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A Comparative Sensitivity Analysis of GPS Receivers

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BIOGRAPHY

Gianluca Falco is an Electronics and Communications Engineering Ph.D candidate in the Electronics Dept. at Politecnico di Torino. He received a B.S. in Telematics Engineering and a M.S. in Communication Engineering both from Politecnico di Torino. His current research interests include investigation of Galileo signal and code structure, and advanced algorithms for PVT computation.

Fabio Dovis is an Assistant Professor of the Information Engineering Faculty of Politecnico di Torino, working at the Electronics Department where he is a member of the Navigation Signal Analysis and Simulation (NavSAS) group. His research topics are focused on the design of user receivers for the Galileo system and integration with GPS, multipath rejection schemes and interference mitigation on GPS and Galileo signal, study of algorithms for indoor positioning.

Gianluca Marucco received the Master Degree in Electronics Engineering from Politecnico di Torino in January 2003. He is a member of the NavSAS Group at ISMB. His research interests range from the study of core technologies for Code and Carrier Phase Multipath Mitigation to the development of enabling technologies for applications related to Global Navigation Satellite Systems (GNSS). He is currently responsible for the Real Time European Geostationary Navigation Overlay System (EGNOS) performance monitoring site in Torino.

Antonio Defina received the Master Degree in Communications Engineering from Politecnico di Torino in July 2005. Since 2005 he is working as researcher in NavSAS Group at ISMB. His research interests cover the field of localization, navigation and communication addressed to the GNSS technologies for applications, focused in particular to the implementation of Local Element systems prototypes relying on EGNOS features and on different communication channels.

INTRODUCTION

GNSS technologies are progressively becoming one of the key elements in most of innovative wireless applications. Most location-based services and systems are in fact employing standalone GPS, GPS+EGNOS (or WAAS), Assisted-GPS and Differential GPS as core technologies and therefore more and more companies have been integrating GNSS receivers into their consumer products. By considering the large number of available GPS receivers on the market and the lack of standard specifications on the performance, a general evaluation of low cost GPS chipset is very interesting. The present paper describes the performance tests of a set of GPS receivers by different manufacturers in different environmental conditions (outdoor, light indoor, temporary blockage of the signal). The results of the tests are compared with the claimed performance reported on the data sheets.

The comparative study on the performance is performed according to different figures of merit: acquisition sensitivity, Time To First Fix (TTFF) and the accuracy.

Performance of the different receivers were tested by means of a hardware platform and a software tool called Sat-Surf and Sat-Surfer respectively.

The paper is organized as in the following: section I is devoted to the introduction of the Sat-Surf/Sat-Surfer suite that was used during the tests to log all the parameters under investigation from the GPS modules.

Section II describes the method used to evaluate the sensitivity in cold start acquisition. A C/N_0 estimation as performed by the receives under test and evaluated over time for different incoming signal power level is shown too.

Section III deals with the measurement of the accuracy of a GPS receiver in different scenarios (open sky, urban canyon, light and deep indoor environment)
Eventually, the Section IV presents the analysis of the TTFF evaluated configuring the receivers in cold, warm and hot start and with GPS modules located in different real environments (opens sky, urban canyon and light indoor) and Section V draws the conclusions.

I. SAT-SURF AND SAT-SURFER

The integration of navigation and communication functionalities is one of the key elements exploited in new location-based systems and services. The growing interest on GNSS technologies leads companies to integrate GNSS receivers as core technologies into their consumer products, employing standalone GPS, Galileo-ready chipsets or using modules able to exploit external corrections (AGPS, DGPS, GPS+EGNOS or WAAS).
A novel platform has been designed and developed by the Navigation Signal Analysis and Simulation (NavSAS) group and it is composed by Sat-Surf, a hardware box integrating NAV/COM capabilities, and Sat-Surfer, a software suite able to control and communicate with the hardware [1].
A graphical image of the hardware/software device is depicted in Fig.1

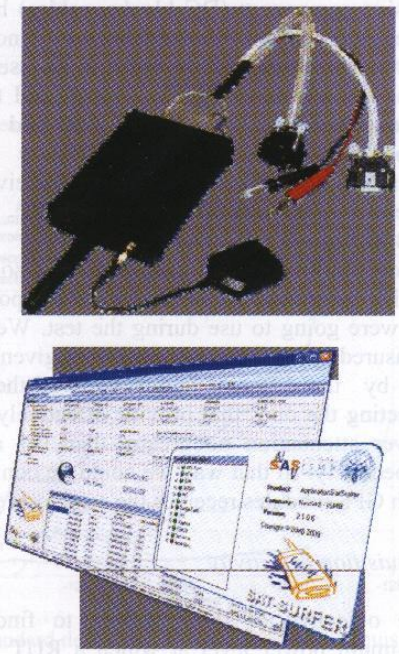


Fig. 1: Sat-Surf hardware and Sat-Surfer user interface

The Sat-Surf hardware includes components of the shelf, i.e. mass market GPS and GSM/GPRS modules. The innovation of this platform resides in its flexibility, since it has been designed not for a GPS module made by a single manufacturer, but it is has been conceived with a multiple footprint (i.e. pinout of a GPS module) of different GPS receivers. In detail, the current version of Sat-Surf can mount the following four GPS modules:

- uBlox ANTARIS 4 GPS module (DGPS compliant);
- uBlox 5 GPS module (OMA-SUPL Assisted GPS compliant);
- Falcom JP13-LP GPS module based on SiRFstarIII (low power consumption);
- Falcom JP15 GPS module based on SiRFstarIIx (DGPS compliant);

