A RAND NOTE

PACSAT: A PASSIVE COMMUNICATION SATELLITE FOR SURVIVABLE COMMAND AND CONTROL

Edward Bedrosian

November 1981

N-1780-ARPA

Prepared For The Defense Advanced Research Projects Agency

Rand
SANTA MONICA, CA. 90406

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PREFACE

This Note documents a briefing presented at the WWMCCS Post-Attack Symposium on 24 June 1981 at The MITRE Corporation, McLean, Virginia. The symposium was sponsored by the WWMCCS Systems Engineer, Defense Communications Agency.

The passive communication satellite system described in the briefing--a gravity-gradient-stabilized array of small beads--has promise for use in an emergency communication network as an inexpensive, survivable alternative, or adjunct, to active communication satellites. The immediate application in the discussion, for purposes of illustration, is to the command and control of the MX system. The Note should be of interest to the strategic planning community and to designers of space communication systems.

The PACSAT research reported herein is sponsored by the Strategic Technology Office, Defense Advanced Research Projects Agency, under the supervision of Dr. Sherman Karp. It is an element of a broad range of strategic communication studies being conducted for DARPA by Rand.

SUMMARY

The hostile environment that can be anticipated in the SIOP (Single Integrated Operational Plan) post-attack period poses an extreme threat to the communication systems available for the command and control of MX. Because of the vulnerability of active comsats in a space war, attention has recently been redirected toward passive repeaters. Inexpensive, survivable, and jam resistant, they offer an attractive low-data-rate alternative to conventional comsats.

PACSAT is a proliferable candidate for the MEECN (Minimum Essential Emergency Communication Network) role. It consists of a long (about 1 km), gravity-gradient-stabilized array of small beads (about 1 cm in diameter) that scatters a narrow, conical, frequency steerable beam back to the earth. The properties of PACSAT are presented and its performance in a representative system for the command and control of MX is evaluated.

The effects of near-field operation and array flexure are discussed and a tradeoff between array length and allowable flexure is evolved. Stability in orbit and the possible use of supporting structures are also considered.

For convenience, the analysis assumes that the MX system is based somewhere in the Western Continental United States. Neither the specific basing that may ultimately be selected nor the geographical region chosen for the deployment of MX has a significant impact on the associated command and control communication problem. In fact, PACSAT would be useful in a variety of point-to-point applications in which survivability is essential and a low data rate is acceptable.

CONTENTS

I. INTRODUCTION

The command and control of strategic forces often requires survivable point-to-point communication at low to moderate data rates over distances up to a few thousand miles. The proposed MX system, for which survivability is a paramount issue, is the most recent example of a strategic weapon system with such a communication requirement. The passive communication satellite concept described in this Note is analyzed in the MX application to illustrate its use graphically. However, its broader utility in similar applications should be borne in mind.

The proposed MX system must be capable of performing effectively in the hostile environment that can be anticipated in the trans- and post-attack SIOP (Single Integrated Operational Plan) periods. As suggested in Chart 1, the associated command and control requirements--to provide reliable, long-range, two-way communication to MX under adverse circumstances--pose a formidable challenge.

THE COMMUNICATION PROBLEM

- Effective command and control of MX requires reliable, long-range, two-way communication
- The stressed configuration:
  - NCA in NEACP orbiting near Washington, D.C.
  - MX LCC airborne or in MGCC in Western CONUS
- Data-rate requirement:
  - One 1000-bit message in 10 sec → 100 bps
  - 100 1000-bit messages in 100 sec → 1 kbps
- Threats:
  - Physical attack
  - Jamming
  - Trapped radiation
  - Propagation disturbances

Chart 1

Under conditions of maximum stress, the National Command Authorities (NCA), orbiting in the National Emergency Airborne Command Post (NEACP) in the vicinity of Washington, D.C., need to be in communication with the MX Launch Control Center (LCC), which is airborne or in a Mobile Ground Command Center (MGCC), taken here to be somewhere in the Western Continental United States (CONUS). It is intended that the MX LCC serve as a gateway into the MX system; a survivable intrasite communication system would then link the LCC with the individual MX missiles.

Command and control of MX does not require large data rates. The problem is one of sending one or more short messages in a relatively short period of time; for example, one 1000-bit message in 10 sec (a data rate of 100 bps). Similarly, 100 such messages can be transmitted in 100 sec at a data rate of 1 kbps. Such data rates are consistent with those of other strategic data transmission systems and will be used below to provide examples of typical link parameters. Extrapolations to other data rates are easily made.

The environment in which the command and control communication system must be capable of operating includes virtually every known threat or countermeasure. Among these are: physical attack by conventional or nuclear warheads and by radiation weapons; jamming, largely from terrestrial sources; trapped radiation (irradiation by energetic electrons trapped in the earth's magnetic field); and propagation disturbances in the earth's atmosphere induced by nuclear explosions. The latter includes dust clouds in the troposphere from terrestrial explosions and ionospheric disturbances caused by high-altitude explosions.

The Minimum Essential Emergency Communication Network (MEECN), which is the component of the National Communication System (NCS) currently used for the command and control of the U.S. strategic forces, relies on redundancy for survivability. As indicated on Chart 2, the terrestrial backbone of the MEECN is an extensive system of landlines, including buried cable and microwave radio relay. These are overlaid by a number of radio systems that operate over a broad range of frequencies. For example: VLF (Very Low Frequency) is used to communicate to submerged submarines; HF (High Frequency) skywave is used to communicate with aircraft when they are beyond line of sight (LOS); UHF (Ultra-High Frequency) is used to provide line-of-sight communication for air-to-air and air-to-ground applications as well as for space relay; and SHF (Super-High Frequency) is used for satellite relay.

THE CURRENT SYSTEM

- The MEECN features redundancy:
  - Landlines
  - VLF
  - HF skywave
  - UHF LOS (PACCS and ERCS)
  - UHF AFSATCOM
  - SHF DSCS
- Data rate: Adequate — 75 bps min
- Vulnerabilities:
  - Physical attack — All elements vulnerable
  - Trapped radiation — Comsats vulnerable in space war
  - Jamming — UHF comsat uplinks vulnerable
  - Propagation disturbances —
    HF skywave vulnerable to blackout
    UHF comsat links vulnerable to blackout and scintillation

Chart 2

The Post Attack Command and Control System (PACCS), which is a system of airborne relays, the Emergency Rocket Communication System (ERCS), which provides taped relay of messages from transmitters in high-altitude ballistic trajectories, and the Air Force Satellite Communication System (AFSATCOM), which is a system of satellite-borne repeaters, are examples of systems using UHF. The Defense Satellite Communication System (DSCS) consists of a number of geostationary relay satellites that operate at SHF.

The current MEECN system offers a considerable range of communication capabilities extending from teletype through analog or digital voice to high-speed computer and video. Thus, it is adequate to support the MX command and control needs under normal conditions. The issue of concern, particularly with respect to MX, is the ability of the MEECN to perform reliably under conditions of extreme stress.

