REFERENCE SYSTEM DESCRIPTION

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1.0 SPS ANTENNA ELEMENT EVALUATION

The SPS transmitting aray requires an architecture which will provide a low weight, high efficiency and high structural rigidity. Several candidate antenna configurations include the parabolic dish, the parabolic cylinder, the lens and the waveguide slot array. As discussed below, the waveguide slot array is preferred over the other options.

Parabolic dishes are widely used on earth. For SPS application, they could be readily laid up in six-foot diameters with lightweight graphite-epoxy materials. On the other hand, the area efficiency of such an array is relatively low. Moreover, a zero spillover feed configuration is not presently apparent.

An array of parabolic cylinders with line-source feeds could give better area efficiency than an array of dishes, but would suffer from feed blockage.

A lens, using lightweight waveguide structures, with zero blockage behind-the-lens feedhorns can have high efficiency and little spillover, but the SPS center-to-edge illumination tapers would give a spatial "lumpiness" which would produce undesirable grating lobes in the far-field pattern.

As noted above, waveguide slot arrays constitute the most desirable option. Consequently, such an array has been chosen for the SPS. Waveguide slot arrays offer high efficiency, uniform illumination, and are fairly lightweight. Bandwidths of such arrays are narrow, typically 1/2-2%. Although this does not directly impact the SPS, which transmits power at a single frequency of 2.45 GHz, the narrow bandwidth does constrain the thermal and mechanical tolerances of the antenna.

2.0 SLOTTED WAVEGUIDE MODULE DESIGN VERIFICATION

2.1 EXPERIMENTAL PROGRAM

The purpose of this program is to better define the electronic aspects of an SPS specific waveguide slot array. The specific aims of the program are as follows:

- To build a full-scale half-module, 10 stick, array, the design parameters for which are to be determined by analytical considerations tempered by experimental data on a single slotted radiating stick.
- To experimentally evaluate the completed array with respect to antenna pattern, impedance and return loss.
- To measure swept transmission amplitude and phase to provide a data base for design of a receiving antenna.

2.2 ARRAY CONFIGURATION

The first step in module design is to fix the gross dimensions, including the module length and width, and the dimensions of the radiating sticks and the feed waveguide. Because the feedguide is a standing wave device in which the coupling slots must be spaced by $\lambda_g/2$, where λ_g is the guide wavelength, and because λ_g is a function of waveguide width, the radiating stick and feedguide dimensions are not independent.

The SPS baseline design calls for a half-module of ten 1.6 m long sticks of 6 cm x 9 cm cross-section. For these dimensions, at the SPS frequency, the feedguide dimensions are also 6 cm x 9 cm. To assess the desirability of the baseline configuration, the ohmic losses of several alternative configurations of equal area were calculated. The I^2R losses for these are plotted in Figure 1 as functions of radiating stick in the loss curve is quite shallow. Also, the values of the minima do not appear to be very configurationally sensitive. On the other hand, it was determined in the course of this study that end-feeding of the feedguide may afford somewhat lower loss than expected of the baseline configuration which utilizes center-feeding.

Based on the above considerations, it was decided to configure the experimental module according to the baseline design. The commercially manufactured waveguide which most nearly approximates the baseline guide, is WR-340, with dimensions of 4.32 x 8.64 cm. Because this was not available in sufficient quantity, WR-284 waveguide was used instead for the developmental module. Because this waveguide is narrower than the baseline, and because it would be used for both the radiating sticks and the feedguide, the design frequency of the developmental module was increased from 2.45 GHz to 2.86 GHz. With 6061 Aluminum feedguide, the ohmic losses in the module are expected to be less than 1%.

2.3 WAVEGUIDE STICK DESIGN

The design of the waveguide stick entails the assignment of values to both the slot offset from the waveguide centerline and the slot length. The slot length, ℓ , is chosen so that the slot is resonant at the design frequency. The slot offset is chosen to give the desired slot conductance. This is determined by impedance matching considerations. Thus, for a waveguide stick containing N identical shunt slots, the desired value of normalized slot conductance, g, is just $g = 1/N$.

For a single isolated stick, the choice of slot length and slot offset is relatively straightforward. The slot length is given to good approximation by $\ell = \lambda_0/2$, where λ_0 is the free-space wavelength. The conductance and slot offset are related to sufficient accuracy by a well known equation.

