tion of hairpin-line filters and a variety of hybrid structures. For bandwidths up to 0.1, the procedure is virtually exact for any reasonable hairpin coupling. For larger bandwidth, the effect of the hairpin coupling on the frequency response should be checked.

In all cases, the VSWR was found to deteriorate long before any significant change in bandwidth was noted. The design applies to odd-order filters only, but this is not a serious restriction. In many cases a hybrid realization is preferred. But a very satisfactory hybrid design for even-order filters is presented.

The new design theory slightly improves the agreement of computed and theoretical response if compared with a design of comparable hairpin coupling given by Cristal and Frankel [2]. But more important is the theoretical explanation the new theory provides for the bandwidth contraction factor introduced in [2]. The relative bandwidth contraction as a function of c_p given in [2] was found to be in close agreement with (29). In their experiments, Cristal and Frankel found an even larger bandwidth contraction that they attributed to the finite-length connections between pairs of lines constituting a hairpin resonator. Such additional contraction was also found in the present experiments. Finally, it should be noted that the amount of bandwidth contraction for hybrid designs following the process in [2] is not precisely known. In contrast, our new design theory gives exact information about possible hybrid forms and about the parameters that control them.

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Holographic Imaging with Object Synthesized Apertures

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***Abstract*—A method for imaging remote moving objects with a giant thinned holographic array by monitoring the range and range-rate (Doppler) histories of a coherently illuminated object at the various elements of the array is discussed. Electrooptic processing and image retrieval from the raw data collected are described together with a technique that compensates for image distortion arising from irrotational object maneuvers. Results of confirming experiments are also given together with remarks on practical implementation.**

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I. INTRODUCTION

An obvious variation of the conventional synthetic aperture radar [1] is one in which the imaging aperture is synthesized by object motion within the beam of a stationary coherent transmitter–receiver complex. An early account of such an imaging concept employing radio waves was given by Rogers [2] in an attempt to extend Gabor's diffraction microscopy (holography) [3] to the imaging of moving ionospheric regions. More recently, infrared and optical imaging apertures synthesized by linear object motion were discussed [4],[5]. In these studies uniformity of object motion was assumed and maintained to avoid image distortion arising from aberrations introduced in the chirp-type signals into which the object information gets encoded [6]. This requirement is, however, not necessary, provided that proper compensation for object deviations from a linear and uniform law of motion is made. In certain situations, such as the imaging of the scattering centers on an object rotating about a central axis, the resulting image distortion can be corrected optically by relatively straightforward means applied in the image retrieval step [7],[8].

The aim of this paper is to present an interpretation of the object synthesized aperture concept based on scanned holography that leads to a general method for correcting image distortion arising from variations in the object velocity vector. Conditions under which image correction can be made are presented together with confirming experiments.

Consider the arrangement of Fig. 1(a) in which a point scatterer is shown traversing with velocity $\bar{v}$ a microwave illuminating beam produced by transmitter T centrally located in the midst of a linear array L or a circular array C of coherent receivers. Microwave energy scattered by the object is coherently detected by the receivers which are allocated in a precisely known manner over a flat ground. The coherence of the array is maintained by furnishing a local oscillator (LO) signal to all receivers from the centrally located transmitter or with the aid of synchronized clocks [9]. Consider for simplicity that the phase of the LO signal at all the receivers is made identical by proper delay networks. Under these conditions each of the two arrays can be viewed as hologram recording arrays with an electronically synthesized normally incident plane reference wave. The intensity distribution in the instantaneous fringe pattern formed by the interference of the spherical wavefield scattered by the object point scatterer and the electronically simulated plane reference wave will be that of a sinusoidal Fresnel zone centered directly below the object. If the object point is moving with a constant horizontal velocity $\bar{v}$, then its projected Fresnel zone will move underneath it with the same velocity. The time signals provided by the receivers which actually represent the Doppler histories of the target as monitored by the different receivers will therefore be a set of chirp signals caused by the sliding of this Fresnel zone intensity pattern over the array of square-law sensors. Obviously, the same set of receiver signals would be obtained where the object point was stationary and the arrays scanned as a whole with velocity $\bar{v}$ across the stationary Fresnel zone intensity pattern projected by the object as in scanned holography [10]. Image retrieval can therefore be realized by displaying the receiver outputs successively and in proper registration by intensity modulation of a CRT and forming a hologram by time-exposure photography of the resulting display. The hologram transparency obtained can then be interrogated employing conventional methods [5] to yield the required image. Because the point object is in fact illuminated by a spherical wavefront and because in practice it can change its velocity vector, its Fresnel zone

