GPS Solutions (2020) 24:19
https://doi.org/10.1007/s10291-019-0935-y

GPS TOOLBOX

# PANG-NAV: a tool for processing GNSS measurements in SPP, including RAIM functionality

**Antonio Angrisano[1] · Salvatore Gaglione[2] · Nicola Crocetto[3] · Mario Vultaggio[1]**

Received: 2 September 2019 / Accepted: 14 November 2019


## Abstract

Global Navigation Satellite Systems (GNSSs) are theoretically able to provide accurate, three-dimensional, and continuous positioning to an unlimited number of users. An important shortcoming of GNSS is the lack of integrity, defined as the ability of a system to provide timely warnings in case of malfunction; this problem is especially felt in safety-of-life applications such as aviation. A common way to fill this gap is the use of Receiver Autonomous Integrity Monitoring (RAIM) techniques, which are able to provide integrity information by analyzing redundant measurements. A possible RAIM functionality is the ability to identify, and so discard, anomalous measurements; this functionality has made RAIM very useful also in case of severe signal degradation, such as in urban or dense vegetation areas, where blunders are common. PANG-NAV is a tool, developed by the PArthenope Navigation Group, able to process GNSS measurements (from RINEX files) in order to obtain a position solution. The core of PANG-NAV is the single point positioning (SPP) technique, including a RAIM functionality. A multi-constellation solution, with GPS and Galileo, can be provided. Both static processing and kinematic processing are possible, and in cases where ground truth is available, error analysis can be carried out.

**Keywords** Receiver Autonomous Integrity Monitoring (RAIM) · GPS · Galileo · Multi-GNSS

## Introduction

Global Navigation Satellite Systems (GNSSs) can provide PVT (Position, Velocity, Time) to an unlimited number of users (Kaplan and Hegarty 2006; Hoffmann-Wellenhof et al. 2001). Unfortunately, GNSS does not deliver information about the integrity of the provided data, necessary for safety-of-life applications such as aviation. The integrity of a system is defined as a measure of the trust, which can be placed in the correctness of the information supplied by the total system and includes the ability to provide timely and valid warnings to the users (ICAO 2006). In order to provide integrity in the aviation context, three augmentation systems have been developed:

- ABAS (Aircraft-Based Augmentation System),
- SBAS (Satellite-Based Augmentation System) and
- GBAS (Ground-Based Augmentation System).

SBAS and GBAS need complex space and/or terrestrial infrastructures, while ABAS only uses information available onboard. Two ABAS implementations are possible:

- RAIM (Receiver Autonomous Integrity Monitoring) and
- AAIM (Aircraft Autonomous Integrity Monitoring).

RAIM is based only on GNSS measurements, while in AAIM, GNSS measurements are merged with other onboard

The GPS Tool Box is a column dedicated to highlighting algorithms and source code utilized by GPS engineers and scientists. If you have an interesting program or software package you would like to share with our readers, please pass it along; e-mail it to us at gpstoolbox@ngs.noaa.gov. To comment on any of the source code discussed here, or to download source code, visit our website at http://www.ngs.noaa.gov/gps-toolbox. This column is edited by Stephen Hilla, National Geodetic Survey, NOAA, Silver Spring, Maryland, and Mike Craymer, Geodetic Survey Division, Natural Resources Canada, Ottawa, Ontario, Canada.

✉ Antonio Angrisano
a.angrisano@unifortunato.eu

[1] University of Benevento Giustino Fortunato, Benevento, Italy

[2] University of Naples Parthenope, Naples, Italy

[3] University of Campania Luigi Vanvitelli, Naples, Italy

Published online: 26 November 2019

available sources, such as inertial sensors, altimeters, or clocks.

Basic RAIM techniques are able to detect the presence of anomalous measurements, which are often referred to in the literature as blunders or outliers. This configuration is referred to as RAIM-FD (RAIM-Fault Detection). Advanced RAIM techniques could also identify the outliers, in order to reject them, allowing a continuous positioning service; this configuration is referred to as RAIM-FDE (RAIM-Fault Detection and Exclusion).

