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Study of a Simplified Approach in Utilizing Information from Permanent Reference Station Arrays

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ABSTRACT

Permanent reference station networks are used all over the world for surveying type applications requiring centimeter accuracy generally reducing the worth of traditional single baseline methods. The well known advantages provided by reference station array information include improved modeling of the remaining tropospheric, ionospheric and orbit biases. Methods and concepts show the improvements in performance and reliability in some kind of closed system approaches. Standardisation discussions underway within RTCM target the interoperability between the reference station systems and roving receivers from various manufacturers. One obstacle in the discussion, and therefore in later interoperability issues, is the creation and proper description of the models used for deriving the biases noted above. This difficulty has to be mitigated and will vanish with time, but this interoperability is needed urgently. This paper details a different approach to utilise and distribute the information from permanent reference station arrays in RTCM-format compact messages. The separation of different calculation tasks affords an easy and efficient standard for the transfer and distribution of network information. The proposed method may solve the current dilemma for interoperability standards.

INTRODUCTION / MOTIVATION

Real-time messages for proper interoperability between different manufacturer equipment have been issued by the RTCM Sub-Committee 104 (RTCM, 2001). All information for precise positioning using baseline approaches can be transmitted using message types 18-21.

Because the use of single reference stations has some disadvantages in that the accuracy and reliability of integer ambiguity resolution deteriorates a few tens of kilometers from the reference station, networks of reference stations are being developed to mitigate the distance-dependency of RTK solutions. With such networks, a provider can generate measurement corrections for receivers operating in the area, that is covered by the network and he can supply this information to the user in some standard format. As the current kinematic and high-accuracy message types do not support the use of data from multiple reference stations, new standards must therefore be considered to facilitate the valuable information afforded by networks of reference stations.

The standardisation of network information and processing models is also necessary to reduce the sizes of the network RTK corrections, as well as the transmission of satellite-independent error information. A simplified approach of transmitting data from reference station networks to roving users is now presented in this paper in the form of a new message standard capable of supporting reference network operations. Its use should help overcome some of the problems encountered in current network RTK concepts.

EXISTING CONCEPTS: FKP AND VRS

At present, there are at least two approaches available commercially, that provide network-based solution information to roving users. The first is based upon the transmission of network coefficients (also known as area correction parameters or FKP, the German acronym), whilst the second is based on the transmission of “virtual reference stations” (VRS) generated from the reference station measurements. A short description of these concepts follows.

In the first concept, computing facilities calculate for every satellite coefficients (FKP) covering ionospheric, tropospheric and orbit effects covering a specific network area at specific time intervals (at least every 10 s). The measurement corrections, reduced by the station-satellite slope distances of the reference stations, are then transmitted via RTCM messages Type 20/21 as well as the FKPs for interpolation via a customized RTCM Type 59 message.

In the VRS concept, the rovers also receive network information but additionally transmit, via NMEA messages, their approximate positions to a central computing facility. This facility calculates the station-satellite slope distances for these approximate positions and then, from the reference station observations, interpolates the corrections corresponding to a virtual reference station near the rover. These virtual measurements are unique to each rover and transmitted to them via RTCM messages of Type 20/21 or 18/19.

Problems of FKP and VRS

Both approaches have their respective advantages as detailed in WÜBBENA and WILLGALIS (2001), and LARGE et al. (2001). Of more interest are their disadvantages and how these may affect general surveying tasks within networks. The providers decision on complexity of the mathematical correction model, the rover cannot influence, is a general problem. The need to select the correct (optimal) FKPs for a rover so it can interpolate its measurement corrections, or VRS' dependence on complex two-way communications over medium-sized networks whilst restricting user numbers are such two concept-dependent examples of problems.

Both approaches are currently using the RTCM Type 59 proprietary information message. The proprietary information content has been partly distributed, but it is neither standardised nor released by a manufacturer independent organisation like RTCM. However both concepts are not fully compatible with the RTCM standard as they contain modelled information.

For some time there have been discussions within RTCM on possible standards for network RTK corrections and one such standard has been proposed in TOWNSEND (2000). However progress has not been significant since the issue is quite complex. Proper interoperability between different manufacturers' equipment must be considered so that models can be agreed upon and described in the standard. The full functionality needs further standardisation effort, also because of additional information, which needs to be transmitted.

The standardisation of network information and processing models is necessary to reduce the sizes of the network RTK corrections as well as the transmission of satellite independent error representations. Such difficult discussions are the main reason for the slow progress but they must continue to yield a future standard. The discussion here proposes an intermediate step toward these standardised messages by describing a means of information distribution where the pure basic information content is transferred to the rover. Specialised models requiring detailed description and discussion are not used in this proposal.

TRANSMISSION CONCEPT PROPOSAL: COMMON AMBIGUITY LEVEL AS THE KEY LINK

It is a well-known fact that the proper resolution of the so-called integer ambiguities is the key to high accuracy positioning for a single baseline. The power of network solutions will be experienced with the proper integer ambiguity resolution between permanent reference stations. Following the resolution of integer ambiguities between reference stations and their removal from the original observations, a common integer ambiguity level can be established across the network.

While the RTCM message types 20 and 21 contain information to process a single baseline the proposed concept shall help to transmit information related to a (part of a) reference station network. The existing message types 20/21 remain untouched and are still part of the information transmission concept. Information of additional reference station measurements are included by forming differences of their corrections to those of a master reference station. In essence one will transmit to the user the corrections of the master reference station via type 20/21 messages and the additional smaller correction differences between the master reference station and each further (slave) reference station in the network via the new proposed message type. As a first proposal let's call it **type 25 message**. The presence of these correction differences will allow each rover to directly interpolate spatially: This could possibly result in corrections for a virtual reference station or in the reconstruction of the original corrections in the sense of types 20/21 messages for each station related to the master reference station.

