GNSS Based Attitude Determination Systems for High Altitude Platforms

Luigi Boccia, Giandomenico Amendola, Giuseppe Di Massa

Università della Calabria
Dipartimento di Elettronica, Informatica e Sistemistica
Via Bucci, 42-C8
87036 Rende CS, Italy
Phone: +39 0984 494700, Fax: +39 0984 494743, e-mail: dimassa@deis.unical.it

Abstract. High Altitude Platforms (HAPs) are a new, promising means of providing innovative wireless services. HAPs can be successfully applied for mobile or broadband communications and for disaster monitoring or response. One of the open issues is whether HAP stations can provide reliable services without temporal outages due to stratospheric winds that can cause an inclination of the platforms. As a possible solution in this paper it is proposed the use of a GNSS based attitude determination system. This technique, which has been successfully applied for both aircrafts and spacecrafts can provide real time three axis attitude data using the GNSS receiver present onboard the platform. In particular, it will be shown how the usage of a particular class of low multipath and lightweight antennas can provide high accuracy without altering the avionic ballast.

1 Introduction

High Altitude Platforms (HAPs) are an innovative technology developed to provide new means to implement innovative wireless services. HAP [1–2] may be either airplanes or airships autonomously operating during long time (up to several years) at altitudes between 15 and 25km and covering a service area up to 1,000 km. The key advantage of HAPs systems with respect to satellite technologies is that these platforms can be deployed in a relatively short time offering a wide range of new opportunities and enabling services that take advantage of the best features of both terrestrial and satellite communications. Using HAP stations can be beneficial to develop and implement regional wireless communication networks providing users with high rate and quality access to internet or with Third Generation (3-G) mobile services. In this context, a single aerial platform can replace a large number of terrestrial masts, along with their associated costs, environmental impact and backhaul constrains. HAPs can be also extremely beneficial to supplement existing services in the event of a disaster (e.g. earthquake, flood, volcano eruption). In a disaster scenario HAP can provide immediate coverage of the disaster area for both communications and monitoring applications.

HAPs are generally large some 200 meters and, even if their operating altitudes can be chosen to limit wind speeds and atmospheric turbulences, sudden gusts of atmospheric currents can alter the inclination and the positional stability of the platform.

In general, the horizontal displacements can be evaluated using an on-board Global Navigation Satellite System (GNSS) such as GPS or Galileo and counterbalanced employing a propulsion mechanism. However, for certain applications, the main HAP limitations derive from the attitude uncertainty. In fact, even if small inclinations can be in some cases compensated by affixing the antennas to a gimbaling system, greater variations require a realignment of the entire platform. In this latter case it is essential to have onboard the aircraft a real-time three-axis attitude determination system.

In this paper it is illustrated the possibility to use of a GNSS for real-time attitude determination of HAP stations. In fact, GNSS based attitude determination systems appear to be very well suited for HAP platforms provided a small, light weight antenna with low multipath capabilities is adopted. In the following, an introduction to GNSS based attitude determination systems will be presented focusing the attention on the receiving antennas, which characteristics strongly affect the system accuracy. Then, an innovative class of low-multipath low profile GNSS antennas will be presented, namely the Shorted Annular Patch (SAP) antennas. It will be shown how these radiators have performances comparable with other high precision GNSS antennas while having smaller size and light weight.

2 GNSS-Based Attitude Determinatio Systems

The possibility to use GNSS for real-time attitude determination of both spacecrafts and aircrafts has been recently introduced in [3]. A GNSS-based attitude determination system is a hybrid sensor that gives a continuous pointing knowledge, completely immune to drift phenomena and therefore without the necessity to be calibrated by a reference sensor thus being well suited for application onboard HAPs which are supposed to operate independently for long time. Furthermore, it gives a reduction in size, power and cost of the sensor hardware as it uses a GNSS receiver already present onboard the platform.

