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Passive Sensor Based on Extended Kalman Filtering

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Abstract: Passive sensor is an essential receiver-only sensor that usually dissociates the receiving system at different location from the illuminator. This paper investigated a new passive sensor system, the antenna was an 8-element microchip phased array and the non-cooperative illuminator was downlink signals radiated from GSM base station. The digital beam forming technology was used to improve the pattern reconfiguration and to determine the Doppler and phase characteristics of the received signal; the Fast Fourier Transform was adopted for each channel's signal processing. And the system was functionally tested by means of detecting civilian plane near WHITECLOUD airport. The experiment result shows that targets can be detected and tracked over a distance up to 3 km; this system may be used for monitoring the low altitude weapons as an efficient supplementary to urban air defense network. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Passive sensor, Doppler frequency, GSM downlink signals, Digital beam-forming, Extended Kalman filter, Plane.

1. Introduction

Passive sensor is basically a receiver-only sensor that usually dissociates the receiving system at different location from the illuminators. It has no transmitter and has the benefits such as anti extra low flight, anti-stealth and anti radiation missile, etc. Most importantly, passive sensor is virtually undetectable to foe surveillance receivers and there is also no constraint of spectrum allocation. Passive sensor original experiment with Yagi antenna was conducted by Arnold Wilkins, using the BBC Empire short-wave radio transmitter at Davently and a receiver about 11 miles away, to demonstrate the detection of a Heyford bomber at a range of 12 km [1, 2]. Since the recent several decades, passive sensor with horn antennas that uses the non-cooperative opportunity illuminator sources, such as: AM, FM, TV broadcast, and GPS signal had already been conducted or experimented [3-9]. And another existing radio signal that is suitable for passive sensor is the GSM (Global System for Mobile Communication). GSM base stations are honeycombed and distributed in a large area. This transmitter-rich communication system is a valuable illuminator source for passive sensor with at least two distinct advantages. One is that the illuminators of such transmissions are abundant. The other is the multiple base stations can be utilized in a multistatic passive sensor network consisting of multiple passive sensor receivers for improving the sensor performance and capability.

Some preliminary groundwork in this area has already been done [10-16]. However, the microchip phased array antenna hadn't been used in the above experiment systems, so that, although good algorithms have been adopted, they are still not easy for reconfiguring pattern, quick steering capability of elevation and azimuth axis.

This paper designed and implemented a passive sensor with microchip phased array antenna based on the GSM signal, and gave a description on its hardware structure and signal processing schemes. Experiments were carried out near Whitecloud airport to demonstrate its ability to detect and track the Doppler frequency of civilian plane targets. And its performance and operating capability significantly is better than the previous system because of the adopting digital beam-forming technology.

2. System Scheme

It is well known the function of a radar receiver is to amplify the echoes of the targets and to filter them in a manner that will provide the maximum discrimination between desired echoes and undesired interference. This bistatic scheme assumes that there is only one micro-strip phased array receiver system and one remotely located GSM base station transmitter; The passive sensor based-on GSM uses an existing operational GSM base station as the non-cooperative transmitter, the micro-strip phased array passive receiver is tuned to a certain carrier frequency of the GSM downlink signal, and its antennas simultaneously receive direct path signal and scattered reflection echoes off the target within the area of coverage dictated by the beam pattern of the antenna in the target echo channel.

The target echo signal is firstly received by eight sub-element of array antenna, and amplified by LNA (low noise amplifier) with AGC (automatic gain control), then was passed into IF (intermediate frequency) digital receivers to be mixed with the local oscillation frequency to produce IF signal. Where one is used to collect the direct path reference signal and the other for the echo signals off the target. Both receivers are co-located but the main beam of each antenna in each channel points to different directions. The direct path signal channel uses an antenna with a directed beam pattern pointing towards the LOS (line-of-sight) of the GSM base station transmitter. The antenna of the target echo signal channel is positioned facing the direction of the closing or receding target to collect the target echo returns. Signals from each channel are processed using the FFT (fast Fourier transform) to provide Doppler and bearing estimates. A threshold is employed to make a decision as to the presence or absence of a signal is P in a background of noise, its performance can be described in terms of CA-CFAR (cell averaging constant false alarm rate). This threshold probability is characterized by value of receiver output voltage Vt (the threshold, equivalent to Marcum's bias level), which, if exceeded, results in the decision report that a signal is present. If the threshold voltage is not exceeded at a particular in instant, the detector reports "no signal." It is used to identify target echoes, and to reject noise and unwanted carrier harmonics. Kalman filter based tracking scheme is used to associate the Doppler and DOA (direction of arrival) of detections belonging to the same target. The Doppler and DOA samples for each target are passed to a track estimation process, which estimates the target's Cartesian co-ordinates and velocity components... So set the main performance parameters for the receiver as following:

The operation frequency is UHF GSM900; Operation bandwidth is 25 MHz; Signal bandwidth is 0.20 MHz; Noise factor is 2.5 dB; Receiver dynamic range is 65 dB; Phase instability: 3.5° (rms); Amplitude instability: 0.5 dB (rms); Amplitude inconsistency is 1 dB (rms); Channel isolation =50 dB.

The system hardware is required to down-convert, digitize and store the GSM signal approximately 200 kHz either side of the GSM signal, and to provide a measuring method for the bearing of target echoes. The GSM based passive sensor consists of 8 separate but co-located antennas/receivers to receive the direct path reference signal from the GSM base station and echo signal reflected off the targets. The system hardware architecture is based on an 8 channel single conversion super heterodyne receiver with intermediate frequency sampling. The desired RF GSM carrier signal from each channel is filtered, amplified and down-converted to an intermediate frequency of 70 MHz and subsequently amplified and filtered again prior to signal digitization. The digital IF signal is down-converted to base band by a tunable digital down-converter module that was integrated in a high performance ADC card and I/Q data is saved continuously to the PC hard disk. Fig. 1 shows the system hardware architecture of the GSM based passive sensor.

In Fig. 1, since the signal-to-noise ration (SNR) is established at the digital output of each receiver, there is no less in SNR when manipulating the digital outputs to form multiple beams. There can be any number of closely spaced antenna beams formed without degradation in SNR. DBF (Digital beam-forming), therefore, doesn't suffer the limitations inherent in analog beam-forming, which are the low crossover of adjacent beams and the loss that occur when trying to obtain lower peak side lobes than -13.2 dB of a uniform illumination. The operation of the beam former is to take the outputs from each element, apply a complex weight (amplitude or phase) to each, and then sum them to provide the output signal. The form of this output is similar to a digital Fourier Transform (or inverse digital FT). DBF gives a passive sensor more favorable attributes, such as: Self-calibration and error correction – errors in the phase and amplitude that occur in the analog portion of the receivers of a DBF can be compensated with relative ease in the digital portion; Low antenna side lobes – the ability to digitally self calibrate the array the potential for achieving low or even ultra low receiving antenna side lobes after digital processing. The effect of mutual coupling can also be compensated; Adaptive mulling of clutter as a function of range – nulls can be formed adaptively in those directions where there are large clutter echoes as well as in those directions in which there are noise sources; Correction for failed elements – the complete failure of a sufficient number of antenna elements can seriously degrade the performance of a low side lobe array antenna. But it is easy to be compensated for the loss of antenna elements in a digital beam-forming receive array by using simple linear operations; Flexible data rates – the DBF array can have a data rate that varies with the operational situation [17].

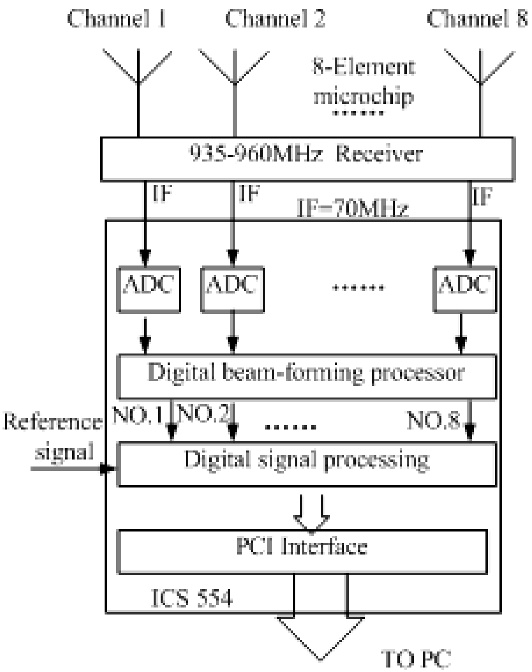

Fig. 1. System hardware architecture of the GSM based passive sensor.