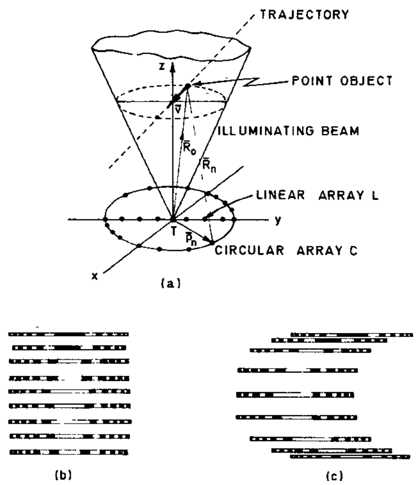

Fig. 1. Coherent imaging with object-synthesized apertures. (a) Basic geometry. Sketch of idealized CRT record of the outputs of the linear array (b), and of half the circular array (c).

projection will change scale (contraction or expansion) or the center of the projected Fresnel zone might deviate from a straight line path. The receivers output signals will therefore generally be distorted chirps. Restoration of these distorted chirps to their original state would be possible from a knowledge of the velocity vector history of the object during traverse. The restored signals would resemble then those obtained as if the target were moving with a constant velocity vector. The preceding concepts can be extended to the imaging of an extended moving object by regarding it as a collection of rigidly connected scattering centers resembling the point object considered above. Each scattering center gives rise, because of the linear superposition property of heterodyne detectors in the coherent receivers, to its own Fresnel zone projection which gets sampled by the stationary ground array. Since all Fresnel zones move congruently, the signals provided by the array receivers will be linear superpositions of chirp signals. Analog data storage and image retrieval can then be effected as described above.

II. ANALYTICAL CONSIDERATIONS

To place the preceding arguments in a more quantitative form we refer again to the simplified geometry of Fig. 1(a) and express the output of the nth coherent receiver located at the end of the position vector $\bar{\rho}_n$ in the form

$$s_n(t) = a_n \cos [kr_n(t)] \tag{1}$$

where $r_n(t) = R_0(t) + R_n(t)$ and a_n is proportional to the strength of the scattered wavefield incident on the nth receiver. R_0 and R_n are as shown in the figure. Let

$$r_n(t) = \alpha(x_c - \beta)^2 \tag{2}$$

where α and β are constants and where

$$x_c(t) = \int_0^t v_n(t)\, dt \tag{3}$$

is the horizontal coordinate on the CRT faceplate while v_n is the horizontal externally controlled sweep velocity of the CRT. Then a linear Fresnel zone will be displayed independent of the variations in the object velocity vector as can be verified by direct substitution of (2) in (1). Making use of (2) and (3), the controlled CRT sweep velocity required to realize this compensation can be shown to be

$$v_n(t) = \dot{x}_c(t) = \frac{\dot{r}_n}{2[\alpha r_n(t)]^{1/2}} = \frac{\dot{R}_0(t) + \dot{R}_n(t)}{2\{\alpha[R_0(t) + R_n(t)]\}^{1/2}}. \tag{4}$$

Thus by monitoring the range and range rate of the target at the central transmitter and at each of the n receivers simultaneously, compensation of the data displayed on the CRT can be achieved. In practice all this can be accomplished almost instantaneously after the target completes traversing the illuminating beam by sequential transmission of the receivers time signals $s_n(t)$ to a central processing location such as that of the common central transmitter together with the values of $R_n(t)$ and $\dot{R}_n(t)$. Note that $\dot{r}_n(t)$ is directly derivable from the Doppler frequency $\omega_{Dn}(t)$ monitored by the nth receiver since $\omega_{Dn}(t) = k\dot{r}_n(t) = k(\dot{R}_0 + \dot{R}_n)$.