The software (Sat-Surfer) can support also other GNSS receivers and binary protocols as Magellan and Septentrio, and interface towards other receivers is currently under development. The communication hardware (i.e. Telit GM862-QUAD quad-band GSM/GPRS module) has been included in order to allow the test of Assisted-GNSS solutions or to provide via COM channel the DGPS corrections.
This platform is an enabling tool that allows study, develop, and test innovative hybrid NAV/COM strategies as well as new Location Based Services (LBSs) [2].
On the other hand, Sat-Surfer is the software suite running on standard PC that gets and process data from Sat-Surfer. Sat-Surfer uses the proprietary protocols (not only NMEA) of GPS modules to get all the available receiver parameters and raw measurements, in addition to conventional positioning information. Such data are displayed in real time on a graphical user interface in order to easily monitor satellites, signals, receiver and user's position. The same data are also logged with the related GPS time stamp and stored in different file formats (ASCII text files, MATLAB® files, Microsoft Office Excel® files, binary files, RINEX 2/3 log, KML files, NMEA files) for easy post-processing and analysis purposes.
Such tool provides the possibility to have a common interface towards different GNSS receivers in order to perform measurements and detailed analysis on a common set of data. In this way the development of new services and algorithms can be done also comparing different receivers.
Some examples of the Sat-Surf and Sat-Surfer features are reported in the following:

- extended data logging capability in order to analyze the evolution of different signal and receiver parameters and observables (including number of satellite in view and

used for the PVT computation, C/N0, Doppler frequency shift, carrier phase, GDOP, ephemeris parameters, ionospheric parameters, satellite positions) versus GPS time and in different environmental conditions (e.g. outdoor vs light-indoor);

- validation of PVT computation strategies using raw pseudorange measurements and reliable comparison of positioning performances;
- comparison of the Time To First Fix (TTFF) obtained in different configurations;
- GSM network parameters measurements and communication capability via the GSM/GPRS modem;
- test of Assisted-GPS (OMA-SUPL compliant) and Differential GPS (DGPS) functionalities with different setups (Stand Alone, LADGPS, RTK Rover, SBAS).

Sat-Surf and Sat-Surfer has already been delivered and successfully used in many education institutions such as Hanoi University of Technology (Vietnam), Asian Institute of Technology (Thailand) and Politecnico di Torino (Italy).

II. SENSITIVITY.

Exploiting the definition as cited on [3] , sensitivity is the lowest signal power, measured in dBm, detectable by a receiver under test.
Many GPS receivers actually specify two sensitivity values [5], [6], [7]:

- Acquisition Sensitivity that represents the minimum power level a receiver is able to correctly identify a satellite signal.
- Tracking Sensitivity is the lowest level at which the receiver reliably tracks a satellite.

In this paper we have evaluated the acquisition parameter only in acquisition (cold start) by using two different mass market receivers (that we will call in the following Receiver A and B respectively) and their performance has been compared with respect to a professional module i.e. Septentrio Polarx2e.
This parameter could be easily tested by exploiting the flexibility of Sat-Surf to work with different GPS chipsets and to log significant data.

Experimental Setup

The receivers under test (RUT) A and B are embedded in the Sat-Surf hardware while the professional receiver provides all the navigation data and other information to Sat-Surfer software through is proprietary protocol.

At first all these GPS modules have been configured to work in a high-sensitivity mode and then connected by means of a splitter to a Signal Generator (SG) that is in charge to simulate a single GPS satellite signal at different power levels.
A block scheme of the experiment set-up is depicted in Fig.2

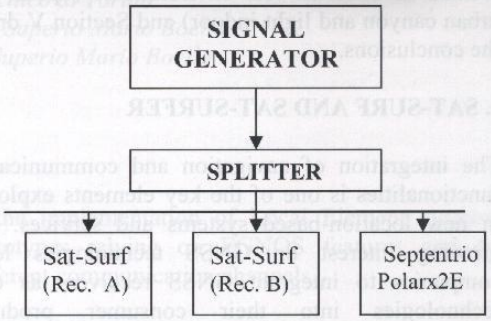


Fig.2 Setup used for the sensitivity receiver analysis

In order to measure accurately the incoming power that we provide to the RUTs we have evaluated the maximum power level that SG is able to generate through a Spectrum Analyzer (SA).
The SA reported a maximum power level P_{max} of -61.66 dBm. The GPS simulator is able to go down to 80 dBm with respect to P_{max} and as consequence to reach a P_{min} equal to -141.66 dBm.
The effects of the attenuator and of any other passive component (DC blocks, cables) have to be taken into account. Mathematically the noise figure of a passive component is equal to its insertion loss. Thus the attenuator, the DC block and the cables have a measured loss of 6 dB , 0.3 and of 0.1 dB respectively.
Therefore the effective minimum received signal level delivered to the RUTs becomes $P_{min,\,eff} = P_{min}$ - 6dB -0.3 dB -0.1 dB = -148 dBm.
Before starting the test campaign we also took care of the calibration of the hardware components that we were going to use during the test. We carefully measured through the SA each loss given by cables and by the different output ports of the splitters, selecting the ones that provide effectively a similar power attenuation no greater than 0.1 and 6 dB respectively. In that way we could be confident that each GPS modules receives the same power level.

Acquisition Sensitivity

The objective of the test was to find out the minimum power level at which a RUT is able to acquire the incoming signal and compare the obtained result with the value reported on its data-sheet.

In particular our focus was to measure the acquisition in cold start condition (i.e. GPS has no initial information on its position and time and no ephermeris and almanac data are stored in its memory).
The trial was carried out as in the following: we have set the SG to work in a range between -120 and -140 dBm. For each different signal power level we have run the RUTs in the cold start mode (Sat-Surf allows to make this operation quite easy) and collected the C/N_0 estimated values for 3-4 minutes.
Afterwards we have computed for each power level the mean value and the standard deviation of the C/N_0 as measured by the GPS modules under investigation.
Results are plotted in Fig 3 and Fig.4.

