynchronous Orbit Satellites

Now, we consider the coverage area of a stratospheric airship. The coverage area of a stratospheric airship varies with respect to the mask angle, and the variation is shown in Fig. 2. For the mask angles of 0° , 5° , 10° , and 15° , the radius of the coverage area are 531 km, 212 km, 116 km, and 80.7 km, respectively. The mask angle for the airships should be larger than the mask angle for the satellites since we are designing for the urban areas. In this paper, we assume a mask angle of 15° as an example. Naturally, we require a large number of stratospheric airships to cover Korea.

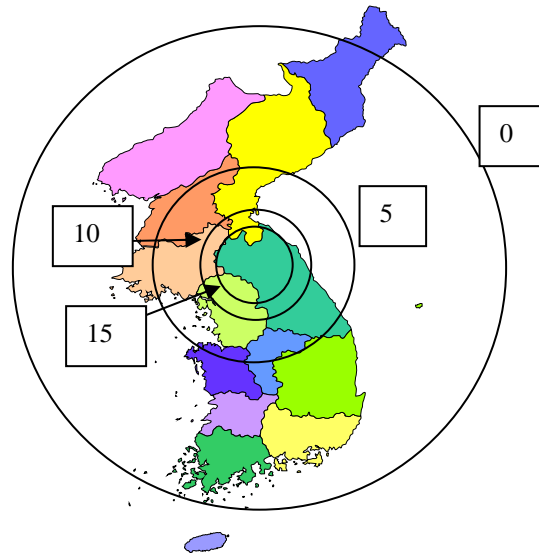


Fig. 2. Coverage Area with respect to the Mask Angle

III. Design Methodology using DOP Values

The design strategy is as follows. Design a regional GSO system that would give acceptable DOP values in your region of coverage. Then design a stratospheric airship system over the major cities and more densely populated areas using larger masking angle. With this information in mind start launching satellites and airships in the desired positions.

A. Regional Geosynchronous Satellites Positioning System

The theoretical minimum number of satellites required for navigation is four. Thus, we have tried by trial-and-error to find a constellation which gives a minimum geometric dilution of precision (GDOP) with four GSOs. The assumptions were 5° masking angle, semimajor axis of 42164.170 km, and epoch of 1 July 1998, 00:00:00. Moreover, the observer position of 127 °E longitude, 37 °N latitude, and 100 m altitude was assumed. Then, we have performed a similar analysis with five and six geosynchronous (GSO) satellites.

The smallest maximum GDOP value for four GSOs was about 270 with the average GDOP value of 18.8. Furthermore, mean HDOP values would give 2drms horizontal positioning error of 38.7 m, assuming root mean square (rms) of the user equivalent range error (UERE) of 2 m [18]. In order to improve this horizontal positioning error, we redesigned the system with five and six GSOs.

Four different GEO/IGSO combinations were tried for five GSO satellite positioning system. The results are summarized in Table II. Orbital elements are given with the standard notations semimajor axis (a), eccentricity (e), inclination (i), argument of perigee (ω), right ascension of the ascending node (Ω), and true anomaly (ν) [19, p.135]. The cases 2 and 3 gave 2 drms horizontal positioning error of about 11.3 m with rms UERE of 2 m.

TABLE II

Five Geosynchronous Orbit Satellite Simulation

No.	Sat.	Orbital elements (a=42164.17km, e=0.0)			Max. GDOP (Mean)
		i	Ω (deg)	ν (deg)	
1	1GEO	0	130	0	16
	4IGSO	30	95,95,165,165	0, 90, 270, 180	
2	2GEO	0	80, 175	0, 0	5.1 (4.77)
	3IGSO	30	103.75, 127.5, 151.25	0, 120, 240	
3	2GEO	0	80, 175	0, 0	5.06 (4.81)
	3IGSO	30	103.75, 127.5, 151.25	0, 130, 260	
4	5IGSO	30	103, 116, 148, 154, 177.5	0, 90, 270, 180	17

For case 3 in Table II, we show the details of the simulation. Assume that two GEOs are located at 80 °E and 175 °E, also assume that three IGSOs are located at 103.75 °E, 127.5 °E, and 151.25 °E. For these IGSOs, depending on the ν value there will a phase difference (i.e. the differences in the ν values). Furthermore these phase differences will affect the DOP value calculation. Thus, the next question is what should the phase difference be for three IGSOs to obtain the minimum DOP value.