All elements of the MEECN, whether terrestrial, airborne, or in space, are vulnerable to physical attack. However, protective measures are available and have been employed. Some fixed terrestrial terminals are hardened, whereas airborne and mobile terrestrial terminals are either hidden or otherwise made difficult to target. Satellites, however, are difficult to protect because of their exposed locations and their sensitivity to radiation damage. Despite protective shielding, they remain vulnerable to radiation effects from nuclear explosions. Damage in the near term (days or weeks) to solar panels by trapped radiation is also a problem. Efforts to disguise or conceal satellites are largely ineffectual except at very high orbital altitudes.

Within the CONUS, geographical and technical considerations favor the MEECN communication links, making them difficult to jam (only the UHF uplinks to comsats from aircraft are vulnerable). However, propagation disturbances can affect communications. High-altitude nuclear explosions over the CONUS can induce widespread and persistent disturbances in the ionosphere thereby disrupting or interfering with communication links that must traverse it. Long-range HF skywave propagation may become erratic or be blacked out. Comsat links at UHF may also be blacked out, though not so extensively or for so long. Comsat links may also scintillate (or fade), causing errors and delays; the effect may be experienced even at SHF, though less intensely.

For the most part, the MEECN, because of its redundancy and protected or rugged design, can be expected to perform some or much of its intended function except under the most stressing conditions. Unfortunately, its least survivable elements may be the communication satellites whose roles are becoming central and on which dependence is growing. Passive satellites, which have few of the vulnerabilities to damage displayed by active satellites, operating at SHF or higher frequencies to minimize propagation disturbances, may be valuable additions to the MEECN.

II. PASSIVE COMMUNICATION SATELLITES

As the name suggests, a passive satellite is one that acts passively in relaying the signal it receives; that is, it simply reflects the incident signal. An active satellite, on the other hand, receives the signal, processes it to some extent, then amplifies and relays it. The processing may consist of as little as translating the signal from an uplink to a downlink frequency band. However, modern sophisticated active satellites often demodulate, decode, combine, and otherwise modify the uplink signals.

The greater signaling capability and flexibility offered by active satellites was recognized long before satellite communications were established. Yet, it is interesting to note that passive satellites were serious contenders at first because of doubt about the technical feasibility of active satellites. Historical activity in satellite communications is shown in Chart 3, which shows not only that the first system, in 1954, used a passive satellite relay (albeit

ACTIVE AND PASSIVE COMSATS

AN HISTORICAL PERSPECTIVE

	Passive	Active
1954	Moon (used operationally)	—
1958		Score (tape delay)
1960	Echo 1 (100 ft. balloon)	Courier (first active)
1962	—	Telstar (medium altitude, inclined)
1962	—	Relay (medium altitude, inclined)
1963	Westford ($\lambda/2$ dipole belt)	Syncom (first geostationary)
1964	Echo 2 (140 ft. balloon)	—
1965	—	LES (medium altitude, inclined)
1965	—	Early Bird (geostationary)
1965	—	Molniya (12 hr. inclined, elliptical orbit
1966	OVI 8 (30 ft. wire mesh sphere)	IDCSP (near synchronous)
1966	—	ATS (geostationary)
1967	—	Intelsat (geostationary)

Chart 3

a natural rather than an artificial one) but that the system was actually used operationally. Although the first artificial satellite, Score, orbited at low altitude in 1958, was active, it used a tape-delay rather than a real-time mode of operation (this is also known as store-and-forward). Echo 1, a 100-ft diameter balloon, launched in 1960, was the first artificial passive satellite; it was soon followed by Courier, the first active real-time satellite. Both were successful, but the 1962 successes with Telstar and Relay, both of which were in inclined orbits at medium orbital altitudes, did much to confirm that active satellites were indeed feasible.

The Westford experiment in 1963 demonstrated the feasibility of the novel concept of using a large orbiting cloud of half-wave dipoles (much like the "chaff" used to confuse radars) for passive communication relay. Though successful, it was opposed on environmental grounds. However, it was followed in the same year by Syncom, the first geostationary satellite, which assured the dominance of active repeaters. Thus, the 1964 launch of Echo 2, a 140-ft diameter balloon, had little impact on the future course of satellite development. Except for the OV1 8 launch of a 30-ft diameter wire-mesh sphere in 1966, no more experiments have been conducted on passive satellites.

Nonetheless, the properties of passive satellites are worth reviewing in light of todays needs. Their advantages of lower cost,* ruggedness, jam resistance, and simplicity listed on Chart 4 are as real today as they were 20 years ago. It is true that the increased complexity of modern active satellites has had the desirable side-effect of reducing the cost of the numerous associated terrestrial terminals, often leading to lower overall system costs. However, the increased cost and capability of these more complex satellites has reduced the number used, thereby reducing their survivability by offering a small number of high-value targets. The ability to proliferate

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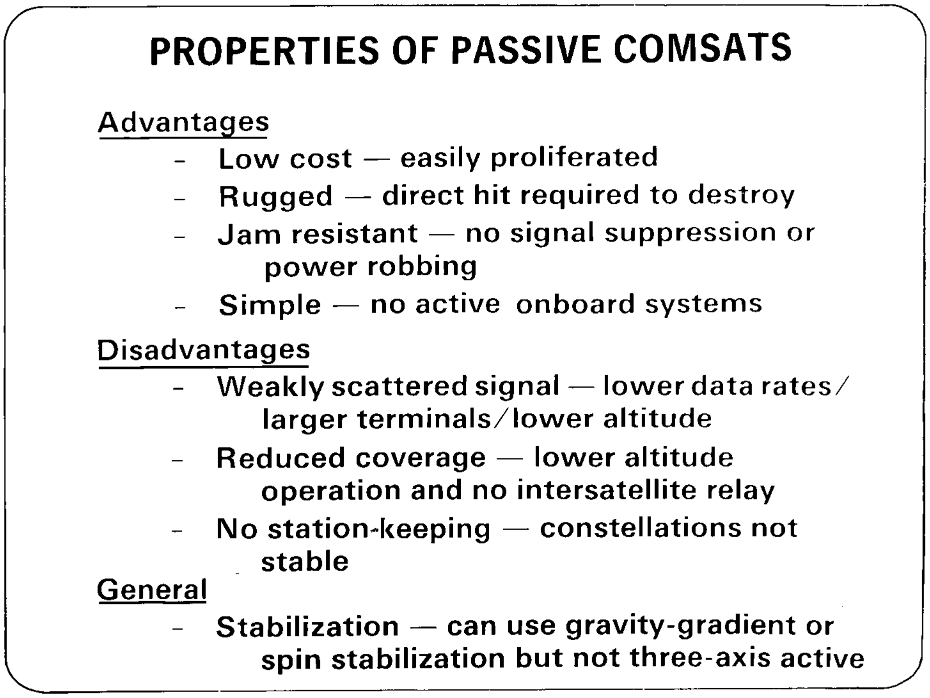
*The advantage of lower cost must be taken in context. If physical survivability and jam resistance were not a consideration, an active satellite having the same communication capability might not differ significantly in cost from a passive satellite. It is when all of these characteristics are required that the cost advantage of a passive satellite becomes apparent.

passive satellites at moderate cost is, if anything, more valuable today than it was in the past.



