GNSS Solutions:

A new version of the RTCM SC-106 standard, the probability of solving integer ambiguities.

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle** and **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

The RTCM has announced a new version of its widely used differential GPS (DGPS) standard. Why did the group decide a new standard – Version 3 – was needed, and what are the benefits compared to Version 2?

Initially, the RTCM (Radio Technical Commission for Maritime Services) Subcommittee (SC104) Version 2 standard was developed with marine DGPS as the target application. One of the design goals for the RTCM SC 104 standard was to have correctional information readily available for user equipment. The outlines of the messages were specifically tailored for low bit rate data links.

Not until the beginning of the 1990s did RTK (real-time kinematic) surveying applications come into focus for RTCM. The committee drafted new RTK messages based on the proven DGPS messages. Although the DGPS messages only contain corrections, the RTK messages also allow transmission of raw observables from the satellite signals. RTCM tentatively published redundant means of disseminating precise RTK information with the aim of gaining practical experience during their implementation.

The first implementations by different manufacturers had diverse interoperability issues. For instance, various manufacturers have different sign conventions for representing the carrier phase observations, which resulted in incompatibilities when mixing receivers of different manufacturers.

The RTCM SC104 version 2.3 standard (the most recent version 2) inherited the legacy of the somewhat bulky data structure from previous versions. Despite this however, this version is well tested, and the raw observation messages and the correction messages for differential phase and pseudorange information are supported by a wide range of GPS surveying equipment.

In the mid-1990s the desire for shorter, more compact messages than the ones defined in version 2 arose and some manufacturers started to establish proprietary message structures for RTK operation. One of the motivations for developing these proprietary messages was to overcome the throughput limitation of the data links typically used in RTK surveying.

A full set of RTK messages of version 2.x requires a data link supporting 9600 baud. Because data throughput and transmission range are inversely proportional, a more compact means for disseminating the raw information was crucially needed for extending the distance from RTK reference stations that roving receivers could operate satisfactorily.

Today communication technology has changed in many parts of the world to GSM or mobile Internet. However, throughput remains a crucial issue. Version 3.0 has been developed with compactness of the messages in mind. The new message formats for RTK baseline operation have reduced the requirement for available throughput by 70 percent. Even though UHF (ultra-high frequency) data links are no longer the major means for disseminating the observation information, the compactness of the messages helps

RTCM SC104 changes version 2 versus 3 at a glance		
Feature	**Version 2**	**Version 3**
Data integrity checksum length / failures to detect corrupted messages	1 Byte 1 out of 256	3 Byte 1 out of 16777216
Throughput requirement for base-line observation information	Inherited message structure from DGPS with slack space	Reduced by 70% in comparison to 2.3
Coordinate information	Sub-millimeter precision only with 2 messages primarily used	One compact message used
Antenna referencing	Messages refer to a non-physical antenna phase center	Antenna Reference Point as used in the international scientific community avoids ambiguous height offsets
Network RTK support	Not defined	Master-Auxiliary Concept (MAC) with version 3.1
Correction of antenna phase center allowed	Not by standard document	In standard in conjunction with MAC with version 3.1
DGPS support	Yes	Messages are not yet defined
RTK raw data	Yes	Yes
Flag supporting Computed Reference Stations	No	Yes

reduce costs for mobile Internet communication via GPRS or other means.

Design changes and future plans for new improved global navigation satellite systems have also been considered in SC104 Version 3.0. The new standard avoids inadequate arrangements of the bit structure and ambiguities, while improving data integrity by use of a three-byte redundancy check instead of the one-byte check of Version 2.

Another important benefit comes from a change in the procedure for introducing new messages. With Version 2, if messages had not been fully tested, they were published in an official released document as tentative and open to change. These tentative messages led to difficulties in the marketplace due to inconsistent implementations by different manufacturers.

Beginning with Version 3.0, this practice is no longer used. RTCM SC104 work groups discuss and critically review new message proposals, and multi-stage interoperability tests are conducted. New messages are released in a standard document only after testing by several different manufacturers. Incompatibilities uncovered during testing of new V3.0 messages are resolved within the working group.

With Version 3.x, operators in the field using receivers from a specific manufacturer are able to operate confidently with DGPS services based on another manufacturer's equipment. Major incompatibilities do not exist as in the past.

In the last decade new approaches for RTK have been developed. Throughout the world diverse permanent reference station networks have been established or are planned. Processed information from these networks can be disseminated to rovers to improve the performance of field systems.

Although such applications have not officially been part of the SC104 standard, they often used RTCM message formats for packaging the derived data, based on proprietary information in a non-standard way. Such applications have undoubtedly improved on traditional baseline techniques; however, such nonstandard practices have prevented further advancements in processing algorithms because details of the information preparation were not publicly available.

