# SPACE-BASED TETHERED ARRAY RADAR (STAR) - A DISTRIBUTED SMALL SATELLITE NETWORK

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The Space-Based Tethered Array Radar (STAR) concept evolved from the DoD need for an affordable, launchable, survivable, and expandable Space-Based Radar for wide-area surveillance of airborne targets and for ballistic missile defense applications. Because low-observable threats can undermine conventional large monolithic Space-Based Radar satellite designs by forcing power-aperture products (inversely proportional to target radar cross-section) so high that the resulting heavy and expensive satellite could not be built or launched, innovative solutions are needed. One such solution is the use of a tether concept which derives strength and stability by tension rather than stiffness and bulk. The tether concept avoids rigid structures by embracing the premise of a Distributed Sparse Array Radar (DSAR) which coherently nets small satellite subarrays which are not physically interconnected. The STAR concept is a network of distributed small satellite subarrays each of which is a tethered set of elements or a "string". Each "string" is a vertical linear array orbiting independently and made up of dipole array elements each with its own transmit/receive module and power source. In order to operate as a Distributed Sparse Array Radar, the relative locations of individual small satellite subarrays must be known to small fractions of a wavelength. In this paper after a brief discussion of SBR architecture, selected methods for cohering the Sparse Array, and for signal distribution, and signal combination are presented. Finally, an example design of a space based DSAR using tethers is described along with a communication scenario.

## INTRODUCTION

The use of multiple tether antennas in space to achieve large apertures with low power requirements was one of the approaches submitted in December 1987 to Rome Air Development Center (RADC) in response to their Program Research Development Announcement (PRDA) number 88-1 PKRZ, entitled "Innovative Concepts For Space Based Radar." Decision-Science Applications Inc. as prime, with Fairchild Space Co., System Control Technology and other subcontractors jointly were awarded a contract to study such an approach. In this paper after a brief discussion of Space-Based Radar (SBR) architecture, selected approaches for each of three critical subsystems will be described. These are: sparse array coherence, transmitter signal distribution and receiver signal combination. Following that an example of a space based Distributed Sparse Array Radar (DSAR) using tethers will be described and the resulting communication interfaces will be presented. Then after some discussion a conclusion will be offered.

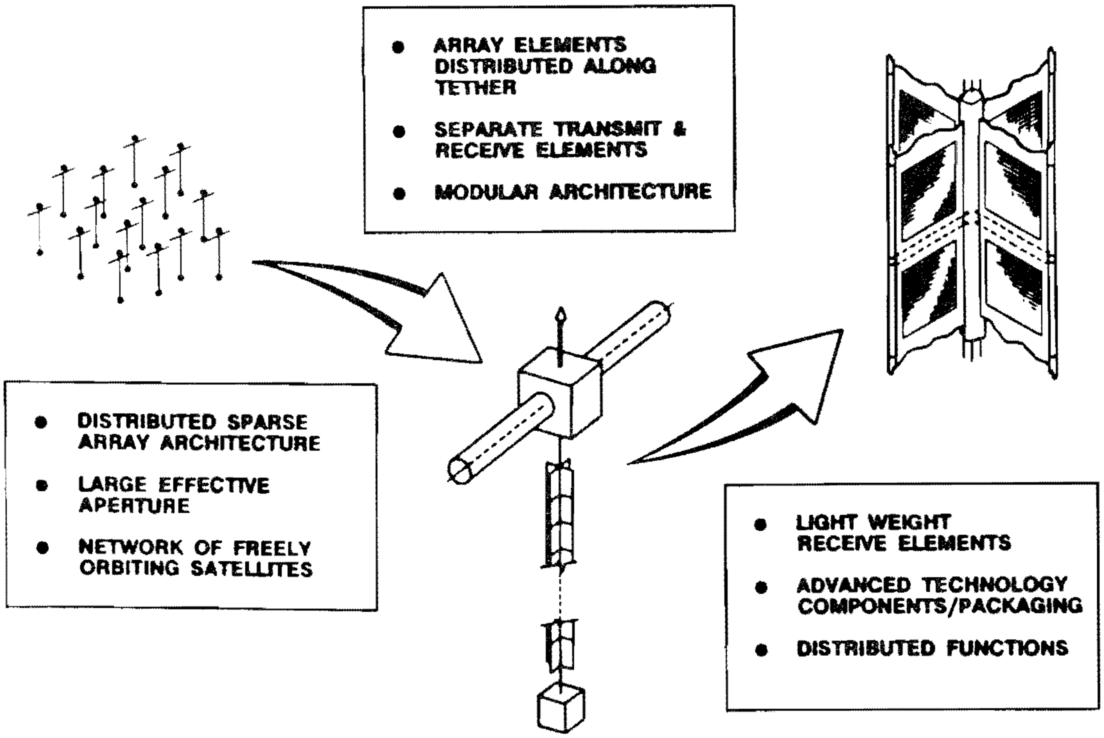
## TECHNICAL CONSIDERATIONS

The tether concept[1] for space-based radar is of interest because of (1) the applied economic value resulting from the engineering use of the earths gravity and the existing orbital centripetal force to form tension in the tether as a substitute for the otherwise required stiff and relatively heavy (and thus space delivery expensive) structural bulk, and (2) the nearly stable state of the same tether aligned vertically (radial to the earth's center) with the gravitational and centripetal forces. The latter avoids expensive and sometimes orbital lifetime limiting, attitude control systems. Since tethers are relatively cheap and lightweight, the long vertical length possible with tethers allow the synergistic achievement of large radar vertical apertures. Companion multiple tethers (other DSAR satellites) provide a horizontal dimension and multiply that vertical aperture which results in a greater "power-aperture product" for the same weight than the equivalent monolithic Space-Based Radar (SBR). See Figure 1. Next a distributed SBR sparse array system architecture will be explained.

