

## **DISTRIBUTED APERTURE RADAR USING SMALL SATELLITES**

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### **ABSTRACT**

Recent work on key technological problems of self-cohering and high speed processing has led to a concept for distributed space based radar. Experimentally demonstrated self-cohering techniques allows a cluster of small satellites to form a coherent aperture even though the position of each satellite in the cluster is not precisely known. The signal processing of the receive beams has been sized and the architecture of spaceborne VLSI processor outlined and shown to be practical in size, weight and power consumption. Clutter is reduced by the extremely narrow receive beams so that small targets can be detected and tracked. The goal is to achieve a low life cycle cost of this sensor system using light satellite technology.

## DISTRIBUTED APERTURE RADAR USING SMALL SATELLITES

Advances in work on self-cohering of antennas at Interspec has led to a concept of a distributed space radar using a cluster of identical small satellites working in concert. Very large apertures and very narrow beamwidths are possible. Small targets can be detected in clutter with such a system. It can view the earth's surface from space and downlink information to ground terminals.

The cluster size is flexible and growth to capability of detection of small cross-section targets is possible.

The signal processor load is distributed with a portion being accomplished on each satellite platform. Although some functions (eg. detection) increase with a larger cluster of N satellites others (eg. beamforming) go up less than proportionally so processing load actually decreases per satellite as the quantity of satellites per cluster increases.

Let's begin by comparing familiar aperture capabilities to that now becoming possible from this new distributed and large array radar technology.

Although Pave Paws (Fig. 1) and the FPS-85 Spacetrack (Fig. 2) phased array radars may be perceived as very large apertures, the table (Fig. 3) shows that in terms of wavelengths across the aperture they have beamwidths on the order of  $1^\circ$ . The technology of self-cohering permits the construction of very large arrays that result in angular resolutions at microwave frequencies that are better than the optical resolution of the human eye [1]. A program known as VFRC line array demonstrated a beamwidth of 0.02 degrees. With the aperture no longer dependent on mechanical tolerance for its coherence, a distributed space based radar can be designed with beamwidths on the order of  $0.003^\circ$ .

Figure 4 is an artist's rendition of the Munition Submunition Tracking System (MSTS) being developed for the US Army by INTERSPEC Incorporated [2]. The MSTS consists of an electronic scan range-only radar and a 100 meter linear array at Ku-band (5500 wavelengths long). It achieves a resolution of 1 meter in range and 1 meter in cross-range at a range of 5.5 km. This will be the first application of self-cohering in an operational radar.

Figure 5 shows an artist's conception of a space based distributed radar. The satellites orbit in clusters and weigh under 500 pounds each. Figure 6 shows estimates of the satellite weight and power budgets.