Tentative radiator stick dimensions in WR-284 waveguide are:

Slot Spacing	3.0 inch	Slot Offset	.187 inch
Slot Length	1.98 inch	Slot Normalized Conductance	.055
Slot Width	.125 inch	Number of Slots	18 or 20

Where several sticks are placed in close proximity, however, as they are in the SPS module, the design problem is exacerbated by mutual coupling between the sticks. That is, the slots in any particular stick are now loaded by the slots in the neighboring sticks and will necessarily exhibit resonant frequencies and conductances which differ significantly from those predicted by single stick equations.

The changes in stick behavior due to mutual coupling effects are shown in Figure 2. Here, both the resonant frequency and the reflection coefficient of a single stick at resonance change noticeably in the presence of a second stick. A theoretical analysis of this problem, based on an adaptation of a mutual coupling analysis for an array of dipoles (L. Stark, Radio Science 1, 361, 1966) is shown in Figure 3. As might be expected, the effects converge rather rapidly, suggesting that a particular slot does not interact to any significant extent with other slots that are more distant than third or fourth neighbors. Figure 3 also shows that mutual coupling effects are also present between neighboring slots of a single stick.

Because of the mutual coupling problem, the choice of slot length and offset has been pursued in an iterative manner beginning from the single stick analytical values. Data for several iterations with two waveguide sticks, are shown in Table 1. Because the slot offsets, once machined, are fixed, stick impedance in these data was varied by changing the number of slots by the means of a sliding short in the waveguide. Adjacent sticks were fed in-phase using home built four-hole directional couplers machined in one end of each stick, permitting swept return-loss/coupling measurements without interference by guide flanges.

2.4 FEED GUIDE DESIGN

The radiating waveguide sticks are fed in-phase by a feed waveguide whose axis is perpendicular to those of the radiating sticks. Like the radiating sticks, the feed-guide supports a standing wave. The power is coupled from the feedguide to each radiating stick through a resonant (length - $\lambda_0/2$) coupling slot which is inclined to the feedguide axis. The transformed radiating stick impedance seen by the feedguide is proportional to $\sin^2 2\theta$, where θ is the inclination angle. The phase of the power coupled to the stick is inverted as the coupling slot is reflected in the feedguide axis. For maximum power transfer to the 10 radiating sticks, each stick must present an impedance to the feedguide of one-tenth the feedguide characteristic impedance. This dictates a rather small coupling slot inclination of about 7°. To maintain proper phasing of the radiating sticks, the coupling slots are alternately reflected in the feedguide axis.

Tentative feed stick dimensions in WR-284 6061 aluminum waveguides for the 1/2-module are:

Slot Spacing	3.0 inch	Slot Normalized Resistance	.10
Slot Length	2.0 inch	Slot Number	10.
Slot Width	.125 inch		
Slot Offset Angle	7.		

3.0 RECEIVING TECHNIQUES EVALUATION

The receiving antenna receives a pilot signal from earth with phase information to keep all modules in-phase. Symmetry considerations argue for the pilot signal to originate from the center of the SPS earth receiving array. Ionospheric phase shift and Faraday rotation call for the pilot signal to be centered on the SPS power frequency with the phase information in symmetrically disposed sidebands. The purposes of the receiving techniques evaluation were to:

- Conduct a shared antenna versus separate receiving antenna analysis to determine feasible pilot beam budget and receiving antenna constraints due to power module.

- Design and select a pilot-beam receiving antenna techniques compatible with a power beam array which must allow simultaneous transmission of an S-Band carrier and reception of the anticipated pilot-beam spread-spectrum signal.

The pilot beam link analysis established that very small low gain pilot receiving antenna elements imbedded in the transmitting array are significantly superior to any scheme of diplexing, because: (1) The total system power losses are two orders of magnitude lower with a separate antenna than with any state-of-the-art diplexing device; (2) The small antenna, due to its inherent broad bandwidth, is fully compatible with a spread spectrum signal; whereas the transmit array is not, (3) The small, low gain antenna represents a much lower development risk than a diplexing device.

Also from the pilot beam link analysis, formalisms have evolved from which to determine values of pilot transmitter power and antenna aperture, as well as pilot receiving antenna aperture. The transmitter power and aperture depend foremost upon the requisite pilot link effective radiated power, ERP. The ERP, in turn, depends upon the signal-to-noise requirement of the pilot link receiver; and hence, the noise environment in which the receiving system must operate. Consequently, the ERP requirements were found to be extremely sensitive to the cut-off frequency of a required receiver I.F. notch filter.

