Increasing the Spatial Limits of LADGPS Using Stratospheric Platforms

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This paper presents the preliminary study of a *stratospheric segment* within a satellite navigation system of present and future generation (GPS and Galileo) implemented by means of High Altitude and Very long Endurance (HAVE) platforms. The paper discusses a possible scenario in which the main features of the HAVE platform are exploited to define an innovative Aerial-Based Augmentation System (ABAS) for the provision of differential services. This particular local segment improves the provision of a differential navigation service. It is suited to the broadcasting of differential corrections in critical areas such as mountainous and sea regions where, to guarantee wide coverage, a large number of terrestrial reference stations would otherwise be required. The study includes a description of the proposed DGPS augmentation system, and a discussion of the system architecture and expected performance.

KEY WORDS

1. GNSS. 2. GPS. 3. Galileo. 4. Augmentation.

1. INTRODUCTION. In recent times, great interest in the development of satellite and terrestrial navigation systems has yielded a large number of spin-offs that are having an extraordinary impact on people's lives and working conditions. Among the many applications developed in the civil field are the automatic landing and take-off systems of aerial vehicles, the automatic guidance of marine and terrestrial vehicles, the integration of positioning services with personal communication systems (also applying novel technologies in the design of user terminals), the possibility of managing human resources more effectively in emergency situations and many others. Since one of the main requirements is the design of a navigation system able to provide global coverage, greater attention has been devoted to satellite-based navigation systems than to terrestrial ones. It is well known that, at present, the only satellite navigation systems that ensure an almost complete global coverage are the Global Positioning System (GPS) developed by the USA and the GLONASS System designed by the Russian Federation. However, these systems alone are not able to provide localization and navigation signals for safety-critical applications and suffer limited performance in some propagation scenarios (for example, the reduction in navigation accuracy in urban and canyon environments). To overcome these problems, several systems have been designed to support GPS to increase its accuracy, continuity, availability and integrity: in general they are denoted as *Augmentation Systems*.

Recently, both the United States and Europe have directed their efforts to the design of future navigation systems (Global Navigation Satellite System 2 – GNSS2)

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with improved capabilities. In the USA a novel set of satellites is being designed for modernisation of GPS, while the European Commission is developing the Galileo System.[1] Even with such improved satellite systems, augmentation systems will always be required to ensure the adequate degree of accuracy and availability over a certain area, for safety-critical applications.

This paper describes the feasibility study of a particular augmentation system for Galileo based on the use of a network of High Altitude and Very long Endurance (HAVE) platforms. Several projects have addressed the design of HAVE platforms with the purpose of defining an unmanned aerial vehicle especially tailored for long endurance operation at an altitude of about 20 km in the stratosphere. Such a platform could support a wide range of possible applications in the fields of telecommunications, remote sensing and localization-navigation. In particular, within the HeliNet (HELIplat NETwork) research project, a new stratospheric platform named HELIPLAT™ (HELIos PLATform) is under development.[2,3] The HeliNet project is funded by the European Commission within the Fifth Framework Programme (IST-11214) and is being developed by a consortium of ten European universities and companies. One of the most important and novel features of such a network of platforms is that it can act as a very near-to-earth part of a satellite system sometimes named Near Earth Orbit (NEO) constellation. The use of HAVEs can be of great advantage, because it leads to the creation of a *stratospheric segment* in the Galileo or GPS systems. This particular application of the HAVE platforms will be discussed in detail in this paper.

In order to provide the reader with some basic background on stratospheric platforms and their applications, Section 2 introduces some technical features of HAVEs within the field of navigation. The factors imposing spatial limits to the Local Area Differential GPS (LADGPS) service broadcasting will be recalled in Section 3. One possible way to mitigate the drawbacks is to define an augmentation system based on an aerial transponder. The general system concept of the aerial transponder is presented in Section 4, while the system architecture and localization advantages are respectively discussed in Section 4.1. and Section 4.2. respectively. Section 5 is a technical paragraph concerning the definition of the data-link between the platform and the users. Conclusions and considerations on future work and activities will be drawn in Section 6.

Since some of the features of GNSS2/Galileo system are still under development, it must be noted that all the results presented in this preliminary work are related to GPS. However, the final research activity goal is complete integration with Galileo, and the results here presented can be considered a guideline for HAVE-based augmentation systems development for Galileo.