The master reference station coordinates have to be provided to the rover using an RTCM type 24 message, whereas the position information of the further (slave) reference stations can be transmitted as coordinate differences. This saves some of bits due to the smaller numbers.

The proposed type 25 message concept will supply more information to rover users at the same transmission rate. By providing a common integer ambiguity level, it simultaneously allows the information to be directly used for spatial interpolation. This concept can be used in one-way communication. So the number of participants is not limited as in a VRS concept realization and the decision on the processing concept can be carried out on the rover side. The roving user's receiver can decide whether to use the complete information of a single reference station or use part or the complete suite of transferred reference station data for deriving its best solution.

Alternative means of transmitting this information are developed in the further sections.

OBSERVATION EQUATIONS

The Basic Observation Equations

Let us represent the undifferenced (raw) pseudoranges and carrier phases as in equation (8) of the publication (EULER, GOAD, 1991). Supplemented with indices for station A (or B, C, … respectively), satellite j and frequency indicator (L1, L2 and in the future L5, for Galileo in a similar way) we have for L1 carrier phase:

$$\Phi^{j}_{A,1}(t) = r^{j}_{A}(t) - \frac{I^{j}_{A}(t)}{f_1^2} + e_{1,\Phi} + \frac{c}{f_1}\cdot N^{j}_{A,1} \qquad (1)$$

where

f_1	…	frequency of L1
c	…	speed of light in a vacuum
t	…	measurement epoch
$\Phi^{j}_{A,1}(t)$	…	raw phase measurement in [meters]
$r^{j}_{A}(t)$	…	geometric range between satellite j and receiver A, including clock errors and non-dispersive contributions such as tropospheric refraction
$I^{j}_{A}(t)$	…	total ionospheric refraction
$N^{j}_{A,1}$	…	initial phase ambiguity in [cycles]
$e_{1,\Phi}$	…	random measurement noise

For other frequencies one gets equivalent equations.

Expanding the Observation Equations

In a further step an ionosphere model and a residual parameter are introduced. Additionally the parameter for the non-dispersive term will be split into the geometric range, the receiver and satellite clock errors, the broadcast orbit error, and the tropospheric path delay. The latter one consists of any model you like plus a residual parameter. Further non-dispersive contributions to the geometric range parameter like multipathing are neglected.

$$\begin{aligned}\Phi^{j}_{A,1}(t) &= \tilde{s}^{j}_{A}(t) + c\cdot dt_{A,1,\Phi} - c\cdot dt^{j}_{1,\Phi}\\ &\quad + \hat{T}^{j}_{A}(t) + d\,T^{j}_{A}(t) - \frac{\hat{I}^{j}_{A}(t)}{f_1^2} - \frac{d\,I^{j}_{A}(t)}{f_1^2}\\ &\quad + \frac{\vec{r}^{\,j}_{A}}{\left|\vec{r}^{\,j}_{A}\right|}\,d\vec{r}^{\;j,BE} + e_{1,\Phi} + \frac{c}{f_1}\cdot N^{j}_{A,1}\end{aligned} \qquad (2)$$

where

$\tilde{s}^{j}_{A}(t)$	…	geometric range between the position of the receiving antenna and the broadcasted satellite position, **includes** antenna phase center variations and multipathing
$\hat{I}^{j}_{A}(t)$	…	modeled ionospheric refraction
$d\,I^{j}_{A}(t)$	…	residual ionospheric refraction effect
$\hat{T}^{j}_{A}(t)$	…	modeled tropospheric refraction effect
$d\,T^{j}_{A}(t)$	…	residual tropospheric refraction effect
$\vec{r}^{\,j}_{A}$	…	station (antenna) - satellite vector
$d\vec{r}^{\;j,BE}$	…	broadcast orbit error
$dt_{A,1,\Phi}$	…	total receiver clock error
$dt^{j}_{1,\Phi}$	…	total satellite clock error

Between Station Single Differences

The concept discussed in this paper uses correction differences, i.e. between station single differences reduced by slope distances, receiver clock errors and ambiguities. These can be directly derived from the equation (2). With a Δ one can denote the between station single difference of a component. In our approach we attempt to determine all components on the right hand side of the resulting observation equation excluding the tropospheric and orbit (non-dispersive) as well as the ionospheric (dispersive) parts, and subtract them from the left hand side (the measurement):

$$\begin{aligned}&\Delta\Phi^{j}_{AB,1}(t) - \Delta\tilde{s}^{j}_{AB} - c\cdot\Delta dt_{AB,1,\Phi} - \frac{c}{f_1}\cdot\Delta N^{j}_{AB,1} =\\ &\quad = \Delta\hat{T}^{j}_{AB}(t) + \Delta d\,T^{j}_{AB}(t) + \Delta d\,r^{j,BE}_{AB}\\ &\quad + \frac{\Delta\hat{I}^{j}_{AB}(t)}{f_1^2} + \frac{\Delta d\,I^{j}_{AB}(t)}{f_1^2} + \Delta e_{1,\Phi}\end{aligned} \qquad (3)$$

where

$\Delta\tilde{s}^{j}_{AB}$	…	geometric range single difference, **includes** antenna phase center variations and multipathing, which are already determined and applied by the network processing software
$\Delta d\,r^{j,BE}_{AB}$	…	broadcast orbit error induced distance dependent effect on baseline AB

This resulting residual shall be transmitted to the rovers, but, as already mentioned above, there arise problems in standardization of models. Note our approach proposes an alternative and transmits the whole right-hand side of equation (3), and therefore the problem is circumvented.

