A SYNTHETIC APERTURE PROCESSOR USING CCD SIGNAL PROCESSING TECHNIQUES

By

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ABSTRACT. The synthetic aperture concept has been known since the early 1950's. Application of the concept has been quite limited due to practical implementation difficulties. Early techniques relied upon photographic film for storage. This exposed film was subsequently developed and used in conjunction with an optical correlator which produced the imagery. The development of integrated circuit technology has made it possible to perform the convolution and storage functions in alternate ways. Only in this decade has it been possible to perform real time SAR processing on board an aircraft. Further reductions are still required in order to meet size, weight, and power objectives for most aircraft and satellite applications. The application of charge coupled devices offers significant advantages in these areas in addition to providing a capability to perform operations in an analog domain.

I. INTRODUCTION

Synthetic aperture radar (SAR) imaging appears to be the most suitable technique for achieving high resolution imagery through atmospheric cloud cover. This feature is important for planetary as well as earth orbiting satellite systems, and for military aircraft applications. Such applications require onboard data processing or wide-band data transmission systems in order to handle the large amounts of raw data produced by such systems. Onboard optical correlators of the conventional nature are unattractive for such applications due to size, mechanical stability problems, and long term operational objectives. Digital techniques offer some hope for onboard processing. However, size and power limitations for this approach currently exist. The charge coupled device promises important reductions in size, power, and weight in the implementation of onboard processors.

One of the first scheduled uses of a satellite borne SAR will be SEASAT-A which is to be launched in 1978. The mission of the SAR will be all-weather imaging of the sea for weather forecasting purposes.

A number of techniques have been utilized in implementing SAR processors. Frequency filtering and Fourier transform operations using both optical and digital techniques have been utilized in SAR processing.[1,2] Most approaches store the data in range lines and read the accumulated data from a given range bin into either a filter or transforming equipment which selectively passes the energy within a selected doppler frequency range. The zero doppler frequency generally corresponds to the point broadside a moving aircraft for clutter locked systems, and is the most commonly utilized frequency component analyzed. Optimal detection criterion would require pulse compression of the doppler chirp waveform found along the azimuthal direction.[3]

Generally speaking, when an image of some physical characteristic is needed, the resolution in the two orthogonal directions should be approximately equivalent. This presents a problem to conventional radar sets which could be used to produce an image of the radar cross section of a section of terrain. The resolution of the conventional radar in the radial direction depends directly on signal bandwidth. Pulse-compression techniques permit signal bandwidth to be expanded with negligible sensitivity loss so that adequate range resolution may be realized for many imaging applications.

Azimuth resolution is a more difficult matter, however. Conventional radar azimuth resolution depends ultimately upon the antenna beamwidth.[1] The antenna beamwidth is reduced by increasing the size of the aperture, increasing the carrier frequency, or both. For long-range imaging, however, this approach cannot provide an azimuth resolution that can be realized easily with modern pulse-compression techniques.

The solution to this dilemma is provided by SAR's in which data processing capability is traded for aperture size. In principle, there is no difference between:

An extremely large real antenna, and

A small real antenna that successively occupies all the positions that would be occupied simultaneously by the large real antenna, provided

The data that are successively collected by the small antenna are properly stored and subsequently combined in a simulation of the large real antenna.

Assuming this condition is satisfied, it is possible for a small antenna to move past a scene and record echo data to permit comparable range and azimuth resolution to be realized in an image of the scene after the recorded data have been properly processed, as indicated in Figure 1.

II. DESIGN CONSIDERATIONS

The use of charge coupled device transversal filters provides a very powerful computational tool in the implementation of the correlators required in a SAR processor.

The CCD filters utilized in these experiments are four-phase surface channel devices having split electrode weighting.[4] Initial device concerns were CTE effects, leakage current, and high frequency operation. Early measurements and analysis[5] indicated these effects are minimal for this

application. The laboratory feasibility breadboard utilized existing chirp filter designs having time bandwidth (TW) products of 62 and 16 for the range and azimuth correlators, respectively. Table 1 indicates the system parameters of the breadboard. Representative system parameters derived from these filter characteristics are indicated in Table 1 using the procedure outlined in Reference 5. The filters for the engineering model were designed using this procedure to be compatable with the system parameters for an existing JPL radar used for flight experiments. The key parameters for this system are indicated in Table 2.

