Network Real Time Kinematic (NRTK) Positioning – Description, Architectures and Performances

Chapter 2

Network Real Time Kinematic (NRTK) Positioning – Description, Architectures and Performances

Alberto Cina, Paolo Dabove,
Ambrogio M. Manzino and Marco Piras

Additional information is available at the end of the chapter

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1. Introduction

As well known, GNSS positioning can be realized adopting two different approaches: using post-processing techniques or adopting real time methods [17]. Post-processing techniques are usually focused when a high level of accuracy is required or when it is not possible to estimate and to apply a model of bias in real time. In the other hand, real time approach is instead traditionally considered when we desire to obtain a better quality, in terms of accuracy, of our positioning, with respect the stand-alone position (i.e. with WAAS correction) or with a centimetric level of accuracy (using RTK correction).

The differential positioning in real time eliminates the bias common to two GNSS receivers and get to centimeter accuracy with fixed phase ambiguity. The correction is calculated from a single base station but it is however a punctual value: it loses its validity as the distance-based rover effect of spatial decorrelation, which leads to variations in the bias spatially correlated (mainly ionospheric and tropospheric delay). Even, when it exceeds distances of about 20-30 kms with variation of the bias of the order of magnitude of a half wavelength, it can be difficult to get to the correct fixing the phase ambiguity.

In this chapter, the theoretical part of differential positioning will be described, in particular the use of network of CORS (Continuously Operating Reference Station) for real time application, so called NRTK. This aspect is particularly interesting for several points of view, both for future purposes and for open problems.

The use of NRTK allows to involve single frequency receiver or mass market receiver for real time or static positioning, even with a centimetrical level of accuracy, by means the products generated by the network, as described in §5. In particular, it is quite interesting the time required to fix the ambiguity solution, that is very short (< 15-20 s)

Some products of network, as ionospeheric and tropospheric model, can be stored in the control centre or broadcasted in real time, with purpose to use these models for improving the quality of positioning into pseudorange receiver only. Another possible application could be the use of the tropospheric model for meteorological forecasting, but it is depends on the extension on the network.

The performance of a NRTK infrastructure can be improved realizing a correct design of network, in term of CORSs inter-distances and geometrical distribution. Considering the quality of the GNSS products used in a NRTK as precise ephemerids and the quality of algorithms devoted to estimate the phase ambiguity, inter-distances can be extended up to 70-80 kms.

The future progress and benefits due to the improvement of NRTK should be very significant, but there are still some open problem, which are studied form the GNSS scientific communities, in order to solve them. The main aspects are the real time quality control of the positioning, in order to avoid false phase ambiguity fixed and the integrity of the solution, especially required for the new constellations (i.e. GALILEO) or for aviation applications. It would be quite important to have in the receiver a dedicated tool for detecting or forecasting the false estimation of the ambiguity, in order to avoid a wrong positioning. This aspect is surely the most critical, in fact in RTK positioning, the coordinates are usually stored in real time with a centimetrical level of accuracy, without acquiring the raw data for the post-processing or some applications require to have in real time this accuracy (i.e. stake out for civil engineering).

Nowadays, the real time positioning (RTK or NRTK) is adopted in several applications, because it allows to be rapid, precise and economic, but the users have to always consider the most critical aspect: the GSM coverage. In fact, the map of GSM coverage is not always available and not always is updated, then in some area this technique is not allowed, forcing the users to adopt or the static approach or to use the radio-modem device for broadcasting the differential correction, but only using a single station.

This is only an overview about the NRTK applications and open problems; in the following, theoretical parts, performances, benefits and limits of the NRTK will be described, considering some real cases and tests.

The positioning with augmentation system as WAAS (Wide Area Augmentation System), GBAS (Ground Based Augmentation system) or SBAS (Satellite Based Augmentation System) are not considered here because they not allow to obtain a centimetric level of accuracy, which is the focus of this part.

2. Network RTK description

The differential corrections which are generated by each GNSS permanent station are valid only in a limit area around the single site, considering a limited space: the main hypothesis is

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that if the bias remain almost the same in the base station and rover they can be eliminated by a differential or relative process.

This hypothesis would lead to install of a large number of permanent stations and an improvise shutdown of one of them would lead to have a "RTK data missing" over an area of hundreds km^2. In order to ensure the reliability conditions of the system should then assume a cautionary overlap between the ranges of the stations, further reducing the spacing between them, with great effort of installation and management of the entire infrastructure.

In order to avoid a huge number of single CORS, since some years has risen the idea to connecting the single CORS into a network, with purpose to obtain an estimation of the spatially correlated bias and their pattern of change over the whole area, starting from the single values which are calculated in the single CORS [10].

The bias in the position of the rover can be derived by interpolation of this model. This is equivalent to the creation of a "virtual base station" that has virtually the same as the rover bias ant the corrections are calculated next to its approximate coordinates. The differential or relative positioning, between the base and rover receiver then leads to a baseline length of almost anything, and the elimination of bias spatially correlated.

The virtual station can also be generated in the form of a data file for post processing. By using the RINEX data format, then we'll talk Virtual RINEX or VRINEX. In this way the spacing between the permanent stations can be reduced by a factor that varies from 1.5 to 3, reducing the number from 25% to 70% [18].

With this approach it is possible to achieve centimeter accuracy with base-rover distances of 40-80 km and also achieve the same performance as you would with an RTK solution from a single station located at about twenty kilometers. We call these networks aimed at GNSS positioning service in real time "Network RTK" or NRTK but they can also be useful in the case of post-processing.