The relationship between transmitting antenna diameter and system power loss (efficiency) is shown in Figure 4. This relationship is not monotonic due to the fact that increasing the antenna diameter produces two opposing effects. It reduces the amount of pilot transmitter power required to produce the requisite ERP, while simultaneously increasing the degree of rectenna blockage. At low diameters, the transmitter power effect dominates, and the loss decreases with increasing diameter; whereas, at larger diameters, rectenna blockage becomes most important, and the system loss increases with increasing diameter. Thus, for a particular ERP, there is a rather limited set of pilot transmitter power/aperture combinations which gives minimum system loss.

The relationship between system losses and pilot-link receiving aperture is shown in Figure 5. For small apertures, an increase in aperture reduces system losses due to a decrease in the required ERP. At large apertures, the system losses increase with increasing aperture, due to receiving antenna blockage of the spacetenna. The specific nature of this relationship depends on the required signal-to-noise ratio, S/N, in the pilot receiver, and also on the bandwidth, f_c, of the intermediate frequency notch-filter. As S/N is increased, the pilot ERP must increase, and so also must the system losses. As f_c is decreased, more of the power transmitter noise spectrum is passed by the receiver I.F. This increase in noise must be overcome by an increase in pilot link transmitter power.

As shown in Figure 5, the optimum receiving aperture, under any foreseeable conditions, is quite small. Consequently, the pilot-link receiving antenna requirement can be satisfied by a simple dipole or slot antenna. Adaptations of these to the SPS array are shown in Figure 6. The slot antenna is inserted in a notch cut in the outer portion of adjacent waveguide narrow walls. The dipole is positioned at a distance $\lambda_0/4$ above the array by a small rigid coax feed, which like the slot, is slipped through a hole in the waveguide walls. These antennas may be dimensioned either to be resonant or non-resonant. The aperture of the resonant structure is larger, but so also is the effect on the impedance of the neighboring transmitting-antenna radiating slots. To the extent that the lower aperture can be tolerated, the non-resonant structure is preferred.

An important consideration in the pilot link design is the isolation of the pilot receiver from noise inherent to the high-power down-link signal. With the dipole, isolation can be improved by rotating the antenna so that it is cross-polarized to the power transmitting antenna. An alternate noise-cancelling scheme utilizes two dipoles per receiving antenna, as shown in Figure 6. These are separated by $\lambda_0/4$ and can therefore be connected to pass, as would a directional coupler, radiation coming from the earth, while rejecting that which is earthbound.

One of the candidate receiving antennas in Figure 6, the slot, or "credit-card" receiving antenna, has been built and sweep-tested. It consists of a 1.75" x .062" teflon-glass microcircuit board shorted around three edges to form a low-impedance waveguide cavity.

4.0 ANTENNA EFFICIENCY MEASUREMENTS

The antenna pattern will be measured on one of the six antenna ranges at Boeing. Besides observing the far-field rule $R > 2D^2/\lambda \geq 180$ ft., high paths and sharp-beam range illuminators will be employed to minimize multipath errors. For the ranges at the Boeing Developmental Center, multipath errors at beam-center are estimated to be well under $\pm$ .1 db. Gain is measured using a Scientific Atlanta SA-1740 Precision Amplifier-Receiver, and SA-12-1/70 Standard gain horn. Measurement accuracies are estimated as follows:

Standard-gain Horn (Δ gain)	± .2 db
Match	± .2 db
Switch mismatch differences between two positions	± .2 db
Receiver/mixer linearity	± .2 db
Total RSS Value	± .4 db or ± 9% in power

By hardwiring the SPS array to the standard gain horn, with their beams pointed near 90% apart to avoid crosstalk, the rf switch and its inherent uncertainty can be eliminated.

The antenna efficiency is obtained from the experimental measurement of gain, G, with respect to a reference horn, and directivity, D. Since the directivity is the gain of a lossless antenna, the ratio of these values represents the efficiency of the antenna. The gain is obtained from the measured value of incremental gain above a calibrated standard horn. The directivity is expressed as the ratio of the maximum radiation intensity, U_{max} to the average radiation intensity $\overline{U}$, which is given by $\overline{U} = 1/4\pi \iint U(\theta,\emptyset)d\Omega$.

