N94-22832

An Active K/K_a-Band Antenna Array for the NASA ACTS Mobile Terminal†

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ABSTRACT

An active K/K_a-band antenna array is currently under development for NASA's ACTS Mobile Terminal (AMT). The AMT task will demonstrate voice, data, and video communications to and from the AMT vehicle in Los Angeles, California, and a base station in Cleveland, Ohio, via the ACTS satellite at 30 and 20 GHz. Satellite tracking for the land-mobile vehicular antenna system involves "mechanical dithering" of the antenna, where the antenna radiates a fixed beam 46° above the horizon. The antenna is to transmit horizontal polarization and receive vertical polarization at 29.634±0.15 GHz and 19.914±0.15 GHz, respectively. The active array will provide a minimum of 22 dBW EIRP transmit power density and a −8 dB/K° receive sensitivity.

INTRODUCTION

The AMT active antenna array [1-3], shown in Figure 1, is a multilayered assembly in which a receive array of radiating slots and transmit array of microstrip dipoles are interleaved such that they share the same aperture to provide a compact, dual-band antenna. The slots are electromagnetically coupled to shielded microstrip lines connected to Monolithic Microwave Integrated Circuit (MMIC) low-noise amplifiers (LNAs) on the back side of the primary ground plane containing the slots. The dipoles reside on a dielectric sheet placed on top of the front side of the slotted ground plane, are interleaved between the slots, and are electromagnetically coupled to microstrip lines connected to MMIC high-power amplifiers (HPAs) on the front side of the primary ground plane. Inherently good isolation is expected since the receive and transmit circuitry are on opposite sides of the primary antenna ground plane.

TRANSMIT AND RECEIVE ARRAY

Printed dipole elements and their complement, linear slots, are elementary radiators that have found use in low-pofile antenna arrays. Low-profile antenna arrays, in addition to their small size and low weight characteristics, offer the potential advantage of low-cost, high-volume production with easy integration with active integrated circuit components.

Both transmit and receive arrays have peak directivities of approximately 24 dB, and will operate over a 1% and a 1.5% bandwidth, respectively. The subarrays of the AMT antenna are linear series-fed-type arrays consisting of nearly identical dipole, or slot, elements transversely electromagnetically coupled to a microstrip transmission line, a configuration selected