### SBR System Architecture

First the host spacecraft will be presented and then the radar payload will be covered.

Once in orbit the tether deployment mechanism is used to deploy the tether which is the antenna array of the radar payload. In Figure 2 the host spacecraft functional block diagram is shown. Notice the integrated digital electronics in the center. This is the architectural key to the host spacecraft for the support of its radar payload. All of



- DISTRIBUTED SPARSE ARRAY ARCHITECTURE
- LARGE EFFECTIVE APERTURE
- NETWORK OF FREELY ORBITING SATELLITES

- ARRAY ELEMENTS DISTRIBUTED ALONG TETHER
- SEPARATE TRANSMIT & RECEIVE ELEMENTS
- MODULAR ARCHITECTURE

- LIGHT WEIGHT RECEIVE ELEMENTS
- ADVANCED TECHNOLOGY COMPONENTS/PACKAGING
- DISTRIBUTED FUNCTIONS

Figure 1. Space-Based Tethered Array Radar (STAR)

the host spacecraft functions are acted on by the integrated electronics. Time tagged position and attitude data are provided to the payload on board target processor, and the regulated power required, is controlled by the appropriate section of the integrated electronics. The fine timing for this and other events of the mission is provided from the precise payload clock. Commands to the radar payload from outside the spacecraft can go through the spacecraft receiver directly to the radar controller. The data from one tether array is first processed at its own spacecraft. The SBR is composed of multiple arrays, each with its supporting spacecraft. If the spacecraft is acting as the master controller of the whole SBR, then there is further processing of radar data (payload data out) sent from other arrays, via their spacecraft transmitters. In that condition the master "payload data out" is the consolidated results of the whole SBR. This contains the information that, for example, the fleet Commander can use.