Table 1. Breadboard Radar/Platform Parameters

Altitude	5.0 km
Slant Range	10.0 km
Nadir angle	60.0 degrees
Velocity	320.0 m/s
Wavelength	32.0 cm
Frequency	936.84 MHz
Transmitted pulse duration	3.58 μs
Transmitted signal bandwidth	17.32 MHz
Slant-range resolution	8.66 m
Along-track ground resolution	10.0 m
Cross-track ground resolution	10.0 m
Range time bandwidth product	62
Range correlation time	0.47 ms
Azimuth time bandwidth product	16
Azimuth correlation time	0.5 s

Table 2. Engineering Model Radar/Platform Parameters

Altitude	10.058 km
Slant range	15.5 m
Nadir angle	39 degrees
Velocity	257 m/s
Wavelength	24.7 cm
Frequency	1215 MHz
Transmitted pulse duration	1.25 μs
Transmitted signal bandwidth	10 MHz
Slant range resolution	15.5 m
Along-track ground resolution	25.1 m
Cross-track ground resolution	24.7 m
Range time bandwidth product	12.5
Range correlation time	58.9 μs
Azimuth time-bandwidth product	2.7
Azimuth correlation time	25.6 μs

Some limitations in the use of CCD transversal filters do exist. Peripheral circuitry limitations such as amplifier slew rates and sampling feedthrough currently limit useable data rates to less than 5 MHz. Practical filter lengths are presently limited to less than 1000 stages[6], although some flexibility exists in trading bar size for filter lengths. Several techniques, such as time expansion and presumming may be utilized to extend the operation of a processor utilizing CCD transversal filters.

The achievement of high range resolution implies the use of wideband chirp signals for a pulse compression radar. The use of a surface wave device range chirp correlation filter is an alternative capable of accommodating the required bandwidths. However, the time windows commensurate with the achievable range resolution are typically tens of nanoseconds, and are difficult to handle with A/D conversions and digital techniques.

The use of a modular processor concept in which each module processes on the order of 200 range cells, makes it possible to sample the radar video at a high rate during a small time window corresponding to the module's swath width once each PRI. The number of samples to be stored is the number of samples required to cover the swath plus the number of bits in the range correlator. While the input sampling rate is constrained by Nyquist considerations, the output data rate is constrained by the PRI making time expansion of the video possible in order to reduce the processor module's data rate to one commensurate with CCD transversal filter operation. Subsequent processing speeds may easily be handled with present CCD technology. Another advantage of such a buffering technique is that radar data from an appropriate range swath may be recorded on a conventional instrumentation tape recorder having a few hundred kilohertz bandwidth.

Presumming is an attractive alternative to minimizing the filter lengths and data rates required in the azimuth correlators. Presumming is the process whereby several consecutive samples from a given range bin are combined into one sample for subsequent processing. Presumming ahead of the azimuth correlator is possible in most cases, since the PRF greatly exceeds the azimuth time bandwidth product resulting in considerable oversampling.

Aliasing in the presum operation is a significant potential problem. Aliasing of the doppler components about harmonics of the PRF is inherent since the radar system is a sampled-data system. The antenna characteristics form a filter for the doppler returns due to the geometrical relationship between the antenna pattern and the locations of sources of higher doppler frequencies. However, the relatively large antenna beamwidth again causes ineffective filtering of the higher frequency components. Since presumming amounts to resampling the data at a lower data rate, these higher aliased frequencies must be removed by filtering in order that the new sampling operation not fold them into the video band of interest. This may be accomplished by incorporating a low pass filter into the presum operation.

Focusing is an important consideration in SAR's which involves degradation of resolution as a function of range. It is convenient in Figure 2 to think of a stationary radar with target motion being a straight line as shown. Using conventional terminology, time t is zero when the target is at the point of closest approach. This minimum range value is called R_0.

Data are assumed to be available from the time that the target enters the 3-dB beamwidth point of the real aperture until it leaves the 3-dB beamwidth point on the other side.

At time t, the target is seen in Figure 2 to

be displaced a distance Vt from the point of closest approach. The range as a function of time is given by

$$R(t) = (R_o^2 + V^2t^2)^{\frac{1}{2}} \quad (1)$$

For most cases of interest, the distance Vt in Figure 2 is much less than R_o, so that

$$R(t) \cong R_o \quad (2)$$

Degradation in resolution occurs when this assumption becomes invalid.