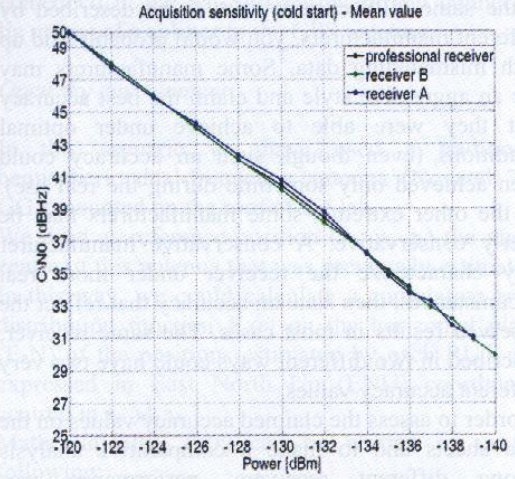


Fig.3: Mean values of the C/N_0 for the Acquisition sensitivity evaluation working with different GPS modules

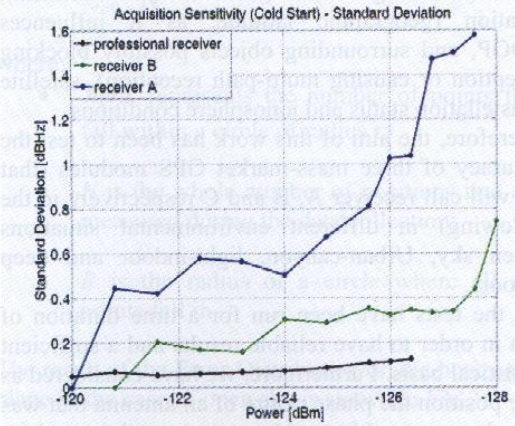


Fig.4: Standard deviation of the C/N_0 for the Acquisition sensitivity evaluation working with different GPS modules

As we can note the professional receiver is able to acquire signals with a strength not lower than -136 dBm that corresponds to a 34 dB/Hz in terms of C/N_0. Comparing the results with the values reported on the data-sheet we note a difference of 1 dBHz between the measured and the nominal value. On the contrary the mass market receivers under test were able to acquire signal with a power level lower than -136 dBm. In details receiver A goes down till to -139 dBm (with a difference of 1 dBm with respect its nominal value) while receiver B works till to -140 dBm that matches the valuesas reported on its data-sheet.
Even though RUTs A and B are able to detect GPS signals with a C/N_0 equal to 31-30 dBHz they perform a C/N_0 estimation with a higher variance than the professional receiver (Fig.4), then increasing the confidence interval of the previous measurements.
The lower the incoming power becomes the larger the variance in C/N_0 assessment is. This trend can be noted for all the RUTs, but in the case of the professional module the variance in the C/N_0 estimation increases slightly and keeps it always under the threshold of 0.2 dB. This means that device can perform accurate estimation of C/N_0 ratio also in the condition of weak signal power.

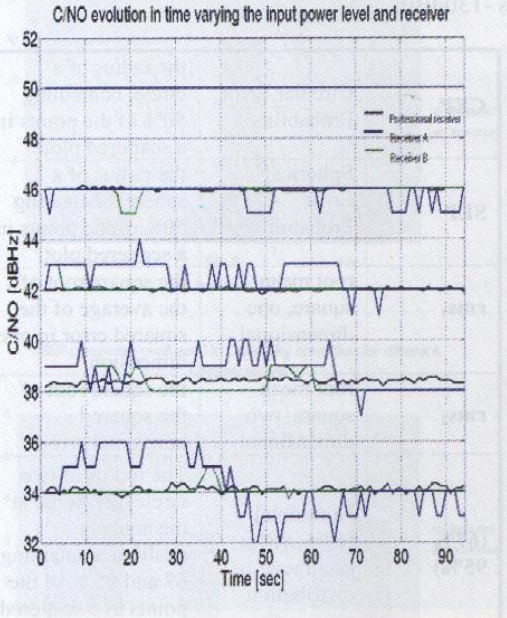


Fig.5: C/N_0 estimation varying with time and with the input power level evaluated for different GPS receivers

On the other hand the mass market receivers compute the C/N_0 with a higher variance when they have a low signal (from -134 to -140 dBm) as stimulus. This can be noted in particular in receiver A whose C/N_0 measurement tends to swing around

the reference value (of the professional one) with a standard deviation σ that rapidly overcomes 1dBHz. This fact is due both to the incapability of the receiver A to assess C/N_0 with a sampling interval lower than 1 dBHz and to the implemented algorithm used by that company to compute the C/N_0 estimation.

Receiver B can perform C/N_0 computation with a more accurate sampling interval (0.3 dBHz) and to maintain a stable value almost till to its limit in acquisition (till to -139 dBm).

In Fig.5 we have plotted the trend of the C/N_0 over time as estimated by the receivers in different condition of signal power levels(-120, -124, -128, -132 and -136 dBm respectively).

It has to be noted the swinging attitude of receiver A in the C/N_0 estimation in particular in the cases of a incoming power strength of -132 and -136 dBm.

This trend can be explained by a different algorithm implemented for the C/N_0 estimation [8] with respect to the other RUTs (i.e. receiver B and Septentrio) and by a rough sampling interval in the C/N_0 assessment.

III. ACCURACY

The GPS signal is typically buried in thermal noise and the minimum signal level that reaches the Earth is -130dBm.

CEP	Circular Error Probability	the radius of a circle, containing 50% of the points in a scattered plot
SEP	Spherical Error Probability	the radius of a sphere, containing 50% of the points in a scattered plot
rms_1	root mean square, one dimensional	the square root of the average of the squared error in one dimension
rms_2	root mean square, two dimensional	the square root of the squared horizontal error
(67% 95%)	Horizontal (67%, 95%) accuracy distribution	The radius of two circles, centered at the antenna position, containing 67 and 95 % of the points in a scattered plot

Table I: common parameters used to evaluate the accuracy of a GPS receiver.

Even if the spread spectrum signal structure and signal processing techniques allow the GPS signal tracking, these algorithms fail in harsh environments such as under dense foliage and in urban canyons.

In order to overcome these shortcomings and to have GPS modules able to work in harsh environmental conditions, a lot of research studies have been carried out during these years. More and more companies are designing and manufacturing chipsets to be used in indoors and urban environments.

The capability of a receiver to maintain precision in the position estimation even if stimulated by a weak signal, has a direct impact on the obtained accuracy.

Accuracy is defined as the magnitude of the distance between the true position and the position fix reported by the receiver at a certain instant [3].

