RADAR PULSE COMPRESSION AND HIGH RESOLUTION SEA REFLECTIVITY

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Abstract

The first part of this paper summarizes the state-of-the-art in radar pulse compression as it applies to spacecraft altimetry. It is illustrated how in the next few years vertical resolutions of 0.5 to 2.0 ft. can be obtained with relative accuracies of 5 to 10% of these values *if* the nature of the sea surface is known. The second part of the paper shows that when high accuracy is desired, second order effects such as the assymetries in the sea surface reflectivity may be taken into account.

Pulse Compression

In simple terms "pulse compression" is the term applied to radar techniques where it is desired to transmit a long duration waveform but retain the resolution and accuracy characteristics of short pulse waveforms. A long duration waveform is desirable since it can be easily shown (Ref. [1] and others) that the ability to "detect" or "acquire" a target with a given antenna and receiver is soley dependent on the energy (E) in the waveform. Most of the more advanced radar transmitters considered for spacecraft such as the SKYLAB traveling-wave-tube are limited in the peak power that they can transmit. However, their average power (energy) is currently limited only by power supply considerations.

The general expression for radar range accuracy is

$$\sigma_\tau \approx \frac{1}{B(2E/N_o)^{\frac{1}{2}} n^{\frac{1}{2}}}$$

assuming optimum processing as with a maximum likelihood estimator.

where σ_τ = the standard deviation of the time delay error

B = the effective bandwidth of the transmission waveform

N_o = noise power density

n = number of independent samples

While there are some additional terms in the altimetry equations, it can be seen that the error is inversely proportional to the waveform bandwidth and the square root of the transmit energy and number of samples. Thus, for a given energy, accuracy improves with bandwidth. Practical considerations usually limit σ_τ to $0.05/B$ to $0.1/B$ for $(2E/N_o)^{\frac{1}{2}}(n)^{\frac{1}{2}} \geq 100$. A typical example calculation is given below. In active radar $\sigma_r = c\sigma_{\tau/2}$, where σ_r is the standard deviation in distance units and c is the velocity of propagation. For a standard deviation of altitude of 10 cm (0.1 m) in distance units, $c = 3 \times 10^8$ meters/sec, and $\sigma_\tau = 0.1/B$

$$\sigma_r = 0.1 = \frac{3 \times 10^8 (0.1)}{2B}$$

Then $B \geqq 1.5 \times 10^8$ Hz = 150 MHz.

Transmit energy considerations for a satellite of the general size and altitude of GEOS-C call for transmit pulse durations of the order of 1 microsecond. Thus, the "pulse compression ratio" equals the time-bandwidth product = $(1.5 \times 10^8)(10^{-6})$ = 150, in the ideal case.

Implementation

There are several possible implementations of this technique. The most widely used is the linear FM or "Chirp" technique. A typical block diagram is shown as Fig. 1A [1]. An impulse at the intermediate frequency with the appropriate bandwidth is inserted into a dispersive

