Coupled Oscillator Based Agile Beam Transmitters and Receivers: A Review of Work at JPL

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Abstract— This is a review of the work done at Caltech's Jet Propulsion Laboratory during the past decade on development of the coupled oscillator technology in phased array applications to spacecraft telecommunications. First, some historical background is provided to set the work in context. However, this is by no means intended to be a comprehensive review of all work in this area. Rather, the focus is on the JPL contribution with some mention of other work which provided either insight or motivation.

In the mid 1990's, R. A. York, and collaborators proposed that an array of mutually injection locked electronic oscillators could provide appropriately phased signals to the radiating elements of an array antenna such that the radiated beam could be steered merely by tuning the end or perimeter oscillators of the array. York, et al. also proposed a receiving system based on such oscillator arrays in which the oscillators provide properly phased local oscillator signals to be mixed with the signals received by the array elements to remove the phase due to angle of arrival of the incident wave. These concepts were viewed as a promising simplification of the beam steering control system that could result in significant cost, mass, and prime power reduction and were therefore attractive for possible space application.

The initial work at JPL was largely theoretical and, in collaboration with York and Maccarini, Pogorzelski developed a linearized formulation of the analysis of such arrays that provided considerable insight into the dynamic behavior of the aperture phase as a function of oscillator tuning. The key results (and limitations) of this theoretical work and their implications for array performance are reviewed here. Subsequently, several experimental arrays were designed, fabricated, and tested. These arrays are described and the salient experimental results are outlined. The body of work described has brought JPL from mere awareness of the concept a decade ago, through development of several experimental transmitters and receivers based on the concept, to the brink of a current effort to integrate the transmit and receive functions in a single unit to be developed for future fight application.

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1. INTRODUCTION

The practical value of the concept of spatial power combining of microwave sources was suggested by Mink in the mid-eighties and his paper spawned a research program in this area spanning two decades.[1] Efficient power combining requires that the sources to be combined be phase locked to each other so as to produce mutually coherent signals for combining. York, then a graduate student at Cornell University studying with Compton, achieved this phase locked condition by mutual injection locking of electronic oscillators.[2] Later, York, as a faculty member at the University of California, Santa Barbara, and graduate student Peter Liao, conceived of a beam steering scheme in which linear phase progressions were generated across a linear array of mutually injection locked voltage controlled oscillators by anti-symmetrically detuning the end oscillators of the array away from the ensemble frequency as shown in Figure 1.[3][4] This scheme completely avoids the use of conventional phase shifters and vastly simplifies the beam steering control system in that the steering angle is determined by two analog varactor biasing voltages. A corresponding receive array concept due to Cao and York is shown in Figure 2.[5] Here, the oscillators provide local oscillator (LO) signals to be mixed with the signals received by the aperture elements to produce in-phase intermediate frequency signals that are then coherently combined. At this point, Caltech's Jet Propulsion Laboratory became interested in the concept as a means of providing, in a simple and low cost manner, agile beams for telecommunications in robotic planetary exploration and began a multi-year collaboration with York and his students.

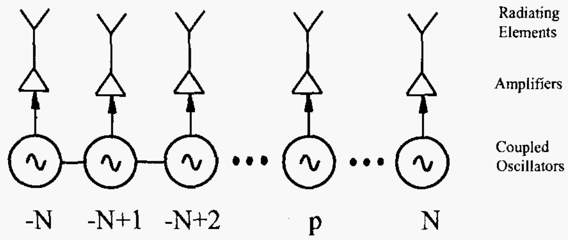


Figure 1. A linear transmit array of coupled oscillators.

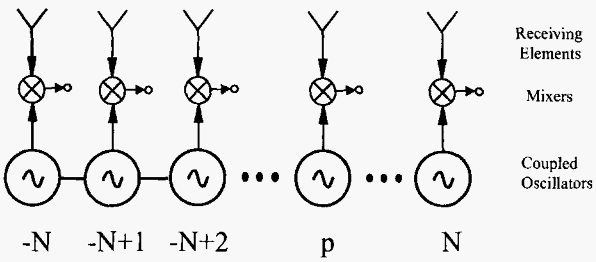


Figure 2. A linear receive array of coupled oscillators.