A network of permanent stations for real-time positioning is an infrastructure consisting of three parts: one part consists of all CORSs (more or less extended), with accurately known position, that transmit their data to a control center in real-time. The second part consists of a control center which receives and processes the data of the stations in real-time, ambiguity fixing phase for all satellites of each permanent station and calculating ionospheric and tropospheric delays, clock biases etc. As described in previous sections, the third part is the set of network products that can be provided from the control center to the user. The less elaborate product is the raw measurement file of each permanent station that the user may require for post processing purposes [11].

The NRTK system is based on:

- physical infrastructure, consisting of the permanent stations and hardware of the control center;
- transmission infrastructure capable of transmitting real-time data flow from the stations to the control center and from this to the user according to own protocols or standard one;

- computing infrastructure, consisting of a software that can improve the estimation of the bias and make them accessible to users spread over the territory.

As far as the physical infrastructure has already been said of the characteristics of GNSS permanent stations in next part. Of course, the mesh network must be designed according to the ability to model the bias with sufficient precision to fixing the phase ambiguity and depends on various factors, including the geographical location and the level of ionospheric activity [26].

We treat now the means and modes of transmission of data, corrections used in various network architectures NRTK.

3. Generation of NRTK differential corrections

We have said that the use of a single station limits the reliability of fixing the phase ambiguity N, with increasing distance of the rover. The solution of using a network of permanent stations synchronized between their, mitigates the dependence of the RTK solution [21]. What is the nature and content of the differential corrections from a network RTK compared to those from single base station?

In the traditional RTK positioning where a single CORS is adopted, the pseudorange correction (PRC) and carrier phase correction (CPC) contain the bias of the clocks of the base station (δ_A); the corrections CPC also contain the phase ambiguity between base stations and satellites (N_A^J).

In NRTK corrections, the common level of phase ambiguity of the network and the common clock bias are considered as known; then it is allowed to move them to the left side (Eq. 1). In order to answer to this question, the general equations of network differential corrections (PRC and CPC) are considered [4]:

$$\begin{aligned} PRC^j(t) &= \rho_A^j(t) - R_A^j(t) - c\delta^j(t) - c\delta_A(t) = I_A^j(t) - T_A^j(t) - E_A^j(t) \\ CPC(t) &= \rho_A^j(t) - \lambda\phi_A^j(t) - \lambda N_A^j - c\delta^j(t) - c\delta_A(t) = -I_A^j(t) - T_A^j(t) - E_A^j(t) \end{aligned} \quad (1)$$

where:

$\rho_A^j(t)=\sqrt{(X_A-X^J)^2+(Y_A-Y^J)^2+(Z_A-Z^J)^2}$=geometrical range calculated with the known coordinates of the base and the rover;

$\lambda\phi_A^j(t)$=carrier phase data multiplied by wavelength;

λN=phase ambiguity multiplied by wavelength, fixed be the control centre;

$c\delta^j(t)$=satellite clock error;

$c\delta_A(t)$=receiver clock error, estimated for all CORSs by the control centre;

$I_A^j(t)$=ionospheric error;

$T_A^j(t)$=tropospheric error;

$E_A^j(t)$=ephemerids error;

It is therefore necessary that the network software first of all arrivals to estimate the ambiguities and errors entire clock on each station in order to bring the differential corrections to the same level of ambiguity and timing [19].

The fundamental function of the network software is going to make a separation of bias in estimating the tropospheric and ionospheric delays to create a model of change to interpolate the position of the rover receiver.

The rover receiver must therefore determine its clock error and phase ambiguity and not the combined value between master-rover. Corrections can then be derived from the previous equations given the known values of bias clock and phase ambiguity, as for pseudorange:

$$R_B^j(t)_{correct} = R_B^j(t) + PRC(t) = \rho_B^j(t) - c\delta_{AB}(t) + \Delta E_{AB}^j(t) - \Delta I_{AB}^j(t) + \Delta T_{AB}^j(t) \tag{2}$$

and carrier-phase

$$\lambda\phi_B^j(t)_{correct} = \rho_B^j(t) + CPC(t) = \rho_B^j(t) - c\delta_{AB}(t) - \lambda N_{AB}^j + \Delta I_{AB}^j(t) + \Delta T_{AB}^j(t) + \Delta E_{AB}^j(t) \tag{3}$$

"Manipulating" as the observations does not change the carrier phase measurement and bias of the ionosphere and troposphere are changed as the integer only. The rover uses such observations with the same level of ambiguity and error and clock corrections will contain only the bias spatially correlated bias and no longer dependent on a single station or different levels of ambiguity.

Isolated bias from all effects dependent on the measurement site, they should be separated into their component dispersive (ionosphere) and non-dispersive (troposphere and ephemeris). Having different nature and in fact the law of change, they should be modeled separately.

Among the main bias is possible, as we shall see, separate the ionospheric error from the orbit and tropospheric error in different ways. These last two are estimated together as a single error of geometric nature. If you are using IGS precise ephemeris produced that have accuracies of a few centimeters, the result is practically the only tropospheric delay [15].

The calculation of the network by the control center must be done in real time, to provide the user with a differential correction at any time. The computational approaches are different and related to various companies that produce such software. They can be based on raw observations or their differences and can exploit or less combinations of observations [30].

4. NRTK architectures

One of the principal aim of a Network of GNSS CORSs is the maintenance of the reference system (so called DATUM). IGS (International GNSS Service) and EUREF (European Reference) networks are two example of CORSs network, which are used to define the DATUM and to offer the GNSS products to GNSS community. They play a strategically role to define the fundamental realization, in particular these reference system are adopted to define each national geodetic networks around the world (Fig. 1) [9], [12].