†The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

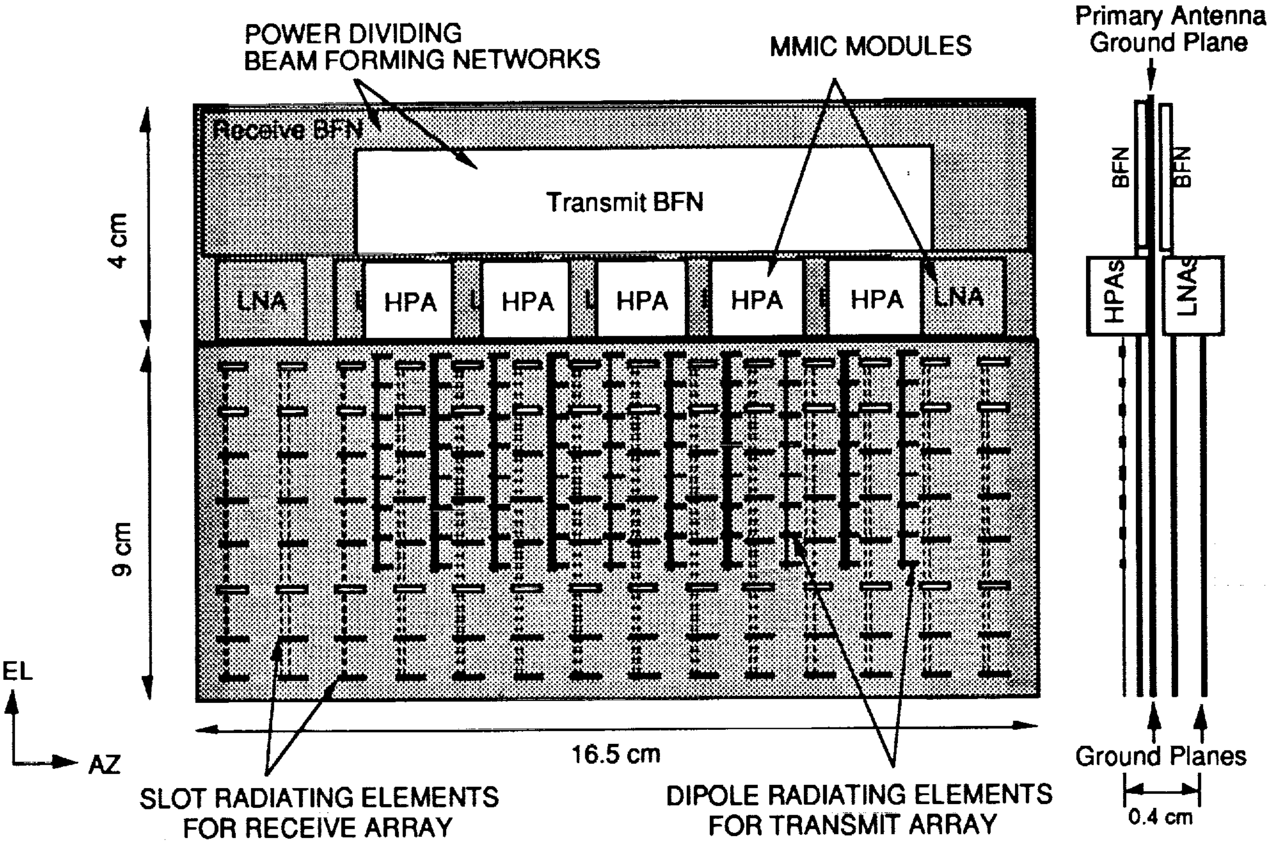

Figure 1. AMT Active Array.

to minimize losses. The transmit array consists of 10 identical linear dipole subarrays spaced $0.964\lambda_0$ apart and the receive array consists of 14 linear slot subarrays spaced $0.648\lambda_0$ apart.

The design of the linear series-fed-type arrays is achieved using transmission line theory with equivalent circuit models for the radiating elements. The element offsets and interelement line lengths are used to obtain the desired amplitude distribution and beam direction, respectively. Summarized in the following are the design and test results of both a dipole and slot series-fed-type linear array, assuming the impedance characteristics of the radiating elements are known.

Elevation Beam Direction

Consider the "symmetrically-fed" linear dipole and slot arrays shown in Figures 2 and 3, respectively, where the spacing

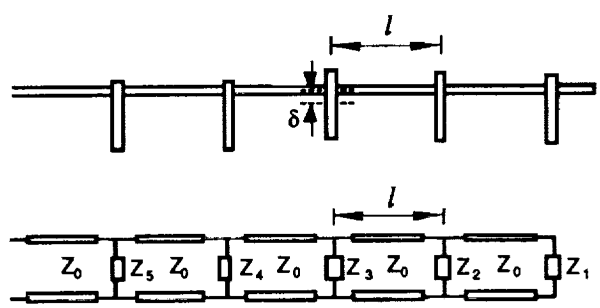

Figure 2. Linear series-fed dipole array and equivalent circuit.

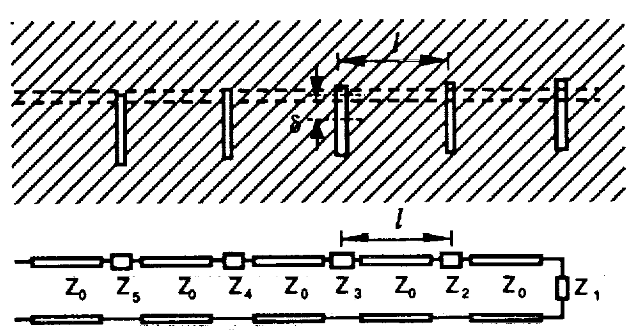

Figure 3. Linear series-fed slot array and equivalent circuit.

between elements is d and the length of the interconnecting transmission line is $\ell \geq d$. To direct the main beam at the proper scan angle θ_0, measured from broadside, or normal to the antenna, the following phase relationship (using $e^{j\omega t}$ time dependence) between the elements should be satisfied

$$\psi = -\beta\ell = \pm k_0 d \sin\theta_0 - m\pi$$

where m is an even integer, $\beta = k_0\sqrt{\epsilon_{r,\text{eff}}}$ is the propagation constant, $k_0 = 2\pi/\lambda_0$ is the free space wavenumber, λ_0 is the free space wavelength, and $\epsilon_{r,\text{eff}}$ is the effective dielectric constant. To minimize ℓ, i.e., minimize line loss, the above equation is solved when $\ell = d$ to obtain

$$\frac{\ell}{\lambda_0} = \frac{m/2}{\sqrt{\epsilon_{r,\text{eff}}} \pm \sin\theta_0}$$

Dipole Linear Array Design

In an equivalent circuit model of a linear array of N series-fed-type dipoles [4], the ith dipole represents a shunt impedance, $Z_i(\omega) = R_i(\omega) + jX_i(\omega)$, to the transmission line as shown in Figure 2, where $Z_i(\omega)$ is a function of the dipole offset, length, and width. The transmission line is characterized by its characteristic impedance Z_0 and wavenumber $k = \beta - j\alpha$, where α is the attenuation constant. Each dipole operates at resonance, such that $Z_i(\omega_0) = R_i(\omega_0)$ $(X_i(\omega_0) = 0)$, where the desired value of $R_i(\omega_0)$ is obtained by selecting the appropriate offset δ_i and length L_i.

