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THE EVOLUTIONARY TREND IN AIRBORNE AND SATELLITE RADAR ALTIMETERS

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ABSTRACT

This paper looks at the manner in which airborne and satellite radar altimeters have developed and where the trend is leading. The airborne altimeters have progressed from a broad-beamed, narrow pulsed, nadir looking instrument, to a pulse-compressed system that is computer controlled, to a scanning pencil-beamed system that can produce a topographic map of the surface beneath the aircraft in real time. The future of the airborne systems seems to lie in the use of multiple frequencies. The satellite altimeters have evolved towards multi-frequency systems with narrower effective pulses and higher pulse compression ratios to reduce peak transmitted power while improving resolution. Future applications seem to indicate wide swath systems using interferometric techniques or beam-limited systems using 100 m diameter antennas.

1. INTRODUCTION

In this paper we will take the term "radar altimeter" to mean a radar system whose data product is primarily a direct range measurement of the sea surface elevation. This eliminates from consideration synthetic aperture radars, side-looking radars, and wave spectrometers since they use range measurements to identify a region on the sea surface from which they measure the backscattered power, not the elevation. We will discuss the airborne systems first since their development has anticipated the satellite systems.

2. AIRBORNE RADAR ALTIMETERS

Table 1 compares the features of three airborne radar altimeter systems of increasing sophistication. The first system was developed in a cooperative effort between the Naval Research Laboratory (NRL) and NASA/GSFC Wallops Flight Facility (WFF) to investigate sea surface scattering experimentally. NRL designed and built two X-band radars capable of transmitted pulse durations down to 1 nsec. The initial radar (Yaplee et al., 1971) investigated near surface scattering from the Chesapeake Light Tower located in the Atlantic Ocean fifteen miles east of Norfolk, Virginia. The second sytem (Yaplee et al., 1972) was flown in a WFF C-54 aircraft.

The transmitter and receiver horns (5° two-way beamwidth) were mounted side by side and looked at nadir through a port cut in the bottom of the fuselage of the aircraft. The received signal was amplified at RF and fed directly into a diode detector with a very fast response time. The detector output was displayed on the sampling scope whose storage also permitted A/D conversion for recording on magnetic tape.

The transmitter operated at 9.75 GHz with a pulse-repetition frequency of 90 kHz. Although a narrower pulse was transmitted and individual pulses recorded the "individual" pulses did not correspond to a single transmitted pulse. The sampling scope technique sequentially looked at different ranges for the returned pulses corresponding to a series of transmitted pulses. The range changed by one quantization for every six pulses but because they were so highly correlated there was no reduction of the Rayleigh fading of the signal. The output display rate was 90 Hz. At the beginning of each sweep, seven external channels were sampled followed by 160 data points from the sampling scope. In a typical display the 160 sample points would cover a 100-nsec time interval for a radar range window of 15 m and a range quantization of 0.625 nsec.

In 1973 this pulse-limited system acquired data at 3 km altitude under various wind and sea conditions during the Joint North Sea Wave Project (JONSWAP-2) off the coastal island of Sylt in Germany. The ability of such sytems to measure significant wave height (SWH) was well demonstrated by inter-comparison with waverider and pitch-roll buoys, a shipborne wave recorder, and a laser profilometer (Walsh <u>et al</u>., 1978).

It was recognized that to achieve high resolution at manageable peak power from space would require leaving the narrow pulses generated by the NRL radar and going to pulse-compression techniques. Also, the data volume which would be associated with increasing the PRF to decrease the noise in the range measurement needed to be reduced. To verify the viability of this approach, Hughes Aircraft, working with WFF under the NASA Advanced Applications Flight Experiments (AAFE) program, developed an airborne pulse compression radar altimeter operating at 13.9 GHz. The AAFE Altimeter was first flown in 1975 and achieved its 3 ns resolution using a wide bandwidth linear FM transmit waveform and a deramp stretch pulse compression processor. The wideband signal is generated by an acoustic Reflective Array Compressor (RAC) device which expanded a narrow pulse into an FM-modulated 3 us pulse. The deramp processor is essentially a correlation mixer which mixed the returned signal with a chirped local oscillator (LO) signal. The LO is a replica of the transmit waveform which is accurately controlled by the altitude tracker to be nearly time coincident with the return pulse. The output of the signal processor is taken from a bank of filters which corresponds to 24 sampling range cells over a 10 m range window.

