Civilian GPS: The Benefits of Three Frequencies

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A third civil frequency at 1176.45 MHz will be added to the Global Positioning System (GPS). This new frequency will bring a number of benefits. The aviation user will be one of the prime beneficiaries because the new frequency is in a protected aviation band. Thus, the system will be more robust against interference and jamming.

The carrier-phase differential user will also be a prime beneficiary as long as his application has a reasonably short baseline. It is this high accuracy use that is explored in some depth. The process of forming linear combinations of both the code and carrier-phase measurements is studied, and the benefits and problems are explained.

INTRODUCTION

As part of the modernization of the Global Positioning System (GPS), a new signal will be made available to the civilian community. This signal will have a frequency of 1176.45 MHz. This new signal is sometimes designated as the L5 signal but will be identified as the Lc signal within this paper. In addition, the modulation of the L2 signal at 1227.60 MHz will be changed to include a C/A code identical to the C/A code on the L1 signal at 1575.42 MHz. While existing receivers can access the L2 signal, they do so by employing proprietary techniques that suffer considerable degradation in signal-to-noise. The modification will allow easy access to the L2 signal without this signal-to-noise penalty.

The addition of a new frequency and an upgrade to the second frequency were motivated by a number of factors. One of the primary factors was the need to provide a measurement of the ionospheric refraction to the aeronautical users. Providing redundancy of signals to overcome intentional or unintentional signal interference or jamming was a second important factor. Because the ionospheric refraction is inversely proportional to the square of the frequency, it can be removed if measurements are available on at least two frequencies. While expensive receivers that use the current L1 and L2 signals to remove the ionospheric refraction effects are available, they are not considered adequate for aviation use for several reasons. First, and most significant, the L2 band is not a protected band for aviation use. In addition, with the current modulation on the L2 signal and the significant signal-to-noise degradation encountered by the unauthorized civilian user, even a small amount of interference is sufficient to make the signal unavailable, particularly at low elevation angles. The modification of the code modulation on the second frequency will increase significantly the availability of the second frequency. However, for the aviation community a protected band is still a necessity because of safety-of-life considerations. The Lc frequency meets this requirement.

A third frequency for GPS was championed also by the surveying and precise navigation user community. A

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third civil frequency could make it much easier to resolve the whole-cycle ambiguities—which is required to enable the centimeter-level accuracy available from carrier-phase differential GPS. There was some conflict in the particular choice of a third civil frequency. Some wanted a frequency relatively close to either the existing L1 or L2 frequencies so that differencing the new frequency with the nearby frequency would lead to a wavelength of several meters and allow single-epoch resolution of the ambiguities over distances short enough to ignore differential ionospheric refraction effects. Others (Enge & Hatch, 1998; Ericson, 1999; Hatch, 1996) wanted a frequency separated significantly from the existing L1 and L2 frequencies. Such a scheme would allow the resolution of the whole-cycle ambiguities for both the existing (L1–L2) difference frequency (wide-lane) and for a second difference frequency formed from Lc and either L1 or L2. These two different ambiguity-resolved wide-lane measurements would have ionospheric refraction effects sufficiently different as to allow for a refraction correction without unduly amplifying the noise. The ability to remove ionospheric refraction effects would allow the baseline separation distance between reference receiver and user receiver to be extended to continental distances. Ambiguity resolution is currently limited to 10 to 20 km separation distances, a limit inside of which refraction effects can be ignored. Unfortunately, no available frequency could be identified that was significantly removed (approximately 300 MHz) from L1 and L2 and that also met the requirements of a secure aviation frequency band. Thus, those desiring a nearby frequency were winners by default.

