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SATELLITE ALTIMETERS AFTER SKYLAB AND GEOS-C --- SHOULD THEY UTILIZE A SINGLE TRANSMITTER OR AN ARRAY OF PULSED AMPLIFIERS?

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Introduction

The first spacecraft radar altimeters to operate over the ocean were those which flew on the Saturn I launch vehicles in 1964 and 1965 (reference 1). These radars, which were used to measure the altitude of the vehicles during their ascent, operated at 1.6 GHz (L-Band) and transmitted 5-kw pulses of 1-μsec duration. A brief summary of the results is given in Table 1.

The first altimeter to fly in Earth orbit will be the one in the Skylab S-193 Microwave Experiment in 1973. This radar will operate at 13.9 GHz (K_u-Band) and transmit 2-kw pulses of 10-ns, 100-ns, and 130-ns compressed to 10-ns. The second altimeter planned for Earth orbital operation is the one for the GEOS-C satellite scheduled for late 1973 or early 1974. This altimeter will also operate at 13.9 GHz and will transmit pulses of about the same length and peak power as the Skylab altimeter.

Table 1

Saturn Radar Altimeter Flights

(Source: Reference 1)

Flight Number	SA-4	SA-5	SA-6	SA-7	SA-9
Date of Flight	3/28/64	1/29/64	5/28/64	9/18/64	2/16/65
Peak Altitude to which altimeter was operated	62 km	264 km	195 km	210 km	499 km
Amount of Data	120 sec	157 sec	184 sec	629 sec	592 sec
Quality of Data	+20m bias	Noisy	+90m bias	+100m bias	+100m bias

One of the things all these altimeters have in common is their reliance on a single transmitter having a single microwave power tube. The Saturn altimeter utilized a L-Band Triode. The Skylab altimeter utilizes a K_u-Band Traveling Wave Tube (TWT). The GEOS-C altimeter is expected to utilize a K_u-Band Magnetron, or a K_u-Band TWT, or possibly a combination of both in order to have two modes of operation, a global mode at low power for extended periods and an intensive data mode at high power for short periods.

The question addressed by this paper is: should the Earth observation satellite altimeters that come after Skylab and GEOS-C continue to use the single transmitter and microwave tube approach, or should they be designed as an array of solid-state K_u-Band transmit/receive modules?

If the choice had to be made today, it would have to be the single transmitter designed around a TWT or Magnetron. Solid-state module technology at K_u-Band for the output power levels required for these radars is not yet available. However, the choice does not have to be made today. The design of the altimeters for the dedicated satellites should await the return of the design data from the Skylab and GEOS-C experiments and that data will not be available for another two to three years. By that time, the state-of-the-art in K_u-Band solid-state technology hopefully will have advanced to the point where the radar designer will have a choice.

System Requirements

The radar designer will be faced with the task of designing a pulsed radar that, like its predecessors, will operate as a pulsewidth limited system. For this condition, the signal-to-noise ratio per pulse, S/N, is given by:

$$S/N = \frac{y\, P_t\, G^2\, \lambda^2\, \sigma^o\, c\, T^2\, \pi\, r_e}{h^3\, N_F\, L_S\, k\, T_a\, (4\pi)^3\, (r_e + h)} \qquad (1)$$

Table 2 defines each term and gives the values used in subsequent calculations.

Table 2

Pulse Limited Radar S/N Equation Terms

Term	Value	Definition
y	-	Pulse compression ratio
P_t	-	Transmitted pulse peak power
G	36.4 dB	Antenna gain. Assumes constant illumination over a circular aperture 60-cm in diameter having a 3-dB beamwidth of approximately 2° and antenna efficiency of approximately 0.6.
λ	2.16 cm	R-f wavelength equivalent to a frequency of 13.9 GHz
σ°	+3.0 dB	Ocean backscatter coefficient at vertical incidence for sea-state 5.
c	$3\text{x}10^8$ m/sec	Velocity of light
T	-	Compressed pulsewidth
r_e	6370 km	Radius of the Earth
h	1000 km	Height of the satellite above the ocean
k	$1.38\text{x}10^{-23}$ joules/°K	Boltzman constant
T_a	290°K	Absolute reference temperature of the receiver
N_F	5.5 dB	Noise figure referred to T_a
L_S	4.1 dB	Sum of all system losses including those projected for the radar equipment and attenuation due to propagation through the troposphere.