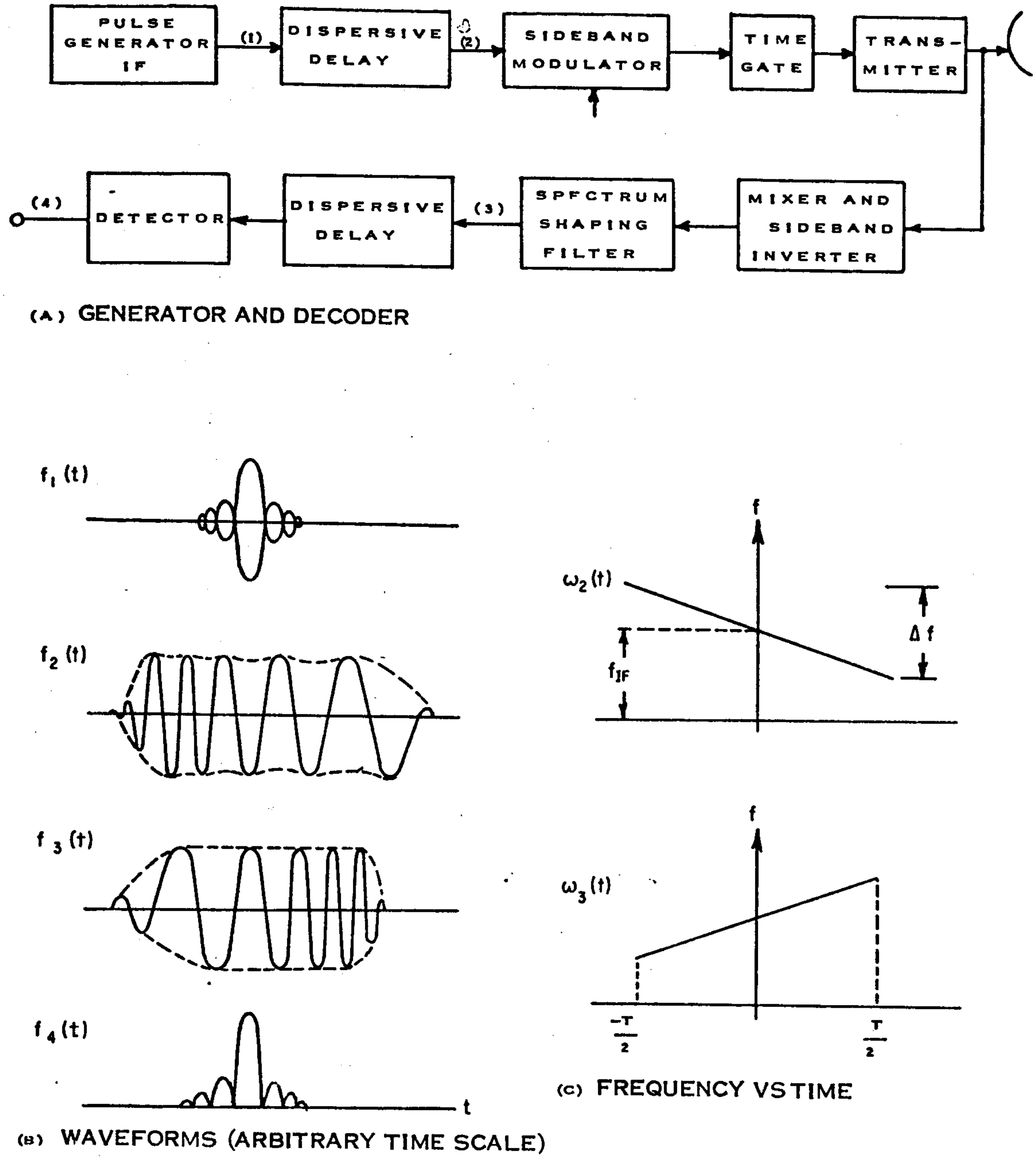


FIG. I PASSIVE SYSTEM FOR LINEAR F.M. PULSE COMPRESSION device which has a linear time delay vs frequency characteristic as shown on Fig. 1B. The signal is amplified, mixed to the transmit frequency, time gated to the desired duration (i.e., 1 microsecond), and transmitted. The received signal is mixed back to the intermediate frequency, shaped to reduce time sidelobes, and the appropriate sideband is inserted into an identical dispersive device (it can be the same one as on transmit). The resultant signal has the same general shape as the input impulse.

In the past 15 years of use of this technique, the main advance has been in the nature of the dispersive device. For the parameters discussed here, the newer surface wave techniques seem to be the most applicable. A sample of the current and planned devices from two of the leading suppliers in the field are shown on Table I.

The rows show the obtainable resolution in meters, the center frequency of the device (lower frequencies are somewhat easier to work with) the pulse compression ratio, the waveform bandwidth, the pulse envelope duration, the insertion loss which can be a problem if it exceeds about 55 db, the weight of the device and transducers, excluding any over the sidelobes or spurious levels in db down from the peak (25 db or less may be a problem when high accuracy is desired), the type of structure, status and price for a single unit or to develop a single unit.