As it is shown in Fig. 1, the attitude information is derived measuring the spatial orientation of three baselines defined on the HAP body as the connection lines from a master antenna to three slave antennas. The basic measurable in GNSS-based attitude determination is a differential measurement across two antennas, the master and one of the three slaves, of the phase of the GNSS signal (Fig. 2). Two GNSS antennas are placed at the two ends of a baseline $\underline{\mathbf{b}}$. They are connected to two different channels of the same GNSS receiver. The channels are made to track the same GNSS satellite. The difference in the measurement of the GPS carrier between the two antennas is proportional to the projection of the baseline vector $\underline{\mathbf{b}}$ onto the direction of arrival of the GNSS signal. If $\underline{\mathbf{s}}$ designates the unitary vector along this direction of arrival, then one can write:

$$\underline{b} \bullet \underline{s} = m\lambda + \Delta\varphi + \Delta\varphi_{error} \tag{1}$$

The phase difference between the two antennas is shown as an integer number m of carrier wavelengths λ. plus the fractional part $\Delta\varphi$.. plus measurement errors $\Delta\varphi_{error}$. Most of the errors in these measurements, such as atmospheric delays or orbital and clock inaccuracies are spatially correlated are generally cancelled through the

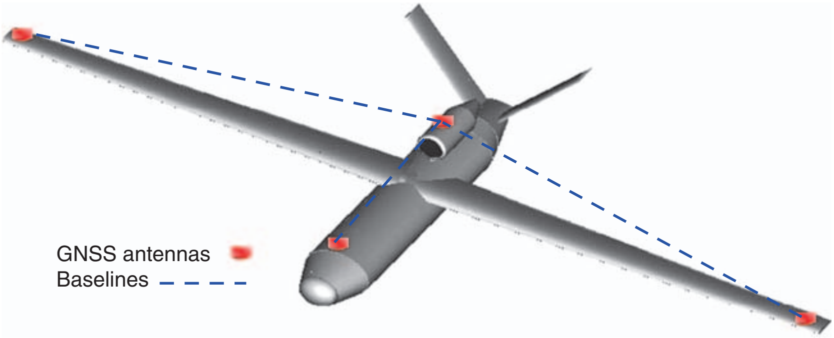


Fig. 1. A schematic of the GNSS-based attitude determination system applied to a HAP platform.

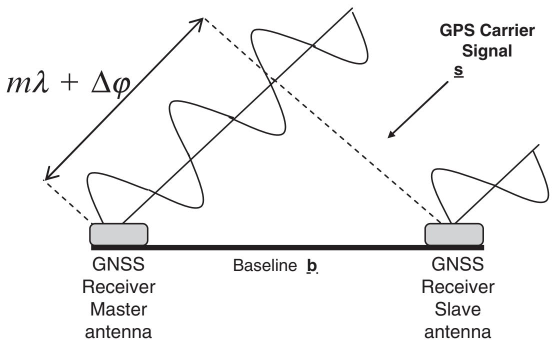


Fig. 2. Principle of GPS-based attitude determination.

differencing process. The major limitation that reduces the accuracy of these systems is owing to the multipath reflections of the GPS signal from surfaces around the antenna. When the length of a reflection path exceeds that of the direct path by more than 10–20 m then multipath errors can be reduced by signal processing techniques at the receiver. Unfortunately, in the most common case the strongest reflected signal component has an excess path length of less than 10 m which makes the receiver unable to detect and remove the multipath contamination. As a further consideration, it should be noticed that, in general, the accuracy of GNSS based attitude determination systems increases with the baseline length $\underline{\mathbf{b}}$ thus being very promising for HAP stations where a large spacing can be used between the antennas.

More effectively, the accuracy of a GNSS-based attitude determination system can be increased by using an antenna capable of rejecting multipath interferences. Antennas can be optimised for GNSS-based attitude determination in two ways. Firstly, they can be designed with high rejection to left-hand circularly polarised (LHCP) signals. This reduces the impact of multipath because the GPS, Glonass and Galileo signal are right-hand circularly polarised (RHCP) while odd reflections are LHCP. Hence, using antennas with a good rejection of LHCP signals, multipath effects arising from direct reflections can be potentially eliminated. Effects due to double reflections remain but they are normally much weaker. Secondly, attitude measurement performance can be improved by shaping the antenna gain pattern to reject low-elevation signals. This is beneficial because reflected signals often impinge on the antenna at low elevations. Hence, a narrow beam minimises their impact. Notice, however, that in order to perform attitude determination, at least two GNSS satellites must be tracked at all times. For this reason, the antenna field of view must be large enough to ensure that two or more satellites are visible throughout the satellite orbit. In practice, this means that the antenna pattern aperture must be greater than 120 degrees (supposing that only GPS is used).