A unit cell of the array of length ℓ, determined from above, may be defined as shown in Figure 4.

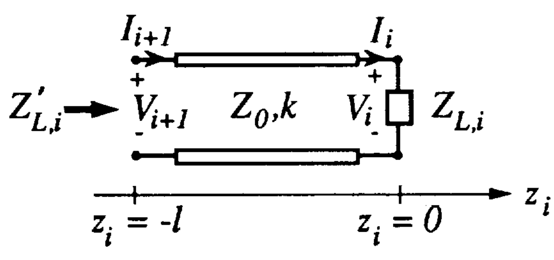

Figure 4. Linear array unit cell.

The voltage and current on the transmission line of the unit cell are given by

$$V(z_i) = V_{i+}e^{-jkz_i}\left[1 + \Gamma_{L,i}e^{j2kz_i}\right]$$
$$Z_0 I(z_i) = V_{i+}e^{-jkz_i}\left[1 - \Gamma_{L,i}e^{j2kz_i}\right]$$

where
$$\Gamma_{L,i} = \frac{Z_{L,i} - Z_0}{Z_{L,i} + Z_0}$$
$$Z_{L,i} = Z_i \parallel Z'_{L,i-1}$$
$$Z'_{L,i-1} = \frac{Z_{L,i-1} + jZ_0 \tan k\ell}{jZ_{L,i-1}\tan k\ell + Z_0} Z_0$$

By taking the ratio of V_{i+1}/V_i

$$\frac{V_{i+1}}{V_i} = \frac{V(z_i = -\ell)}{V(z_i = 0)} = \frac{\left[1 + \Gamma_{L,i}e^{-j2k\ell}\right]}{\left[1 + \Gamma_{L,i}\right]} e^{jk\ell}$$

a recursive expression for the voltage at successive points along the array is obtained. The power dissipated in each dipole radiator is given by $P_i = |V_i|^2/(2R_i)$. For a given amplitude distribution, $\sqrt{P_i}$ $(i = 1, 2, \ldots, N)$, and a given transmission line length $k\ell$ and R_1, the desired resonant resistances R_i are specified by the following recursive expression

$$R_i = \frac{1}{2}\frac{|V_i|^2}{P_i} = \frac{1}{2}\frac{|V_{i-1}|^2}{P_i}\frac{|1 + \Gamma_{L,i-1}e^{-j2k\ell}|^2}{|1 + \Gamma_{L,i-1}|^2}$$

When the main beam direction is broadside, or normal, to the antenna, $\theta_0 = 0$, R_1 should be specified larger than Z_0 to maintain a good input impedance match to the array. For a main beam direction off broadside, $\theta_0 \neq 0$, R_1 is set equal to Z_0 to prevent reflections that result in a second, undesired scanned beam. Note that the above equation accounts for multiple reflections on the transmission line, resulting in a progressive phase shift along the radiating elements that nearly approximates the ideal phase shift given by $\psi = \pm k_0 d \sin\theta_0 - m\pi$.

To meet the sidelobe requirement, the amplitude distribution along each linear dipole subarray must be tapered. Table 1 summarizes the required resonant resistances R_i/Z_0 given the amplitude distribution $\sqrt{P_i}$ specified in the table.