The first column is an existing item by Autonetics, Anaheim, California. For a 100 mHz bandwidth, it seems acceptable for some applications except for a somewhat marginal spurious level specification. The second column is a unit built by Andersen Labs, Bloomfield, Connecticut. It has 250mHz bandwidth, but in this form it most likely has an unacceptable insertion loss for most applications. The last three columns give characteristic of devices that can be built in the near future with a reasonable development cost. It can be seen that bandwidths of 200 to 500 mHz

TABLE I STATUS OF WIDEBAND PULSE COMPRESSION LINES

	PARAMETER	AUTONETICS	ANDERSEN			
1.	Resolution (M)	1.5	0.6	0.5-0.75	0.5	0.3
2.	Center Frequency (GHz)	0.3	0.5	~ 1.25	0.8	1.0-1.5
3.	Compression Ratio (before weighting)	100	250	200-600	300	500
4.	Bandwidth (mHz)	100	250	200-300	300	500
5.	Transmit Pulse (μsec)	1.0	1.0	1.0-2.0	1.0	1.0
6.	Insertion Loss (db)	42-50	68-75	45-65	45-50	45-50
7.	Weight with Filter (oz)	5	< 8	< 8	< 8	< 8
8.	Sidelobe Supression (db)	> 25	~ 30	30-35	> 25	> 25
9.	Type of Structure	Surface Wave	Wedge	Surface Wave	Quartz Surface Wave	Sapphire Wave
10.	Status	Shelf	5 Built	~ .5 year	95% Conf.	
11.	Price * (Small Quantity)	$1700 +		$50-100 K Devp. $5 K Quant.	~ $20K	~ $50K

*Not including driver amplifiers.

can be obtained in the near future with acceptable spurious levels. The only problem areas involve temperature variations that will limit absolute accuracy, the conversion of wideband video into digital form for further processing or retransmission to earth, and the lack of flexibility.

A second and more flexible technique involves a step frequency approximation to the FM waveform. As an example, let the transmit waveform be a contiguous transmission of N(sixteen in this example) 0.1 microsecond pulse segments. Each segment is a pulse of sine wave on a different carrier frequency spaced Δf = 10 mHz apart as shown on Fig. 2. The frequencies must all be derived by mixing or multiplying from a single coherent stable oscillator. The spectrum of this waveform is $N\Delta f$ = 160 mHz, and since they are "coherent" they can be added vectorially by adjustment of their phases after time realignment with a tapped delay line of 16 segments of 0.1 microsecond delay. To achieve low spurious levels the frequency spacing must equal the inverse of the segment duration. The compression ratio of this type of waveform is N^2 and extremely wideland signals have been generated. Since each segment may be processed through a filter having only a 10 mHz bandwidth, the transition to digital form is made simpler if multiple parallel channels are used. Analog to digital converters of 6-8 bits are currently limited to this bandwidth. Various weighting functions can be used to control the time sidelobes resulting from the transmission of a rectangular spectrum. The primary disadvantage is the relative complexity of this multi-channel approach probably resulting in several times the hardware of the dispersive line system.

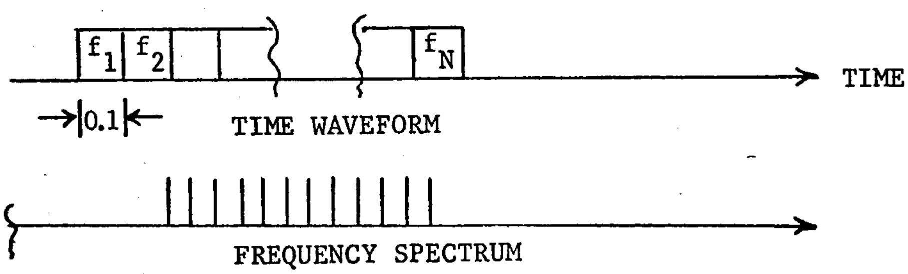


FIG. 2 STEP FREQUENCY PULSE COMPRESSION

A third technique with more flexibility than the single dispersive line, but less complexity than the step frequency approximation, was developed by Airborne Instrument Laboratory, and called STRETCH. It is recently been declassified and is described in Ref. [3]. The basic elements are the same as the linear FM system on Fig. 1 except that the slope of the frequency-vs-time characteristic is made different between transmission and reception yielding either a time expansion (bandwidth reduction) of a portion of the received waveform or a time compression. Time expansion is more appropriate to the study of sea surface topography.