2. HAVE PLATFORMS PROVIDING NAVIGATION SERVICES.

Several projects addressing the design of HAVE platforms have proved the feasibility of a solar-powered aircraft for high altitude and long endurance flight. For example, the Helios [4] developed by NASA within the Environmental Research Aircraft and Sensor Technology Program (ERAST). These studies demonstrated the possibility of employing stratospheric platforms with payloads providing telecommunication services (cellular telephony) or access to broadband digital networks (Internet, ISDN) and remote sensing applications.[5] In particular, such platforms could effectively

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integrate or substitute for terrestrial and satellite systems in different ways. For example, they can be rapidly deployed to provide immediate coverage of disaster areas, and they can be a cost-effective infrastructure with respect to terrestrial networks for regions with low user density. Furthermore, they constitute a flexible infrastructure: in fact, they can be relocated, expanded and upgraded with new payloads in order to reduce the risk of technology obsolescence experienced with traditional satellites.

The creation of a stratospheric segment in a satellite navigation system is a promising method of improving system performance by increasing the localization accuracy and, if feasible, the availability and the integrity of the overall system. Several techniques have been proposed in the literature in order to improve GPS accuracy.[6,7] These techniques are based on the knowledge of the accurate geographic location of a ground Reference Station (RS), which is used to evaluate corrections to the GPS parameters exploited by the users. These methods are usually gathered under the denomination of *differential techniques*. The reference station, tracking all the satellites in view, is able to compute corrections based on its measurements and its known geodetic position. In the basic concept of LADGPS, the evaluated biases of the GPS signals are transmitted to the users in a defined region: this allows civil aircraft, ships and land vehicles to refine the uncertainty of their estimated position, even employing the Standard Positioning Service (SPS) (i.e. without knowledge of the military codes).

Within this framework, two possible strategies for the use of a stratospheric platform as an active part of the navigation system can be foreseen:[8]

(a) the platform can be used as a transponder for the DGPS signals evaluated by a terrestrial RS as represented in Figure 1.
(b) the platform can be used as an Aerial Pseudolite, with its own pseudo-ephemeris parameters and able to provide users with additional pseudo-range measurements.

Broadcast of differential corrections with a GPS-like signal is an interesting perspective, and a study of the possible system architecture, including an aerial pseudolite, is underway. As a first step in the definition of the aerial pseudolite, this paper investigates the use of HAVE platforms as transponders for the DGPS signals, with the goal of improving the quality of the differential service and enlarging its area of coverage.

3. SPATIAL LIMITS OF LADGPS.

One of the main problems related to the broadcasting of differential corrections is the dimension and shape of the coverage area over which the differential corrections are available. Since conventional DGPS is mainly based on the principle that the main error sources in the user's locality (e.g. atmospheric noise) are spatially correlated, the obvious drawback of such systems is the range over which the differential corrections are valid, and the dependence of their validity with time. In fact, the de-correlation of each error factor contribution increases with the distance between the reference station and the users.[6] It is known[9] that the corrections can be considered valid over a large area (i.e. 100–500 km) so that the service region boundary is mainly determined by propagation problems. The factors limiting this region can be roughly summarized as:

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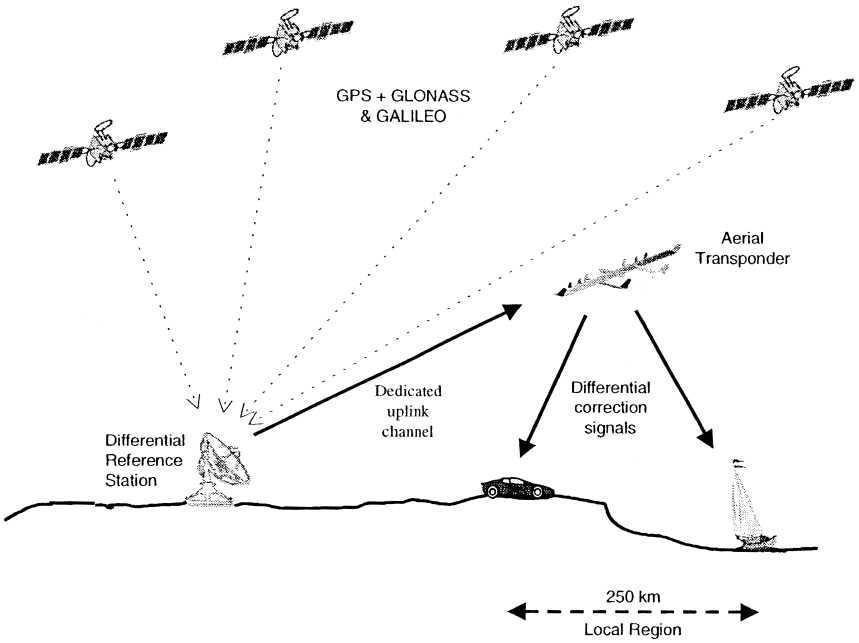