Besides, a new antenna will be suitable for HAP applications only if its size is small enough and lightweight to permit an easy installation on the aircraft. Indeed one essential advantage of using GNSS for attitude determination is that different sensors and their interfaces can be eliminated and, in turn, costs, power requirements, weight and complexity reduced. Attempts to simultaneously meet these antenna requirements have been made in several ways and various types of GPS and Glonass antenna design have been proposed including spiral or helix antennas, patch elements placed on choke rings or "stealth" ground planes and several array configurations. Even if these solutions can be designed to reduce the multipath error they result in large and heavy structures that are not well suited for HAP applications especially if it considered that these antennas should be mounted at the opposite corners of a platform.

As a possible solution, in this paper it is proposed the use of an innovative class of patch antennas, namely the Shorted Annular Patch (SAP) antennas that demonstrated accuracy comparable to other larger and heavier solutions [4]. The key advantage of SAP antennas with respect to other concurrent radiators is that their weight is usually less than 500 gr while their overall size do not exceed 15 cm of radius. In practice, this implies that such antennas can be easily installed on HAP stations without affecting the overall avionic ballast and providing high accuracy attitude information.

3 Shorted Annular Patch Antennas

The SAP antenna geometry is shown in Fig. 3. An annular patch with external and internal radii *a* and *b* respectively is printed onto a dielectric grounded slab having relative dielectric constant ε_r and height *h*. At variance of conventional annular patches the inner SAP border is shorted to the ground plane thus making the dominant cavity mode a TM_{11} field variation. The SAP radiation pattern is therefore similar to that of the circular disk. However, once the dielectric characteristics and the operating frequency are fixed, the disk radius is uniquely determined and its radiation pattern cannot be modified. Conversely, the radiation characteristics of the shorted ring can be easily controlled varying the antenna geometry so that larger patches have higher amplitude roll-off near the horizon. Thanks to this feature, SAP antennas can be in fact optimized for high precision GNSS applications choosing the outer radius to minimize the multipath interference and adjusting the inner radius to make the patch resonate at the desired frequency.

As a proof of the SAP peculiarity, three shorted annular patch antennas resonating at the nominal GPS L1 frequency, 1.57542 GHz, with an external radius of 35,

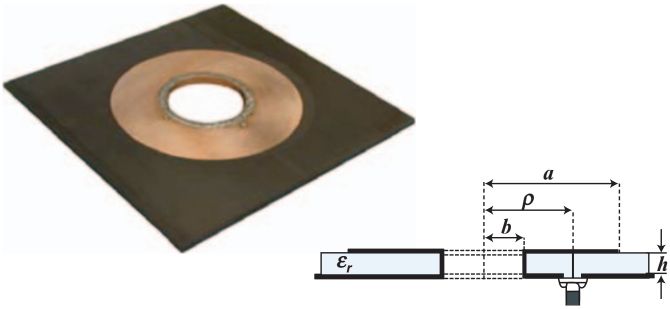


Fig. 3. Shorted annular patch geometry.

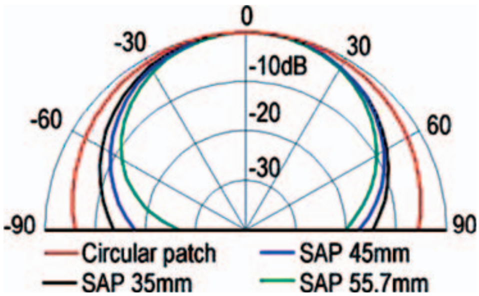


Fig. 4. SAP radiation pattern flexibility.

