Defining Primary, Secondary, Additional Secondary Factors for RTCM Minimum Performance Specifications (MPS)

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1.0 Introduction

The Radio Technical Commission for Maritime Services (RTCM) Special Committee 127 (SC127) is currently working on the minimum performance specifications (MPS) for enhanced Loran (*eLoran*) maritime receiver. The MPS defines the requirements that an *eLoran* receiver must meet in order to support harbor entrance approach (HEA).

HEA requires a high level of accuracy with 95% error levels of around 10 meters. To achieve such a performance, the *eLoran* user will require an additional secondary factor (ASF) grid and differential Loran. The grid corrections accounts for spatial variations in ASF. Differential Loran corrects for temporal variations in the nominal primary, secondary and additional secondary factors (PF, SF, ASF, respectively). As such, it is important to have consistent definitions of these factors. It allows for smoother transitions for different regimes of operations (such as from areas with and without differential Loran). It also gives receiver manufacturers and service providers a common standard so that ASF grids and differential corrections can be generated in a way that can be consistently applied throughout the world.

This paper presents the definitions and equations for PF, SF, and ASF to be used for RTCM receiver MPS. It discusses rationale for these choices. In particular, it highlights issues and discrepancies with past definitions, particularly in the PF. In also addresses other issues such as discontinuities in the past definition of the SF and clarifies the accounting for handling ASF. An additional point is that while all the definitions for PF, SF, ASF can be specified in terms of distance or time, RTCM will specify in terms of time and use the speed of light, c, to convert to and from distance.

2.0 Primary Factor

Traditionally, primary factor (PF) is the term that accounts for the time of propagation of the Loran signal through the atmosphere. This is given in equation (1) with being the index of refraction for air (η). For the determining the primary factor, RTCM SC127 has decided that the *eLoran* MPS will use:

- Speed of light, free space (c) = 299792458 m/s
- Speed of light, atmosphere (vpf) = 299691162 m/s
- Index of refraction in atmosphere (η) = 1.000338

The reason why this needs to be clearly defined is because several other values have been used in the past. The *Loran User Handbook* provides a value of the speed of light in the atmosphere as 161,829 nautical miles/second (nm/sec) [2]. This value comes from Bowditch and is equivalent to 299707308 m/s [3]. This is equivalent to η being 1.000284. On the other hand, the United States (U.S.) Coast Guard Loran-C signal specifications uses a value η = 1.000338 in Appendix A[4]. Additionally, Johler, as early as 1958, discussed using η = 1.000338 [5][6]. The fact is that one definition is not necessarily more correct than the other. The index of refraction for air can vary with values, with its value typically around 1.0003. While there is no one correct value, for the sake of having consistent ASF grid and differential corrections, a set and agreed upon value should be used.

$$PF(\sec) = \frac{d}{vpf} = \frac{d}{\left(\frac{c}{\eta}\right)} = \eta \frac{d}{c} \qquad \textbf{(1)}$$

An alternative definition of PF is also found in the literature. Traditionally, PF has been defined as the propagation time of the Loran signal through the atmosphere (see Equation 1). The alternative definition specifies PF as the difference in propagation time between a signal traversing through vacuum versus the atmosphere. This definition is seen in Equation 2. Figure 1 shows how the components of measured time of arrival break down given the definition. For the MPS, either definition is sufficient – they depend on the same parameters and are can be easily derived from each other. Hence it does not matter which is used as long as the full time of propagation through the atmosphere is accounted for. However, the alternative definition is the one used by the Brunavs equation when it calculates PF. Since the Brunavs equation will be used for calculating SF (Section 3), this alternate definition may be preferred by manufacturers.

$$PF_{alternate}(\sec) = \frac{d}{vpf} - \frac{d}{c} = \eta \frac{d}{c} - \frac{d}{c} = (\eta - 1)\frac{d}{c} \qquad \textbf{(2)}$$