III. PRACTICAL CONSIDERATIONS

It is known that the number of resolvable spots on the object equals roughly the number of samples required to be taken within the hologram recording aperture [11]. Because the number of scattering centers to be resolved on objects of interest in remote microwave imaging applications is expected to be quite low, the arrays being referred to in this paper are greatly thinned, consisting of perhaps tens of receiving stations. The resolution capability of such a thinned array is determined by its maximum linear extent transverse to the projected direction of motion of the target. Thus a linear array of N receiving stations is preferred when the general direction from which the object is approaching is fixed. When this direction is not known, a circular array of $2N$ equally spaced isotropic or steerable elements is more suitable because of its nonpreferential nature. Resolution of object detail transverse to the direction of motion is then determined by the imaging wavelength and the diameter of the circular array, while resolution of longitudinal object details will be determined by the imaging wavelength and the width of the illuminating beam traversed by the target and therefore by the listening time. A sketch of records obtainable with a linear array and by an equivalent circular array monitoring a point scattering object are shown, respectively, in Fig. 1(b) and (c). Because of the nature of the circular array the adjacent linear scans of the Fresnel zone projection are not in registry lengthwise. However, because the relative positions of the circular array elements are known precisely, appropriate shifting of the individual records on the CRT display can be readily made to obtain a corrected record equivalent to that provided by the linear array.

Several methods can be used to obtain the range and range rate or Doppler data. The essential requirement is the availability of a reference signal at the receivers. This can be provided by direct transmission of a reference signal from the central transmitter to all receivers or through the use of synchronized clocks. It is worthwhile to note that since the method discussed pertains to the imaging of objects for which all scattering centers are rigidly connected, difficulties may arise when the imaging of two or more objects moving with different velocity vectors is attempted.

IV. EXPERIMENTAL VERIFICATION

Concepts presented in the preceding sections were experimentally verified in the laboratory employing convenient millimeter microwaves. Imaging of a reflecting letter *V* made of 1-in-wide flat braided flexible wiring and mounted on a rotating canvas belt 5 in wide and 9 ft long was attempted, first using the geometry shown in Fig. 2 in which a photograph also is included of the experimental setup. In this geometry the synthesized aperture was generated by the motion of the letter *V* through a 70-GHz ($\lambda = 4.3$ mm) illuminating beam of 40-cm diameter while a linear receiving array oriented transverse to the direction of motion was simulated by discrete linear translation of a single coherent receiver each time the object was passed within the beam. A 21-element linear array was simulated by the displacement of a phase-locked homodyne receiver consisting of a 70-GHz klystron source, a hybrid T, a 20-dB transmitting–receiving horn, and a mixer. The Doppler history of the target was obtained in each pass for a different aspect angle of the transmitter–receiver and displayed on the CRT after amplification. Because the object velocity vector in this arrangement was constant, the CRT was triggered in the horizontal direction with constant sweep velocity v_n at the instant the object entered the illuminating beam. A time-exposure record of the CRT display obtained in this fashion is shown in Fig. 3(a). The image retrieved from a reduced transparency record of this display employing laser interrogation [5] is shown in Fig. 3(b). Two conjugate images of the letter *V* are obtained. The quality of the images retrieved is slightly degraded because of reflections from the canvas belt and because of the somewhat specular nature of the object. Furthermore, the records produced by the simulated linear array might not have been properly registered on the CRT because of random errors in the triggering time of each trace. The retrieved images, which are nevertheless readily recognized, were separated spatially from the zero-order light in the reconstructed record of Fig. 3(b), by inclining the linear path of the object somewhat (14°) with respect to the illuminating beam axis of symmetry. In this fashion, off-axis Fresnel pattern records of the scattering centers on the object are obtained and