Many GPS receivers actually provide several additional statistical accuracy metrics as reported in Table I.

Among them usually CEP and SEP are reported in data sheets.

If the same GPS chipset were to be described by different manufacturers, you would probably end up with mismatching data. Some manufacturers may use an aggressive style and claim the best accuracy that they were able to achieve under optimal conditions (even though such an accuracy could been achieved only sometime during the real use). At the other extreme, some manufacturers may be overly conservative. A conservative manufacturer may characterize the receiver under more real circumstances, then state an accuracy that reflect the observed results in most cases. The same receiver, described in two different ways could have two very different accuracy values.

In order to assess the claimed accuracy values on the data sheets and to make a comparative analysis among different receivers, performance was measured at different locations and times.

In fact, position accuracy will vary with GPS receiver configuration (receiver and antenna), location (geographic latitude, as it influences HDOP, and surrounding objects possibly blocking reception or causing multi-path reception), satellite constellation status and ionosphere conditions.

Therefore, the aim of this work has been to test the accuracy of three mass-market GPS modules (that we will call receiver A, B and C respectively in the following) in different environmental situations (open sky, Urban-canyon, light-indoor and deep indoor).

All the tests have been run for a time duration of 24h in order to have reliable results and a sufficient statistical basis. Furthermore, we have considered as true position the phase centre of an antenna that was at a known position with respect to the geodetic network.

Experimental setup

The hardware testing setup that we have used during the trials is shown in Fig.6

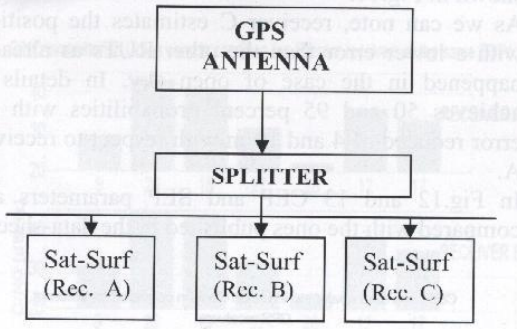


Fig.6 Setup used for the accuracy receiver analysis

The Receivers Under Test (RUTs) A, B and C are embedded in the Sat-Surf hardware and connected by means of a splitter to the GPS antenna.

Open sky environment

In this scenario we have used a traditional hemispheric dual-frequency antenna (Novatel 702 GG) mounted on the roof of the lab.
We used as reference position (x_0, y_0, z_0) the phase centre of this antenna that was previously estimated. In this way, we could calculate a cumulative error distribution function $F_e(r)$ on the horizontal plane (E-N) of the positions estimated by each RUT and expressed in East North Up (ENU) coordinates centred in x_0, y_0, z_0.
Mathematically, $F_e(r)$ can be written as in the following:

$$F_e(r) = \sum_{r=0}^{R} \frac{n(r)}{N} \text{ with } r = 0,1,2,..\ R \text{ m} \qquad (1)$$

where:

- $n(r)$ represents the number of points that fall within a circle of radius r;
- N is the whole number of positions that are measured during the data collection;
- R is the radius of a circle where all the points fall in.

The result of the Error Distribution on the horizontal plane in the case of open sky is shown in Fig.7

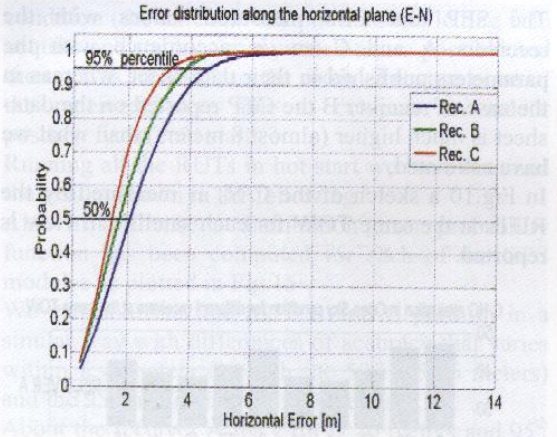
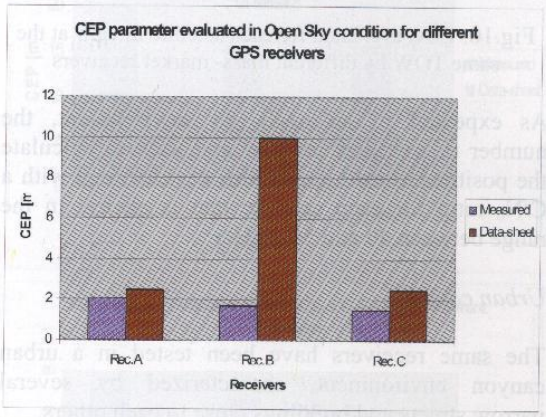


Fig.7: Error Distribution on the horizontal plane for different GPS modules in Open Sky condition

The receiver C offers the best performance with a lower error than the other RUTs.
In all the cases the error is less than 2 meters for CEP and less than 5 meter for 95% percentile.
In Fig.8 and Fig.9 CEP and SEP parameters are compared with the ones reported on the RUTs data-sheets.



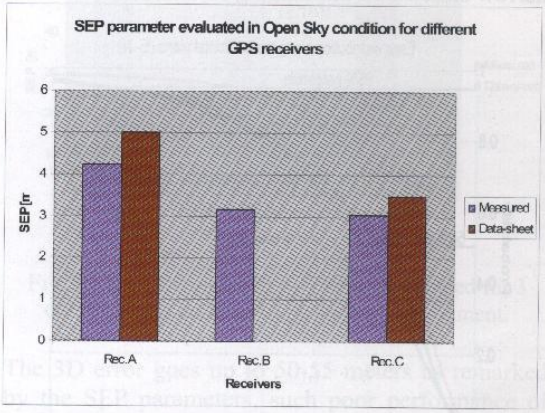


Fig.8-9: CEP and SEP parameters evaluated for different GPS modules and in an open sky environment.