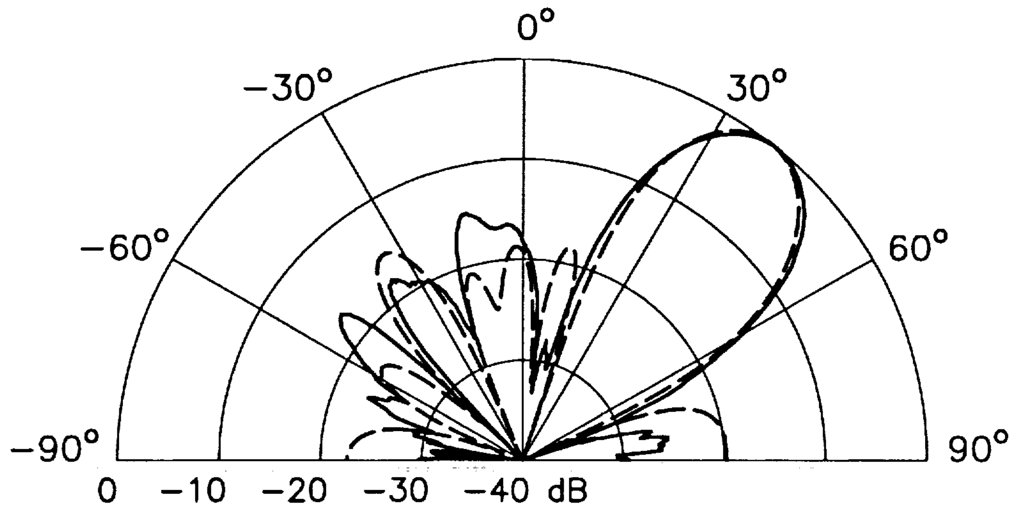

Figure 5. Elevation pattern of linear slot array.
Measured (—). Calculated (- -).

i	P_i	R_i/Z_0
1	.36	1.00
2	.49	0.75
3	.81	2.14
4	1.0	2.36
5	1.0	2.86
6	.81	6.47
7	.49	10.0
8	.36	14.5

Table 1. Linear dipole array P_i and R_i/Z_0.

Slot Linear Array Design

Similarly, in an equivalent circuit model of an array of series-fed-type slots [5], the ith slot represents a series impedance, $Z_i(\omega) = R_i(\omega) + jX_i(\omega)$, to the transmission line as shown in Figure 3. A unit cell of the array may be defined, as shown in Figure 4, similar to that of the dipole array, with the exception that

$$Z_{L,i} = Z_i + Z'_{L,i-1}$$

By taking the ratio of I_{i+1}/I_i and noting that the power dissipated in each slot radiator is $P_i = |I_i|^2 R_i/2$, a recursive expression for the slot resistances R_i is given by

$$R_i = \frac{2P_i}{|I_i|^2} = \frac{2P_i}{|I_{i-1}|^2} \frac{|1 - \Gamma_{L,i-1}|^2}{|1 - \Gamma_{L,i-1} e^{-j2k\ell}|^2}$$

when the amplitude distribution, $\sqrt{P_i}$ ($i = 1, 2, \ldots, N$), the transmission line length $k\ell$, and R_1 are specified. Similar to the transmit array, the amplitude distribution along each linear slot subarray must also be tapered to meet the sidelobe requirement. Table 2 summarizes the required resonant resistances R_i/Z_0 given the amplitude distribution $\sqrt{P_i}$ shown.

i	P_i	R_i/Z_0
1	.36	1.00
2	.49	1.33
3	.81	0.52
4	1.0	0.37
5	1.0	0.36
6	.81	0.18
7	.49	0.08
8	.36	0.07

Table 2. Linear slot array P_i and R_i/Z_0.

Experimental Results

A linear, cavity-backed slot array, consisting of 8 elements with an interelement spacing of $0.485\lambda_0$, has been fabricated and tested, operating at 20 GHz with a main beam direction approximately 40° from broadside. The slot elements were characterized both theoretically and