PROPERTIES OF PASSIVE COMSATS

Advantages
- Low cost — easily proliferated
- Rugged — direct hit required to destroy
- Jam resistant — no signal suppression or power robbing
- Simple — no active onboard systems

Disadvantages
- Weakly scattered signal — lower data rates/ larger terminals/lower altitude
- Reduced coverage — lower altitude operation and no intersatellite relay
- No station-keeping — constellations not stable

General
- Stabilization — can use gravity-gradient or spin stabilization but not three-axis active

Chart 4

The ruggedness of passive satellites is due, of course, to the absence of sensitive, solid-state electronic components. Only physical damage caused by high levels of radiated energy or by collision with bomb fragments or debris will destroy a passive satellite.

The jam resistance of passive satellites derives from their inherent linearity. The output power of an active satellite, on the other hand, is a fixed quantity. If a simple repeater is used, an in-band jammer, even though not co-channel, causes a reallocation of the output power between itself and the desired signal in proportion to their relative strengths. The resultant "power robbing" can substantially decrease the desired signal strength. If an amplitude-limiting repeater is used, as is often the case, a jammer may cause a further signal suppression of up to 6 dB, depending on the character of the jamming signal. These effects, which are not present in passive repeaters, can be defeated or ameliorated only by the use of complex signal-processing techniques.

The absence of electronic circuitry or moving parts allows passive satellites to be relatively simple. Thus, the benefits of reliability and long life can be added to those of low cost and ruggedness.

As might be expected, passive satellites have their disadvantages as well. Foremost among these is the relatively weak signal returned to the earth. The up- and downlinks formed by an active satellite repeater are essentially an independent tandem pair. The satellite-borne receiver and its antenna complete the uplink, while the transmitter and its antenna establish the downlink. Each link has its own inverse-square spreading loss and its associated signal-to-noise ratio. A passive satellite, on the other hand, forms a single link analogous to that formed by a bistatic radar. The passive satellite acts as the target, its scattering cross section and the cascaded inverse-square spreading losses serving to establish the signal intensity at the terrestrial receiver. As a result, the signal received from a passive satellite is generally considerably weaker than that available from an active satellite. This, in turn, necessitates the use of lower data rates, larger receiving and transmitting terminals, and lower satellite altitudes. Further, the use of lower altitudes and the inability to form intersatellite relay links between passive satellites reduce the coverage area on the earth that can be served. Also, the lack of a station-keeping capability precludes the use of regular constellations of passive satellites. Thus, a larger number of satellites is needed to provide reliable coverage; fortunately, such a requirement is consistent with using proliferation for survivability.

Because a passive satellite would preferably not use active subsystems, stabilization, if required, would have to be achieved passively by using either gravity-gradient or spin stabilization. Passive three-axis stabilization is possible using gravity-gradient with magnetic dampers that can align a second axis along the earth's magnetic field.

The technological advantages of active satellites are even greater today than they were 20 years ago. Improved repeater design and booster capabilities offer communication capacities that are far greater than those provided by early active satellites. Thus, although costs have risen, modern active satellites continue to increase in efficiency and effectiveness.

However, as noted on Chart 5, the anticipated SIOP environment has become increasingly severe during this same period. The qualities of simplicity and ruggedness offered by passive satellites are now more compatible with the harsh SIOP environment than are those of active satellites.

PASSIVE COMSATS TODAY

The technological advantages of active satellites are even greater today than they were 20 years ago

But

The SIOP environment is one in which the simplicity and ruggedness of passive comsats may now be preferable

Also

Newly conceived coherent arrays offer large scattering cross sections and can form directive, frequency-steerable beams from structures of moderate size

PACSAT is a promising design of this type

Chart 5

Further, new concepts for passive satellites incorporating coherent scattering from arrays offer dramatic increases in scattering cross section and, hence, in communication capability. These arrays form directive, frequency steerable beams that provide signaling flexibility and jam resistance. The PACSAT array considered here is a promising design of this type.

The basic PACSAT concept was advanced by Yater in 1972 and studied for DARPA by SRI, which performed theoretical and systems analyses and made measurements of a balloon-borne array.* The results reported herein are based on these references and on subsequent analyses of military applications of PACSAT for DARPA by Rand.

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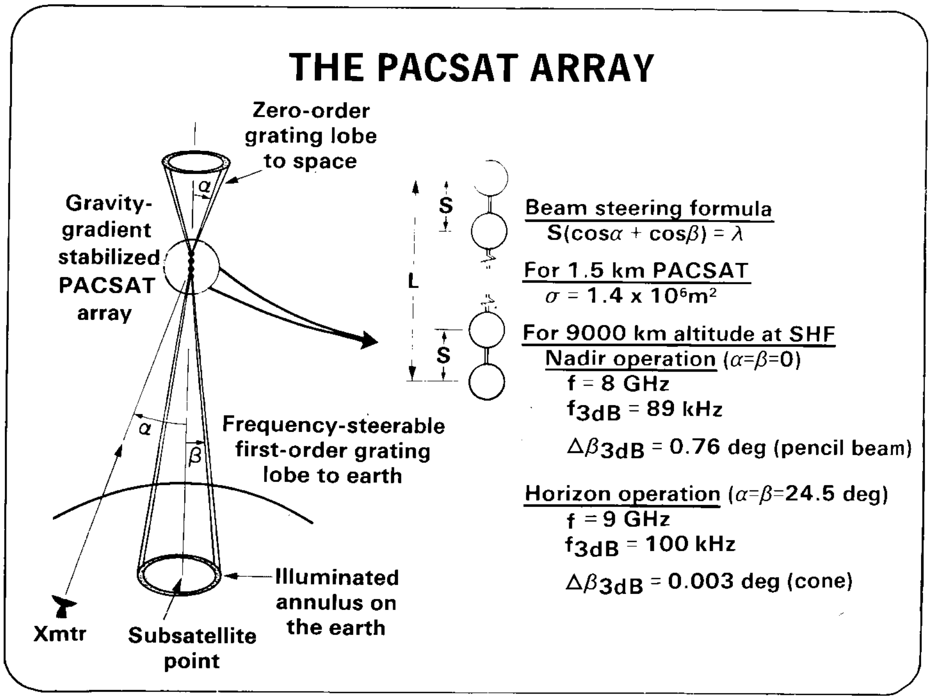
*J. C. Yater, "Signal Relay Systems Using Large Space Arrays," *Trans IEEE*, v. COM-20, n. 6, pp. 1108-1121, December 1972; and W. A. Edson et al., *Passive Space Communication Array (PACSAT)*, Stanford Research Institute, October 1976.

III. THE PACSAT ARRAY

The PACSAT design is illustrated on Chart 6. It consists of a linear array of scatterers that form a one-dimensional diffraction grating. The simplest embodiment, referred to as the unsupported PACSAT, would use gravity-gradient stabilization to make the array straight and erect, i.e., with its axis pointed toward the center of the earth.