In addition to testing the 1000 to 1 pulse compression application, this sytem had greatly increased sophistication. It is computer controlled and has selectable PRF, pulse width, and range tracker parameters. It preaverages return pulses over 0.1 second intervals to reduce the data volume, and computes and displays SWH in real time, in addition to range and AGC. Its tracking accuracy is better than 10 cm.

Up to this point, a pulse-limited radar altimeter's capabilities were limited to measuring the range to the sea surface, the backscattered power, and the SWH of the height distribution. It was decided to build a computer controlled, scanning narrow-beamed, radar system at 36 GHz which could generate a false-color coded elevation map of the sea surface below the aircraft in real time and routinely produce ocean directional wave spectra with off-line data processing. The Surface Contour Radar (SCR), developed jointly by NRL and WFF under the AAFE program, became operational in 1978. The system (Kenney <u>et al</u>., 1979) has an oscillating mirror which scans a 0.85° x 1.2° pencil-beam laterally at 10 Hz to measure the elevations at 51 evenly spaced points on the surface below the aircraft (Figure 1). At each of the points the SCR measures the slant range to the surface and corrects in real time for the off-nadir angle of the beam to produce the elevation of the point in question with respect to the horizontal reference. The elevations are false-color coded and

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displayed on the SCR color TV monitor so that real time estimates of SWH, dominant wavelength, and direction of propagation can be made. The real time display allows the aircraft altitude and flight lines to be optimized during a flight over a visibility obscured sea without prior knowledge of the wave conditions.

The limited peak power available at 36 GHz precludes the transmission of a 1 ns pulse, but the SCR employs a different modulation technique than the AAFE Altimeter. The continuous wave (CW) transmitter is biphase modulated by a digitally generated maximal length code sequence. The return signal is autocorrelated by a like sequence with a variable time delay inserted. The code length and clock rate can be varied, providing selectable range resolutions of 0.15, 0.30, 0.61, and 1.52 m. For the 0.15 m resolution there is an effective 2048 to 1 compression ratio. At the maximum beam scan rate of 10 Hz the range window is 4 m for the 0.15 m resolution.

Transformation by a two-dimensional FFT of the elevation map generated by the SCR produces the sea surface directional wave spectrum (DWS). Comparison of the SCR DWS with in-situ sensors was made during the Atlantic Remote Sensing Land Ocean Experiment (ARSLOE), a multiorganization experiment held October 6-November 30, 1980, near Duck, North Carolina. When the SCR DWS was compared with waveriders and the XERB and ENDECO pitch-and-roll buoys, there was excellent agreement between the non-dimensional spectrum and the angles associated with the A_1, B_1, and A_2, B_2 Fourier coefficients. There were indications that the in-situ sensors had calibration problems with the magnitudes of the higher Fourier coefficients, and that the radar system may be able to measure up to 13 Fourier coefficients compared to the five of the pitch-and-roll buoys. The high spatial resolution and rapid mapping capability over extensive areas make the SCR ideal for the study of fetch-limited wave spectra, diffraction and refraction of waves in coastal areas, and hurricanes and other highly mobile wave phenomena.

The future of airborne altimetry lies in using multifrequency systems to refine our knowledge of the effects of frequency dependent surface scattering as well as the perturbing effects of rain and clouds. Preliminary work has already begun in this area using the combination of the AAFE Altimeter and the SCR which are both presently located on the WFF P-3 aircraft.