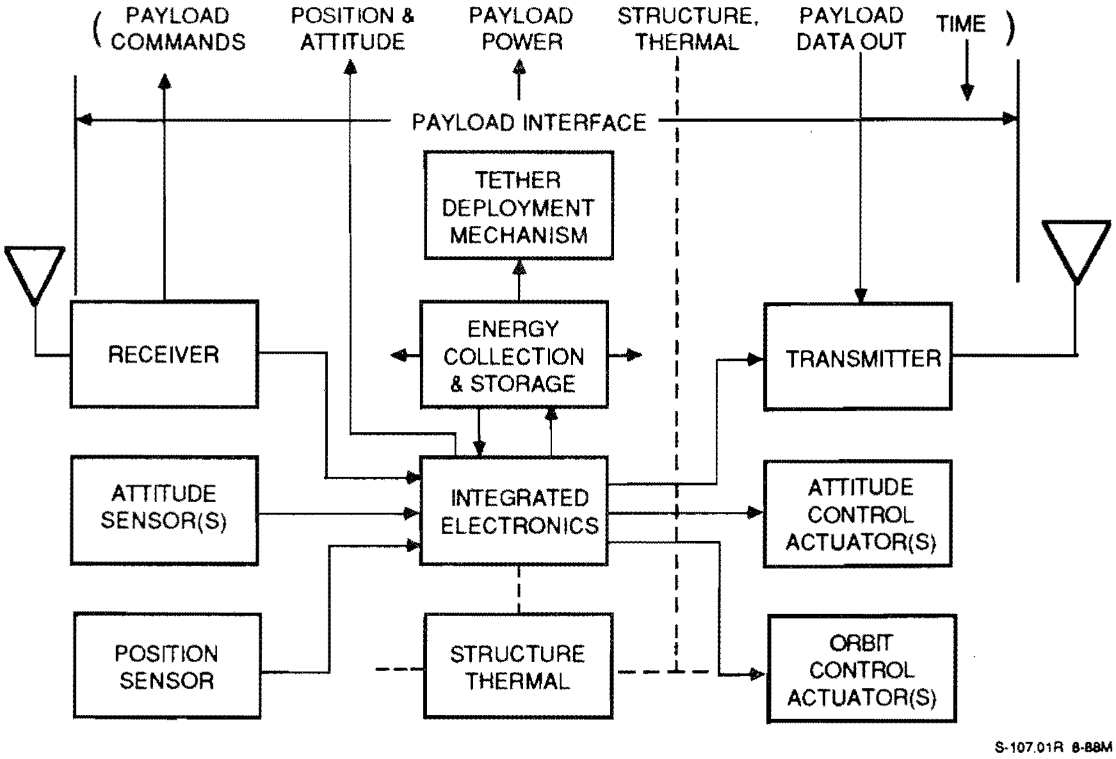
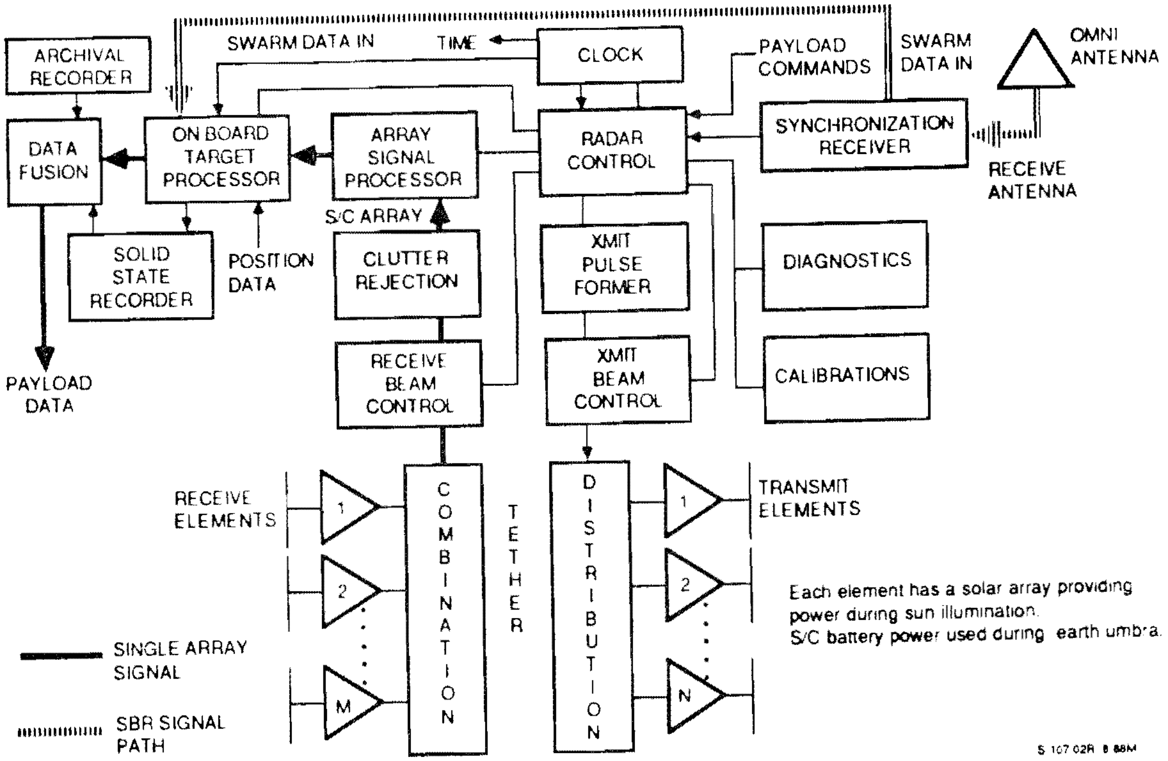


Figure 2. Host Spacecraft Functional Block Diagram Utilizing Integrated Digital Technology

The basic functional block diagram of the space based DSAR payload is shown in Figure 3. The "radar control" block will be used to start the examination of the payload's basic architecture. Consistent with a defined clock input, "radar control" initiates a transmit sequence via the "xmit pulse former". The transmit elements of the tether array are adjusted to form the desired taper and beam pointing, by the "xmit beam control". The "Distribution" network performs the task of getting the pulse to be transmitted to each transmit element with low distortion and relatively low attenuation. At the transmit element, the transmit pulse is amplified in the element's RF amplifier and radiated towards its target area by its dipole antennas. When the reflected return pulse arrives back at the receive elements' antennas it is amplified by the receiver's low noise amplifier (LNA) and sent to the "combination" network or combiner for further processing.



Each element has a solar array providing power during sun illumination.
S/C battery power used during earth umbra.

Figure 3. Distributed Sparse Array Radar Payload-Basic Functional Block Diagram

Next "clutter rejection" by the appropriate processing occurs and then the output consists primarily of the undetected signal (and noise) of <u>one</u> tether called the "spacecraft array" input to the "array signal processor" as shown in Figure 3. After array signal processing the output goes to the "On Board Target Processor". If the spacecraft was not acting as the SBR master controller of the SBR then the processed array signal is simply identified as to which array it is from, and time tagged by the "on-board target processor". However if the spacecraft is acting as the SBR master controller, then the other array inputs of the swarm or (cluster), some of which may be already stored in the "solid state recorder", would be appropriately correlated in mission time sequence. Now in the correct sequence, the aggregate signal of the whole SBR would be detected and processed as a whole for targets by the "on-board target processor". Then in "data fusion" the targets are related to relatively stable or repeatable information (such as geographic locations) retrieved from storage in the slower archival recorder, and to more dynamic information retrieved from the "solid state recorder". After this stage the SBR target data is ready to be transmitted as "payload data" to users or to ground stations, direct or via relay, for further processing and assimilation. Next a more detailed view of four critical subsystems will be presented, starting with the coherence of the sparse array.