Beam steering formula
$S(\cos\alpha + \cos\beta) = \lambda$

For 1.5 km PACSAT
$\sigma = 1.4 \times 10^6 m^2$

For 9000 km altitude at SHF
Nadir operation ($\alpha = \beta = 0$)
$f = 8$ GHz
$f_{3dB} = 89$ kHz
$\Delta\beta_{3dB} = 0.76$ deg (pencil beam)

Horizon operation ($\alpha = \beta = 24.5$ deg)
$f = 9$ GHz
$f_{3dB} = 100$ kHz
$\Delta\beta_{3dB} = 0.003$ deg (cone)

Chart 6

When illuminated from the earth at an angle, α, with respect to its axis, the individual elements of the array scatter energy in all directions. Grating lobes, in the form of cones, appear at half-angles, β, at which the scattered energy adds coherently. At these angles the path lengths via adjacent scatterers differ by integral numbers of wavelengths. Thus,

$$S(\cos \alpha + \cos \beta) = k\lambda \qquad (1)$$

where S is the element spacing, λ is the wavelength, and k is the order of the grating lobe. It can be seen that for $k = 0$, $\beta = \pi - \alpha$ so the zero-order grating lobe is scattered out to space with a cone half-angle equal to that of the illumination. For $k = 1$, the first-order grating lobe can be directed back toward the earth at any desired angle, β, by choosing the wavelength, λ, such that

$$S(\cos \alpha + \cos \beta) = \lambda \qquad (2)$$

This is the beam-steering formula that governs the formation of practical communication links between points on the earth. It should be noted that the back-scattered first-order grating lobe illuminates an annulus on the earth. For practical values of α and β, the element spacing can be chosen such that only the zero- and first-order grating lobes will appear.

Ideally, the array elements would be resonant, to intercept as much of the incident energy as possible, and retrodirective to concentrate the scattered energy in the direction of the desired first-order grating lobe. Dipoles, rings, spheres, etc., can be used to achieve resonance but directional scattering is difficult to attain with simple scatterers. Resonant spheres, i.e., spheres with circumferences slightly larger than one wavelength, are considered here. For such array elements, the scattering is nearly isotropic and the array scattering cross section is given approximately by

$$\sigma = 0.6\ L^2 \qquad (3)$$

where L is the array length. A 1.5 km PACSAT, which might weigh about 100 kg, would therefore have a scattering cross section of about $1.4 \times 10^6\ m^2$.

Inasmuch as the scattered beam is frequency steerable, it has an inherent bandwidth in the sense that the array amounts to a spatial filter. One measure of this bandwidth is the frequency difference between the 3 dB points; that is, the frequency change required, for a given desired direction, β, to steer the beam center from one 3 dB point through the peak of the main lobe to the other 3 dB point. The 3 dB bandwidth is a slowly varying function of α and β.

The other beam measure is the wall thickness of the cone, in degrees, between the 3 dB points. When $\beta = 0$, the cone degenerates [redacted] into a retrodirective pencil beam. As β increases, the cone opens and, because the scattering cross section is only weakly dependent on α and β, the total solid angle subtended by the walls of the cone is nearly constant. As a result, the cone wall thickness varies principally as csc β with a weak inverse dependence on α.

To illustrate, consider a 1.5 km PACSAT array operating at SHF at an orbital altitude of 9000 km. Let the retrodirective frequency be chosen as 8 GHz. Then, a transmitter and receiver at or near the satellite nadir would use an operating frequency of about 8 GHz and the first-order grating lobe would be in the form of a pencil beam having a 3 dB bandwidth of 89 kHz and a 3 dB beamwidth of 0.76 deg. If the transmitter and receiver were both at the horizon, the operating frequency would have to be increased to 9 GHz and the beam would be in the form of a cone having a 3 dB bandwidth of 100 kHz and a 3 dB beamwidth or wall thickness of only 0.003 deg. The precision in frequency control required to form and maintain a link via PACSAT is apparent.

The significance of scattering cross section can be seen from Chart 7. As illustrated on the previous chart, PACSAT produces a first-order grating lobe that illuminates an annulus on the earth. By definition, the scattering cross section of the array is the physical cross section of a perfectly conducting sphere that, for a given illumination, produces the same intensity in this annulus. The difference, of course, is that such a sphere scatters isotropically and therefore produces the same intensity in all directions. Thus, as shown on Chart 7, the scattering cross section of the 1.5 km PACSAT is equal to that of a sphere *1.3 km in diameter*. By contrast, the scattering cross section of the 140-ft diameter Echo 2 balloon was only 1430 m^2. The 30 dB difference between that value and the

1.4 x 10^6 m^2 scattering cross section of the 1.5 km PACSAT provides the added signal strength that makes modern coherent passive arrays practical.

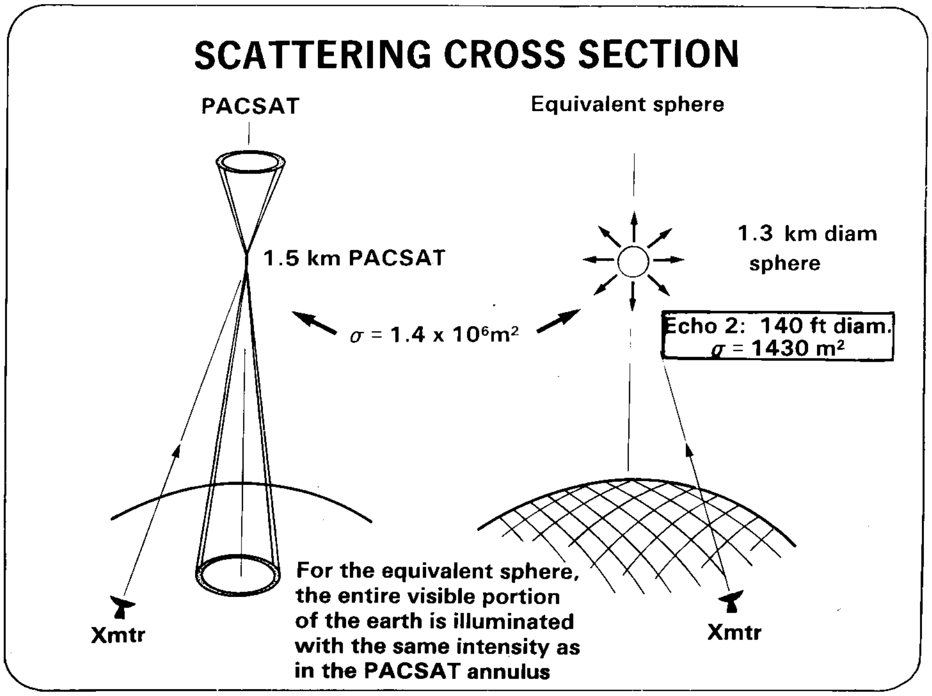


Chart 7

The 1 GHz frequency difference between the extremes of frequency required to operate an erect PACSAT array orbiting at 9000 km altitude, as indicated on Chart 6, is typical of the frequency steering range that must be provided if all possible transmitter-PACSAT-receiver geometries are to be accommodated. Such frequency steering ranges are impractical not only because suitable frequency allocations are not available but also because of the difficulties in acquiring, steering, and tracking the signal (in frequency). Thus, inclined orbits, which can result in a wide range of satellite transit geometries, should be avoided. A further constraint is that gravity-gradient stabilization, which is required to keep the array erect, is feasible only in circular orbits.