Since the SCR measures both returned power and elevation to high spatial resolution, it can determine for various sea states how the backscattered power per unit area varies as a function of the displacement from MSL (Walsh et al., 1984). The SCR uses its pencil beam to determine the spot on the surface to be interrogated. This allows independent histograms of the sea surface height distribution and the return power distribution to be developed from SCR data. The return power distribution (which is what an orbiting altimeter would measure) is shifted towards the troughs relative to the surface height distribution. The measurements indicate that the range measured by a 36 GHz pulse-limited altimeter in space would be biased approximately 1.1% of the value of SWH towards the troughs. However, the EM bias of an altimeter operating at 13 GHz is of more immediate interest because of the TOPEX mission. Since the AAFE Altimeter does not have the spatial resolution to measure EM bias by itself, the SCR will take simultaneous data at 850 m altitude with the AAFE Altimeter (13 GHz) to provide a direct measure of EM bias at 13 GHz.

The indications are that satellite altimeters operating at 13 GHz should be subject to an EM bias equal to 3% of the significant wave height (SWH) but this has not been directly verified. Because of the high spatial resolution of the pencil beam of the SCR, its range measurements are not subject to the EM bias effect and it can determine the actual aircraft altitude.The SCR and AAFE Altimeter will take data simultaneously during the NOAA Artic Cyclone Experiment in January, 1984, while the aircraft proceeds offshore of Greenland under fetch-limited conditions and returns. The antennas of the two systems have been colocated. The ranges determined from the systems will be subtracted and any bias removed to make the difference zero at the start of the flight where the wave height was low. The range difference between the two instruments should increase to 30 cm as the wave height increases to 10 m and then decrease back to zero as the aircraft returns to shore. Figure 2 shows some preliminary data acquired at 1350 m altitude with the SCR-AAFE Altimeter combination. The top of the figure shows the variation in the raw altitude measurements of the two systems. The bottom of the figure shows the range difference between the two systems after some minor corrections to the SCR data. The high frequency noise in the range difference is not a problem since SWH has a slow, trending variation and the data could be averaged over several minutes. A potential problem is the slow oscillation in the mean value which was probably induced by aircraft pitch and roll effects on the AAFE Altimeter. The altimeter beamwidth has been broadened from 15° to 45° to eliminate the attitude sensitivity and a delay line has been added to allow it to operate at 850 m altitude where the signal level and spatial resolution on the SCR is better.

3. SATELLITE RADAR ALTIMETERS.

Table 2 compares the features of four satellite radar altimeters. Three of these radars have been placed in orbit. The first was aboard Skylab, which was launched in May, 1973. The second was on GEOS 3, launched in March, 1975, and the third was aboard Seasat-1, launched in June, 1978. The AAFE Altimeter was the prototype of the Seasat altimeter which used a similar pulse compression technique and effective pulse and also preaveraged returned pulses over 0.1 sec. These altimeters contributed to geodesy and earth physics and measured ocean mesoscale features, wave height, wind speed and ice boundaries.

The Geosat altimeter is scheduled for launch in the fall of 1984 and the ERS-1 altimeter is projected for 1988. Geosat and ERS-1 are essentially Seasat class altimeters. The TOPEX altimeter is under development. Table 2 shows that the trend has been towards more narrow effective pulses and higher PRF. There has not been much motivation for narrowing the effective pulse width beyond the 3 ns width achieved on Seasat. However, the pulse compression ratio has increased so that a longer transmitted pulse with lower peak power could be utilized.

To date, the satellite altimeter has been a narrow swath instrument, but studies have been carried out which indicate the possibility that a multibeam altimeter with additional beams displaced 25 to 50 km on either side of the nadir beam could greatly improve the ocean mesoscale feature mapping capability. One suggestion for the multibeam altimeter (Bush et al., 1984) is to use a TOPEX class altimeter and augment the nadir tracking pulse-limited altimeter with an additional antenna deployed cross-track (Figure 3). Each of the antennas would have multiple feeds to permit the illumination of patches both left and right of nadir. The antenna pair would be connected by a T and driven by a single transmitter-receiver so that interference lobes would be produced. Each interferometer lobe would produce a return similar to that which would be obtained from a large antenna, allowing the radar to obtain precision off-nadir altimetry by centroid tracking the central interferometer lobe. A single antenna would be used to track the nadir.