AN/FPS-115 PAVE PAWS SLBM  
DETECTION PHASED ARRAY RADAR

AN/FPS-85 SPACETRACK PHASED ARRAY RADAR

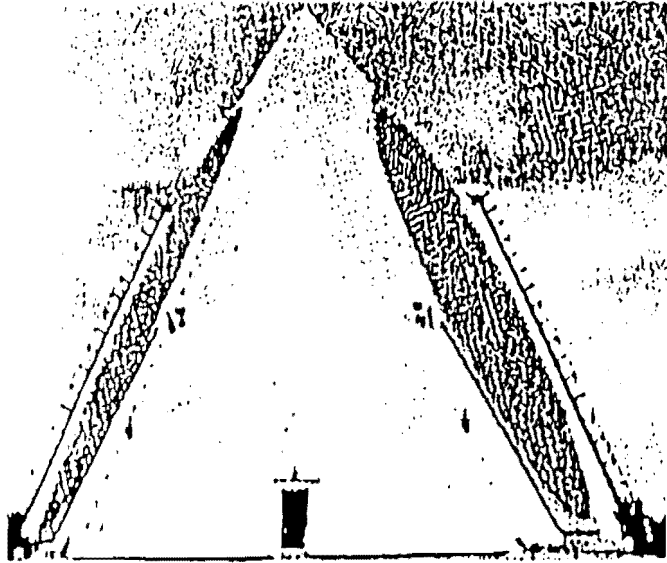


FIGURE 1

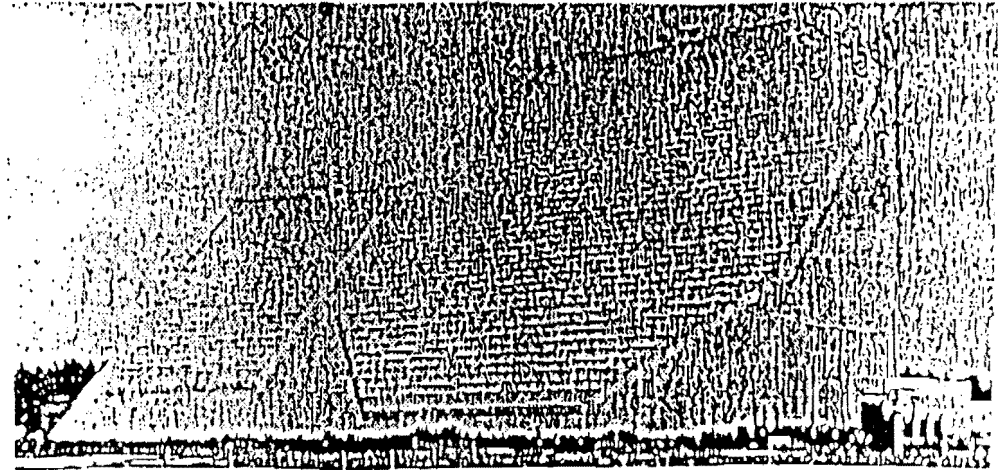


FIGURE 2

COMPARISON OF VARIOUS SYSTEM APERTURES

$$\Delta\theta \approx \frac{\lambda}{a} \begin{matrix} \text{radiation wavelength} \\ \text{aperture linear dimension} \end{matrix}$$

