3D LOCALIZATION FOR LAUNCH VEHICLE USING COMBINED TOA AND AOA

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ABSTRACT

Generally, a ground telemetry station for launch vehicle (LV) has tracking function only; therefore, position measurements depend on radar. Time of arrival (TOA) and angle of arrival (AOA) are typical location techniques for emitting targets. In this paper, we propose a Combined TOA and AOA localization method for LV using two ground stations. When transmitter (Tx) time is not known, it is necessary to make virtual onboard timer for TOA estimation. The virtual onboard timer generates time stamps of streaming frame according to data rate. First station which is located in space center has no tracking function. But it can generate the virtual onboard timer. Second station has tracking function, so it generates AOA information. By solving sphere equation(s) of TOA from at least one station and a line equation of AOA, target position in three-dimensions (3D) can be obtained. We confirm the localization performance by means of comparison with an on-board GPS of a real launch mission.

Keyword: AOA, Ground Telemetry Station, Launch Vehicle, Localization, TOA.

1. INTRODUCTION

Various techniques have been proposed for location estimation, depending on the measurements collected by the wireless networking infrastructure. These techniques can be broadly classified as time-based and angle-based localization. Time of arrival (TOA) is a form of time-based localization, in which a circle centered on the base station (BS) is produced and the target position is determined by the intersection of at least three circles. Angle of arrival (AOA) uses angle-based localization, in which defines a line of bearing from the BS to the target is defined, and the position calculated from the intersection of a minimum of two bearing lines. Due to noisy measurements, the position is typically determined by statistical estimation, in which a set of nonlinear equations constructed from the TOA and/or AOA statistics is processed using knowledge of the BS geometry[1][2].

Generally, in a launch mission for a launch vehicle (LV), a ground telemetry station contains only tracking function, which uses an antenna control unit (ACU) to obtain the AOA from the

LV on the azimuth and elevation axes. There is no function for measuring the LV's range (or distance). Therefore, the 3D LV position measurements depend on radar or received on-board LV telemetry data. Each ground telemetry station is synchronized with GPS time, and its location has already been measured or synchronized with GPS position. Furthermore, since there is no time synchronization between the LV and ground stations, TOA measurement is not available. The on-board telemetry transmitter sends streaming frames, which include a frame counter.

Under the previous described conditions, we suggest a Combined TOA and AOA 3D localization method for LV, using two ground stations. First station which is located in space center has no tracking function. But it can generate virtual onboard timer to estimate TOA. Second station has tracking function, so it obtain AOA. We make nonlinear equations with the TOA and AOA, then solve these to find 3D position of LV.

The remainder of this paper is organized as follows. Section 2 describes typical localization methods, while section 3 provides details of the proposed proposed TOA and AOA method. In section 4, the performances of the proposed methods are evaluated by means of comparison with measured results from an on-board GPS during an LV flight test.

2. TYPICAL LOCALIZATION

2.1 TOA METHOD

If only time delay estimates are available, at least three or four stations are required for 2D or 3D localization, respectively. TOA algorithms are based on the signal delay from the target to station, in order to estimate the distance. Each distance estimate can be represented as a circle's radius, the center of which is the station's location. Therefore, we obtain a number of circles depending on the number of stations, and the point of intersection of all the circles is the target's position [3][4].

Let (x, y) be the coordinates of the unknown target and (x_i, y_i) those of i^{th} station, with $i = 1, 2, 3 \dots N$ and N being the number of stations; then, the distance between the target and station is

$$\widehat{d_i} = \sqrt{(x - x_i)^2 + (y - y_i)^2} + n_i, \tag{1}$$

where n_i is zero mean Gaussian; that is, $n_i \sim \left(\mathcal{N}\left(0, \sigma_{n_i}^2\right)\right)$.