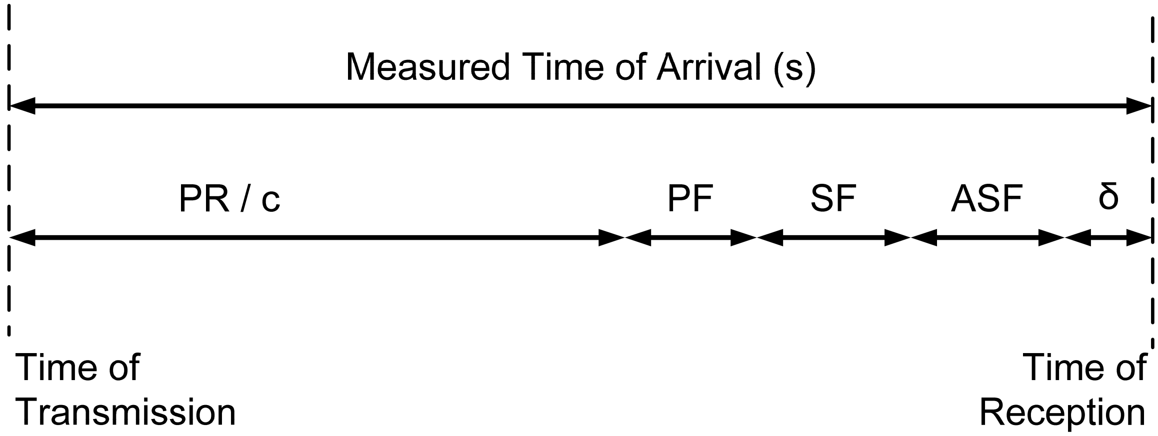

Figure 1. Components and factors affecting measured time of arrival using alternative definition of PF.

3.0 Secondary Factor

Secondary factor (SF) accounts for the difference in propagation time from a Loran signal propagating over an all sea water path rather than through the atmosphere. The MPS prescribes a specific equation for calculating SF which differs from the one given in the *Loran User Handbook*.

The *Loran User Handbook* provides for the calculation of SF using a Harris polynomial given in Equation 1 where *d* is the distance in statute miles. The discontinuity can result in a jump in SF of about three meters at 100 statute mile from the transmitter. This is seen in Figure 2. Such a discontinuity is not acceptable for the precise navigation required for HEA. The discontinuity is minimized if the transition from the top to bottom equation occurs at 117.35 statute mile (188.866 km). However, there is still 3.75 nsec or more than 1 meter of discontinuity.

$$SF(\mu\text{sec}) = \begin{cases} -.01142 + 0.00176d + {}^{.510483}\!/_{d} & d \le 100 \text{ statute mile} \\ -.40758 + 0.00346776d + {}^{24.0305}\!/_{d} & d \ge 100 \text{ statute mile} \end{cases} \qquad \textbf{(3)}$$

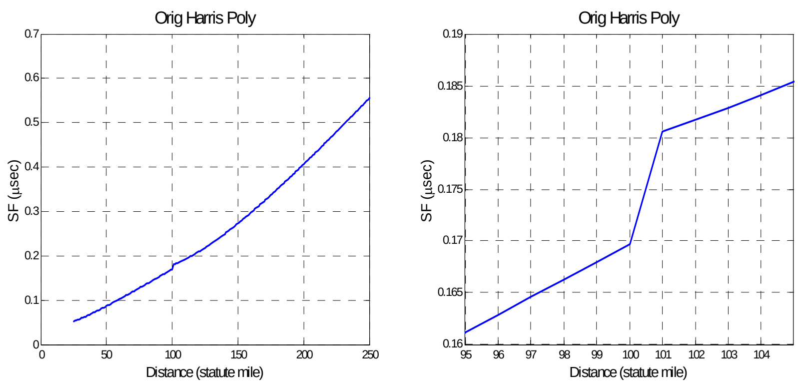

Figure 2. Harris Polynomial for Secondary Factor [2], Zoom around 100 statute mile (Right)

Two possibilities for eliminating the discontinuity are possible. The first is to modify the existing Harris polynomial to eliminate the discontinuity. Our modification is seen in Equation 4 where *d* is meters. Equation 4 can be reduced many significant digits, as seen in Equation 5, without causing a large difference (>> a meter). The second is to use a version of Paul Brunavs phase lag model given in Equation 6 where *D* is the distance in meters divided by 10000 [7]. The Brunavs model accounts both the primary factor (η = 1.000338) and secondary factor. The PF used in Brunavs follows the alternative definition. The RTCM definition for PF is consistent with the assumption used in Brunavs. Both models are plotted in Figure 3 and the difference between two options is plotted in Figure 4. The models are similar but with differences of up to 6.6 m (22 nsec), they are not interchangeable. Both are acceptable and SC127 decided to use Brunavs since its derivatives are continuous.

