RANDOM SAMPLING ADAPTIVELY FOCUSING SYNTHETIC APERTURE RADAR

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SUMMARY

Valley Forge Research Center is designing a high resolution narrow angle of view imaging radar system. It will employ an airborne synthetic aperture of 600 meters operating at X-band to produce a beamwidth of approximately 0.05 mr. This system differs from a conventional SAR in that only a smaller number of wavefront samples, spaced randomly over the aperture are processed, and adaptive beamforming with open loop scanning is used. As a result, the processing requirements are reduced to within the capability of present day small computer technology, and the tolerance on flight path stability is loosened by about 100:1. The system will be described and initial analysis and evaluation results will be presented.

INTRODUCTION

The system design to be described is a product of the ongoing research program to study the application of the theory of large, random, adaptive arrays to the implementation of high resolution airborne ground surveillance radars. This design combines adaptive beamforming and synthetic aperture techniques to provide a 100-fold improvement in the resolution capability of a helicopter radar system. The assumed helicopter radar has a beamwidth of about 5 milliradians; the high resolution system will sharpen the beamwidth to 0.05 milliradians. This increased resolution will be provided over only a limited field of view as this high resolution system is designed to be used in a manner analogous to a telephoto lens. The conventional radar will be used to identify a small region of interest, perhaps 5 mr in angular extent and a few hundred meters in depth; at the assumed range of about 60 km this target area would be about 300m on a side. The high resolution 0.05 mr array pattern will be scanned over this region providing a resolution cell 3 meters wide.

The depth of the resolution cell will be determined by the range gate of the radar and is assumed to be about 15m. It is advantageous to limit the angular extent of the area of high resolution imaging (scanning) since this permits much greater uncertainty in the position of the radar platform without loss of resolution. Also, if pipeline processing is used, the amount of data to be stored will be greatly reduced, since for the parameters assumed above there would be only about 100 resolution cells in the azimuthal direction and about 20 range bins in depth.

High resolution imaging requires that the effective aperture of the receiving antenna is very large; 0.05 milliradian beamwidth demands an aperture size of about 20,000 wavelengths. This corresponds to a physical dimension of 600 meters (about 2,000 ft) if the system is operating at X-band (a wavelength of approximately 3 centimeters) [1]. The system uses a single helicopter which moves along a path to construct the large array sequentially. When the small area to be imaged has been selected, the helicopter will maneuver so that its position is coincident with a line determined by a prepositioned cooperative corner reflector and the target region. The corner reflector will serve as an aiming point for adaptive focusing of the array.

The use of a corner reflector for adaptive beamforming results in major differences between this adaptive synthetic aperture radar (ASAR) and a conventional SAR system. Adaptive beamforming will be accomplished by cophasing the corner reflector returns as measured at each of the sample points of the array to place the peak of the main lobe of the array's receive pattern in the direction of the corner reflector. Adaptive beamforming thus permits forming a beam without knowledge of the positions of the sample points of the array. The aiming point reflector must be readily identified in spite of the normal ground clutter; consequently, this "corner reflector" might be implemented as a high power transponder beacon or perhaps a coded retrodirective array offering a large time-bandwidth product. Once the helicopter has established its position along the line determined by the aiming point and the target region, it will move horizontally in a direction perpendicular to this line, sampling the signal returns from the target region as it is illuminated by the helicopter radar. The samples of the target wavefront will be collected at random intervals over the entire pathlength (600m at X-band).

Random sampling permits thinning the array to reduce the amount of data required to image the target region. The collected target wavefront data will then be processed to yield an image of the target region. This will be accomplished by first organizing the array through adaptive beamforming on the aiming point corner reflector. Once the array pattern has been established adaptively, phase shifts can be added to each of the wavefront samples to shift the focus of the array from the corner reflector out to the target range. Then sequences of phase shifts can be added to the wavefront samples to scan the array beam over the target region. The last two operations require an approximate knowledge of the locations of the array sample points. It is assumed that this position determination will be supplied by a separate independent system. It can be shown that the position data need not be precise; only the relative positions of the sample points are needed and accuracy on the order of 1 meter is adequate. An inertial navigation system can provide this precision with ease.