Clearly, (1) is non-linear and can be solved by using iterative techniques; however, a linear least-squares method can also be used by first linearizing (1). Let $\hat{d}_i^2$ be the 2D noisy distance estimates:

$$\hat{d}_i^2 \approx (x - x_i)^2 + (y - y_i)^2 \tag{2}$$

Then, a reference station is selected and its distance equation is subtracted from (2) for $i = 1, 2, 3 \dots N$ $(i \neq r)$. Let d_r represent this reference station's reference distance. Hence, we obtain:

$$(x_i - x_r)x + (y_i - y_r)y = 0.5[(x_i^2 + y_i^2) - (x_r^2 + y_r^2) + \hat{d}_r^2 - \hat{d}_i^2] \tag{3}$$

In matrix form, we have:

$$\mathrm{A}_t u_t = 0.5\hat{b}_t, \tag{4}$$

$$\text{where } A_t = \begin{bmatrix} x_1 - x_r & y_1 - y_r \\ x_2 - x_r & y_2 - y_r \\ \vdots & \vdots \\ x_N - x_r & y_N - y_r \end{bmatrix} \in \mathbb{R}^{N\times 2}, \quad u_t = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^{2\times 1},$$

$$\hat{b}_t = \frac{1}{2}\begin{bmatrix} (x_1^2 + y_1^2) - (x_r^2 + y_r^2) + \hat{d}_r^2 - \hat{d}_1^2 \\ (x_2^2 + y_2^2) - (x_r^2 + y_r^2) + \hat{d}_r^2 - \hat{d}_2^2 \\ \vdots \\ (x_N^2 + y_N^2) - (x_r^2 + y_r^2) + \hat{d}_r^2 - \hat{d}_N^2 \end{bmatrix} \in \mathbb{R}^{N\times 1}.$$

The Moore-Penrose pseudo inverse is taken on both sides to obtain the location estimates:

$$\hat{u}_t = 0.5(A_t^T A_t)^{-1} A_t^T \hat{b}_t \tag{5}$$

2.2 AOA METHOD

If only angle estimates are available, only two or three stations are required for 2D or 3D localization, respectively. Each station forms a line on a 2D plane, on which the station and target are situated; hence, we obtain a certain number of lines depending upon the number of stations. The point of intersection of these lines is the target's estimated position. The AOA system generally exhibits effective results; however, the estimation error increases significantly as the target moves away from the stations [3][5].

Using the same notation as for TOA, we have

$$\hat{\theta}_i \approx \arctan\left[\frac{(y - y_i)}{(x - x_i)}\right] + m_i, \tag{6}$$

where m_i represents the zero mean Gaussian noise in the estimate of the i^{th} angle; that is, $m_i \sim \left(\mathcal{N}\left(0, \sigma_{m_i}^2\right)\right)$.

Equation (6) can be written in matrix form as

$$A_a u_a = \hat{b}_a, \tag{7}$$

$$\text{where } A_a = \begin{bmatrix} tan\,\hat{\theta}_1 & -1 \\ tan\,\hat{\theta}_2 & -1 \\ \vdots & \vdots \\ tan\,\hat{\theta}_N & -1 \end{bmatrix} \in \mathbb{R}^{N\times 2}, \quad u_a = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^{2\times 1},$$

$$\hat{b}_a = \begin{bmatrix} x_1 tan\,\hat{\theta}_1 - y_1 \\ x_2 tan\,\hat{\theta}_2 - y_2 \\ \vdots \\ x_N tan\,\hat{\theta}_N - y_N \end{bmatrix} \in \mathbb{R}^{N\times 1}.$$

For the standard linear least-squares estimator, the solution is given by

$$\hat{u}_a = (A_a^T A_a)^{-1} A_a^T \hat{b}_a \tag{8}$$

3. PROPOSED LOCALIZATION

3.1 Combined TOA and AOA

In this study, the TOA spheres of two station and AOA line are used for estimating a 3D point. Figure 1 shows that TOA spheres of two stations are intersected and it generate the intersected plane and circle.