Although RAIM has been developed to meet the stringent integrity requirements of civil aviation (Sturza 1988; Brown 1992; Walter and Enge 2004), it has been successfully adapted to work in signal-degraded areas, with the purpose of reducing the effects of the frequent blunders (Kuusniemi et al. 2004, 2007; Angrisano et al. 2013; Castaldo et al. 2014).

PANG-NAV is a tool, developed in the MATLAB environment, able to process GNSS measurements in order to obtain the position. If ground truth is available, PANG-NAV can also carry out an error analysis. PANG-NAV implements single point positioning mode, including a RAIM-FDE module, able to indicate the solution reliability, to identify and reject blunders, and to compute protection levels. The supported GNSSs are GPS and Galileo.

## Single point positioning

GNSS single point positioning (SPP) is based on trilateration, with satellites as anchor points. The distances between receiver and satellites are measured by one-way ranging technique, i.e., the time of propagation of signals transmitted by the satellites is measured at the receiver and is scaled by the speed of light (Kaplan and Hegarty 2006; Hoffmann-Wellenhof et al. 2001). The measured distance is affected by the asynchrony between the receiver and satellite clocks. Therefore, the measurement is called a pseudorange (PR). Further error sources influencing the PR are orbital errors, relativistic errors, atmospheric errors (specifically related to troposphere and ionosphere), multipath, and noise.

The pseudorange equation is

$$PR = \rho + b + \varepsilon \tag{1}$$

where $PR$ is the pseudorange measurement, $\rho$ is the geometric range between receiver and satellite, $b$ is the offset between receiver and system timescale, multiplied by the speed light, and $\varepsilon$ includes the residual errors after the application of suitable models (satellite clock, relativistic, atmospheric) and the errors not modeled in SPP (orbit error, multipath, noise).

Equation (1) is nonlinear for the unknowns, namely receiver coordinates and clock offset, and hence, after a linearization around a nominal state, a set of $m$ equations like (1) becomes

$$\underline{z} = H\underline{\Delta x} + \underline{\varepsilon} \tag{2}$$

where $\underline{z}$ is a vector containing the difference between actual and computed PRs, $H$ is the design matrix, $\underline{\varepsilon}$ is the vector of the residual or un-modeled errors, and $\underline{\Delta x}$ is the vector of the unknowns of the linearized observation equation.

The vector $\underline{\Delta x}$ should be summed to the nominal state to obtain the receiver coordinates and clock offset. In SPP, Eq. (2) is usually solved by a weighted least squares (WLS) estimator. A general scheme of SPP is shown in Fig. 1; although not mandatory in SPP, a RAIM-FDE block is also present. Further details on RAIM-FDE algorithms are in the following section.

## RAIM

RAIM techniques consist of checking the self-consistency of redundant measurements and are usually based on the analysis of residuals (Brown and Chin 1997), defined as the difference between actual and predicted measurements:

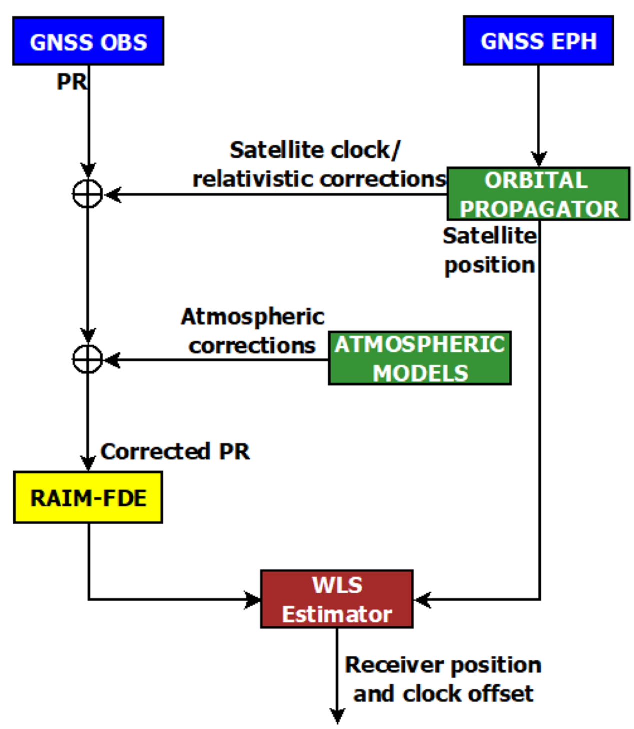



**Fig. 1** SPP scheme (adapted from Angrisano et al. 2013), showing the main steps of the algorithm, from the GNSS measurements and ephemerides, in input, to the estimation of the receiver position and clock offset (in output)

$$\underline{r} = \underline{z} - H\underline{\widehat{\Delta x}} \quad (3)$$

where $\underline{r}$ is the vector of the residuals, $\underline{z}$ and $H$ have been defined previously, and $\underline{\widehat{\Delta x}}$ is the vector of the unknowns, estimated by WLS.

The relationship between residuals and measurement errors is

$$\underline{r} = R\underline{\varepsilon} \quad (4)$$

where $R$ is the redundancy matrix, whose expression is $R = I - H\left(H^T H\right)^{-1} H^T$.

From (4), it is evident that the residuals are strictly related to measurement errors, but while $\underline{\varepsilon}$ is not known, $\underline{r}$ is simply computable by (3). In RAIM, the residuals are used to define a decision variable, which is compared with a threshold to check the presence of outliers among the measurements. The most common RAIM approach, in the GNSS literature, often referred to as a "global test" (Kuusniemi et al. 2004), adopts as a decision variable a quadratic form of the residuals

$$D = \frac{\underline{r}^T \underline{r}}{\sigma^2} = \frac{\left|\underline{r}\right|^2}{\sigma^2} \quad (5)$$

where $\sigma^2$ is the measurement error variance, assumed to be the same for all the measurements.

Assuming that the elements of $\underline{\varepsilon}$ have a normal distribution and are uncorrelated, the variable $D$ follows a Chi-squared distribution with $(m - n)$ degrees of freedom (DOF), where $m$ is the number of measurements and $n$ the number of unknowns. In the case of the absence of blunders, $D$ has a central Chi-squared distribution. Otherwise, it has a noncentral Chi-squared distribution with noncentral parameter $\lambda$. Defining $P_{FA}$ as the probability of false alarm, the threshold $T$ is the abscissa value corresponding to a probability value $\left(1 - P_{FA}\right)$ of a central Chi-squared distribution of $(m - n)$ order. (In Fig. 2, an example with DOF = 3 is shown.) The probability of false alarm is a RAIM parameter, fixed according to the considered application.

If D exceeds T, the presence of an anomalous measurement is supposed, and, in case of FD algorithm, an alarm is raised. On the other hand, FDE algorithms try to identify the anomalous measurements in order to reject them. A common FDE scheme is the "observation subset testing" (Kuusniemi et al. 2007; Angrisano et al. 2013), which iteratively applies the global test to all the possible combinations of the available measurements up to identifying a blunder-free subset if it exists.

RAIM techniques are finally able to provide the protection levels (PLs), which define a region of the space containing the true position of the receiver with a fixed probability; the determination of the PLs requires the computation of minimum detectable bias (MDB) and maximum slope, which will be introduced below.