Satellite roll constitutes a problem when trying to accurately measure range to a point off-nadir. In an 800 km orbit, a multibeam altimeter looking 50 km cross track would experience a 1 cm range change if the satellite roll angle changed by only 200 nanoradians. How would one tell the difference between a roll angle charge and a mesoscale surface feature? The solution is to measure the roll independently. Measurements (Green et al., 1979) on a modified breadboard Dry Rotor Inertial Reference Unit-II (DRIRU-II is the NASA standard dual redundant attitude reference for spacecraft) have demonstrated its ability to measure angles to a precision of better than 100 nanoradians over a period of one hour. Achieving this angular noise performance assumes a system operating in conjunction with other sensors and algorithms which can estimate changes in the fixed drift of the gyro. Since mesoscale features would be high frequency occurrences with encounter times on the order of ten seconds compared to the slow, trending variation of roll whose dominant period would be on the order of an orbit for a free flying satellite, low-pass filtering of the range data could supply the information needed by the attitude system. The effect of the roll variation could then be subtracted from the range data for studying mesoscale features.

The advent of the space shuttle has made feasible the deployment of large antennas in space. A large antenna would allow a down-looking real aperture imaging system that has several advantages over the SAR. It could image the reflectivity of the surface while it simultaneously measured the altitude, viewing the surface at near normal incidence. The near nadir imaging capability would provide a viewing angle that could easily be matched with other imagery such as from cameras and IR scanners. Studies have shown that near nadir radar is particularly sensitive to the ripening of crops and soil moisture. The image production is a very simple low data rate assignment of reflectivity to a ground position not requiring the motion compensation, Fourier transformations, or high data rates normally associated with SAR systems. The additional height information provided for each resolution area would contribute to understanding terrain contributions to plant conditions, measurement of plant heights or growth rates, determination of snowdepths, resolving atmospheric conditions such as rain, and surveillance of ships and/or aircraft and other applications.

Large antenna studies such as recently conducted at the NASA Marshall Space Flight Center (MSFC) and presently being conducted at the NASA Langley Research Center (LaRC) are directly leading to the feasibility of a pushbroom image and contouring (PIC) radar for future earth observations. The Harris Corporation (Marvin Sullivan, private communication) is under contract to LaRC to fabricate a 15 m diameter hoop-column space antenna which is a one-seventh scale engineering model for an eventual flight application of a 100 m diameter antenna. The 15 m diameter antenna is presently being assembled and is scheduled for RF testing in late 1984. It is projected to be flight tested on the space shuttle in the 1986-87 time frame. In its initial configuration the collapsible antenna will be roughness limited to a maximum operating frequency of 6 to 8 GHz. However, the addition of more contouring cabling could increase its frequency response up to 13 GHz.

Recent algorithm development for satellite radar altimeters has focused on instruments of the Seasat class. Since that instrument has the demonstrated capability of measuring surface height variations to less than 10 cm, significant wave height to within 10 cm of data buoys, and surface wind speeds to within 1.4 m/s of the data buoys, the need for a new generation instrument might be questioned. But bear in mind that the maximum wave height in the buoy comparisons was approximately 5.5 m and the bulk of the wind speed values were less than 15 m/s (Fedor and Brown, 1982). Although the Seasat altimeter worked very well, none of the above measurements have been verified within severe storm regions; not necessarily because of the high wind speeds and wave heights asociated with storms, but due to the presence of rain which attenuates and distorts the transmitted pulse. The ideal instrument to use to correct for the effects of precipitaion is the radar altimeter itself, since the data corrections will be co-located in space and time with the data to be corrected. When the proper techniques and algorithms exist, the instrument could provide its own measurement of rain rate. The advantage of aircraft borne instruments for this development is that it is economically reasonable to design experiments in an iterative fashion, to test techniques and theories, and to compare the results with the data from other instruments.