FUNDAMENTALS

As indicated previously, the benefits of three frequencies arise from two considerations. First, multiple frequencies provide redundancy in the event of either intentional or unintentional electromagnetic interference or jamming. This is quite significant, particularly to the aviation user. Second, multiple frequencies can be of significant benefit in quickly resolving the whole-cycle ambiguities of the carrier-phase measurements. These whole-cycle ambiguities must be resolved before the very high accuracy of carrier-phase differential GPS can be realized. The process of resolving the whole-cycle ambiguities is much easier when one can form "wide-lane" differences (beat frequencies) with lower effective frequency and hence longer wavelength whole-cycle ambiguities. It is this latter aspect that we wish to consider in detail in this paper.

Complicating the process of ambiguity resolution are several error sources that must be considered in some detail. These include ionospheric and tropospheric refraction as well as multipath (signal reflection) and receiver tracking noise.

Table 1 lists the most significant signal and signal-combination characteristics that are of interest. The first column specifies the signal or signal combination. The second column gives the associated frequency, and the third column gives the associated wavelength. The last two columns give the relative magnitude of the ionospheric refraction encountered by the signals; first relative to the amount suffered by the L1 carrier signal and then relative to the difference in ionospheric refraction between the L1 and L2 signals.

If the code measurements—P1, P2, and Pc—are scaled into the units of the corresponding carrier-phase wavelengths, a table virtually identical to Table 1 can be constructed for the code measurements and their principal combinations. (Without the scaling, the frequency-weighted differences and frequency-weighted averages must be formed to get equivalent ionospheric dependence.) However, the sign of the ionospheric refraction error is of opposite sign to that of the carrier-phase measurements.

Of course, the code measurements differ from the carrier-phase measurements in a number of important ways. First, as indicated previously, the ionospheric refraction effects are of opposite sign. Second, the code measurements are typically about two orders of magnitude noisier than the carrier-phase measurements. Depending on receiver design, the tracking-loop noise in the carrier-phase measurements will usually be less than one mm.

The principal and very significant advantage of the code measurements is that no whole-cycle ambiguities need be determined.

Multipath effects are also about two orders of magnitude larger on the code measurements than on the carrier-phase measurements and generally dominate the fundamental receiver tracking noise. When multipath effects are present, the carrier-phase noise in double-differenced measurements will generally be between 3 and 10 mm one sigma. New receiver designs with carrier-phase multipath mitigation may reduce this noise by a factor of three. Further, the multipath-induced errors have time correlations, typically in the multiple minutes and, hence, require significant aver-

TABLE 1

Characteristics of carrier-phase signals and principal combinations

Signal	Frequency MHz.	Wavelength meters	Ionospheric error relative to L1	Ionospheric error relative to L1/L2 Diff.
L1 Carrier	1575.42	0.1903	1.0	1.5457
L2 Carrier	1227.60	0.2442	1.6469	2.5457
Lc Carrier	1176.45	0.2548	1.7932	2.7718
L1 – Lc Difference	398.97	0.7514	–1.3391	–2.1501
L1 – L2 Difference	347.82	0.8619	–1.2833	–1.9836
L2 – Lc Difference	51.15	5.8610	–1.7185	–2.6563
(L1 + L2) Sum	2803.02	0.1070	1.2833	1.9836

aging time for any substantial averaging benefit to accrue. These errors are also significantly larger at the low elevation angles.

TWO-FREQUENCY BACKGROUND

Before discussing the benefits of using three-frequencies further, it is worth reviewing the situation with the existing L1 and L2 frequencies. Two principal techniques have been developed to resolve the whole-cycle carrier-phase ambiguities. The first technique, referred to as the "Geometry-Free" or "Measurement-Space" technique, uses smoothed code measurements to determine the whole-cycle ambiguities of the carrier-phase measurements. The second technique, referred to as the "Geometry-Dependent" or "Position-Space" technique, uses a search process to determine which combination of whole-cycle ambiguities give the "best" solution according to some criteria, typically a minimum sum square of the residuals.