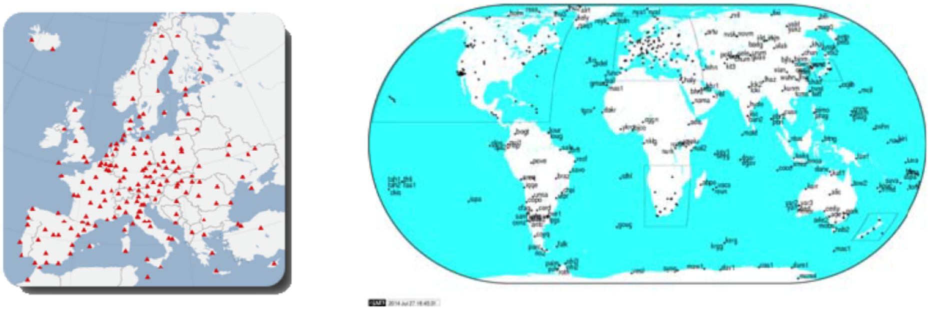

Figure 1. EUREF *(left)* and IGS *(right)* networks

The distance between the CORSs of these networks, however, is rather large (100 or more kilometers) and the data are often issued with a rate of 30 s. This is useful for high-precision geodetic and very long periods of time (weeks, months or years of data), but less for topographic applications. A station that materializes the reference system could not provide real-time data because it is not a primary purpose.

The GNSS permanent stations can be considered as "active" vertices, because they are in continuous measurement and the networks NRTK are periodically calculated. This aspect changes how the surveyor considers the reference system today. In a network RTK the reference system is transmitted implicitly through a stream of data, normally according to the protocol RTCM [11], [24], which contains information on the coordinates of the stations and on the corrections in the reference system in which the network is framed. Consequently, the user with the rover receiver is framed in real-time in the reference frame of the network that is supported. In real-time measurements the user has even the perception of detecting in a direct "triplets" of coordinates.

The accuracy is, however, only one of the possible improvements of the positioning. In many applications, it is especially important to the "integrity", that is the definition of a confidence level position error with alarm in case of anomalies [22].

The kinematic positioning by NRTK network is increasingly popular and to make it operational and usable by professional users have been developed various network architectures.

They are summarized at least the following types:

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- Virtual Reference Station (VRS);
- Multi-Reference Station (MRS);
- Master Auxiliary (MAC or MAX).

In the following part, positioning methods from network NRTK and augmentation systems will be described from the point of view of the control center that manages the network or service and the rover receiver.

5. Virtual Reference Station (VRS)

In the VRS approaches, pseudorange and carrier phase observations which comes from at least three stations are continuously collected and processed by a control center. Once achieved and maintained over time, a network solution for fixed ambiguity, begins the phase of modeling bias [2].

At this point the control center is able to interpolate these values in a specific location and can generate a set of observations and corrections GNSS calculated as if they were acquired by a hypothetical receiver station in place in that position, obtaining what you would in a "virtual station". If it is generated in the position of the rover carries with it a baseline length of almost nothing, resulting in elimination of bias spatially correlated.

To determine where to place the virtual station, the communication must be bi-directional in that the rover must make its position known to the control center that carries out the calculation, sending your location via the NMEA protocol. This position can be "improved" with the reception of the first differential corrections and re-sent back to the control center. When the position of the virtual station has been defined, the differential corrections are continuously transmitted using the RTCM protocol or, in some case, own format Figure 2.

From the rover point of view, RTK positioning starts with the research of ambiguity, which is easily fixed because the initial baseline is practically equal to zero.

On the other hand, considering the control center point of view, the continuous monitoring of the distance between the rover and the virtual station is realized: if it exceeds a defined threshold (typically a couple of kms), a new virtual station has to be determined close to the new position of the rover.

These approach has advantages and disadvantages, which are described in the following [27]:

- it requires a dual-way communication system, as GSM or Internet, because it is necessary to guarantee the data broadcasting from Control Center to rover and vice versa. Radio-modem is not allowed;
- the number of simultaneous access is depending on the performance of the server, where the network realizes the computation of the VRS correction. In fact, for each user, a new VRS is estimated and transmitted, then more increase the number of user at the same time, more the computational load increasing;

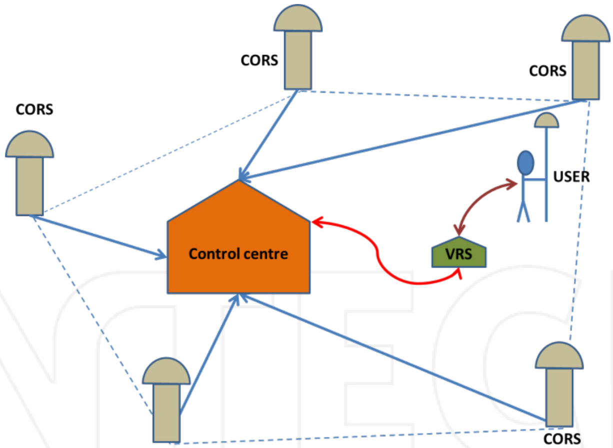

Figure 2. Schema of the Virtual Reference Station correction

- when a VRS is newly estimated and repositioned, the rover has to repeat again the initialization, in order to fix the new phase ambiguity values;
- the protocol RTCM 3.x is able to support the VRS correction, but also RTMC 2.x (messages *type* 18&19 or 20&21) can be used, even old receiver can works this type of correction. In this way, single frequency receiver or mass market solution can also take benefits from a NRTK, using the VRS product, only broadcasting their approximate solution by NMEA messages.