GENERATING THE COMMON INTEGER AMBIGUITY LEVEL

Due to the fact, that integer ambiguities are normally resolved in a double difference approach, the question arises as to how the ambiguities in the equation (3) above are considered. If one looks at the relationship of undifferenced, single and double differenced ambiguities as in (JÄGGI, BEUTLER, HUGENTOBLER, 2001), one gets:

$$N^{j}_{B} = N^{j}_{A} + \Delta N^{j}_{AB} = N^{j}_{A} + \Delta N^{ref}_{AB} + \nabla\Delta N^{ref,j}_{AB} \qquad (4)$$

The derivation of single difference ambiguities from double difference ambiguities is not possible in a correct way without the knowledge of the single difference ambiguity to the reference satellite ΔN_{AB}^{ref}. Admittedly neglecting this would result only in a constant bias in all contributing single differences related to the two stations involved. So this bias will either cancel out in any baseline estimation performed later at the rover side or estimated as a modified receiver clock error term.

RTCM CORRECTION DIFFERENCES PROPOSAL

Before we describe the correction differences proposed for a message type in detail, we shall recap on the RTCM corrections of type 20 in the notation used here. The carrier phase correction (exemplary given for L1) for a station *A* is defined to:

$$d\Phi_{A,1,RTCM}^{j} = s_A^j(t) - \Phi_{A,1}^{j}(t) + c \cdot dt_{A,1,\Phi} - c \cdot dt_{1,\Phi}^{j} \quad (5.1)$$

The variable $s_A^j(t)$ denotes the geometric range between the position of the receiving antenna and the broadcasted satellite position.

For a second station *B* the correction can be written in the same way, as well as for further reference stations:

$$d\Phi_{B,1,RTCM}^{j} = s_B^j(t) - \Phi_{B,1}^{j}(t) + c \cdot dt_{B,1,\Phi} - c \cdot dt_{1,\Phi}^{j} \quad (5.2)$$

As discussed above a network algorithm will generate an ambiguity leveled set of RTCM type 20 messages for every reference station. These messages could be directly transmitted in parallel by every broadcast station, but due to throughput issues, it is desirable to have more compact means than doing that. Therefore we are proposing only to transfer the differences for the slave reference stations.

In the case, that station *A* denotes the master reference station and the station *B* stands for one of the slave reference stations, one can form directly from the equations above single differences always related to station *A*, following the equation (3).

As a result of the network processing either the single difference or double difference ambiguities will be taken into account. In the case of double difference ambiguities, it must be assured that they all relate to the same reference satellite at each epoch, although a change of the reference satellite may appear between epochs. As already stated, this bias remaining over all single differences can be reduced by subtracting a constant (integer cycle) bias from all correction differences relating to one reference station pair. This yields a further reduction in the size of the numbers, that have to be transmitted.

Basically one has to transmit all information relating to the master reference station. This will include corrections (in message types 20,21) and the master station's coordinates and antenna information (message type 23 and 24 in RTCM 2.3). Related to that master reference station the correction differences of the other (slave) reference stations *B*,*C*,*D*,… are generated. These will be transmitted in the proposed message format. So the new message type contains all relevant data:

$$\begin{aligned} d\Delta\Phi_{AB,1,RTCM}^{j} &= \Delta s_{AB}^{j}(t) - \Delta\Phi_{AB,1}^{j}(t) + c \cdot \Delta dt_{AB,1,\Phi} \\ &\quad + \frac{c}{f_1} \cdot \Delta N_{AB,1}^{j} \end{aligned} \quad (6)$$

If one considers splitting the correction in two components, namely a dispersive and a non-dispersive part, one has to form the geometry-free and the ionosphere-free linear combination from L1 and L2, so that the two resulting correction differences will become

$$\begin{aligned} d\Delta\Phi_{AB,1,RTCM}^{j,\ disp} &= \frac{f_2^2}{f_2^2 - f_1^2} d\Delta\Phi_{AB,1,RTCM}^{j} \\ &\quad - \frac{f_2^2}{f_2^2 - f_1^2} d\Delta\Phi_{AB,2,RTCM}^{j} \end{aligned} \quad (7)$$

$$\begin{aligned} d\Delta\Phi_{AB,1,RTCM}^{j,\ non-disp} &= \frac{f_1^2}{f_1^2 - f_2^2} d\Delta\Phi_{AB,1,RTCM}^{j} \\ &\quad - \frac{f_2^2}{f_1^2 - f_2^2} d\Delta\Phi_{AB,2,RTCM}^{j} \end{aligned} \quad (8)$$

so that both are expressed in meters and the dispersive part (equation 7) is related to the L1 frequency.

While the multiple frequency option (e.g. named as L1/L2/L5 option) is easier to handle, the dispersive/non-dispersive option has the advantage to change the rates of one part in comparison to the other, due to its smoother behaviour.

However there are two possible ways of using the dispersive/non-dispersive option: firstly their direct interpolation similar to the FKP concept or secondly in the reconstruction of the message type 20/21 like corrections. In the latter case, when the dispersive and non-dispersive terms are derived by L1 and L2, one will miss information related to L5 in the future. To be able to reconstruct all three (L1, L2 and L5) corrections as independent information, an additional residual has to be provided. However this should not be discussed at the present time.

A format proposal draft covering the dispersive/non-dispersive option can be found as **Appendix**. A very similar format proposal for the multi-frequency option can be formulated, but has been neglected.

ASSESSING THE RANGES OF THE MESSAGE COMPONENTS

To get an idea of the ranges related to the dispersive and non-dispersive effects, the impacts of ionospheric and tropospheric refraction as well as of orbit errors have to be considered. Note we have assumed, that antenna phase center variations and multipathing have been mitigated to a negligible amount by the network software.

Satellite Orbit

In order to significantly reduce the orbit errors one could use IGS predicted orbits during data processing. However in reality one has to use the model provided by the broadcast message in a real-time approach. This less accurate orbit representation contains errors, which are satellite, distance and time dependent. The radial error generally is less than 10 m, equating to an error of 0.4 ppm in baseline length. In extreme cases, 40 m of radial error are possible (1.6 ppm). The change in satellite orbits with time is very smooth unless a maneuver appears or the broadcast representation shows a break. Assuming maximum distances of reference station separations of about 300 km, then one gets certainly less than 0.5 m.