We assume that the phase difference between satellites with Ω of 103.75° and 127.5° is equal to the difference between satellites with Ω of 127.5° and 151.25°. By doing this we realize that we are reducing a degree of freedom in the optimization process and this may not be a true optimum. We varied that phase difference by 5° starting from 0°. Then the phase difference that gave the smallest maximum GDOP was found. The optimal phase difference was found to be 130°. To verify this result we have assumed the initial orbital elements given in Table III and performed the DOP calculations.

TABLE III
Five GSOs Initial Orbital Elements

Orbital elements	Sat 1	Sat 2	Sat 3	Sat 4	Sat 5
a(km)	42164.170				
e	0.0				
i (deg)	0	30	30	30	0
ω (deg)	0				
Ω (deg)	80	103.8	127.5	151.3	175
ν (deg)	0	0	130	260	0

The results are given in Table IV, where the average, standard deviation (Std.), and maximum (Max.) DOP values are shown. When the phase difference was 120° the results are shown in Table II, case 2. Comparing these two tables, we note that the smallest maximum GDOP is obtain from the phase difference of 130°, but the mean GDOP is larger for the 130° phase difference case.

TABLE IV
DOP Values with Optimal Phase difference of 130°

	GDOP	PDOP	HDOP	VDOP	TDOP
Mean	4.8053	3.9818	2.8210	2.7796	2.6886
Std.	0.1590	0.1053	0.3328	0.2814	0.1460
Max.	5.0584	4.1923	3.4363	3.2973	2.8516

In order to see how much improvement one can obtain by adding one more satellite, we have performed the simulations with six GSOs. The results are summarized in Table V.

TABLE V
Six Geosynchronous Orbit Satellite Simulation

No.	Sat.	Orbital elements (a=42164.17km, e=0.0)			Max. GDOP (Mean)
		i	Ω (deg)	ν (deg)	
1	2GEO	0	80, 175	0	4.2
	4IGSO	30	111,122, 133,144	0, 90, 180, 270	(3.99)
2	6IGSO	30	103,103, 116, 116, 177.5, 177.5	0,90,225, 135,180, 270	15.2 (8.50)

We note that the mean GDOP value decreases by 83.6% compared to the best four GSO satellites case, and 16.3% compared to the five GSO satellites case.

B. Regional Stratospheric Airships Positioning System

A stratospheric communication system is at the preliminary design phase in Korea. The plan is to build and test the system by 2004, and launch and operate about twenty-five airships by the year 2014. This system is being developed mainly for communication purposes. Studies to

control these airships in the stratosphere are underway and the details are not fully known yet, but it is likely that the airships will be unmanned and they will be kept within a +/-1 km box at an altitude of about 22 km. The stratospheric platform shall have a diameter of 47 m, a length of 146 m, and a weight of 40 tons [14]. Thus, it is natural to consider a regional navigation system using this stratospheric platform. In this study the feasibility of using this stratospheric platform with navigation payload is performed.

For this stratospheric system to be a truly independent navigation source, the position of these airships must be known without using GPS or any other navigation system. One possible method of doing this is with an inverse positioning system (IPS). In inverse positioning, a number of reference stations with known locations receive the navigation signals from the airship and then send these signals to a master control station, where the data are collected and the airship locations are computed. The schematic diagram of IPS is shown in Fig. 3.