In Fig. 2, the target bearing measurement is performed using phase interferometers, with an eight-element microchip phased array antenna, horizontally spaced about 1.5 wavelengths apart, giving an unambiguous measurement range of approximately ±180° about bore sight. As the system operates in the UHF-GSM 900 frequency bands, multi-path propagation is a potential cause of reduced low-level coverage. To overcome this, the antennas are mounted on an 8 m high mobile tower, 25 wavelengths above the ground. Fig. 2 shows the microchip phased array antenna and tower.

Each microchip element antenna is for a dedicated processing channel, which down-converts the received signal to GSM signal in a two-stage process, mixing to produce IF (intermediate frequency) 70 MHz. This IF signal is then sent into an 8 channels ICS554 based digital receiver card, then the IF signal was down converted to base band of bandwidth 100 Hz ~ 16 kHz, before sampling, digitizing and providing output in the form of 16-bit I/Q samples. The whole system is frequency locked to an oven-controlled 10 MHz reference. Fig. 3 shows the ICS554 receiver system. The experiment field is shown in Fig. 4.

Fig. 2. Triangle-tower mounted 8-element phased array and target flying over.

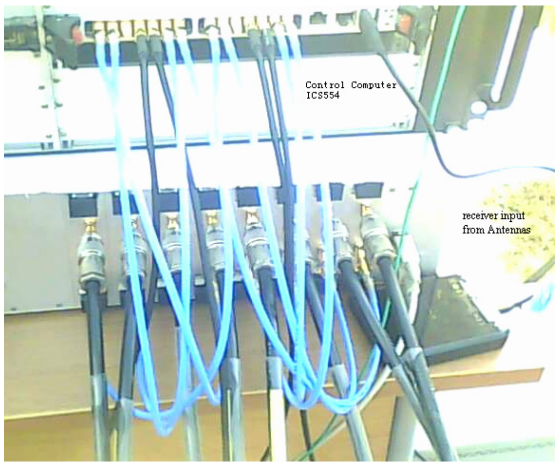

Fig. 3. ICS554-based digital receiver system.

To evaluate the performance and capabilities of the designed GSM based passive sensor hardware and its associated signal processing schemes, extensive field experiments based on non-cooperative plane targets were conducted using a selected operational GSM base station transmitter near White-cloud Airport. The strongest frequency carrier at 951.6 MHz is chosen for all the measurements and all resulting plots use a CIT of 0.2 s.

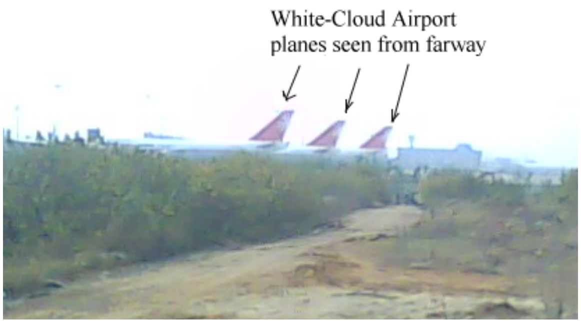

Fig. 4. White-Cloud airport planes.

3. Signal Processing Schemes

3.1. Doppler and Bearing Analysis

Once the pure direct path reference signal from direct path channel and pure target echo signal from target echo channel is acquired, target detection can be easily implemented by applying the cross-ambiguity coherent processing [8]. The time/Doppler history of the signal is calculated using a mixed radix FFT. This typically involves taking 0.2 s sample of the time waveform on each channel, using a Hanning weight function, calculating the FFT of each sample, and then repeating the process for the next two-block of data. As the spectrum from the FFT is complex, the phase difference between the channels can be used to calculate the bearing of the target θ, using the equation

$$\theta(k) = \sin^{-1}\left(\frac{\lambda \Delta \psi(k)}{2\pi d}\right), \tag{1}$$

where λ is the signal wavelength, d is the spacing between the two antennas, and Δψ is the phase difference between the two channels. It is assumed that -sin-1(λ/2d) <θ<sin-1(λ/2d) to avoid directional ambiguities.