BASIC SIGNAL PROCESSING CONCEPTS

The adaptive synthetic aperture system uses the adaptive beamforming corner reflector to compensate for the motion induced effects of the helicopter. Figure 1 shows the geometry which exists if a linear random array is focused on a near field target. If the target is illuminated from the ith element,

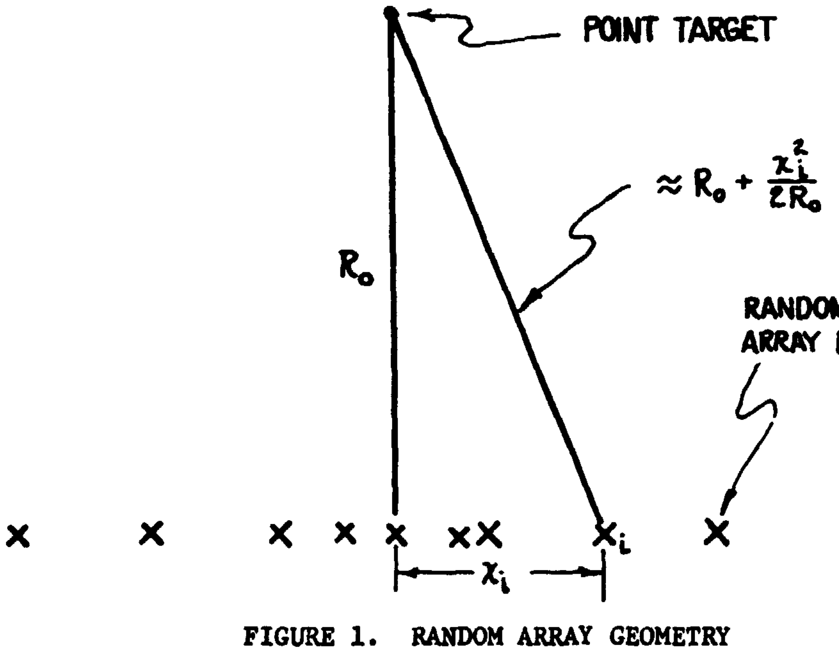

FIGURE 1. RANDOM ARRAY GEOMETRY

the phase of the target return at that element relative to reference element x_o is

$$2K_\lambda R_o + \frac{K_\lambda x_i^2}{R_o} \tag{1}$$

The second term exhibits the quadratic phase variation required to focus the array on a near field target.

The storage and processing requirements for digital computation in the case of the ASAR are much less than those of the conventional SAR. A primary source for this reduction is the use of random sampling to thin the array. Random sampling is used to eliminate grating sidelobes and the sampled array will be thinned to a high degree. The number of samples taken along the 600m flight path will be approximately 1,000; this number of samples implies an average sidelobe level of approximately -30 dB [2]. Thus if the wavelength is assumed to be about 3 centimeters, then on the average, samples will be taken every 20 wavelengths, and the array is thinned below that of a filled array by a factor on the order of 40 to 1. At each sample point, three types of information will be stored, the phase of the transmitted pulse, the return from the corner reflector and the values from the 20 target range bins. If quadrature components are stored for 22 range bins for each of the 1,000 sample points, a maximum of 44,000 words of memory would be required. This amount of storage would permit off-line processing; however, the memory requirements can be reduced still further making real time processing practical for the ASAR.

The required multiplication rate for the ASAR would be similar to that of the conventional SAR if it were necessary to complete the processing during a single interpulse period; however since the ASAR array is highly thinned, additional time is available for processing. For example, if a helicopter traverses a 600m path at 50 m/s while collecting 1000 samples of the target wavefront, the average interval between samples would be about 12 milliseconds. A fraction of this time might be required for sweep integration or other processing, but on the average an interval of about 10 ms is available for processing. If the processing is accomplished while the data are being collected, the data memory could be reduced to 2000 words, one for each resolution element in the target image (100 azimuth cells x 20 range bins). The processing and memory requirements for the sampled random array are quite compatible with modern small computer technology; the same can not be said for the SAR technique.

Thus there are important differences between the conventional SAR and the ASAR. The conventional synthetic aperture approach uses the quadratic phase history arising from the doppler shift to compress the target signal in azimuthal beamwidth. The ASAR array described herein will compensate the signal to remove the doppler offset so that the target and the array can be treated as stationary. Furthermore in the case of this randomly sampled array, the number of samples is kept small compared to a usual synthetic aperture array. The ASAR array will beamform adaptively on the signal return from a corner reflector. The use of this technique greatly increases the tolerance permitted on the uncertainty in the position of the sampling points. It will be shown later that the uncertainty in sample point position can be as much as 20λ. The helicopter motion need not be regular, and the system can tolerate relatively large position errors. The characteristic is in sharp contrast to an SAR approach where it is desired to hold phase errors to less than 1 radian and preferably less than 1/10 radian [3].