Ionospheric Refraction

The ionospheric effect is both distance and time dependent. The latter characteristic is treated in a further section. The error due to ionospheric refraction can reach some ppm (parts per million) in baseline length, up to 15 ppm in mid-latitudes, whereas in equatorial zones some tens of ppm are possible. WANNINGER (1994) noted up to 80 ppm, e.g. in South Brazil in 1992. Such large amplitudes vary slower (large scale travelling ionospheric disturbances). Assuming maximal separation of reference stations of about 300 km, this corresponds to ±24 m maximum. With a correction difference resolution of 1 mm, this needs a data slot of 16 bits, if one considered a "dispersive" message slot.

Tropospheric Refraction

With large height differences in reference station networks and low satellite elevation angles, e.g. around 5°, the modeled single difference error contribution can exceed more than 10 m. Theoretically one can think about specifying a very simple model in the RTCM standards to eliminate this part. However such a model has to consist of a standard atmosphere (using defined values for temperature, pressure and relative humidity, as well as of the related gradients with height) and of a simple formula for the tropospheric delay including the mapping function. The prime reason to create our pure observation correction based message is avoid the introduction of models!

For the whole non-dispersive amount one has to reserve at least 15 bits. Considering a realistic maximum height difference of 2000 m over 300 km station distances, one gets maximal tropospheric refraction effects of less than ±12 m. ±11 m is due to height and elevation difference covered by a model and ±1 m due to non-modeled errors (i.e. time and location dependent variations). This is an optimistic estimate so it is better to reserve 16 bits for such a message part equivalent to a range of ±24 m. The other significant non-dispersive effects, i.e. the orbit errors, should not exceed more than one meter for baselines less than 300 km. Consequently one can include this together with the tropospheric effect to afford one "non-dispersive" or "geometric" part, and for this also only a slot size of 16 bits is required.

Range of the Correction Differences

The following table summarizes the maximum ranges noted above for the ionospheric, tropospheric and satellite errors and also the number of bits required for their resolution (in 1/256th of a L1 cycle). As already mentioned in the troposphere section the latter two components are often combined to a geometric (or: non-dispersive) group of systematic errors.

Effects	**Non-Dispersive**		**Dispersive**
Specific	**Orbit**	**Troposphere**	**Ionosphere**
Site dependent	-	< ±12 m (dh < 2000 m)	-
Distance dependent	< 1.6 ppm	some few ppm	< 80 ppm
Sum (distance < 300 km)	max. ±1 m	max. ±12 m	max. ±24 m
Bits Required	16 bits		16 bits
	17 bits		

Table 1: *Maximum error summary*

Concluding the above, one has two possibilities with which to realize the approach. Firstly one can take into account only one component comprising the whole correction differences for all frequencies L1. L2 and L5, that has to be broadcast at a high rate; alternatively one considers the dispersive and non-dispersive components which can allow the broadcast of e.g. the non-dispersive component at a lower rate than the dispersive. In addition, the latter then has to be scaled by a frequency dependent factor, before it can be added to the non-dispersive part and subsequently used for correction of the L2 or L5 observations. Finally it is most convenient to relate both components generally to L1 cycles. Corrections for the other frequencies can be easily derived. A discussion of the possibilities, that arise from observations on three frequencies, can be found in HAN and RIZOS (1999) or HATCH et al. (2000).

For the first case, one certainly has to expect less than ± 48 m. This results in 17 bits for a 1 mm carrier phase resolution (as considered in the type 20 RTCM message and needs 24 bits) for each satellite and frequency (L1, L2 and L5).

For the second case one has to expect less than ±24 m for the dispersive part (a data slot of 16 bits) and certainly less than ±24 m for the non-dispersive part (16 bits also). In total one gets 32 bits (plus two for indicating the kind of component) for each satellite. Consequently the second case has the advantage of saving around 200 bits for 12 satellites considering the anticipated L1/L2/L5 scenario on GPS. As already mentioned the non-dispersive part can be broadcast at a lower rate thereby also contributing to a significant data throughput saving.

Resolution of the Coordinate Differences

As the coordinates of the master reference station are transmitted fully via a message type 24, the coordinate information of the slave stations can be reduced to differences relative to the master reference station.

The resolution needed for the coordinate differences depends on whether the correction differences will be used for spatial interpolation purposes only or to reconstruct the undifferenced type 20/21 like corrections from the proposed type 25 messages.

If the station coordinates will be used for the interpolation of correction differences, then the coordinates can be provided with a lesser resolution of 2.5 meters. This means that, in the limits of the specifications, the correction differences in the proposed type 25 message do not change more than 1 mm from one interpolation grid point to the other. These interpolation grid points are separated in geocentric coordinate vector components dX, dY and dZ by 2.5 m.

If the rover will attempt to ‘reconstruct’ the measurements of each slave reference station, then the coordinates of the slave reference stations should be transmitted to a resolution of 1 millimeter.

The definition of the antennas for all slave reference stations has always to be consistent with the master reference station. It can be easily solved by using a model type antenna, e.g. a “nullantenna”, for all reference stations. In this approach the phase center variations are totally reduced by applying absolute calibration values.

ASSESSING THE MESSAGE UPDATE RATES

General Considerations

With the consideration of dispersive and non-dispersive terms, different update rates can be specified. For example, the non-dispersive effects (tropospheric and orbit effects) are assumed to change more slowly relative to the dispersive effects (ionospheric effects). A recent questionnaire completed by RTCM members suggested the following maximum tolerated latency values: orbits at 120 seconds, troposphere at 30 seconds and the ionosphere at 10 seconds.