MSTS ARTIST CONCEPT

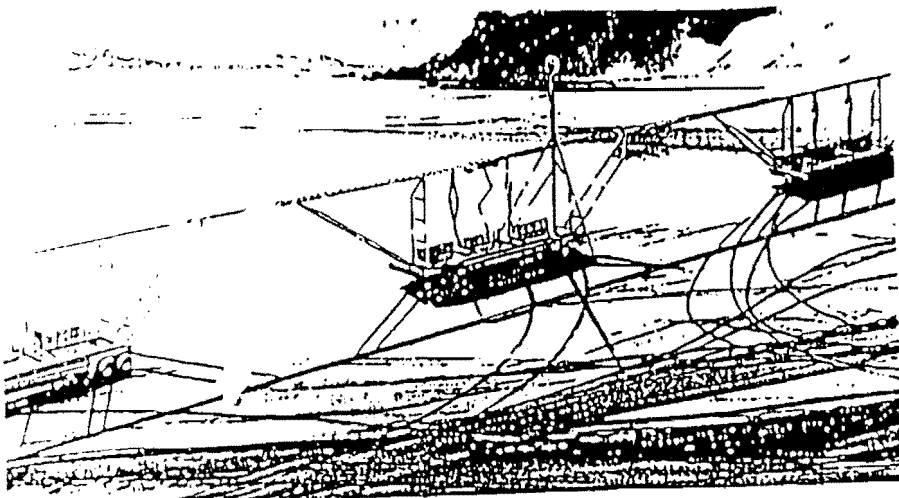
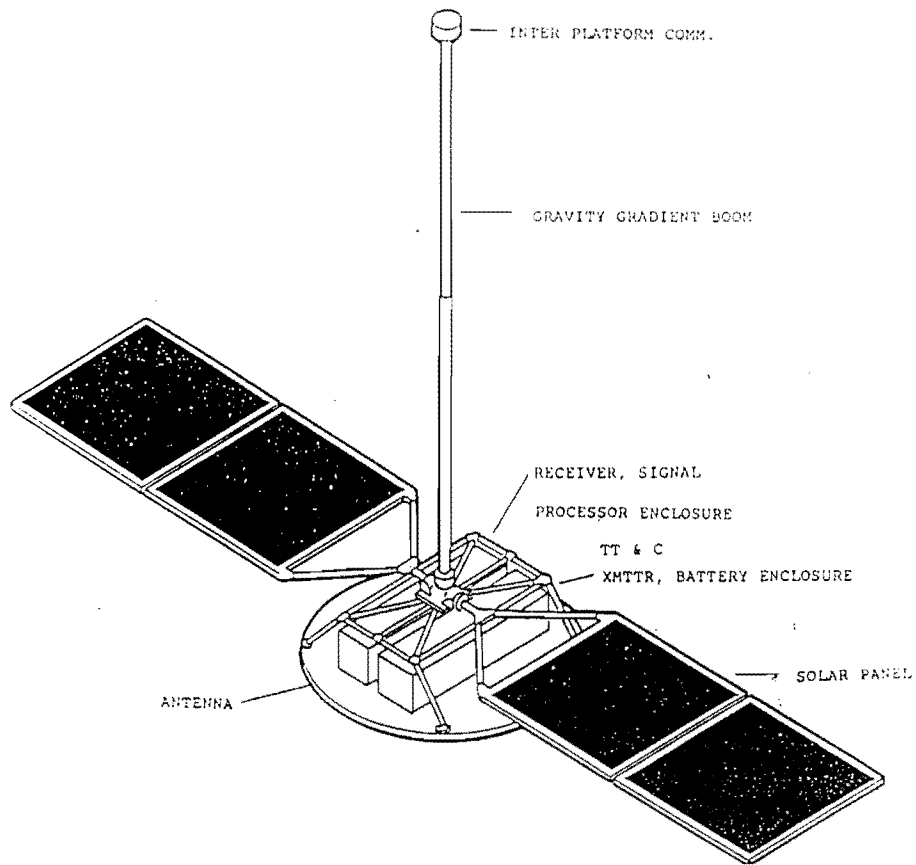


FIGURE 4

	$\lambda$	$a$		$\Delta\theta$
	METERS	METERS	$\lambda$	DEGREES
PAVE PAWS	0.70	31.1	44.4	1.29
SPACETRACK	0.64	58.0	85.3	0.67
HUMAN EYE	$5 \times 10^{-7}$	0.0011	2200	0.026
VFRC LINE ARRAY	0.050	83.0	2770	0.020
MSTS	0.018	100.0	5555	0.010
DISTRIBUTED SPACE BASED RADAR	0.30	5000.0	16700	0.003
HT. PALOMAR	$5 \times 10^{-6}$	5.08	$1.02 \times 10^7$	$5.64 \times 10^{-6}$



DAR SATELLITE ELEMENT

FIGURE 5

## POWER AND WEIGHT ASSESSMENTS

SUBSYSTEM	AVERAGE POWER (WATTS)	WEIGHT (LBS)
RADAR		
• TRANSMITTER/RF/ANTENNA	200 - 400	100 - 200
• PROCESSOR	50 - 100	10 - 20
COMMUNICATIONS	20 - 100	20 - 50
TELEMETRY, TRACKING AND CONTROL	10 - 50	10 - 50
THERMAL CONTROL	1 - 1	5 - 5
STRUCTURE		50 - 100
SOLAR PANELS (64 WATTS/LB)	1 - 1	8 - 18
BATTERIES (NICKEL HYDROGEN) 25 WATT HOURS/LB		20 - 45
<hr/>		
TOTALS	282 - 652	223 - 488

FIGURE 6

Both the mainbeam clutter amplitude at the radar and the mainbeam clutter spread are reduced because of the small patch of ground clutter in the narrow receive beam. Enhanced performance in clutter is important for any space based radar because as target size becomes smaller the limitation to target detection is dependent upon signal to clutter ratio, not signal to noise ratio [3].