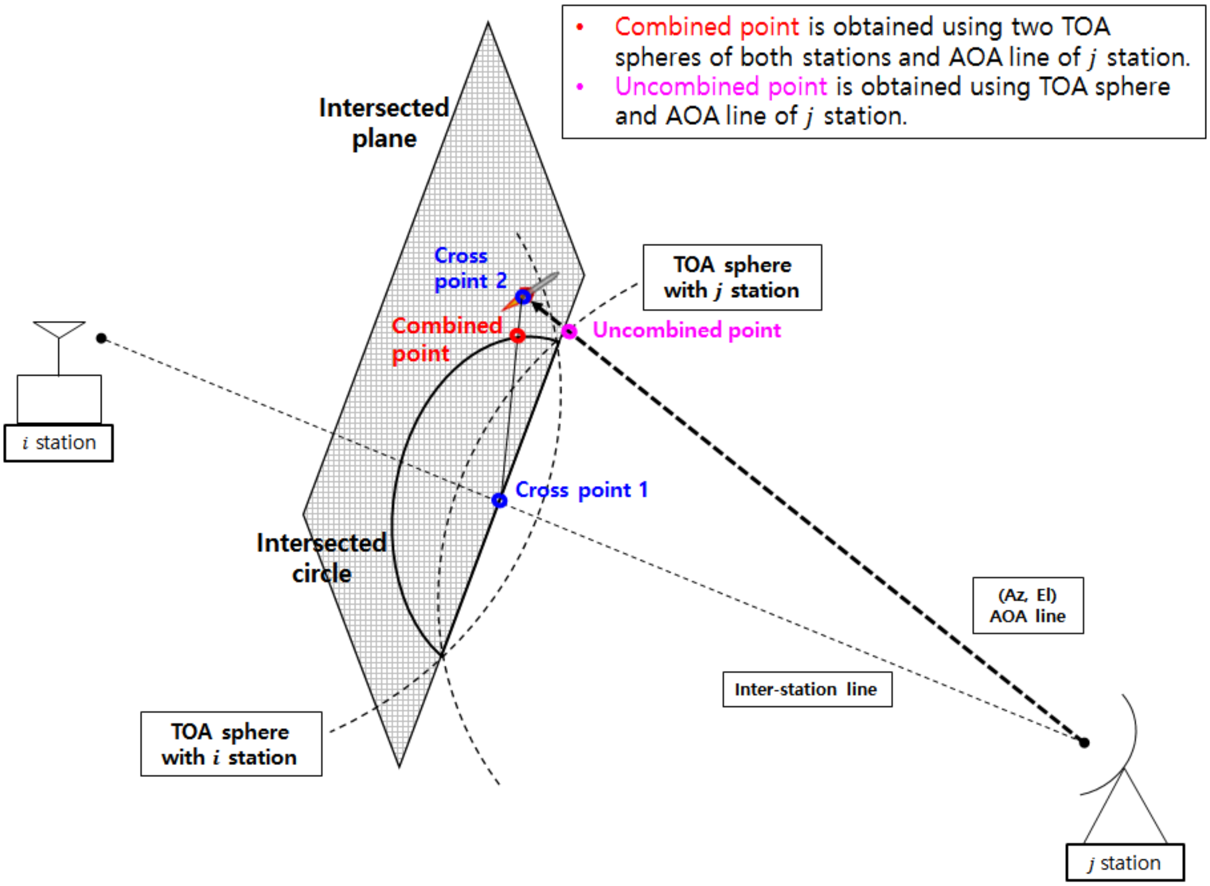

Figure 1. Combined TOA and AOA localization

In order to combine the TOA and AOA methods, we create sphere equations (9) and (10) with the estimated TOA range as radius, a connection line (11) between *i* and *j* station, and AOA line (12) at a reference station which is *j* station.