$$SF(\sec)=\begin{cases}\left[-11.42+0.001124619720830351d+{}^{821542.753152}\!/_{d}\right]\bullet 10^{-9} & d\le 188.866174464km\\ \left[-407.58+0.002154766165592937d+{}^{38897092.75541760}\!/_{d}\right]\bullet 10^{-9} & d\ge 188.866174464km\end{cases} \quad \textbf{(4)}$$

$$SF(\sec)=\begin{cases}\left[-11.42+0.00112462d+{}^{821543}\!/_{d}\right]\bullet 10^{-9} & d\le 188.866km\\ \left[-407.58+0.00215477d+{}^{38897093}\!/_{d}\right]\bullet 10^{-9} & d\ge 188.866km\end{cases} \quad \textbf{(5)}$$

$$Brunavs_{PF+SF}(m)=-111+98.2D+(13.0D+113.0)e^{\frac{-D}{2}}+\frac{2.277}{D} \quad \textbf{(6)}$$

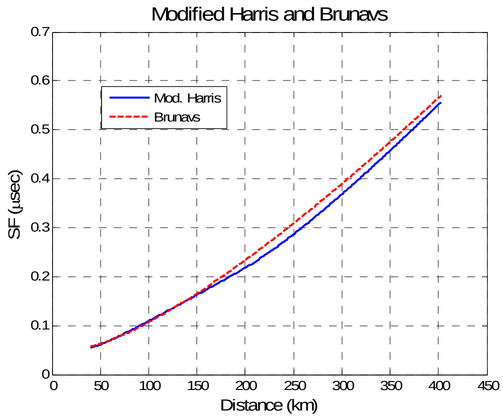

Figure 3. Two Options for Continuous SF: Modified Harris Polynomial and Brunavs (SF term only)

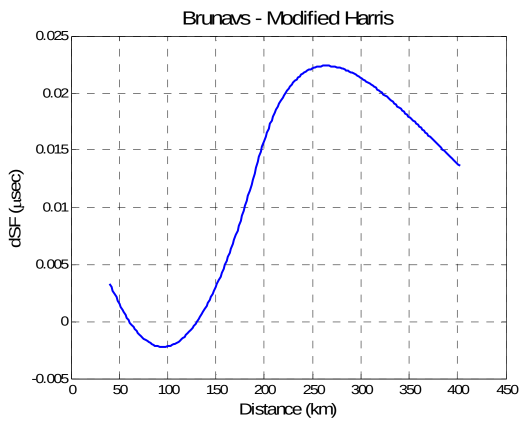

Figure 4. Difference between Secondary Factor calculated using Modified Harris Polynomial and Brunavs

4.0 Additional Secondary Factor

Additional secondary factor (ASF) is the extra delay on the time of arrival (TOA) of the Loran signal due to propagation over nonhomogenous, rough land path rather than an all seawater path. This delay can be significant and a rough estimate is useful so that stand alone Loran can achieve absolute accuracies in the tens to hundreds of meters. Additionally, ASF can vary significantly spatially and temporally. To achieve HEA level accuracies, ASF grid and differential Loran corrections are used to account for the spatial and temporal variations, respectively. The MPS proposes that service providers issue three forms of ASF compensation: 1) nominal ASF, 2) local ASF grid, 3) differential Loran corrections. The full compensation is shown in Figure 5 and is given by Equation 7.