3.2. Target Detection

A time-acting CA-CFAR algorithm is employed to reject picture harmonics. The 6 dB is employed as the threshold to make a decision as to the presence or absence of a signal be P in a background of noise, its performance can be described in terms of CA-CFAR (cell averaging constant false alarm rate) .This threshold probability is characterized by value of receiver output voltage Vt (the threshold, equivalent to Marcum's bias level), which, if exceeded, results in the decision report that a signal is present. This threshold value was chosen as a compromise between detecting targets with a low SNR and minimizing the number of false detections. 951.60 MHz data collection is shown in Fig. 5.

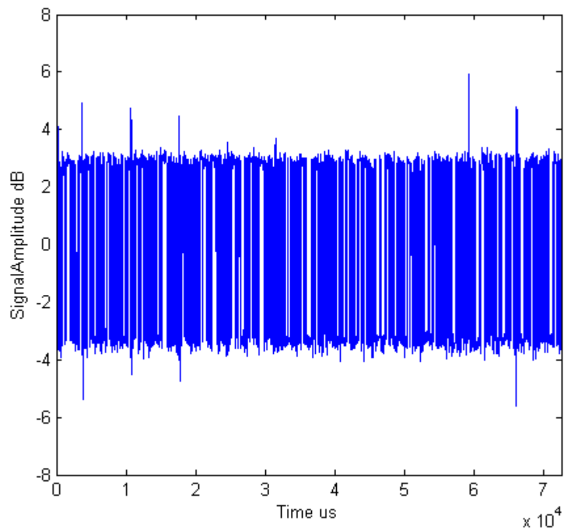

Fig. 5. 951.60 MHz data collection.

If an echo is not declared a target by this process, its power is used to update the noise map instead. The algorithm also contains features to cope with spectral gap between strong target echoes and the drifting of GSM harmonics in time.

3.3. Target Track Estimation Algorithm

It has been shown previously [7] how the nth measurements of Doppler shift Fd (k) and bearing θ(k) of a target echo in a passive sensor system are related to the parameters of the target track as following:

For Doppler filter: $\sigma_{pn} = 0.0015$,

$$p_x(x) = \begin{bmatrix} 4.5 & 0 \\ 0.0 & 0.45 \end{bmatrix},\ P_v(0) = [4.0];$$

For DOA filter: $\sigma_{pn} = 0.0015$, $\sigma_{mn} = 0.15$;

$$P_v(0)=[55.0],\ p_{(x)} = \begin{bmatrix} 42.0 & 0.0 \\ 0.0 & 20.0 \end{bmatrix}.$$

For both Doppler / DOA filter: Maneuver threshold J=0.25; Max consecutive rate aids (confirmed /unconfirmed) =15/12; Min track length for rate aids=6; No points defining track overlap=8.

The basic Kalman filter structure is as shown in Fig. 6.

The basic Kalman filter equations group as following:

Filter equation

$$\bar{x}(k|k) = \bar{x}_S(k) = \bar{x}(k|k-1) + K(k)[\bar{y}(k) - \bar{G}\bar{x}(k|k-1)] \tag{2}$$

Measurement vector

$$\bar{y}(k) = \bar{G}\bar{x}(k) - \bar{v}(k), \tag{3}$$

where $\bar{v}(n)$ is Gaussian white noise of zero mean value and variance R_c, and

$$R_c = E\{\bar{y}(k)\ \bar{y}^t(k)\}. \quad (4)$$

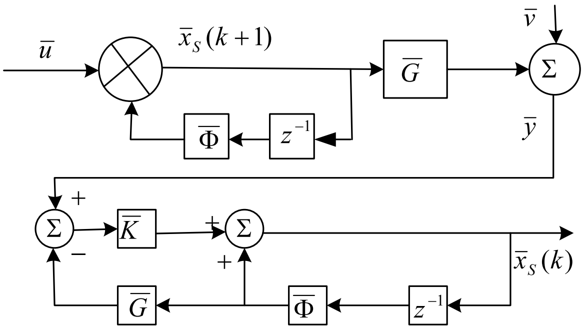

Fig. 6. Basic Kalman filter structure.