Accuracy studies have shown that rms altitude errors reduce as T is narrowed and as S/N is increased, up to a point. T cannot usefully be narrowed below the wave height, and higher S/N ratios yield little improvement if increased above 12 dB. Since the radar should provide the desired accuracy of 10-cm over most ocean conditions, a wave height corresponding to sea-state 5 is taken to limit the minimum value of T which sets T at 20-ns.

For a three gate tracker, the 20-ns pulsewidth results in an rms error of about 6.2-cm and a bias uncertainty of about ± 5.5-cm. The radar is assumed to have a prf of 1000 Hz, and the tracker time constant is set at 0.5 seconds. Raising the prf will not be effective because of pulse-to-pulse correlation which will occur, and the integration time must be kept low enough to provide sufficient resolution of surface topographical features, given a satellite horizontal velocity in the neighborhood of 7 km/sec.

Substituting the S/N of 12 dB and the compressed pulsewidth of 20-ns into equation (1) gives a value for yP_t equal to 200 kw.

The radar designer may now consider what pulse compression ratio to employ in order to reduce the pulse peak power requirements. For the purposes of this paper, a compression ratio of 500:1 will be used and then two systems will be examined, first a single transmitter system utilizing a TWT, and second a system based on an array of solid-state T/R modules. Both systems will transmit 400-watt 10-μsec long pulses compressed to 20-ns. The prf will be 1000 Hz.

Single Transmitter System

A block diagram for a single transmitter system using a TWT power amplifier, a high voltage power supply and modulator, and pulse compression is shown in Figure 1. Upon receipt of a trigger from the logic and control circuits, the impulse generator will provide a signal to the pulse compression network. The output of the network will be switched, filtered, gated, frequency converted, and finally amplified in a high powered TWT stage. The transmitted signal is then fed through a duplexer to the antenna.

The received signals will be directed by the duplexer to a tunnel diode amplifier, converted in frequency, amplified, and then compressed in a pulse compression network and processed to produce range, pulse shape, and AGC data.

The reliability and life of such a system will depend to a large extent on the Traveling Wave Tube and its associated high voltage power supply. The HVPS will operate at several kilovolts, and in the space environment this can present problems with electrical breakdown, corona, arcing, and electromagnetic interference. With a single transmitter in the system, it is estimated that system life will be on the order of 10^3 hours of assured operation. With an extra transmitter which can be switched in if the primary unit fails, the system life expectancy would be almost doubled.