The effects of defocusing can be analyzed in terms of chirp slope mismatch degradation as outlined by Cook and Bernfeld.[7] The time bandwidth product of the azimuth chirp waveform for the unweighted case may be determined from[6]

$$TW_{AZ} = \frac{0.405\ \lambda R_o}{\delta_{AZ}^2} \quad (3)$$

where λ is the radar carrier wavelength, R_o is the range in meters, and δ_{AZ} is the azimuth resolution in meters.

If the filters are assumed matched at the center of the swath, the above equations may be used to determine the differences in time bandwidth products between the nominal value at the center of the range swath, and the near and far extremities of the swath. Analysis of the SEASAT geometries indicate a focusing degradation of approximately 2% could be anticipated over the 100 km swath width for 50 m resolution.

III. LABORATORY BREADBOARD

The first of the two breadboard SAR processors constructed at Texas Instruments in conjunction with this effort is a laboratory model which was developed around existing CCD filter designs. This breadboard simulates the operation of a filter bank approach to the azimuth correlators.[8] A block diagram of the laboratory breadboard is shown in Figure 5.

A single azimuth correlator was constructed which is sequentially stepped through the 200 range bins with a minicomputer in order to minimize hardware construction. The radar/platform parameters for this breadboard system shown in Table 1, are relatively representative of an aircraft radar environment. Range and azimuth correlation is accomplished with Hamming weighted linear FM complex filter pairs having TW products of 62 and 16, respectively. Range and azimuth correlation times are 0.47 ms and 0.5 s, respectively.

In order to form a 200-by-200-element picture with this breadboard, a TI 960A computer with 28K memory used in conjunction with a 1,100,000 word disk memory and a nine-track, 800-BPI magnetic tape unit were used. The simulated radar echo pulses were transferred from the tape to the disk. The simulated radar bursts correspond to radar returns from a swath of interest at sequential azimuthal locations. By recirculating this sequence of bursts to the breadboard while sliding the azimuth read-in time window across the swath time, a complete picture can be processed an azimuth column at a time. To reconstruct the picture, the output of the azimuth correlator is digitized and stored in memory. The memory can then be used much as a scan converter to refresh a CRT display. The time required to process a 200 x 200 element picture is 1 1/3 hours due to the long azimuth correlation time. Real time processing could be accomplished by expanding the system to 200 azimuth correlators.

A number of test images have been processed with this breadboard. Two of the more significant images are shown in Figures 3 ard 4. The upper photographs of Figure 3 indicate a portion of the uncompressed video signal corresponding to 48 point targets arranged in four rows in the range dimension. The point targets have a random signal phase and increase in intensity along the azimuth direction in 2-, 4-, 6-, and 8-percent increments for each of the range rows. Since the range and azimuth TW products are different, each point target's uncompressed video appears as a set of concentric ellipses. Compressing this video with the breadboard reconstructs the point targets as shown in the lower portion of Figure 3.

A second image was processed from an ERTS photograph, which was optically scanned with a microdensitometer, with the resulting picture element intensities stored on a computer tape. A decompression operation was then carried out on the minicomputer which convolved each picture element with a two dimensional chirp similar to that corresponding to a point target in Figure 3, and superimposed the resultant waveforms from picture elements having overlapping correlation functions. These decompressed data were then compressed utilizing the CCD breadboard and a compression program written for the minicomputer. Figure 4 reveals a 400 x 400 image which was processed as four 200 x 200 images.

A few subtle problem areas have been discovered in the process of evaluating this breadboard. The processed picture of Figure 4 indicates an intensity shading from left to right which is due to insufficient low frequency response in the ac coupling network at the squaring converter input. Efforts to direct couple this node were unsuccessful due to the thermal drift problems associated with the prior circuitry and the sensitivity of the analog multiplier to a precise null. An additional problem concerning dynamic range was encountered in processing the simulated pictures. A normalized 8 bit encoding scheme was used in the minicomputer data handling hardware. Since the point target test pattern of Figure 3 has non-overlapping correlation functions, the input waveforms are similarly non-overlapping, resulting in minimal amplitude reduction in the normalization process. However, the composite decompressed waveforms from the ERTS photograph of Figure 4 are formed by the superposition of two dimensional chirp waveforms from a large number of adjacent point targets. Normalization of this composite waveform to 8 bits makes the quantization error significant relative to the maximum chirp amplitude from a single picture element. As a result, the signal-to-noise ratio of many of the picture elements is relatively low. The dynamic range goal in the design of this breadboard was approximately 40 dB and was crudely based upon conventional TV grey scale detectability. The dynamic range of the breadboard was limited by the analog multipliers which perform the squaring function to approximately 40 dB. Additional dynamic range for the processor and test system would be desirable, but the desired increase is difficult to quantitatively assess.