The Seasat class radar altimeters were specifically designed for ocean returned pulses which assumed a distribution of specular points. When the pulse is reflected from a few smooth surfaces, the signal can be highly peaked and variable, making it difficult to track and estimate returned power with the existing algorithms. It is necessary to develop models for surfaces that are encountered over land, sea ice, and sheet ice. It would be beneficial to develop a new generation aircraft borne radar altimeter as a mobile laboratory to expand the capabilities of future satellite radar altimeters. In addition, it could be used as an AIR/SEA interaction instrument in concert with other remote sensing instruments both meteorological and oceanographic, in a variety of experiments. These experiments would be concerned with hostile environments (such as provided by topical and extra-tropical cyclones and the marginal ice zone), oceanographic features provided by current systems, and the passage of meteorological fronts.

In order to be able to provide the research capabilities for problems such as described above, the Advanced Technology Airborne Radar Altimeter (ATARA) would have to have several distinct characteristics. First, it would need to have at least 100 dB of dymanic range in order to sample the large specular returns encountered from new sea ice without saturating and also weak returns from rain and liquid water above the surface. Within existing technology, it is possible to provide intensive sampling of the returned pulse both from and above the surface. It is possible to sample the whole returned pulse using several thousand sampling gates. Having the capability of recording every pulse return would aid in the development of scattering models over land and ice, improved tracking algorithms that would automatically respond to the type of surface being interrogated, and precipitaion models that would extend the physical parameters that can be measured by a radar altimeter. ATARA would have on board data processing capabilities that could be refined for eventual satellite applications. It would be used as a validation instrument for future satellite radar altimeters.

The development of airborne and satellite radar altimeters has been closely intertwined. Although ATARA could provide the research tool to understand some of the more complex returns encountered by the satellite instruments, each has unique operational capabilities. The airborne altimeter could be used in specific experiments to understand physical proesses, while the satellite altimeter could provide high resolution global measurement of the same processes.

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Table 1. A COMPARISON OF AIRBORNE ALTIMETER PARAMETERS

	1971 NRL NANOSECOND RADAR	1975 AAFE ALTIMETER	1978 SURFACE CONTOUR RADAR
ALTITUDE INTERVAL (m)	surface to 4000	850 to 4000	surface to 1500
ANTENNA BREADWIDTH	7.0°	15° or 45°	1.2° X 0.85° (2-way)
FREQUENCY (GHz)	9.75	13.9	36
PEAK RF POWER (W)	10	20	10
AVERAGE RF POWER (W)	0.0009	0.05	10
PULSEWIDTH (UNCOMPRESSED)	1 ns	3 μs	CW
PULSEWIDTH (ns) (COMPRESSED)	---	3	1,2,4,10
TRANSMITTER PRF (KHz)	90	0.85	90
OUTPUT WAVEFORM FREQUENCY (Hz)	90	10	20 raster lines
RANGE WINDOW (m)	15	10	4 at 1 ns resolution 8 at 2 ns resolution
FOOTPRINT DIAMETER (m)	12 at 150 m alt. 60 at 3 km alt.	104 at 3 km alt.	6 X 8 at 400 m altitude 11 X 16 at 800 m altitude
ALTITUDE PRECISION (rms)	< 10 cm	< 10 cm	< 10 cm

Table 2. A COMPARISON OF SATELLITE ALTIMETER PARAMETERS

	1973 SKYLAB	1975 GEOS-3 (Intensive)	1978 SEASAT-1	TOPEX
MEAN ALTITUDE (km)	435	840	800	1334
ANTENNA BEAMWIDTH (°)	1.5	2.6	1.6	1.04 at K_u band 2.6 at C band
FREQUENCY (GHz)	13.9	13.9	13.5	13.7 (K_u) 5.3 (C)
PEAK RF POWER (kW)	2	2	2	0.020 (K_u) 0.020 (C)
AVERAGE RF POWER (W)	0.05	0.24	6.5	8 (K_u) 2 (C)
PULSEWIDTH (UNCOMPRESSED)	100 ns	1 µs	3.2 µs	102 µs
PULSEWIDTH (ns) (COMPRESSED)	---	12.5	3.125	3.125
REPETITION FREQUENCY (Hz)	250	100	1020	4000 (K_u) 1000 (C)
RANGE WINDOW (m)	60	15	29	62
FOOTPRINT DIAMETER (km)	8	3.6	1.7	2.2
ALTITUDE PRECISION (rms)	< 1 m	< 50 cm	< 10 cm	2.4 cm at 2 m SWH 2.7 cm at 4 m SWH 3.2 cm at 8 m SWH