The initial collaborative effort was largely theoretical. York, and later Nogi and Itoh [6] had formulated the analysis of arrays of coupled oscillators by application of Adler's theory of injection locking [7] using Van der Pol's model of the oscillators [8]. It should be noted that the inter-oscillator phase difference is limited to ninety degrees for maintenance of lock and that this limits the achievable scan angle of the array. However, Alexanian, et al. suggested that this limitation can be mitigated via frequency multiplication. [9] For N coupled oscillators, this resulted in a system of N first order non-linear differential equations governing the array dynamics. Pogorzelski noticed that the formalism was reminiscent of a finite difference approximation of a diffusion equation and that, as a consequence, the phase variation across the array would be approximately analogous to temperature in a heat conduction problem. This idea was pursued in collaboration with York and Maccarini and resulted in a theory covering not only mutual injection locking but, also, arrays with external injection signals.[10][11] Subsequently, this theory was generalized to planar arrays.[12][13] Meanwhile, York and his students continued to gain understanding of the phase behavior of such arrays and proper design of the coupling network needed to achieve the desired phase behavior.[14][15] In the same time frame, Ispir, et al. built and tested the first planar agile beam array based on these principles.[16]

The preceding, while certainly not an all-inclusive description of work in this area, is presented to provide the context in which JPL began designing, building, and testing breadboard agile beam arrays based on coupled oscillators to investigate their applicability in space exploration and perhaps remote sensing. This paper summarizes that work.

A much broader overview of the general area of nonlinear technologies in antennas is given by Meadows, et al. [17]

2. THE THEORETICAL WORK

The theoretical work built upon the original formalism created by York, et al. based on that of Adler and van der Pol as described above. A continuous phase function was devised that took on the value of the phase of each oscillator as its argument became equal to the index of that oscillator. The value of this function between the oscillators is physically meaningless but the function satisfies a partial differential equation, the diffusion equation, that can be solved analytically in many cases of interest. The boundary conditions at the ends of the array were determined to be of Neumann type via a clever artifice due to York in which the lack of injection signal from a neighboring oscillator that arises at the ends of the array is simulated by a fictitious oscillator dynamically tuned so as to produce no injection. This condition requires that the phase of the fictitious oscillator be equal to that of the end oscillator resulting in a zero derivative of the phase function; i.e. a Neumann boundary condition.

Linear Arrays

As described in detail in [10], the dynamic behavior of a linear array of mutually injection locked oscillators with nearest neighbor coupling can be determined approximately by solving,

$$\frac{\partial^2 \phi}{\partial x^2} - \frac{\partial \phi}{\partial \tau} = -\frac{\omega_{tune} - \omega_{ref}}{\Delta\omega_{lock}} \tag{1}$$

where ϕ is the phase function, ω_{tune} is the tuning function, ω_{ref} is a reference frequency (usually the ensemble frequency of the array), and $\Delta\omega_{lock}$ is the inter-oscillator locking range. τ is the time measured in inverse locking ranges. If, in an array of 2a+1 oscillators, the oscillator at x=b is detuned by an amount C locking ranges, the solution for ϕ can be written,

$$\begin{aligned} \phi(x,\tau) = & \frac{C\tau}{2a+1} \\ & + C\sum_{n=0}^{\infty} \frac{2\cos\left(b\sqrt{\sigma_n}\right)\cos\left(x\sqrt{\sigma_n}\right)}{(2a+1)\sigma_n}\left(1-e^{-\sigma_n \tau}\right) \\ & + C\sum_{m=0}^{\infty} \frac{2\sin\left(b\sqrt{\sigma_m}\right)\sin\left(x\sqrt{\sigma_m}\right)}{(2a+1)\sigma_m}\left(1-e^{-\sigma_m \tau}\right) \end{aligned} \tag{2}$$

where,

$$\sigma_n = \left(\frac{2n\pi}{2a+1}\right)^2$$

for n = 0, 1, 2, ... and

$$\sigma_m = \left(\frac{(2m+1)\pi}{2a+1} \right)^2$$

for m=0, 1, 2, ...