## Coherence of the Sparse Array

In the sparse array radar considered, the received pulses will be collected by a number of strings (tethers) constituting a SBR cluster of size m x n. This is an array structure where m = number of parallel tethers and n = number of receiving dipoles in each tether. Each pulse or subset of pulses received by each dipole or the subarray of dipoles in each tether will differ in phase and amplitude. The received pulses or subset of pulses have to be combined together to optimize the signal to noise ratio (S/N) from each tether. Again m tethers outputs have to be combined for optimal decision.

Let us assume each elemental receive dipole generates 1 volt of receive signal thus the total receive signal of a tether if summed arithmetically will generate n volts. Whereas, n added noise samples, each having unit standard deviation before addition, have a standard deviation (fluctuation of voltage) equal to $\sqrt{n}$. Therefore signal-to-noise voltage ratio from each tether is $n/\sqrt{n} = \sqrt{n}$. Consequently, the signal-to-noise power ratio, S/N = n. Similarly, m parallel tethers output signal-to-noise power ratio will be mn.

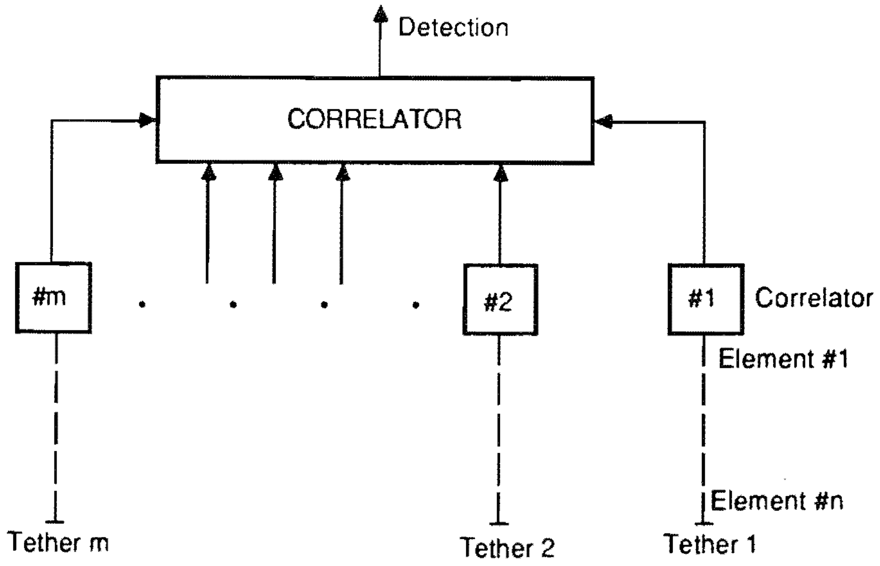


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Figure 4. Basic Concept of m x n Signal Integration

The above calculations assume that all the receive signal components superimpose on each other with equal phases. Since the receiving elements in each tether and m tethers are spatially distributed and furthermore the tethers are in motion, the phase of the receive signals are basically random in nature. The summation or integration of pulses or subset of pulses is a specific form of the more general process: cross correlation. It can be accomplished by utilizing a storage device, such as a delay line, so that the signals received at a particular instant can be added to signals received earlier (phase advanced). The basic concept of the integration of m x n signal components is illustrated in Figure 4.

Mathematically, the waveform of the composite receive pulse from m parallel tethers can be written as,

$$S(t)=R_e\left[\sum_m \sqrt{2E_R}\cdot e^{j\omega_o t}(1+\beta m)B_m e^{j\psi_m(t)}\cdot\sum_n (1+\alpha_n)A_n e^{j\theta_n(t)}\cdot\phi(t-n\tau)\right] \quad (1)$$

where $n$ = number of the subpulses collected by the elements in a single tether

$R_e$ = the real part of the signal

$E_R$ = receive energy of the pulse from a single tether

$\omega_o$ = carrier angular frequency

$A_n$ = ideal weight of nth subpulse

$\tau$ = interpulse spacing

$\phi(t)$ = subpulse wave shape

$\alpha_n$ = amplitude error of nth subpulse

$\theta_n(t)$ = phase difference of nth subpulse due to spatial separation

$\beta_m$ = amplitude error of mth pulse

$B_m$ = ideal weight for mth pulse

$\psi_m(t)$ = phase difference of mth pulse due to spatial separation

Summation of n subpulses constitute a pulse.

For superposition and coherent integration of all subpulses from n receiving elements in a tether and m pulses from m parallel tethers, $\theta_n(t)$ and $\psi_n(t)$ have to be corrected for superposition.

An implementation concept of superposition and coherent integration scheme for pulse doppler radar is illustrated in Figure 5.

considered and the fiber optic compounded to handle the radiation without significant discoloration. Careful attention must be devoted to non-natural radiation effects also. Two of the most vexing problems are phase dispersion, which uses up the system phase error budget, and the determination and selection of a small, light, solid-state laser with low electrical power requirements.

