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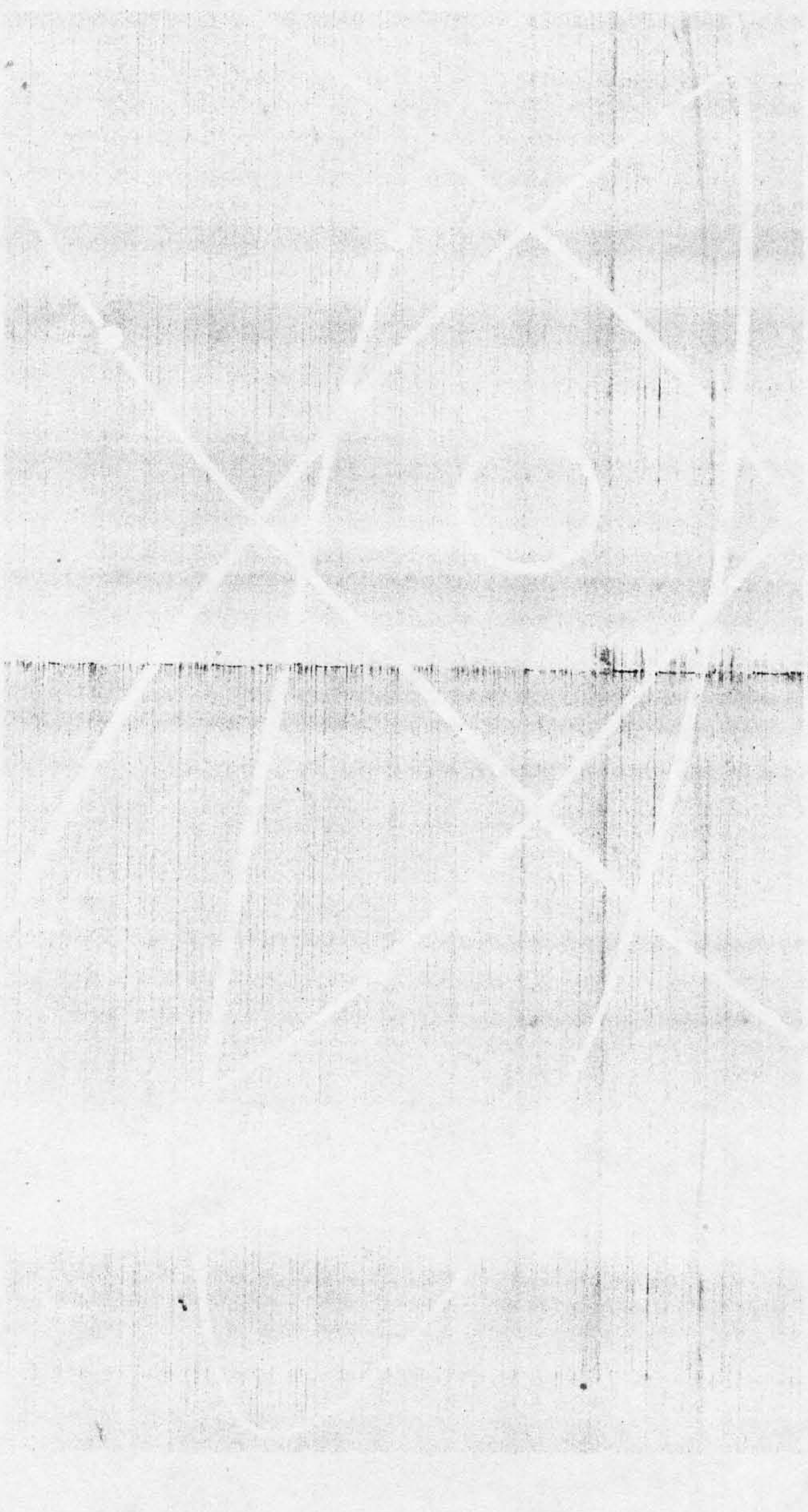

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DIGITAL METHODS OF ESTIMATING TIME POSITION OF BELL-LIKE RADIO PULSES

V. I. Slyusar

Kiev

The paper has considered deterministic and stochastic range-finding procedures for narrow-band reception channels based on the envelope of radio pulses in the form of the $\sin^2$. It has been shown that the processing of quadruples of readings of the analog-to-digital converter is more universal.

In narrow-band reception channels of pulse radars the output signal, with a measure of conventionality, can be referred to as a bell-like pulse whose envelope is characterized by the Gaussian exponent $\exp(-\beta t^2)$ [11].