$$corr(x,t) = NomASF(x) + GridASF(x) + diffLoran(t) \qquad \textbf{(7)}$$

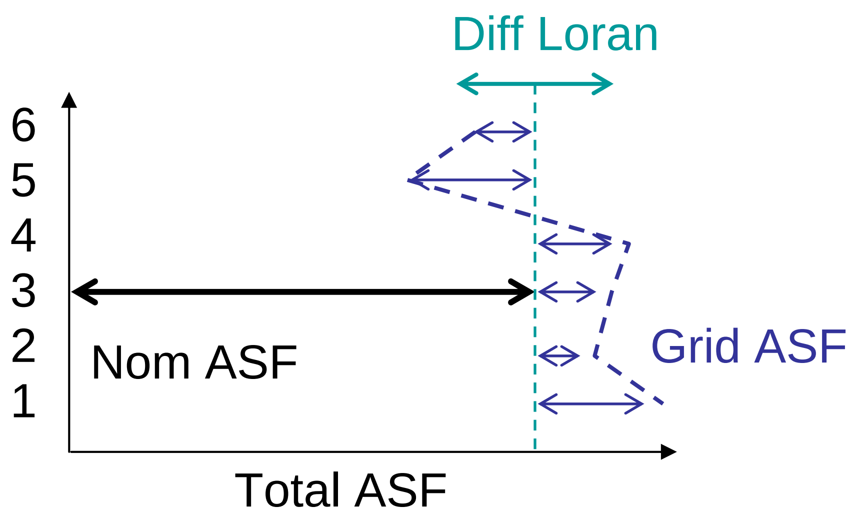

Figure 5. Definition of components to ASF

Nominal ASF is a seasonally averaged value of ASF for a “large” region. This is a coarse value that can serve a region that is tens or hundreds of square kilometers in area. The idea is that the service provider publishes a table of these values for the entire service volume covered by their Loran system. These values are useful for increasing the accuracy of eLoran receivers regardless of whether they apply differential corrections or not. For areas supporting HEA, this value may be the seasonal average or nominal measured ASFs of the local monitor site(s) supporting differential Loran corrections. The measurements can also be used with tools such as BALOR to determining other values [9].

The use of a nominal ASF is beneficial for two reasons. The first is that it allows for a reasonably smooth transition of the position solution when a user traverses from an area supporting HEA to one without. HEA support means having an ASF grid and differential Loran corrections. Second, it allows for better utilization of the data channel by accounting for much of the ASF common to all locations in the region. In that way, the dynamic range of the differential correction message can be better utilized. Notionally, the locations where the nominal ASF values may be provided are the black dots in Figure 6. Figure 6 is for illustrative purposes and is not intended to convey the actual locations for the nominal ASF and the ASF grids discussed next.

Figure 6. Nominal ASF and HEA ASF grid

The ASF grid is a grid indicating the relative local variations of ASF relative to the nominal value for the region. The grid ASF values are provided at intervals that are on the order of tens of meters. These locations are indicated on Figure 6 by the denser blue dot regions. Ongoing studies are being conducted to determine reasonable balance in terms of grid spacing [8]. Issue of data (IOD) may be used to align the nominal ASF database with the ASF grid.

Differential Loran corrections account for the residual ASF not corrected for by the previous two terms. In fact, these corrections also account for other slowly varying errors such as the residual errors from our PF and SF models as well as some transmitter errors. Again, recall that the index of refraction used for PF is only an estimate. But since both signal propagation path to the monitor station providing the corrections and the user receiver are roughly the same, the error will be eliminated by the corrections. For this reason, the term “differential Loran correction” rather than “ASF correction” is used as the correction does more than compensate for residual ASF.

Note that differential corrections may induce some errors as well. This is due to mismatches between monitor receiver and user receiver hardware and processing. While mandating matching equipment may reduce the errors, it would greatly constrain receiver manufacturers’ ability to innovate. Hence, some mismatches will occur and it is thought the resulting errors will be tolerable.

5.0 Other Clarifications

In creating the MPS, RTCM SC127 also found it useful to clarify other commonly used Loran terminology. The MPS often refers to the Standard Zero Crossing (SZC). It is defined as per the usual definition:

“The positive zero crossing at 30 microseconds of a positively phase coded pulse on the antenna-current waveform. This zero crossing is phase-locked to the Loran-C station’s cesium time reference. The standard zero crossing is used as a timing reference for measurement of Loran signal specifications.”

Another common sample point used in Loran is the Standard Sampling Point (SSP). It is defined as:

"The point on the Loran-pulse envelope that is 25 microseconds after the beginning of the pulse to which far-field field strength calculations or measurements are referenced. For the standard Loran pulse with 0.0 ECD, the amplitude at the standard sampling point is .506 times the peak amplitude."

While this is a common measurement point for Loran, it is traditionally used for measurements at the transmitter. For practical matters such as calculation of signal to noise ratio (SNR), the difference in strength at the SSP versus the SZC is less than one dB in amplitude or 1.83 dB in power. As a result, this term is not used in the receiver MPS.

6.0 Summary

RTCM SC127 is about the complete a draft of the enhanced Loran user receiver minimum performance specifications for harbor entrance and approach operations. This paper explains the basic models used to compensate for propagation delays. It also documents discuss the rationale behind the choice of those models with the hope of providing future generations a better understanding to how those models came to be.

7.0 Disclaimer

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security or any other person or organization.

8.0 Acknowledgments

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