The SBR application at UHF could involve an array of up to 15,000 receiving antenna elements uniformly spaced at approximately 1-ft intervals along a tether some 3 mi in length. The prime goal is to send the transmit signal with little distortion to thousands of distributed RF amplifiers via a fiber optic cable in the tether. Several different architectures can be envisioned to accomplish this task.

The most straightforward fiber optic architecture would consist of independent point-to-point links as shown in Figure 6. This approach requires placing an optical receiver at each antenna element. The distributed light from the transmitted laser in the radar payload is coupled into a dedicated fiber which leads to a dedicated optical receiver in the RF transmitter module located in the tether. At that optical receiver, the light signals are converted back to the electrical domain for RF amplification and transmission. However in this approach the fiber optic bundle is of considerable size and weight.

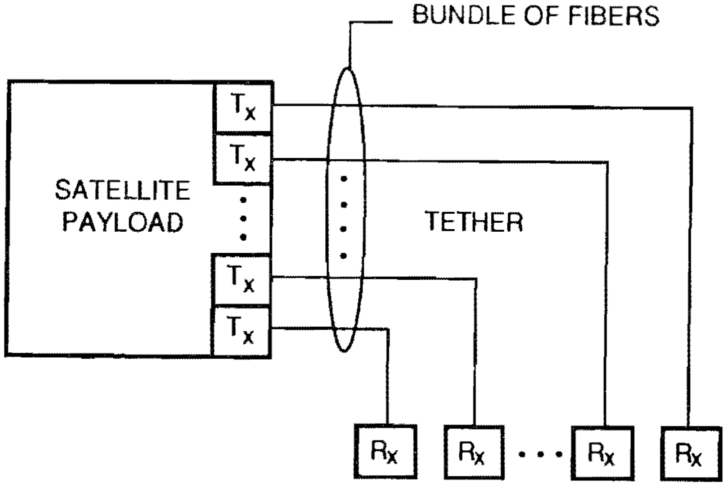

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**Figure 6. Point-to-Point Fiber Optic Distribution Approach**

A second option for implementing a fiber optic feed system would utilize fiber optic couplers or taps so that the signals for numerous antenna elements could be transmitted simultaneously on a single fiber. This approach is shown in Figure 7. This option can drastically reduce the number of individual fibers which would be required by allowing several receivers to share the same transmission fiber. In effect this creates a subarray. With this approach, great care must be exercised to adjust the length of the short "pigtail" fiber between the laser transmitter and the fiber optic tap to insure that the proper phase relationships are maintained among the various antenna elements. Note that with this option, each antenna element no longer has a dedicated transmission path to the satellite payload. Because of the fiber optic tap loses, the entire array can not be distributed on only one fiber. So appropriate subarrays are formed to match the fiber optics capabilities. Each transmit distribution subarray has its own single fiber optic input. Other fiber optic distribution approaches involve the optical equivalent of multiplexing and other schemes that are conceptually available but lightweight reliable space qualified hardware for these approaches may not be actually available in the time frame of interest.

### Receiver Signal Combination

The challenge here is to perform the opposite functional task of the distribution system just presented--specifically to combine, with very low loss and distortion, the signals received at thousands of receive elements into one composite signal for processing in the "array signal processor". Similar design alternatives also exist. In general the reader can go back to the preceding section and substitute "$R_X$" (receiver) for "$T_X$" (transmitter) and vice versa in the past two figures and get some perspective of the task. In the interest of compactness for this paper, the above exercise will be left for the reader. For example, if fiber optics were in use, at each of the thousands of RF receivers, there would be output into a "combination" network via a local fiber optic transmitter "$T_X$" and the eventual output of that combined signal would go into the "array signal processor". Next an example system will be presented.

## EXAMPLE DISTRIBUTED SPARSE ARRAY

### Space Based Radar Using Tethers

The tether acts as a one dimensional phased array radar which can scan in a single dimension - in this case the vertical direction - the radiation pattern of a dipole is, $E = \cos(\pi/2 \cos \theta)/\sin \theta$, and hence the intensity of radiation is bidirectional, i.e., $E^2$ is maximum at $\theta = \pm \pi/2$ (perpendicular to equatorial axis). The directional ambiguity can be resolved by placing a parallel passive element at $\lambda/4$ separation from the tether containing active elements.