There are other issues to be addressed before the new system will coexist with the current

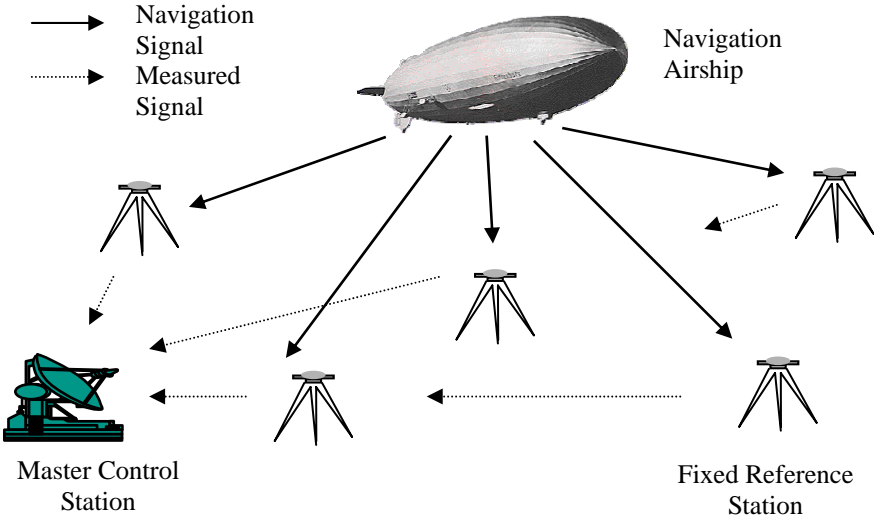


Fig. 3. Inverse Positioning System

system (GPS) and future (GNSS) systems. This system would have to be compatible with the existing system and the Korean receivers would need more correlation channels. Moreover, all the

clocks on the airships must be synchronized from the ground infrastructure. The accuracy of the clocks should be comparable to the GPS clocks, which has fractional frequency stability of 2×10^{-13} .

We define the five regions around the major cities in Korea as shown in Fig. 4. Then we position the stratospheric airships by 0.5° longitude and 0.5° latitude in order to increase availability in the urban areas. Each region is approximately $40,000 \text{ km}^2$ in area.

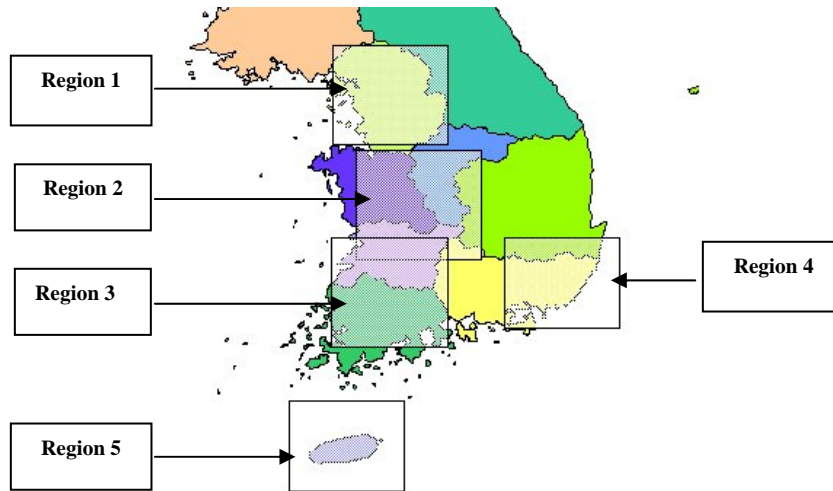


Fig. 4. Regional Breakdown of Stratospheric System

Table VI shows the DOP analysis results for all five regions specified in Fig. 4. These regions are designed to encompass all the major cities in Korea. Note that all the GDOP values are less than 2.5 and HDOP values are around 1.0, which is as good or better than usual GPS DOP values.

TABLE VI
DOP Analysis for the Five Regions

Region Number	Receiver Location	No. of Airships	Mean GDOP	Mean PDOP	Mean HDOP	Mean VDOP	Mean TDOP
1	Seoul	8	2.2261	1.9866	0.9077	1.7671	1.0044
2	Taejon	10	2.1471	1.9692	0.7610	1.8162	0.8558
3	Kwangju	10	2.4328	2.2396	0.8010	2.0925	0.9501
4	Pusan	9	2.4079	2.1952	0.9265	1.9901	0.9895
5	Cheju	6	2.4727	1.1976	1.0975	1.9039	1.1336