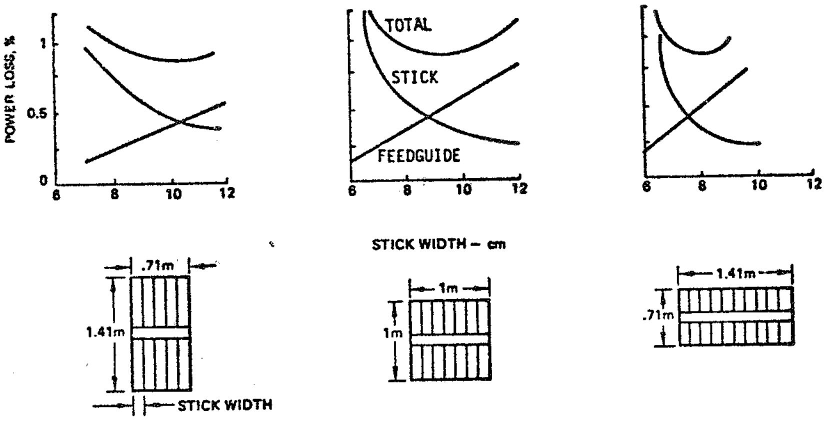
The directivity measurement is carried out separately by rotating the antenna continuously through selected azimuth and elevation angles and integrating the far field contributions over a solid sphere, thus obtaining the directivity with reference to an isotropic radiator as $D = U_{max}/\overline{U}$.

The efficiency is obtained from the ratio of two separately measured experimental values, $\eta = G/D$. With currently available antenna range accuracy, this measurement is typically determined to ± .4 db accuracy. The resulting efficiency value will give an indication of ohmic losses in the waveguide feed system and in the radiating sticks. In the SPS baseline design, this loss is estimated to be less than 0.1 db, and the antenna range measurement will thus provide a crude verification only.

TABLE: I ITERATIVE DESIGN PROCEDURE FOR RADIATING STICK PARAMETERS

STICK NUMBER	NO. OF SLOTS[1] FOR BEST MATCH		SLOT[3] OFFSET	SLOT LENGTH	COMMENT
	SINGLE STICK	WITH[2] NEIGBOR			
1	22	20	.18"	2.04"	RESONANCE @ 2800 MHz SLOT TOO LONG
2	16	14	.20"	1.94"	RESONANCE @ 2880 MHz SLOT TOO SHORT TOO MUCH CONDUCTANCE PER SLOT
3	18	16	.187"	1.98"	RESONANCE AT 2875MHz
4	18	18	.180"	2.00"	EXPECT 2860 MHz[4]

1. SLIDING SHORT MEASUREMENT: VSWR AT RESONANCE $<$ 1.1
2. NON-DUPLICATE STICKS ARE USED TO APPROXIMATE MUTUAL COUPLING EFFECT
3. AFFECTS PRIMARILY SLOT CONDUCTANCE
4. DESIRED FREQUENCY FOR FEED GUIDE TO BE IDENTICAL TO RADIATING STICK GUIDE (WR240)



- NOT SENSITIVE TO MODULE ASPECT RATIO
- NOT VERY SENSITIVE TO WAVEGUIDE SIZE
- STICK STANDING WAVES SUGGEST END FEEDING PREFERABLE

Figure 1 : RF Module I^2R Optimization

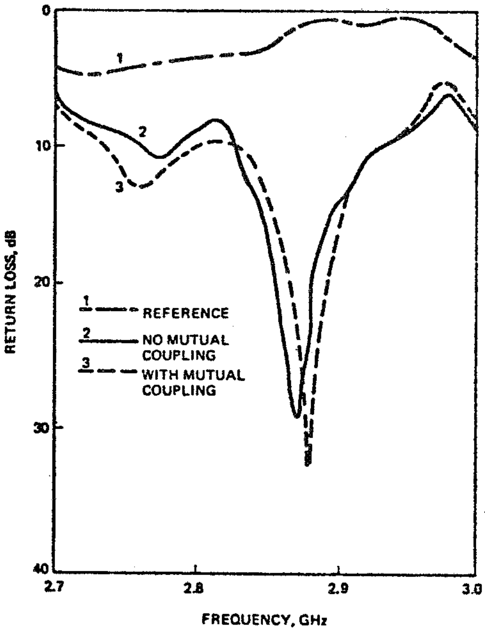


Figure 2: Effect of Mutual Coupling — Two Stick Measurement

ANALYTICAL EXPRESSION[1]

$$\frac{y}{Y_o} = \frac{4\,a\,S_e\,S_H\,(1-jw)}{b\lambda^2\left[1+w^2\right]\,1-\left(\frac{\lambda}{2a}\right)^2}\;\cos^2\left(\frac{\pi}{2}\sqrt{1-\frac{\lambda^2}{2a}}\right)\;\sin^2\left(\frac{\pi X}{a}\right)$$