IV. AIRCRAFT ENGINEERING MODEL

The aircraft engineering model, indicated in Figure 6 which is currently being constructed, is designed to match the system parameters of a radar utilized for SAR experiments on a CV-990 aircraft. This breadboard will be capable of real time SAR processing onboard the aircraft. The architecture of this breadboard differs from that of the earlier version by utilizing a digital "corner-turning" memory as opposed to the filter bank approach previously simulated. The primary justification for this choice was a short term economic consideration.

This breadboard utilizes a CCD delay line time expander to acquire approximately 500 range samples at a 25 MHz rate from the appropriate range swath each PRI. These samples are unloaded at a relatively slow rate (543 KHz) reducing the speed requirements of the remainder of the processor and making it possible to record unprocessed data from the desired swath on a conventional instrumentation tape recorder. This input sampler and recorder have been flown and data recorded for laboratory test purposes. This data will be played back into the range correlator which requires only a I and Q filter, since this radar system utilizes a frequency offset linear FM waveform. The output of this correlator is then digitized. The signals subsequently enter presum filters having 2nd order Butterworth low pass responses and presum numbers of 8. The data are then stored in the "corner-turning" memory in range lines (constant azimuth) and are read out in range bins (constant range). The "corner-turning" memory's outputs drive digital to analog converters which supply inputs to the azimuth correlator producing a compressed image line along the azimuth direction. This output is again digitized and subsequently applied to a digital scan converter which stores the data and uses it to refresh the CRT display.

The CCD correlators for the aircraft engineering model utilize a weighting coefficient modification of an existing bar design to produce a 32 stage frequency offset chirp and chirp-through-zero filter pairs for the range and azimuth correlators, respectively. The filter characteristics utilized in the design of these devices were derived from the parameters of the CV-990 radar to be utilized in the flight experiments. Table 2 lists many of the important system parameters. Figure 7 indicates the impulse and correlation characteristics of these filters. System operating frequencies for these correlators were 543 KHz and 1.25 MHz for the range and azimuth correlators, respectively.

V. CONCLUSIONS

The use of CCD's in onboard SAR processors appears to offer tremendous advantages through the powerful computational equivalency of transversal filters and the high density achievable with either analog or digital memories.

The two architectural approaches considered in this paper have numerous advantages and disadvantages. The filter bank processor utilizes CCD filters for both signal storage and convolution calculation eliminating the need for a large memory. CCD data rates with this configuration are minimal, since data is transferred at the PRF (or lower if presumming is utilized). Many filters are required to implement a system covering a large number of range bins. However, the feasibility of integrating multiple complex correlators on a single chip has been demonstrated.[8] Storage times and gain uniformity are additional concerns for the filter bank approach.

The "corner-turning" memory approach requires only a single azimuth correlator through which data is multiplexed. Storage time in the correlator becomes inconsequential, but operating speeds may become quite high for some systems. Redundant memories are likely to be required due to load/unload difficulties. Storage times within the memory may be a concern with this architecture. Although this configuration appears quite simple in block diagram form, control and addressing logic may become significant relative to the remainder of the system.

Improvements in SAR processors may be expected in the areas of improved resolution, multiple look imagery, focusing, motion compensation, and wider dynamic range. Techniques for accomplishing these improvements will likely influence the architecture of future processors.

