ATTITUDE DETERMINATION USING GPS:

MULTIPATH REDUCTION THROUGH GPS ANTENNA DESIGN

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ABSTRACT

Multipath is recognised as the performance driver for GPS-based attitude determination, so that multipath reduction and mitigation is the key to significantly improve the achievable accuracy, today experimentally demonstrated to about 0.2 to 0.4 deg. RMS. Being a slowly-varying bias with time constants determined by spacecraft dynamics relative to the GPS constellation, multipath filtering appears operationally hardly feasible. Multipath calibration is a promising avenue, but requires an independent and accurate attitude reference if to be performed on-orbit. This paper is therefore focused on the third major class of solutions, the reduction of multipath at antenna level, by experimental investigation of alternatives to the conventional GPS patch antenna.

Indeed, one of the main conclusions of the experimental assessment of GPS-based attitude determination is that the major error source is the so-called "intrinsic multipath" of the GPS antennas, caused by the mismatch between antenna diagrams. Patch antennas, widely used for GPS applications, were recognised as poor candidates for accurate attitude determination because of the large dependence of the antenna diagram to the geometry of the supporting plate (in fact patch antennas do not work properly if not attached to a sufficiently large conductive plate). As a consequence, large "edge effect" were observed, resulting in multipath-like error of several tens of mm, about the same level of actual multipath obtained when large obstacles were implemented on the plate.

This paper compares test results & attitude determination performance of conventional GPS patch antennas to those obtained with alternate types of antennas with reduced dependence to the supporting plate. The first investigated antennas are 4-wire helical antenna prototypes derived from classical S-band TTC antennas, implemented at the corners of a 1.2 x 1.2 m plate installed on a building roof. Very significant performance improvements compared to patches (30%) have been demonstrated during this test campaign, yet smaller than expected from multipath predictions through detailed RF simulations. The most probable source of this discrepancy between predictions & tests was found in an artefact of the test set-up, the "external" multipath introduced by parasitic reflections on distant obstacles, allowing to expect further improvements in real space environment.

Key words:
GPS, attitude determination, antenna, multipath.

ACRONYMS

ADGPS	Attitude Determination using GPS
AOCS	Attitude & Orbit Control System
ADOP	Attitude Dilution Of Precision
DD	Double Difference (phase measurements)
GPSS	GPS Satellite
MBD	Matra BAe Dynamics
MMS	Matra Marconi Space
PVT	Position Velocity and Time
RLS	Recursive Least Squares
SD	Single Difference (phase measurements)

1. INTRODUCTION

One of the main conclusions of past experimental investigation of GPS-based attitude determination conducted at MATRA MARCONI Space (MMS) (see e.g. [1]) is that performance is driven by the so-called "intrinsic multipath" of the GPS antennas, caused by the mismatch between antenna diagrams. Patch antennas, widely used for GPS applications, were recognised as poor candidates for accurate attitude determination because of the large dependence of the antenna diagram to the geometry of the supporting plate (in fact patch antennas do not work properly if not attached to a sufficiently large conductive plate). As a consequence, large "edge effects" were observed, resulting in multipath-like error of several tens of mm, about the same level of actual multipath obtained when large obstacles were implemented on the plate.

Therefore, a primary avenue for performance improvement is to test alternate types of antennas with reduced dependence to the supporting plate. Similar conclusions were independently obtained by the GPS team in CNES (see [3]), resulting in the initiation of the development of more directional GPS antennas. "Cup dipole" antennas (basically a patch antenna in a "cup" providing a protection against grazing RF signals) have been selected by CNES, mainly to keep antenna height as small as possible in order to ease implementation on the satellite (especially on the very constrained interface with the launcher, often considered for antenna implementation).

Complementing CNES investigations, MMS has undertaken to test another promising type of antenna, the so-called "helical antennas", quite similar in shape to conventional S-band TTC antennas. These antennas have several interesting features. First, even though TTC antennas are designed to have a wide coverage; the antenna diagram can easily be narrowed by proper adjustment of the antenna internal geometry in order to be more directional than patches. Second, the helical antenna pattern is largely independent from the supporting structure. Finally, they are much easier to model than patches for RF simulation, allowing largely improved accuracy in the prediction of antenna diagram and therefore multipath effects.