Such a model of the signal, according to [1, 2] in its active portion exceeding the level of 0.5, nearly coincides with the shape of the bell-like pulse being determined by the $\sin^2$. In contrast to the Gaussian representation, the $\sin^2$ approximation of the envelope is a finite time function which has a more pronounced physical nature, is characterized by a smaller variance of the error in estimating the signal location [2] and makes it possible, as we are going to show below, to unify range finding by the methods of spectral estimation based on the operation of the fast Fourier transform [FFT].

Such a list of advantages of the $\sin^2$-treatment of a narrow-band radio pulse can be considered a sufficient reason for its use in the problem of digital range finding. Therefore, the objective of the present article is the synthesis of one-target ranging procedures for narrow-band reception channels based on the representation of their output signal by $\sin^2$-pulses.

As is known, the voltage of the radio frequency signal mixture in terms of the analog-to-digit converter output (ADC) is a material time series. To streamline computational procedures it is advisable to go from the material series of discrete readings to a complex one, for instance, by means of sliding Hilbert filtering. In this case the complex voltage of the digitized signal mixture can be written down in the following form

$$U_s = \begin{cases} a \cdot K(s - s_1) \cdot \exp[j\,\omega\,\Delta t\,(s - s_1) + \psi] + \dot{n}_s, & \text{при } s_1 \le s < s_1 + N \\ \dot{n}_s, & \text{при } s < s_1 \text{ и } s \ge s_1 + N, \end{cases} \qquad (1)$$

where s is the ordinal number of the complex reading; a is the signal amplitude; s_1 is the ordinal number of the first ADC readings within the limits of the radio pulse existence;

$$K(s - s_1) = \begin{cases} \sin^2 (s - s_1)\,x & \text{at } s_1 \le s < s_1 + N \\ 0 & \text{at } s < s_1 \text{ и } s \ge s_1 + N, \end{cases}$$

$x = \pi/N$, N is the signal time in the ADC readings; ω is the frequency of filling a radio pulse; Δt is the signal digitization period; ψ is the initial phase of a radio pulse; $\dot{n}_s$ is the noise complex value.

In the given case an assumption was made that the envelope of radio pulses in both the Hilbert components was identical. It is true for all readings which are beyond the transition process of the Hilbertian filtering on the envelope front and cut.

A feature of model (1) is that the problem of measuring the time position of radio pulses can be reduced to the solution of trigonometric equations. Within the framework of the deterministic approach to this end it is enough to use a pair of complex ADC readings within the radio pulse duration

$$U_1 = a \cdot \sin^2 dx \cdot \exp(j\,\omega\,\Delta t\,d + \psi) + \dot{n}_1;$$

$$U_2 = a \cdot \sin^2 (z + d) x \cdot \exp (j \omega \Delta t (d + z) + \psi) + \dot{n}_2 \tag{2}$$

where d is the time shift of the first readings among those used in respect to the pulse beginning in the digitization periods Δt; z is the time interval between readings used in periods Δt.

Ignoring the presence of noises let us go to particular modulus (2) of the readings

$$\frac{|U_2|}{|U_1|} = \frac{\sin^2 (z + d) x}{\sin^2 d x} = \frac{1 - \cos 2 (z + d) x}{1 - \cos 2 d x}.$$

In this case, we used that circumstance under which the modulus of the exponent for any complex argument is always equal to 1.

Thus, the relative time shift d of the first of the readings U_1 can be determined from the following equation

$$|U_2| \cos 2 d x - |U_1| \cos 2 (z + d) x = |U_2| - |U_1|. \tag{3}$$

Using the substitution

$$t = \frac{|U_2| - |U_1| \cos 2 z x}{|U_2| - |U_1|}; \quad w = \frac{|U_1| \sin 2 z x}{|U_2| - |U_1|}$$

it is possible to bring (3) to the canonical form $t \cdot \cos 2 d x + w \cdot \sin 2 d x = 1$.

In conclusion we obtain

$$d = \frac{1}{2x} \left\{ \arcsin \frac{1}{\sqrt{t^2 + w^2}} - \arcsin \frac{t}{\sqrt{t^2 + w^2}} \right\}. \tag{4}$$

A more universal approach, in the computational point of view, is reduced to using a pair of difference of two complex ADC readings. Its universal nature is in that the measurement of the time delay by the form appears analogous to known procedure of direction finding used in azimuthal or Doppler FFT-systems.