The system derives its spatial coherence by developing a phase reference across the array based on clutter returns from the land and sea. These techniques have been demonstrated using airborne radar data [4]. The highly thinned array has multiple sidelobes which are handled by the system design and adaptive processing of the clutter returns.

As indicated, distribution of radar assets among many identical platforms that operate coherently permits the system to degrade gracefully over the life of the system and never suffer a critical failure that puts the system off the air completely. The system, in essence, can operate forever if any failed unit is replaced in orbit by a "low cost space transportation system". This leads to the most important reasons for pursuing distributed space based radar and small satellite systems in general: High Survivability and Low Life Cycle Cost. The potential for both arises from (1) identical small satellites permit learning curve and mass production economies. and (2) over the total life of the system the overall operating cost is lower since a failure of a single element does not cause system failure.

Although the signal processing load is very high, advances in digital technology has developed to make the processor practical. Each satellite has an identical processor and each processes part of the range and angle bins. Considerable cross tell data is shared with a broadband communications link between satellites, bridging the distance between satellites in the cluster. The short range, 1 to 10 km, makes a low power communications link practical.

Figure 7 shows DAR Advantages, Figure 8 the Key Enabling Technologies and Figure 9 the Technical Challenges.

Let's take just one of the technological challenges, self-cohering, and describe the need and the solution.

The need for self-cohering arises in that a large array can be physically distorted or may also have different electrical lengths in each array element prior to summing the individual element outputs. Self-cohering is a technique in which the array, based on signal returns from its environment, compensates for errors caused by array distortion or differences in array element electrical lengths. The technique, shown in Figure 10, also corrects for any other deterministic errors prior to beamforming. Therefore self-cohering also corrects for propagation anomalies. One technique for performing self-cohering is to have a very strong signal source present in the environment. This source could be a beacon, corner reflector, or large point target of opportunity. The strong signal is received at each of the array elements and is used as a synchronizing source that determines the element phase correction that electrically aligns the array. The array elements shown represent actual elements in a monolithic array, subarrays in a monolithic array, or individual platforms in a distributed sparse array. Once the phase corrections have been determined and applied the array functions as a well formed array system. Steering of the array beam from the cohered direction is done by applying a linear phase taper across the

SPACE BASED DISTRIBUTED APERTURE  
RADAR ADVANTAGES

- SURVIVABILITY
- IMPROVED CLUTTER PERFORMANCE
  - REDUCED AMPLITUDE (C/S)
  - REDUCED SPREAD (MDV)
- HIGH ANGULAR RESOLUTION
- ENHANCED ECCM
- GRACEFUL DEGRADATION
- REPLENISHABLE
- LOW LIFE CYCLE COST

FIGURE 7

KEY ENABLING TECHNOLOGIES

- SELF-COHERING ADAPTIVE BEAM FORMING
- POST-DOPPLER CLUTTER CANCELLATION
- ADAPTIVE NULLING OF ECM
- VLSI/VHSIC PARALLEL  
PROCESSING ARCHITECTURES
- MILLIMETER WAVE SATELLITE  
COMMUNICATIONS

FIGURE 8

## TECHNICAL CHALLENGES

- COHERENT OPERATION
  - SPATIAL
  - TEMPORAL
- CLUTTER REJECTION
  - MAINBEAM
  - SIDELOBES
- OPERATION IN ECM ENVIRONMENT
- DATA PROCESSING LOAD
- WIDE BAND INTER-SATELLITE COMMUNICATIONS