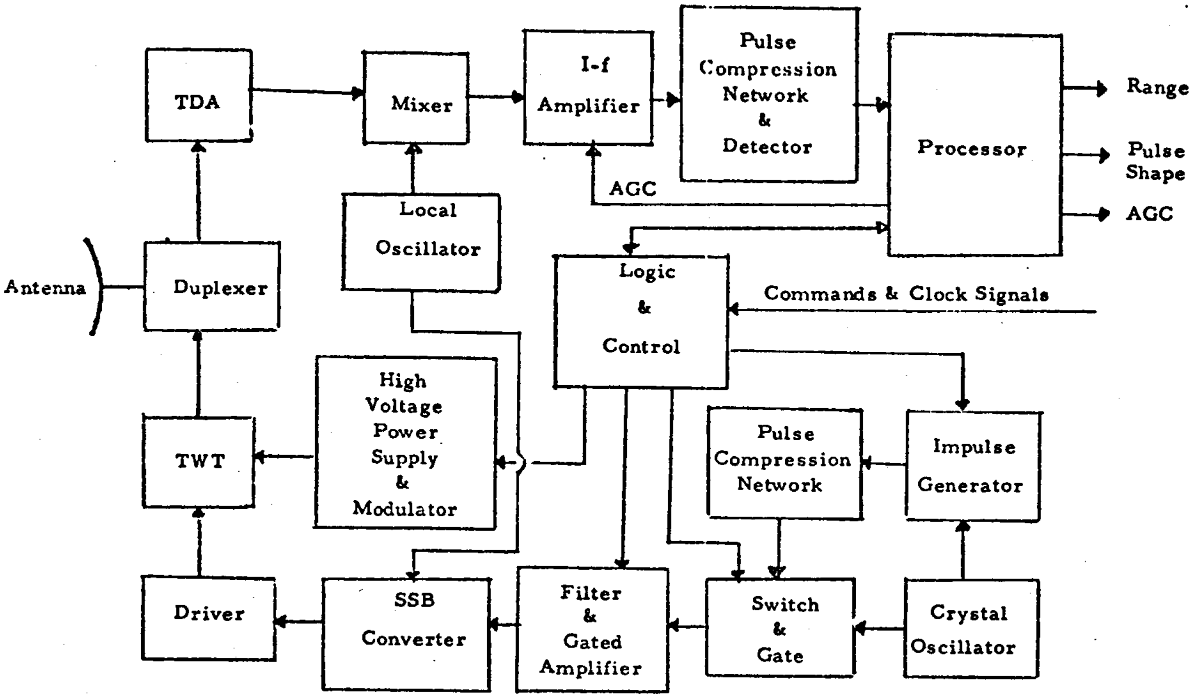

Figure 1 - Block Diagram of Single Transmitter System

It is estimated the system would require about 70 watts of dc power, exclusive of the power required to reposition the antenna in the event the radar senses it is more than 0.5° off the vertical. It may also be desirable for the antenna to scan to either side every so often so that the sea-state can be measured over a swath instead of just along the ground track. System weight, including the second transmitter, is estimated to be approximately 60 lbs.

Array of Solid-State T/R Modules

A block diagram of an altimeter that would use a modular array, with a large number of solid-state low power amplifiers in place of the high power TWT, is shown in Figure 2. Each of the transmit/receive modules would contain several of the elements shown in Figure 1, such as a power amplifier, duplexer or circulator, low noise amplifier, and switching circuits. The output of the impulse generator would be fed through the pulse compression network and the wide pulse would be switched, filtered, gated, and frequency converted. A feed system would distribute the signal to the T/R modules. The received signals from the modules would be combined in a feed system and the single output converted to the I-f, compressed and processed.

In order to estimate the number of T/R modules, it will be assumed that each radiating element in the antenna is fed directly by a module.

