On the feasibility of localization using DVB-T signals and combining TDOA and TWR measurements

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***Abstract*—Due to vulnerabilities of Global Navigation Satellite Systems (GNSS) there is an increased interest in alternative navigation solutions, such as using signals of opportunity (SOPs). We propose a system where a mobile navigator localizes itself using two-way ranging (TWR) measurements to a stationary base station at a known location as well as time difference of arrival (TDOA) measurements from two terrestrial digital television transmitters. We investigate the feasibility of such a system by deriving the Cramér-Rao Lower Bound (CRLB) for varying noise levels and optimizing the placement of the base station, using the real-life positions of transmitters in the area around Linköping, Sweden. We simulate measurements and compute snapshot estimates, verifying that root mean square errors similar to the CRLB can be obtained. The results indicate that for the investigated levels of TWR noise, as long as the TDOA noise is sufficiently low it could be possible to achieve errors of a few tens of meters.**

***Index Terms*—localization, TDOA, TWR, CRLB, signals of opportunity**

I. Introduction

Many navigation systems rely on Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), for accurate positioning. As GNSS is vulnerable to jamming and spoofing, the interest in alternative navigation methods has increased.

One alternative navigation method that has emerged in recent years is navigation using signals of opportunity (SOPs). SOPs are signals that are not primarily intended for navigation purposes, originating from, e.g., AM/FM radio [1, 2], digital television [3, 4], cellular signals [5, 6], and low-Earth orbit (LEO) satellites [7] such as Iridium [8] or Starlink [9]. SOPs are typically more difficult to jam or spoof than GNSS signals, but as they are not intended for navigation purposes they typically lack position and timing information. One approach is therefore to simultaneously estimate the position and clock error of the navigator and the SOP emitters [10], i.e., similar to a simultaneous localization and mapping (SLAM) framework.

While LEO satellites and cellular signals have perhaps shown the most promising results and received the most attention for outdoor applications, other signal sources such as FM radio or digital television have been mostly overlooked. Such signals lack timing information, making time of arrival (TOA) measurements impossible, and are not necessarily synchronized between transmitters, making time difference of arrival (TDOA) difficult. However, the locations of FM radio transmitters and digital television transmitters are in many cases known, unlike the locations of, e.g., cellular towers, which simplifies the SLAM problem to a localization problem.

In this work, we consider a problem where a navigator localizes itself in a GNSS-denied environment using SOPs received from digital television transmitters at known locations. The transmitted signals do not include information about their time of transmission, and the different transmitters do not transmit the same signals. We propose using what will be referred to as a base station, at a known location, that communicates with the navigator. This makes it possible to use one TDOA measurement per transmitter as well as one two-way ranging (TWR) measurement between the navigator and the base station.

A. Related Work

There are several works on positioning using terrestrial digital television signals. We focus here on the European standard DVB-T [11]. In [12, 13], TOA tracking of DVB-T signals is analyzed. Positioning using TDOA measurements is considered in [3], where TOA errors are reported as having standard deviations of a few tens of meters (after bias correction), as well as in [14]. The latter considers the DVB-T2 standard and makes use of transmitter signature waveforms to distinguish between transmitters that send at the same frequency.

In [15], receivers at known locations use TDOA measurements to localize FM radio transmitters as well as DVB-T. They conclude that DVD-T signals perform better than FM radio signals as FM radio signals have poorer cross-correlation functions and lower bandwidths.

Similar problems where TDOA and TWR measurements using cellular signals are used for localization have been investigated in [16–18]. In [17] one TDOA measurement and

This work was partially supported by the Wallenberg Artificial Intelligence, Autonomous Systems and Software Program (WASP), funded by Knut and Alice Wallenberg Foundation.

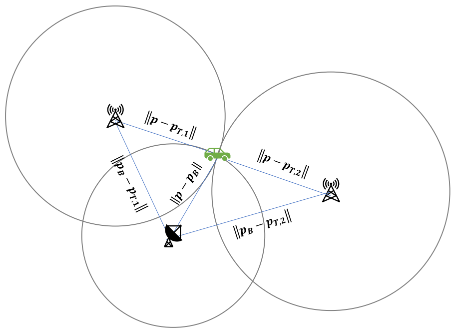


Fig. 1: On overview of the intended scenario. A mobile navigator as well as a stationary base station receive SOPs from two stationary transmitters at known locations.

one TWR measurement are used, whereas [18] combines TDOA, TWR and direction of arrival (DOA).