The number of corner reflectors required will depend upon how rapidly the high resolution image must be constructed. Figure 2 shows a typical airborne surveillance situation. The area of surveillance is assumed to extend over a sector 120° wide by 30 km in depth. N corner reflectors will be placed on the accessible side of the surveillance area boundary. The conventional low resolution helicopter radar will be used to identify a small target region to be scanned with the high resolution array pattern. The helicopter will then move from its initial point 0 to point A to place a convenient corner reflector, reflector i, in the vertical plane defined by the helicopter and the center of the target region. If it is assumed that the N corner reflectors are evenly spaced and that the helicopter has a reasonable top speed of perhaps 50 m/s, the number of reflectors required to limit the maximum time required to move the helicopter to an imaging point is readily computed since the greatest helicopter movement will be a distance equal to 1/2 the segment BC. The length of the arc segment BC at the maximum distance is

$$BC = \frac{60 \times 10^3 \mathrm{m}}{N} \times \frac{2\pi}{3} \simeq \frac{125\mathrm{km}}{N} \qquad (2)$$

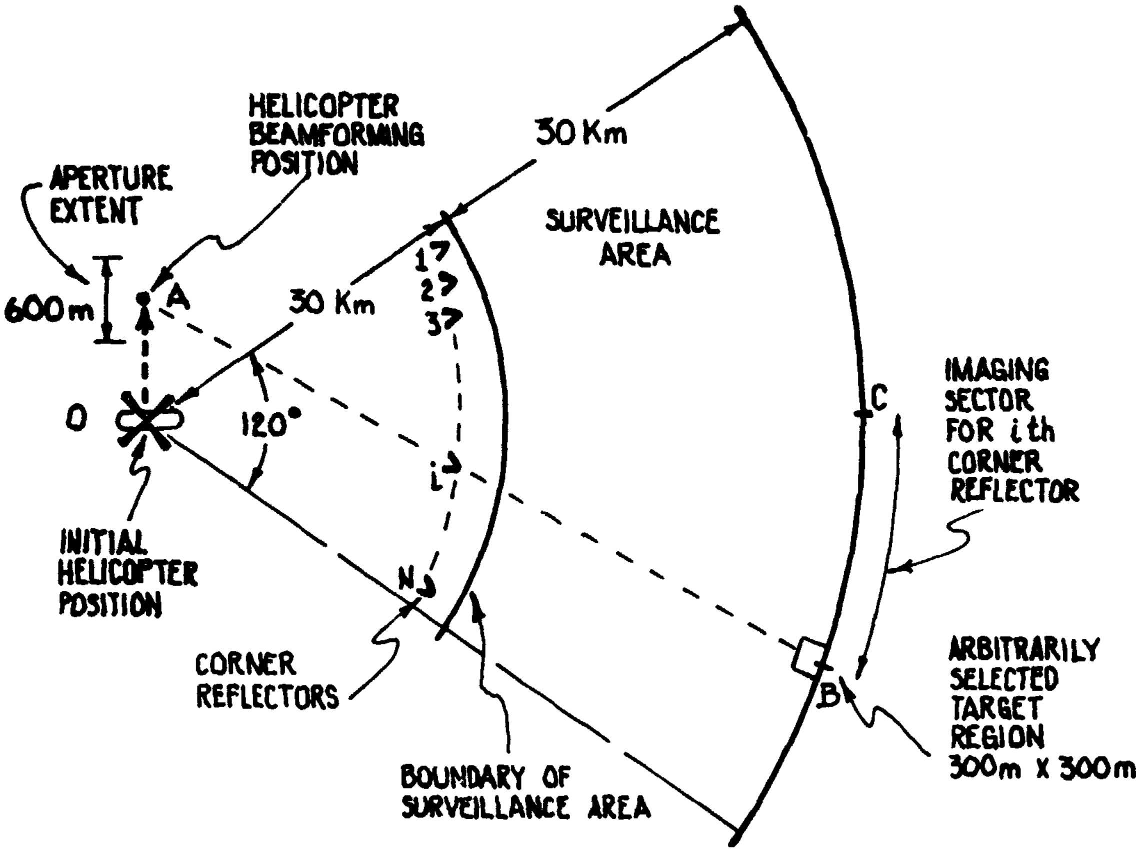

FIGURE 2. AIRBORNE RADAR ENVIRONMENT

The time required for the helicopter to move the maximum required distance on the other side of the surveillance area boundary at 50 m/s is