Figure 1. System architecture employing the aerial transponder.

Table 1. Estimated GPS C/A-code pseudorange error budget.

Segment Source	Error Source	GPS 1σ Error [m]	LADGPS 1σ Error [m]
Space	Satellite Clock Stability	3·0	0
	Satellite perturbations	1·0	0
	Other (thermal radiation, etc.)	0·5	0
Control	Ephemeris prediction error	4·2	0
	Other (thruster performance, etc.)	0·9	0
User	Ionospheric delay	5·0	0
	Tropospheric delay	1·5	0
	Receiver noise and resolution	1·5	2·1
	Multi-path	2·5	2·5
	Other (Inter-channel bias, etc.)	0·5	0·5
System UERE	Total (rms)	8·04	3·3

(a) variable ground conductivity does not allow a uniform coverage in zones with variable morphological configuration;
(b) dependence on different frequency bands used for broadcasting differential correction affects the size of the service region;
(c) atmospheric noise degrades the performance;
(d) near-far effect is a problem for receivers operating close to the RS which have to manage signals with very different power levels.

These limiting factors are mainly related to propagation aspects and to the terrestrial scenario in which the RS is located. Due to such problems, actual LADGPS systems are typically implemented to serve users within a restricted area around the RS.

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LADGPS accuracy depends on the fact that some of the pseudo-range (PR) error components are common to all receivers within the local geographical area. Table I, as reported in Reference 10, gives estimates of the PR-error components from various sources in the space, control and user segments for the SPS. The total root-mean-square (rms) non-differential PR-error is estimated to be 8·04 metres. The last column shows the reduction in PR-error that is possible with DGPS when the user receiver is located close enough to the reference station so that the signal paths from the satellites to the user and reference station receiver are essentially identical. In this case, the errors due to most sources are completely correlated (except those due to multipath and receiver characteristics, like inter-channel bias and noise). It must be noted that Selective Availability is not considered in this Table. In fact, on 1 May 2000, the US Government stopped this intentional degradation of the SPS-GPS signal. Although this will allow more precise localisation with conventional civil receivers, augmentation systems will always be required for safety critical applications demanding superior accuracy (e.g. aircraft landing and departure).

With increasing separation distance between users and reference receivers, a slight de-correlation occurs with the ionospheric and tropospheric delays and satellite ephemeris errors due to difference in satellite viewing angles. Reference 10 provides a complete study of the differential corrections, which shows that the difference between the errors ε_m (ephemeris error evaluated at the reference station) and ε_u (ephemeris error evaluated at the user position) is bounded by the expression:

$$\varepsilon_m - \varepsilon_u \leqslant \frac{\varepsilon_s}{d_m} p \sin^2 \phi_m, \tag{1}$$

where ε_s is the error in the estimated satellite position (i.e. the broadcast ephemeris), p is the separation between user and reference station, d_m is the distance between the user and the satellite (or the HAVE platform), and ϕ_m is the angle formed by the directions of the reference station to the actual satellite position. In the most critical case (i.e. $\phi_m = 90$ deg.) for a separation of $p = 100$ km and an ephemeris error of $\varepsilon_s = 10$ m, the difference $\varepsilon_s - \varepsilon_u$ is negligible (less then 0·05 m).

Thus, while the spatial correlation of the uncertainty is sufficient to bound the validity area of the differential GPS corrections to a few hundred kilometres, the propagation obstacles or variation in the media conductivity can further limit the service region. In order to overcome such problems, the use of a properly designed aerial transponder can be of great help.