In steady state, this becomes,

$$\begin{aligned} \phi_{ss}(x,\tau) &= C\sum_{n=1}^{\infty} \frac{2\cos\left(b\sqrt{\sigma_n}\right)\cos\left(x\sqrt{\sigma_n}\right)}{(2a+1)\sigma_n} \\ &+ C\sum_{m=1}^{\infty} \frac{2\sin\left(b\sqrt{\sigma_m}\right)\sin\left(x\sqrt{\sigma_m}\right)}{(2a+1)\sigma_m} \\ &= \frac{C}{2(2a+1)}\left[x^2 + b^2 - (2a+1)|b-x| + \frac{1}{6}(2a+1)^2\right] \end{aligned} \tag{3}$$

indicating that the fundamental form of the phase function when the end oscillators are detuned is parabolic.

Now, for an array in which the end oscillators are anti-symmetrically detuned by $\Delta\omega_T$ to produce beam steering, one may superpose two such solutions to obtain,

$$\phi(x,\tau) = \frac{\Delta\omega_T}{\Delta\omega_{lock}} \sum_{m=0}^{\infty} \frac{2\sin\left(b\sqrt{\sigma_m}\right)\sin\left(x\sqrt{\sigma_m}\right)}{(2a+1)\sigma_m}\left(1 - e^{-\sigma_m \tau}\right) \tag{4}$$

and the steady state solution becomes,

$$\phi(x) = \left(\frac{\Delta\omega_T}{\Delta\omega_{lock}} \right) x \tag{5}$$

that is, a linear phase distribution. Here a limitation of the linearization leading to the diffusion equation becomes evident. The diffusion equation results if one assumes small phase differences between oscillators permitting the sine functions appearing in York's fully nonlinear formulation to be replaced by their arguments. This approximation fails when the phase differences become large and completely breaks down near the limits of lock. Thus, when the detuning is nearly equal to the locking range, the above formula gives a phase equal to x when, in fact, the exact result is $(\pi/2)$x.

The dynamic behavior of the phase given by (4) above is shown in Figure 3 and the corresponding dynamic behavior of the far-zone antenna beam is shown in Figure 4.

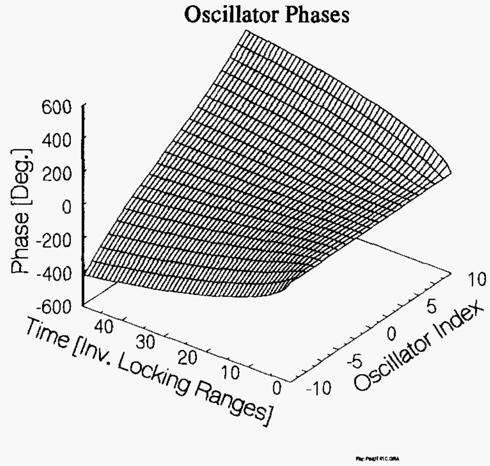


Figure 3. The dynamic behavior of the aperture phase.

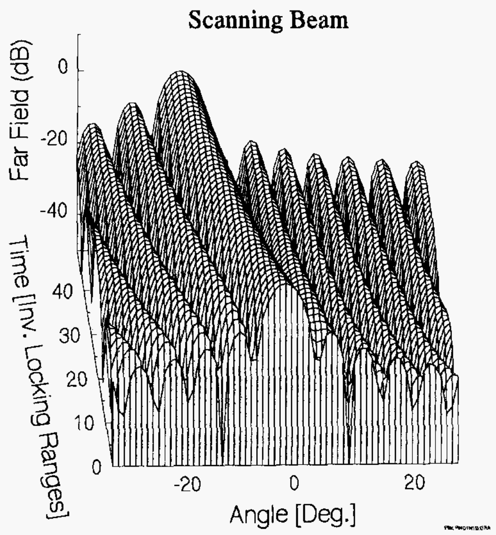


Figure 4. The dynamic behavior of the far-zone beam.

It was further noted that such an array of coupled oscillators could conveniently provide excitation signals to the elements of a linear phased array implementing Kott's patented sidelobe suppression scheme.[18] In this scheme one adds a pair of elements at the ends of an array and excites them in such a manner as to form an interferometer pattern that matches the sidelobe pattern of the original array in a certain angular range. The needed excitation signals for these added elements arise naturally in an oscillator array in which radiating elements are connected to every other oscillator.[19] (This, by the way, has been suggested as an alternative to frequency multiplication as a means of extending the steering range of the antenna.)