45, and 55.7 mm, have been designed considering a substrate with dielectric constant $\varepsilon_r = 2.55$ and thickness of 3.2 mm. Adequate circular polarization purity is attained by feeding the antenna by means of two 50 Ω coaxial probes located 90 deg. apart and having 90 deg. of phase difference.

The effect of a larger external radius is shown in Fig. 4 where the co-polar radiation patterns of the three SAP antennas have been compared with the one of a conventional circular patch resonating at the same frequency and designed using the same substrate. As expected, a larger outer radius of the antenna results in a narrower beam. Obviously similar characteristics can be obtained considering the Galileo contellation.

3.1 Radiation Characteristics

Prototypes of the three shorted annular patch antennas were then fabricated machining the inner hole in the dielectric substrate and shorting the internal boundary by means of a soldered copper foil. The geometrical characteristics of the three prototypes are shown in Table 1. In order to keep the circular polarization characteristics of each antenna as much as possible independent from the feed network

Table 1. Inner and outer radii, feed positions and dielectric size.

Antenna	*a*	*b*	*d*	*ρ*
SAP-G	55.7 mm	30.08 mm	140 mm	36.5 mm
SAP-M	45.0 mm	18.83 mm	150 mm	25 mm
SAP-P	35.0 mm	6.0 mm	160 mm	12 mm

design, each prototype was driven by means of an external quadrature hybrid (Pasternack PE2051) providing 90° ± 0.2° of phase difference within the GPS-L1 bandwidth and having a maximum VSWR equal to 1.07.

3.1.1 Radiation Patterns. In a first assessment the radiation characteristics of the three shorted rings were evaluated considering different figures of merit like the amplitude roll-off from broadside to the horizon, the polarization purity over all the hemispherical coverage and the phase response uniformity. All the measurements presented in this section have been taken at 1.575 GHz. Circular polarization characteristics have been obtained using a linearly polarized probe with a co-polar to cross-polar ratio higher than 40 dB in the broadside direction.

The radiation pattern of the SAP-M antenna was also measured and results are provided in Fig. 5. As expected, with respect to the SAP-G radiator, the SAP-M shows a reduced amplitude roll-off from broadside to the horizon that is around 20 dB. The on-axis gain is 8.97 dB while the RHCP to LHCP isolation is 23 dB. Coherently, the SAP-P antenna provides a more uniform hemispherical coverage with a gain at the horizon 15 dB lower than the one on axis (Fig. 6). In the broadside direction, the gain and the RHCP to LHCP ratio are 8.06 dB and 26 dB respectively.

It should be noticed that the amplitude response of the three prototypes is not uniform. However, this amplitude inhomogeneity is not so critical for a GPS system [5] as the only requirement is to have a signal level sufficient for all the coverage angles so that the receiver electronics can maintain lock with adequate signal to noise ratio.

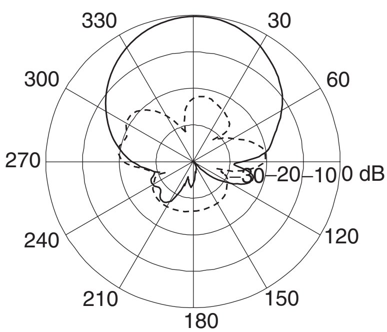


Fig. 5. Measured radiation pattern of the SAP-G antenna in the cut plane Φ = 45°: solid line RHCP, dashed line LHCP.

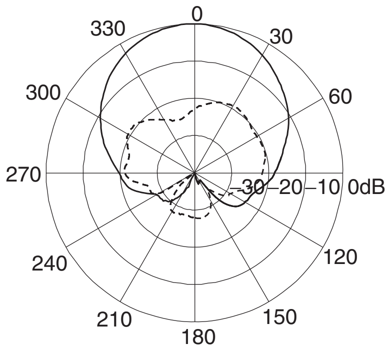


Fig. 6. Measured radiation pattern of the SAP-M antenna in the cut plane Φ = 45°: solid line RHCP, dashed line LHCP.