B. Contributions

We propose a framework for localization using signals of opportunity where a base station is used to obtain two TDOA measurements as well as a TWR measurement between the base station and the navigator. We investigate the feasibility of implementing such a framework in a real-world scenario by looking at available DVB-T transmitters in the area around Linköping, Sweden, and determining what noise levels that would be acceptable in order to achieve sufficiently low Cramér-Rao Lower Bound (CRLB) values as well as where the base station should be placed in order to optimize the performance.

We conduct a small simulation study where we simulate measurements at selected positions and estimate the position using weighted nonlinear least squares in order to verify that the CRLB can be expected to be reached.

II. Proposed Positioning Method

A mobile navigator attempts to estimate its (2D) position $\mathbf{p} = (x, y)^T$. The navigator communicates with a stationary base position at the known location $\mathbf{p_B} = (x_B, y_B)^T$, and the navigator and base station both receive SOPs in the form of signals from two DVB-T transmitters at known locations $\mathbf{p_{T,1}} = (x_{T,1}, y_{T,1})^T$ and $\mathbf{p_{T,2}} = (x_{T,2}, y_{T,2})^T$, respectively. This is illustrated in Fig. 1. We assume that the transmitters broadcast at different frequencies, or that the received signals can be correctly associated to the corresponding transmitter in some other way.

The available measurements are one TWR measurement, and two TDOA measurements. The TWR measurement between the mobile navigator and the base station can be modelled as

$$z_0 = ||\mathbf{p} - \mathbf{p_B}|| + e_0, \tag{1}$$

where $e_0 \sim \mathcal{N}(0, \sigma_0^2)$.

The TDOA measurement obtained for the transmitter i can be modelled as

$$z_i = ||\mathbf{p} - \mathbf{p_{T,i}}|| - ||\mathbf{p_B} - \mathbf{p_{T,i}}|| + e_{i,n} - e_{i,B} \quad i = 1, 2, \tag{2}$$

where $e_{i,n} \sim \mathcal{N}(0, \sigma_{i,n}^2)$ and $e_{i,B} \sim \mathcal{N}(0, \sigma_{i,B}^2)$ are the TOA error terms for the navigator and the base station i, respectively. Under the assumption that the navigator and base station errors are independent, the error terms can be replaced by

$$e_i = e_{i,n} - e_{i,B} \sim \mathcal{N}(0, \sigma_i^2) \tag{3}$$

where $\sigma_i^2 = \sigma_{i,n}^2 + \sigma_{i,B}^2$. We will assume that $e_{1,n} = e_{2,n} = e_{1,B} = e_{2,B}$, and consequently that $\sigma_1 = \sigma_2$.

The measurements can therefore be modelled as

$$\mathbf{y} = (z_0, z_1, z_2)^T = h(\mathbf{p}) + \mathbf{e}, \tag{4}$$

where

$$h(\mathbf{p}) = \begin{pmatrix} ||\mathbf{p} - \mathbf{p_B}|| \\ ||\mathbf{p} - \mathbf{p_{T,1}}|| - ||\mathbf{p_B} - \mathbf{p_{T,1}}|| \\ ||\mathbf{p} - \mathbf{p_{T,2}}|| - ||\mathbf{p_B} - \mathbf{p_{T,2}}|| \end{pmatrix} \tag{5}$$

and

$$\mathbf{e} = (e_0, e_1, e_2)^T \sim \mathcal{N}(\mathbf{0}, \mathrm{diag}(\sigma_0^2, \sigma_1^2, \sigma_2^2)). \tag{6}$$

Note that as the locations of the base station and the transmitters are known, $r_i = ||\mathbf{p_B} - \mathbf{p_{T,i}}||, i = 1, 2$ are known constants. In the noise-free case when $(z_0, z_1, z_2)^T = h(\mathbf{p})$ it can be seen that

$$\begin{aligned} ||\mathbf{p} - \mathbf{p_B}|| &= z_0 \\ ||\mathbf{p} - \mathbf{p_{T,1}}|| &= z_1 + r_1 \\ ||\mathbf{p} - \mathbf{p_{T,2}}|| &= z_2 + r_2, \end{aligned} \tag{7}$$

and consequently the position $\mathbf{p}$ can be computed as the intersection of three circles centred at $\mathbf{p_B}, \mathbf{p_{T,1}}$ and $\mathbf{p_{T,2}}$ with radius $z_0, z_1 + r_1$ and $z_2 + r_2$, respectively.