4. USE OF AN AERIAL TRANSPONDER FOR THE DGPS SIGNALS.

The use of a stratospheric platform as aerial transponder is an interesting method of mitigating the problems related to the DGPS coverage. A stratospheric platform – with a height of 20 km – is a new factor that can improve system performance significantly. Since each stratospheric platform is necessarily linked with its Telemetry, Telecommand and Control (TT&C) ground station, such a station can also act as reference station, equipped for the evaluation of differential corrections. Such corrections could be used for two different purposes:

(a) using a dedicated up-link channel, the reference station transmits the differential corrections to the platform, achieving an accuracy better than 10 m in platform localization;

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(b) the stratospheric aerial vehicle is used to re-broadcast the differential corrections to users in the coverage region.

As an example, in the case of mountain regions, the terrain irregularities can significantly reduce the coverage of terrestrial station transmissions. This reduction can be more limiting than the validity of the differential corrections, simply because of natural obstacles. One possible solution to overcome this problem is to locate a large number of ground transmitters at strategic points. However, a much more cost-effective solution is to use an aerial transmitter to broadcast the differential corrections evaluated by a ground reference station (positioned in order to have suitable visibility of the satellite constellation). Similar advantages can be foreseen for sea regions that are currently served by coastal DGPS radiobeacons. Since HAVE platforms are unmanned, and especially tailored for long endurance operation, they are a suitable solution for the aerial re-broadcasting of the differential corrections.

Furthermore, both in the case of mountainous and sea regions, broadcasting the DGPS information from the platform guarantees a uniform coverage since the signal experiences the same propagation conditions all over the service area. The HAVE platform could be coupled with a movable reference station able to evaluate its position with geodetic precision, in order to provide an on-demand DGPS service, according to particular needs such as natural disasters or other emergency situations. Furthermore, the navigation service can be integrated with other telecommunication services, and the HAVE platforms can be a cost-effective solution for regions with low-user density. The improved localization service would be an added-value service exploiting the HAVE platform infrastructure. The advantages offered by the stratospheric transponder will now be analysed in more detail.

4.1. *System Architecture.* A scenario of the proposed augmented system is depicted in Figure 1, where the basic elements are represented: the system consists of a space segment, a differential segment, a user segment and a stratospheric segment. When fully deployed, the space segment of GPS will consists of 33 satellites provided in the GPS Block II follow on (GPS IIF) program and, in addition to the next generation of GPS satellites, there are also the satellites of the Galileo system still under development. The user segment consists of the equipment necessary to derive position, velocity and time from the information received from the satellites. The 'stratospheric differential segment' represents the new concept of the differential operations. A reference station with a precise receiver is placed at a known location; it evaluates corrections (e.g. to the satellite ranging signals) and broadcasts these corrections to the users by means of a stratospheric transmitter. The couple constituted by the ground station and the aerial platform is a new equivalent differential reference block, as illustrated in Figure 2. Unlike a terrestrial differential reference station, whose block diagram is described in Reference 7, the aerial station requires the design of two different data-links:

(a) the DATA UP-LINK which communicates the corrections from the ground station to the aerial platform using a dedicated channel;
(b) the DATA DOWN-LINK which communicates the corrections from the stratospheric platform to the users with the format, protocol, and data rate (50 baud) typical of the RTCM recommended standards.[7]

A HAVE platform can be used as transparent repeater or, more generally, as a regenerative repeater able to perform demodulation-modulation of the data. The

