Comparative analysis of single-channel direction finding algorithms for automotive applications at 2400 MHz in a complex reflecting environment

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ABSTRACT

This paper presents an amplitude-based single-channel direction finding system for automotive applications and compares its performance against two different phase-based single-channel direction finding algorithms in a complex reflecting environment (parking garage) at 2400 MHz. All three direction finding algorithms utilize a multi-element receiving antenna array placed at two locations on a vehicle. The received complex electric fields at each antenna element within the receiving antenna array are used as inputs to the three direction finding algorithms, resulting in a direction of arrival estimate. The results from this research provide insightful information on the performance of various direction finding algorithms as a function of complex reflecting environment, transmitter height, receiving antenna array location, number of receiving antenna elements and pass rate acceptance criteria.

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1. Introduction

Radio Direction Finding (DF) is a technique that identifies the bearing angle or the coordinates of an incoming radio signal(s). Direction of arrival (DOA) and angle of arrival (AOA) estimation have a wide range of applications which include but are not limited to avionics, military, emergency services and amateur use in HAM radios.

Popular implementations of DF systems consist of antenna arrays, as opposed to single antennas that are mechanically rotated, followed by one or more receivers. Single-channel (receiver) DF systems provide moderate accuracy, but a significant benefit in terms of weight, complexity, cost and power consumption. Two of the widely known single-channel DF systems are based on the Watson–Watt (WW) and the Doppler/Pseudo-Doppler (PD) algorithms [1,2]. The WW algorithm is amplitude based, while the PD algorithm is phase based. A good comparison between the two is provided in [2]. Multiple-channel (receiver) systems provide better AOA estimates at the expense of complexity and hardware cost. Two of the most widely known examples that utilize multiple channels are the MUSIC and ESPRIT algorithms [3,4].

The PD DF method is not a new scheme for AOA estimation, and some of the limiting factors for the accuracy of this method were discussed in [1]. The literature has shown that most of the PD DF algorithms have been implemented with multiple channels as opposed to a single channel. In [5,6], an implementation methodology that highlights the receiver structure of a PD DF algorithm was provided with correlative/adaptive algorithms for reconstructing the phases received by the antenna array elements which are ultimately processed to yield an AOA estimate. No actual results were presented or obtained. An amplitude/phase-based DF system was proposed in [7] that operates in the 20–1000 MHz range. The system was tested in a simple open site environment.

In [8–10], a digital phase locked loop (PLL) approach (using the discrete Fourier transform (DFT)) was suggested
that performed really well in the laboratory environment. It achieved a mean accuracy of about 1° in a non-reflective scenario. The transmitter to receiver separation was about 1 m, and antenna arrays of 8 as well as 16 elements were investigated. The results presented were proof of concept ones and the channel was well behaved (only AWGN was incorporated in the results).

This paper presents a detailed performance comparison of three DF methods for automotive applications in a complex reflecting environment at 2400 MHz: one amplitude-based method and two phase-based methods. The comparison is made in a parking garage environment with a single car and 47 cars (to complicate the channel model). Also, the effect of the number of antenna array elements, location of the antenna array and transmitter height is investigated. A criterion for the accuracy of the DOA estimate is set, and the pass rate is found for each of the investigated scenarios. The results of this study provide insightful information for characterizing the performance of such implementations.

The paper is organized as follows. Section 2 describes the single-channel direction finding methods (algorithms) assessed in this paper. Section 3 presents the description and model of the wireless propagation channel. Section 4 presents a detailed performance comparison with a discussion of the results. And Section 5 concludes the paper.