TOA sphere from *i* station:

$$r_i = (Tx - Rx_i) \times c$$
$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = r_i^2, \quad (9)$$

TOA sphere from *j* station:

$$r_j = \left(Tx - Rx_j\right) \times c$$
$$\left(x - x_j\right)^2 + \left(y - y_j\right)^2 + \left(z - z_j\right)^2 = r_j^2, \quad (10)$$

Inter-station line between *i* and *j* station:

$$\frac{x - x_j}{s_{xj}} = \frac{y - y_j}{s_{yj}} = \frac{z - z_j}{s_{zj}} = k$$

$$x = ks_{xj} + x_j,\ y = ks_{yj} + y_j,\ z = ks_{zj} + z_j, \tag{11}$$

AOA line of *j* station:

$$\frac{x - x_j}{a_{xj}} = \frac{y - y_j}{a_{yj}} = \frac{z - z_j}{a_{zj}} = t$$

$$x = ta_{xj} + x_j,\ y = ta_{yj} + y_j,\ z = ta_{zj} + z_j, \tag{12}$$

where i, j: station index,

$P_i(x_i, y_i, z_i)$, $P_j(x_j, y_j, z_j)$: point of each station,

r_i, r_j: TOA range,

c: speed of light; 299792458 (m/s),

$\vec{a}_j = (a_{xj}, a_{yj}, a_{zj})$: AOA unit vector, it is coordinate converted of $\overrightarrow{AOA}_j$ $(range_j = 1, El_j, Az_j)$, and

$$\vec{s}_j = \frac{P_i(x_i, y_i, z_i) - P_j(x_j, y_j, z_j)}{\left\| P_i(x_i, y_i, z_i) - P_j\left(x_j, y_j, z_j\right) \right\|_2}.$$

Intersection plane of the spheres of *i* and *j* station is obtained in (13) using equations (9) and (10).

$$x\left(x_i - x_j\right) + y\left(y_i - y_j\right) + z\left(z_i - z_j\right) = \frac{r_i^2 - r_j^2 - x_i^2 + x_j^2 - y_i^2 + y_j^2 - z_i^2 + z_j^2}{-2} \tag{13}$$

Cross point 1 is obtained in (14); cross point between the intersection plane (13) and inter-station line (11).

$$XP_1(x_1, y_1, z_1) = P_j\left(x_j, y_j, z_j\right) + k \cdot \vec{s}_j \tag{14}$$

(15) is radius of the circle on the intersection plane of *i* and *j* station

$$r = \sqrt{r_j^2 - k^2} \tag{15}$$

Cross point 2 is obtained in (16); cross point between the intersection plane (13) and AOA line (12).

$$XP_2(x_2, y_2, z_2) = P_j\left(x_j, y_j, z_j\right) + t \cdot \vec{\mathrm{a}}_j \tag{16}$$

Combined point can be obtained in (17) using two TOA sphere and a AOA line equations.

$$P(x, y, z) = XP_1(x_1, y_1, z_1) + r \cdot \overrightarrow{\mathrm{xp}}, \tag{17}$$

where $\overrightarrow{\mathrm{xp}}$ is unit vector between cross point 1 and 2.

Finally, combined range of the LV is obtained in (18)

$$r_{combined} = \overrightarrow{xp}_j \cdot \vec{a}_j, \quad (18)$$

where $\overrightarrow{xp}_j$ is line between j station and Combined point $P(x, y, z)$.

In this paper, we only estimate range information. There is no adjustment on the AOA information of j station. The combined range (18) is inner product between vector $\overrightarrow{xp}_j$ and AOA unit vector $\vec{a}_j$ of j station. This is estimated range information using two TOA sphere and an AOA line.