Referring to the previous example of a 1-2 microsecond (T) pulse envelope and a 150 mHz bandwidth (B), information theory shows that 2BT or 300 to 600 samples of information describes the received signal. Since 2 mircroseconds of echo describe 300 meters (ΔR) of altitude ($\Delta R = c\tau/2$) and after acquisition wave heights are rarely over $\pm$ 15 meters, we can afford to throw away all the information greater than 15 meters from the "mean" sea surface altitude and "stretch" the echoes in that vicinity by a factor of about 10. The output signal bandwidth would be reduced to 15 mHz, detected, and analog-to-digital converters used to store the information for further processing and later transmission to ground stations on a narrow band communication link.

A fourth technique is the use of binary phase coded waveforms. Unfortunately the best codes are limited to a length of 13 (pulse compression ratio) and low relative sidelobe level codes are not available again until the code length exceeds about 256. Broadband analog processing is not practical much beyond the 100 mHz, 13:1 code used in SKYLAB, and broadband digital processing requires hard limiting and hence distortion of the sea surface echoes.

The choice of technique is dependent on the system requirements, allowable size, weight and cost and the nature of the recording or retransmission of the signals to earth.

Anomalies in High Resolution Sea Backscatter at Vertical Incidence

If a resolution of a few nanoseconds is employed it will become increasingly important to have a better model of the radar backscatter of the sea at vertical incidence. This section describes what I believe to be an important "second order" effect that I have not seen taken into account.

In radar altimetry from satellites and aircraft, the statistics of the radar sea return at vertical incidence affect the quality of the altitude data and the surface conditions inferred from this data. The parameter of interest is σ_o, which is usually defined as the mean backscatter cross section per unit illuminated area of a reflecting surface.

Since the reflectivity is highest for a specular surface at perpendicular incidence σ_o is greatest for a calm sea, and is predicted to be as high as + 25 db. For very rough seas, the ocean surface consists of numerous scatterers, and the value of σ_o drops to near 0 db. The trend of data taken near grazing incidence would be expected to follow the general curves of Fig. 3. However, this has not been the general case. There have been numerous measurements at vertical incidence by NRL, Sandia, Ohio State and others which show 5-10 db variations from each other as well as from the predictions. Only a portion of these variations can be explained by calibration errors, broad beamwidths, various definitions, etc.

This note suggests that there may be another factor that has been overlooked. I am questioning the symmetry of σ_o near the vertical in the upwind-downwind direction. Schooley [3] has shown that the distribution of slopes of wind driven waves is not symmetrical near the vertical but is centered about 4^o upwind. I have illustrated this with an idealized cross section of ocean waves on Fig. 4A and the resultant contours of constant reflectivity from a Satellite on Fig. 4B. Figs. 5A, B, show that the larger facets tend to peak somewhat in this direction. As a result,