Resolving the whole-cycle ambiguities using the geometry-free technique is accomplished by determining the difference between the code measurement and the carrier-phase measurement. This difference is used to determine (generally by simple rounding) the whole-cycle ambiguity of the carrier-phase measurement. Because of the much larger (multipath colored) noise in the code measurements, the determination of the whole-cycle offset requires that either the code or the code/carrier difference be smoothed over multiple epochs (Hatch, 1982). A similar, but generally shorter, smoothing of the code measurements is needed for the geometry-dependent approach, not to determine the whole-cycle ambiguity directly but to provide a decreased uncertainty in the initial code position so that the subsequent ambiguity-search process can be more tightly constrained.

Tropospheric refraction effects cause both the code and the carrier-phase measurements to be increased in value. The error induced in the measurements is much larger at the low elevation angles than at the high elevation angles. Fortunately, a large percent of the error can be removed by modeling. But significant error can still remain. This error affects the geometry-dependent technique of whole-cycle ambiguity resolution because it causes the measurement residuals to grow as the residual differential tropospheric error increases. By contrast, because the code and carrier-phase measurements are affected equally by the troposphere, the geometry-free method of whole-cycle ambiguity resolution remains unaffected. This is a significant advantage for the geometry-free approach.

A second advantage for the geometry-free approach is that the ambiguity resolution can be done on a satellite-by-satellite basis. However, the geometry-dependent approach needs at least five satellites visible, else a position fix with residuals cannot be computed and one has no measure of the goodness of the solution.

For the moving user, a third advantage accrues to the geometry-free approach. Because the code and carrier are both affected equally by movement, that movement has no effect on the code/carrier difference, which is used to determine the whole-cycle ambiguity. However, depending on the implementation strategy, the geometry-dependent approach may need to propagate the position forward in time when the user is moving.

The geometry-dependent approach does seem to have one advantage over the geometry-free approach. Specifically, the geometry-dependent approach has fewer degrees of freedom, that is, only four independent whole-cycle ambiguity values are needed to obtain a position solution (Hatch, 1990). By contrast, the geometry-free approach requires that the whole-cycle ambiguity be determined independently for each satellite. However, rather than a negative, this characteristic of the geometry-free approach can be used to advantage in the ambiguity verification process.

It is generally highly desirable that the whole-cycle ambiguity values be verified in some manner. This verification process is needed to insure against an incorrect value, which could result in a significantly biased position. The verification process in the geometry-dependent approach generally consists of finding the two sets of whole-cycle ambiguity values, which result respectively in the two smallest values of root-sum-square (rss) of residuals. Only when the ratio of these two smallest values of rss residuals exceeds a selected threshold is the set with the smallest rss residuals chosen as the correct set. Thus, the verification process for the geometry-dependent technique can cause the time required to obtain a verified set of ambiguities to increase significantly. By contrast, the geometry-free approach will generally take longer to obtain a complete set of whole-cycle ambiguity values. But because the ambiguity values are individually independent, they can be used immediately to compute a position and will generally not result in a position with small rss residuals unless all of the values are correct. Thus, because of the greater degrees of freedom, the verification process for the geometry-free technique is much simpler.

The advantages seem to favor the geometry-free approach and, as we shall see, this is even more the case when three frequencies are available.

CASCADED WHOLE-CYCLE AMBIGUITY RESOLUTION

The geometry-free technique of whole-cycle ambiguity resolution with two frequencies has been described briefly. Over short distances (less than 10 to 20 km) the ionospheric refraction error at the reference station receiver is strongly correlated with the error at the user receiver. Thus, the error is essentially removed when the differential corrections are applied (or when the measurement differencing across receivers is done). This allows one to use the geometry-free technique to resolve the longest whole-cycle ambiguities and then to use the results to step successively to the smaller wavelengths (Forsell et al., 1997; Volath et al., 1998).