FIGURE 9

## SELF-COHERING ADAPTIVE BEAMFORMING

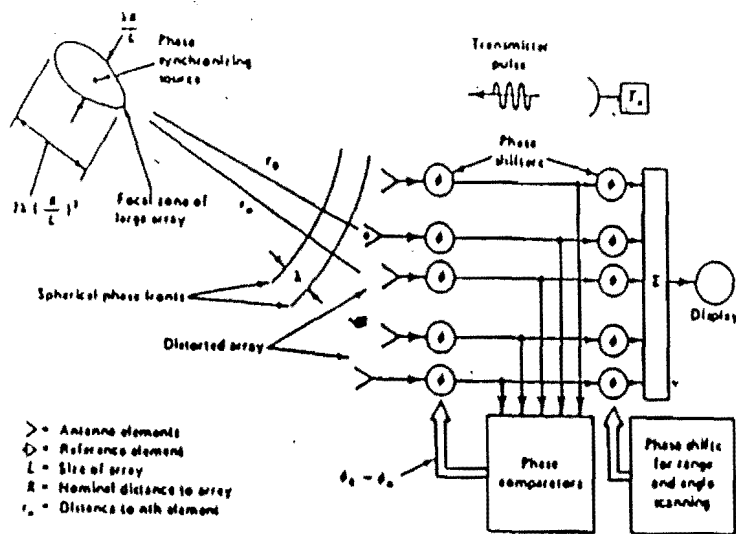


FIGURE 10



elements. Two sets of phase shifters are shown in Fig. 10. The first set for inserting the phase correction and the second set to steer the antenna beam. In most applications phase correction and beam steering are performed digitally and phase shifters are not required.

Figure 11 is experimental data from a 80 meter aperture radar. It is a picture the target area that results from phase scanning the 300 element receive array prior to inserting a phase correction at each element.

The region that is being examined by the radar is a series of row houses 6.5 km from the radar. Successful radar operation would result in 3 meter angular resolution of this scene by the 80 meter aperture operating at X-band. The arrow in the center of the photograph indicates an empty lot between two houses.

The data in Figure 11 is noise like, as expected, because there is no coherence achieved between the elements of the array due to uncontrolled uncertainty in element positions between the 300 element locations along the 80 meter array.

If, however, a pilot signal is transmitted to each array element and the proper phase correction is inserted at each element location, the result shown in Figure 12 is obtained. Microwave pictures of this scene were developed initially by placing a corner reflector in the field of view and using the return from the corner reflector to phase correct each element. The results obtained in Figure 11 were achieved by using a strong return from one of the row houses, i.e. a target of opportunity.

Figure 12 clearly shows the row houses, some single homes, and a series of row houses on a parallel street. Also note that a radar range resolution of 3 meters is being achieved by transmission of a signal with an instantaneous bandwidth of 60 Mhz. However, what is truly amazing is that the angular resolution of this radar system is 3 meters, 6.5 km from the radar site, comparable to the radar range resolution. This is the diffraction limited angular resolution that is expected from an 80 meter array operating at X-band and proves that this jelly-like line array, when self-cohered, obtains results equivalent to that of a fully rigid accurately surveyed line array. It is this technique that can be used to cohere a spaceborne distributed array radar system and results in full aperture coherent.

Figure 13 and 14 show the result of applying these self-cohering algorithms to large aperture and inverse synthetic aperture microwave images of aircraft of opportunity. In Figure 13, the 727 is 3.5 km from the radar site. The pixels represent 1 meter range by 1 meter cross range resolution.

Figure 14 is a radar image of Shorts 330 aircraft 5.5 km from the radar site. It represents a resolution of 1 meter in range by 1 meter in cross range. Note the detail that indicates the wings, tail, fuselage, and engine mounts.

The system concepts of using self-cohering to allow a cluster of small satellites to operate as a coherent large aperture space based radar shows great promise. Although a great deal remains to be done the advantages are large and the complex signal processing is now realizable due to the rapid progress in digital processing using VLSI. Small satellite technology in conjunction with the economics of mass production is the key to making this system concept affordable.