In the noisy case, the position $\mathbf{p}$ can be estimated using weighted nonlinear least squares (WNLS) as

$$\hat{\mathbf{p}} = \arg\min_{\mathbf{p}} \frac{1}{2} \sum_{k=1}^{N} (\mathbf{y}_k - h(\mathbf{p}))^T R^{-1} (\mathbf{y}_k - h(\mathbf{p})) \tag{8}$$

where N is the number of measurements and $R = \mathrm{cov}(\mathbf{e})$.

III. Estimator Performance

In this section we investigate the performance of the proposed positioning method.

A. CRLB

The covariance of an unbiased estimator $\hat{\theta}$ of the parameter θ given the measurement $\mathbf{y} = h(\theta) + \mathbf{e}$ is bounded by the CRLB

$$\mathrm{cov}(\hat{\theta}) \geq I(\theta_\mathbf{0})^{-1}, \tag{9}$$

where $\theta_\mathbf{0}$ is the true parameter value and $I(\theta)$ is the Fisher information. The Fisher information is defined as

$$I(\theta) = -\mathbf{E}\left[\frac{\partial^2}{\partial \theta^2} \log p(\mathbf{y}|\theta)\right]. \tag{10}$$

Fig. 2: The locations of the transmitters in Linköping and Norrköping. The Norrköping transmitter is located roughly 48 km to the east and 32 km north of the Linköping transmitter.

In the case when $\mathbf{y} \sim \mathcal{N}(\mu(\theta), \Sigma)$, then entry (m, n) in the Fisher information matrix is

$$I_{m,n} = \frac{\partial \mu^T}{\partial \theta_m} \Sigma^{-1} \frac{\partial \mu^T}{\partial \theta_n}. \tag{11}$$

With $\theta = \mathbf{p}$ and

$$\mu(\theta) = (||\mathbf{p} - \mathbf{p_B}||, ||\mathbf{p} - \mathbf{p_{T,1}}|| - r_1, ||\mathbf{p} - \mathbf{p_{T,2}}|| - r_2)^T, \tag{12}$$

this gives

$$\frac{\partial \mu}{\partial \theta} = \begin{pmatrix} \frac{(\mathbf{p} - \mathbf{p_B})^T}{||\mathbf{p} - \mathbf{p_B}||} \\ \frac{(\mathbf{p} - \mathbf{p_{T,1}})^T}{||\mathbf{p} - \mathbf{p_{T,1}}||} \\ \frac{(\mathbf{p} - \mathbf{p_{T,2}})^T}{||\mathbf{p} - \mathbf{p_{T,2}}||} \end{pmatrix}. \tag{13}$$

Assuming that the TDOA errors and the TWR error are mutually independent we also have that $\Sigma = \text{diag}(\sigma_0^2, \sigma_1^2, \sigma_1^2)$.

We take as an example the digital television transmitters located in or nearby Linköping, Sweden. There is one transmitter in Linköping, as well as transmitters in nearby towns Norrköping, Motala, Åtvidaberg and Kisa [19]. The locations of the transmitters in Linköping and Norrköping are shown in Fig. 2. For the location of the base station we choose Linköping University. The resulting CRLB for transmitter locations at Linköping and Norrköping is shown in Fig. 3.

The resulting mean CRLB for the same area for varying noise levels is shown in Fig. 4. It can be seen that the CRLB is affected more by an increase in $\sigma_{1,n}$ than by an increase in σ_0 for the investigated noise levels. This is somewhat unfortunate, as σ_0 can be influenced by choosing a better link between the navigator and the base station, whereas $\sigma_{1,n}$ is going to depend largely on the properties of the DVB-T transmitter and signal, over which there is no control. However, as seen in Fig.4, as long as $\sigma_{1,n}$ is on the scale of a few tens of meters it is possible to achieve mean CRLB values of a few tens of meters in the area of interest.