2. Single-channel direction finding algorithms

The received direct signal captured by antenna element $i$ at the input of the receiver can be written as:

$$r_i(t) = \left[ m(t) \cos \left( \omega_0 t + \theta_0 + \frac{2\pi r}{\lambda} \cos \left( \frac{2\pi i}{Na} + \phi \right) \right) \right]$$

$$\times G_i(\theta, \phi) + n_i(t)$$

(1)

where $m(t)$ is the modulating message signal, $\omega_0$ is the carrier radian frequency, $\theta_0$ is the phase shift of the incoming carrier signal, $\lambda$ is the wavelength, $r$ is the circular array radius, $Na$ is the number of array antenna elements, $\phi$ is the DOA and $G_i(\theta, \phi)$ is the $i$th antenna gain in the elevation ($\theta$) and azimuth ($\phi$) directions of the incoming direct signal. $n_i(t)$ is the noise in the antenna path inside the receiver. The total signal captured ($r_{T1}(t)$) will be a combination of the direct signal as well as the reflected and diffracted signals from the wireless channel. Thus, with reflected and diffracted signals added, the signal at the input of the receiver will be described by

$$r_{T1}(t) = \sum_j r_{i_j}(t)G_{i_j}(\theta, \phi) + n_i(t)$$

(2)

where $r_{i_j}(t)$ is the $j$th reflection/diffraction of the $i$th direct antenna element signal. The received signal is passed to the single-channel receiver module for DOA estimation. The following sections describe the three algorithms used in this study: The Received Power Level (RPL), the Analog Single-Channel PD (A-SCPD) algorithm and the Digital Phase Locked Loop (D-PLL) algorithm. The block diagram of a single-channel DF system is shown in Fig. 1. This architecture is common to all three methods, and a different algorithm is used for each.

2.1. Received power level (RPL)

This approach utilizes a circular array of eight directional antennas on the vehicle. Each antenna is to cover a sector of 45° in azimuth. The antenna array is connected to a rotating switch that completes a full revolution in $T_{rev}$ s. Each antenna sector will have $T_{rev}/8$ s of dwell time. The data from each antenna is passed to a single receiver module. The RF front-end will amplify and filter the incoming signal, down convert it to an acceptable IF, and then pass it to an analog-to-digital converter (ADC). The ADC will sample and digitize the data for a single antenna, and it passes the digitized data to the algorithm. The algorithm will calculate the power level (a received signal strength indicator, RSSI) estimate for the $T_{rev}/8$ sec time interval for a specific antenna, and it dumps the results in a specified memory location. This process is repeated 8 times, once for each antenna. Then the algorithm compares the power levels and sorts them according to a selection routine. This will give the antenna location with highest probability (signal strength) of the incoming signal, and that sector is chosen. The RPL algorithm pseudo-code is presented in Table 1.

Although the RPL uses eight directional antenna elements compared to five in a WW-based receiver [2], the
proposed method utilizes a less complex and lower cost receiver at the expense of providing ranges of DOA (sectors) compared with absolute values from the WW receiver. For the application at hand, this gives the RPL a more favorable advantage.

### 2.2. Analog single-channel pseudo-Doppler (A-SCPD) DF algorithm

The receiver architecture for the A-SCPD DF algorithm was implemented based on [2,6]. The incoming RF signal is received by an Na-element circular antenna array (equally spaced elements with array radius of \( \lambda/4 \)), and the output of one antenna at a time is passed to the receiver module. Omnidirectional antennas are used within the array. An RF rotating switch gives the output of each antenna to be analyzed for \( T_{sw}/Na \), where \( T_{sw} \) is the period of the rotating switch.

The A-SCPD algorithm pseudo-code is presented in Table 2. The RF signal from each antenna is sampled using a rotating switch that adds a phase component to the incoming signal phase which includes all phase effects due to signal path delay, reflection, diffraction and antenna pattern. The continuous input RF signal is then converted to IF and passed to a phase demodulator. The output of the phase demodulator is filtered, thus giving a sinusoidal output that has a time delay with respect to the rotating switch. The DOA estimate is found from the measured time delay difference between the rotating switch signal and the filtered one.