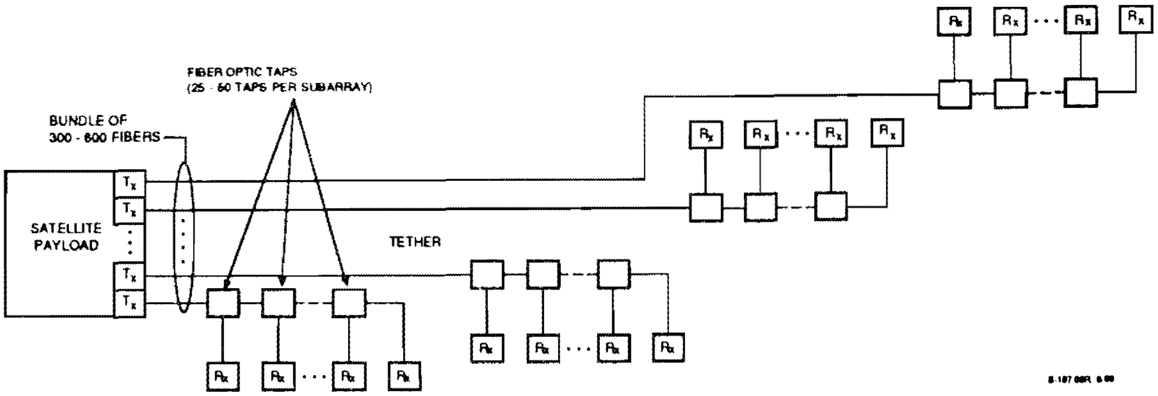
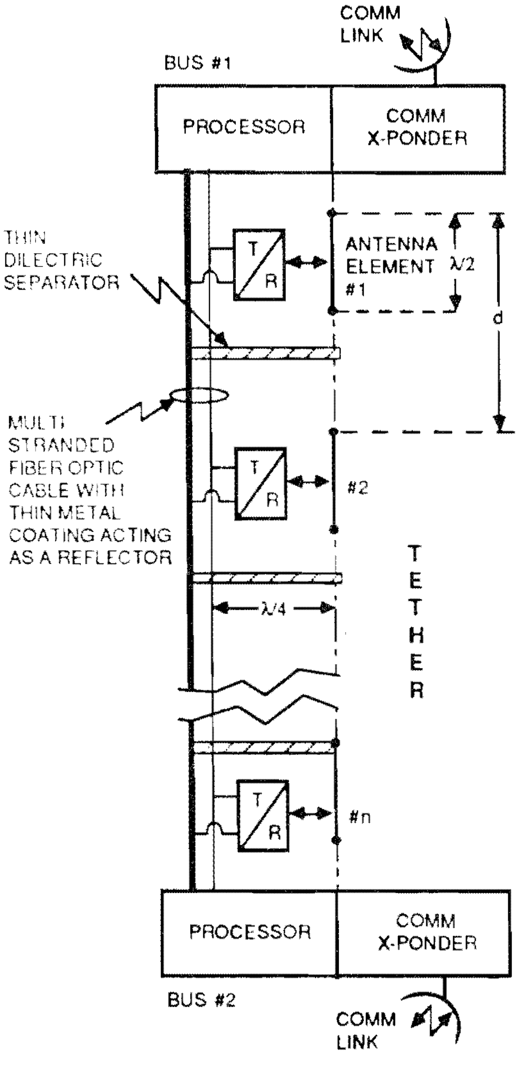


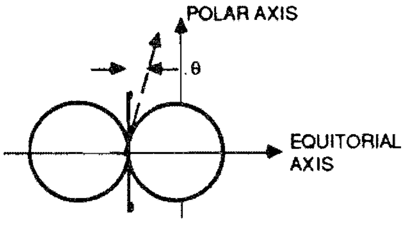
Figure 7. Tapped-Fiber Optic Distribution Approach

Now if we launch a large number of these tethered antennas, each on a pair of gravity gradient satellites orbiting in east-west direction and the outputs from each tether array are summed together coherently thus forming a (m x n) elements beam in north-south direction; m represents the number of parallel tethers, and n represents the number of active elements in each tether. Coherent addition of m inputs and appropriate phasing of m outputs can be controlled by computer to generate a scan beam in the horizontal direction (scanned perpendicular to polar axis) resulting in two dimensional scanning.

From the above discussion, we can conceive a single-tethered antenna array of dipoles as shown in Figure 8(a), where an equally spaced linear array of n collinear dipoles is assumed; each element is approximately half wavelength ($\lambda/2$) long and the distance between two successive elements is d. Each element has its own Transmit/Receive (T/R) module. The T/R waveforms, which are fed to and from the active elements via a pair of multi-stranded fiber optic cable, are computer controlled. Parallel processing in both satellites is assumed for reliability and faster acquisition, if needed. The fiber optic cable sheath is assumed to be coated by a thin layer of metallic paint. If this metallic painted cable sheath is placed ($\lambda/4$) apart from the radiating tether, then this sheath will act as a reflecting screen thus producing a unidirectional beam eliminating directional ambiguity. Light weight nonmetallic separators can be provided at appropriate distances to keep the ($\lambda/4$) separation. In addition, these separators can also be used as damping elements to suppress mechanical oscillations of the elongated tether fixed between the top and bottom spacecraft.