The First Step

Obviously, the whole-cycle ambiguities should be easiest to resolve when the wavelength is the longest. Thus the (L2–Lc) carrier-phase measurement should be easiest to resolve since it has a wavelength of 5.86 m. In fact, any of the code measurements should be accurate enough to determine the 5.86 whole-cycle ambiguity over short distances. However, the frequency-weighted average of the P2 and Pc code measurements is specifically recommended for two reasons. First, an average of the code measurements is more accurate than either measurement alone when both measurements have approximately the same noise statistics. (There are indications that the code measurement, Pc, may be significantly more accurate because of the new signal structure and additional signal power. In which case the Pc code measurement can be used over considerable distances.) Second, the frequency-weighted average of the two code measurements has an ionospheric refraction induced error that is exactly the same as the error induced in the carrier-phase measurement differences over the same two frequencies. Thus, even though the short-distance case where the ionospheric errors cancel is of the most interest, it is desirable, all else being equal, to cover the long-distance case as well. The recommended equation for solving the 5.86-m whole-cycle ambiguity is then:

$$N_{5.86} = \frac{f_2 P_2 + f_c P_c}{\lambda_{5.86}(f_2 + f_c)} - (L_2 - L_c) \tag{1}$$

where we have used P to denote the code measurements and L to denote the carrier-phase measurements—both are assumed to have been corrected using the reference receiver measurements and, hence, to have noise proportional to single differences. Note that the 5.86 whole cycle ambiguity is just the difference of the L2 and Lc whole-cycle ambiguities. Implementation of this equation should allow the resolution of the whole-cycle ambiguity in a single epoch for both short and long separation distances between the reference and user receivers.

The Second Step

The ambiguity-resolved whole-cycle (L2–Lc) measurement, scaled into meters, will be about 35 times noisier, because of amplifying effects, than the L2 and Lc single difference measurements scaled into meters. This maps into a noise level of 7 to 25 cm one sigma for most receivers. Receivers with the noise level near the lower end of this range can now use this measurement to resolve the ambiguities of the next shorter wavelength, that is, the 86 cm (L1–L2) measurement in a single epoch. Receivers with the higher noise level should use a multiple-second average of Equation (1) before rounding and stepping to the 86 cm wavelength measurement. Jung (1999) gives equations that relate the probability of successful ambiguity resolution to the standard deviation of the noise and the amount of round-off present when the computed value of the whole-cycle is converted to an integer. He also shows graphs of the code noise as a function of averaging time. Because of the colored nature of the multipath noise, the reduction does not decrease as the inverse square root of the number of epochs for either code or carrier-phase measurements.

With modern multipath-mitigation receivers the frequency-weighted average of the L1 and L2 code measurements approaches the accuracy of the ambiguity-resolved (L2–Lc) measurement. Further, it has the added advantage that the ionospheric error is exactly matched to the (L1–L2) carrier-phase measurement. Thus, it is valid to use it over very long separation distances and for long smoothing intervals. However, as noted in Table 1, the scaling of the ionospheric refraction error is not a lot different for the (L2–Lc) measurement and the (L1–L2) measurement. This means one can step from the one to the other over substantial separation distances and the Equation (2) can be smoothed (averaged) for several hundred seconds before any significant bias would arise from differential ionospheric effects. The equation to step from the (L2–Lc) measurement to the (L1–L2) measurement is:

$$N_{0.86} = (L_2 - L_c + N_{5.86})\frac{\lambda_{5.86}}{\lambda_{0.86}} - (L_1 - L_2) \qquad (2)$$

The alternative equation to use while the third frequency is still unavailable or to use for very long distances and/or for long averaging intervals is:

$$N_{0.86} = \frac{f_1 P_1 + f_2 P_2}{\lambda_{0.86}(f_1 + f_2)} - (L_1 - L_2) \qquad (3)$$

The noise in the whole-cycle resolved (L1–L2) measurement, scaled to meters, is about 6 times larger than the noise in the L1 and L2 measurements when scaled to meters. Thus, this ambiguity-resolved measurement will generally have noise between 2 and 4 cm, plus any bias that is present from the residual differential ionospheric refraction.