Filter gain (weight) vector equation

$$K(k) = \bar{P}(k|k-1)\bar{G}^t[\bar{G}\bar{P}(k|k-1)\bar{G}^t + R_c]^{-1}, \quad (5)$$

where the measurement noise matrix $\bar{P}$ represents for covariance matrix of estimator

$$\bar{P}(k+1|k) = E\{\bar{x}_S(k+1)\bar{x}^*{}_S(k)\} = \bar{\Phi}\bar{P}(k|k)\bar{\Phi}^t + \bar{Q}, \quad (6)$$

Where $\bar{Q}$ is the covariance matrix of input $\bar{u}$.

$$\bar{Q} = E\{\bar{u}(k) \quad \bar{u}^t(k) \ \} \quad (7)$$

Smoothed estimate covariance

$$\bar{P}(k|k) = [\bar{I} - \bar{K}(k)\bar{G}]\bar{P}(k|k-1) \quad (8)$$

Estimator equation

$$\bar{x}(k+1|k) = \bar{\Phi}\bar{x}(k|k). \quad (9)$$

Maneuver noise

$$V = \begin{cases} \begin{pmatrix} \dfrac{\sigma_{\rho a}\Delta^4}{2} & \dfrac{\sigma_{\rho a}\Delta^3}{3} \\ \dfrac{\sigma_{\rho a}\Delta^3}{3} & \sigma_{\rho a}\Delta^2 \end{pmatrix}, when \sqrt{J} \succ 0.25 \\ 0, \qquad\qquad else \end{cases} \quad (10)$$

Maneuver threshold

$$J(k) = [h_X(k)\bar{x}(k) - y(k)]'[h_X(k+1)\bar{P}(k)h_X'(k) + P(k)]^{-1} * [h_X(k)\bar{x}(k) - y(k)] \quad (11)$$

$$F_d(k) = -\lambda^{-1}\{\frac{[\bar{x}(0) + kT\bar{x}(k)]\bar{x}(k) + [\bar{y}(0) + kT\bar{y}(k)]\bar{y}(k)}{\sqrt{[\bar{x}(0) + kT\bar{x}(k)]^2 + [\bar{y}(0) + kT\bar{y}(k)]^2}} + \frac{[\bar{x}(0) + kT\bar{x}(k)]\bar{x}(k) - [L - (\bar{y}(0) + kT\bar{y}(k)]\bar{y}(k)}{\sqrt{[\bar{x}(0) + kT\bar{y}(k)]^2 + [L - (\bar{y}(0) + kT\bar{y}(k)]^2}}\} \quad (12)$$

$$\theta(k) = \tan^{-1}[\frac{\bar{x}(0) + kT\bar{x}(k)}{\bar{y}(0) + kT\bar{y}(k)}], \quad (13)$$

where λ is the wavelength of the GSM signal carrier, $\bar{x}(0)$ and $\bar{y}(0)$ are the Cartesian coordinates of the target, $\bar{x}(k)$ and $\bar{y}(k)$ are the Cartesian components of the target's velocity, T is the CIT (coherent integration time), and. To for initializing the target track, it is necessary to perform a nonlinear fit of Eq. (12) and Eq. (13) and to a batch of Doppler and DOA samples. This nonlinear fit can be expressed as the minimization of the functional formed from the least squares difference of the equations and data:

$$J_{LS} = 0.5[y(k) - h_X(k)]'[y(k) - h_X(k)], \quad (14)$$

where y is the measurement vector containing N measurements of Doppler and DOA, and F_i and Γ_i denote the i-th measurements of Doppler and DOA, respectively:

$$y(k) = [F(0), \Gamma(0), F(1), \Gamma(1), ..., F(k-1), \Gamma(k-1)]' \quad (15)$$

And $h_X(k)$ is the vector containing the corresponding measurement equations for each time sample (from Eq. (12) and Eq. (13)):

$$h_X(k) = [F_d(0), \theta(0), F_d(1), \theta(1), ..., F_d(k-1), \theta(k-1)]' \quad (16)$$

Consideration of the information content in a batch of data, for correct initialization, k should be of the order of 20. The estimation algorithm seeks to determine the optimal target vector $X = (x, \bar{x}, y, \bar{y})'$, which minimizes J_{LS}.