The circular equatorial orbit illustrated on Chart 8 offers an excellent choice, provided polar coverage is not required. For any pair of points within the coverage area, every satellite makes the same transit across the sky thereby facilitating antenna pointing and tracking. Moreover, for terminal locations within the United States, the angles α and β vary in such a way during a PACSAT array transit that the sum of their cosines does not change much. The consequence, as seen from Eq. (2), is that the beam steering frequency also does not change much. For example, the 12.5 percent tuning range (i.e., from 8 to 9 GHz) to cover all the possible geometries for the 9000 km altitude array shown in Chart 7 would be reduced to only about 1.1 percent for an erect PACSAT array in a circular equatorial orbit at the same altitude.*

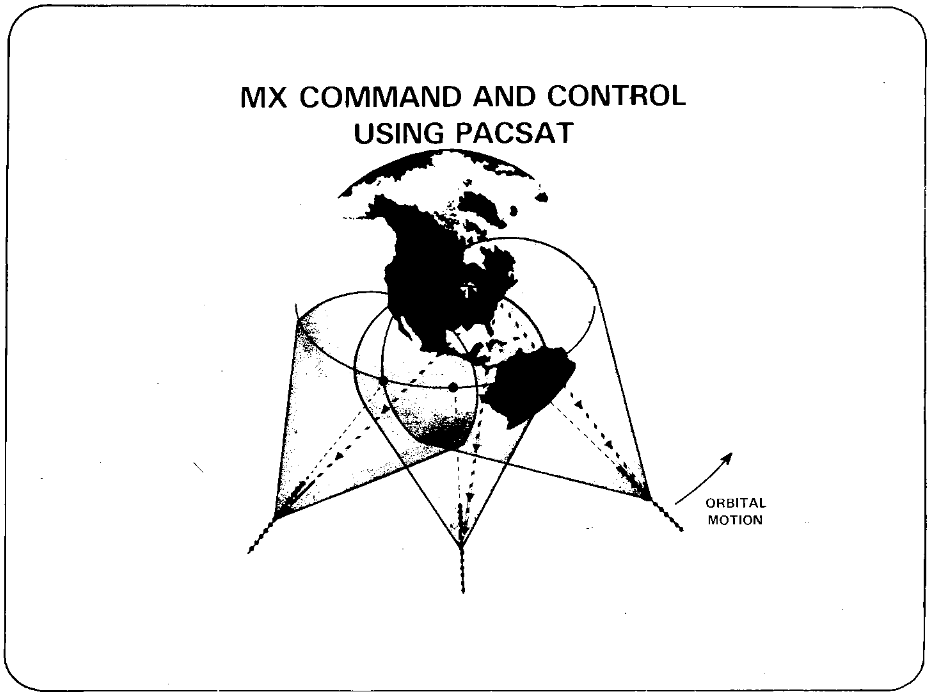


Chart 8

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*This assumes terminals at 38 deg N, 77 deg W (Washington, D.C.), and 38 deg N, 115 deg W (east central Nevada).

Unfortunately, the situation is exacerbated if the array librates; the tuning range in the preceding example increases to 2.7 percent for a 1 deg libration and to 4.4 percent for a 2 deg libration. To operate at SHF, for instance, where the available bandwidth is only 6.3 percent (7900 to 8400 GHz, earth-to-space), it is apparent that PACSAT libration would have to be limited to no more than about 3 deg through accurate array erection and effective damping.

Typical azimuth and elevation trajectories for a PACSAT array in a circular equatorial orbit at an altitude of 6378 km (one earth radius), as viewed by the terminals in the preceding example, are shown in Chart 9. Because the latitudes are the same, so also are the apparent satellite transits. In each case, the satellite rises 27 deg south of west (243 deg azimuth), ascends to an elevation of 25 deg when due south, then sets 27 deg south of east (117 deg azimuth). The arc of mutual visibility is 63 deg (from 232 deg E to 295 deg E), and the

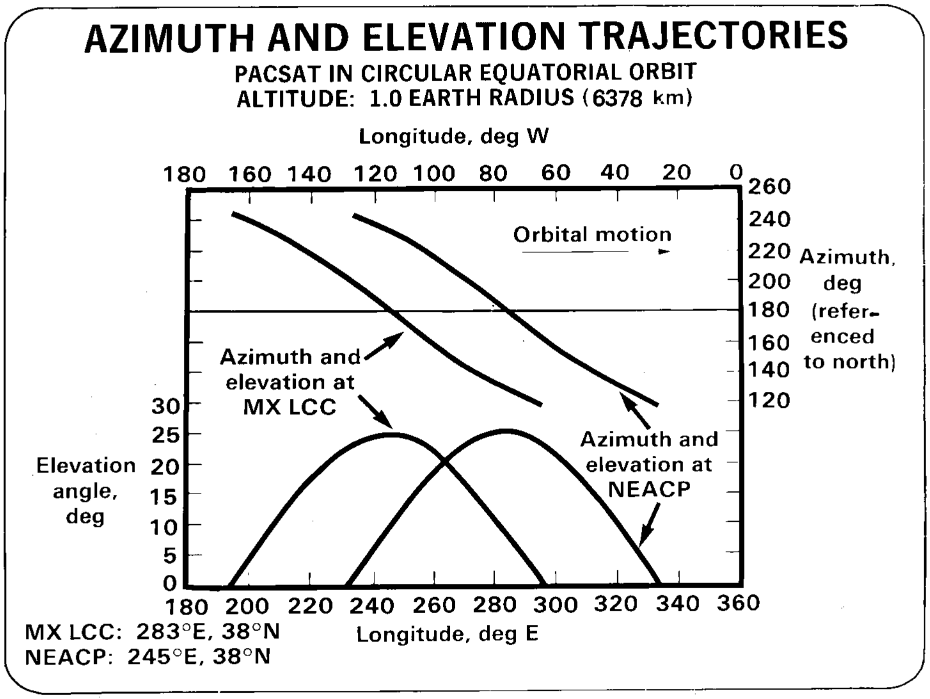


Chart 9

mutual viewing time is 50 min. Orbital altitudes much below 5000 to 6000 km are not of much interest because of the low elevation angles the satellites attain, the short mutual viewing time, and the large number of satellites required to provide continuous coverage.

Typical PACSAT link parameters for an array at an orbital altitude of 6000 km are tabulated on Chart 10. Operation is assumed to be at SHF (8 GHz) for the data rates of 100 bps and 1 kbps mentioned on Chart 1. The path lengths are both taken as 10,000 km (the distance to the horizon is 10,600 km at this altitude), and nominal values of 100 deg K for system noise and 10 dB for losses, margin, and threshold are assumed. Also, the PACSAT scattering cross section is taken as 10^6 m^2 (corresponding to an array about 1300 m long). It is seen that a 5 kW transmitter can maintain 100 bps between 75 and 70 cm diameter dishes and that a 10 kW transmitter can maintain 1 kbps between 1 and 1.2 m diameter dishes. Such components can readily be accommodated on large aircraft and mobile ground terminals. A 20 dB increase in transmitter power and antenna gains (e.g., 25 kW with 2.5 m diameter dishes) would permit a PACSAT link to support a data rate of 100 kbps, which is roughly the maximum that the array can support, between terrestrial terminals of moderate size.