If external injection signals are supplied to the oscillators of the array, the equation corresponding to (1) is,

$$\begin{aligned}\frac{\partial^2 \phi}{\partial x^2} - V(x)\phi - \frac{\partial \phi}{\partial \tau} \\ = -\frac{\omega_{tune} - \omega_{ref}}{\Delta\omega_{lock}} - V(x)\phi_{inj}(\tau)\end{aligned} \quad (6)$$

where V(x) is a continuous function that takes on the amplitude of the injection signal at a given oscillator when x takes on the value of the index of that oscillator and ϕ_{inj} gives the time dependence of the injection signals. Here again, many solutions of interest may be obtained analytically. In particular, a beam steering scheme due to Karl Stephan [20] involving injection of the end oscillators with appropriately phase shifted signals can be modeled in this approximation yielding a steady state solution for the phase in the form,

$$\phi(x,\infty) = \frac{B_2 p_2 + B_1 p_1 + \frac{1}{2} B_1 B_2 \left[(b_2 - b_1)(p_2 + p_1) + \left(|b_1 - x| - |b_2 - x| \right)(p_2 - p_1) \right]}{B_2 + B_1 + B_1 B_2 (b_2 - b_1)} \quad (7)$$

where the constants, B, represent the strength of the injection signals while the constants, the p's represent their phases, and the b's represent their locations in the array. Again, small inter-oscillator phase differences are assumed. Details of this analysis are given in [11].

The network that couples the oscillators together was initially assumed to have a Q much lower that that of the oscillators; i.e., a broadband network. This was achieved by terminating the coupling transmission lines in their characteristic impedances thus minimizing standing waves (resonances) on the line. The coupling strength, which was assumed to be weak, was controlled using series coupling resistors between the lines and the oscillators. The strong coupling case was treated by Nogi, et al. and resulted in modes with amplitude variation across the array that had to be suppressed by means of resistors at the center of the coupling lines.[6] In our circuits, the coupling was implemented between the tank circuits (resonators) of the oscillators to decouple the design from that of the radiating aperture but, coupling between oscillator outputs is also applicable. Details of the design of coupling networks are presented in [21].

Planar Arrays

The above approximate analysis can be generalized to planar arrays. Initially, a Cartesian lattice was assumed resulting in four nearest neighbors to which each oscillator is coupled as shown in Fig. 5.

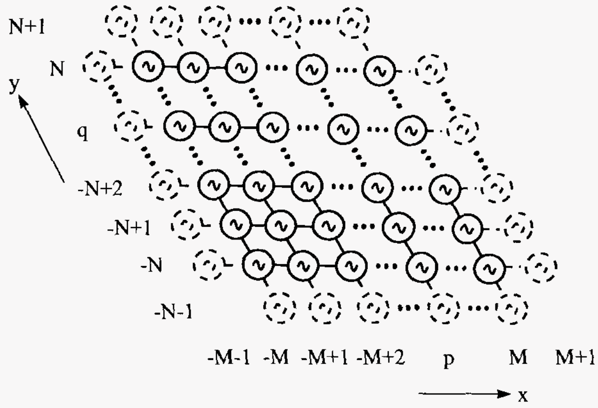


Figure 5. A planar coupled oscillator array.

The oscillators and coupling lines shown dashed are the fictitious boundary oscillators leading to the Neumann boundary condition as described in the linear array case. Assuming small inter-oscillator phase differences permits one to derive the planar analog of equation (1) in the form,

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} - \frac{\partial \phi}{\partial \tau} = -\frac{\omega_{tune} - \omega_{ref}}{\Delta\omega_{lock}} \quad (8)$$

Thus, in the planar case the phase is again analogous to temperature in heat conduction in that it is governed by a diffusion equation. Beamsteering may be accomplished by detuning the perimeter oscillators corresponding to the source function,

$$\begin{aligned}\frac{\omega_{tune}}{\Delta\omega_{lock}} = \frac{\omega_{ref}}{\Delta\omega_{lock}} + \Big[\Omega_{x_1}\delta(x' - c_1) + \Omega_{x_2}\delta(x' - c_2) \\ + \Omega_{y_1}\delta(y' - d_1) + \Omega_{y_2}\delta(y' - d_2)\Big]u(\tau)\end{aligned} \quad (9)$$