### 2.3. Digital phase locked loop DF algorithm (D-PLL)

A digital PLL algorithm (using the discrete Fourier transform (DFT)) was implemented following that in [8–10]. This method utilizes a bank of PLLs to estimate the phases from each antenna output. Each antenna output is selected for a period of time equals to \( T_{sw}/Na \), where Na is the number of antennas within the array. Omnidirectional antennas are used within the circular array. A phase difference metric is then created between adjacent antenna elements. These phase difference estimates are called the given difference curves. Since the location of each antenna is known a priori, a set of theoretical phase differences can be created. This set of curves is called the target difference curves. The mean square error (MSE) is then calculated between the given and target difference curves. The DOA is found by calculating the N-point fast Fourier Transform (FFT) of the difference curves, where the phase of the fundamental component is the desired DOA. Table 3 summarizes the algorithm steps in a pseudo-code fashion.

### 3. Complex reflecting environments

A channel model for a parking garage environment was created to assess the performance of the RPL, A-SCPD and D-PLL DF algorithms. A parking garage represents a stringent automotive reflecting environment for DF applications because of the rapid power fluctuations in both amplitude and phase of the received signal. The purpose of the channel model is to determine the received complex power level at each element within the circular receiving antenna array from a given transmitter.

The commercial off-the-shelf (COTS) software package Wireless InSite™ was used to create the parking garage environment. A parking garage structure was created with cars (Fig. 2) and without cars (Fig. 3) to represent stringent and moderate reflecting environments, respectively. Fig. 4 is a sky view plot of Fig. 3 containing all pertinent dimensions for the parking garage structure. A Wireless InSite™ scenario contains the following basic elements: (1) objects, (2) waveforms, (3) receivers, (4) transmitters and (5) a propagation model.

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**Table 1**

RPL DF algorithm pseudo-code.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Set parameters: Rotating switch frequency, IF, Antenna spacing, No. antennas, Sampling frequency, filter type and order</td>
</tr>
<tr>
<td>2.</td>
<td>Import the complex channel and antenna response for each array element</td>
</tr>
<tr>
<td>3.</td>
<td>For ( i = 1:Na ) Calculate the RSSI (power level)</td>
</tr>
<tr>
<td>4.</td>
<td>Apply selection criteria</td>
</tr>
<tr>
<td>5.</td>
<td>Determine DOA by selecting the sector corresponding to selection criteria</td>
</tr>
</tbody>
</table>

**Table 2**

A-SCPD DF algorithm pseudo-code.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Set Parameters: Rotating switch frequency, IF, antenna spacing, No. antennas, Sampling frequency, filter type and order</td>
</tr>
<tr>
<td>2.</td>
<td>Create a CW signal</td>
</tr>
<tr>
<td>3.</td>
<td>Import complex channel and antenna response for each array element</td>
</tr>
<tr>
<td>4.</td>
<td>For ( i = 1:Na ) Generate PM signal with channel and antenna effects</td>
</tr>
<tr>
<td>5.</td>
<td>Demodulate and Filter incoming PM signal</td>
</tr>
<tr>
<td>6.</td>
<td>Determine AOA based on time delay estimates</td>
</tr>
</tbody>
</table>

**Table 3**

D-PLL DF algorithm pseudo-code.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Set Parameters: Rotating switch frequency, IF, antenna spacing, No. antennas, Sampling frequency, FFT points</td>
</tr>
<tr>
<td>2.</td>
<td>Create PLL function</td>
</tr>
<tr>
<td>3.</td>
<td>Import complex channel and antenna response for each array element</td>
</tr>
<tr>
<td>4.</td>
<td>For ( i = 1:Na ) Calculate the given difference curves</td>
</tr>
<tr>
<td>5.</td>
<td>Compute the MSE between given and target curves</td>
</tr>
<tr>
<td>6.</td>
<td>Find AOA from the fundamental FFT component</td>
</tr>
</tbody>
</table>
3.1. Objects

The reflecting environment is comprised of various physical objects. Each object has a physical size and is made up of materials with specific electrical properties. The objects within the parking garage environment were the floor, ceiling, support posts, massive room and vehicles (Fig. 4). The floor, ceiling, and support posts of the parking garage were comprised of concrete. In addition, a massive room serving as an entry way into the building was modeled as a cube in which five of the faces were made of concrete and the front face was made of glass. Finally, a vehicle was modeled using metal for the body and rubber for the wheels. All objects were created using flat polygonal plates with double-sided normals. Table 4 provides a list of the physical dimensions and materials for each of the five objects while Table 5 provides the electrical properties of the four materials used in the parking garage channel model, respectively.