The SEP and CEP measured values with the receivers A and C are in accordance with the parameters published in their data-sheet, whereas in the case of receiver B the CEP reported on the data-sheet is much higher (almost 8 meters) than what we have estimated.

In Fig.10 a sketch of the C/N_0 as measured by the RUTs at the same TOW for each satellite in view is reported.

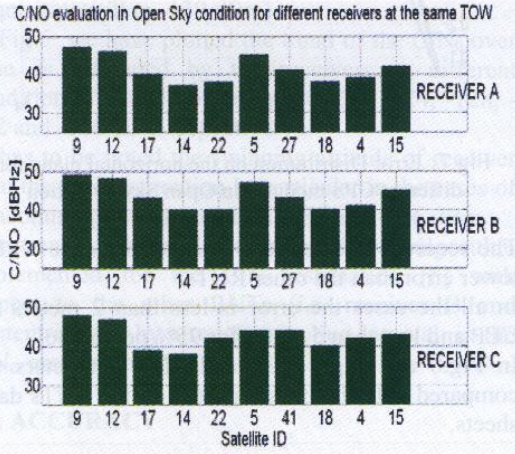


Fig.10: C/N_0 evaluated for each satellite in view at the same TOW by different mass- market receivers

As expected in an open sky environment, the number of satellites in view and used to calculate the position fix, is high (in this case 10) and with a C/N_0 ratio for each satellite that is always in the range between 40 and 50 dBHz.

Urban canyon

The same receivers have been tested in a urban canyon environment, characterized by several narrow streets and buildings close to each others.

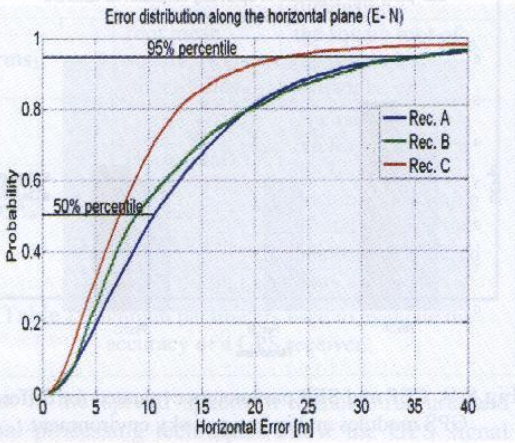


Fig.11: Error Distribution on the horizontal plane for different GPS modules in urban canyon condition

Also in this case the cumulative error distribution function $F_e(r)$ has been measured and its trend is shown in Fig.11.

As we can note, receiver C estimates the position with a lower error than the other RUTs as already happened in the case of open sky. In details it achieves 50 and 95 percent probabilities with an error reduced of 4 and 10 m with respect to receiver A.

In Fig.12 and 13 CEP and SEP parameters are compared with the ones published in the data-sheets.

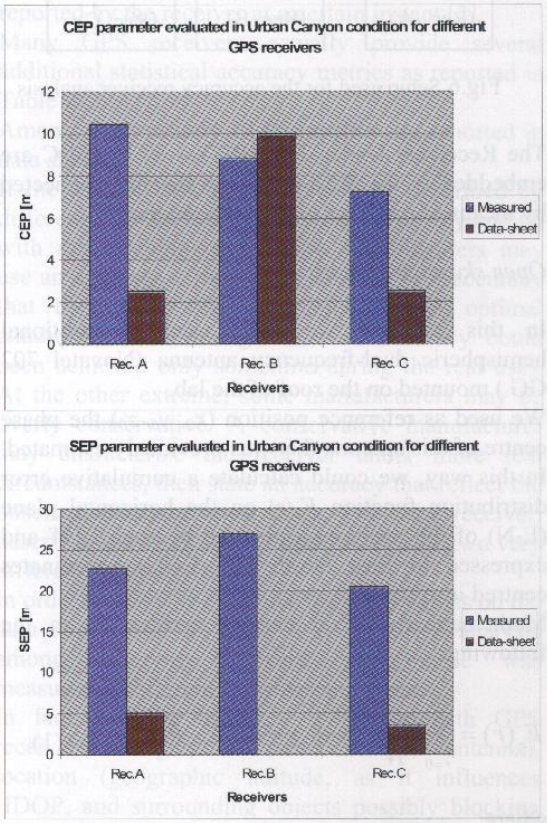


Fig.12-13: CEP and SEP parameters evaluated for different GPS modules in an Urban Canyon environment.

Analyzing the CEP and SEP parameters it is evident how the urban canyon makes worse the accuracy of a GPS receiver. In fact the 50 percent error ranges from 7.5 (receiver C) to 10.4 m (receiver A) with an increase of almost 5 meters with respect to the case of open sky environment.

Concerning the performance of receiver B the CEP is equal to 8.6 m that is close to the value reported in its data-sheet.

The most of accuracy loss is due to the error along the vertical axis as stressed by the SEP that raises from 4 meters in open sky conditions till 25 meters in the case of urban canyon.

In Fig.14 plots an example of power received by the RUTs in a location with reduced visibility of the sky.

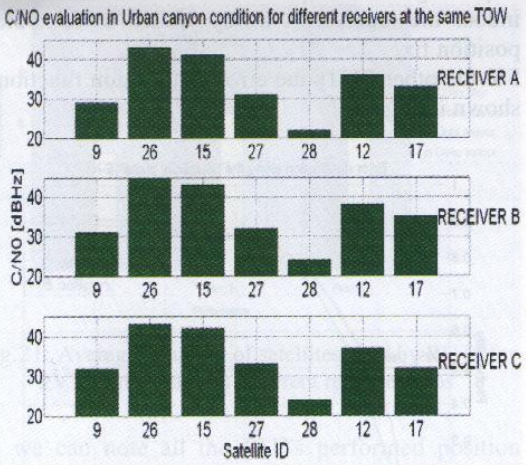


Fig.14: C/N_0 evaluated for each satellite in view at the same TOW by different mass- market receivers

We can clearly see how the number of satellites used to compute the position decreases from 10 (in the case of Open Sky) to 7.
Also the power incoming from the satellites in view and received by the RUTs goes down to the range of 30-40 dBHz with a difference of more or less 10 dBHz with respect to a situation of good visibility.