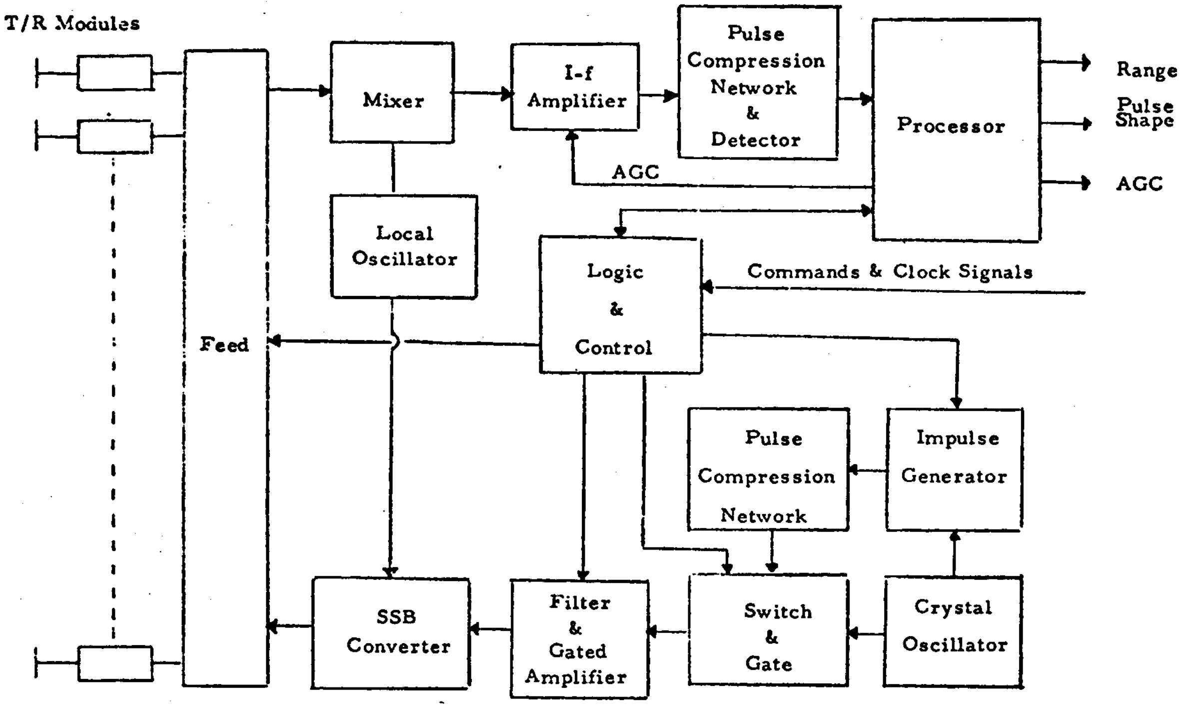

Figure 2 - Block Diagram of Solid-State Module System

In an equilateral-triangular arrangement of radiating elements, the maximum area, A_e, allowed per element if grating lobes are to be avoided is:

$$A_e = \frac{2\lambda^2}{\sqrt{3}\left(1 + \sin\Theta_m\right)^2} \tag{2}$$

where Θ_m is the maximum scan angle away from boresight (reference 2).

Therefore, the minimum number of elements is:

$$n = \frac{A_a}{A_e} \tag{3}$$

where A_a is the antenna aperture area.

Since $A_a = \frac{\pi D^2}{4}$

$$n = \frac{\pi\sqrt{3}}{2}\left[\frac{D\left(1 + \sin\Theta_m\right)}{2\lambda}\right]^2 \tag{4}$$

A 2° beamwidth is desirable to minimize satellite pitch and roll control requirements, and since $\lambda = 2.16$-cm, D is selected as 60-cm, as indicated in Table 2. Θ_m is selected as 10° so it will be possible to scan the beam at times out to 10° off the vertical in order to measure sea-state to either side of the satellite ground track. Substituting these values for λ, D, and Θ_m in equation (4) gives n = 700 elements. Since P_t is 400-watts, the output required of each module becomes approximately 570-milliwatts per module.

An example of where the K_u-Band state-of-the-art is today is the module recently built and tested by Sylvania under an Air Force contract (reference 3). This module provides 100-milliwatts using a two-stage avalanche diode as the power amplifier in the module.

The life of the solid-state T/R modules is expected to be on the order of 10^5 hours per module, and the system life in this case should be about 5×10^4 hours of assured operation. The high voltages of the single transmitter system have been eliminated, and the highest voltages will be well under 100 volts.

However, system power requirements will be significantly greater than those for the single transmitter system. It is estimated that system power, exclusive of beam steering, will be approximately 120 watts. System weight will also be higher. It is estimated the array system will weigh approximately 100 lbs.

Summary and Conclusions

A summary of the reliability, power, and weight estimates for the two system approaches is given in Table 3.

If progress is made in avalanche diodes and microwave hybrid integrated circuit fabrication techniques at K_u-Band, the use of the modular array approach should be considered carefully. Although it will require more power and be substantially heavier, its advantages in life and reliability may more than outweigh these disadvantages. When sufficient progress has been made, this question should be rigorously examined in detail, rather than the cursory way it has been examined here, so that a sound decision may be made on the system approach that should be adopted for the altimeters that come after Skylab and GEOS-C.

Table 3

Summary

	Single Transmitter System	Array Solid-State T/R Modules
System Life (Estimated)	2×10^3 hours	5×10^4 hours
System Power (Estimated)	70 watts	120 watts
System Weight (Estimated)	60 lbs.	100 lbs.

References

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2. Array Antennas T. Cheston and J. Frank, APL, Chapter 11 in Radar Handbook M. Skolnik, NRL, McGraw-Hill 1970

3. Integrated K-Band Transceiver Report No. AFAL-TR-71-26 prepared under Air Force Contract F33615-67-C-1896, A. Solomon, Sylvania, January 1971