As a confirmation of this let us consider two pairs of complex voltages of the signal having written them similar to (2) in the form

$$U_1 = \dot{a} \cdot \sin^2 d x \cdot \exp (j \omega \Delta t d + \psi) + \dot{n}_1;$$
$$U_2 = \dot{a} \cdot \sin^2 (d + z_1) x \cdot \exp (j \omega \Delta t (d + z_1) + \psi) + \dot{n}_2;$$
$$U_3 = \dot{a} \cdot \sin^2 (d + z_2) x \cdot \exp (j \omega \Delta t (d + z_2) + \psi) + \dot{n}_3;$$
$$U_4 = \dot{a} \cdot \sin^2 (d + z_3) x \cdot \exp (j \omega \Delta t (d + z_3) + \psi) + \dot{n}_4.$$

Going to moduluses, after simple transformations, let us form the relationship of differences

$$\frac{|U_1| - |U_2|}{|U_3| - |U_4|} = \frac{\sin (2 d + z_1) x \cdot \sin z_1 x}{\sin (2 d + z_3 + z_2) x \cdot \sin (z_3 - z_2) x}. \tag{5}$$

Obviously, that for determination of d it is convenient to take readings of signal voltages through equal time intervals. Then $\sin z_1 x = \sin (z_3 - z_2) x$, which makes it possible to reduce (5) by the value $\sin z_1 x$. Further trigonometric calculations lead to the sought-for result

$$\operatorname{tg} 2 d x = \frac{p \cdot \sin (z_3 + z_2) x - q \cdot \sin z_1 x}{q \cdot \cos z_1 x - p \cdot \cos (z_3 + z_2) x} \tag{6}$$

where $p = |U_1| - |U_2|$, $q = |U_3| - |U_4|$.

The subsequent transition to the unknown d does not require any explanation.

In all fairness it should be noted that relationship (6) loses the measuring accuracy in procedure (4). However, a possibility of using, for the problems of direction finding, measuring methods of the same type with the spatial-frequency selection in many cases spoke to the benefit of the considered approach. A loss in accuracy, as it turned out, can be reduced, if in place of the differences of reading neighboring in time we use the values $|U_1| - |U_3|$, $|U_2| - |U_4|$. With a regular sampling step their relationship similar to (6) is transformed to the form

$$\operatorname{tg} 2 d x = \frac{P_M \cdot \sin (z_1 + z_3) x - q_M \cdot \sin z_2 x}{q_M \cdot \cos z_2 x - P_M \cdot \cos (z_1 + z_3) x} \tag{7}$$

where $P_M = |U_1| - |U_3|$, $q_M = |U_2| - |U_4|$.

Stochastic methods of estimation synthesized, for instance, by means of the method of the least squares is an alternative to the deterministic procedures. Their feature is minimization of a mean-square error of measurements under conditions of a noise interference. In this case the quadrature components U_s^c and U_s^s of all complex readings of voltages used except for the first one, should be preliminary processed using the rule

$$\widetilde{U}_s^c = U_s^c \cos p_s + U_s^s \sin p_s; \quad \widetilde{U}_s^s = U_s^s \cos p_s - U_s^c \sin p_s \tag{8}$$

where $p_s = \omega \, \Delta t \cdot z_s$, z_s is the time interval between the first and the s-th in counting of the signal complex readings used.

Ignoring the Doppler shift of the carrier frequency, such reception makes it possible to consider as an unknown complex amplitude of the signal the value

$$\tilde{a} = a \cdot \exp\left[j\,(\omega \, \Delta t d + \psi)\right].$$

As a result, the estimation of the time position of radio pulses can be obtained based on information contained in their envelopes.

In particular, considering in (6) the quadrature components instead of the moduluses of voltages it is not difficult to go to minimization of the functional formed for the approach generality in several quadruples of voltages (8)

$$F = \sum_{s=1}^{S} \left[\left\{ \operatorname{tg} 2\,dx\,(q_s^c \cos \alpha_s x - p_s^c \cos \beta_s x) - p_s^c \sin \beta_s x + q_s^c \sin \alpha_s x \right\}^2 + \right.$$

$$\left. + \left\{ \operatorname{tg} 2\,dx\,(q_s^s \cos \alpha_s x - p_s^s \cos \beta_s x) - p_s^s \sin \beta_s x + q_s^s \sin \alpha_s x \right\}^2 \right] = \min \tag{9}$$

where

$$p_s^{c(s)} = U_{1s}^{c(s)} - U_{2s}^{c(s)}, \; q_s^{c(s)} = U_{3s}^{c(s)} - U_{4s}^{c(s)}; \; \alpha_s = z_{1s} + 2\,k_s, \; \beta_s = z_{2s} + z_{3s} + 2\,k_s;$$

k_s is the shift of the s-th quadruple of voltages with respect to the first in the ADC readings and in this case $k_1 = 0$.