TYPICAL PACSAT LINK PARAMETERS
PACSAT IN CIRCULAR EQUATORIAL ORBIT
ALTITUDE: 6000 km

Frequency	8 GHz	8 GHz
Transmitter power	5 kw	10 kw
Data rate	100 bps	1 kbps
Transmitter antenna diam.	75 cm	1 m
Range to transmitter	10,000 km	10,000 km
Scattering cross section	10^6 m^2	10^6 m^2
Range to receiver	10,000 km	10,000 km
System noise temp.	100° K	100°K
Losses, margin, and threshold	10 dB	10 dB
Receiver antenna diam.	70 cm	1.2 m

Chart 10

IV. DEFOCUSING

The coherent scattering on which PACSAT relies for its large scattering cross section is achieved by getting in-phase contributions from each of the elements of the array at the receiver. If phase errors appear, the effect is a defocusing that reduces the scattering cross section. When large numbers of scatterers are involved, as is the case with PACSAT, minute phase errors between adjacent elements can accumulate to intolerable levels across the entire array. The result is a stringent requirement on array straightness and on the viewing geometry.

The effect of defocusing on the array directivity pattern is illustrated on Chart 11. The patterns shown on Chart 11 are calculated assuming a square-law phase error, which is dominant for moderate amounts of defocusing, and uniform element illumination and spacing. A single defocusing parameter, U, then serves to specify the directivity pattern (this parameter has also been called "span" because

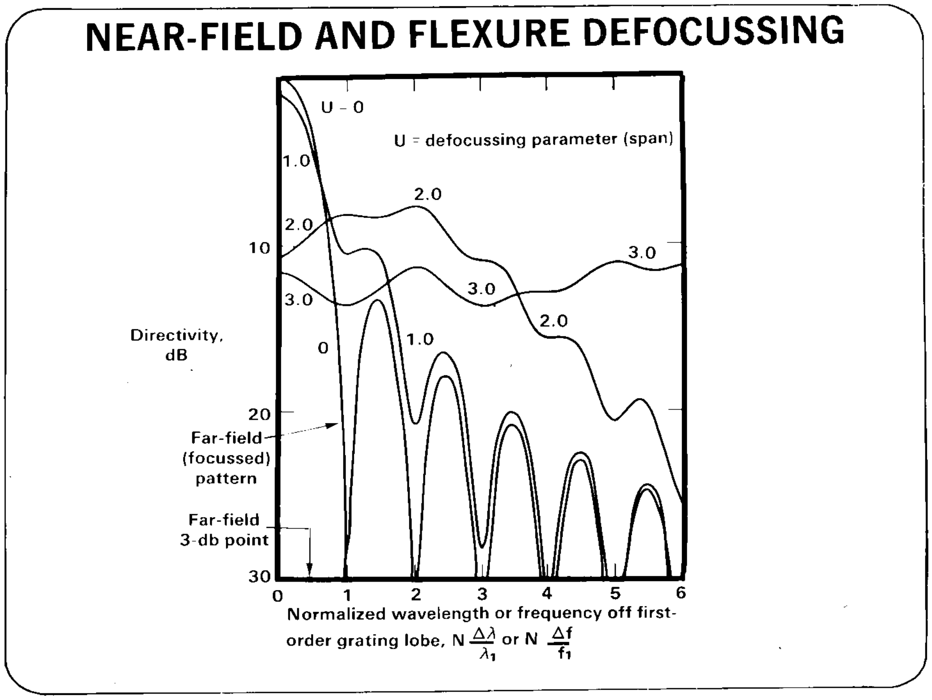

NEAR-FIELD AND FLEXURE DEFOCUSSING

Chart 11

it is related to the distance spanned by a pair of points on the array's Cornu's spiral). The far-field or focused pattern obtains for $U = 0$ and is seen to be of the familiar sin x/x form. As the defocusing parameter increases, the scattering cross section in the principal direction (i.e., in the main lobe of the directivity pattern) falls off and the side lobe levels are raised and their structure is altered. For example, at $U = 1.0$, the scattering cross section is reduced by about 1 dB, the first null is virtually filled in, and the first side lobe is raised by about 3 dB. Beyond the third side lobe, however, the effect is hardly distinguishable.

Further increases in the defocusing parameter result initially in large losses in scattering cross section (by about 10 dB for $U = 2.0$) followed by lesser but steadily increasing losses (for example, the loss is about 15 dB for $U = 4.0$). However, even if such losses in scattering cross section could be tolerated, the effects on the near side lobes might not be. For example, the 10 dB scattering cross section loss for $U = 2.0$ is accompanied by an elevation of the first three side lobes to the point that the newly created main lobe has a 3 dB dip in its center and a fivefold increase in its 3 dB beamwidth. For $U = 3.0$, all semblance to a directivity pattern is lost for the near side lobes.

The frequency parameter, U, can be brought into the form

$$U^2 = \left| c_1 \frac{D}{\lambda} + c_2 \frac{L^2}{\lambda R_e} \right| \tag{4}$$

where D is the maximum departure of the array from linearity, λ is the operating wavelength, L is the length of the array, and R_e is the radius of the earth. The coefficients, c_1 and c_2, are functions of the orbital altitude, the link geometry, and the array tilt (i.e., its libration about the local vertical).

The tradeoff between the normalized flexure, D/λ, and the normalized array length, $L^2/\lambda R_e$, when the defocusing parameter is limited to a value of unity, is plotted on Chart 12 for a number of normalized orbital altitudes, h/R_e, and array tilts, ψ. The terminals

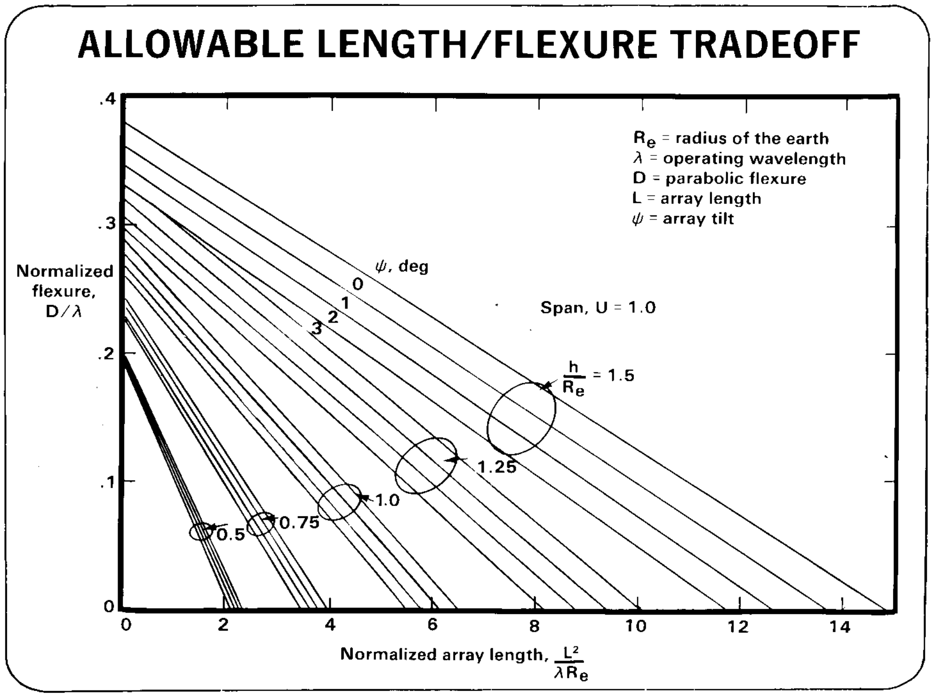


Chart 12

are at the locations indicated on Chart 8, at the midlongitude of the terminals. The array is assumed to be flexed in the form of a parabola, concave north, in the plane of the meridian; the tilt is also in the plane of the meridian with the outer end of the array inclined toward the north.