$$t_A = \frac{125}{2N} \text{km} \times \frac{1}{50 \text{m/s}} = \frac{1.25 \times 10^3}{N} \text{ seconds} \qquad (3)$$

Thus if four corner reflectors are used, about 5 minutes would be required for the initial positioning of the helicopter in the worst case. It should be noted that knowledge of the exact position of the reflector is not required for beamforming. Thus the use of adaptive beamforming via a corner reflector need not be a large disadvantage if the required rate of imaging is low.

The details of the system will be developed by considering the simplest case where helicopter motion is ignored and it is assumed that both the corner reflector and the target are in the far field of the array. The subsequent section will consider the corrections required to focus the array when the target region is in the near field of the array, and the effects of helicopter motion.

FAR FIELD SYSTEM

Figure 2 shows typical geometry. Initially it will be assumed that the helicopter is stationary at each of the sample points; consequently no doppler correction will be required. It will also be assumed for the initial discussion that the corner reflector and the target region are both located in the far field of the array. (Both of these restrictions will be removed after the basic system description has been developed.)

It is assumed that the helicopter will move from point to point along its flight path as indicated in Figure 3. At each of the sample points, for example, point i, the helicopter will transmit a number of pulses that will illuminate the corner reflector and then at a later time the target region.

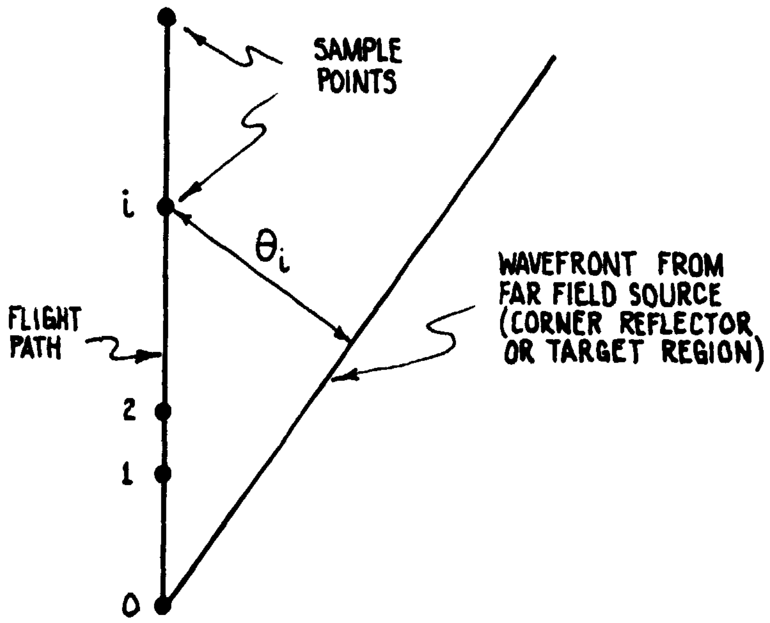

FIGURE 3. PHASE RELATIONSHIPS, FAR FIELD

The first return of interest received by the radar set at point i will be a return from the corner reflector. This return will be phase detected against a local reference signal. The return from the corner reflector θ_{CRi} as measured against a local stable reference is

$$\theta_{CRi} = \theta_{oi} + \theta_{pc} = \theta_{oi} + 2\theta_i \tag{4}$$

where θ_{oi} is the phase of the transmitted pulse relative to the local reference, θ_{pc} is the phase accumulated by propagation from the transmitter to the corner reflector and return, and $2\theta_i = \theta_{pc} \bmod 2\pi$. The phase detection process will not be sensitive to integral wavelengths, and θ_{pc} may be replaced by $2\theta_i$. The phase of the return from the corner reflector can be expressed as the sum of the phase delay from the element to a planar wavefront from the far field reflector, θ_i, and the transmitted phase θ_{oi} (see Figure 3).