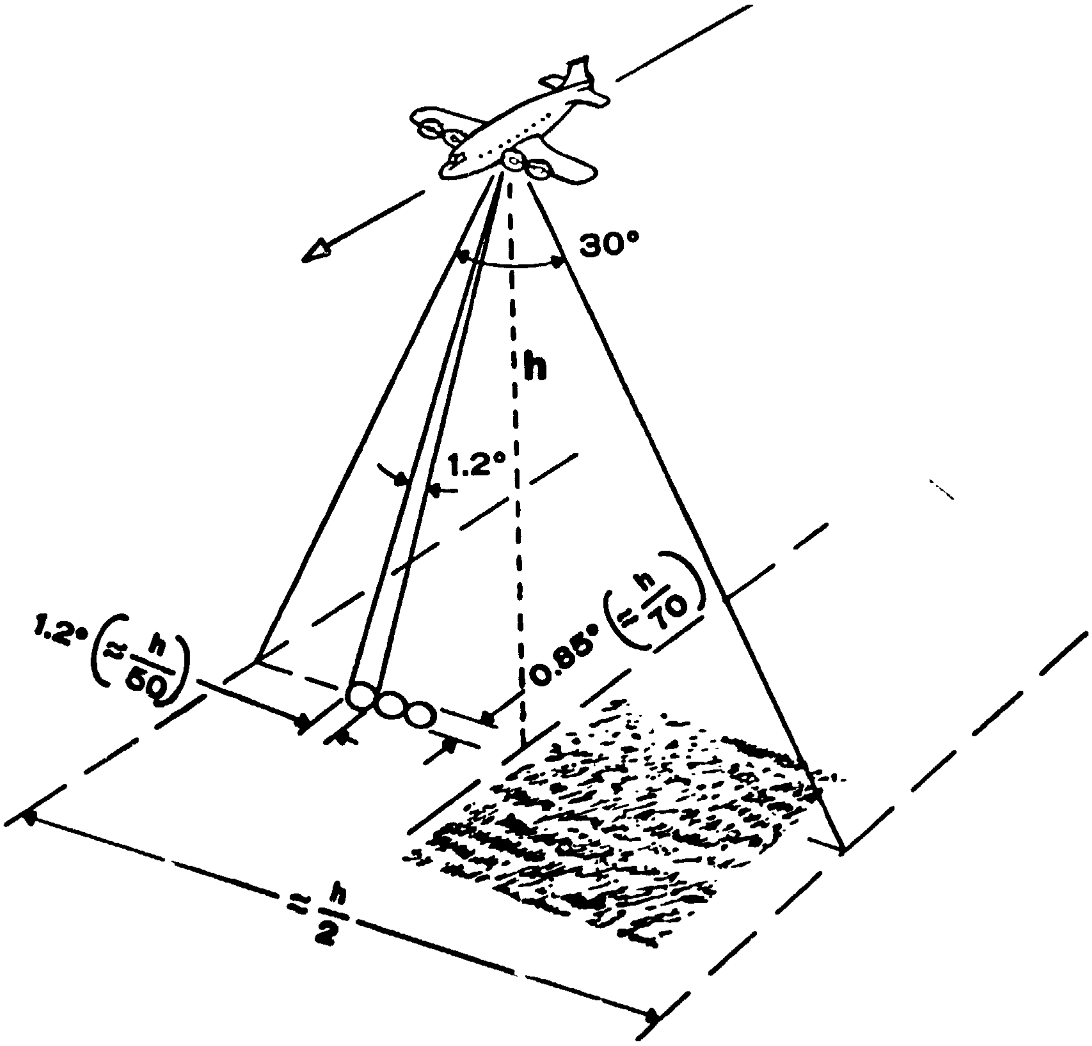

Figure 1. The basic measurement geometry of the Surface Contour Radar.