3.4. Using One Order EKF for Track Modification

Once initialized, a target track is maintained using the one order EKF (extended Kalman filter) that may be efficiently commutated. The EKF provides an updated estimate of the target state for every new Doppler and DOA sample data, and hence responds more rapidly to maneuvering target.

One order Extended Kalman filtering algorithm as listed in Eq. (17) to Eq. (25):

Measurement equation

$$y(k+1|k) = h[\hat{X}(k+1|k), k+1] + v(k+1|k) \quad (17)$$

The associate covariance

$$S(k+1) = h_X(k+1)P(k+1|k)h_X'(k+1) + R(k+1) \quad (18)$$

One step state prediction

$$\hat{X}(k+1|k) = f[k, \hat{X}(k|k)] \tag{19}$$

Kalman gain matrix

$$K(k+1) = P(k+1|k)h_X^{'}(k+1)S^{-1}(k+1) \tag{20}$$

State update equation

$$\hat{X}(k+1|k+1) = \hat{X}(k+1|k) + K(k+1)\{Y(k+1) - h[\hat{X}(k+1|k), k)] \tag{21}$$

Covariance of one step prediction

$$P(k+1|k) = f_X(k)P(k|k)f_X^{'}(k) + Q(k) \tag{22}$$

Covariance update equation

$$P(k+1|k+1) = [I - K(k+1)h_X(k+1)]P(k+1|k)[I + K(k+1)h_X(k+1)]' - K(k+1)R(k+1)K'(k+1), \tag{23}$$

where I is unit matrix with same dimension as covariance matrix.

A maneuvering target is detected using the normalized error between the measured and predicted target positions, by modified threshold given in as follows:

$$J = \{h[k+1, \hat{X}(k+1|k)] - y(k+1|k)\}^{'}[h_X(k+1|k+1)P(k+1)h_X^{'}(k+1) + P(k+1)]^{-1}h_X[\hat{X}(k+1|k), k+1) - y(k+1|k)] \tag{24}$$

The measurement vector contains the latest pair of Doppler and DOA measurements, and is defined as

$$y(k+1) = [F(k+1), \Psi(k+1)]' \tag{25}$$

4. System Experiment

The results are from real data collected nearby White-cloud civilian airport using the GSM base station transmitter, broadcast from the 2 km away, at a frequency of 951.6 MHz. Fig. 7 shows tracking results for a 15 seconds collection made on 21st November 2010. A wide coverage region was again apparent, with targets tracked at ranges of up to 3 km from the receiver. It can track the airport plane target taking-off and climbing stage from White-cloud airport.

5. Conclusion

This paper has implemented a passive sensor system using GSM base station transmitter as a non-cooperative opportunity illuminator. A tracking technique has been developed and demonstrated which allows targets to be tracked to ranges of about 3 km. According to the processing results, GSM based passive sensor is capable of detecting and tracking the Doppler frequency of the plane. The approach includes microchip phased array antenna, digital beam forming technology, the measurement of the Doppler shift and DOA of echoes of the GSM downlink signal, and thus uses a receiver bandwidth of only 25 MHz.

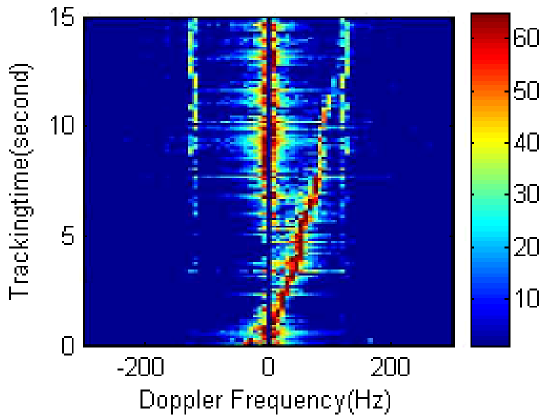

Fig. 7. Doppler frequency of non-cooperative plane in taking-off and climbing.

The processing technique is equally applicable to any carrier wave transmission, and hence could be used with other transmitters of opportunity, or with a simple dedicated carrier wave transmitter. In a military scenario, this approach is believed to provide a low-cost supplementary to low altitude air defense surveillance in urban regions. Exploiting existing broadcast transmissions circumvents the need to try to obtain military frequency allocations in bands already allocated for civilian purposes.

Acknowledgments

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