Differentiating (9) by variables tg2dx we obtain

$$\operatorname{tg} 2\,dx = \frac{\sum_{s=1}^{s} \left\{ P_{12s} \sin(\alpha_s + \beta_s)\,x - 0{,}5\,p_s^2 \sin 2\,\beta_s x - 0{,}5\,q_s^2 \sin 2\,d_s x \right\}}{\sum_{s=1}^{s} \left\{ p_s^2 \cos^2 \beta_s x + q_s^2 \cos^2 \alpha_s x - 2\,P_{12s} \cos \alpha_s x \cdot \cos \beta_s x \right\}} \tag{10}$$

where $P_{12s} = p_s^c \cdot q_s^c + p_s^s \cdot q_s^s$.

Relationship (10) by its form coincides with the known procedure of measuring angle coordinates by the responses of secondary channels of the linear digital array. Note that under conditions

$$p_s^{c(s)} = U_{1s}^{c(s)} - U_{3s}^{c(s)}, \; q_s^{c(s)} = U_{2s}^{c(s)} - U_{4s}^{c(s)},$$

$$\alpha_s = z_{2s} + 2\,k_s, \; \beta_s = z_{1s} + z_{3s} + 2\,k_s,$$

it should be considered as an alternative of estimation (7).

If to confine ourselves to the processing of only two quadruples of readings having assigned intervals k_s, z_{1s}, z_{2s} and z_{3s} for them as identical, then the volume of calculations in (10) can be substantially scaled down at the expense of redundant calculation operations

$$\operatorname{tg} 2\,dx = \frac{\sin(\alpha + \beta)\,x \sum_{s=1}^{2} P_{12s} - 0{,}5 \sin 2\,\beta x \sum_{s=1}^{2} P_s^2 - 0{,}5 \sin 2\,\alpha x \sum_{s=1}^{2} q_s^2}{\cos^2 \beta x \sum_{s=1}^{2} P_s^2 + \cos^2 \alpha x \sum_{s=1}^{2} q_s^2 - 2 \cos \alpha x \cos \beta x \sum_{s=1}^{2} P_{12s}}. \tag{11}$$

In this case, it is assumed that the signal time makes it possible to choose mixing of the first quadruple with respect to the pulse beginning as equal to $d + k_1$, where k_1 is the assigned number. With weak correlation of voltages by noises, addition in (10) and (11) can be fulfilled with different mutual overlapping of quadruples of readings in time depending on a specific signal length. It should also be noted that similar to all procedures of algorithmic accumulation, estimates (10) and (11) can yield biased results due to addition of squares of noises in coefficients of the type $\sum_{s=1}^{S} p_s^2$ and $\sum_{s=1}^{S} q_s^2$. To avoid this it makes sense to resort to a technique recommended for the FFT-system, which is reduced to the replacement of the said coefficients by the differences $\sum_{s=1}^{S} p_s^2 - 2\,S \cdot \sigma_n^2$ and $\sum_{s=1}^{S} q_s^2 - 2\,S \cdot \sigma_n^2$, where σ_n^2 is the variance of noises in quadrature of components of voltage of signal (8). As for the aggregate of the sums of scalar products P_{12s} then for non-correlated voltages there is no need for such "clearance".

Obtained relationships for estimations of time position of radio pulses are also applicable in the case of narrow-band video signals. In this case, instead of moduluses of ADC readings it is preferential to use the voltage of material time series, while in the interests of stochastic procedures (10) and (11), to form a complex video signal in the analog form with the subsequent digitizing of the voltages in two quadrature channels [3]. If necessary, the efficiency of accumulation in (10) and (11) can be raised if the processing incorporates a batch of pulses or in the antenna array – responses of several reception channels. In both cases it is important to proceed from an assumption that the mixing of signals during the accumulation time is negligibly small. In this case, in estimations (10) and (11) the buildup of voltage with respect to index S should be supplemented by addition in the amount of pulses of the batch or channels of the antenna array. Not only primary but also secondary channels can be used as the latter, provided the time for fulfilling the operation of diaphragm formation (eg. FFT) does not exceed the interval between the ADC readings used in the measurements.

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