C. DOP SIMULATIONS SUMMARY

The DOP simulation results are summarized in Table VII below. Theoretically, the minimum number of satellites that can provide the navigation service is four, but the simulation results show that the 2 drms horizontal positioning accuracy is over 38.7 m. Thus we propose to use at least five GSOs to meet the 2 drms horizontal positioning accuracy of about 10 m. Using six GSOs improved the mean GDOP value by 16.3% compared to using five GSOs, but the cost of adding an additional satellite should be taken into consideration. We also studied the use of stratospheric airships to augment GPS and as a backup navigation system. The use of stratospheric airships as an alternative navigation system gave surprisingly good HDOP values; the positioning error improved by a factor of two compared to the GSO case. In fact the best positioning accuracy of 5.07 m was achieved using five stratospheric airships. Furthermore, for the five major urban areas in Korea, we have studied the DOP values. The results show that to obtain GDOP value of less than 2.5, we require six to ten airships for a 40,000 km² region.

TABLE VII
Simulation Results Summary

GPS Augmentation	Mean GDOP	Regional Navigation System	Mean GDOP
Stand-alone GPS	1.9969	4 GSO	18.815
GPS+1GEO	1.8994	2GEO+3GSO	4.770
GPS+1Airship	1.8094	2GEO+4GSO	3.9916
GPS+1GEO+1Airship	1.7289	5Airships	2.3871
GPS+2GEO+3GSO	1.5469	6Airships (Region 5)	2.4727
GPS+5Airships	1.5627	8Airships (Region 1)	2.2261
		9Airships (Region 4)	2.4079
		10Airships (Region 2)	2.1471
		10Airships (Region 3)	2.4328
		2GEO+3GSO+1Airship	4.5234

V. LINK BUDGET CONSIDERATIONS

In this section we consider IGSOs with the inclination angle of 30° and altitude of 35,786 km. The link budget for the IGSO satellite with the frequency of 1,595.44 MHz was performed. The analysis was performed so that the farthest point user minimum received power matches GPS C/A code power level of -160.0 dBW. We note that the user minimum received power was -159.1 dBW for the nearest point. The required transmit power was 28.8 W.

HPA reserve end-of-life loss was set at 1 dB and feeder loss was budgeted at 3 dB [20]. Free space propagation loss was computed using the standard textbook equation, and a mean atmospheric loss of 0.1 dB was used as in [20]. Precipitation loss margin of 2 dB was assumed as in [21]. Small antenna misalignment loss of 0.5 dB was assumed, and we used a polarization mismatch loss of 3.4 dB as in [21].

For a stratospheric airship at an altitude of 22 km, we performed the link budget analysis so that the user minimum received power was again -160.0 dBW for the frequency of 1,595.44 MHz. Since we do not have to compensate for ionospheric delay, one frequency would suffice. We note that the transmitter power came out to be 0.501 mW, which is very low. Thus to use higher transmitter power, we may have to use negative transmit antenna gain. For the previous GSO case, we assumed the same transmit antenna gain for the nearest and farthest point because the resulting user minimum received power difference was only 0.9 dBW. But for the airship case the power difference would be too large, about 12 dB, so we plan on using different transmit antenna gain for the beam center and beam edge, matching both user minimum received power to be -160.0 dBW.

VI. CONCLUSIONS

The DOP analysis shows that we require at least five GSOs to have a regional (Asia Pacific region) satellite navigation system. Since it is difficult to launch all five satellites in the near future, we propose to start with GPS augmentation and gradually switch over to the independent navigation system as the satellites become available. The use of stratospheric airships for navigation purposes has been studied with favorable results. We propose to use stratospheric airships in densely populated urban areas to increase the availability of the signal. With a masking angle of 15° , we found that about 6 to 10 airships are required to service a region of about $40,000 \text{ km}^2$. We have also found that adding a GSO or an airship gives better DOP values. Thus, using the GSO and airships to augment the existing GPS constellation would increase the availability and accuracy of the navigation signal. We have also calculated the link budget for a GSO and an airship so that both signals have the same minimum received power of -160.0 dBW . For a country with limited resources, this may be a way to participate in the exciting area of global navigation.

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