The noncentral parameter $\lambda$ is related to the magnitude of the blunders: the larger the blunders, the larger the value of $\lambda$. With a fixed threshold $T$ (depending on DOF and $P_{\mathrm{FA}}$) and the probability of missed detection $P_{MD}$, the particular $\lambda$, for which the area below the noncentral Chi-squared between 0 and $T$ is equal to $P_{\mathrm{MD}}$, is called $\lambda_{\mathrm{MDB}}$. $\lambda_{\mathrm{MDB}}$ is the minimum detectable bias, homogeneous to $D$; blunders yielding $\lambda > \lambda_{\mathrm{MDB}}$ have a low probability of being undetected, while blunders yielding $\lambda < \lambda_{\mathrm{MDB}}$ have high probability of being not revealed. Blunders corresponding to a noncentral parameter exactly equal to $\lambda_{\mathrm{MDB}}$ are detectable with probability $\left(1 - P_{\mathrm{MD}}\right)$. In Fig. 3, an example with DOF = 3 and $\lambda = \lambda_{\mathrm{MDB}}$ is shown.

The MDB homogenous to $\left|\underline{r}\right|^2$ is simply $\sigma^2 \lambda_{\mathrm{MDB}}$, while the MDB homogenous to $\left|\underline{r}\right|$ is $\sigma\sqrt{\lambda_{\mathrm{MDB}}}$ and in the literature is often referred to as pbias.

To obtain the PLs, the pbias, which has the same units as the measurements, must be projected on the position domain. The "slope" parameter is the ratio between the position error (horizontal or vertical) and the magnitude of the vector of the residuals $\left|\underline{r}\right|$, assuming that a single measurement is affected by a bias and in the absence of stochastic perturbations (Brown and Chin 1997). The slopes associated with the $i$th measurement are

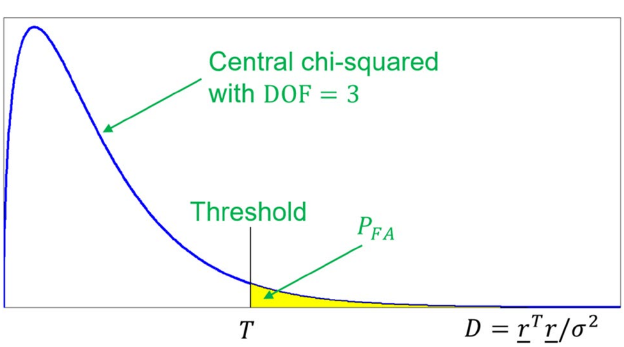



**Fig. 2** Central Chi-squared probability density function and the probability of false alarm

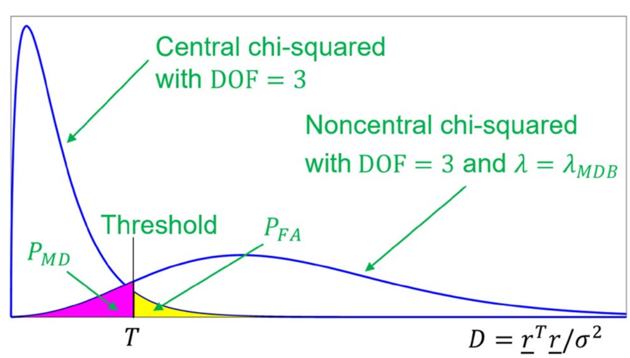



**Fig. 3** Noncentral Chi-squared probability density function with noncentral parameter $\lambda$ equal to the minimum detectable bias $\lambda_{\mathrm{MDB}}$