2. PROTOTYPE HELICAL GPS ANTENNAS

Given the time and budget constraints of the activity, an already existing antenna design has been favoured, even though it is anticipated that optimisation of the antenna should allow improved immunity to multipath. The selected antennas are an adaptation of MATRA BAe Dynamics 4-wire helix S-band antenna commonly used for TM/TC (Figure 1). The considered antennas are obtained by homothetical size increase of the radiating element by about 30% for adaptation to the L-band GPS carrier. Moreover, the design of the RF coupler has been modified to reduce antenna height.

The resulting antenna is 28 mm in diameter, 170 mm high, of which 120 mm of active element and 50 mm of RF coupler. Such an antenna has a very good performance potential, with a wide open antenna pattern (see Figure 2), similar to patch antennas and a high rejection of cross polarised signals (i.e. a good immunity to reflected signals).

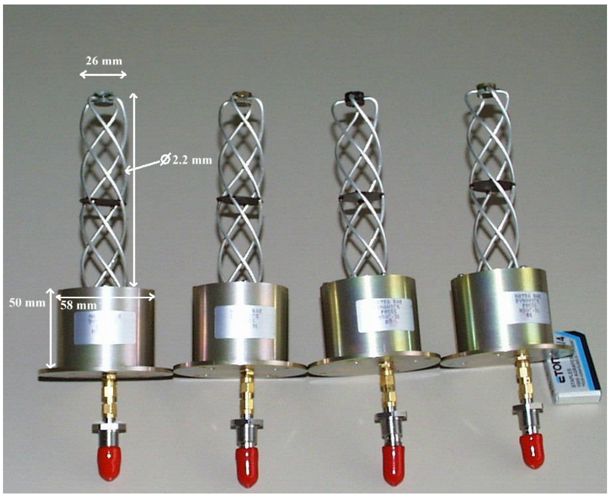


Figure 1 - Prototypes of the helical GPS antennas

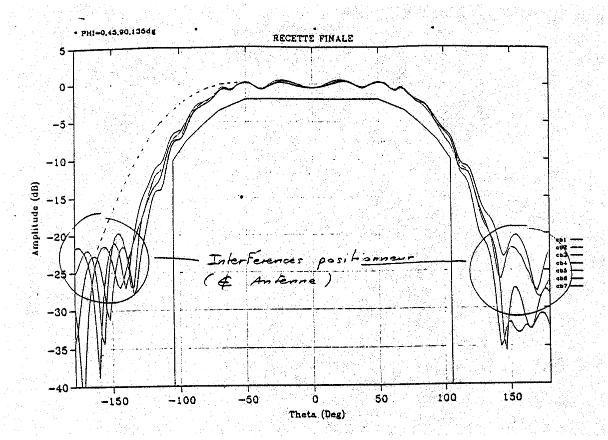


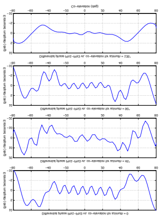
Figure 2 - Antenna pattern of the helical GPS antennas

3. MULTIPATH PREDICTION

In order to have a reliable reference for test results analysis, a prediction of the intrinsic phase error for the selected 4-wire helix antennas has been performed. High accuracyRF simulation tools have been used, based on the Method of Moments, i.e. Maxwell Equations resolution in each cell of the finite element model.

The first step was to set up a detailed finite element model of the antenna. In order to validate the model, the computed antenna pattern has been compared to the measurements performed by the manufacturer. This required to attach in the numerical the antenna to a 18 cm diameter disk to properly reproduce the antenna characterisation test conditions. The results fully validate the antenna modelling, with very good consistency of the computed & measured antenna patterns, better than 2 dB within +/-70° of the boresight.

The second step was to attach the validated finite element model of one antenna to the corner of the plate through a local



of the grid describing the plate (over a 20 x 20 cm e corner).

The antenna diagram was then computed using the Method of Moments applied to the resulting large model. In order to reduce the modelling & computation effort, the phase difference have been computed considering the symmetry of the model (difference between initial and rotated antenna pattern). The only resulting approximation on the computed phase differences is the effect of the other antennas (considered as reflecting obstacles) on the computed pattern, confidently expected to be negligible. Figure 3 describes configuration and notations. Figure 4 presents an example of differential phases between two antennas ($\varphi_1 - \varphi_3$) as azimuth cuts, using the following notations:

$$\theta_X = \theta.\cos(\varphi) = CoEl.\sin(Az) \quad ; \quad \theta_Y = \theta.\sin(\varphi) = CoEl.\cos(Az) \cdot$$

These RF simulation outputs are compared in section 6 with test results, in order to assess the multipath prediction capability, expected to be much better than with patch antennas. This will constitute a key input to future investigations for the definition of an "ideal" antenna for GPS-based attitude determination.