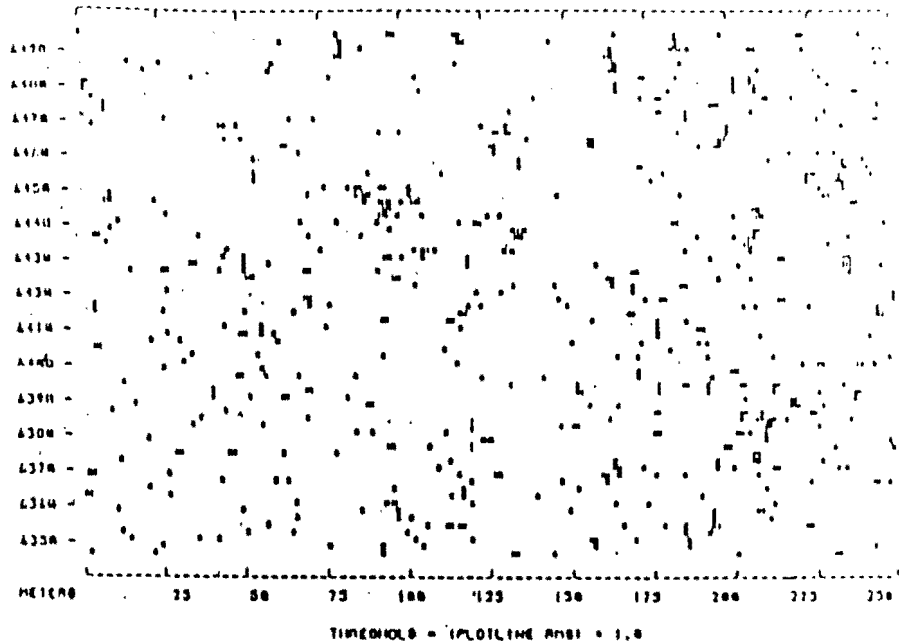


FIGURE 11

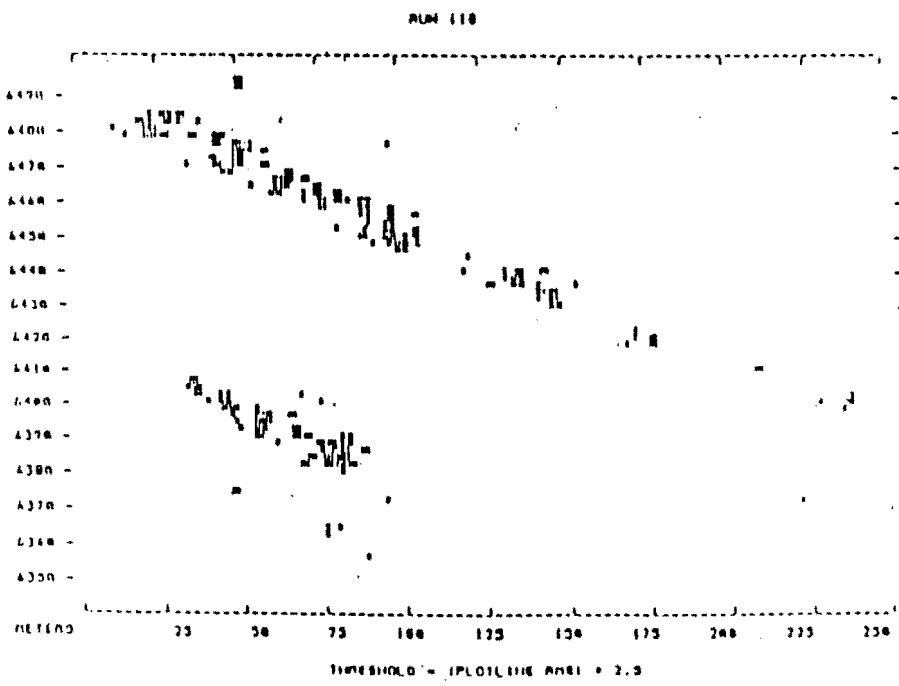


FIGURE 12

HIGH RESOLUTION ISAR RADAR IMAGE OF 727  
 (Courtesy of the University of Pennsylvania)