Light Indoor

In order to evaluate the light indoor conditions we placed a patch antenna on a windowsill in the lab and collected data for a whole day.

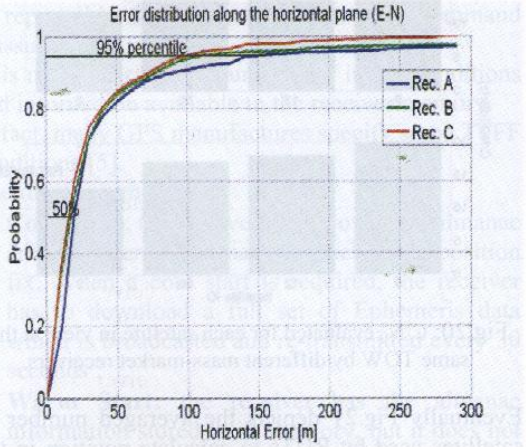


Fig.15: Error Distribution on the horizontal plane for different GPS modules in Light Indoor condition

It is worth to say that all these measurements have been performed starting from an outdoor initial condition (the antenna was put outdoor, letting it to acquire and track as many satellites as possible and then it was moved into the room), because none of the receivers were able to compute an indoor position fix in cold start.
Running all the RUTs in hot start we have obtained the results shown in the following.
Also in this case a distribution error probability function has been computed for each of the GPS modules as plotted in Fig.15
We can note that the RUT B and C perform in a similar way with differences of accuracy that varies within few meters for both the 50th (15-16 meters) and the 95th percentile (95-100 meters).
About the receiver A the CEP is 20 meters and 95th percentile error is 140 m with a difference of 40 meters with respect to the other RUTs.
CEP and SEP parameters have been computed too and reported in Fig.16 and Fig. 17.

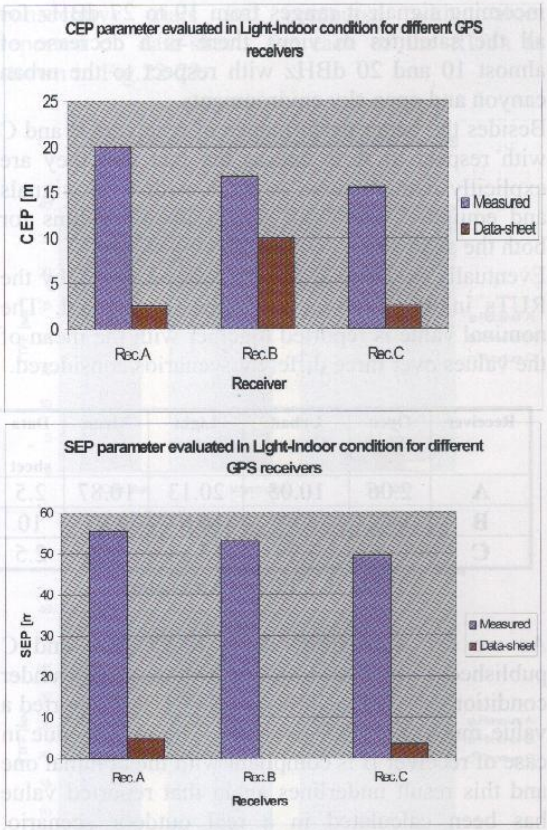


Fig.16-17: CEP and SEP parameters evaluated for 3 GPS modules and in a Light Indoor environment.

The 3D error goes up to 50-55 meters as remarked by the SEP parameters, such poor performance of the RUTs in particular along the vertical component is due to the reduced number of satellites used to compute the position and the low power level of the satellites signal received by the patch antenna.

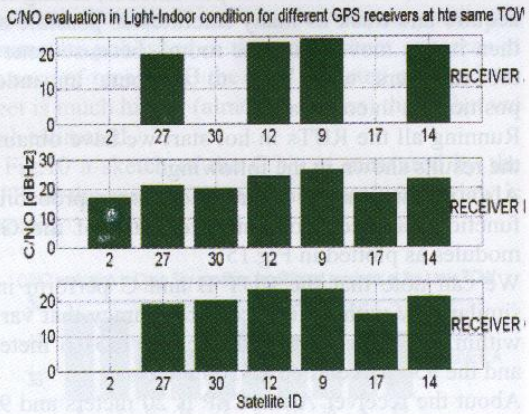


Fig.18: C/N_0 evaluated for each satellite in view at the same TOW by different mass-market receivers

Fig.18 depicts the C/N_0 ratio, that provides the information about the signal strength of the incoming signal; it ranges from 19 to 27 dBHz for all the satellites in view, there is a decrease of almost 10 and 20 dBHz with respect to the urban canyon and open sky environments.

Besides the better performance of receivers B and C with respect to A is due to the fact that they are explicitly manufactured to work with weak signals and equipped with high sensitivity algorithms for both the acquisition and the tracking stages.

Eventually in Table II the CEP as estimated by the RUTs in the different scenarios is resumed. The nominal value is reported together with the mean of the values over three different scenarios considered.

Receiver	Open Sky	Urban Canyon	Light Indoor	Mean	Data - sheet
A	2.06	10.05	20.13	10.87	2.5
B	1.72	8.82	16.67	9.07	10
C	1.49	7.23	15.54	8.06	2.5

Table II. CEP [m] parameters

As we can note from Table II RUT A and C published a value that can be obtained only under condition of good visibility while RUT C reported a value much more conservative. The mean value in case of receiver B is compliant with the nominal one and this result underlines again that reported value has been calculated in a real outdoor scenario, formed of tracks with several satellites in visibility and others characterized by momentary blockages and reduced satellite availability.

Deep Indoor

The last test we have run was inside an apartment. Repeating the same procedure as in the case of light indoor the receiver A always failed to compute a position fix.