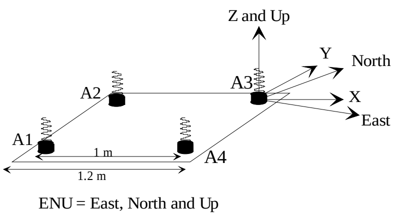


Figure 3 - Antenna Implementation on the plate model

Figure 4 - Azimuth cuts of predicted differential phase error

The worst case phase error obtained within a +/- 60° co-elevation angle (from antenna boresight) is 12° (6.3 mm).

4 TEST SET-UP DESCRIPTION

The tests are conducted using the GPSEA ("GPS Estimation of Attitude") test bench developed during the ADGPS study (see ref.[1]). The test set-up is configured for static tests since dynamic tests are actually of minor interest.

The four helical antennas are zenith-mounted on a 1.2 x 1.2 m carbon fibre honeycomb plate (see Figure 5), itself rigidly attached to the supporting truss. The test bench is installed on a building roof at MMS premises to avoid as much as possible the multipath effects through reflection on distant objects. Accurate alignment relative to the optical cube attached to the building roof has been performed in order to predict the attitude of the antenna plate relative to the ENU (East North Up) reference frame in which the GPS solution is given with an accuracy better than 0.02°.

Three test configurations have been considered. The first tests have been run with patch antennas for validation through comparison with the ADGPS study results. In subsequent tests helical antennas have been used, first on the bare plate, for multipath level and daily repeatability assessment and finally with obstacles (240x220x130 mm metalled box and TTC S-band antenna mock-up) between the antennas, so as create a conservative multipath environment typical of a difficult satellite configuration.

Figure 5 Test set-up with helical antennas, bare plate

The breadboard receiver is composed of two main units. First, the BRU (Breadboard Receiver Unit) developed by Alcatel Space Industries Valence, located close to the antenna plate comprises the four RF pre-amplifiers and the low level signal processing electronics necessary to produce raw carrier phase measurements. The second unit is the RPU (Receiver Processing Unit) developed by GMV and hosted in a de-located PC (connection through a 50-metre serial link). The RPU is in charge of BRU monitoring, navigation solution and storage of raw carrier phase measurements. Results processing for antenna baselines calibration (self-survey) and attitude determination are performed a posteriori under MATLAB.

5 TEST RESULTS ANALYSIS

The multipath error is first investigated through the analysis of the time histories of raw phase residuals $\Delta\varphi(t) = \hat{\varphi}(t) - \varphi_{mes}(t)$ where $\hat{\varphi}$ represents the phase predicted using the known attitude of the antenna plate, and φ_{mes} the measured phase. These phase residuals contain the phase error introduced by the antennas, plus the measurement error of the receiver (noise & biases), plus possibly external errors such as multipath introduced by the environment. The worst case error (3σ over time & channels) of the phase residuals are summarised in the following table for three tests, one with patch antennas and two with helical antennas:

	Baseline 1	Baseline 2	Baseline 3
Test 1.1-l (patch ant.)	20.4 mm (39°)	18.8 mm (36°)	17.5 mm (33°)
Test 1.1-o (helical ant.)	14.3 mm (27°)	12.2 mm (23°)	13.1 mm (25°)
Test 1.1-p (helical ant.)	14.5 mm (27°)	12.7 mm (24°)	12.5 mm (24°)

These results show a 30 % reduction of the phase error with helical antennas, compared to patch antennas.

The phase residuals are then processed using a recursive attitude determination algorithm using the baseline vector estimates obtained by self-survey of each configuration. Figure 6 shows typical time history of the attitude estimation error over 24 hours for helical antennas.

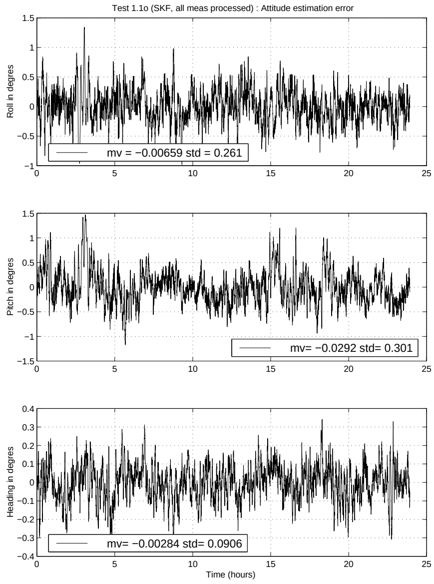


Figure 6 Attitude Estimation error with helical antennas

Since the dominant long-term attitude estimation error is expected to be caused by multipath, it is necessary to consider long duration test to asses the worst case attitude estimation error. Attitude performances are summarised in the following table:

Attitude performances (3σ)	Roll (around East axis)	Pitch (around North axis)	Head (around Up axis)
Patch antennas, bare plate	1.1°	1.23°	0.4°
Helical antennas, bare plate	0.78°	0.90°	0.27°
Helical antennas with obstacles	1.03°	1.04°	0.34°

According to these results, and whatever the considered axis, **the improvement relative to patch antennas for attitude determination errors is about 30 %**. This brings the 3-sigma estimation error below 1° for the worst axes and below 0.3° for the best observable angle, a performance compatible with some medium accuracy pointing missions.

The better heading performance is due to the improved observability given by double difference phase measurements (imposed by the parallel architecture of the receiver) about the normal to the antenna plate. Observability on roll and pitch is theoretically the same, so the slightly degraded performance on pitch is likely to be due to the test conditions (distant obstacles for instance, or unsymmetrical distribution of GPS satellites).

A very good correlation between the five tests performed with helical antennas and bare plate demonstrate that the long-term error is actually repetitive with a 24 h period, as can be expected from errors related to the direction of the incoming GPS signal. The verification of this 24h repetition of the dominant attitude estimation error makes quite promising a calibration approach, either a priori on the ground or on-orbit if an external attitude reference is available.

Tests with obstacles show a degradation of attitude estimation error up to 30 % compared to results with bare plate, quite consistent with previous results using patch antennas (see ref. [1]). Therefore, the improvement allowed by helical antennas is of the same order as the effect of unfavourable implementation conditions of the antennas.

6 COMPARISON BETWEEN TEST RESULTS AND RF SIMULATIONS

In this section the predicted phase difference from RF simulations (see section 3) are compared to test results.

Figure 7 presents azimuth cuts of phase errors vs. Co-elevation with test results superimposed as stardots to the predictions. The maximum phase residuals within +/-80° of the antenna boresight are summarised in the following table:

	A1-A3	A2-A3	A4-A3
RF simulation results	+/- 18° (+/- 9.5 mm)	-20 ° (-10.5 mm)	+ 20° (10.5 mm)
Test results	-50° (-26 mm)	-25° (-13 mm)	-40° (-21 mm)

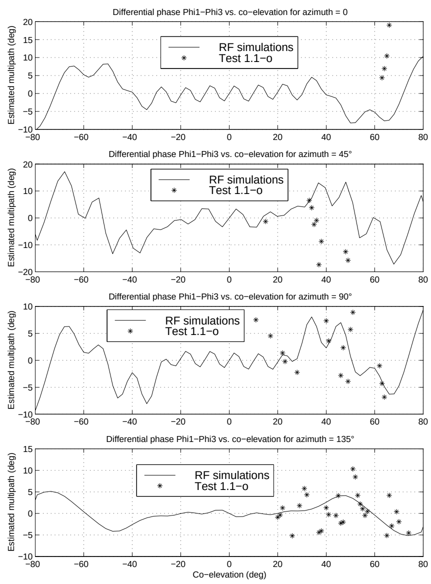


Figure 4.2.5 / 3: Comparison of azimuth cuts of differential phases between tests and RF simulation for baseline 1

These results show that worst case difference phases are significantly larger for tests than for RF simulations. Moreover, the comparison of azimuth cuts of differential phases shows that spatial distributions are also not in good agreement.

A first explanation to this discrepancy is that RF simulations are actually single differences, when tests results are double differences in order to remove the contribution of inter-channel biases, excessive for the considered parallel receiver architecture. The computation of the double difference using measurements from a particular GPS satellite signal (the so-called "pivot satellite"), here the one with the maximum elevation is detailed below:

a_i : antenna i

$\mathrm{S_k}$: satellite k

$\mathrm{S_{piv}}$: pivot satellite

$\Delta\Delta\varphi_{\mathrm{ij}}$: double difference phase between antenna i and antenna j

$$
\begin{aligned}
\Delta\Delta\varphi_{\mathrm{ij}} &= \Delta\varphi_{a_i S_k} - \Delta\varphi_{a_{ji} S_k} \\
&= \left[\varphi_{a_i S_k} - \varphi_{a_i S_{piv}}\right] - \left[\varphi_{a_{ji} S_k} - \varphi_{a_{ji} S_{piv}}\right] \\
&= \left[\varphi_{a_i S_k} - \varphi_{a_{ji} S_k}\right] - \left[\varphi_{a_i S_{piv}} - \varphi_{a_{ji} S_{piv}}\right] \\
&= \Delta\varphi_{\mathrm{ij\,S_k}} - \Delta\varphi_{\mathrm{ij\,S_{piv}}} \\
&= \text{Simple difference k - Simple difference pivot}
\end{aligned}
$$