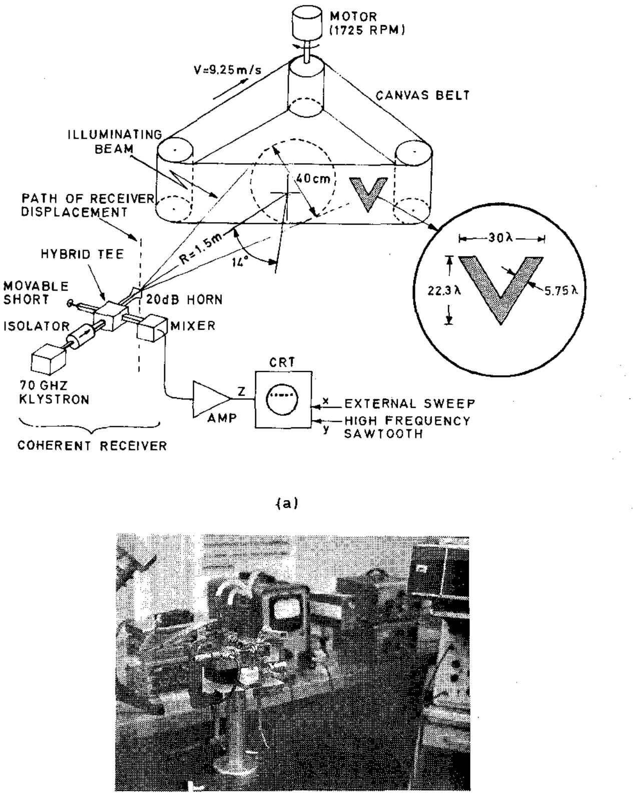

Fig. 2. (a) Sketch of the laboratory arrangement employed in the verification of the object-synthesized imaging aperture concept. (b) Coherent receiver on vertical displacement tripod.

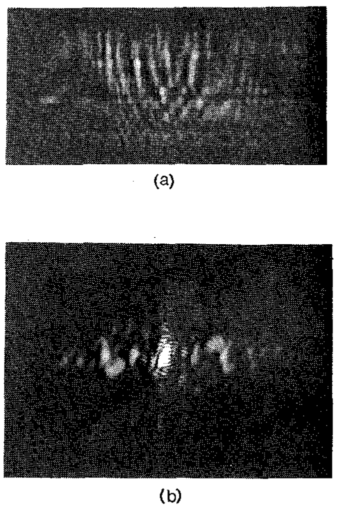

Fig. 3. Imaging of moving letter *V*. (a) Hologram. (b) Retrieved image.

image isolation was attained [5]. It is worthwhile to note that the inclined illumination geometry is consistent with practice where in order to image distant approaching objects the illuminating beam shown in Fig. 1(a) needs to be inclined towards the direction of approach.

The effect of reflections from the canvas belt on the retrieved image is demonstrated in Fig. 4 which shows the

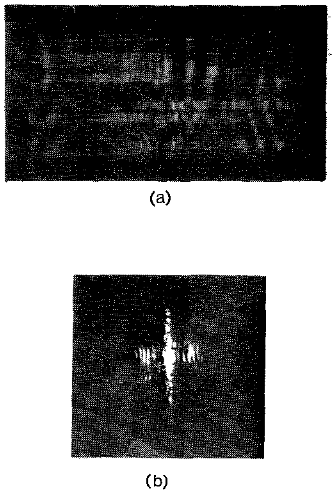

Fig. 4. Imaging of canvas belt with the object removed. (a) Hologram. (b) Retrieved image.

hologram of the canvas belt with the object removed in (a) and an overexposed record of the image retrieved from the hologram in (b). The intensity of the off-axis structure arising from "flapping" in the belt motion is much smaller than the image intensity of Fig. 3.