ACKNOWLEDGEMENT

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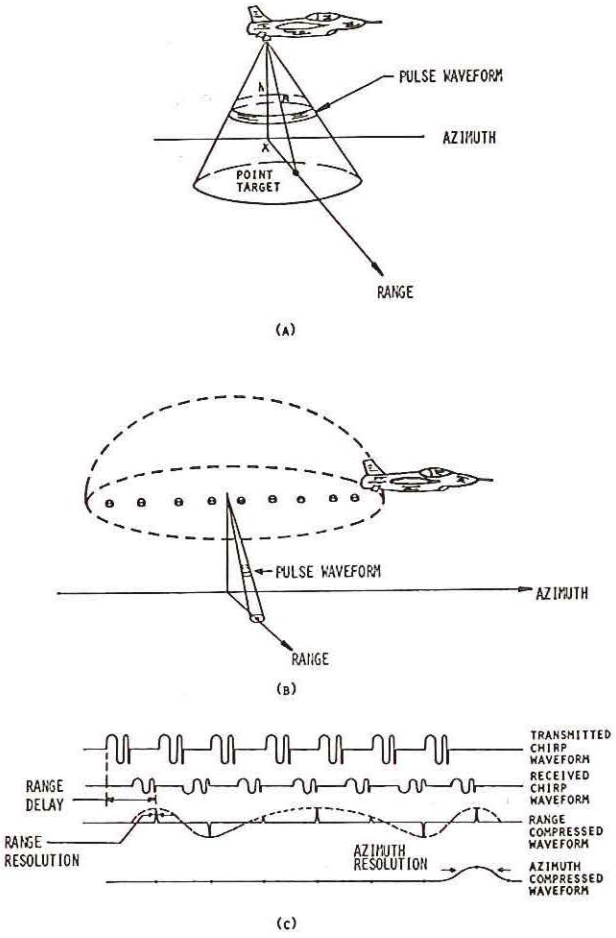
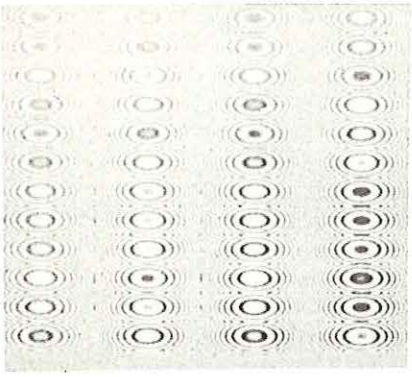
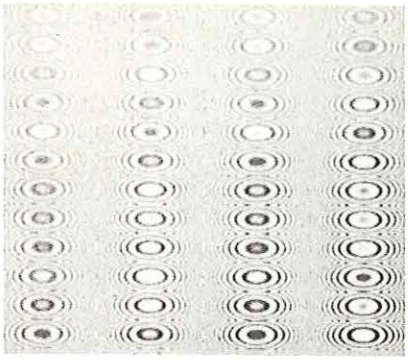


FIGURE 1. SYNTHETIC APERTURE RADAR PROCESSING CONCEPT, SHOWING:

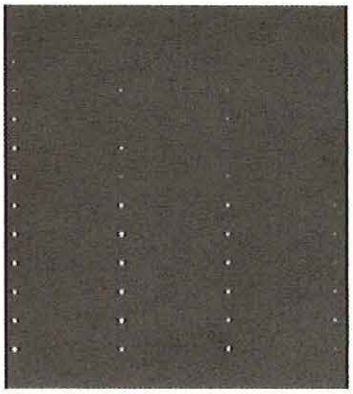
(A) REAL ANTENNA PATTERN, (B) SYNTHETIC ANTENNA PATTERN, AND (C) WAVEFORM PROCESSING.



I INPUT



Q INPUT



CCD PROCESSED OUTPUT

FIGURE 3. POINT TARGET AMPLITUDE TEST (48 POINT TARGETS WITH LINEARLY INCREASING INTENSITY, AND RANDOM PHASE)

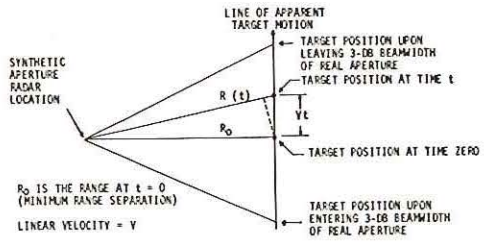
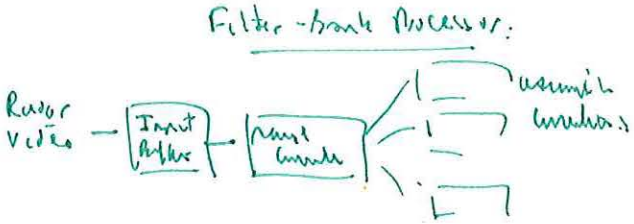
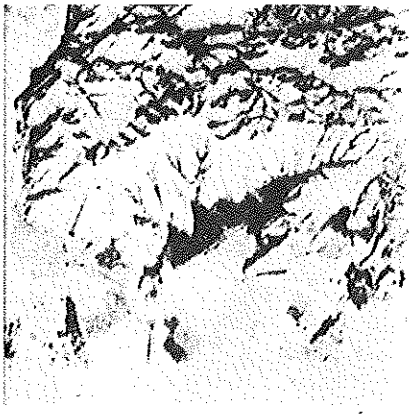