3.2 Test Configuration

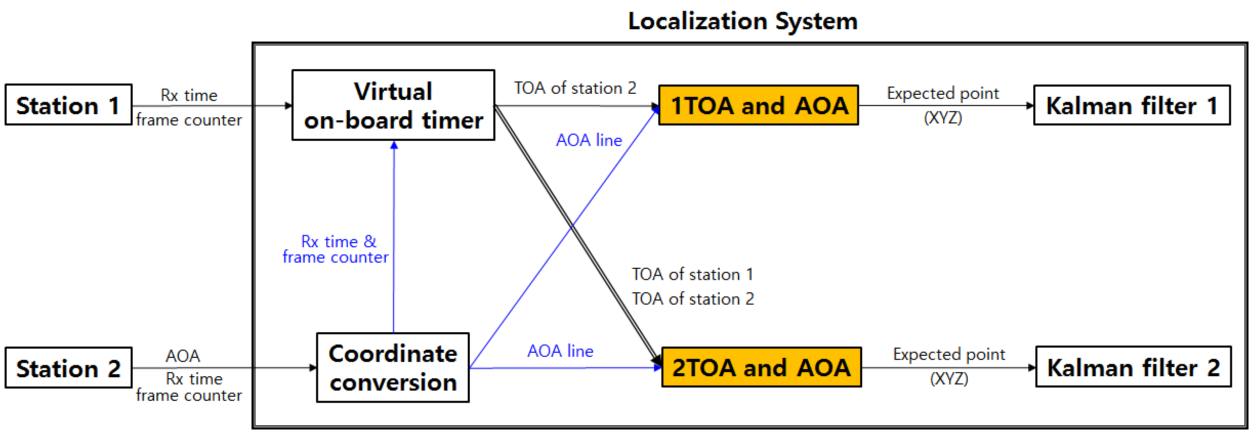

Figure 2. Proposed localization system.

In this study, we configure two ground telemetry stations. Station 1 is at the space center where the launch pad is located. It has no tracking function, but contains a wide beam to receive telemetry signals. Station 2 is located approximately 150 km from the space center. It contains a monopulse tracking beam of $\pm 0.4^{\circ}$ and exhibits a tracking accuracy of 0.05°. At Station 1, there is no AOA information, but a virtual on-board timer can be created. At Station 2, both TOA and AOA are available.

Figure 2 displays the proposed localization system. For the virtual on-board timer, the input parameters are received frame counters and Rx time stamps of each station. The TOA sphere of each station can be obtained using this on-board timer. In this study, we selected Station 2 as the reference station for the two localization methods. For the 1TOA and AOA method, the input parameters are the virtual TOA sphere and AOA line for Station 2. For the 2TOA and AOA method, the input parameters are the virtual TOA spheres for both stations and AOA line for Station 2.

4. PERFORMANCE RESULTS

Figure 3 illustrate the 3D GPS trajectory and Combined TOA and AOA results for the LV. At Station 1, TOA was available during CT 0 ~ 300s. At Station 2, TOA and AOA were available during CT 10 ~ 521s. Therefore, Combined TOA and AOA method use only one TOA of Station 2 when TOA of Station 1 is not available.