Assessments for Update Rates

As already well investigated e.g. by WANNINGER (1999), rapid changes in corrections using data from reference stations in mid-latitudes can reach 1.5 ppm per minute for the dispersive part and only 0.1 ppm per minute for the non-dispersive part. This supports the proposal, that these two components should be transferred at different rates.

Our own investigations have shown that both the dispersive and non-dispersive components exhibit trends of some mm, sometimes with rapid changes of the short-term trend including a change in its sign. In some extreme cases at low geomagnetic latitudes variations reaching 1 cm per second have been found in the dispersive part. There are also some high-frequency changes between epochs of 1 Hz data, that reach up to 4 cm in both dispersive and non-dispersive parts, for baseline lengths of up to 300 km.

Following are some initial suggestions for the update rates that must be defined when using corrections within RTK networks, not just for the concept described here.

Probably the most important factor to be considered, when assessing optimal update rates for all network information, is the implication that such rates will have on the Time-To-First-Fix (TTFF). A roving user would demand that they should receive all correction differences as soon as possible after they begin surveying. This would mean that all relevant network information (Type 20/21/24/25) should be transmitted as often as possible so as to minimise the TTFF and provide rapid access to all network information – an initial suggestion is at least every 15 seconds. The dispersive terms should be transmitted at an equal or higher rate, as should the non-dispersive terms. Ideally the first would be at least every 0.1 Hz. However it still has to be clarified if the correction differences or at least a non-dispersive component can be transmitted at a even lower rate than the dispersive terms.

THROUGHPUT ANALYSIS

Although we developed also format for the L1/L2/L5 option, only the dispersive/non-dispersive option is documented in the **Appendix** due to page number reducing reasons. Nevertheless we want to provide you the related throughput assessments. Let us assume 1 set of reference station corrections or correction differences in addition to a master reference station, then we get the following throughput rates, if Ns is the number of satellites, Nf is the number of frequencies and “ceil” denotes a rounding to the nearest integers towards plus infinity:

Message type	Bits / message transmission
20/21/24	30 * (8Ns + 20)
20/21	30 * (8Ns + 12)
disp/non-disp lo res	30*ceil (1.25*(48*Ns+122)/30)
disp/non-disp hi res	30*ceil (1.25*(48*Ns+158)/30)
e.g. disp only lo res	30*ceil (1.25*(24*Ns+122)/30)
e.g. disp only hi res	30*ceil (1.25*(24*Ns+158)/30)
L1/L2/L5 lo res	Nf*30*ceil (1.25*(24*ns+124)/30)
L1/L2/L5 hi res	Nf*30*ceil (1.25*(24*Ns+160)/30)

Table 2: *Throughput formulas for 1 set of reference station corrections, or correction differences respectively*

In the table above "lo res" and "hi res" means low and high resolution, i.e. a resolution of 2.5 m or of 1 mm respectively for the coordinate differences, "disp/non-disp" means the dispersive/non-dispersive option and so on.

We want to give a short outline of some results based on these throughput formulas. For the master reference station one has always to transmit the full station information present in the messages of type 20, 21 and 24. But for each additional station a larger proportion of bits can be saved if using the proposed type 25 message. For the dispersive/non-dispersive case this factor is generally between 3 and 4 compared to the conventional 20/21/24 realization, if only L1 and L2 are taken into account. When including L5 in the future, this factor will further increase. Also a lower update rate of the non-dispersive component will increase the throughput savings. For the L1/L2/L5 case, one will see an improvement of better than 2.5 over the conventional type 20/21/24 approach.

Six different message type scenarios are now presented in the figures 2 and 3. These are the transmission of the reference station information as type 20, 21 and 24 messages, again but without 24 (contains station coordinates etc., that can be transmitted at a lower rate), as the proposed type 25 message for both dispersive/non-dispersive and L1/L2/L5. Both of the latter two proposed message types are given for coordinate difference resolutions of 2.5 m and 1 mm. Note that the higher resolution needs an additional 36 bits in the message header.

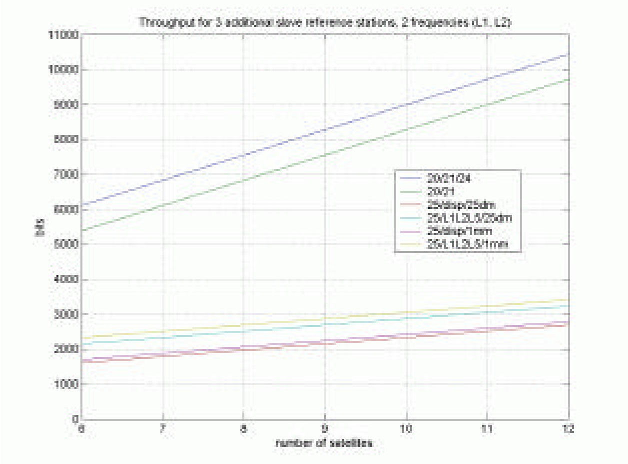

Fig. 1*: Throughput values yielded by 6 different message type options for 3 slave reference stations observing multiple satellites on 2 frequencies*

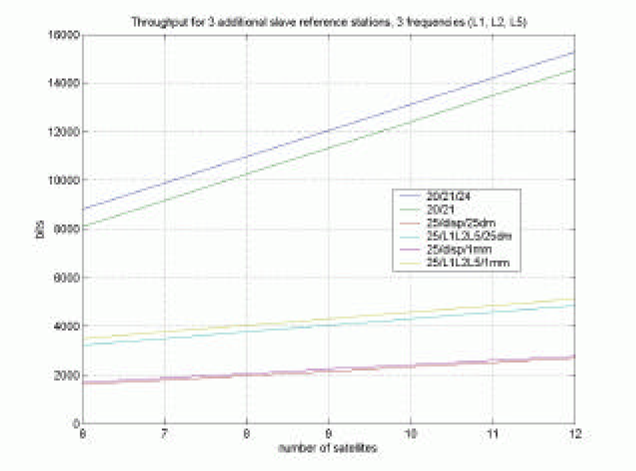

Fig. 2: *Throughput values yielded by 6 different message type options for 3 slave reference stations observing multiple satellites on 3 frequencies (L1 ,L2,L5 or Galileo)*