With this source function substituted on the right side, (8) may be solved via Laplace transforms to obtain the dynamic phase behavior given by,

$$\phi(x,y;\tau)=\left(\frac{\Omega_{x_1}+\Omega_{x_2}}{2a+1}+\frac{\Omega_{y_1}+\Omega_{y_2}}{2b+1}\right)\tau u(\tau)$$

$$+\frac{\Omega_{x_1}}{(2a+1)}\sum_{p=1}^{\infty}\frac{\cos\left[\frac{p\pi}{2a+1}(x-c_1)\right]+(-1)^p\cos\left[\frac{p\pi}{2a+1}(x+c_1)\right]}{\left(\frac{p\pi}{2a+1}\right)^2}\left[1-e^{-\left(\frac{p\pi}{2a+1}\right)^2\tau}\right]u(\tau)$$

$$+\frac{\Omega_{x_2}}{(2a+1)}\sum_{p=1}^{\infty}\frac{\cos\left[\frac{p\pi}{2a+1}(x-c_2)\right]+(-1)^p\cos\left[\frac{p\pi}{2a+1}(x+c_2)\right]}{\left(\frac{p\pi}{2a+1}\right)^2}\left[1-e^{-\left(\frac{p\pi}{2a+1}\right)^2\tau}\right]u(\tau)$$

$$+\frac{\Omega_{y_1}}{(2b+1)}\sum_{p=1}^{\infty}\frac{\cos\left[\frac{p\pi}{2b+1}(y-d_1)\right]+(-1)^p\cos\left[\frac{p\pi}{2b+1}(y+d_1)\right]}{\left(\frac{p\pi}{2b+1}\right)^2}\left[1-e^{-\left(\frac{p\pi}{2b+1}\right)^2\tau}\right]u(\tau)$$

$$+\frac{\Omega_{y_2}}{(2b+1)}\sum_{p=1}^{\infty}\frac{\cos\left[\frac{p\pi}{2b+1}(y-d_2)\right]+(-1)^p\cos\left[\frac{p\pi}{2a+1}(y+d_2)\right]}{\left(\frac{p\pi}{2b+1}\right)^2}\left[1-e^{-\left(\frac{p\pi}{2b+1}\right)^2\tau}\right]u(\tau)$$

(10)

This behavior is shown in Fig. 6 for a step application of the tuning biases. The corresponding beam motion is shown in Fig. 7 at equal time increments and the dynamic behavior of the gain is shown in Fig. 8. In steady state, if the tuning is antisymmetric, this becomes,

$$\phi(x,y;\infty)=\frac{\Omega_x}{2}\left(|x+c|-|x-c|\right)+\frac{\Omega_y}{2}\left(|y+d|-|y-d|\right) \quad (11)$$

which represents a planar phase distribution with slope controlled by the tuning. The desired steering angle determines the needed tuning coefficients via the expressions,

$$\Omega_x=2\pi\frac{h}{\lambda}\sin\theta_0\cos\phi_0$$
$$\Omega_y=2\pi\frac{h}{\lambda}\sin\theta_0\sin\phi_0 \quad (12)$$

where h is the element spacing in the radiating aperture and λ is the wavelength. Sequential application of appropriate steering biases can produce beam motion on an arbitrary trajectory in space as shown in Fig. 9. More detail on this approach is presented in [12]. Finally, it is noted that the Kott sidelobe suppression scheme can also be implemented in planar arrays.[19]