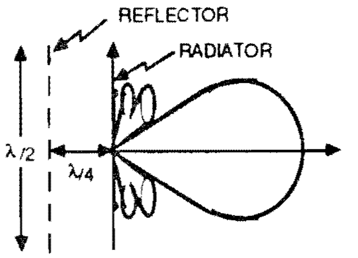


(a) **Single Tethered Antenna Array Configuration**

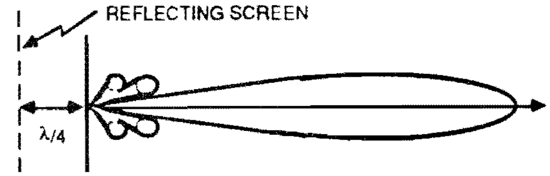


$$E = \frac{\cos(\pi/2 \cos\theta)}{\sin\theta}$$

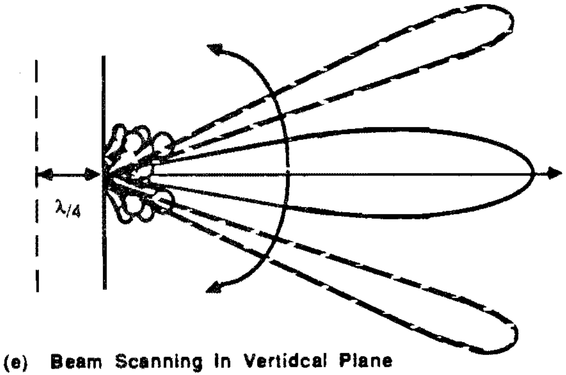
(b) **Bidirectional Radiation Pattern of a Single Element**



(c) **Unidirectional Pattern with Reflector**



(d) **n - element Array Pattern**



(e) **Beam Scanning In Vertidcal Plane by Element Phase Variation**

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**Figure 8. Example SBR**

Bidirectional radiation pattern of a single dipole is illustrated in Figure 8(b), the unidirection pattern with a reflector is illustrated in Figure 8(c). The unidirectional n-element pattern is illustrated in Figure 8(d). Beam scanning in the vertical plane by individual element phase variation is illustrated in Figure 8(e).

## Communications Scenario

A four-tether cluster scheme is examined as an example. In this example each satellite is composed of two spacecrafts (one at each end of the tether). We assume each spacecraft will have a processor on-board, ground based master control center will have a main frame computer and distributed ground based tracking stations will have some processing capability. For security the master control center function will perhaps be duplicated. A T/R processing concept is illustrated in Figure 9, buses (1,1′), (2,2′), (3,3′) and (4,4′) constitute a cluster. Each spacecraft is provided with its own processor, T/R command generator and processed data handling capability. Bus processors (1,2,3,4) assume the cluster controlling function in a sequential order.

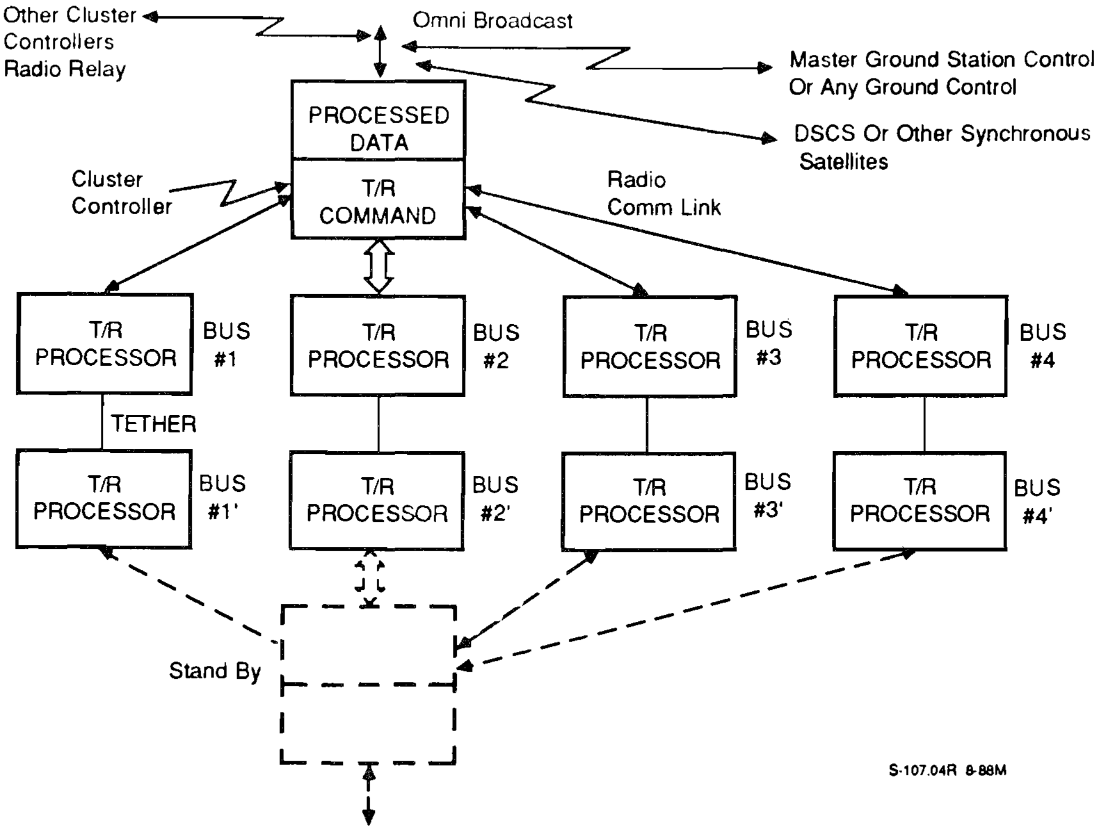

Figure 9. T/R Processing Concept in a Cluster

At the same time bus processors (1′, 2′, 3′, 4′) remain in a standby role thus increasing system reliability. Direct radio communications links between cluster processors exchange T/R command data.