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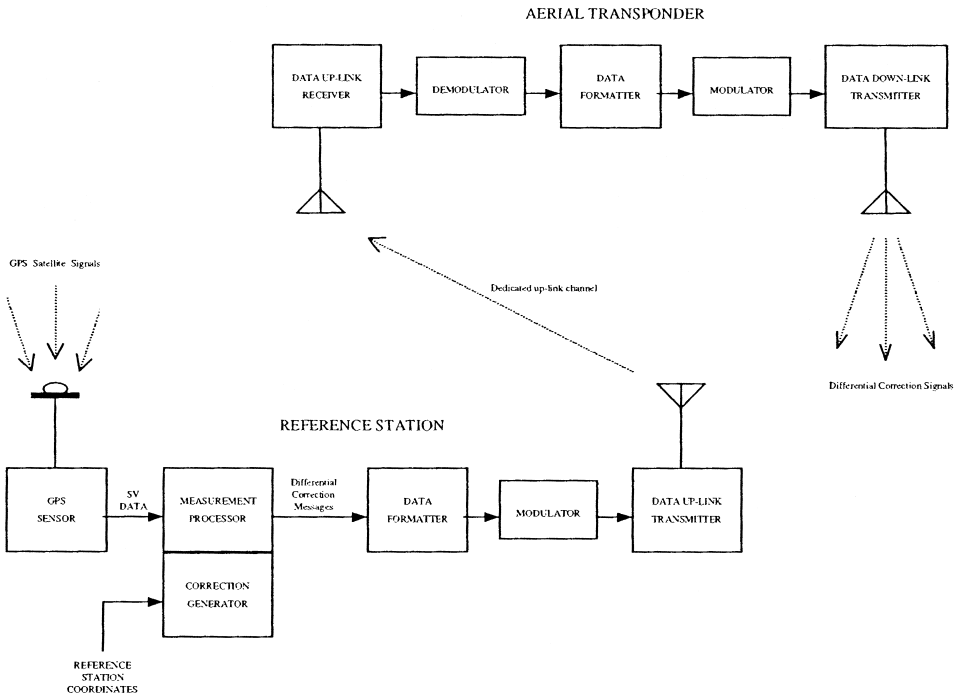


Figure 2. Differential reference segment block diagram.

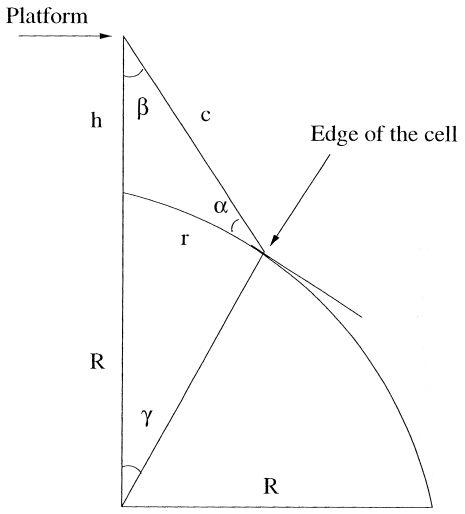


Figure 3. Geometrical model.

operations of the DATA UP-LINK are totally transparent to the users so the protocols, formats, frequency and data rate can be established in accordance with the others services provided by the aerial platform (i.e. telecommunication base station for broadband communications) using the indispensable, dedicated, Tele-

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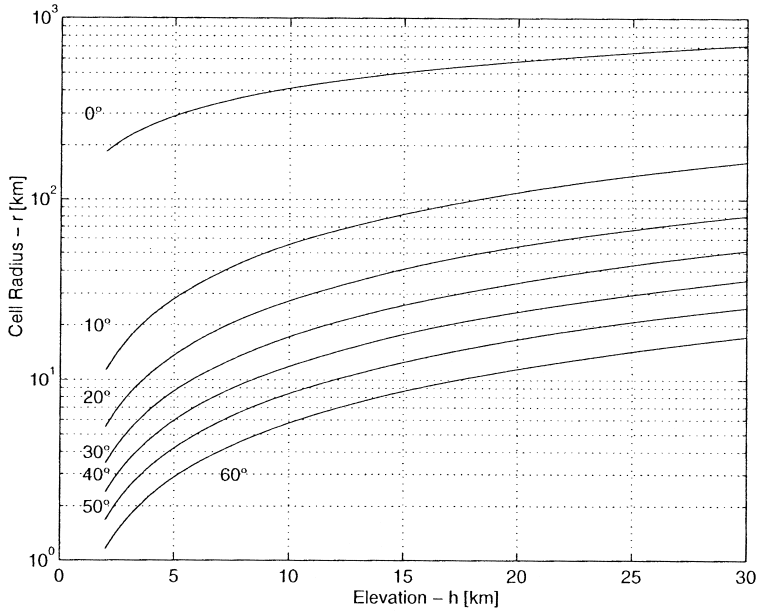


Figure 4. Coverage region radius versus elevation.

metry Telecommand and Control (TT&C) channel. A user receiver with antenna and interfacing equipment receives the corrections from the HAVE and a data processor applies them to the pseudo-ranges measured by the receiver of the satellite signals.