In order to reduce the computational load into control centre, it is possible also to adopting an alternative approach, where the differential correction broadcasting from a VRS are adopted to one or more user, if they are working into a common range, which is defined by the control centre manager and it is usually fixed as 10-15 km [29].

Moreover, it is also possible to use the direct differential corrections estimated by the "real" CORSs which belong to the network, if the distance master-rover is below to 30 kms. This approach is so-called *Nearest Differential Correction*, because the nearest CORS is used as master.

These two alternative method allow to reduce the computational load in the control centre, but the performance of the positioning, in terms of accuracy, precision and time to fix, are partially compromised, because the differential corrections are not optimized for the single user but they are locally estimated.

6. Multi Reference Station (MRS)

MRS approach is based on an interpolative model of differential correction, which is estimated starting from all available raw data from the single CORS and each satellite [13], [14], [23].

In this case, corrections are broadcasted as a local model, where close to each permanent station, a polynomial function as a linear plane is created. The slope of this plane represents the change in the bias area covered by the network (Fig. 3). The coefficients of the polynomial are called "parameters of area" and are transmitted in their dispersive (ionospheric bias) and non-dispersive (ephemerids and tropospheric bias) component by means the FKP format (Wubbena, 2002).

Considering the rover approximate coordinates (φ, λ), the FKP model can be described as:

$$\begin{aligned} \text{Not dispersive term:} \quad & \delta r_0 = 6.37\left(N_0\left(\varphi - \varphi_R\right) + E_0\left(\lambda - \lambda_R\right)\cos\varphi_R\right) \\ \text{Dispersive term:} \quad & \delta r_I = 6.37H\left(N_I\left(\varphi - \varphi_R\right) + E_I\left(\lambda - \lambda_R\right)\cos\varphi_R\right) \\ & H = 1 + 16\left(0.53 - \frac{E}{\pi}\right)^3 \end{aligned} \tag{4}$$

where:

N_0: FKP parameter N-S direction, ionospheric delay [ppm]

E_0: FKP parameter E-O direction, ionospheric delay [ppm]

N_I : FKP parameter N-S direction, tropospehric delay

E_I: FKP parameter E-O direction, tropospheric delay

E : satellite elevation [°]

The corrections on L_1 and L_2 are:

$$\delta r_1 = \delta r_0 + \frac{120}{154}\delta r_I \qquad \delta r_2 = \delta r_0 + \frac{154}{120}\delta r_I \tag{5}$$

and the correct range is:

$R_{correct} = R - \delta r_i (i = 1 \div 2)$

As above mentioned, FKP is not a standard like RTCM but it is a "de facto standard", therefore it is adopted by the most popular software devoted to generate NRTK products and in geodetic receivers. In the RTCM is not available a message for FKP model, but it is transmitted in type 59, which is a not fixed message. In order to use the FKP model, it is necessary that the rover has a decoder firmware or eventually (for old receiver) hardware devices, to decrypting the model and use the correction in the dispersive and non-dispersive component.

The estimation of the corrections values in the rover positions is realized by the rover itself, therefore the computational load is independent of the number of connected users.

Although this architecture network MRS has its advantages and disadvantages, which can be summarized as:

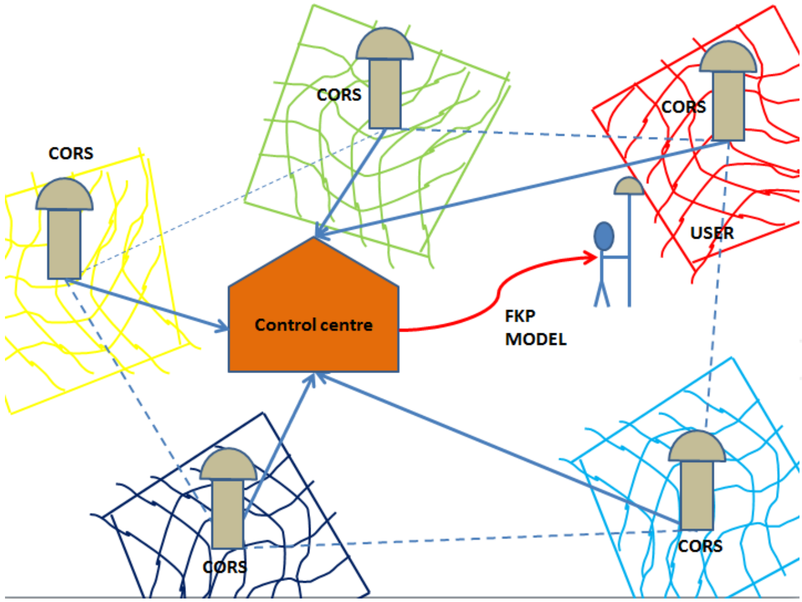

Figure 3. Schema of the Multi Reference Station correction

- does not require the position of the rover and the transmission medium can also be one way: the calculation of the correction is done by the firmware of the same rover receiver from its position and the parameters of the message FKP;
- there are no limits to the number of accesses, in theory, using the IP transmission over the Internet since the calculation of the parameters is only one valid in a large neighborhood of the station;
- requires a data format suitable to contain the parameters area network: the solution is to send them as in FKP format RTCM Type 59 message. Not all receivers in single frequency or older are able to use this format.
- It is the user to decide which network station to receive RTCM messages and FKP. Alternatively, the rover can send its position to the control center which shall send the correction by choosing the nearest permanent station. This requires, however, a 2-way communication.