To verify the concept of correcting image distortion arising from a variable velocity vector, an electronic simulation was employed because of the difficulty of varying the velocity vector of a test object in the laboratory. (An exception is an object suspended on the tip of a pendulum. However, the velocity changes here proved to be too small to produce sufficient structure in the Doppler histories required.) A linear FM (chirp) signal simulating a line scatterer with a sinusoidally varying velocity vector with sinusoidal frequency distortion was therefore generated employing a voltage-controlled oscillator (VCO) and the arrangement of Fig. 5. The distorted chirp shown in Fig. 6(a) together with the sinusoidally distorted ramp (lower trace) controlling the VCO was displayed on a CRT with constant sweep velocity. The resulting CRT record is therefore uncompensated and is shown in Fig. 6(b). The image retrieved from a transparency replica of this uncorrected record is shown in Fig. 6(c). The record of the compensated chirp obtained when the CRT sweep velocity was controlled by a voltage proportional to the instantaneous frequency of the distorted chirp, namely the VCO control voltage, and the corresponding image retrieved from it are shown in Fig. 6(d) and (e) for comparison. Correction of the line scatterer's image is clearly demonstrated.

V. CONCLUSIONS

A method for remote imaging that combines a giant thinned circular or linear array with a linear target synthesized aperture to form a two-dimensional imaging aperture has been described. Of particular interest is the

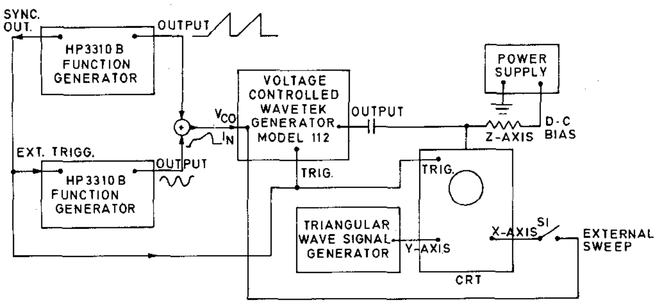

Fig. 5. Simulation of target-synthesized aperture imaging of a moving point scatterer with electronic compensation of its velocity vector perturbations.

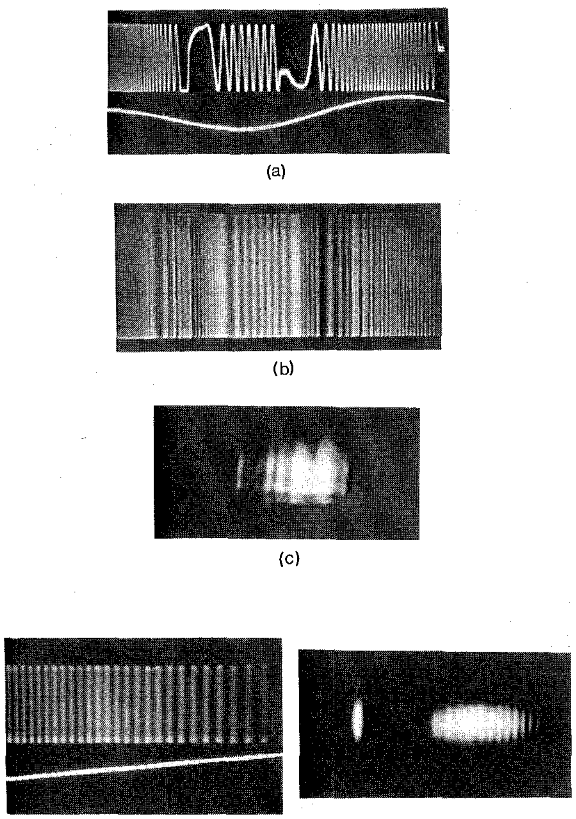

Fig. 6. Electronic compensation of image distortions arising from object velocity perturbations.

circular thinned array configuration because of its nonpreferential direction which allows remote imaging of targets approaching from any direction provided that the elements of the array are isotropic or readily steerable to be able to face the direction from which the target is approaching. There will be directions of target approach for which the records of some receivers in the circular array will coincide after their shifting, leading to redundancy. To minimize occurrence of this situation it might be desirable to distribute the circular array elements unequally. Because the imaging principle described is compatible with giant thinned arrays, low microwave frequencies combining all-weather capability with useful resolutions can be used. Assuming that the range and range-rate histories of the target as measured at each array station are available, a relatively straightforward technique which can be used to correct image distortions arising from irrotational target maneuvers appears feasible.

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