4.2. *Advantages of the aerial transponder.* The simultaneous use of a differential reference station and an aerial transponder integrated in a LADGPS system can have an important role in improving the performance of GPS. The geometrical model of the scenario is depicted in Figure 3. The coverage area radius (cell radius) r of a single flying platform as a function of the elevation h, the grazing angle a and the terrestrial radius R is given by

$$r = R\left(\frac{\pi}{2} - \alpha - arc\sin\left[\frac{R}{R+h}\cos(\alpha)\right]\right). \tag{2}$$

This equation is graphically shown in Figure 4. As expected, the coverage area increases as h increases and α decreases. Given a minimum grazing angle of 10 degrees, the platform can theoretically serve a region of approximately 125 km radius.

Considering a grazing angle of 1 degree, the coverage radius increases up to more than 400 km. If a line-of-sight propagation is required, as in the pseudo-satellite case, an $\alpha = 10$ degrees has to be assumed. In the classic DGPS case, when UHF-VHF frequencies are used for broadcasting from the terrestrial transmitting stations, differential corrections are received by the ground and sea-borne users a few tens of kilometres away.

Thus a HAVE platform with its ground reference station can substitute for a number of standard differential reference stations, with the advantage of increasing the service availability when it is not possible to establish a direct connection between the user and a standard ground reference station due to propagation problems. In

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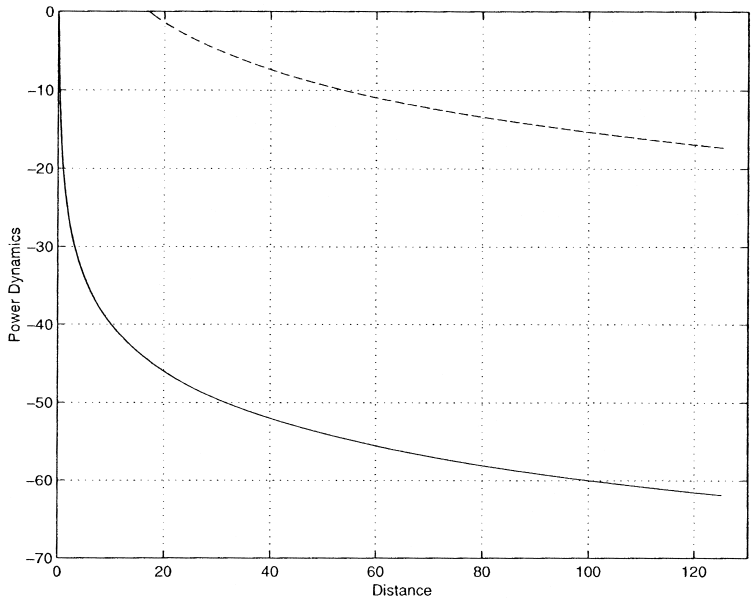


Figure 5. Received power dynamics for terrestrial system (continuous line) and the HAVE-based system (dashed line).

particular, use of a network of HAVE platforms as an augmentation system for GPS/Galileo will improve several of the factors summarized in Section 3, which at present are limiting the service.

(a) The DGPS signals propagate under free space conditions from the aerial transmitter to all the users in a certain area. Thus, the terrestrial region covered by a single platform will mainly depend on the error decorrelation and on the transmitted power. Since the difference in ground conductivity is not a relevant factor, the shape of the uniformly covered region is practically circular.

(b) The presence of natural obstacles or buildings does not limit the dimension of the aerial transmitter coverage area or the validity of the differential corrections.

(c) The atmospheric noise (mainly generated by lightning) and the man-made noise (mainly generated by other radio transmitters) are the same as in the case of terrestrial transmitters.

(d) The near-far effect is largely reduced. The ratio $D_P = P_{max}/P_{min}$ between the maximum and the minimum received power within the same cell is shown in Figure 5. It is possible to observe how a much smaller power dynamic (10 dB) can be obtained with an aerial system in comparison to terrestrial one. Moreover, if a large region is served by a terrestrial station, the hypothesis of free space propagation is not valid for very small grazing angles (smaller than 10 degrees).

(e) Because of the improved propagation conditions, for a given transmitted power, the stratospheric platform guarantees a larger coverage area, e.g. a larger region over which the minimum required SNR for digital data demodulation is achieved.