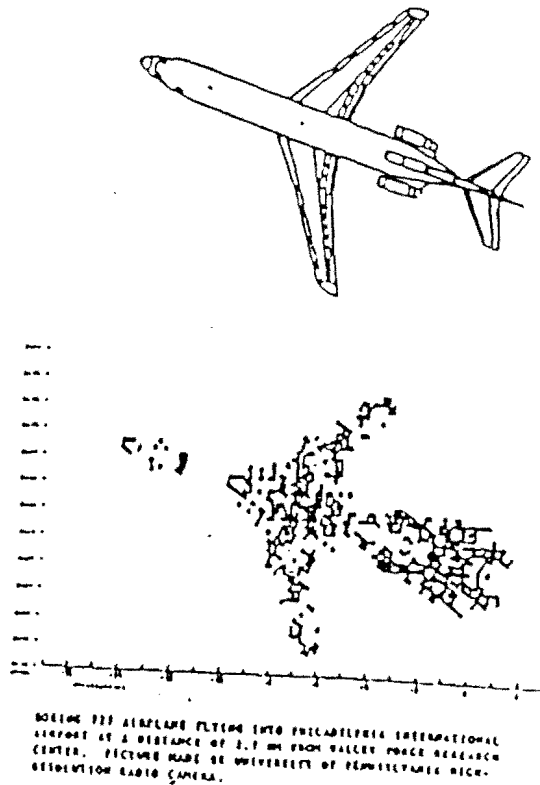


FIGURE 13

HIGH RESOLUTION ISAR RADAR IMAGE OF SHORTS 330  
 (Courtesy of the University of Pennsylvania)

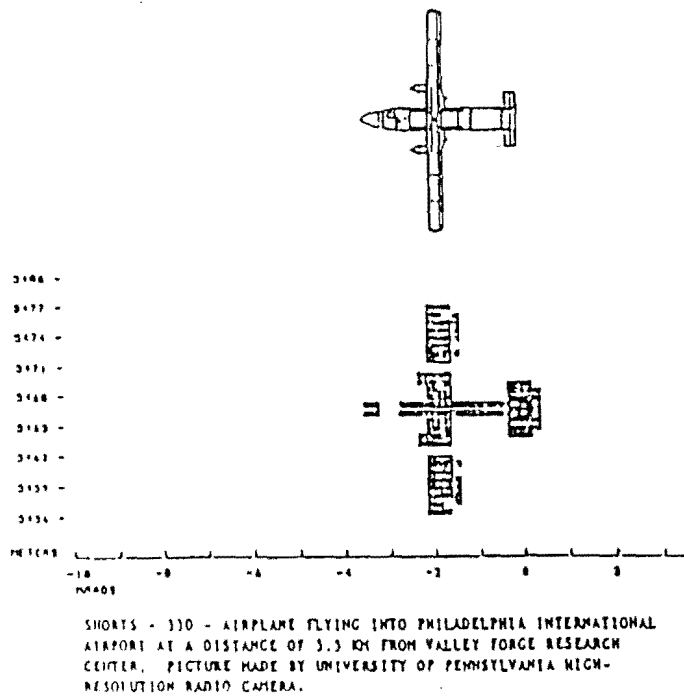


FIGURE 14

## SUMMARY

- HIGH potential PAYOFF FOR DISTRIBUTING SPACE BASED RADAR ASSETS
- KEY TECHNICAL CHALLENGES
  - COHERENT OPERATION
  - CLUTTER REJECTION
  - ECM REJECTION
  - PROCESSING LOAD
  - WIDE BANDWIDTH INTER-PLATFORM COMMUNICATION
- KEY TECHNOLOGIES HAVE BEEN IDENTIFIED
  - SELF-COHERING
  - ADAPTIVE CLUTTER CANCELLATION
  - ADAPTIVE JAMMER NULLING
  - DISTRIBUTED PROCESSING ARCHITECTURE

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- [4] ATTIA, E. H., SELF-COHERING AIRBORNE DISTRIBUTED ARRAY FINAL REPORT, USAF RADDC CONTRACT NUMBER F19628-84-C-0080, DECEMBER, 1985.