FIGURE 2. BASIC SAR AZIMUTH GEOMETRY





SCANNED IMAGE

DIGITALLY PROCESSED IMAGE

CCD PROCESSED IMAGE

FIGURE 4. IMAGING RADAR MOUNTAIN SCENE (400 x 400)

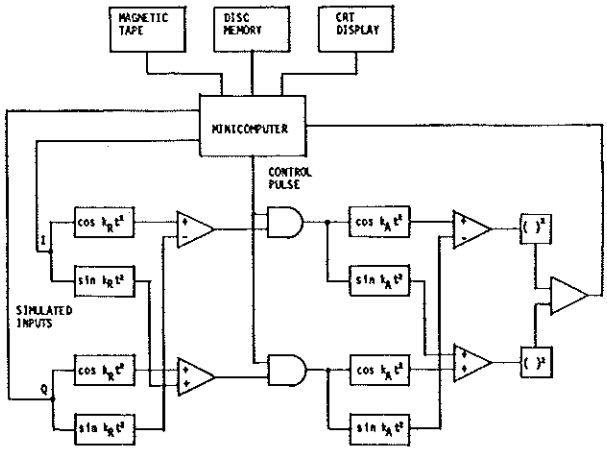


FIGURE 5. LABORATORY BREADBOARD BLOCK DIAGRAM

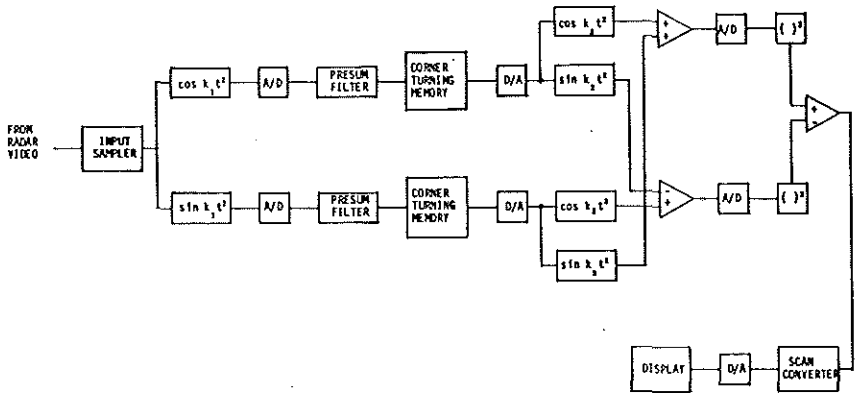
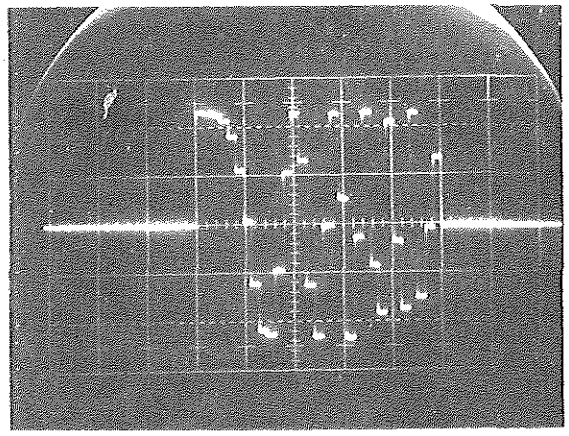
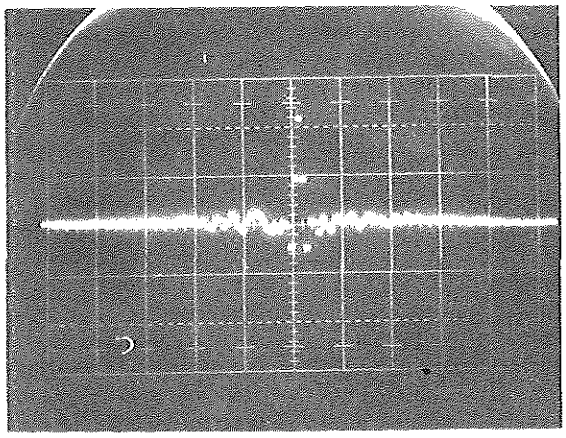


FIGURE 6. ENGINEERING MODEL BLOCK DIAGRAM



(A)



(B)

FIGURE 7. RANGE FILTER CHARACTERISTICS SHOWING:
(A) INPUT AND (B) OUTPUT