WHERE

$$w = \sum_{\substack{m=-l\\ m\neq 0}}^{m=+l}\;\sum_{\substack{n=-k\\ n\neq 0}}^{n=k}\left[\frac{\sin\left[\frac{\pi g m}{S_E}\right]}{\frac{\pi g m}{S_E}}\right]^2\left[\frac{\cos\left[\frac{\pi n\lambda}{2S_H}\right]}{1-\left[\frac{n\lambda}{S_H}\right]^2}\right]^2\frac{\left[\left[\frac{n\lambda}{S_H}\right]^2-1\right]}{\sqrt{\left(\frac{n\lambda}{S_H}\right)^2+\left(\frac{m\lambda}{S_E}\right)^2}}$$

l = ½ THE NUMBER OF NEIGHBORING SLOTS CONSIDERED IN THE 'e' PLANE

k = ½ THE NUMBER OF NEIGHBORING SLOTS CONSIDERED IN THE 'H' PLANE

a =	GUIDE I.D. WIDTH	x =	XLOT OFFSET
a =	GUIDE I.D. WIDTH	X =	SLOT OFFSET
b =	GUIDE I.D. HEIGHT	g =	SLOT WIDTH
S_e =	SLOT 'e' PLANE SPACING	y =	SLOT SHUNT ADMITTANCE
S_H =	SLOT 'H' PLANE SPACING	Y_o =	GUIDE CHARACTERISTIC