7. Master Auxilary Concept (MAC)

Master Auxiliary (Euler, 2005) method so-called MAC or MAX, has been developed after the VRS and MRS and it is based on the new protocol RTCM ver. 3.x, where new data field are dedicated for this type of correction.

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In Master Auxiliary approach, the rover receiver estimates the bias around its position, using the correction data withe respect some closest CORS, at least 5, which create a cell. The selection of the CORSs which compose the cell is made by the control centre, considering the single CORS availability and the number of satellites. An example of different criteria for cell definition is reported in Fig. 4: in the left side, it is shown the cell (orange area) which is created considering all CORSs available in the network. In the right side, it is shown a new configuration of the cell, which is estimated using restricted number of CORSs.

As well demonstrated in this case, the cell geometry and the number of the CORSs included change with respect the effective operability of the network and the "master station" not always is the closest CORS.

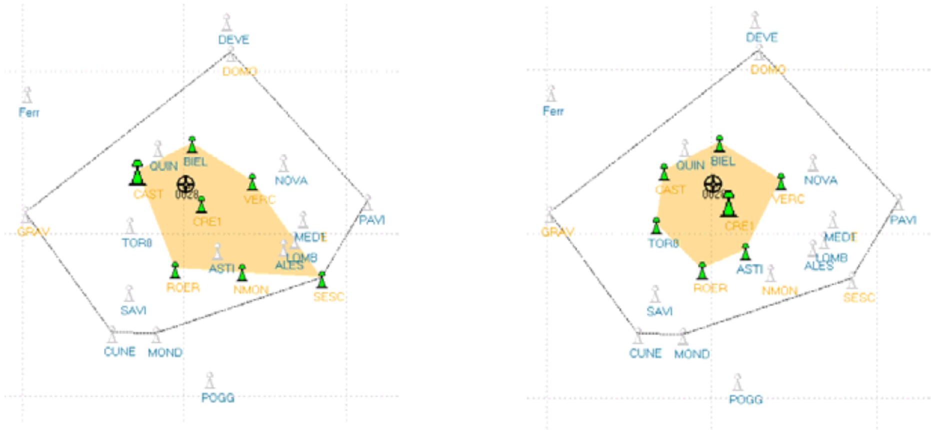

Figure 4. Example of different cell definition in a Master Auxiliary architecture: with all CORSs available (left) and with a restricted number of CORSs (right) (using LEICA SPIDERNET® software)

In this case, the computational load of the control centre is smaller than the VRS or FKP method, in fact the control centre has only to estimate the common level of ambiguity and the common error clock of the network, in order to calculate the dispersive and not-dispersive bias. The greater part of the calculus is moved on the rover.

RTCM ver. 2.x is not able to contain the information of this new architecture as "multi-station". The introduction and realization of the RTCM ver. 3.x has helped the GNSS community to bridge this gap.

$$DCPC_{L1} = CPC_{L1-AUX} - CPC_{L1-M} = \Delta\rho_{A-M}(t) - \lambda\Delta\phi_{A-M}(t) - \lambda\Delta N_{A-M} + c\Delta\delta_{A-M}(t) + \Delta A_{A-M} \quad (6)$$

For practical reason, the NRTK in master auxiliary approach is divided in several smaller subnet, which are processed in block, with a common level of ambiguity. In conclusion, over the *Master Auxiliary* can be made the following considerations:

- in this case, the method is dependent to the "computational performance" of the rover;
- it is based on real CORSs;
- master station is not always the closest station to rover position and it can be substituted with an auxiliary, when it falls down or it is over.
- unlimited number of user, with internet communication;
- rover has to be able to decoding the RTCM 3.x.

The user can use three different types of products, in a NRTK with master auxiliary:

- pre-defined cell, where the control centre decides the correct cell, considering the rover position; a dual-way communication is required.
- *auto MAX* service, where the cell is automatically created by the control centre, considering the rover position. a dual-way communication is required.
- i-MAX (*Individualized Master Auxiliary*), which is similar a VRS, where the control centre estimates the correction for the rover position and the rover receives immediately the correction values, which are directly applied to their data; RTCM 2.x can be used.

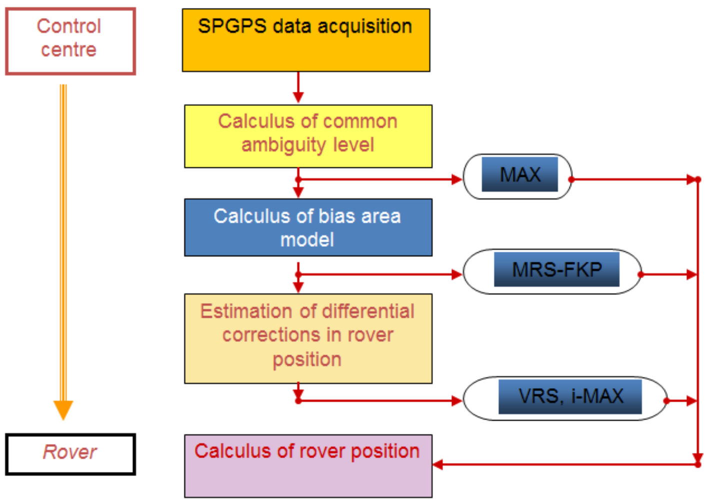

Figure 5. Flowchart of Master auxiliary approach

In Fig. 5 is shown a flowchart, where is compared the computational load in the control centre and in the rover, for each type of correction. From up to down, the computational load is moved to rover receiver, limiting the activities of the control centre only to estimate the common level of ambiguity and clock error of the network.