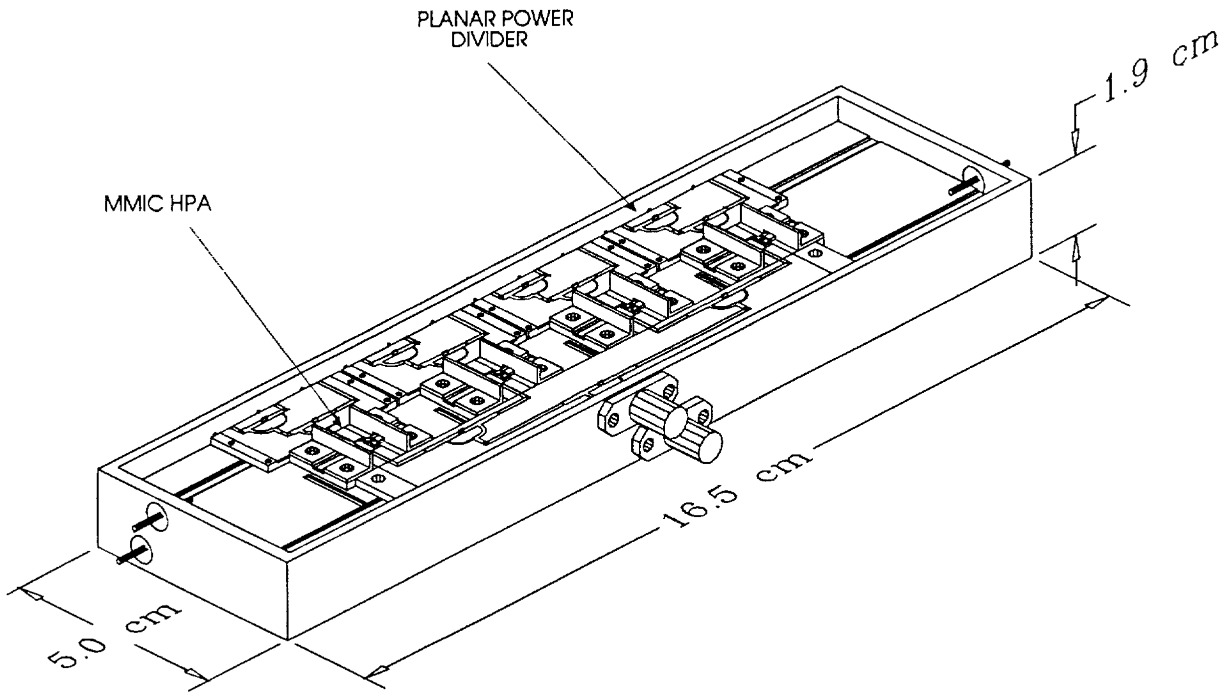

Figure 6. Transmit/Receive MMIC module.

experimentally as a function of offset, with the experimental characterization performed using the TRL calibration technique. The effective dielectric constant was taken to be approximately $\epsilon_{\text{eff},r} = 2.1$. Due to the fact that the element resonant frequency is a function of offset, the element slot lengths are all slightly different. Shorting pins are used to suppress undesirable cavity modes. As shown in Figure 5, good agreement between predicted and measured patterns was obtained. Total loss in the slot array was measured to be approximately -1.3 dB. (Note that the attenuation of a shielded microstrip line is measured to be approximately -0.24 dB/λ_0.) Experimental results will be presented for a similar linear series-fed-type array of dipoles operating at 30 GHz.

T/R MMIC MODULE

The AMT active array antenna MMIC module contains MMIC HPAs for the transmit array and MMIC LNAs for the receive array. The MMIC circuits are connected to the transmit and receive linear subarrays: one LNA for each receive linear slot array, and one HPA for each pair of transmit linear dipole arrays. All the MMIC circuits and power dividers are assembled onto a single transmit/receive module, with the HPAs and LNAs on opposite sides of the module as illustrated in Figure 6. The T/R module is mechanically attached to the transmit and receive array structure, as shown conceptually in Figure 1, via coaxial feed-throughs.

The transmit module provides greater than 1 Watt of RF power to the dipole array at the 30 GHz transmit frequency band. Five MMIC MESFET amplifiers provide up to 0.5 W to each pair of transmit subarrays. All five MMIC HPAs are mounted on molybdenum subcarriers with a copper heat spreader beneath each device. The transmit modules are designed to maintain gate junction temperatures below 125°C. A planar five-way power dividing circuit distributes the RF signal to each amplifier subcarrier.

The receive module consists of 14 MMIC pseudomorphic HEMT (PHEMT) LNAs. Each LNA has a noise figure of approximately 3.2 dB and a gain of 9 dB at 20 GHz. Two additional MMIC LNAs are located on the antenna platform to meet the G/T requirement and the DC power consumption constraint. All 14 LNAs are mounted in the receive portion of the T/R module with a 14-way planar power divider.

CONCLUSION

An active K/K_a-band antenna array is currently under development at the Jet Propulsion Laboratory for NASA's ACTS Mobile Terminal (AMT). Satellite tracking for the land-mobile vehicular antenna system involves azimuthal "mechanical dithering" of the antenna, where the antenna radiates a fixed beam 46° above the horizon. The antenna is to transmit horizontal polarization and receive vertical polarization at 29.634±0.15 GHz and 19.914±0.15 GHz, respectively, and will provide a minimum of 22 dBW EIRP transmit power density and a −8 dB/K° receive sensitivity. The AMT active antenna array is a multilayered assembly in which a receive array of radiating slots and a transmit array of microstrip dipoles are interleaved such that they share the same aperture to provide a compact, dual-band antenna. The low-profile active array design, in addition to its small size and low weight characteristics, offers the potential advantage of low-cost, high-volume production with easy integration with active integrated circuit components.

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