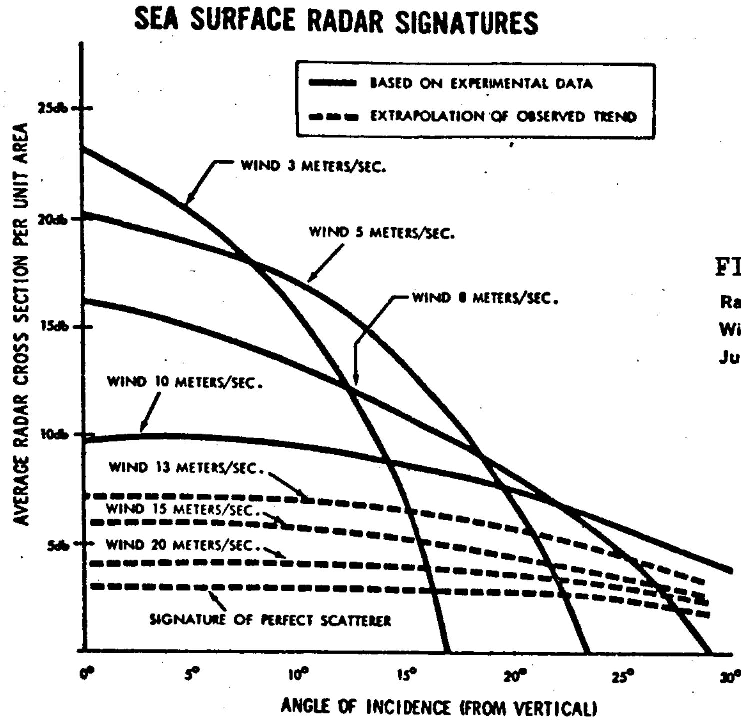


FIG. 3

Radar Reflectivity for Sea Conditions at Various Wind Speeds as a Function of Incidence Angle; June 1967, Pierson, New York University

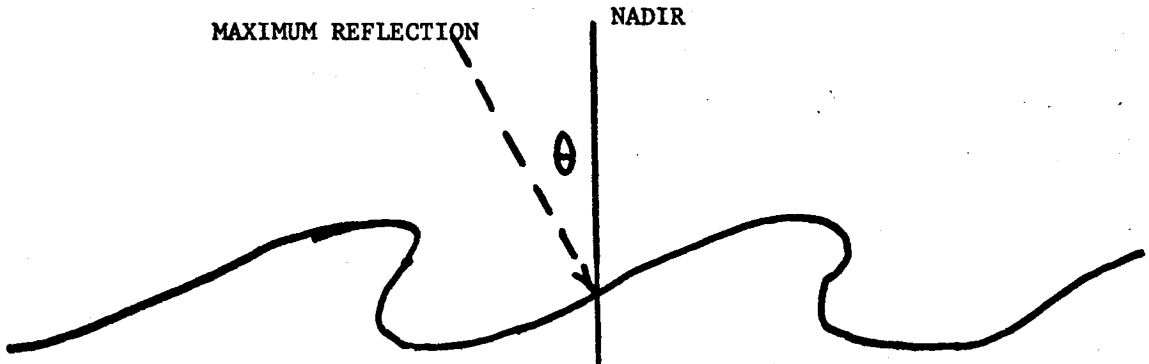
I would predict that the peak value of σ_o might occur as much as 4^o from the vertical. The implications are;

1. In radar altimetry, with short or compressed pulses, it is assumed that σ_o is symmetrical about the vertical and hence the radar return vs time (altitude) consists of a linear rise plus a flat top portion. The true altitude is found by an interpolation method based on this assumption. Assymetry may cause a small error in the absolute accuracy.