8. Some examples of NRTK performances

Today many NRTK networks are available in terms of inter-station distance: it is possible to find a local network (with mean inter-station distance of about 10 km), a regional network (with distance between stations of about 40-50 km) and national networks (distances of about 80-100 km). An example of the first type of network can be found in Italy and it is represented by the Provincia di Treviso network (http://siti.provincia.treviso.it/Engine/RAServePG.php/P/558610140303/T/Rete-GNSS-Stato-della-rete): this infrastructure is characterized by a small number of permanent station with a very low inter-station distance (10-15 kms). The second type of network can be represented by the Italian regional network, such as the Regione Piemonte (http://gnss.regione.piemonte.it/frmIndex.aspx) one, with a medium inter-station distance of about 40 kms. An example of the last type can also be found in Italy: in this case, this is represented by a network of private corporation such as Leica Geosystems (http://it.smartnet-eu.com/) or Topcon (http://www.netgeo.it/index.php). While in the first two cases the service is free of charge very often, in the last case it is necessary to pay a fee in order to obtain the service.

To be honest, also different types of GNSS networks exist (i.e. the EUREF network-http://epncb.oma.be/ or the IGS one-http://igscb.jpl.nasa.gov/network/netindex.html) but there are not used to perform a NRTK positioning.

9. Tests and results

As previously described, both many differential corrections and NRTK types are available. In this section we present some results obtained only considering a regional and national networks because we believe that they are the more interesting examples.

Moreover, if we consider the differential corrections, some of them are available today. In order to give an overview of the performances obtainable today, in this paper only the VRS® (Virtual reference Station), Nearest (hereinafter NRT), MAC (Master Auxiliary Concept) and FKP (Flächen-Korrektur-Parameter) corrections were considered. The last two ones require a double frequency instruments while the first two corrections are available also for single frequency instruments.

Two different schema of networks have been considered:

- a regional network, using the Regione Piemonte CORSs network (hereinafter REG);
- a national network, adopting the ItalPos network (hereinafter IPOS), that is a commercial service managed by the Leica Geosystems® company.

The choose of these networks has been suggested by their differences, in particular:

- CORSs interdistance:
- geometric schema and regularity;

- data processing strategy.

REG could be considered as a "small" network because it covers only a the Piedmont area, the mean CORSs interdistance is about 40kms. The single site of each CORS has been analysed, on the electromagnetic noise point of view, and selected, with purpose to have a regular geometry of the network. The NRTK products are estimated considering only the CORSs which belong to REG, therefore they can be used only in Piedmont area or, eventually in the closer boundaries (Fig. 6– red points and lines).

IPOS could be considered as a "large" network because it covers all Italian area, but the CORSs inter-station distance is not constant, because the network was not designed. The used CORSs have been selected considering only the available Leica Users CORSs in Italy. This aspect has led to have an irregular distribution of the CORSs in IPOS.. The NRTK products are estimated considering all the CORSs, allowing a national distribution of the services (Fig. 6– green points and lines). The distance between stations is approximately twice that of the network REG.

The tests were carried out in Vercelli (Italy) (Fig. 6– yellow triangle), in order to be in the middle of the grid of the networks, to have around at least four CORSs for each network and to realize the tests longer than 24 hours.

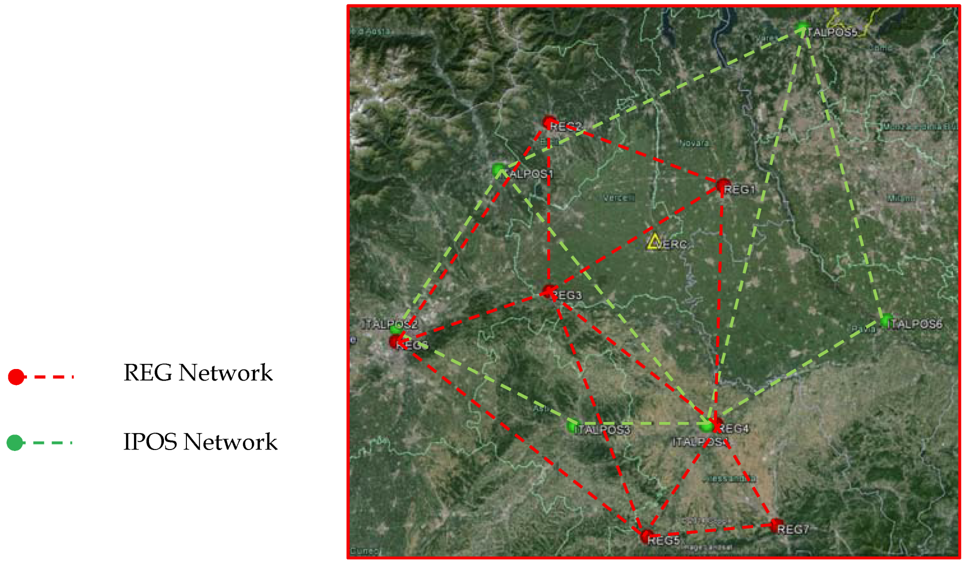

Figure 6. Test site (left) and definition of networks (right)

In the next two paragraphs we have decided to show the actual performances of a geodetic, GIS and mass-market receivers (seeTable 1) if the previous two types of CORSs networks were considered both for real-time and for post-processing applications.