The fundamental tradeoff illustrated on Chart 12 is between the defocusing produced by flexure, characterized by D/λ, and that produced by the near-field effect, characterized by $L^2/\lambda R_e$. The immediate observation to be made is that little flexure can be tolerated under any circumstance. At SHF (8 GHz), the wavelength is 3.75 cm and it is seen that the flexure must be limited to a small fraction of that.

As a practical example, consider operation at an orbital altitude of one earth radius ($h/R_e = 1$) and little tilt ($\psi < 1$ deg). Under these circumstances, if the flexure of the unsupported array can be limited to $\lambda/8$ (4.7 mm at 8 GHz), a normalized array length of

$L^2/\lambda R_e = 3.5$ can be accommodated. It is not known if such a degree of straightness can be attained using only the feeble gravity-gradient-induced tension to overcome the various perturbing forces that might be experienced in orbit. If the array were supported by some sort of structure, near straightness could probably be assured. In that event, a normalized array length of about 6.0 would be accommodated in the same example.

It can be seen from Chart 12 that libration further constrains the flexure/near-field tradeoff at all orbital altitudes. However, given the already stringent straightness requirement, even without tilt, it would appear that the principal motivation for limiting libration will be to reduce the frequency tuning range required to maintain the communication link rather than to ease the maximum allowable flexure.

Increasing the orbital altitude relaxes the flexure/near-field tradeoff. However, the straightness requirement still remains stringent so that the principal benefit of higher altitudes is in the longer array length that can be used. The resulting increase in scattering cross section must, of course, be balanced against the greater inverse-fourth-power path loss that accompanies operation at higher orbital altitudes.

The actual array lengths and the associated scattering cross sections corresponding to the normalized array lengths are plotted on Chart 13 as a function of operating frequency (or wavelength). For example, at a frequency of 8 GHz, the normalized array length of 3.5, derived in the example above, is seen to correspond to an array 920 m long with a scattering cross section of 5.1×10^5 m^2; the normalized array length of 6.0 corresponds to an array 1200 m long with a scattering cross section of 8.6×10^5 m^2.

It is apparent that the maximum usable scattering cross section that can be achieved in a practical system may be determined by the defocusing caused by flexure and near-field operation rather than by the length of the array that can be erected. The scattering cross section of 10^6 m^2 used in the power budgets presented on Chart 10, for example, requires, from Eq. (4), an array almost 1300 m long.

SCATTERING CROSS SECTION AND NORMALIZED LENGTH

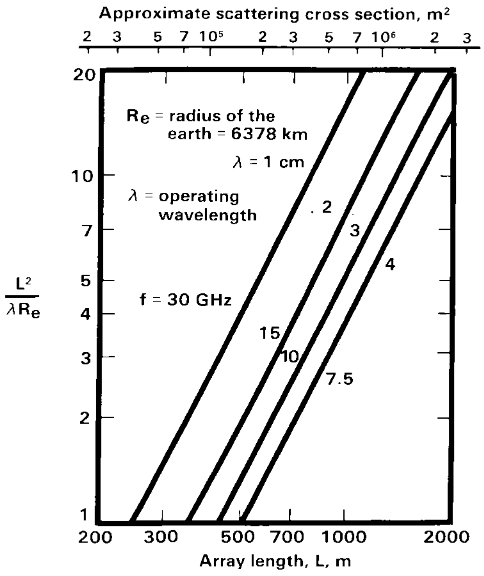


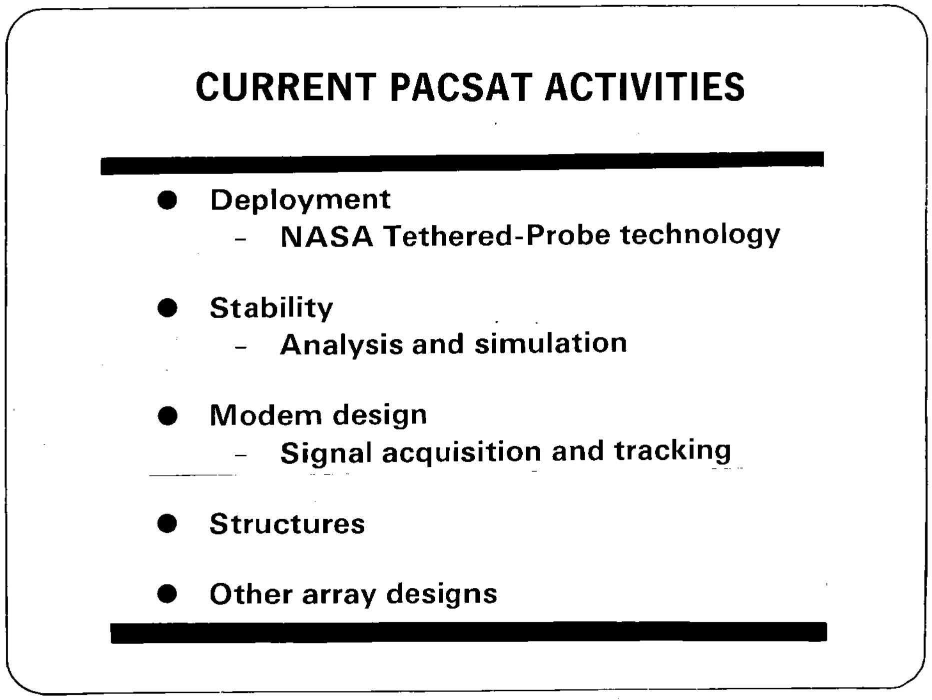
Chart 13

It can be seen from Chart 13 that this results in a normalized array length, $L^2/\lambda R_e$ of 7.0 at 8 GHz. The tradeoff on Chart 12 shows that this might be achieved at an orbital altitude of 1.5 earth radii (9567 km) with an unsupported array having a flexure not exceeding 0.15 to 0.20 wavelengths (0.56 to 0.75 cm). Alternatively, it could be achieved at an orbital altitude of about 1.1 earth radii (7016 km) using a supported array having no flexure.

Operating at lower altitudes or experiencing greater flexure will reduce the realizable scattering cross section and limit or degrade the utility of the array. Inasmuch as the feasibility of attaining the degree of straightness discussed above can probably be demonstrated with confidence only by an orbital test, it is the consequence of significant flexures that is of greatest concern. If the unsupported array cannot satisfy the straightness requirement, it may be necessary to use a structure to support the array and thereby virtually eliminate flexure.