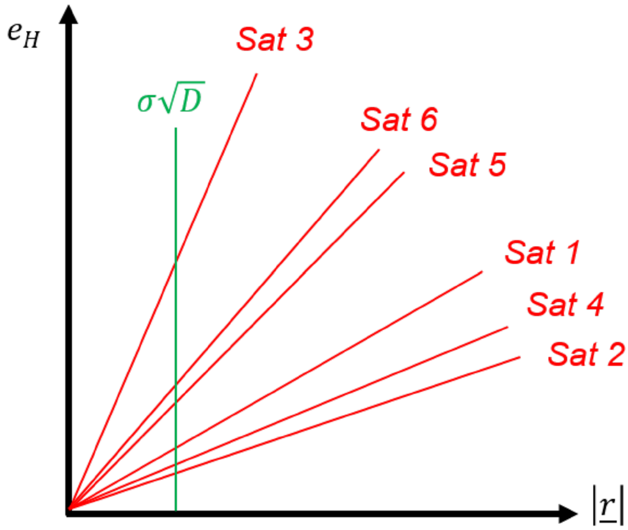



**Fig. 4** Representation of "slope" parameters in the $(e_H, |\underline{r}|)$-plane. In the example, the available satellites are six; the maximum horizontal slope is related to "Sat 3", and the corresponding measurement is the most "dangerous"

$$\begin{aligned} \text{slope}_H(i) &= \frac{\sqrt{[A(1,i)]^2 + [A(2,i)]^2}}{\sqrt{S(i,i)}} \\ \text{slope}_V(i) &= \frac{A(3,i)}{\sqrt{S(i,i)}} \end{aligned} \tag{6}$$

where $\text{slope}_H$ and $\text{slope}_V$ are, respectively, referred to horizontal and vertical errors, the matrix $A$ is defined as $A = \left(H^T H\right)^{-1} H^T$, and the matrix $S$ is defined as $S = I_\text{m} - \text{HA}$, where $I_\text{m}$ is a $m \times m$ identity matrix.

In Fig. 4, an example of horizontal slopes in case of six available satellites and horizontal error ($e_H$) is shown. It is evident that the measurement with the largest slope (in the example, the one corresponding to the satellite 3) is the most "dangerous" because a defined value of the decision variable corresponds to the largest error. So the horizontal and the vertical protection levels (HPL and VPL) are defined as the product between, respectively, the largest $\text{slope}_H$ and $\text{slope}_V$ and the pbias:

$$\begin{aligned} \text{HPL} &= \max\left(\text{slope}_H\right) * \text{pbias} \\ \text{VPL} &= \max\left(\text{slope}_V\right) * \text{pbias} \end{aligned} \tag{7}$$

HPL and VPL are compared with suitable threshold values, respectively, the HAL (Horizontal Alarm Limit) and the VAL (Vertical Alarm Limit), related to the considered application; in case HPL > HAL (or VPL > VAL), the RAIM is considered not available and consequently the position is not reliable.

In Fig. 5, a general RAIM scheme is shown. The inputs to RAIM block include measurements, the design matrix,

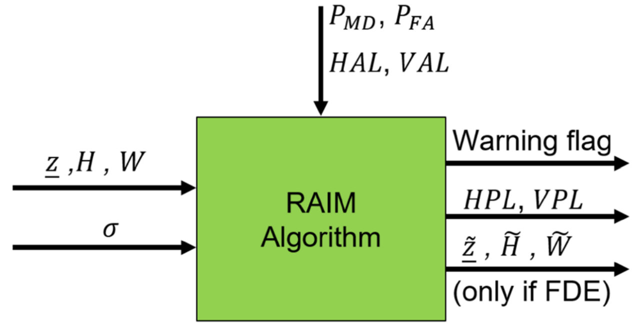



**Fig. 5** Scheme of a generic RAIM algorithm. The measurements, the design matrix, the weight matrix, and the measurement error precision are the input. The probabilities of false alarm and missed detection and the horizontal and vertical alarm limits are the settings. In the output, the warning flag, the protection levels, and the non-rejected measurements (in case of FDE functionality) are provided

weight matrix, and measurement error precision; moreover, settings $P_\text{MD}$, $P_\text{FA}$, HAL, and VAL must be defined. In output, a RAIM algorithm should be able to provide a "warning flag" indicating if the solution is reliable, the protection levels and, in case of FDE algorithm, the measurements (and the corresponding design and weight matrix) with the exclusion of the anomalous ones.

## PANG-NAV tool

The PANG-NAV tool is a software package for processing single-frequency GNSS measurements, developed by the PANG (PArthenope Navigation Group) (http://pang.uniparthenope.it).