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Receivers	GX1230+GNSS (Leica Geosystems)	GRS-1 (Topcon)	LEA EVK-5T (u-blox)
Image			
Antenna	LEIAX1203+GNSS	TPSPG_A5	patch
Nr. of channels	120	72	50
Constellations	GPS+GLONASS	GPS+GLONASS	GPS
Position update rate	20 Hz	N/A	0.25 up to 1000 Hz
Type of protocols	RTCM 2.x RTCM 3.0 CMR / CMR+	Yes	RTCM 2.x, RTCM 3.0, SBAS (WAAS/ EGNOS/MSAS/GAGAN) AssistNow Online & Offline
Internal modem	Yes	N/A	N/A
Type of correction	RTCM 2.x, RTCM 3.0 CMR / CMR+	RTCM 2.x RTCM 3.0 CMR / CMR+	RTCM 2.x, RTCM 3.0, SBAS (WAAS/ EGNOS/MSAS/GAGAN) AssistNow Online & Offline

Table 1. Receivers considered

The antenna used for these experiments was a mass-market antenna because in literature there are several works where the performance of mass market GNSS receiver coupled with a geodetic antenna have been tested [22]. In this case we have considered the Garmin GA29-F (Fig. 7) with a cost of about 40 €.

Figure 7. The antenna used in these experiments

10. Post-processing performances

First, the performances of these type of receivers for post-processing have been tested. We have considered both networks above described (REG and IPOS) and for each network, the nearest station and the VRINEX product have been used [3], [7].

We have decided also to increase the CORSs interdistance between rover and VRINEX in order to analyze since at which distance this product is useful for each type of GNSS receiver (Fig. 8).

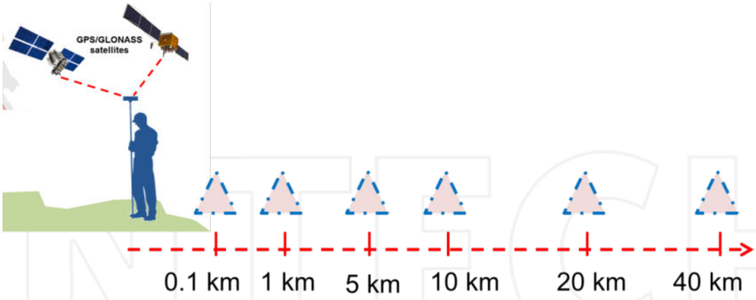

Figure 8. VRINEX distance

We have decided to consider a session length of 24 hours of acquisition with a sample rate equal to 1 s; after that we have splitted the entire file in small parts with a session length of 10 and 5 min in order also to show what is the minimum session length in order to obtain centimetrical accuracy. In the following tables are reported the standard deviation of the positioning, both in horizontal and vertical components, not reporting the mean values because they are practically equal to zero, in any cases.

The results obtained with the Regione Piemonte network are shown inTable 2.

	Nearest* - 5 min		VRINEX - 5 min		Nearest* - 10 min		VRINEX - 10 min	
Receiver	σ_{2D} [m]	σ_{3D} [m]	σ_{2D} [m]	σ_{3D} [m]	σ_{2D} [m]	σ_{3D} [m]	σ_{2D} [m]	σ_{3D} [m]
Geodetic	0.15	0.23	0.03	0.05	0.07	0.11	0.02	0.03
GIS	0.25	0.29	0.15	0.23	0.09	0.15	0.06	0.09
Mass-market	0.6	0.82	0.29	0.35	0.08	0.16	0.05	0.11

* Nearest-rover distance=19km

Table 2. Post-processing performances with Regione Piemonte network (REG network)

The Nearest was about 19 km far from the rover: this choice was made in order to consider the maximum distance that it is possible to have in these type of networks. As it is possible to see from previous table, the VRINEX product, which is generated close to rover position, is very useful starting from geodetic receiver to the mass-market one because it allows to decrease the inter-station distance between master and rover: if a session length of 10 min is considered, the obtainable accuracies could has a centimetric level and are very useful for many types of applications, such as some activities of precise farming, mobile mapping, cartographic activities etc. [6], [8], [16], [25].

If the inter-station distance between CORSs increase, the accuracy of the rover positions obviously decrease: these results are shown in Table 3.

	Nearest* - 5 min		VRINEX - 5 min		Nearest* - 10 min		VRINEX - 10 min	
Receiver	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**
Geodetic	0.36	0.41	0.06	0.11	0.04	0.09	0.02	0.03
GIS	0.45	0.68	0.19	0.26	0.09	0.15	0.04	0.10
Mass-market	0.84	0.97	0.23	0.37	0.11	0.19	0.06	0.09

* Nearest-rover distance=19km

Table 3. Post-processing performances with ItalPos network (IPOS network)

As it is possible to see from the previous table, with the nearest station and a session length of 5 min the results are so bad: this is done because the software for post-processing is not able to fix the ambiguity phase for all types of receivers. This is not happen if we consider the VRINEX or if the session length increase: in this case the results are more accurate and the 3D accuracy is less than 20 cm even if the mass-market receiver is considered.

So it is possible to affirm that considering the post-processing approach, the results of this study show that an accuracy of some centimeters with the single-frequency mass market GNSS receivers can be achieved, considering some expedients such as the minimum acquisition time, baseline length and suitable antenna. In fact, all these results are obtained with a mass-market GNSS antenna shown in Fig. 7. We have decided to consider this type of antenna because it is possible to find in bibliography [7] many studies that analyze the performance of these receivers with geodetic antennas but no one consider this type of antenna.

