Localization of Target Tracking and Navigation by Correcting Atmospheric Effects
Junho Choi and Sung Kwak
Integrated C4I Branch
U.S. Naval Research Laboratory
Washington, D.C. 20357

Abstract - For any type of target tracking and navigation, the localization is critical for tracking/navigation missions. The real-time localization error correction for the atmospheric refraction can be achieved through the ray bending compensation by the refractivity profiles or ray-tracing. Ray-tracing can be computed through the real-time weather data (surface temperature, pressure, and relative humidity or dew-point) from daily/hourly, local meteorology, or global climatology data. Operational results of this new technique indicate that the time difference of arrival (TDOA) of radio-waves vary dynamically in hours, days, months, seasons and geographically. Errors for the low elevation angles less than 10 degrees are much higher than expected for higher frequencies above 300 MHz, and it should be calibrated or corrected in tactical operation and strategic system implementation. The localization of tracking and navigation mission can be achieved within a couple of hundred meters if the integrity of measured tactical data is well within the confidence boundary.

I. Introduction

Radio signals that pass through the Earth’s atmosphere are sensitive to time delays and angle errors in the radio frequency (RF) signal propagation. If the signal does not travel in parallel with the air density gradient of the atmosphere, it is subject to the refraction, causing its path to deviate from a straight line. Geometrical bending of the signal path is greatly intensified in the low atmosphere, most notably the troposphere, due to the dynamic variation of air density near the Earth’s surface. This bending effect on atmosphere is significant at low (ground station-to-spacecraft) elevation angles (less than 10 degrees). Consequently, an improved modeling technique for propagation delay due to the bending effect of the atmosphere must be incorporated into the tracking and navigation mission for more accurate localization. For tracking and navigation systems, the localization depends on the measurement techniques and the way the system is mounted and deployed. The error correction for both time delays and angle of arrival can be achieved by means of radio wave ray bending compensation through the refractivity profiles or ray tracing computed through the real time weather data. In order to use weather information, the exponential tropospheric model (ETM model) had been developed at the U.S. Naval Research Laboratory in 1997. Since the initial development of the ETM model with improved climatology and meteorology databases, data analyses, model performance test, and tropospheric model integration with database have been conducted and published [1,2]. During this period, users from many services and national organizations have applied the NRL’s ETM model, implementing it into their respective systems. Feedback from various users has been encouraging and positive. In this paper, the ETM model and database are used to improve localization correction. Section II discusses the procedure of localization measure and troposphere delay with RF wave path bending. Section III shows the results of the application of the tropospheric program into the localization process. Section IV derives conclusions from this simulation effort.

II. Localization Measure with Troposphere Delay

The localization measure of the radio transmitter is mainly based on the techniques that relate to one or a combination of frequency and time information. The set of time delays (TDOA) associated with each of the RF wave fronts between receivers can be used to determine the source of location by solving a nonlinear equation or linear system equations:

\[ y = f(x) + v \]  

(1)

where \( y \) is measured TDOA, \( x \) is estimated geolocation, and \( v \) is measurement noise. The estimate of \( x \) is a matter of minimizing a cost function defined as the weighted sum of squared residuals:
\[ c(x) = c'(x)Wc(x) \]  (2)

where \( c(x) \) is the residual vector \((\tilde{r}(x) - y)\) for a given solution of \( x \) and \( t \) stands for transpose of a vector. The resulting iterative solution for \( x \) by the least-square estimate gives:

\[ x_{x+1} = x_{x} - [A'(x)WA(x)]^{-1}A'(x)We(x) \]  (3)

where \( A(x) \) is a partial derivative matrix of \( c(x) \) in equation (2) with respect to localization. \( W \) is noise covariance matrix.