The Third Step

Because the (L1–Lc) wavelength is not much shorter than the (L1–L2) wavelength, it is generally possible to skip the second step above and step directly to the (L1–Lc) measurement. This gives:

$$N_{0.75} = (L_2 - L_c + N_{5.86})\frac{\lambda_{5.86}}{\lambda_{0.75}} - (L_1 - L_c) \qquad (4)$$

Again, if one were interested in determining the seventy-five-centimeter whole-cycle over very long separation distances, one could implement the equivalent of equation (3) which gives:

$$N_{0.75} + \frac{f_1 P_1 + f_c P_c}{\lambda_{0.75}(f_1 + f_c)} - (L_1 - L_c) \qquad (5)$$

Finally, because the noise in the (L1 – L2) measurement is small compared to the 75 centimeter wavelength of the (L1 – Lc) carrier-phase measurement, implementing the true third step could be done without any averaging of the following equation:

$$N_{0.75} = (L_1 - L_2 + N_{0.86})\frac{\lambda_{0.86}}{\lambda_{0.75}} - (L_1 - L_c) \qquad (6)$$

The noise in the whole-cycle resolved (L1–Lc) measurement will be about the same as the noise in the whole-cycle resolved (L1–L2) measurement. Over long distances it will have a slightly larger bias due to the greater differential ionospheric refraction error.

Before going on to the next step we need to make a very important point. The aviation user because of safety-of-life considerations will probably not want to depend on receiving the L2 signal. But even at long distances the aviation user could still determine his whole-cycle ambiguity by averaging Equation (5) for a long time interval. Even though a considerable ionospheric bias would be present in the resolved measurement, if the reference receiver is located at the airport where the aviation user intends to land, the ionospheric bias in the aviation receiver solution would decrease to a negligible value as he approached the airport—and the 2 to 4 cm one sigma accuracy is more than adequate for landing.

The Fourth Step

The fourth step is the critical step. With between 2 and 4 cm accuracy, one would expect that the results of either the second or third step could be used to step easily to a final narrow-lane solution—and such is the case for short distances between reference and user receivers. It is this fourth step that limits the distances to less than 10 to 20 km of separation distance. The reason is the large sensitivity to the differential ionospheric refraction effects. Table 1 shows that the difference frequencies have a large negative sensitive to the ionospheric refraction, while the primary frequencies have a large positive sensitivity.

Short Distances

For short distances one can step to any one of the three primary carrier frequencies, or to an average of any two, or to an average of all three. Stepping to one of the averages reduces the phase noise somewhat since the multipath is independent on the different frequencies. There is no benefit to picking the widest of these primary carrier-phase measurements first because the widest is also the measurement most sensitive to the differential ionospheric error. For illustrative purposes and because it can be performed using currently available dual-frequency data, the equation for determining the whole-cycle ambiguity of the average of the L1 and L2 carrier-phase measurements using the ambiguity-resolved (L1–L2) carrier-phase measurement is given:

$$N_{0.21} = (L_1 - L_2 + N_{0.86})\frac{\lambda_{0.86}}{\lambda_{0.21}} - (L_1 + L_2)/2 \qquad (7)$$

Once the ambiguities are resolved the position accuracy obtained is a function of the residual ionospheric error and, hence, a function of the separation distance. For the shortest distances the receiver carrier-phase multipath error dominates and the accuracy for most receivers is between a few millimeters and one centimeter one sigma.

Long Distances

At long distances, the 2 to 4 cm accuracy of either the 75- or 86-cm wide-lane carrier-phase measurement is adequate for most purposes. The problem is that a residual differential ionospheric refraction bias is also present, which increases as the separation distance increases. One needs to be able to form a refraction-corrected ambiguity-resolved carrier-phase measurement in order to remove this ionospheric bias.