The MATLAB software, sample data sets, and user manual are available on the GPS Toolbox website at: https://www.ngs.noaa.gov/gps-toolbox.

The inputs of the tool are observation and navigation RINEX files, version 3.00 or higher. PANG-NAV implements the single point positioning technique with RAIM-FDE, described in previous sections. To reduce the tropospheric and ionospheric effects, Saastamoinen and Klobuchar models are, respectively, implemented. A common weighting scheme, with measurements weighted as the squared sine of the satellite elevation, is available. The "observation subset testing" RAIM algorithm is implemented.

The PANG-NAV tool basically provides the estimated receiver position and clock bias, satellite visibility, and geometry information. If RAIM is active, the warning flag, the number of rejected measurements, and the PLs are provided too. In case a ground truth is available, an error analysis is carried out.

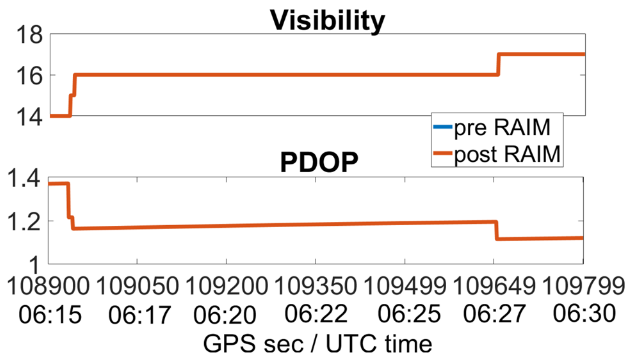



**Fig. 6** Satellite visibility and PDOP of satellites before (blue) and after (red) RAIM application. The processed dataset does not contain blunders (Thus, the red lines overwrite the blue lines exactly.)

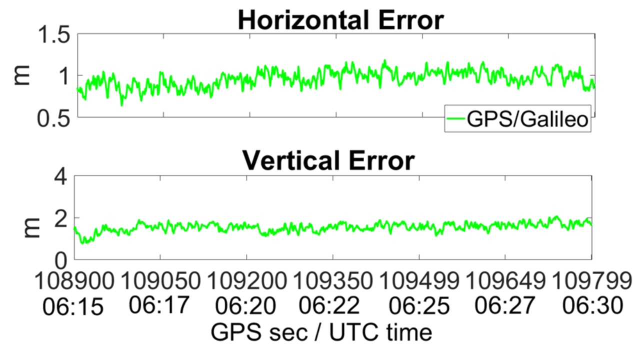



**Fig. 8** Horizontal error (top) and vertical error (bottom) in meters. The errors are obtained comparing the SPP solution with the ground truth. The processed dataset does not contain blunders

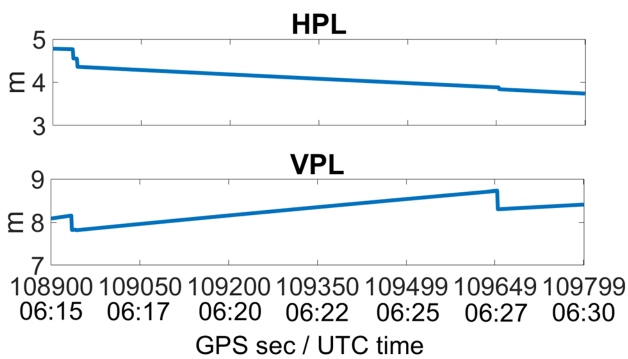



**Fig. 7** Horizontal protection level (top) and vertical protection level (bottom). The processed dataset does not contain blunders