These proprietary methods only achieve maximum performance when both rover and network applications are from the same manufacturer. Without a clearly defined standard, optimal performance of mixed-equipment operation is often prevented because of lack of tuning opportunities for rover firmware manufacturers.

With the forthcoming RTCM SC104 Version 3.1 document, to be published shortly, an interoperable definition for network RTK operation is available for the first time. Using the new standard, network RTK services providers can serve their customers with reliable information regardless of the brand of equipment their customers are using.

The new suite of messages is based on the so-called Master-Auxiliary Concept (MAC). RTCM interoperability testing verified that two different commercial reference station networking software packages, with identical input information, can produce identical content for network RTK messages when using the new standard. User equipment in the field receiving these V3.1 network RTK messages will be able to perform optimally regardless of the provider software solution.

Because of legacy reasons, V2.x has a variety of ways to provide sub-millimeter coordinates for reference stations; Version 3 makes these available in a single compact message. Older message types refer the coordinates to an antenna phase center while the newer message allows for proper antenna definition. Version 3 also avoids ambiguous height offsets between different antenna correction files used by the reference station and the rover. Furthermore, an additional flag has been introduced in the coordinate message to signal to the user that computed observation information referring to a non-physical (computed) reference station is being received.

Eventually SC104 will prepare a follow-up Version 2.4 because of legacy issues for DGPS operation. Infrastructure, especially at coastlines, has been build to support marine navigation. This infrastructure cannot be converted easily to newer versions due to limitations in available frequencies for transmission and the vast amount of navigation equipment relying on version 2.x. Version 3.1 will remain the preferred standard for RTK applications.

Editors' note More information on the concept of network RTK information dissemination is available online from the IAG (International Association of Geodesy) Working Group 4.5.1: Network RTK at <http://www.network-rtk.info/euler/euler.html>.

DR. HANS-JÜRGEN EULER

Since 1993 **Dr. Hans-Jürgen Euler** has been with Leica Geosystems in Heerbrugg, Switzerland, where he is a Leica Research Fellow. His research interests are with GNSS, especially Galileo and combination with other sensors such as INS or digital imaging for positioning and navigation. Euler has actively participated in RTCM SC104 discussions since 1996.

What is the probability of correctly resolving integer ambiguities and how can it be evaluated?

Resolving, or "fixing", carrier phase ambiguities to integer values is ultimately based on statistical assumptions and testing. As such, a probability is associated with resolving any particular ambiguity correctly. Evaluating the probability of correct fix (PCF), that is, the probability that the ambiguities are fixed to the correct integer values, is particularly important for safety-critical applications where an incorrect ambiguity fix would produce hazardously misleading information (HMI).

In fixed-ambiguity carrier phase processing, the usual procedure is to begin by estimating the carrier phase ambiguities as real-valued ("float") parameters and then to determine their integer values. A difficulty with this method is that, although the least-squares adjustment or Kalman filter used to estimate the real-valued ambiguities provides an estimate of their quality (a covariance matrix), it is not obvious how to obtain an estimate of the quality of the integer ambiguities.

In most carrier phase ambiguity estimation methods, integer quality is validated using some sort of statistical test. These generally involve testing the least-squares sum-squared residuals of the best fitting integer solution against the second best fitting solution. The test statistic is then compared against a threshold value, the idea being that if the best solution is sufficiently better than the second-best solution, then it must be correct.

However, validation tests are only relative measures for comparing two candidate solutions and do not evaluate the probability that a given solution is correct. A more rigorous approach is to use the covariance matrix of the float ambiguities along with knowledge of the ambiguity resolution technique used to derive a statistical estimate of the probability of correct fix.

Ambiguity Pull-In Region

Although the ambiguities themselves are unique, the ambiguity resolution process is not, and it is possible to define many different functions to map an n-dimensional space of real numbers to an n-dimensional space of integers (where n is the number of ambiguities to be resolved). It is helpful to consider what is called an ambiguity pull-in region. A pull-in region is the volume S_z in ambiguity space surrounding a particular integer combination, where for a given ambiguity mapping function $M : \mathbb{R}^n \mapsto \mathbb{Z}^n$, all float solutions y in that volume will be mapped to the particular integer solution z.

$$S_z = \{ y \in R^n | z = M(y) \}, \quad z \in Z^n \quad (1)$$

The simplest pull-in region to visualize is the pull-in region of ambiguity resolution by rounding. In this case, the pull-in region is an n-dimensional box, extending from (N – 0.5) to (N + 0.5) in each direction, where N is the (rounded) integer ambiguity value. Any float solution that is located in this box will be mapped to the integer at the center of the box.