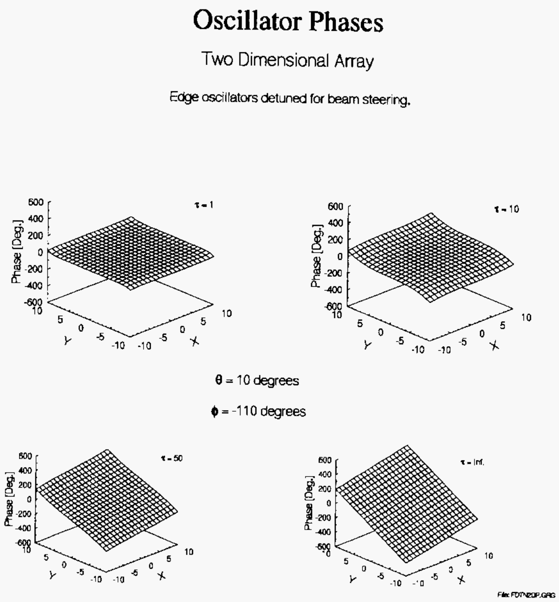


Figure 6. Phase dynamics during beamsteering.

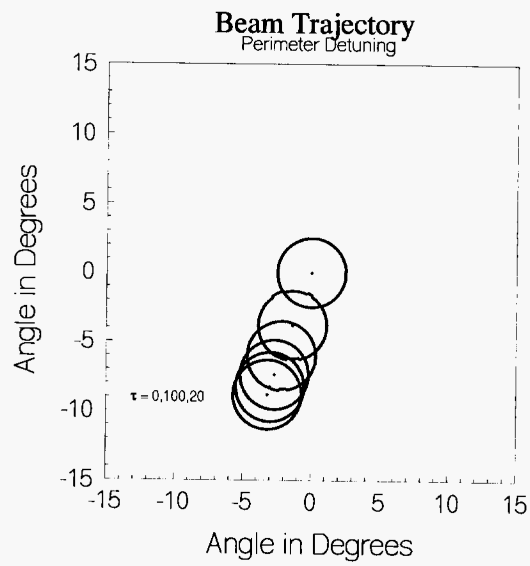


Figure 7. Antenna beam peak and three dB contours.

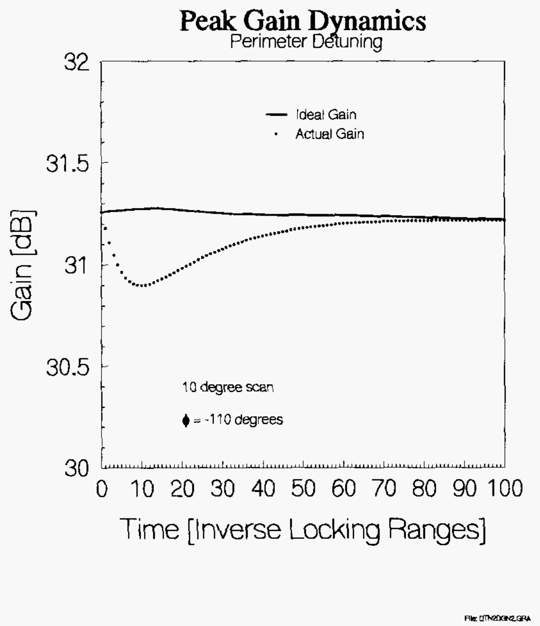


Figure 8. Antenna gain during beamsteering.

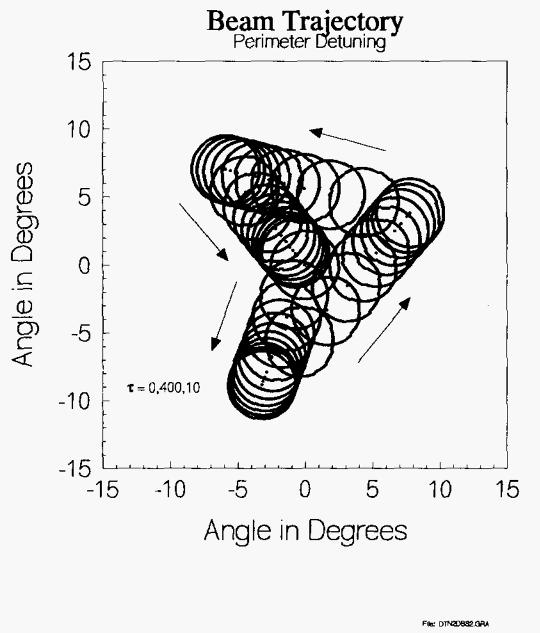


Figure 9. Sequential beamsteering.