It must be underlined that the VRINEX enables us to limit the length of the baseline and improve the success percentage for fixing the phase ambiguity.

The performance analysis of single frequency receiver was carried out in "ideal conditions" of satellite visibility in order to assess the obtainable level of precision. Each site must be tested before installing any GNSS infrastructure dedicated to monitoring in order to evaluate their suitability for GNSS measurements (i.e. number of satellites, satellite geometry, electromagnetic noise, etc.), both for geodetic and mass market receivers.

11. Real-time performances

In order to synthetize the results obtained considering the big amount of data acquired and to show in a more clear way the performances of the previous receivers, the results reported below are average values, considered significant for the three sets of instruments used in the experiments. Geodetic and GIS real time solution have been automatically estimated by the receiver and internally stored, whereas for the mass-market solution, RTK-lib package has been used in order to receive and to apply the differential correction, connecting the receiver to a laptop.

From Table 4 it is interesting to see as the performances of mass-market receiver are quite the same as the geodetic one. The N/A values in the MAC correction of the mass-market and GIS receivers are due to the fact that these receivers are only L1 instruments while the MAC correction require a double frequency instruments: so in this case it is not possible to have any type of comparison.

	VRS		NRT		MAC	
Receiver	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**
Geodetic	0.015	0.018	0.021	0.027	0.012	0.017
GIS	0.016	0.021	0.022	0.023	N/A	N/A
Mass-market	0.018	0.020	0.025	0.031	N/A	N/A

Table 4. NRTK positioning considering the Regione Piemonte Network (REG network)

If the inter-station distance of the network increase, the performances of the rover decrease: in Table 5 there are the results obtained considering the IPOS. This consideration is more visible if the mass-market is considered, especially analysing the results obtained with the Nearest correction: the performances are 4 time worse respect to the other type of CORSs network even if the 3D accuracy is always better than 10.5 cm. In this case, the Nearest station was about 40 km far from the rover.

	VRS		NRT		MAC	
Receiver	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**	**σ2D [m]**	**σ3D [m]**
Geodetic	0.031	0.041	0.040	0.046	0.029	0.035
GIS	0.041	0.053	0.061	0.097	N/A	N/A
Mass-market	0.045	0.052	0.070	0.103	N/A	N/A

Table 5. NRTK positioning considering the ItalPos Network (IPOS network)

Another important parameter that must be considered is the Time To Fix (TTF) period: this is the time required by the receiver to fix the ambiguity phase. In order to obtain representative statistics, a time window of three days with an acquisition rate equal to 1s was considered, due to the “Instantaneous” mode of the ambiguity fixing. This choice was made in order to determine both the quality of the ambiguity fixing and to obtain a significant number for it.

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	VRS		NRT		MAC	
Receiver	**mean TTF [s]**	**n°of FIX**	**mean TTF [s]**	**n°of FIX**	**mean TTF [s]**	**n°of FIX**
Geodetic	57 s ± 20 s	135	67 s ± 23 s	50	41 s ± 18 s	188
GIS	90 s ± 41 s	68	95 s ± 39 s	49	N/A	N/A
Mass-market	87 s ± 23 s	57	115 s ± 52 s	43	N/A	N/A

Table 6. TTF considering the Regione Piemonte Network (REG network)

	VRS		NRT		MAC	
Receiver	**mean TTF [s]**	**n°of FIX**	**mean TTF [s]**	**n°of FIX**	**mean TTF [s]**	**n°of FIX**
Geodetic	95 s ± 40 s	98	107 s ± 44 s	49	106 s ± 55 s	85
GIS	115 s ± 61 s	55	121 s ± 74 s	45	N/A	N/A
Mass-market	110 s ± 53 s	56	119 s ± 66 s	40	N/A	N/A

Table 7. TTF considering the ItalPos Network (IPOS network)

As it is possible to see from Table 6 and Table 7 both the geodetic, the GIS and the mass-market receivers are able to fix the ambiguity phase in a period less than 2 min even though a national network is considered. This is very interesting because thanks to these infrastructures is possible to reach a centimetric level of accuracy in less than 2 minutes, which is a reasonable time for many types of applications (from professional surveys to cadastral applications, to precise farming, etc.). Also in this case, the antenna play a fundamental role in order to decrease the TTF: in the previous case we have analysed the performances obtained with the Garmin antenna, that is in general less efficient respect to a geodetic one [22].

It must to be underlined that the levels of precision and noise of the results greatly depends also on the antenna used. However, it is possible to find a good compromise and a favourable price/performance ratio by using receivers and antennas.

12. Acronyms

CORS: Continuously Operating Reference Station

CPC: Carrier Phase Correction

FKP: Flachen Korrektur Parameter

GBAS: Ground Based Augmentation System

GNSS: Global Navigation Satellite System

MAC: Master Auxiliary Concept

NRTK: Network-Real time Kinematic

PRC: Pseudo Range Correction

RINEX: Receiver Independent Exchange Format

RTCM: Radio Technical Commission for Maritime Services

SBAS: Satellite Based Augmentation System

VRINEX: Virtual RINEX (Receiver Independent Exchange Format)

VRS: Virtual Reference Station

WAAS: Wide Area Augmentation System

Author details

Alberto Cina, Paolo Dabove*, Ambrogio M. Manzino and Marco Piras

*Address all correspondence to: paolo.dabove@polito.it

Politecnico di Torino, DIATI-Department of Environment, Land and Infrastructure Engineering, Turin, Italy

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