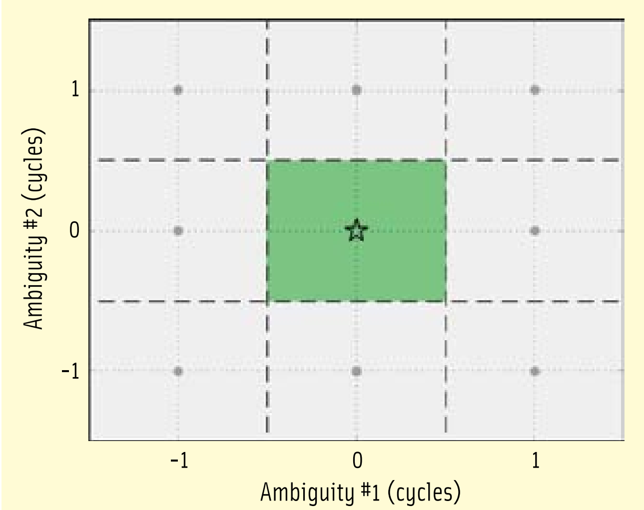


FIGURE 1 Pull-in region of ambiguity rounding (green) for integer combination (0,0) denoted by a star

The pull-in region for the rounding approach is shown in **Figure 1** for the two-dimensional case. Other ambiguity resolution strategies can have differently shaped pull-in regions.

Probability of Correct Fix

The probability that a given float ambiguity solution, $\hat{a}$, is mapped to particular integer ambiguity solution, z, can be computed by integrating the probability density function (PDF) of the float ambiguities, $p_{\hat{a}}(x)$, over the pull-in region associated with the integer solution z

$$P(\hat{a} \in S_z) = \int_{S_z} p_{\hat{a}}(x)dx \quad (2)$$

The probability of correct fix is the special case where $z = a_{true}$

$$PCF = P(\hat{a} \in S_z | z = a_{true}) = \int_{S_{a_{true}}} p_{\hat{a}}(x)dx \quad (3)$$

For ambiguity resolution by rounding, this multi-dimensional integral is simple to evaluate because the integration domain (i.e., pull-in region) is easily defined and is shown in **Figure 2**. Of course, rounding is rarely used in ambiguity resolution because it is only effective when the ambiguities are not highly correlated, which is rarely the case. Most modern ambiguity resolution methods make use of an integer least-squares search method.

Unfortunately, the pull-in region for integer least-squares is not easily defined, making integration of the float ambiguity PDF over the region difficult. To overcome this, researchers — for instance at the Technical University of Delft, The Netherlands — have developed theoretical bounds for the probability or correct fix of integer least-squares that are easy to calculate.

In particular, a lower bound for the PCF can be obtained from the PCF of integer bootstrapping (described in the next paragraph), and an upper bound on probability of correct fix can be derived from the determinant of the float ambiguity covariance ma-trix. Usually the lower bound is of more interest than the upper since the lower bound can be used to guarantee a minimum level of confidence in the solution.

Integer bootstrapping is a method of ambiguity resolution in which ambiguities are successively rounded to their nearest integer value, conditioned on all previously rounded ambiguities. This is usually accomplished by rounding the most precisely known ambiguity to the nearest integer and then decorrelating that ambiguity from the remaining float ambiguities. The remaining ambiguities are sequentially rounded and decorrelated until all of the ambiguities have been fixed (rounded). For this reason this method is sometimes called sequential integer rounding. The conditional standard deviations $\sigma_{i|I}$ (i.e., the standard deviation of ambiguity *i*, conditioned on the previous ambiguities being fixed) are obtained as a by-product of this process and are then used to compute the lower bound on the probability of correct fix as

$$PCF \geq \prod_{i=1}^{n} \left[2 \cdot \Psi\left(\frac{1}{2\sigma_{i|I}} \right) - 1 \right] \quad (4)$$

where $\Psi(x)$ is the area under the normal distribution described mathematically as

$$\Psi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left[-\frac{1}{2} n^2 \right] \cdot dn \quad (5)$$

An important detail of this approximation is that the bootstrapping bound will more closely approximate the integer least-squares probability of correct fix if the ambiguities are more decorrelated. One method to accomplish this is to use an integer linear combination, such as the decorrelating function of the Least-squares AMBiguity Decorrelation Adjustment or LAMBDA method developed at TU Delft, to re-parameterize the ambiguities before bootstrapping.

In general, use of LAMBDA decorrelation results in a tighter bound for probability of correct fix. One should keep in mind, however, that the LAMBDA decorrelation function is not unique; a change in the linear combination used may cause a relatively large increase or decrease in the computed lower bound from epoch to epoch even though the true (but unknown) bound has only minimally changed.