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5. DATA-LINK. To achieve the advantages of using an aerial platform and the benefits of a transmitting antenna located at a height of 17 km, the characteristics of the differential data-link are very important. The data-link bearer used to support more traditional DGPS operations is usually a radio channel of some sort. The frequency band used for broadcasting the differential GPS corrections is matched to the requirements of different applications, but two types are dominant:

(a) line-of-sight communications (e.g. VHF/UHF, L-band, microwave) wherein the transmitter tower must be strategically located and tall enough to be visible to the users in the coverage area;
(b) ground wave communications (e.g. MF radiobeacons), wherein the frequency is low enough to propagate at low altitudes and reach surface targets beyond the horizon.

The second method is used to increase the radius of the coverage area, but the bandwidth available is very limited. For the aerial transponder system described above, VHF/UHF line-of-sight transmission is quite satisfactory. The platform itself provides adequate line-of-sight coverage, and the VHF/UHF part of the radio spectrum gives the bandwidths required to support high data rates (i.e. 2400, 9600 or even 19200 bps) and the data update rates (i.e. updates every 0·5 sec rather than the more leisurely 10 sec more typical of differential operation) used in the more recent and accurate differential carrier phase techniques (e.g. Real Time Kinematic techniques).

5.1. *Maximum coverage*. Reference 9 describes a DGPS reference station operating at VHF/UHF frequencies limited to line-of-sight communications. The maximum distance d that can be theoretically achieved is:

$$d = 3{\cdot}75\alpha(\sqrt{h_t} + \sqrt{h_r}), \tag{3}$$

where h_t and h_r are the heights in metres of the TX and RX antennas above the horizon, and α is the effective Earth radius factor considering atmospheric refraction. A typical value for α in temperate climates is 1·16.

In a classical scenario in which the transmitter is located at an height of 30 metres and the receiver at an height of 2 metres, the computed maximum propagation distance is 28 kilometres. However, it can be difficult to achieve such maximum distances in practice. Any obstruction along the propagation path will affect the signal range.

5.2. *Attenuation on the signal path*. Even in the absence of obstacles along the signal propagation path, the signal suffers from free space attenuation according to the inverse square law of the propagation distance. But in addition to the direct-path signal, the receiver often obtains a signal that is reflected from the ground and combined with the direct-path signal. So, the total signal path loss depends on several factors, including ground reflection characteristics, terrain, and the presence of buildings and other structures. It is difficult to predict the path loss accurately unless a detailed description of the environment through which the signal travels is available. Using the Egli empirical propagation model, the predicted loss in dB is given by:

$$L = 88 + 20\log f - 20\log h_t - 20\log h_r + 40\log d, \tag{4}$$

where the frequency, f, is given in MHz, the antenna heights in metres, and the

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distance in kilometres. Note that the signal power decays with the fourth power of distance.

Using the antenna heights of the earlier example ($h_t = 30$ m, $h_r = 2$ m), a 450 MHz signal is attenuated by about 146 dB at a distance of 10 kilometres. This means that the received signal is some 146 dB weaker than the transmitted signal. If the transmitter has an output power of 2 watts to an isotropic antenna, the received power at an isotropic antenna 10 kilometres away is -143 dBW, or $5{\cdot}10^{-15}$ watts.

When transmitted from a stratospheric platform ($h_t = 17$ km), the signal can be considered travelling in free space, at least while the user is located within the region in line-of-sight. In this case, the minimum distance between the transmitter and the user is 17 km (i.e. the flight altitude of the platform); the attenuation is 110 dB and the received power, with the above conditions, is -108 dBW or $5{\cdot}10^{-12}$ watts.

It has to be noted that, in the hypothesis of free-space attenuation, it is possible to determine the radiation pattern that makes the link budget of the user-to-platform link independent of the user position within the cell. Since the attenuation is proportional to the squared distance d^2, the antenna gain $G_T(d)$ must be proportional to d^2 giving the radiation pattern shown in Figure 6.