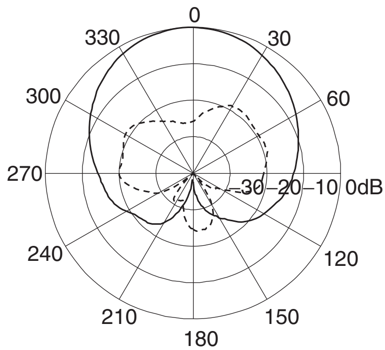
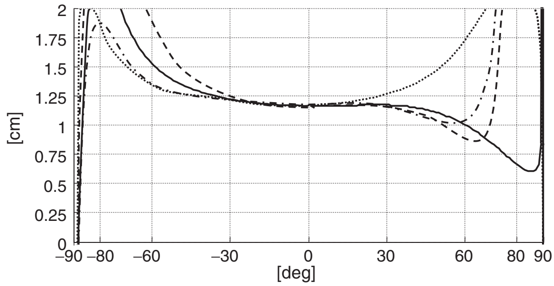
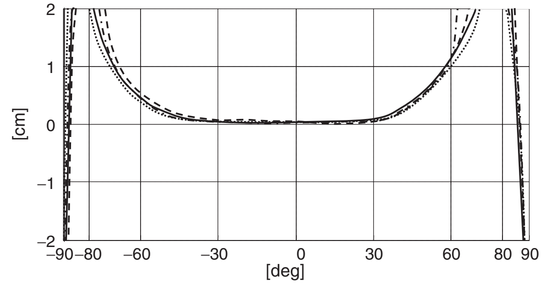


Fig. 7. Measured radiation pattern of the SAP-P antenna in the cut plane Φ = 45°: solid line RHCP, dashed line LHCP.

3.1.2 Phase Centre. The phase response uniformity was estimated considering the phase centre variations versus the observation angle. For each prototype, the phase centre location was determined positioning the antenna to be coaxial with the positioner axes of rotation and elaborating the RHCP phase measurements by means of the code proposed in [6]. The horizontal and vertical phase centre offsets with respect to the mechanical centres in the cut planes Φ = 0°, 45°, 90° and 135° are shown in Figs. 6–10. As can be seen, for all the antennas both the horizontal and vertical phase centre locations diverge when the observation angle is taken near the horizon. However, a fair evaluation can be obtained taking into account only the variations achieved for observation angles comprised between +/–80°. Under this condition, the maxima of the horizontal and vertical phase offsets calculated for the three prototypes are reported in Table 2. These results indicate that the larger the antenna radius the more distributed is the phase centre. However, this effect is not exclusively related to shorted rings as a similar behaviour is typical of many other antennas such as horns or helixes [5]. In fact, the pattern cut-off near the horizon increases in antennas with a wide radiating surface due to a process of phase interference which in turn deteriorates the antenna phase front and polarization [5].



(a)



(b)

Fig. 8. SAP-G phase centre variations vs. observation angle θ with respect to the mechanical centre of the antenna. a) Vertical offset, b) Horizontal offset.
—— $\Phi = 0°$, --- $\Phi = 45°$; -·- $\Phi = 90°$; …… $\Phi = 135°$.

Table 2. Maximum horizontal and vertical phase centre variations for the SAP-G, -M and -P.

Antenna	Vertical [cm]	Horizontal (cm)
SAP-G	± 2.24	± 2.53
SAP-M	± 0.543	± 0.812
SAP-P	± 0.29	± 0.40

3.2 On Field Assessment

The results presented in the previous section indicate that the axial ratio and the phase stability of SAPs deteriorate as the external radius increases. Thus, while larger SAP antennas have higher amplitude roll-off near the horizon and therefore better immunity to grazing signals, they lack in terms of phase uniformity and polarization purity. As has been noticed before, this consideration is not limited to shorted rings, but it can be extended to many other radiators. In fact, it is very difficult to have a single GPS antenna that simultaneously satisfies all the high precision radiation requirements, especially when physical constraints such as limited size