V. CURRENT ACTIVITIES

The initial technical and systems analyses of the application of PACSAT for the command and control of MX have been largely completed and will be published soon. During the course of these analyses, a number of important issues, listed in Chart 14, have been identified and are currently under investigation.



CURRENT PACSAT ACTIVITIES

- **Deployment**
  - **NASA Tethered-Probe technology**
- **Stability**
  - **Analysis and simulation**
- **Modem design**
  - **Signal acquisition and tracking**
- **Structures**
- **Other array designs**

Chart 14

A problem of considerable interest is that of devising a suitable technique for erecting the unsupported array into an initial straight and erect configuration. One approach, suggested by SRI (op. cit.), is to coil the array on the inside of a large drum and then eject it toward the nadir by a drive mechanism within a deployment bell at the end of the drum. (SRI also proposes a number of lossy joints along the array to damp flexure and coiled end sections to damp libration.)

Another approach is to use the technique devised by NASA to deploy its tethered probe into the earth's upper atmosphere from a low-earth-orbit shuttle flight. Their technique is to use a rocket to drive the probe downward toward the earth, thereby unreeling its tether from a drum aboard the shuttle. Analysis shows that the relative bearing of the probe and the straightness of its tether can be maintained, despite the drag forces they experience, by controlling the tension in the tether by a braking motor as it plays out. Used on a smaller scale, with a 1 to 1.5 km array instead of a 100 km tether, this technique may be suitable for erecting PACSAT.

The stability of the unsupported array is also a matter of concern. Analysis indicates that the array will be stable, once straight and erect, for small displacements. Unfortunately, it is difficult to relate the character of the displacements that may occur to the perturbations that produce them and to determine the point at which the motion becomes unstable. Some computer simulations have been conducted to help gain an understanding of this complex phenomenon. It may be that only an orbital experiment can resolve the issue (the problem of designing an experiment that can measure the straightness of a kilometer-long wire to within a few millimeters is itself a challenge).

Modem design is under way for DARPA to develop transmitting and receiving equipment suitable for use with PACSAT. Devising a protocol for satellite selection, acquisition, and handover is straightforward; so also is developing algorithms for pointing and tracking the terrestrial antenna beams. More difficult is the problem of determining, at both transmitter and receiver, the appropriate frequency for directing the scattered beam to the intended recipient. This problem is compounded by array libration, satellite and terminal motion, and oscillator instability.

If flexure of the unsupported array proves to be excessive or if the unsupported array is found to be unstable under actual orbital conditions, then some sort of support structure may be required. As already mentioned, the tension induced in the PACSAT array by gravity-gradient is weak. For example, consider a 1500 m long array of aluminum spheres designed for operation at 8 GHz (1.190 cm diameter) on 1.875 cm centers) strung on a steel central wire 1.32 mm in diameter.[*] The gravity-gradient tension would be distributed parabolically along the array, zero at the ends and maximum at the center. If the array were at an orbital altitude of one earth radius (6378 km), the peak tension at the center would equal about 2200 dynes, which is somewhat less than half the weight of a U.S. five cent coin at the surface of the earth.

It is not known if such a small tension is adequate to limit flexure to the few millimeters or so permitted by the defocusing criterion (see Chart 12). However, the flexural displacements are inversely proportional to the tension so that moderate flexures may be reduced to acceptable levels by using a structure to support the array under tension. For instance, increasing the tension to 4.45 Newtons (1 lb force) will reduce displacements by a factor of 200 or so for the example above.

Structures under consideration include trusses (like antenna towers) made of dielectric members and which surround the array, and bow-like supports, made of dielectric or metallic material, that hold the array between their tips. Important considerations are weight, volume before erection, and vulnerability to damage in space.

Finally, although this Note concerns itself with the PACSAT approach to achieving large scattering cross sections, there are other designs that offer similar performance. Among these is one, also under investigation for DARPA, that uses a planar array to generate a fan beam that can be frequency steered in one angle. Spinning it will give stability in orbit and will also scan the beam across the earth in the other angle. The result will be periodic coverage as the beam scans the field of view horizontally, while being deflected vertically, somewhat like the trace on an oscilloscope.

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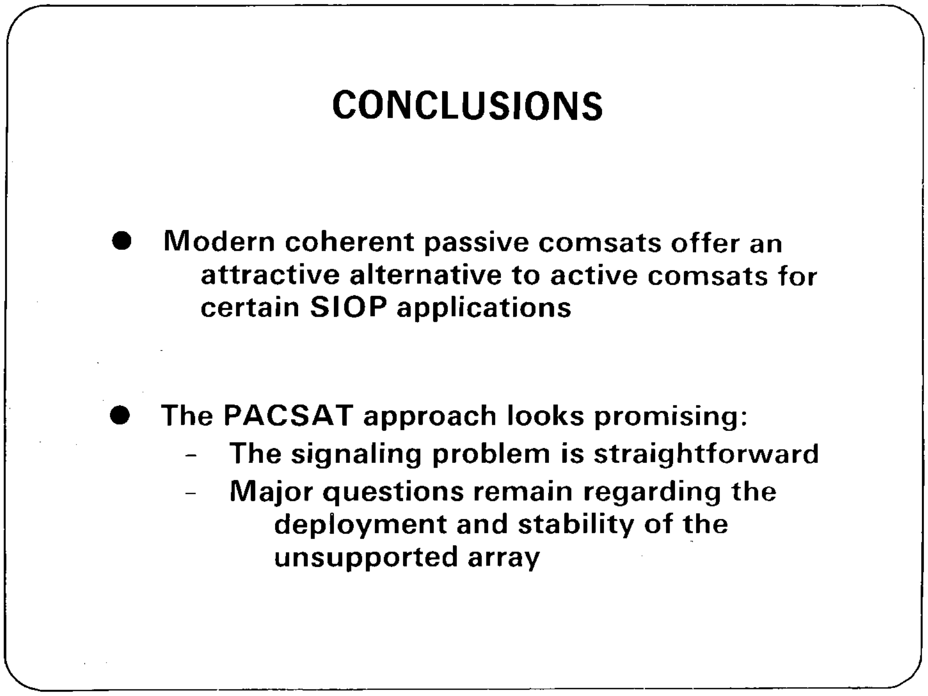
[*] Such an array would weigh about 200 kg, of which the central wire would account for 16 kg.

VI. CONCLUSIONS

The anticipated environment in space during a nuclear war is sufficiently hostile that there is concern about the survivability and endurance of active military communication satellite systems. The physical characteristics of passive satellites coupled with the much larger scattering cross sections available from modern coherent passive satellite designs make them an attractive alternative for certain SIOP applications (see Chart 15).



CONCLUSIONS

- **Modern coherent passive comsats offer an attractive alternative to active comsats for certain SIOP applications**
- **The PACSAT approach looks promising:**
  - **The signaling problem is straightforward**
  - **Major questions remain regarding the deployment and stability of the unsupported array**

Chart 15

The PACSAT approach, which is described in this Note, looks promising for point-to-point communication at medium ranges and low data rates. The signaling problem is straightforward although it requires the development of unique modems suited to the frequency steerable beam that is generated. However, major questions remain regarding the deployment and stability of the unsupported PACSAT array.

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