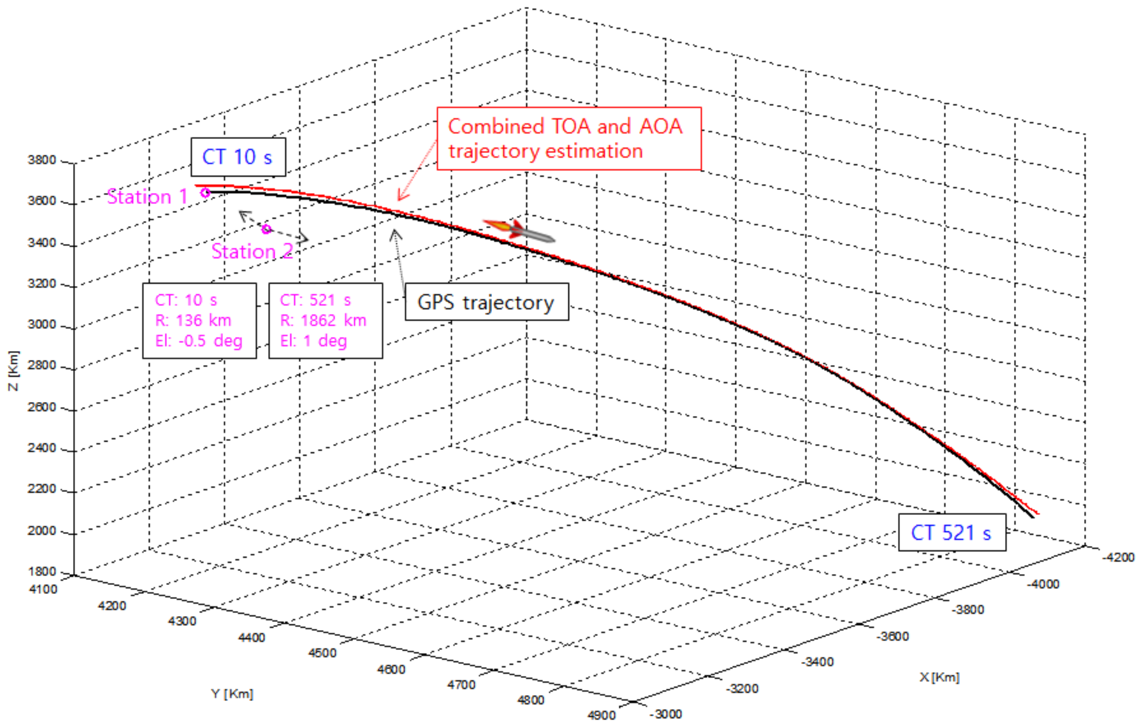

Figure 3. 3D Trajectory comparison.

Figures 4 show the slant range comparison with GPS for the each localization methods; 1TOA and AOA, and 2TOA and AOA methods. As mentioned above, 2TOA and AOA method uses only TOA of Station 2 around at CT 100 s when TOA of Station 1 is not available. It shows that 2TOA and AOA method is more closed to GPS than 1TOA and AOA; refer to 1TOA_AOA_R and 2TOA_AOA_R. Figure 5 shows the slant range errors of each localization method and the KALMAN filtering results compared to GPS; refer to 1TOA_AOA_R_error, 1TOA_AOA_ Kalman_R_error , 2TOA_AOA_R_error, and 2TOA_AOA_ Kalman_R_error. It is clear that there is a smoothing effect with the KALMAN filters for each method.

The 1TOA and AOA method shows range error of +26 km at CT 50 s and +7 km at CT 300 s. On the other hand, 2TOA and AOA method shows range error of +24 km and +5 km at the time. We can reduce range errors of 2 km by combining two TOAs information. As described section in 3.2, TOA information is estimated using the virtual on-board timer. Therefore, there is estimation errors; which is corresponding range errors in Figure 5.