Table 4
Basic properties of objects used in the parking garage channel model.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Physical dimensions</th>
<th>Materials</th>
<th>Faces</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vehicles</td>
<td>4.8 m × 1.8 m × 1.5 m Thickness of 0.0 m.</td>
<td>Metal rubber</td>
<td>99</td>
</tr>
<tr>
<td>2. Floor with short</td>
<td>See Fig. 4. Side wall height of 1 m. Floor and walls have 1m thickness.</td>
<td>Concrete</td>
<td>9</td>
</tr>
<tr>
<td>Support wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Support post</td>
<td>Diameter of 0.6 m. Height of 3.0 m. Thickness of 0.05 m.</td>
<td>Concrete</td>
<td>6</td>
</tr>
<tr>
<td>4. Ceiling with I-beams</td>
<td>See Fig. 3. I-beams are 0.6 m in height &amp; width. Thickness of 1 m.</td>
<td>Concrete</td>
<td>120</td>
</tr>
<tr>
<td>5. Massive room</td>
<td>7.2 m × 2.7 m × 3.6 m. Thickness of 0.3 m for concrete walls. Thickness of 0.03 m for glass wall.</td>
<td>Concrete glass</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 5
Electrical properties of materials used to build objects in the parking garage channel model.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Concrete</td>
<td>15.0</td>
<td>1.0</td>
<td>0.015</td>
<td>Floor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Support posts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ceiling with I-beams</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Massive room</td>
</tr>
<tr>
<td>2. Glass</td>
<td>2.4</td>
<td>1.0</td>
<td>0.0</td>
<td>Massive room</td>
</tr>
<tr>
<td>3. Rubber</td>
<td>3.1</td>
<td>1.0</td>
<td>0.0</td>
<td>Vehicle</td>
</tr>
<tr>
<td>4. Metal (PEC)</td>
<td>1.0</td>
<td>1.0</td>
<td>Infinite</td>
<td>Vehicle</td>
</tr>
</tbody>
</table>

3.2. Receivers

An eight-element (RPL) and a four/eight-element (A-SCPD and D-PLL) receiving circular antenna array were placed at two different locations within a single vehicle. In each case, the circular array was centered on the vehicle’s roof at heights of 1.45 m for the interior location and 1.5 m for the exterior location. For the two-phase-based DF algorithms (A-SCPD and D-PLL), each receiving antenna element possessed the radiation pattern of a vertically polarized dipole in order to provide a constant gain and phase pattern at the antenna horizon. For the amplitude-based DF algorithm (RPL), a directional antenna with half-power beam widths of 45° and 90° in both the E and H planes were used in order to provide a directional gain in each of the eight sectors comprising the circular array. Fig. 5 shows the normalized gain patterns for the three antennas used in the parking garage channel model simulations.
3.3. Transmitters

Sets of 122 transmitters were placed on the horizontal plane of the parking garage channel model at heights of 1.0 m, 1.25 m, 1.5 m and 1.75 m, producing a total of 488 transmitters in the parking garage scenario. The radiation pattern of a vertically polarized dipole antenna was placed at each transmitter point. The 488 transmitter points were chosen to provide statistical confidence in the evaluation of each algorithm within the parking garage channel model. Each transmitter point can be thought of as a user at a specific location trying to obtain a unique DOA estimate.