The information regarding the master reference station is not considered here, because it is always transmitted by type 20/21/24 messages. The figure 1 corresponds to 3 slave reference stations using 2 frequencies (L1 and L2), whereas the figure 2 corresponds to – again – 3 slave reference stations but using 3 frequencies, i.e. considering that L5 (or Galileo) is available. From the above graphs one can conclude, that the ratio of the proposed type 25 message to the existing messages of type 20/21/24 is not dissimilar for 2 frequencies, but changes considerably, if additionally L5/Galileo are taken into account. The option of dispersive/non-dispersive correction differences then shows its enormous advantage.

To aid in the discussion of how the reference station information will be transmitted at realistic rates, let us consider, what the RTCM 2.3 draft (RTCM, 2001) states:
" However, the data update requirement of RTK is much higher than conventional differential GNSS, since it involves double-differencing of carrier measurements. Data must be updated every 0.5 - 2 seconds. The data rate is driven not by SA variations that are no longer relevant, but by the RTK technique, which requires measurement-by-measurement processing. As a consequence, the data links are more likely to utilize UHF/VHF, with transmission rates of 4800-9600 baud. "

Looking at the situation objectively one has take into account a lower throughput rate than the nominal, because transmission includes stop and parity bits. So considering this overhead of 20% one gets for nominal rates of 4800/9600 bps a real rate of 3840/7680 bps. With some spares for safety's sake one can expect about 3500/7000 bps real data transfer rate. At present GPS suppliers normally recommend radio modems with a transmission rate of 9600 bps or greater. In Europe, GSM modems capable of 9600 bps, become more and more the standard communication solution.

Considering a nominal baud rate of 9600, 10 satellites tracked simultaneously on 2 or 3 frequencies using a co-ordinate difference resolution of 1 mm, results in a different number of slave reference stations, whose information can be transmitted in 1 second, using three different alternatives. The following table shows the results using the messages a) 20/21/24, b) the proposed 25 in the dispersive/non-dispersive option and c) the proposed 25 in the L1/L2/L5 option.

Number of Slave Reference Stations Using …		
Message Format	**L1+L2**	**L1+L2+L5**
a) RTCM 20/21/24	2	1
b) dispersive/non-disp.	8	8
c) L1/L2/L5	6	4

Table 3: *Number of slave reference stations, that can be transmitted in 1 sec. at 9600 bps with 10 satellites tracked at 2 or 3 frequencies, using different message formats*

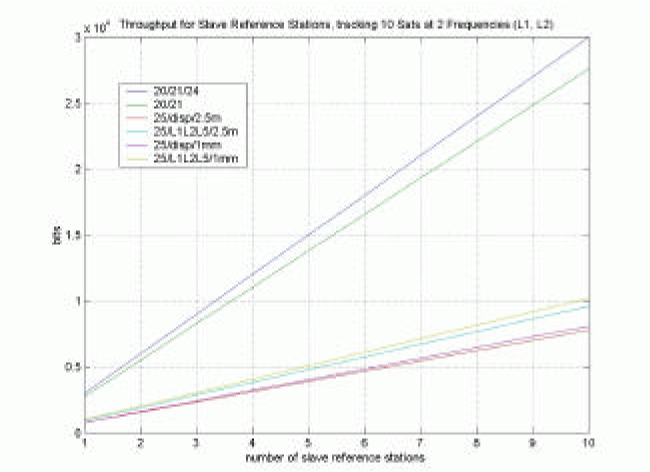

Fig. 3: *Throughput of slave reference stations for one epoch, tracking 10 satellites at 2 frequencies, comparison of different proposals*

Note that the information of the master reference station has been omitted in this theoretical calculation. Considering a third frequency, there is a problem in case a) to transmit more than the information of the master reference station. This highlights the need of a new message format for the transmission of reference station network information.

The need to transmit the information of more than e.g. five reference stations leads to the discussion, how often the station information should be updated (especially regarding the high-frequent changes of the dispersive effects) and which latency can be accommodated by the rover processing software. This may result in the distribution of the information related to one specific measurement epoch over a specific number of seconds. The likely demand of transmitting the data of as many stations as possible favorites the dispersive/non-dispersive option, because it allows the transmission of one component at a lower rate. This will afford a great saving of bits and so allow the transmission of more stations' data at the same time.

CONCLUSIONS AND SUMMARY

A new message standard has been proposed to aid the support of reference network applications. Its use should overcome some of the problems seen in recent proposals for reference station network positioning concepts.

Our concept is based on transmitting messages of type 20/21/24 for a master reference station and a newly proposed message type for further reference stations. The more additional reference stations are transmitted using the proposed message type, the greater the savings are compared to using RTCM messages of type 20,21 and 24.

The main advantages of the proposed message formats are as follows:

- There are less data bits to transmit in general
- The correction differences can be used for direct interpolation, once adjusted to the common integer ambiguity level
- No detailed model specifications are needed (e.g. for troposphere)
- One-way communication is sufficient
- Kinematic applications can work without interruptions and discontinuities unlike a VRS system, which has to change its VRS position during motion.
- There are no restrictions on the number of users in a reference station network
- No dependency exists to a specific concept approach: The rover user gets the full reference station network information and can independently use its own models, interpolation and processing concepts

This approach can be used with update rates of up to 1 Hz, elevation masks down to 5° and reference station distances up to 300 km.