So, RF simulation results ($\Delta\varphi_{ij\,\mathrm{S_k}}$) and test results ($\Delta\Delta\varphi_{ij}$) are not exactly comparable. Moreover, since multipath errors are quite correlated, they are likely to add linearly, which could explain the increased error in tests (even though the multipath error for the pivot satellite is expected to be smaller thanks to its high elevation).

Another potential source of discrepancy between simulation & tests is the effect of the environment of the test set up, i.e. surrounding obstacles (the surface of the roof top and distant building). This effect was shown in previous studies (see ref. [1]) to be non predominant, by repeating the experiment for various tilt angles of the antenna plate. This was however for patch antennas, which are shown in this study to induce a intrinsic phase error 30% larger than what is measured here, so that the contribution from the surroundings, negligible at that time could now be significant.

Since the predictions results are considered to be quite reliable, because of the antenna type (which can be exactly modelled) and of the selected high performance simulation method, it seems reasonable to consider that the performances of the helical antennas are to some extent "masked" by an artefact of the experiment.

As a consequence, a further 30% reduction of the intrinsic phase error of the antenna could probably be expected, which could be extrapolated to **the attitude determination performance as about 0.6° (3σ) on the worst axes and 0.2° (3σ) on the best one**.

Two complementary avenues can be considered to verify this hypothesis, either to perform tests in a multipath free environment (e.g. the anechoic chamber used by CNES in Toulouse, see ref. [3]), or to predict the effect of the distant obstacles by RF simulation, using this time a ray tracing method adapted to such large geometries.

7 CONCLUSIONS

The test campaign conducted on the GPSEA test facility with the prototype receiver developed in a previous ESA TRP contract ("Attitude determination using GPS" study, ref. [1]) has allowed to demonstrate the interest of helical antennas as an alternative to conventional GPS patch antennas for GPS-based attitude determination.

A number of long duration tests have been performed with helical antennas. They allowed first to confirm the daily repeatability of multipath errors. These multipath errors are the performance driver and can not be eliminated by filtering, so "multipath" calibration techniques are recommended for investigation as the avenue for significant performance enhancement. The demonstrated worst case (3σ) attitude determination performances for double difference processingwith helical antennas on a bare plate, are: : 0.78° / 0.90° in the horizontal plane and 0.27° about the antenna boresight. This represent a 30 % improvement compared to patch antennas. Extrapolation of these results to a single difference processing indicates a pitch/roll performance of 0.3 to 0.4° (3σ) and a yaw error below 1° (3σ), which are interesting performances for a number of missions. Raw phase measurement analysis confirmed this 30% improvement. Test with helical antennas with obstacles fixed on the plate shows a 30 % degradation of ADGPS performance, which is not surprising, according to past test campaign results.

RF simulations have been performed using antenna models validated by comparison with antenna patterns measured by the manufacturer to finely predict multipath in the test configuration. Comparison between simulation and test results shows that worst case phase difference are about twice in test data compared to simulations (20° in the worst simulation case and 50° in the worst test case). In other words, the predicted performance improvement is larger than actually measured. Since simulations are expected to be quite reliable due to the accurate model and the high performance methods used, the origin of this major discrepancy must be in the test conditions. A first possible explanation resides in the fact that the test data are double difference phase measurements, in order to remove the large inter-channel bias inherent to a parallel receiver architecture. A more convincing origin is however that the phase measurements are corrupted by "external" multipath induced by reflection on distant obstacles. If these assumptions can be confirmed, either by complementary simulations or by tests in a multipath-free environment, the improvement compared to patches would be a 50% instead of 30%, which would bring the attitude estimation error below 0.6° (3σ) on a worst case axis and 0.2° (3σ) on the best ones.

As a conclusion, 4-wire helix antennas are demonstrated to be promising candidates for GPS-based attitude determination. The already demonstrated performance improvement (30 %) compared to patches being quite significant, with a potential for further improvements through antenna geometry optimisation.

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