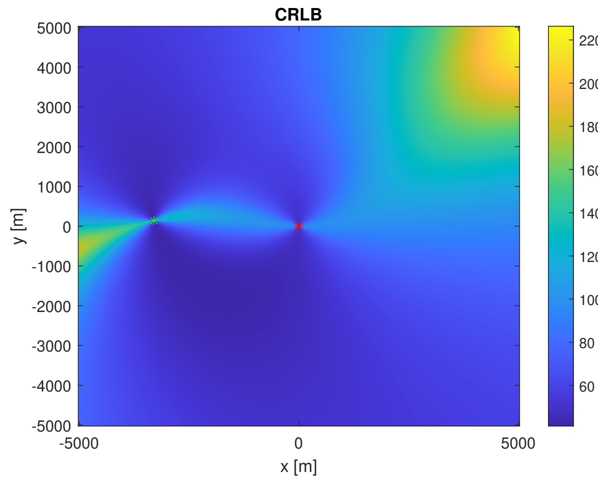


Fig. 3: The resulting CRLB $\left(\sqrt{\text{tr}(I^{-1}(\theta))}\right)$ for $\sigma_0 = 10, \sigma_{1,n} = \sigma_{2,n} = 40$. The green dot shows the base station location, and the red dot shows the location of the transmitter in Linköping (the second transmitter is outside the bounds of the plot).

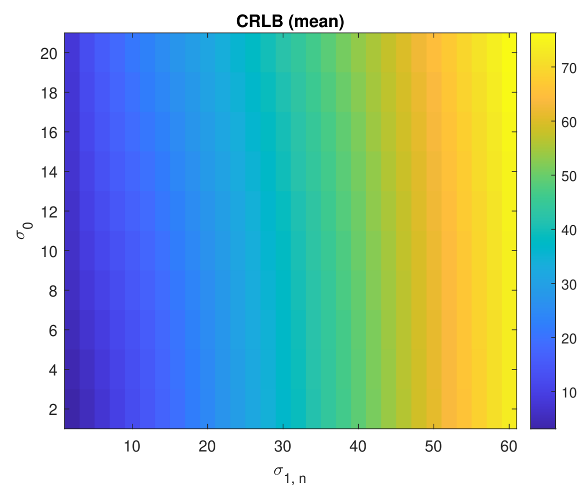


Fig. 4: The resulting mean CRLB $\left(\sqrt{\text{tr}(I^{-1}(\theta))}\right)$ over the area $-5000 \leq x, y \leq 5000$ for varying noise levels.

B. Placement of Base Station

We consider the problem of deciding where to place the base station in order to minimize a given performance measure. The optimization problem can be defined as

$$\underset{\mathbf{p_B}}{\text{minimize}} \quad f(\mathbf{p_B}) \tag{14}$$

$$\text{subject to} \quad \mathbf{p_B} \in X_B \subset \mathcal{R}^2 \tag{15}$$

As cost function to minimize, we choose the cost function

$f(\mathbf{p_B})$ defined by

$$f(\mathbf{p_B}) = \sum_{\theta \in \Theta} \sqrt{\text{tr}(I^{-1}(\theta))} \quad (16)$$

where Θ is a finite set of positions of interest, e.g., points on a grid. Minimizing f then corresponds to minimizing the average CRLB on the set Θ. Note that $I(\theta)$ depends on $\mathbf{p_B}$. Here we consider points on a grid with resolution 250 m such that $\max(|x|, |y|) \leq 5000$. We also restrict possible placements of the base station to a grid with the same resolution but with $\max(|x|, |y|) \leq 7500$. The optimal placement is then found by iterating over all possible placements and selecting the one that results in the lowest cost function value.

The resulting base station positions for varying noise levels are shown in Fig. 5, where it can be seen that all optimized positions are on the edges of the grid, with $|y| = 7500$. However, we have not considered here that the signal quality decreases over longer distances. If this is taken into account, base station placements that are closer to the Linköping transmitter might be preferred. As seen in Fig. 5b, the position seems to depends on the ratio between σ_0 and $\sigma_{1,n}$.

The resulting CRLB for the optimized base station position for $\sigma_0 = 10, \sigma_{1,n} = 40$ is shown in Fig. 6. Compared to the CRLB in Fig. 3, it can be seen that the CRLB in general is lower. With the previous base station placement, the CRLB varied between 41 m and 226 m, with an average value of 76 m. With the new base station placement, the CRLB varies between 41 m and 59 m, with an average of 50 m.