For all cases, the covariance matrix \([A'WA]^{-1}\) at the final step gives the statistics of final position estimates. For the estimator of a two dimensional vector, such as position coordinates on the surface of the Earth, the bivariate covariance matrix can be expressed as:

\[ P = \begin{bmatrix} \sigma_i^2 & \sigma_{12} \\ \sigma_{12} & \sigma_j^2 \end{bmatrix} \]  (4)

and with the assumption that the error distribution is a Gaussian, the parameter of error ellipse with \( a = \) Semi-Major Axis (SMA) and \( b = \) Semi-Minor Axis (SMI) are determined by the equation as follows:

\[ a^2 = \frac{2[\sigma_i^2\sigma_j^2 - \sigma_{ij}^2]}{\sigma_i^2 + \sigma_j^2 - (\sigma_i^2 - \sigma_j^2)^2 + 4\sigma_{ij}^2} \]  (5)

\[ b^2 = \frac{2[\sigma_i^2\sigma_j^2 - \sigma_{ij}^2]}{\sigma_i^2 + \sigma_j^2 + (\sigma_i^2 - \sigma_j^2)^2 + 4\sigma_{ij}^2} \]

The axis direction is

\[ \theta = \frac{1}{2} \tan^{-1} \left( \frac{2\sigma_{ij}}{\sigma_i^2 - \sigma_j^2} \right) \]  (6)

The miss distance and uncertainty equation give,

miss distance: \((A'WA)'(A'W)e\)  
Uncertainty: \((A'WnA)^{-1}\)  (7)

where \( W_n \) is an inverse of the systematic covariance matrix.

III. Analysis Results

The TDOA analysis for target localization requires an accurate model of the time delay due to the changing velocity of RF wave with the refractivity variation in the troposphere region. The precise localization algorithm produces significant errors in computing the time delay at low elevation (less than 10 degrees). At negative elevation angle from the target to the spacecraft, current algorithm (using Hopfield model [3]) neglects atmospheric effect in estimating localization of the transmitter location. The ETM model uses the historical climatology weather data and an improved algorithm to provide a more accurate time delay profile. The time delay profile of the ETM model would provide better location and reduce the uncertainty associated with those inferred target positions. Figure 1 through 3 shows three different ellipse error probable (EEP 95%) plots for different elevation angle ranges in one test scan data set. In figure 1, the ellipse indicates the elevation angle from 9.08 degrees to 18.48 degrees. The miss distance of the ETM model is 1166.20 feet with the Hopfield model 3570.85 feet. In figure 2, the ellipse shows the elevation angle from 13.47 degrees to 31.49 degrees and then decreased to 15.66 degrees. The missing distance of the ETM model is 355.17 feet with the Hopfield model 667.20 feet. In figure 3, the ellipse presents the elevation angle from 17.77 degrees to negative 0.66 degree. The miss distance of the ETM model is 3428.26 feet with the Hopfield model 4406.05 feet. Figure 4 shows six ellipses in the same scale. The localization accuracy of the ETM model is reduced approximately 50% of the uncertainty as reflected in the SMA and the miss distance. We observed that the ETM model appears to improve localization accuracy of the target miss distance and to reduce in SMA (uncertainty in the calculated position). We can infer from these six events with different data sets that the ETM model reflects a significant improvement in the target miss distances and uncertainties (SMA and SMI).

IV. Conclusion

There are two dominant factors in tropospheric RF propagation, angular bending and time delay. These measurement errors can readily be corrected by means of ray-bending compensation through refractive profiles or ray tracing algorithms. The ray tracing algorithm can be computed by the real or near real-time weather data (i.e., surface temperature, pressure, and relative humidity or dew point). The ETM model has reduced errors of time delay and angle of arrival in near real-time or real-time bases.
The ETM model dramatically improves the localization accuracy errors more than 25% for miss distances and by 50% of target containment. The new algorithm (ETM model) has also improved the localization accuracy when the intentional interference or jamming has been applied to the intended RF transmission and reception in the atmosphere.

Reference

[1] Junho Choi and Sung Kwak, "Propagation Anomaly in the Tropospheric Atmosphere," IGARSS '98 Conference, July 6, 1998.

[2] Junho Choi, "Performance Comparison of Tropospheric Propagation Model: Ray Trace Analysis Results Using Worldwide Tropospheric Databases," Naval Research Laboratory, Washington, D.C., September 1997.

[3] H.S. Hopfield, "Two-quadratic Troposphere Refractivity Profile for Correcting Satellite Data," J. Geophysics Research. (18) pp. 4487-4499 (1969).