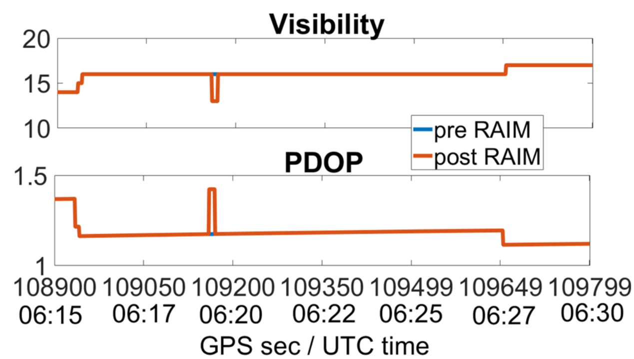



**Fig. 9** Satellite visibility (top) and PDOP (bottom), before (blue) and after (red) RAIM application. The processed dataset contains simulated blunders

## Test and results

The PANG-NAV tool has been used to process the measurements stored by the permanent station BRUX00BEL, belonging to the EUREF Permanent GNSS Network. The station is equipped with a Septentrio PolaRx4TR receiver and a Javad choke ring antenna, and it is able to provide GPS, GLONASS, Galileo, and BeiDou measurements at L1 and L2 frequencies. The stored dataset has a duration of about 30 min at a data-rate of 1 Hz.

In Fig. 6, the number of visible satellites and the PDOP values (for GPS and GLONASS) are plotted with respect to time. RAIM is active, but no blunders have been detected, so the number of satellites before and after RAIM application is the same; the same concept is valid for PDOP. In Fig. 7, the horizontal and vertical protection levels are shown, while in Fig. 8, the error behaviors are plotted.

To test the tool in case of anomalous measurements, in the same dataset, a series of blunders have been added to the pseudoranges. In detail, three errors of about 100, 50, and 40 meters are added on GPS satellites G18 and G31 and on Galileo E08, respectively, between the epochs 06:19:20 and 06:19:29. In Fig. 9, the visibility and PDOP behaviors are shown, and it is evident that the number of satellites used for the solution computation ("post-RAIM") is different from the number of visible satellites ("pre-RAIM"), because RAIM rejects the blunders. After RAIM application, also PDOP (Fig. 9) and PLs (Fig. 10) increase, owing to measurement discard.

## Conclusions

PANG-NAV is a tool, developed in the MATLAB environment, for processing single-frequency GNSS measurements in single point positioning mode, including RAIM-FDE functionality. PANG-NAV starts from RINEX files and provides receiver coordinates and clock offset. Moreover,

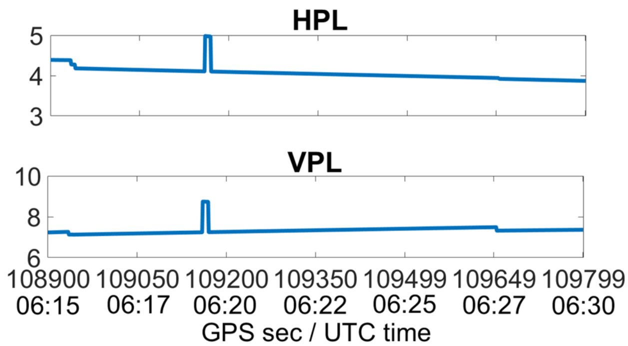



**Fig. 10** Horizontal protection level (top) and vertical protection level (bottom). The processed dataset contains simulated blunders

visibility and DOP behaviors are provided too. Owing to the RAIM block, the anomalous measurements are identified and rejected, and the protection levels are computed. In cases where a ground truth solution is available, an error analysis is carried out.