C. Simulation study

To evaluate the performance of the system in simulation we consider the positions

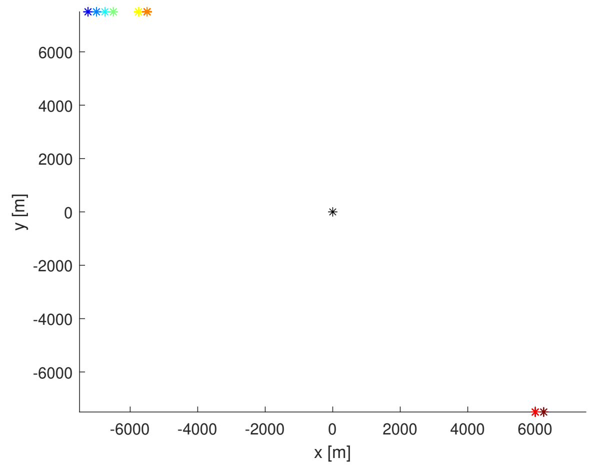
$$\mathbf{p}_i = (R \cos \phi_i, R \sin \phi_i)^T \quad (17)$$

with $R = 2000$ m, and $\phi_i = i\frac{\pi}{8}, i = -8, \dots, 7$. With the base station as determined previously for $\sigma_0 = 10, \sigma_{1,n} = 40$ we simulate 100 measurements for each position and estimate the position $\hat{\mathbf{p}}$ according to (8) for each measurement by optimizing over a 300 m by 300 m grid with resolution 1 m centred at the true position. We then compute the root mean square error (RMSE) for each position. The resulting RMSE and the CRLB for each position are shown in Table I. As seen in Table I, the RMSE is similar to the CRLB for all positions, indicating that it is possible to achieve the CRLB. By using a filtering solution where measurements from an inertial measurement unit (IMU) are incorporated rather than just snapshot estimates we can also expect the performance to improve a little further.

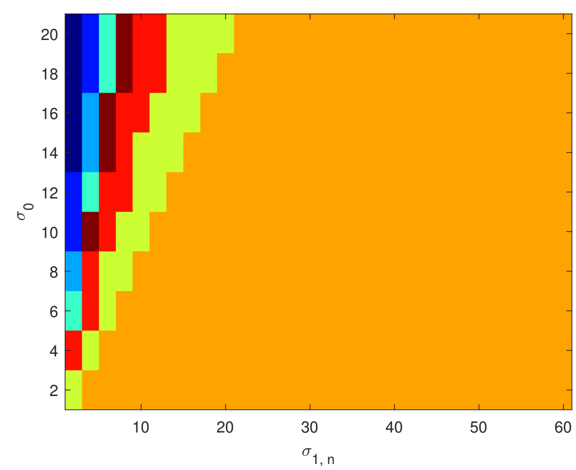
D. Discussion

The results presented in this section indicate that a positioning system with an RMSE on the level of a few tens of meters is not impossible, but also not without challenges. It is necessary that the communication link between the base station and the navigator is sufficiently good as we have assumed $\sigma_0 \leq 20$ m. More importantly, the TDOA error is the limiting factor. We have modelled the TDOA error as a sum of two TOA errors, that should be kept on a scale of a few tens of meters. The results in [3] indicate that this is possible, but that there is a bias that must be corrected for.

As demonstrated here, the choice of the base station location is also important, as it affects the achievable accuracy. The results from the small simulation study are promising, as they indicate that it is possible to come close to the CRLB. By combining these measurements with an IMU and using a filtering solution it should be possible to improve the performance further as well. If there are signals from additional transmitters available it might also be possible to improve the performance



(a) The resulting base station positions. The black dot shows the transmitter in Linköping.



(b) The color code of the resulting base station position as a function of the noise.

Fig. 5: The resulting base station position for varying noise levels. The base station positions are shown in (a), and the corresponding position for each noise level is indicated by the color shown in (b).