With the implementation of L5, the dispersive/non-dispersive option will easily provide the most efficient use of throughput. Variations in the dispersive component will then dictate the lower limit for the correction difference updates.

Further Considerations

In addition to the issues raised in this paper, one has to discuss some further:

- In the case of a third frequency one has possibly to consider an additional correction residual for the proposed dispersive/non-dispersive option. This would be necessary, if really independent corrections or observations of all three frequencies shall be reconstructed.
- "Static" information as the coordinates can be extracted of the proposed message type and foreseen to be transmitted at a low rate. A therefore created extra message type format should include a network ID, the reference stations' IDs and coordinate differences. This would increase the throughput.
- The coordinate differences of the slave reference stations could alternatively represented by latitude-, longitude- and height differences related to one system refer-

ence ellipsoid (e.g. the WGS84). While a resolution in the millimeter level is necessary for the height, the resolution of the horizontal components can be held at a lower level, possibly 2.5 m. This helps to save some bits and so to increase the throughput.

- Suppose a larger number of slave reference stations. Their coordinate differences shall be transmitted in sequence, but related to the same epoch. This possibly takes longer than the update interval of the 20/21 messages of the master reference station, that are updated at a higher rate related then to more recent epochs. The potentially arising synchronization problems have to be discussed.

Finally one can state, that the proposed concept can mitigate or solve many of the problems of the existing concepts.

REFERENCES

Euler H-J., Goad C.C. (1991): On optimal filtering of GPS dual frequency observations without using orbit information. Bulletin Géodésique (1991) 65: 130-143, Springer-Verlag Berlin.

Han, S., Rizos, C. (1999): The impact of two additional civilian GPS frequencies on ambiguity resolution strategies. 55th National Meeting U.S. Institute of Navigation, "Navigational Technology for the 21st Century", Cambridge, Massachusetts, 28-30 June, pp. 315-321.

Hatch, Jung, Enge, Pervan (2000): Civilian GPS: The Benefits of Three Frequencies. GPS Solutions Volume 3, Number 4, Spring 2000, pp. 1-9.

Jäggi A., G. Beutler, U. Hugentobler (2001): Using Double Difference Information from Network Solutions to Generate Observations for a Virtual GPS Reference Receiver. Paper presented at the IAG 2001 Scientific Assembly, 2 - 7 September 2001 - Budapest, Hungary.

Large, Goddard, Landau (2001): eRTK: A New Generation of Solutions for Centimeter-Accurate Wide-Area Real-Time Positioning. Trimble Navigation Limited, Dayton, Ohio.

Rizos, C., Han, S., Chen, H.Y. (2000): Regional-scale multiple reference stations for real-time carrier phase-based GPS positioning: a correction generation algorithm. Earth, Planets & Space, 52(10), pp. 795-800.

RTCM (2001): RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service, First Committee Draft, Future Version 2.3, under development by RTCM Special Committee No. 104, march 22, 2001.

Townsend B, K. Van Dierendonck, J. Neumann, I. Petrovski, S. Kawaguchi, and H. Torimoto (2000): A Proposal for Standardized Network RTK Messages. Paper presented at ION GPS 2000, Salt Lake City.

Vollath U., A. Buecherl, H. Landau, C. Pagels, B. Wagner (2000/1): Multi-Base RTK Positioning Using Virtual Reference Stations. Paper presented at ION GPS 2000, Salt Lake City.

Wanninger (1994): Der Einfluß der Ionosphäre auf die Positionierung mit GPS. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover Nr. 201.

Wanninger, L. (1999): The Performance of Virtual Reference Stations in Active Geodetic GPS-Networks under Solar Maximum Conditions. Proceedings of ION GPS 99, Nashville, S. 1419-1427.

Wübbena. G, A. Bagge, G. Seeber, V. Böder, P. Hankemeier (1996): Reducing Distance Dependent Errors for Real-Time Precise DGPS Applications by Establishing Reference Station Networks. Paper presented at ION 96, Kansas City.

Wübbena, G., A. Bagge, M. Schmitz (2000): GPS-Referenznetze und internationale Standards. Vorträge des 3. SAPOS-Symposium der Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland (AdV), 23.-24.Mai 2000, München, Germany, pp. 14-23.

Wübbena. G., S. Willgalis (2001): State Space Approach for Precise Real Time Positioning in GPS Reference Networks. Presented at International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, *KIS-01*, Banff, June 5-8, Canada.

APPENDIX: PROPOSAL FOR A RTK NETWORK RTCM MESSAGE TYPE 25 FORMAT

These appendices are related to the formats and contents of the proposed Message Type 25 messages as described in the sections above. Both the structures and the format examples have been created in a format identical to those detailed in RTCM 2.3 (RTCM, 2001).