## References

Angrisano A, Gioia C, Gaglione S, Del Core G (2013) GNSS reliability testing in signal-degraded scenario. Int J Navig Obs. Vol. 2013, Article ID 870365, 12 pages, 2013 https://doi.org/10.1155/2013/870365

Brown R (1992) Receiver autonomous integrity monitoring. In Global Positioning System: Theory and Applications Volume II, Parkinson, B. W. and Spilker, J. J. Jr. (Eds), AIAA, 143–165

Brown RG, Chin GY (1997) GPS RAIM Calculation of Threshold and Protection Radius Using Chi Square Methods - A Geometric Approach. Global Positioning System: Inst. Navigat., vol. V, pp. 155–179

Castaldo G, Angrisano A, Gaglione S, Troisi S (2014) P-RANSAC: an integrity monitoring approach for GNSS signal degraded scenario. Int J Navig Obs. Vol. 2014, Article ID 173818, 11 pages, 2014 https://doi.org/10.1155/2014/173818

Hoffmann-Wellenhof B, Lichtenegger H, Collins J (2001) Global Positioning System: Theory and Practice. Springer, Berlin Heidelberg New York

ICAO (2006) Annex 10, Vol. I Radionavigation Aids. July 2006

Kaplan ED, Hegarty J (2006) Understanding GPS: principles and applications, 2nd edn. Artech House, Norwood

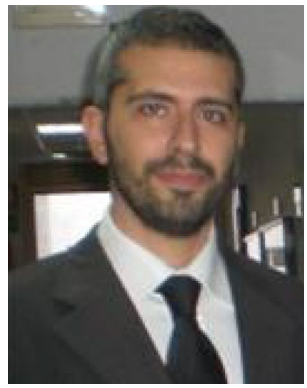
Kuusniemi H, Lachapelle G, Takala J (2004) Position and velocity reliability testing in degraded GPS signal environments. GPS Solut 8(4):226–237. https://doi.org/10.1007/s10291-004-0113-7

Kuusniemi H, Wieser A, Lachapelle G, Takala J (2007) User-level reliability monitoring in urban personal satellite-navigation. IEEE Trans Aerosp Electron Syst 43(4):1305–1318. https://doi.org/10.1109/TAES.2007.4441741

Sturza M (1988) Navigation system integrity monitoring using redundant measurements. Navigation 35(4):483–501. https://doi.org/10.1002/j.2161-4296.1988.tb00975.x

Walter T, Enge P (2004) Weighted RAIM for precision approach. In: Proceedings GPS 1995. Institute of Navigation, Palm Springs, Sep 12–15, 1995, pp 1995–2004

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Antonio Angrisano** is an Assistant Professor at G. Fortunato University since 2015. He obtained the M.Sc degree (Cum Laude) in Science of Navigation and the Ph.D. in "Geodetic and Topographic Sciences" at the University of Naples "Parthenope"; in 2010, he joined the PLAN (Position Location and Navigation) Group at the University of Calgary. His research interests include GNSS and Augmentation Systems, Inertial and Integrated Navigation, RAIM, and Integrity.

**Salvatore Gaglione** is an Associate Professor at University of Naples "Parthenope" and scientific director of the PArthenope Navigation Group (PANG) Laboratory. In 2010, he was a Visiting Academic at "Department of Geomatics Engineering" at the University of Calgary. His research activities are focused on GNSS positioning and other sensors (INS, Camera, etc.) integration algorithm for several applications. Professor Gaglione is a member and delegate for Europe of the "Istituto Italiano di Navigation".

**Nicola Crocetto** is a Full Professor at the Engineering Department of the "Luigi Vanvitelli" University of Campania since 2009. His teaching activity covers topography, remote sensing, numerical cartography, and territorial information systems. His main research themes are the statistical treatment of observations, compensation of planimetric and/or altimetric networks, numerical stability of algorithms of topographical interest, three-dimensional geodetic networks, reference systems in Geodesy, GPS satellite technique, advanced remote sensing techniques, and quantitative information extraction from remote sensing images.


**Mario Vultaggio** is Professor of Navigation at G. Fortunato University; up to 2014, he was a Full Professor at Parthenope University of Naples. His field of research was in oceanographic surveying between 1972 and 1979. Since 1979, his research interests are in navigation, cartography, VTS (Vessel Traffic Services), and space and astronomical navigation. He was director of Institute of Navigation "G. Simeon" and President of Nautical Science course of study at Parthenope University.