3.4. Waveform

A modulated waveform with a carrier frequency of 2400 MHz and a bandwidth of 1 MHz was chosen for this channel model. This waveform is then associated with all transmitters and receivers in the channel model. A 1 MHz bandwidth was used because an implementation of a DF system requires communication between the transmitter and receiver.
3.5. Ray-tracing method

Wireless InSite™ provides four ray-based propagation models. These models all combine ray-tracing algorithms with the Uniform Theory of Diffraction (UTD) [11–13]. The ray-tracing procedure is used to find the propagation paths to each receiver point, and the UTD is used to evaluate the complex electric field associated with each ray path. The propagation predictions for quantities such as received power, path loss, complex impulse response, direction of departure (DOD) and DOA are computed from the electric fields and propagation paths. The Full 3D Model was chosen within Wireless InSite™ for this research. This ray-tracing method does not place restrictions on the shape of the objects and all object faces are chosen with double-sided normals so that reflections on both sides of a face are considered. The Full 3D Model was configured to consider up to one reflection, three transmissions and one diffraction for a specific propagation path [14].

3.6. Output parameters

The received complex power levels and DOA were of interest in this work. For a particular simulation there were 488 transmitters and 8 receivers. The data were organized into a matrix of dimensions 488 by 8, corresponding to 488 independent row vectors containing 8 elements. Each row vector is input to the three DF algorithms described in this paper. Both the amplitude and phase of each row vector are important for the A-SCPDD and D-PLL DF algorithms (phase-based DF algorithms) since the DOA estimate is based on the relative phase relationship between the 8 receiving antenna elements. In contrast, the amplitude of each row vector is important for the RPL DF algorithm (amplitude-based DF algorithm) since the DOA estimate is selected in the direction of the antenna element receiving the highest power.

In this work, only the forward link (user to car) was of interest. For a particular simulation there were 488 transmitters and 8 receivers. The data were organized into a matrix of dimensions 488 by 8, corresponding to 488 independent row vectors containing 8 elements. Each row vector is input to the three DF algorithms described in this paper. Both the amplitude and phase of each row vector are important for the A-SCPDD and D-PLL DF algorithms (phase-based DF algorithms) since the DOA estimate is based on the relative phase relationship between the 8 receiving antenna elements. In contrast, the amplitude of each row vector is important for the RPL DF algorithm (amplitude-based DF algorithm) since the DOA estimate is selected in the direction of the antenna element receiving the highest power.

In this work, only the forward link (user to car) is extensively analyzed, and the DOA estimate was made in the vehicle receiver module with respect to true North. It is assumed that the coordinate systems of the transmitter and receiver are aligned. The reverse link (car to user) is not considered in this work, and is the focus of future research.

4. Comparative analysis via simulation

The 488 by 8 complex power levels generated from the parking garage channel model simulations were used to assess the performance of the three DF algorithms as a function of the number of antenna elements (phase-based DF algorithm), the half power beam width (HPBW) of the receiving antenna element (amplitude-based DF algorithm), complexity of the reflecting environment (with and without cars) and the receiving antenna array location on the vehicle (interior and exterior). The quantitative metric utilized to assess the performance of each DF algorithm is the pass rate percentage (Fig. 6). The pass rate percentage is defined as the total number of DOA estimates that fall within ±22.5° of the true DOA out of the possible 488 points (Routine 1).

$$\text{Pass} = 0$$
$$\text{if } i = 1 : N$$
$$\text{if } \left| \left| \text{DOA}_i - \hat{\text{DOA}}_i \right| \right| \leq \xi$$
$$\text{Pass} = \text{Pass} + 1$$
$$\text{end}$$
$$\%\text{Pass} = \frac{1}{N}\text{Pass} \times 100\%$$

where N is the number of estimates performed, DOA is the ith DOA estimate, DOA is the true DOA value, and ξ is the threshold value of the absolute error. ξ was chosen to be ±22.5° to cover a sector of 45° within the eight-element array.