For the other RUTs the error distribution function is shown in Fig.19

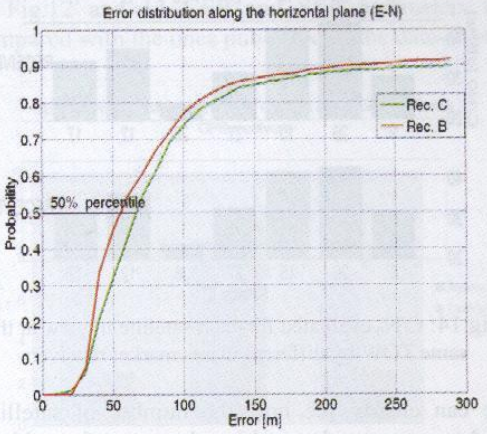


Fig.19: Error Distribution on the horizontal plane for different GPS modules in Deep Indoor condition

As we can note the error at the 50th percentile grows till 50 and 66 meters for the RUT B and C respectively.

In this harsh scenario also the number of satellites used to compute the position and the incoming signal power decrease greatly as shown in Fig.20

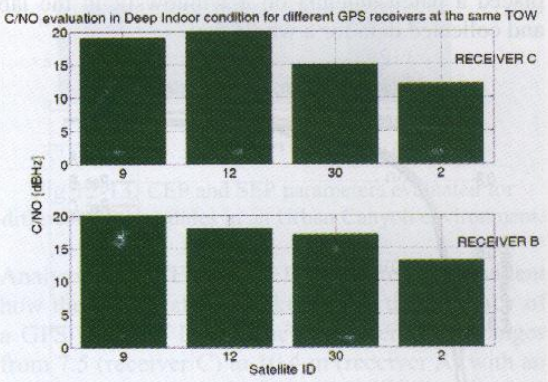


Fig.20: C/N_0 evaluated for each satellite in view at the same TOW by different mass-market receivers

Eventually Fig.21 depicts the averaged number of satellites used by RUTs to calculate position in the four scenarios that we have considered: open sky, urban canyon, light and deep indoor.

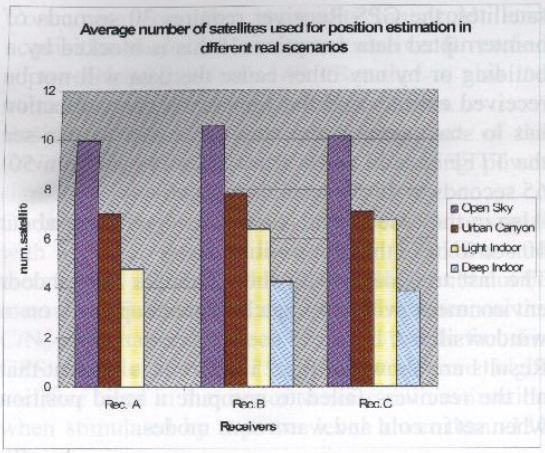


Fig.21: Averaged number of satellites used by RUTs for PVT computation in different real scenarios

As we can note all the RUTs performed position estimation in good visibility conditions, by using a mean number of satellites equal to 10. In urban canyon GPS receivers worked with 7 satellites in view. In more difficult circumstances such as an indoor environment RUT A was able to use for the PVT computation only 4 satellites and it failed in deep indoor location. On the contrary the other GPS modules, equipped to detect weak signals, performed position computation by using 6 and 4 satellites in light and deep indoor scenarios respectively.

IV. TTFF

Another investigated parameter under investigation has been the TTFF (Time To First Fix) that means "how long a GPS module takes for a position fix to be reported back to the user after a 'start' command is issued [3].

This metric varies as a function of initial conditions and information available in the receiver memory.

In fact, many GPS manufactures specify some TTFF conditions [5].

The most common are:

- **Cold Start**: the receiver must download almanac and ephemeris information to achieve a position fix. When a cold start is required, the receiver has to download a full set of Ephemeris data which is broadcasted and re-transmitted every 30 seconds ;
- **Warm Start:** the receiver has the almanac information stored in its memory, but it does not have any ephemeris information. It has also an approximate time and position knowledge;
- **Hot Start**: it occurs when a receiver has updated almanac and ephemeris information. In this scenario, the GPS modules only needs to obtain timing information from each satellite to return its position fix.

Hot, warm and cold start are also the parameters reported on the data-sheets of the RUTs A, B and C.

In particular receiver A and C declare that the published values have been obtained in condition of good visibility whereas the GPS module B does not specify any detail.

In order to have a comparison in terms of TTFF among these RUTs, we have measured through Sat-Surf the time they need to compute a position fix in different configurations and environmental conditions: open sky, urban canyon and light indoor. In fact, Sat-Surf as explained in Section I, is able to run the receiver in different acquisition modes (hot, warm and hot) and to measure the time to first fix.

The first test was performed simultaneously for all the receivers in open sky condition with several satellites in view.

Results have been achieved by averaging over 20 consecutive trials and compared with values reported on data-sheets for each of the RUTs as shown in Fig.22-23.

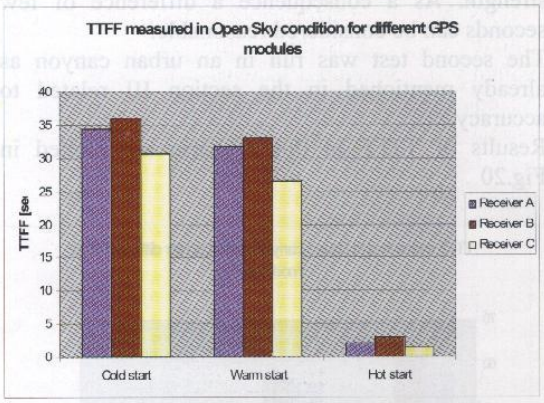


Fig. 22: TTFF measured in open sky

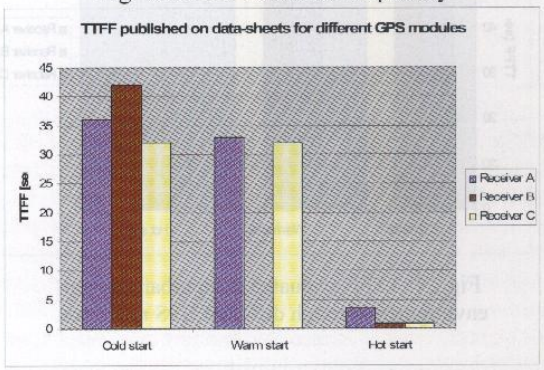


Fig. 22-23: TTFF as reported on data-sheet

Results show clearly that receiver C is the fastest to compute the first user's location in all the three acquisition modes as reported in Table III.