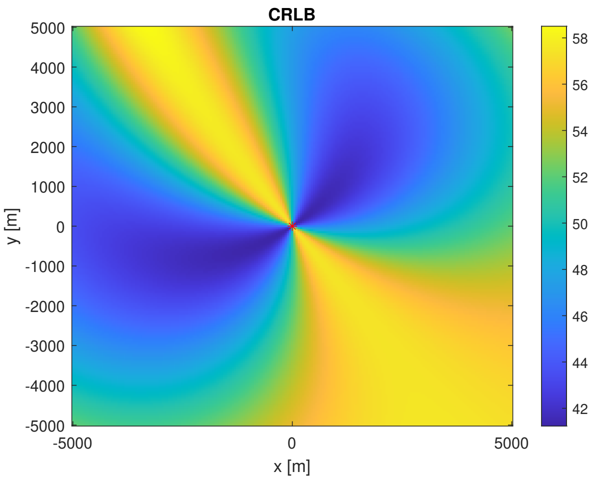


Fig. 6: The resulting CRLB $\left(\sqrt{\mathrm{tr}(I^{-1}(\theta))}\right)$ when the base station location has been optimized for $\sigma_0 = 10, \sigma_{i,n} = 40$ for $i = 1, 2$. The base station is located at $(-5500, 7500)^T$, outside the bounds of the plot. The red dot shows one transmitter location (the second transmitter is located outside the bounds of the plot).

TABLE I: The resulting RMSE and the CRLB

ϕ	**RMSE [m]**	**CRLB [m]**
$-\pi$	42.17	43.30
$-\frac{7\pi}{8}$	44.42	41.50
$-\frac{3\pi}{4}$	40.94	42.83
$-\frac{5\pi}{8}$	45.39	46.59
$-\frac{\pi}{2}$	57.72	51.87
$-\frac{3\pi}{8}$	61.42	56.44
$-\frac{\pi}{4}$	49.81	57.05
$-\frac{\pi}{8}$	53.03	53.22
0	49.90	47.96
$\frac{\pi}{8}$	42.63	43.85
$\frac{\pi}{4}$	44.47	42.02
$\frac{3\pi}{8}$	41.78	43.14
$\frac{\pi}{2}$	45.11	48.08
$\frac{5\pi}{8}$	54.71	55.61
$\frac{3\pi}{4}$	56.10	56.50
$\frac{7\pi}{8}$	48.71	49.04

by using additional TDOA measurements.

It is also clear from the results that there is a limit on how good we can expect the performance to be, and there are several challenges that have not been considered. We have not considered multi-path propagation or not being able to maintain line of sight at all times, which would need to be considered in a practical implementation and could affect the choice of suitable base station location. It is unlikely that meter level precision is going to be achieved, but for applications where less precision is needed it could be an alternative, either as a stand-alone solution or as support for other positioning systems. It could perhaps also be used to help detect anomalies in a GNSS system.

IV. Conclusion and Future Work

We have considered a positioning problem where a mobile navigator attempts to localize itself based on a two-way ranging (TWR) measurement to a base station at a known location and two time difference of arrival (TDOA) measurements from terrestrial digital television transmitters at known locations to the navigator and the base station. Using the real locations of transmitters near Linköping, Sweden, we have looked at the Cramér-Rao lower bound (CRLB) for varying measurement noise levels and seen that for sufficiently low TWR noise levels ($\sigma_0 \leq 20\,\mathrm{m}$) and sufficiently low TDOA noise levels (corresponding to a time of arrival(TOA) noise level of a few tens of meters) it is possible to achieve a mean CRLB of a few tens on meters in an area around one of the transmitters. We have also shown that by optimizing the placement of the base station it is possible to reduce the CRLB. In a small simulation study, we investigate the root mean square error (RMSE) for snapshot estimates using weighted nonlinear least squares (WNLS) and verify that it is on similar levels as the CRLB. This shows that as long as it is possible to implement a communication link between the navigator and the base station that achieves a sufficiently low noise level, and as long as the time of arrival error (which we use to model the TDOA error) for the television signals is on the level of a few tens of meters, it should be possible to achieve an accuracy of a few tens of meters for snapshot estimates.

Future work includes experiments with real television signals using the DVB-T standard to investigate the noise levels and implementing the system on actual hardware for real-world experiments. Another possible extension is to integrate an inertial measurement unit (IMU) and estimate the position using a filter rather than only performing snapshot estimation.

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