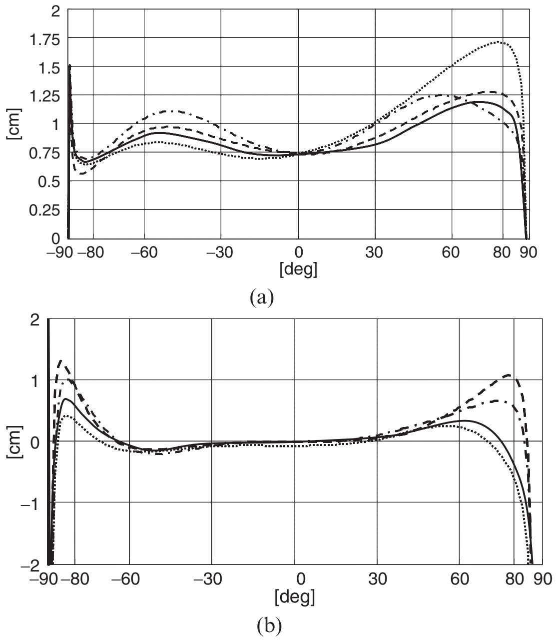


Fig. 9. SAP-M phase centre variations vs. observation angle θ with respect to the mechanical centre of the antenna. a) Vertical offset, b) Horizontal offset.
—— $\Phi = 0°$, ---$\Phi = 45°$; -·- $\Phi = 90°$; …… $\Phi = 135°$.

are also considered. As a consequence, the performance evaluation uniquely based on the radiation characteristics can be ambiguous and an experimental on-field assessment is necessary to find the optimal design.

In this paper, in order to clearly identify the SAP design with best immunity to the multipath error, a comparative test campaign was conducted at the GEO-GPS facility, an on-ground GPS test range of the National Research Centre (Centro Nazionale delle Ricerche, CNR) in Rende (Cs), Italy. This facility, normally used to test DGPS-based geodetic systems, is constituted of two identical GPS receivers with 10 Hz reporting capability connected to a workstation. Each receiver is paired with a 30 dB amplifier and with an antenna mounted atop a rigid support and aligned with True North. The system is fixed on the rooftop of a 15 m tall building located in a dense urban zone and with an unobstructed view for elevations above 7°. The basic measurable quantity of this differential GPS configuration is the baseline separation between the two antennas which essentially depends upon the differential path delay of the received GPS signal. Therefore, this kind of measurement provides a valid means to assess the performances of a GPS antenna, since it is the major error source owing to multipath interferences. In fact, other inaccuracies such as differential line bias can be easily cancelled correcting the baseline reference vector through a calibration process. However, it should be noticed that the test set-up used in these experiments is not intended to be representative of the best multipath performances attainable with the antennas under test. Indeed, a precise

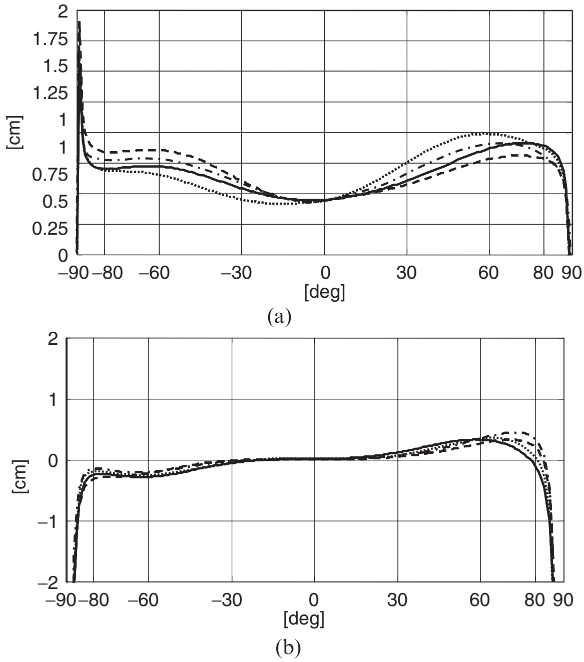


Fig. 10. SAP-P phase centre variations vs. observation angle θ with respect to the mechanical centre of the antenna. a) Vertical offset, b) Horizontal offset.
—— $\Phi = 0°$, ---$\Phi = 45°$; -·- $\Phi = 90°$; …… $\Phi = 135°$.

assessment would be strongly influenced by the configuration of the environment surrounding the receiving antennas and by the baseline distance. As a consequence, a fair evaluation can be only inferred on the basis of a comparative test campaign.