Estimated TTFF [sec] – Open Sky			
Receiver	Cold Start	Warm Start	Hot Start
A	34.4	31.8	2
B	36	33	3
C	30.6	26.5	1.5
TTFF [sec]- Data sheet			
A	36	33	3.5
B	42	-	1
C	32	32	1

Table III: Estimated TTFF in Open Sky vs Data-sheet

It is also in accordance with the values published on its data-sheet that indicates the device C as the quickest one to measure the position fix.
Furthermore the measured values differ for all the RUTs only by few seconds with respect to the nominal ones and this is reasonable if we take into account that in a real scenario TTFF is dependent on the number of satellites in view and the signal strength. As a consequence a difference of few seconds can be considered reasonable.
The second test was run in an urban canyon as already mentioned in the section III related to accuracy.
Results of TTFF in this scenario are plotted in Fig.20

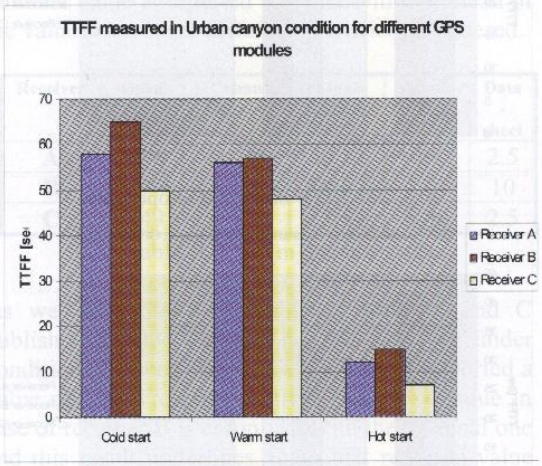


Fig.24: TTFF evaluated in an urban canyon environment through different GPS receivers.

As expected, the time to compute the first position increases with respect to the open sky case.
This happens because of a reduced visibility and as a consequence the GPS receiver has not been able to receive the full amount of data in the quickest time possible. To load the Ephemeris data from the satellites, the GPS Receiver requires 30 seconds of uninterrupted data reception. If this is blocked by a building or by any other cause the data will not be received entirely and the Ephemeris data collection has to start again at the next cycle. As we can see the TTFF in cold and warm modes ranges from 50-65 seconds to 48-56 seconds respectively.
Also in the case of hot start the receiver takes about 10 sec to have the first position fix.
The last trial deals with the case of a light indoor environment with the patch antenna placed on a windowsill.
Results are shown in Fig.25 where it is evident that all the receivers failed to compute a valid position when set in cold and warm start modes.

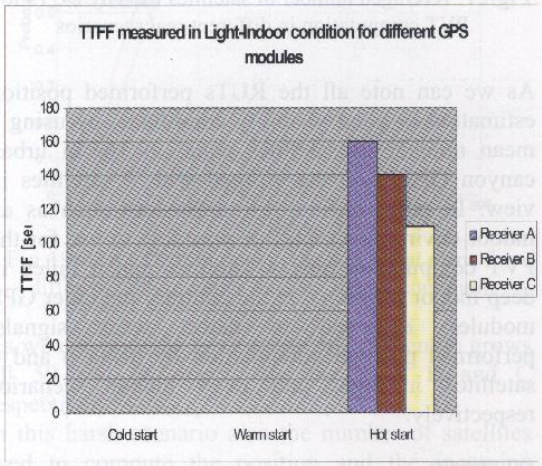


Fig.25: TTFF evaluated in a light indoor environment through different GPS receivers.

In fact, as already explained in Section III referring to accuracy, the unique way to achieve a position fix was through an outdoor start: the patch antenna is placed outdoor to allow the receiver to record ephemeris and almanac for each satellite in view. After that the antenna is moved into the room and the RUTs restarted in hot start mode.
It is worth to be highlighted that all the GPS modules take a long time (almost 2 minutes with a maximum of 2 minutes and 40 seconds for receiver A) to achieve a first position estimation. This is due to the fact that all the GPS modules take a lot of time before successfully acquiring and tracking at least three satellites in view in order to compute a valid position.

V. CONCLUSIONS

In this paper the RUTs have been analyzed under different environmental conditions and several parameters commonly reported on data-sheet have been verified and compared to each others.

Concerning on the sensitivity in cold start acquisition mode, we have noted receiver B reached a power level limit of -140 dBm that is also the value as reported on its technical document.
Besides it kept a low variance estimation of the C/N_0 also in the case of weak incoming power signal.
On the contrary receiver A failed to acquire signal with a power strength lower than -139 dBm and therefore its nominal value (-140 dBm) could not be measured. Furthermore a poor performance on the C/N_0 computation has been observed too. In fact this GPS module showed a very unstable and high-variance trend in the carrier to noise ratio estimation when stimulated by a power level lower than -134 dBm.
The tests related to the evaluation of the accuracy in different scenarios have given the following results: both receiver B and C have worked successfully also in a harsh environmental situation (deep indoor) whereas receiver A failed to measure a valid position in a similar condition.
In particular receiver C performed better than the other receivers in all the examined environments (i.e. open sky, urban canyon and indoor) in terms of precision in the PVT computation.
In this paper we have also verified that both the modules A and C have published on their data-sheets a value of CEP only related to the accuracy in good visibility condition whereas receiver B has reported a parameter that describes the performance in a more conservative way.
Eventually, analyses carried out to estimate the TTFF, revealed that receiver C is the quickest to have a position fix in all the surveyed environments and that all the GPS modules could not compute a valid measurement in indoor unless aided with an initial assistance.

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