With two frequencies, only two carrier-phase and two code measurements are available. These two measurements can be made independent in the range and ionospheric-error space by forming the frequency-weighted average and frequency-weighted difference of the code measurement and by forming the average and difference of the carrier-phase measurements. As seen previously, the frequency-weighted average of the code measurement has an ionospheric refraction error that exactly matches that of the carrier-phase difference. This was the basis of Equation (3). It is also true that the frequency-weighted difference of the code measurements has an ionospheric error that exactly matches that of the average of the carrier-phase measurements. In fact, the ionospheric refraction error of these two measurements is of the same magnitude, but of opposite sign to, the first two measurements. Thus, if we can find the whole-cycle ambiguity in the average of the carrier-phase measurements, we can form a refraction-free measurement by averaging the result with the ambiguity resolved carrier-phase difference. The equation to resolve the whole-cycle ambiguity for the average carrier-phase is:

$$N_{0.21} = \frac{f_1 P_1 - f_2 P_2}{\lambda_{0.21}(f_1 - f_2)} - (L_1 + L_2)/2 \qquad (8)$$

Note that if $N_{0.86}$ is odd then $N_{0.21}$ will have half integer values. But once $N_{0.21}$ is known it can be multiplied by two to give $N_{0.107}$ the whole cycle ambiguity for the sum frequency.

The real problem is that the frequency-weighted differencing process amplifies the noise in the code measurements. And this very noisy code measurement is used to attempt to resolve a narrow whole-cycle ambiguity. Thus, an accuracy of a few centimeters one sigma is needed. It turns out that this is practically impossible to accomplish. By the time one has averaged Equation (8) over very long intervals, biases, such as clock divergence between the L1 and L2 channels (which affect the sum and differences in opposite fashion), will develop and the required accuracy in the code measurement cannot be achieved. Furthermore, since this is the only measurement orthogonal to the carrier-phase difference measurement in the range/ionospheric refraction error space, it cannot be found for any other combination that would allow a refraction-corrected measurement to be formed.

One could consider using a geometry-dependent search process to resolve the refraction-free cycle ambiguities. It turns out that once the wide-lane, 86-cm ambiguities are resolved, a 10.7 cm whole-cycle ambiguity remains in the refraction-corrected result. That there is no way to change this 10.7 whole-cycle ambiguity using only the L1 and L2 measurements is shown by giving three different equations that can be derived directly.

$$(L_1 - L_2 + N_{0.86})\lambda_{0.43} + (L_1 + L_2 + N_{0.107})\lambda_{0.107} = \rho \tag{9}$$

$$(L_1 - L_2 + N_{0.86})\lambda_{0.484} + (L_1 + N_1)\lambda_{0.107} = \rho \tag{10}$$

$$(L_1 - L_2 + N_{0.86})\lambda_{0.377} + (L_2 + N_2)\lambda_{0.107} = \rho \tag{11}$$

where ρ is the pseudorange and contains no ionospheric-refraction error. In these three equations the whole-cycle ambiguity value, $N_{0.86}$, is known. But the second whole-cycle ambiguity is unknown and needs to be resolved in the search process. In each case, it has an effective ambiguity whole-cycle value of 10.7 cm. But over large separation distances (broadcast) orbit errors will clearly be too large to obtain positions with the required few centimeter accuracy. Tropospheric errors would also be difficult to remove to the required accuracy.

This analysis was done for the existing two-frequency situation. What about the situation when three frequencies are available? It turns out that because the Lc frequency is so close to the L2 frequency, no significant benefit is obtained to assist in the refraction-correction process. The L1/Lc pair of frequencies can be used together in a manner completely parallel to the L1/L2 pair. But this pair has exactly the same problem as far as obtaining a refraction-corrected result is concerned. L2 and Lc are so close together that the two difference frequencies with L1 cannot be used for refraction correction because of the large refraction-correction multiplier that results. Thus with the specific three frequencies chosen, it remains impossible to perform a refraction correction process.