4.1. Received power level (RPL)

Fig. 7 shows the pass rate percentage results for the RPL DF algorithm when implemented with receiving antenna radiation patterns possessing HPBW of 45° and 90° in terms of the four different heights and the composite for all heights. The following observations can be made. First, the parking garage model with 47 cars was more severe than the parking garage model with a single car. This is expected since the parking garage environment with a single car produces fewer signal interactions for each transmitter to receiver pair. Next, the RPL DF algorithm performed best when the receiving antenna exhibited an HPBW of 45°. This is because each of the eight antenna elements provides coverage over a 45° sector. An antenna possessing an HPBW greater than 45° incurs increased error since the adjacent antenna elements have equal gain in the fringe areas. Finally, the RPL DF algorithm performed best when the receiving antenna array was placed on the exterior of the vehicle’s roof. Fig. 7 clearly shows that, in the parking garage environment with 47 cars, the RPL DF algorithm performed best when the transmitter heights were greater than or equal to the height of the externally located receiving antenna array. At these heights the ray interactions for each transmitter to receiver pair were less severe since the transmitted signals were above the vehicle roof line. For the internally located receiving antenna array, the trends were different since significant ray interactions for each transmitter to receiver pair took place. In summary, the RPL DF algorithm with a receiving antenna HPBW of 45° had average pass rate percentage results of 75.6 and 54.3 for externally and internally located receiving antenna arrays, respectively for the parking garage channel model with 47 cars. All numerical results are listed in Table 6.

4.2. Analog single-channel pseudo-Doppler DF (A-SCPDD)

Fig. 8 shows the pass rate percentage results for the A-SCPDD DF algorithm when implemented with four and eight receiving antenna elements in terms of the four different heights and the composite for all heights. The following observations can be made. The four-element receiving antenna array worked slightly better than the eight-element receiving antenna array for the A-SCPDD DF algorithm. The A-SCPDD DF algorithm performed slightly better in the parking garage environment with a single
The four-element antenna implementation of the A-SCPDDF algorithm worked slightly better when it was located internal to the vehicle while the eight-element implementation of the A-SCPDDF algorithm worked slightly better when located external to the vehicle. The pass rate percentage for each height was determined based on 122 transmitter points. Since the phase of the received power is affected at all heights, no consistent trend in terms of pass rate percentage is achieved for the various implementations of the A-SCPDDF algorithm in both environments. The best overall implementation of the A-SCPDDF algorithm for the parking garage environment with 47 vehicles occurred with four-antenna elements, producing pass rate percentage results of 13.9 and 14.8 for external and internal array locations, respectively. All numerical results are listed in Table 7.
4.3. Digital phase locked loop (D-PLL)

Fig. 9 shows the pass rate percentage results for the D-PLL DF algorithm in terms of the four different heights and the composite for all heights. The following observations can be made. The eight-element implementation of the D-PLL DF algorithm performed better than the four-element implementation of the D-PLL DF algorithm for a given antenna array location and environment. The four-element implementation of the D-PLL DF algorithm performed better in both environments when located external to the vehicle while the eight-element implementation of the D-PLL DF algorithm performed better in both environments when located inside the vehicle. A marginal performance difference was noticed for the D-PLL DF algorithm between the two environments. Since the phase of the received power is affected at all heights, no consistent trend in terms of pass rate percentage was achieved for the various implementations of the D-PLL DF algorithm in both environments for each antenna array location. The best pass rate percentage results for the parking garage channel model with 47 cars occurred for the eight-element implementation of the D-PLL DF algorithm in the parking garage channel model. Values of 18.6 and 20.3 were obtained for the external and internal antenna array locations on the vehicle, respectively.

4.4. Comparative analysis of the RPL, A-SCPD and D-PLL DF algorithms

Fig. 10 investigates the performance of all implementations of the RPL, A-SCPD and D-PLL DF algorithms for both parking garage channel models. The RPL DF algorithm implemented with receiving antennas possessing an HPBW...
of 45° located external to the vehicle performed best, with pass rate percentages of 75.6 and 83.4 for parking garage channel models with 47 cars and 1 car, respectively. Neither of the phase-based DF algorithms exhibited a pass rate percentage above 20%. All numerical results are provided in Table 8.

5. Conclusions

A rigorous analysis of three distinct DOA algorithms was undertaken to find the direction of a vehicle in a complex reflecting environment. The RPL (amplitude-based) algorithm significantly outperformed the A-SCPD and D-PLL (phase-based) algorithms in a parking garage environment for various antenna locations. The complex environment clearly illustrates that reflected and diffracted rays significantly degrade the performance of phase-based DOA algorithms.

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References


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