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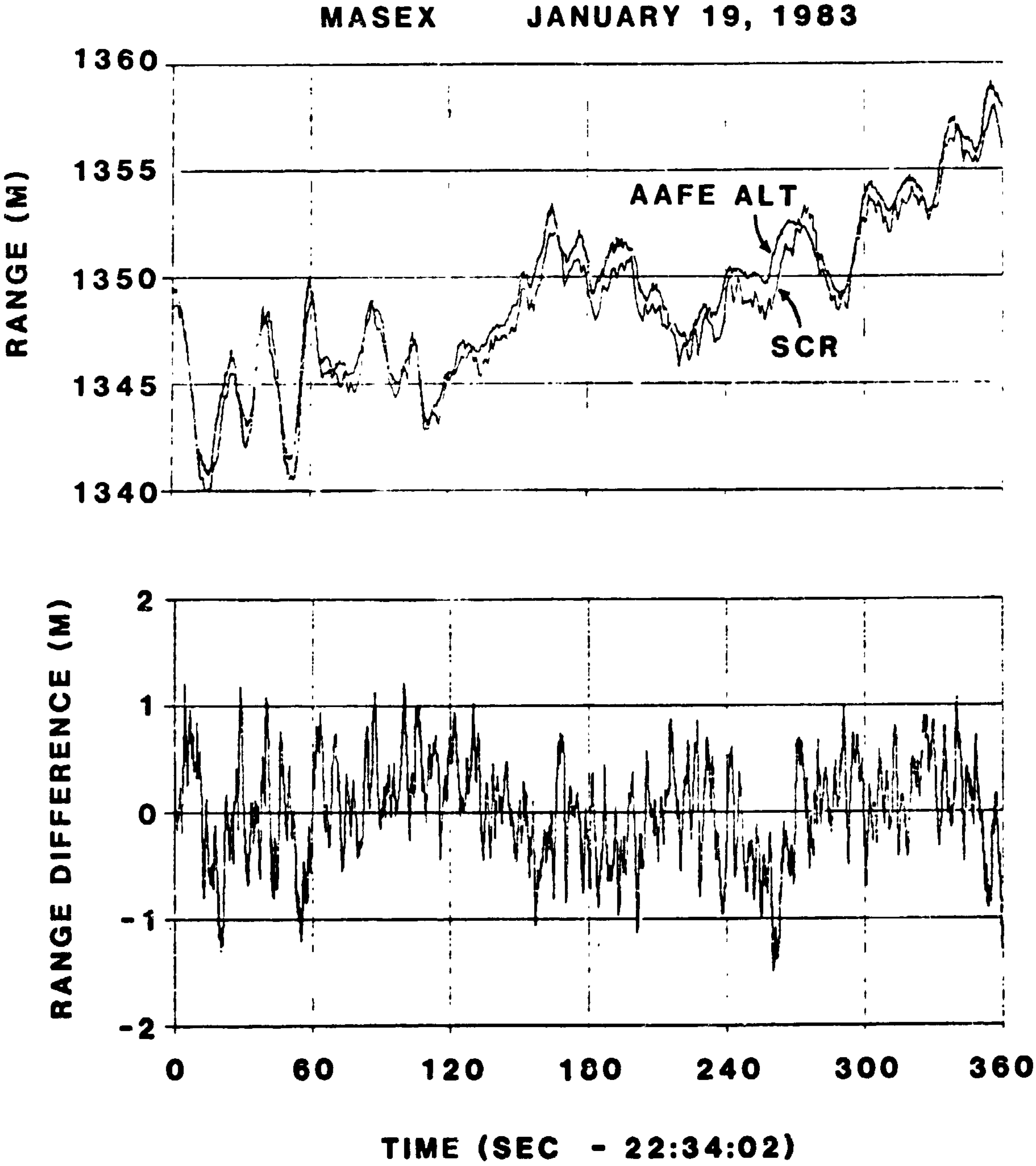

Figure 2. Preliminary range difference measurements for the AAFE Altimeter and the Surface Contour Radar.