Processed data are sent by Omni directional broadcast to all other cluster controllers for relaying purposes to nearest ground tracking terminal or to the master control terminal. Each cluster controller also attempts to send its own broadcast data directly to its nearest ground tracking terminal or to the master control center via direct radio links or geosynchonous satellites. This scheme essentially makes it a more secure system. Broadcast data from cluster controllers, and ground tracking terminals are transmitted via an RA/TDMA (Random Access/Time Division Multiplex Access) channel using packet switching protocol. The master control center communicates with cluster controllers via a TDM broadcast channel with multiplexed data packets addressed to different controllers and ground tracking terminals via satellite relay. The communications architecture concept is illustrated in Figure 10.

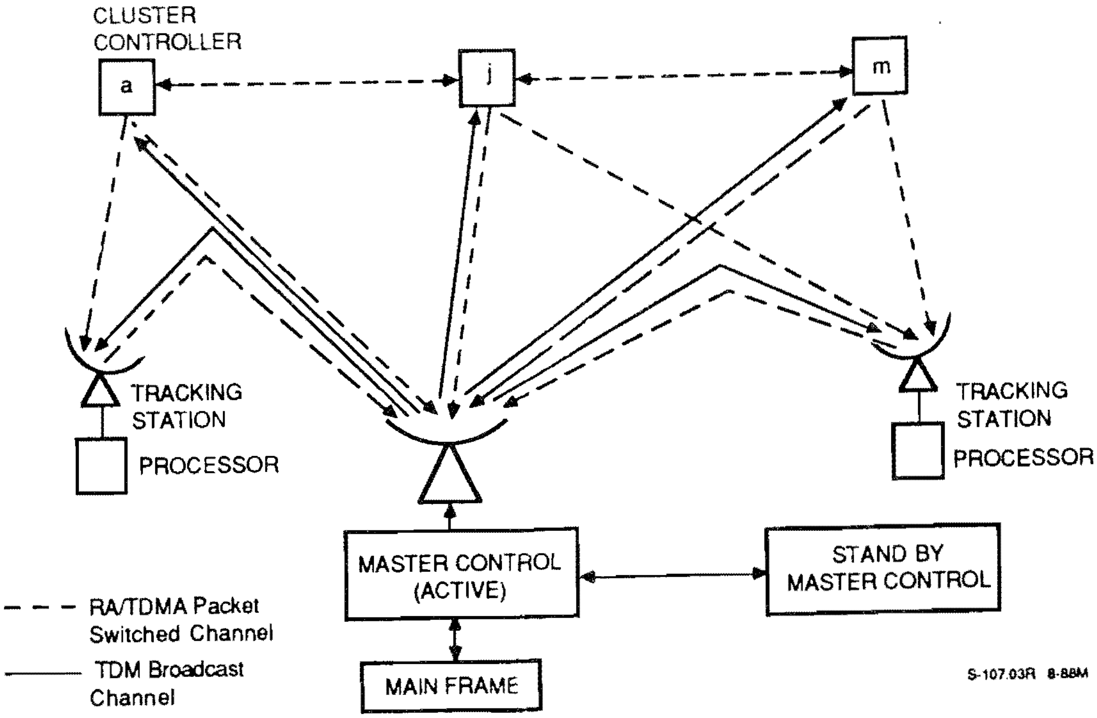

Figure 10. Communication Architecture Concept

## DISCUSSION

In such an innovative approach as the space based DSAR, there is a substantial R&D challenge to arrive at a fully qualified design. Such variables as radar clutter, precise longitudinal tether location, and control, which have been only mentioned in the context of this paper, must be satisfactorily handled in that design. There are also many other substantive design trade-offs required to reach such an integrated solution. And of course, there are some genuine technical application challenges. One of the most obvious trades is the availability, weight and reliability aspects of having two essentially identical spacecrafts -- one at each end of the tether to form the satellite (as shown in the example SBR). Also striking the appropriate balance in inter-array signal communication for a whole SBR requires diligent attention. Materials research for reliable flexible tether components for cold deployment of the array and for repeated orbital temperature cycling) ranging from about -80°C to +80°C every 90 minutes or so is not a trivial exercise. However since the DSAR approach offers the potential of detecting and tracking small objects more economically, or put another way; the potential of significant 'low observable target' performance to cost ratio improvement, over conventional large monolithic Space-Based Radar satellites, it is worth carefully examining the innovative concept.

## CONCLUSION

This paper, after a brief discussion of SBR architecture, presented selected methods for cohering the Sparse Array, and for signal distribution, and signal combination; and it described an example SBR using tethers, and a communication scenario. These initial concepts bring up a number of issues that need to be resolved during the upcoming contractual study phase. These issues are i) practical feasibility of a space based DSAR, ii) survivability, iii) clutter control, and iv) cost effectiveness.

## ACKNOWLEDGEMENT

The authors wish to credit the late Dr. Harry Davis for his innovative and wide ranging but intensive contributions to space based DSAR. His counsel will be sorely missed.

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