A covariance analysis with five states, pseudorange, ionosphere delay and three integer ambiguities, and six double-difference measurements (code and carrier-phase measurements from three frequencies) is carried out to investigate effects of differential ionosphere delay on integer cycle ambiguity resolution. Geometry-free, cascaded whole-cycle ambiguity resolution is used, with assumptions that multipath and receiver noise of carrier phase measurements are 1% of their wavelength. For code measurements, 30 cm is used as one sigma value of multipath and receiver noise. It is also assumed that differential ionosphere delay has a linear gradient of 3 part per million. Troposphere delay is canceled out in geometry free approach. Figure 1 shows results of this analysis.

As expected, due to increase in differential ionosphere delay, a user can resolve the cycle ambiguity of Lc carrier phase measurement only up to 2 km from the reference station, the L1–L2 cycle ambiguity up to 7 km from the reference station, and the L2–Lc cycle ambiguity beyond that with 99.999999% success rate. For a 99.9% success rate, it is possible for a user to resolve the Lc cycle ambiguity up to 4 km from the reference station, and the L1–L2 cycle ambiguity beyond that baseline distance.

The most successful real-time process that has been used to extend the range of carrier-phase differential navigation has been to use multiple reference stations together with ionospheric modeling. Estimation of the ionospheric gradient using a single reference station also shows promise (Jung, 1999). Some such ionospheric modeling will still be required when three frequencies are available.

CONCLUSIONS

Substantial benefits will derive from the addition of a third frequency to the GPS system. Aviation will be one of the prime beneficiaries. For the first time a protected second frequency will be available to the aviation user and measured ionospheric-refraction effects can be made to the code and differential-code measurements. Also the presence of redundant signals to combat interference and jamming will be of significant benefit.

Carrier-phase differential users will be able to resolve the whole-cycle ambiguities much more quickly—often in a single epoch when employed over short distances. The longer distance user of carrier-phase differential measurements will see limited gains from the new frequency. However, some significant benefit can be expected for particular applications. This was illustrated by the use of the wide-lane (e.g., 75 cm) resolved measurement for landing of aircraft. When the reference receiver is at the airport, the ionospheric bias error will be insignificant at exactly the time when maximum accuracy is desired. ■