The low multipath performances of the three SAP antennas were evaluated fabricating pairs of identical prototypes and performing 24-h tests to collect differential baseline displacements. This experiment duration is optimal because it evens out daily temperature oscillations and because it is equal to the repeatability period of the GPS constellation as seen from the ground. Thanks to the high gain of the SAP antennas and to the amplifier present in the receiving chain, it was possible to lock the GPS signals coming from all the satellites with elevations above 10°. Furthermore, in order to provide an additional reference for the evaluation of the SAP performances, two pairs of commercial GPS antennas were also tested in the same facility; namely, a single feed patch (Ma-Com 1141 [8]) and a dual-band multi-feed GPS antenna (AT2775-42A W from AeroAntenna Technology, Inc [24]). These radiators are referred to as Ref-1 and Ref-2 respectively. The Ref-2 element is a high precision antenna [9] specifically designed for GPS-based geodetic applications and it was tested in the GEO-GPS facility with a ground plane extension having 20 cm of external radius. Both the Ref-1 and the Ref-2 antennas having an internal amplifier, it was possible to test these two radiators without any additional amplifier.

Table 3. Experimental results RMS of the differential baseline displacement.

Antenna under test	RMS [mm]
Ref-1	2.021
SAP-G	1.697
SAP-P	1.215
Ref-2	0.979
SAP-M	0.759

For each antenna under test, the measured data were statistically evaluated considering the RMS of the differential baseline displacement whereas the nominal baseline length was 5m in all the experiments. For uniformity, the data collected from satellites with elevation lower than 10 degrees were filtered out in all the test cases and the Ref-2 data for the L2 band were discarded. The experimental results are presented in Table 3 showing that the three SAP elements have very different performances. As expected, the accuracy achieved with all the shorted rings is better than the one of the Ref-1 patch. In particular, the minimum baseline displacement is obtained with the SAP-M antenna whose RMS is 0.759 mm whereas the SAP-G and SAP-P errors are 1.697 mm and 1.215 mm respectively. Hence, the SAP-M performances are 55% better than the ones of the SAP-G antenna and this result might be even optimized designing and testing other SAP prototypes and using a multi-feed arrangement. However, this is beyond the scope of this work which shows that the shorted annular patch accuracy can be significantly improved when the RSW criterion is abandoned and a trade-off between all the antenna radiation parameters is considered. As an additional achievement, it should be noticed that under this condition the SAP performances are competitive even when compared with other high accuracy GPS antennas such as the Ref-2 antenna whose measured error is 0.979 mm.

A similar on field assessment has been performed at the European Space Agency GPS Test Facility at Estec and obtaining similar results thus confirming the correctness of the presented performance assessment.

4 Conclusions

GNSS based attitude determination systems are a promising candidate for HAP stations. In general, this class of sensors provides real time attitude determination with an accuracy that is strongly influenced by the antenna immunity to multipath signals. In this paper it has been presented a class of low multipath antennas very promising for usage in HAP stations. The proposed solution, namely the Shorted Annular Patch antenna, has been selected for its appealing characteristics in terms radiation pattern flexibility. SAP radiators, in fact, are low profile antennas which can be designed to have high precision performances while keeping their size and weight low. A comparative analysis of the performances of different SAP antennas has been proposed showing that such antennas can provide an accuracy comparable to that of other high precision antennas but with a reduced size and weight. This feature makes these antennas very attractive for usage in space applications or for HAP stations. It should be noticed that a GNSS-based attitude determination sensor could be employed onboard a HAP station provided the antennas are sufficiently immune to multipath signals and only when the radiators fulfil the physical constrains. For this reasons, it appears extremely important the individuation of a class of GNSS receiving antennas satisfying both this important features.

As a further possibility to improve the accuracy of SAP antennas, the simultaneous employment of both GPS and Galileo systems could be considered.

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