For larger steering angles, one must resort to numerical solution of the full nonlinear set of differential equations because the present linearized theory breaks down. Nevertheless, this simplified analysis provides intuitive understanding of the behavior of such arrays.

Here again, if external injection signals are applied to the array, equation (8) can be generalized in analogy with (6) resulting in,

$$\frac{\partial^2 \phi}{\partial x^2}+\frac{\partial^2 \phi}{\partial y^2}-V(x,y)\phi-\frac{\partial \phi}{\partial \tau}=-\frac{\omega_{tune}-\omega_{ref}}{\Delta\omega_{lock}}-V(x,y)\phi_{inj}(x,y;\tau) \tag{13}$$

where the function V gives the distribution of injection signals and ϕ_{inj} gives their time dependence. Beamsteering may be accomplished by injection of the perimeter oscillators only and phase shifting these injection signals as proposed by Stephan.[20] Solution of (13) in such cases is more complicated than in cases without external injection but can be carried out as described in [13] leading to approximate prediction of the dynamic behavior of the phase distribution. It should be noted that changing the phase of the injection signals too rapidly can result in loss of lock but this can be avoided by using a more gradual phase change. Here again, it is emphasized that the linearized theory resulting in (13) assumes small inter-oscillator phase differences and that cases involving large inter-oscillator phase differences require the solution of the fully non-linear equations and must be carried out numerically. The present linear approximation, however, permits analytic treatment of many cases of interest.[13]

Non-Cartesian Lattices

The preceeding analysis of planar arrays assumed a Cartesian lattice with each oscillator having four nearest neighbors. However, two other lattices are common in phased array design, the triangular lattice with six nearest neighbors shown in Fig. 10 and the hexagonal lattice with three nearest neighbors shown in Fig. 11.

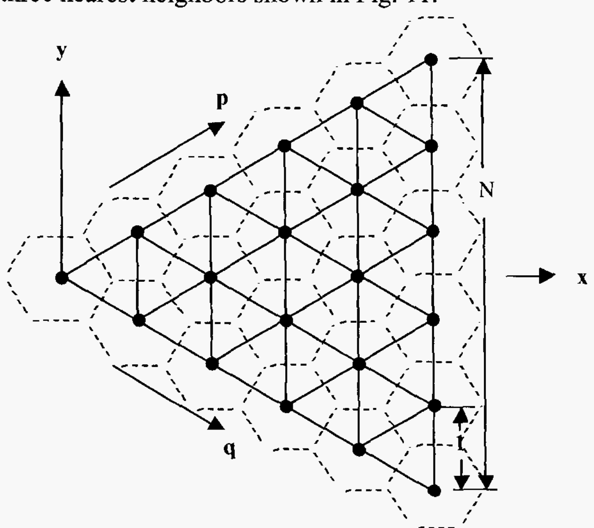


Figure 10. Triangular coupling.

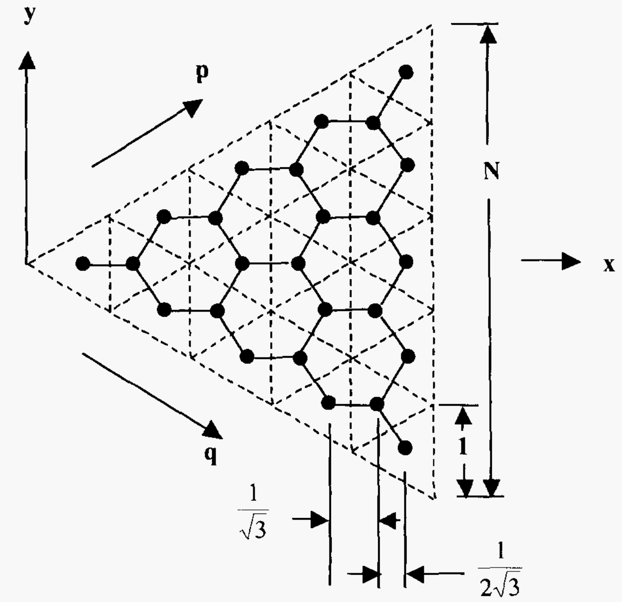


Figure 11. Hexagonal coupling.