At a slightly later time the signal return from the target region will be compared against the same local phase reference. The phase of this return is given by (5)

$$\text{Measured phase from target region} = \phi_{Ti} =$$

$$\theta_{oi} + \theta_{pT} + \theta_\varepsilon = \theta_{oi} + 2\theta_i + \theta_\varepsilon + n2\pi \tag{5}$$

θ_{pT} = propagation phase for the target signal

This equation is similar to (4) except that (5) also contains a quantity θ_ε which represents phase drift which might occur in the phase reference against which incoming signals are measured during the time between the reception of the return from the corner reflector and the detection of the return from the target region. For the geometry shown in Figure 2, the difference in propagation time between the corner reflector and the target will result in a maximum delay of approximately 200 microseconds. If we demand that the oscillator stability in the receiver system be such that maximum phase error is on the order of 10°, then as indicated by (6) the stability required of the receiver LO (the most critical of the phase determining components) will be on the order of 1 part in 10^8.

$$\frac{\Delta f}{f} = \frac{((1/36)\ \text{cycle}/(200\mu\text{sec})}{10^{10}\ \text{Hz}} = 1.38 \times 10^{-8} \tag{6}$$

Assuming X-band operation ($f = 10^{10}$ Hz)

This is a severe requirement but not beyond the capability of present-day hardware. The stability required of the lower frequency portions of the system, for example IF detection reference sources, will be substantially less due to the lower operating frequency.

It is apparent from (4) and (5) that if the error signal θ_ε is small, then the information exists in the phase measurement of the returns from the corner reflector to permit cophasing the target returns at least in the far field case. It should be noted that the transmitter phase θ_{oi} is independent from pulse to pulse, consequently it would not be possible to combine successive phase returns from the target region for the purpose of sweep integration unless a correction is made for this fluctuation. This correction can be accomplished by storing θ_{oi} and comparing it against the corner reflector return. Upon reception of the return from the corner reflector, the transmitted phase will be subtracted to obtain the quantity $2\theta_i$. The same correction would be performed on the target return phase measurement, thus the transmitted phase variation is removed and successive returns from the target region can be added for sweep integration and the reduction of noise components.

In summary, three phase quantities will be measured at each sample point. The first is the transmitter phase. This information will provide a reference phase correction to permit combining successive returns from the target region. The second quantity to be measured will be the return from the beamforming in the direction of the corner reflector; and since the position of the helicopter has been deliberately chosen to place the corner reflector in the direction of the target region, a beam can be formed in the direction of the desired angle of view. The third set of data to be recorded will be returns from the target region. The number of pieces of information to be recorded will depend upon the desired number of range bins. It has been assumed as typical that the range gate duration will be approximately 100 nanoseconds corresponding to a two-way propagation distance of 50 ft. Then approximately 20 range bins will be required to cover the target region depth of about 300 meters.

When these three sets of information have been collected from all of the sample points, it will be possible to beamform and scan over the target region assuming only that the approximate locations of the sampling points are known. The precision required on the determination of the position of the sampling points is low. Since the maximum scan angle required of the array will be of the order of 5 milliradians, the uncertainty in the sample point positions can be high; the 5 milliradian scan angle implies that scanning can be accomplished even with an uncertainty in element position, on the order of 20 wavelengths [4]. A 20 wavelength uncertainty at X-band corresponds to about 0.6 meters. Position determination to this accuracy can be obtained from a variety of distance or position determining equipments. The most desirable would probably be an inertial navigation system since this would permit self-contained operation within the helicopter system. It should be noted that the position determination is particularly nonrestrictive since absolute values are not required. Only the relative position of the helicopter at each of the sampling points will be stored along with the phase data. The amount of memory required might be reduced if the sequential array is constructed as the data are collected. That is, there are only 2000 resolution cells in the target region (100 azimuth cells x 20 range bins), if the processing can be performed in a pipeline fashion it would not be necessary to store more than one word per resolution cell. This type of operation would involve the following operations at each sample point. The first step would require subtraction of the phase of the transmitted pulse from the target returns followed by beamforming as the data are collected by using the corrected corner reflector phase. This phase could be subtracted from the corresponding target values, i.e., a new array of numbers identified only by the element number and range gate position would be constructed. Open loop scanning would result in a final array of numbers identified by azimuth and range.