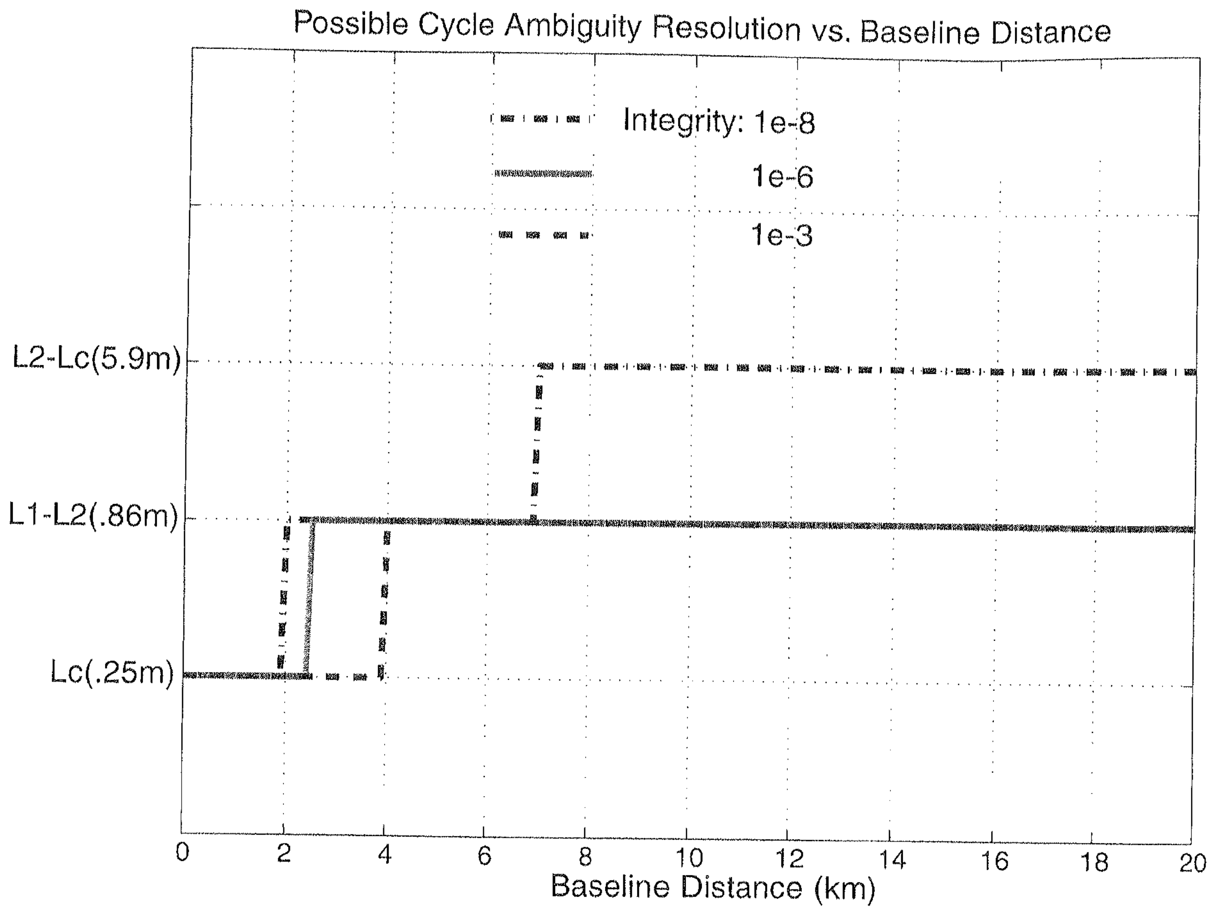

FIGURE 1.

REFERENCES

Enge, P. & Hatch, R. (1998). Benefits of second and third civil frequencies. In Proceedings of the 1998 National Technical Meeting (pp. 31–40). Alexandria, VA: The Institute of Navigation.

Ericson, S. (1999). A study of linear phase combinations in considering future civil GPS frequencies. In Proceedings of the 1999 National Technical Meeting and 19th Biennial Guidance Test Symposium (pp. 677–686). Alexandria, VA: The Institute of Navigation.

Forsell, B., Martin-Neira, M., & Harris, R. (1997). Carrier phase ambiguity resolution in GNNS-2. In Proceedings of ION GPS-97, (pp. 677–686). Alexandria, VA: The Institute of Navigation.

Hatch, R. (1996). The promise of a third frequency. GPS World, 7(5), 55–58.

Hatch, R. (1990). Instantaneous ambiguity resolution. In Proceedings of the KIS Symposium (pp. 299–308). Banff.

Hatch, R. (1982). The synergism of code and carrier measurements. In Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning (pp. 1213–1232). Las Cruces, NM: New Mexico State University.

Jung, J. (1999). High integrity carrier phase navigation for future LAAS using multiple civilian GPS signals. In Proceedings of ION GPS-99 (pp. 14–17). Alexandra, VA: The Institute of Navigation.

Volath, U., Birnbach, S., Landau, H., Fraile-Ordonez, J.M., & Martin-Neria,M. (1998). Analysis of three-carrier phase ambiguity resolution (TCAR) technique for precise relative positioning in GNSS-2. In Proceedings of ION GPS-98, (pp. 1213–1231). Alexandra, VA: The Institute of Navigation.

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Dr. Boris Pervan is an Assistant Professor of Mechanical and Aerospace Engineering at the Illinois Institute of Technology in Chicago. He received his B.S. from the University of Notre Dame, his M.S. from the California Institute of Technology, and his Ph.D. in Aeronautics and Astronautics Engineering from Stanford University, all in aerospace engineering. Previously, he was a Mission Analyst at Hughes Space and Communications Group and served as Project Leader for Local Area Augmentation System (LAAS) research and development at Stanford. Dr. Pervan was the 1996 recipient of the RTCA William E. Jackson Award. His research is focused on high-integrity differential GPS.

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