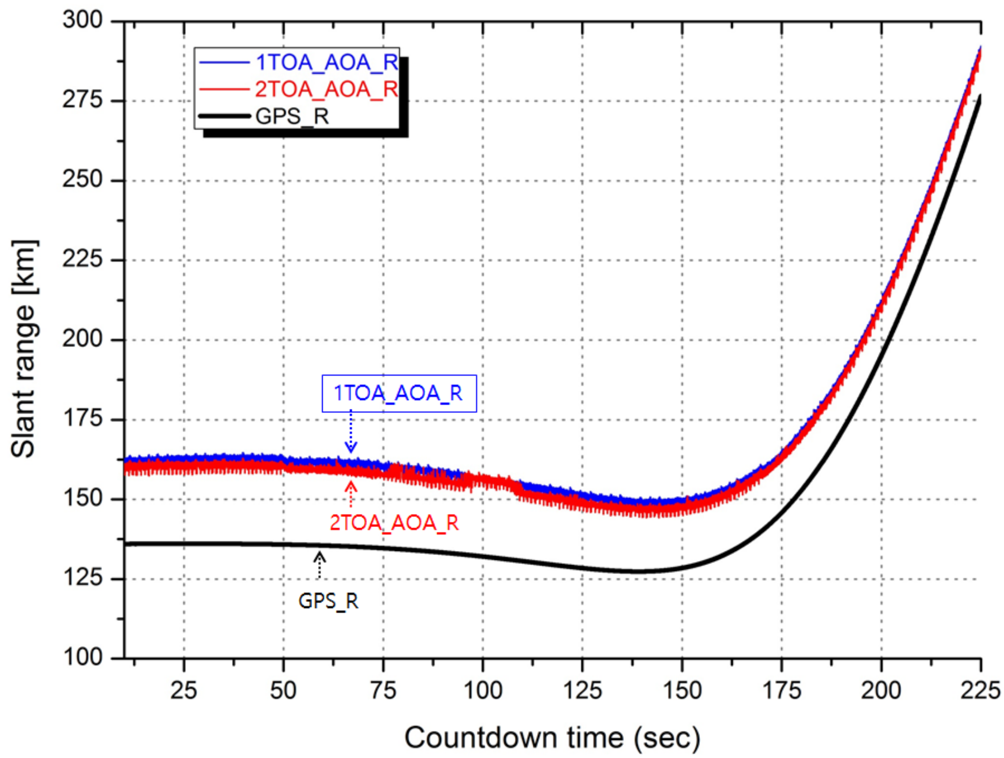

Figure 4. Slant range comparison for each method.

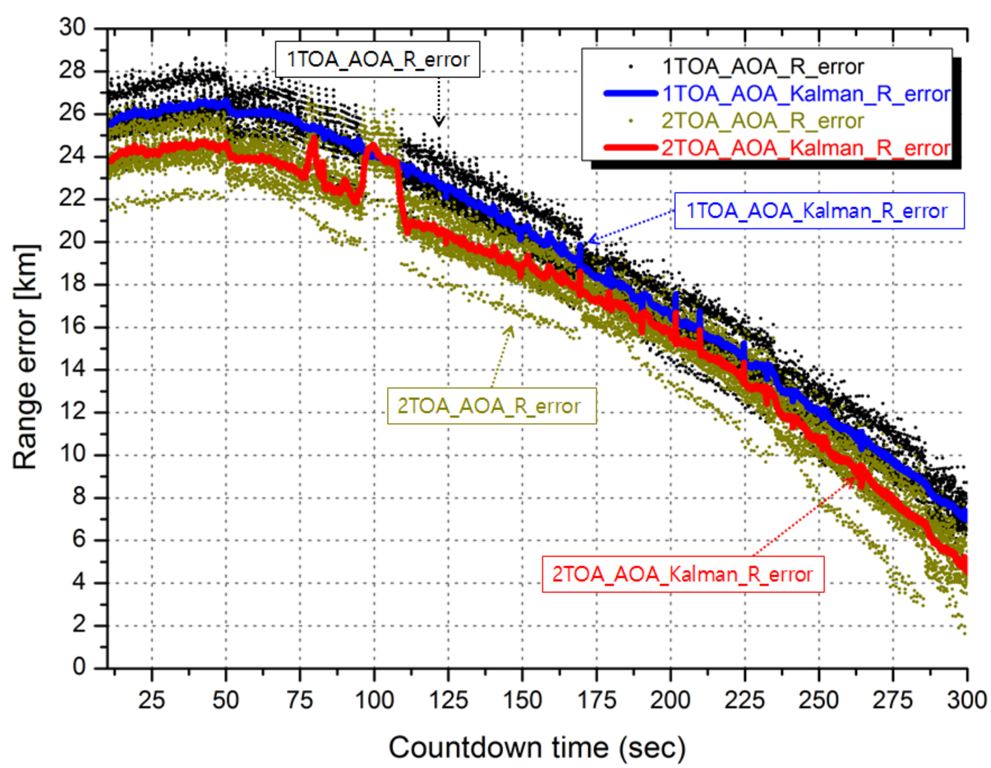

Figure 5. Slant range error with KALMAN filtering.

5. CONCLUSIONS

In this paper, we have proposed a 3D localization system for an LV. For the proposed system, Combined TOA and AOA method were applied using two ground telemetry stations; no-tracking station at the space center was used for the virtual on-board timer generation, while a monopulse tracking station was used for the AOA information. The performance of proposed system was compared to that of an on-board GPS, which was obtained during the LV flight test. The analysis results indicate that if two TOAs are used, the range errors are reduced about 2 km. And the results demonstrate a similar performance to GPS and illustrate that the obtained 3D position can be applied to other systems, such as radar.

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