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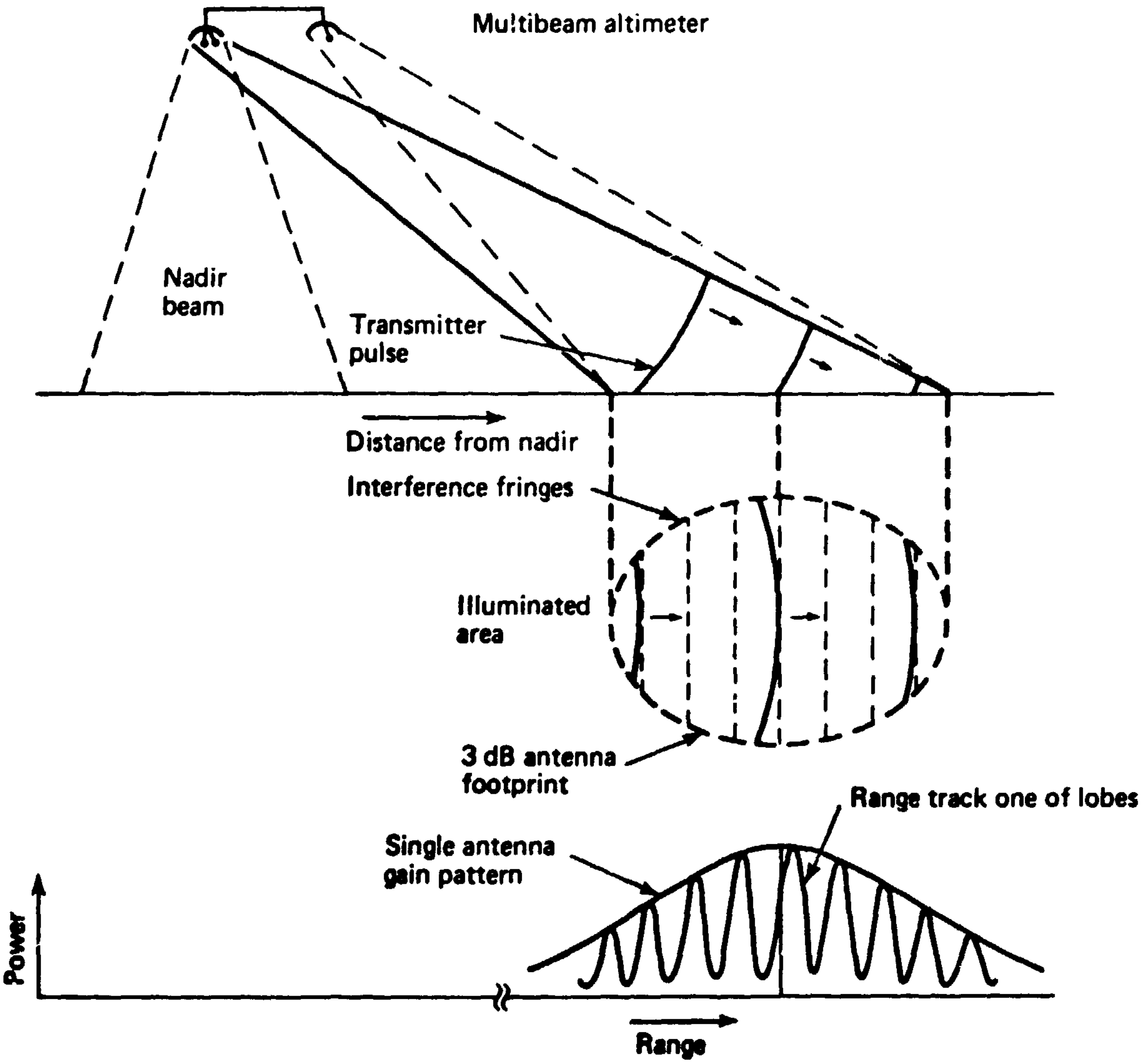

Figure 3. The basic measurement geometry of the interferometric multibeam altimeter.