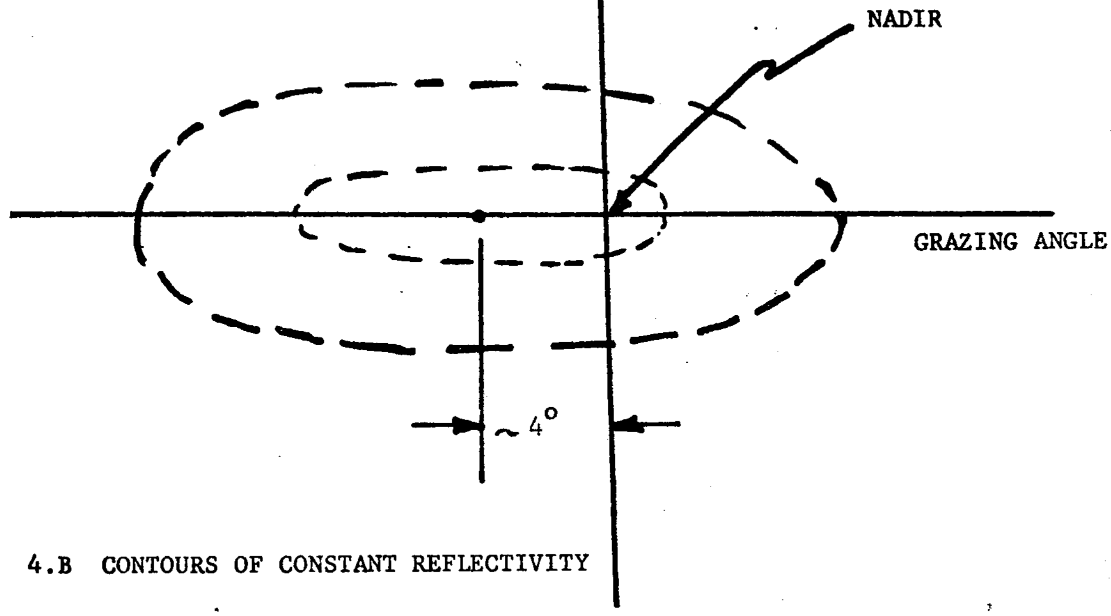
2. In satellite work, the local vertical is sometimes derived by looking for the peak backscatter angle as the beam is scanned in angle near the vertical (a nadir seeker). This may not be an optimum technique.

3. Early data on σ_o at vertical incidence should be used with caution.

Before completely defining the instrumentation for a high resolution satellite altimeter I would suggest that older data should be examined to determine if this anomaly has been observed and further information can be extracted. Also, any bridge or satellite-borne altimeter experiments should be performed with careful calibration of incidence angle.



4.A WAVE GEOMETRY



4.B CONTOURS OF CONSTANT REFLECTIVITY

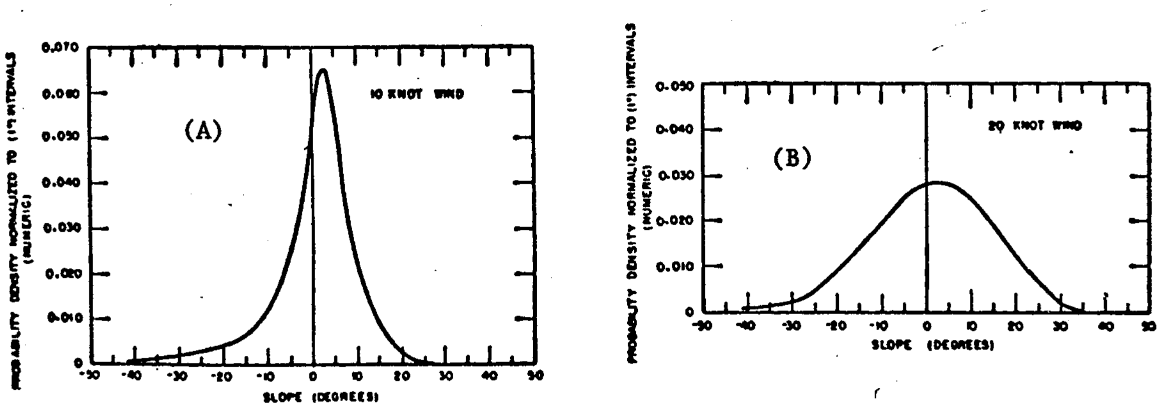


FIG. 5 SLOPE PROBABILITIES FOR 10 AND 20-KNOT WINDS [3]

References

[1] Nathanson, F. E., Radar Design Principles, McGraw-Hill Book Company, New York, October 1969.

[2] Caputi, Jr., William J., "Stretch: A Time-Transformation Technique," IEEE Trans., AES, Vol. AES-7, No. 2, March 1971, pp 269-278.

[3] Schooley, A. H., "Upwind-Downwind Ratio of Radar Return Calculated from Facet Size Statistics of a Wind-Disturbed Water Surface," Proceedings of the IRE, April 1972, pp 455-461.