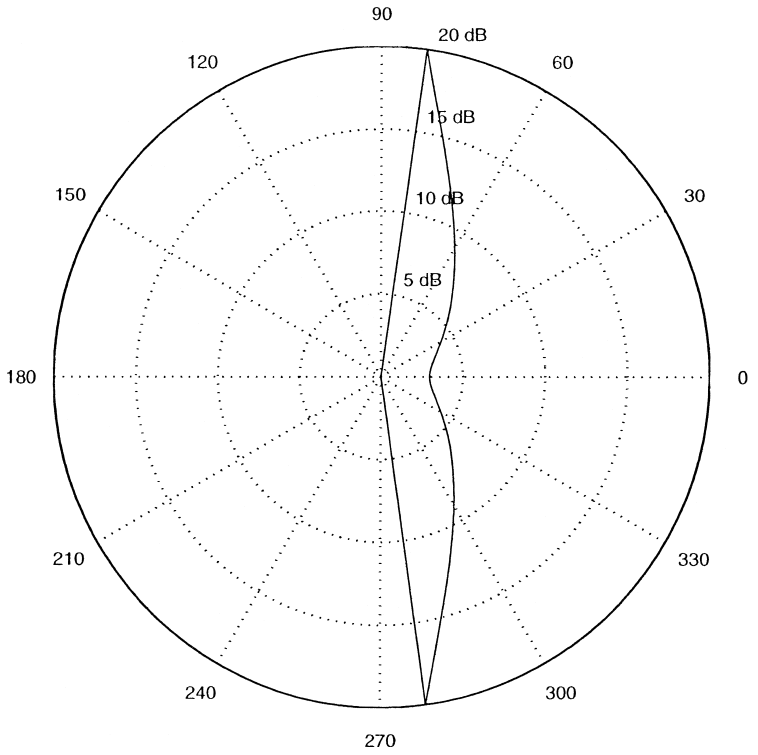


Figure 6. The antenna gain in polar representation.

5.3. *Platform-user link analysis.* In order to determine the reliability of the link, various variable parameters have to be taken into account; in fact, the received signal strength may fluctuate, which could result in fading. The received power is given by:

$$P_r = P_t - C_t + G_t - L - FM + G_r - C_r, \tag{5}$$

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where P_t and P_r are the transmitted and received powers respectively, C_t and C_t are losses internal to the transmitter and receiver respectively, G_t and G_t are the transmitting and receiving antenna gains respectively, L is the path loss, and FM is the fading margin (for digital links a typical Rayleigh model is considered with an outage probability of 10^{-2} and an availability of 99 %).For the case of pure terrestrial propagation the received power is:

$$P_r = 3dBW - 1{\cdot}8dB + 3dB - 146dB - 18dB + 3dB - 1{\cdot}8dB = -158dBW. \quad (6)$$

For the system employing the stratospheric platform with an antenna assuring a uniform coverage of the service region, the received signal power is:

$$P_r = 3dBW - 1{\cdot}8dB + 3dB - 110dB - 16dB + 3dB - 1{\cdot}8dB = -120dbW. \quad (7)$$

The link budget of Eq. (7) has been evaluated for a carrier frequency of 450 MHz and the fading margin has been estimated using a Rice model with an outage probability of 10^{-2} and an availability of 99 %, considering a ratio of 2 dB between the total transmitted power and the power of the path in line-of-sight.

Comparing Eq. (6) and Eq. (7), the improvement that can be obtained using the aerial transponder can easily be seen. Given a certain sensitivity of the user receivers, the higher level of the received power provides increased link reliability.

6. CONCLUSIONS.

In this paper, a new augmentation system based on the use of HAVE platforms has been proposed and described. Several advantages can be foreseen from using such platforms for augmentation of GPS and Galileo systems. Some preliminary results have been presented for the possible application of a HAVE platform purely as a transponder for the DGPS signals. The use of a HAVE platform can increase the coverage of differential correction broadcasts and improve the overall navigation system performances. In the proposed system architecture, a ground DGPS transmitter can be substituted with the stratospheric platform linked with its RS.

Further investigations are considering the possibility of broadcasting a GPS-like signal from the HAVE platform in order to define a stratospheric segment able to provide users with additional pseudo-range measurements; this would allow an improvement in system accuracy and availability in scenarios of poor satellite geometry. In this case, the stratospheric platform – that can be considered as a movable pseudo-satellite – may theoretically have an independent role within the satellite navigation system. Possible differential corrections evaluated by a terrestrial RS can be modulated, as the navigation message, on the GPS-like signal transmitted from the aerial pseudo-satellite that has been named *stratolite*, and that will be the main object of future research.

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