NEAR-FIELD CORRECTIONS

Several additional considerations arise from study of the near-field model. These include the necessity for increasing the beamwidth of the transmitter antenna and for refocusing the array. As shown in Figure 2 the target region is assumed to be about 300 meters on a side. The flight path required for the generation of the array is approximately 600 meters. Consequently the center of a 5 mr transmit antenna beam from the helicopter will sweep over a transverse distance of 600 meters at the maximum target range, and the target region will not be uniformly illuminated for all positions along the flight path. It will be necessary to increase the beamwidth by a factor on the order of 4 to 1; a beamwidth of 20 milliradians would have cross-section at a distance of 60 km of 1200 meters. This beamwidth will be adequate to illuminate the target region continuously and uniformly as the helicopter moves.

A focused array will be required. The far-field boundary as given by (7) is located approximately 12,000 kilometers away from the array [5].

$$\text{Far Field Boundary} \approx \frac{L^2}{\lambda} = 12 \times 10^6\text{m}$$

$$L = \text{array extent} = 600\text{m},\ \lambda = 3\text{ cm for X-band} \qquad (7)$$

Consequently the target region will be in the extreme near field. Also, the depth of field will not be great enough to achieve simultaneous focus on the target region and the corner reflector. The depth of field as given by (8) is approximately 525 meters at a distance of 30 km from the 600 meter array operating at a 3 centimeter wavelength [6].

$$\text{Depth of field} = 7\lambda\left(\frac{F_o}{L}\right)^2 = 525\text{m} \qquad (8)$$

F_o = 30 km, helicopter to beacon

L = 600m, array extent

λ = 3 cm wavelength

It will be necessary to refocus the array after beamforming by adding phase corrections to the data received at the sequential sampling points.

HELICOPTER MOTION

The next topic to be considered in this description of the high resolution imaging radar system is the effect of helicopter motion. Fortunately, the corner reflector provides a means of compensating for the phase change arising from radial motion of the helicopter, that is if the transmitted phase is compared with the phase return from the corner reflector, an indication of the pathlength between the helicopter and the corner reflector is obtained. Comparing this length on a pulse-to-pulse basis will permit generating a history of the motion of the helicopter in the radial direction with respect to the corner reflector. This measurement of pathlength change can be used to correct the measured phase of the returns from the target region. The phase shifts due to the helicopter's radial motion can be predicted if the rate of movement is not so large that the helicopter can move an ambiguous number of wavelengths during an interpulse period. If we assume a pulse rate of 1 KHz, then the motion of the helicopter must be such that it moves less than 1/2 of the assumed wavelength of 3 centimeters in the interpulse period of 1 millisecond. This corresponds to a maximum radial velocity on the order of 15 meters per second.

CONCLUSION

An adaptive SAR system has been described which may be used with a helicopter radar to provide high resolution imaging over a limited target region (e.g., approximately 300m on a side at 60 km). Array organization will be accomplished by adaptive beamforming on a corner reflector in the direction of the target region. Since the corner reflector is nearby relative to the target, refocusing after beamforming will be required. The array will be formed sequentially by moving the helicopter and sampling at random intervals. Random sampling is used to permit data reduction through array thinning while preventing grating sidelobes. Approximately 10^3 sample points will be recorded along a 600 meter flight path. These data will be used to construct an image by adaptive beamforming and then open loop scanning. Since the maximum scan angle will be about 5 mr, the element position uncertainty can be high, e.g., 20λ. This thin, random adaptive array offers several advantages over a conventional SAR approach. First, the amount of storage required for realistic processing rates is much lower, (at least 10:1) and the processing rates are within the capability of modern small computer technology. Secondly, the operation of a conventional SAR is much more sensitive to motion uncertainties of the platform, i.e., 100:1. These advantages arise because the ASAR array is highly thinned relative to a filled array (40:1), and the use of adaptive beamforming on a corner reflector permits greatly increased uncertainty in sampling point positions.

REFERENCES

[1] Bernard D. Steinberg, Principles of Aperture and Array System Design, John Wiley & Sons, New York, 1976, p. 42.

[2] Ibid., p. 142

[3] Robert O. Harger, Synthetic Aperture Radar Systems, Academic Press, New York, 1970, p. 20.

[4] Steinberg, Principles of Aperture and Array System Design, p. 249.

[5] Ibid., p. 12

[6] Ibid., p. 53