As a final note, the PCF approximation presented in equation (4) assumes that the float ambiguities have an expected error of zero and are normally distributed. This means the PDF of the float ambiguities is symmetric about the pull-in region, thus producing the relatively simple form of the equation shown.

Applying this equation when the statistical assumptions do not hold true will yield less accurate PCF estimates. This may happen, for example, if the float ambiguities are biased due to large differential atmospheric errors, or if the errors are not normally distributed. In these situations, care should be exercised when interpreting PCF estimates. Alternatively, equation (2) could be evaluated with full consideration for the biases and/or the ambiguity PDF, although such an approach will be computationally expensive.

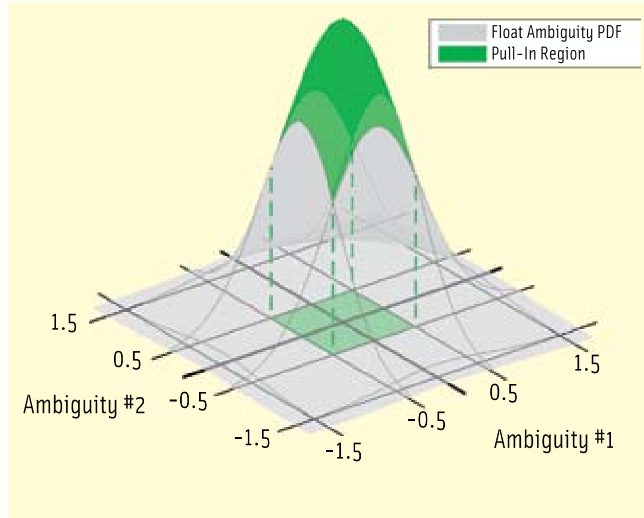
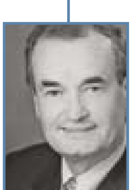


FIGURE 2 **Integrating ambiguity PDF over the pull-in region for ambiguity rounding**

Mark Petovello is a Senior Research Engineer in the Department of Geomatics Engineering at the University of Calgary. He has been actively involved in many aspects of positioning and navigation since 1997 including GNSS algorithm development, inertial navigation, sensor integration, and software development.

Email: mpetovello@geomatics.ucalgary.ca



Professor Gérard Lachapelle holds a CRC/iCORE Chair in Wireless Location in the Department of Geomatics Engineering at the University of Calgary. He has been involved with GNSS since 1980 and has received numerous awards for his contributions in the area of differential kinematic GPS and indoor location.

Email: lachapel@geomatics.ucalgary.ca

Editors' Note For more information about integer bootstrapping, the LAMBDA method or assessing PCF, visit the website of the Mathematical Geodesy and Positioning group at Technical University of Delft at <http://www.lr.tudelft.nl/live/pagina.jsp?id=c637235b-081a-4c15-8428-ee4f6bf3f705&lang=en>.

Studies assessing PCF are also available at the website of the Position, Location And Navigation (PLAN) group at the University of Calgary <http://plan.geomatics.ucalgary.ca>

Correction

In response to an article in the July/August "GNSS Solutions" column on the availability of Galileo receivers, Javad Ashjaee, CEO of Javad Navigation Services, wrote: "Our chip cannot generate the codes as specified in the Galileo ICD. In tracking a satellite one must generate identical code pattern as the satellite and then try to shift the code to align it with the incoming signal. When we cannot generate the code, then there is no chance to track that satellite.

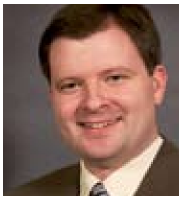
"After seeing Galileo's official ICD, in all of our advertisements we took out the claim that the GeNiuSS chip can track Galileo satellites."

Because the GeNiuSS chip technology is licensed from Topcon Positioning Systems (TPS), we asked TPS for comment on the subject.

In reply, Eduardo Falcon, TPS senior vice-president of product development, wrote: "Topcon G3 GNSS technology is able to receive all signals currently available and to provide the option to receive all signals available in the foreseeable future, including Galileo. Topcon engineers have successfully tested the world's first production model receivers (GR-3 and Net-G3) tracking GPS, GLONASS, and the GIOVE-I signal."

As *Inside GNSS* went to print, we had not received a reply to a follow-up question seeking details on the future Galileo signal option as it applies to TPS's current G3 Paradigm GNSS chip.

KYLE O'KEEFE AND MARK PETOVELLO



Kyle O'Keefe is an assistant professor in the Department of Geomatics at the University of Calgary, where he completed his Ph.D. in 2004. His research interests include GNSS ambiguity resolution and ground-based wireless location.

Mark Petovello is the co-editor of "GNSS Solutions." His biographical details can be found on page 24. IG