1. MODIFICATION OF STARK'S DIPOLE EXPRESSION TO SLOTS

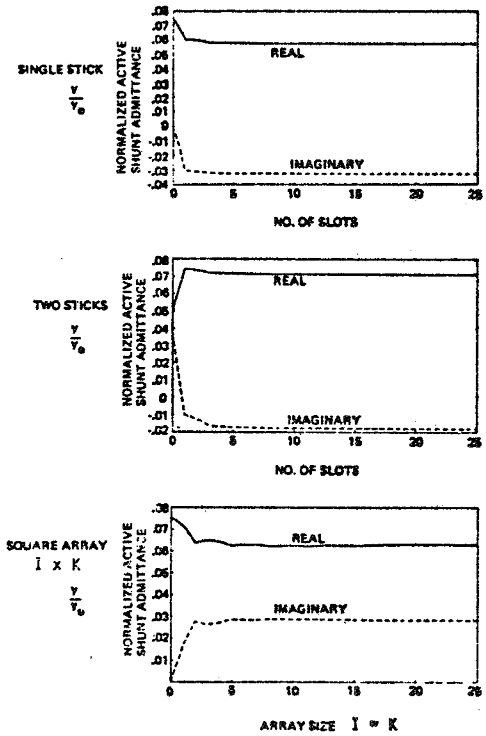


Figure 3: Estimate of Mutual Coupling in SPS Slotted Waveguide Array

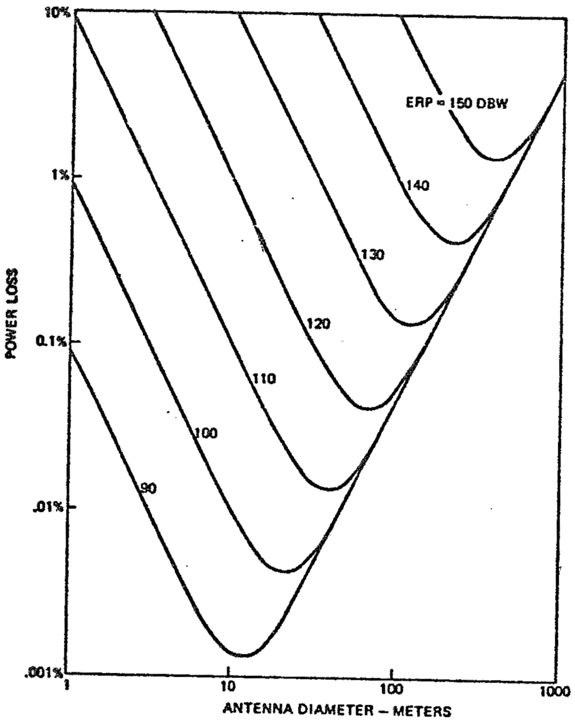


Figure 4 System Power Loss Vs. Pilot Transmit Antenna Diameter and ERP Required

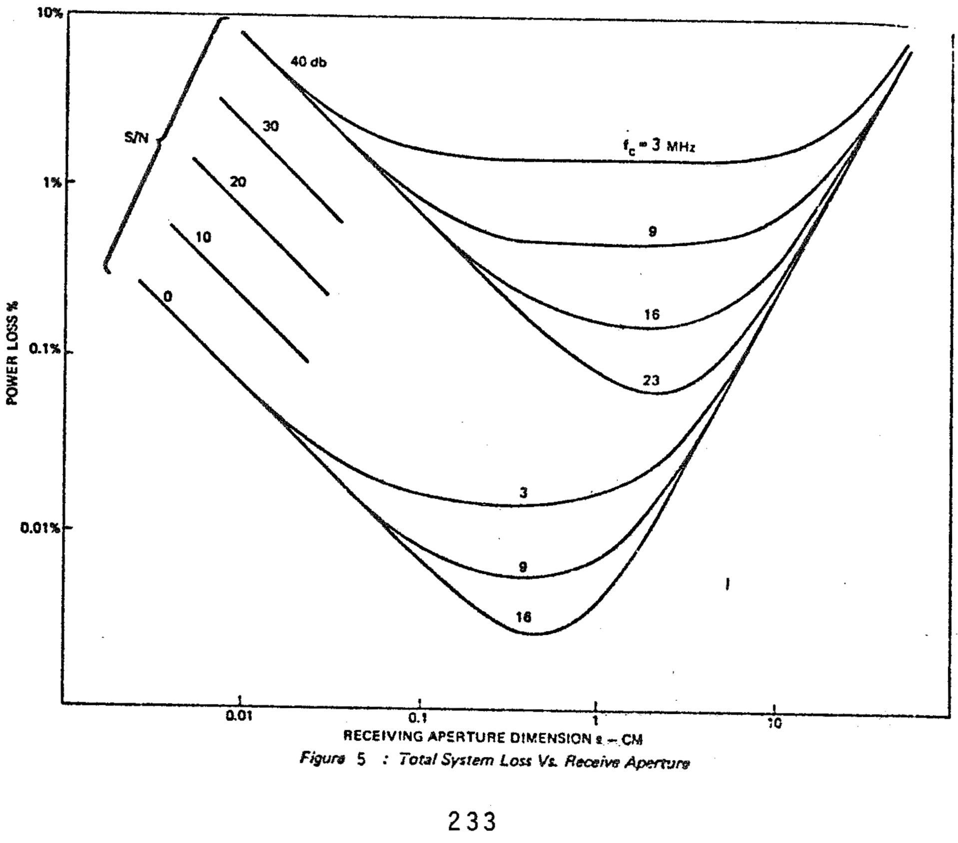


Figure 5 : Total System Loss Vs. Receive Aperture

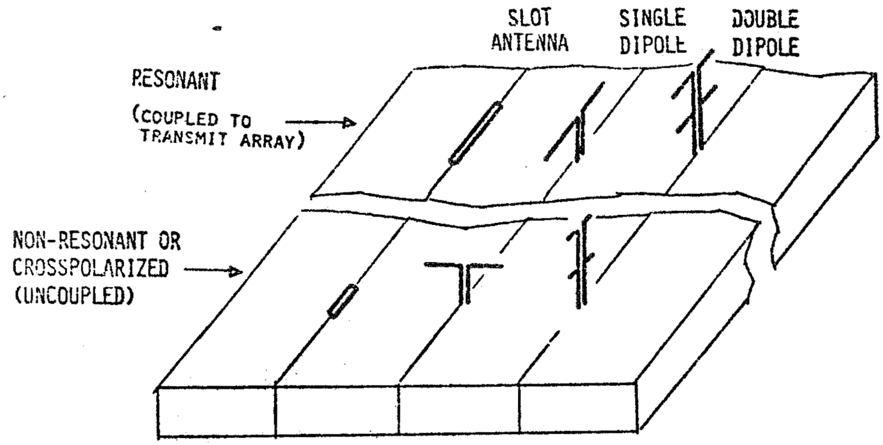


FIGURE 6: POTENTIAL SPS PILOT-LINK RECEIVING ANTENNA CONFIGURATIONS. THE DOUBLE DIPOLE CONFIGURATIONS AFFORD PARTIAL NOISE CANCELLATION.