Table. CONTENTS OF A PROPOSED TYPE 25 MESSAGE: RTK NETWORK CORRECTION DIFFERENCES

PARAMETER	NUMBER OF BITS	SCALE FACTOR AND UNITS	RANGE
GNSS TIME OF MEASUREMENT	3	0.1 s	0.0 to 0.5 s *(See Note 1)*
M = MULTIPLE MESSAGE INDICATOR	1	--	“0” – informs the receiver that this is the last message of this type (proposed 25) having this time tag “1” – informs the receiver that another message of this type (proposed 25) with the same time tag will follow
GS = GLOBAL SATELLITE SYSTEM INDICATOR *(See Note 2)*	2	--	“00” – Message is for GPS satellites “10” – Message is for GLONASS satellites “01” – Message is for GALILEO satellites “11” – reserved for future systems
NUMBER OF STATIONS TRANSMITTED	4	1	0 to 15 *(See Note 3)*
DIFFERENCING STATION ID	10	1	0 to 1023 *(See Note 4)*
ECEF DX CO-ORDINATE	18	2.5 m	±327677.5 m *(See Note 5)*
ECEF DY CO-ORDINATE	18	2.5 m	±327677.5 m *(See Note 5)*
ECEF DZ CO-ORDINATE	18 S = 74	2.5 m	±327677.5 m *(See Note 5)*
* ECEF DX CO-ORDINATE	30	1 mm	±536870911 mm *(See Note 5*)*
* ECEF DY CO-ORDINATE	30	1 mm	±536870911 mm *(See Note 5*)*
* ECEF DZ CO-ORDINATE	30 * S = 110	1 mm	±536870911 mm *(See Note 5*)*
P/C = CA-Code / P-Code INDICATOR	1	--	"0" – C/A-Code "1" – P-Code
SATELLITE ID	6	1	0 to 63 (if GALILEO uses >32 SV IDs)
DISPERSIVE OR NON-DISPERSIVE INDICATOR	1	--	"0" – Dispersive correction follows "1" – Non-dispersive correction follows *(See Note 6)*
CARRIER PHASE CORRECTION DIFFERENCE	16	1/256 cycle	±128 full cycles *(See Note 7)*
Total	$24xN_s+74$ * $24xN_s+110$		Coarse Reference Station Co-ordinate Resolution * Fine Reference Station Co-ordinate Resolution
PARITY	Nx6		

Note 1: GNSS TIME OF MEASUREMENT For this data slot only 2 bits are required, if a resolution of 1 Hz seems sufficient for customers and suppliers (to be decided)

Note 2: GS – GLOBAL SYSTEM INDICATOR The anticipated presence of Europe's GNSS GALILEO, and its additional signals, in around 2008 should be kept in mind. GALILEO is expected to be a multiple frequency system also.

Note 3: NUMBER OF STATIONS TRANSMITTED A maximum of 15 stations has been assumed as an extreme value. This value may only be reached in high-density monitoring networks.

Note 4: DIFFERENCING STATION ID Analogously to the Master Station ID in the header

Note 5: DIFFERENCING STATION CO-ORDINATES: RESOLUTION DEPENDENT There are two levels proposed for the resolution of the differencing station co-ordinates, 2.5 meters and 1 millimeter respectively. The former resolution would assist the rover in its interpolation of correction differences whereas the latter would allow the rover to 'reconstruct' the measurements of each slave reference station.

Note 6: DISPERSIVE OR NON-DISPERSIVE INDICATOR Identifies whether the carrier phase correction difference message contains corrections for the dispersive or the non-dispersive component.

Note 7: CARRIER PHASE CORRECTION DIFFERENCE The carrier phase correction differences are represented in L1 cycles for consistency. They are always related to the phase center, i.e. the Antenna Reference Point (ARP) of the reference stations involved (analogous to message type 24) corrected by the model type antenna PCVs (e.g. a "nullantenna"); in any case their antenna phase center behaviour has to be consistent with that of the master reference station. At a resolution of 1/256 of a cycle, 16 bits allows a range of correction differences of ±128 full cycles. This corresponds to ±25.3 meters in terms of L1 cycles.

FIRST TWO WORDS OF HEADER - (RTCM agreed standard) transmitted at the beginning of the message string

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th></th></tr>
<tr><td>1</td><td colspan="8">PREAMBLE</td><td colspan="6">MESSAGE TYPE
(FRAME ID)</td><td colspan="10"><i>MASTER REFERENCE</i>
STATION ID</td><td colspan="6">PARITY</td><td>Word 1</td></tr>
</table>

<table>
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<tr><td>2</td><td colspan="13">MODIFIED Z-COUNT</td><td colspan="3">SEQUENCE
NUMBER</td><td colspan="5">NUMBER OF
DATA WORDS</td><td colspan="3">STATION
HEALTH</td><td colspan="6">PARITY</td><td>Word 2</td></tr>
</table>

THIRD TO 7TH WORD - transmitted at the beginning of the proposed type message and includes satellite-independent data

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th></th></tr>
<tr><td>3</td><td colspan="3">GNSS
TIME OF
MMENT</td><td colspan="1">M</td><td colspan="2">G S</td><td colspan="4"># OF STNS
TRANSMITTED</td><td colspan="10">DIFFERENCING STATION ID</td><td colspan="4">ECEF DX
CO-ORD</td><td colspan="6">PARITY</td><td>Word 3</td></tr>
</table>

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th></th></tr>
<tr><td>4</td><td colspan="24">ECEF DX
CO-ORDINATE (cont)</td><td colspan="6">PARITY</td><td>Word 4</td></tr>
</table>

<table>
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<tr><td>5</td><td colspan="2">ECEF DX
CO-ORD
(cont)</td><td colspan="22">ECEF DY
CO-ORDINATE</td><td colspan="6">PARITY</td><td>Word 5</td></tr>
</table>

<table>
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<tr><td>6</td><td colspan="8">ECEF DY
CO-ORDINATE (cont)</td><td colspan="16">ECEF DZ
CO-ORDINATE</td><td colspan="6">PARITY</td><td>Word 6</td></tr>
</table>

<table>
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<tr><td>7</td><td colspan="14">ECEF DZ
CO-ORDINATE (cont)</td><td colspan="10">FILL / SPARE</td><td colspan="6">PARITY</td><td>Word 7</td></tr>
</table>

EACH SATELLITE - 1 WORD for the Dispersive as well as for the Non-dispersive component

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th></th></tr>
<tr><td></td><td colspan="1">P-C</td><td colspan="6">SATELLITE
ID</td><td colspan="1">D/
N-D</td><td colspan="16">CARRIER PHASE
CORRECTION DIFFERENCE (L1 cycles)</td><td colspan="6">PARITY</td><td>Word Ns + 7</td></tr>
</table>

Figure. PROPOSED MESSAGE TYPE 25 - RTK NETWORK CORRECTION DIFFERENCES