Analysis of these alternative coupling schemes has been carried out in the linear approximation described above and the solution procedure and results are described in detail in [22]. Interestingly, the analysis involves the eigenfunctions of a triangular waveguide. In essence, it was found that the behavior of arrays using the triangular and hexagonal coupling schemes, both with triangular boundaries, is similar to that of the Cartesian case except that the triangular coupling results in a dynamic behavior about 50% faster than that of the Cartesian scheme while the hexagonal coupling is about four times slower. In each case, beamsteering requires constant detuning of the oscillators along each of the three edges of the array and the three constants are related leaving two independent steering biases for full two dimensional steering. As in all previous geometries, here too the steering angle is limited by the ninety degree limit on inter-oscillator phase necessary to maintain lock, a limit which can be mitigated by frequency multiplication.[9]

Probably the most significant result of the above analysis is the fact that planar steady state phase distributions, while exact solutions of the approximate linearized equations, are not in general solutions of the fully non-linear equations for the hexagonal coupling scheme except at six discrete azimuthal beamsteering angles. Between these angles, the solution is nonplanar and an exact expression for this nonplanar steady state solution has been obtained analytically by Pogorzelski.[23]

3. The Experimental Work

The experimental program at JPL began in the mid-nineties with very simple three element oscillator arrays used in studying mutual injection locking. The oscillator used was an S-Band MMIC voltage controlled oscillator (VCO) with external varactor for tuning suggested by Professor York. [Pacific Monolithics PM-2503] This permitted the coupling to be implemented at the tuning port rather than at the output thus separating the antenna design from the oscillator array design. (If coupling is done at the oscillator output, the inter-element coupling in the radiating aperture also contributes to the inter-oscillator coupling thus complicating the design. This was the scheme used by Isper, et al. [16]) As confidence was gained in our ability to reliably build mutually injection locked arrays, a 2.5 GHz seven element transmit array was constructed using the MMIC VCO's mentioned above.[24] This array is shown in Fig. 12.

Initial tuning of this array was carried out pairwise using a network analyzer and this process proved nearly prohibitively time consuming. Therefore, a phase diagnostic system was designed that used mixers as phase detectors as shown in Fig. 13. Hybrid couplers were used to provide a ninety degree phase shift in one mixer input so that the zero of output voltage corresponded with zero phase difference. This provided a six channel system to indicate the phase differences between adjacent oscillators in the seven element array. The output voltages were digitized and processed with LabView to display the phase distribution across the array with the center oscillator as the reference as shown in Fig. 14.

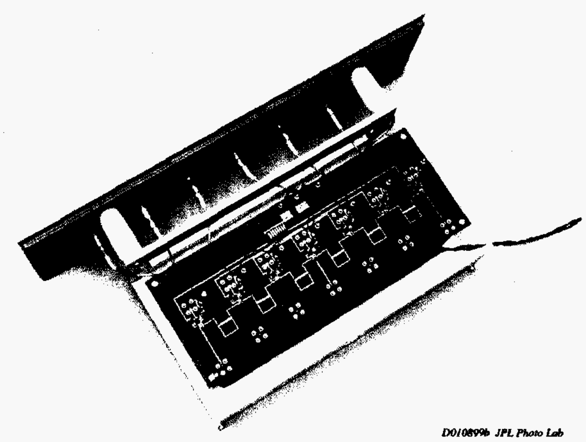


Figure 12. Seven element S-band array.

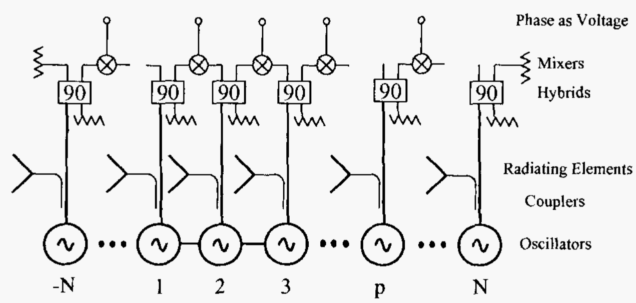


Figure 13. Phase diagnostic system.

Figure 14. Early phase diagnostic system and display.

This array was evaluated on an antenna measurement range and produced the radiated beams shown in Fig. 15.

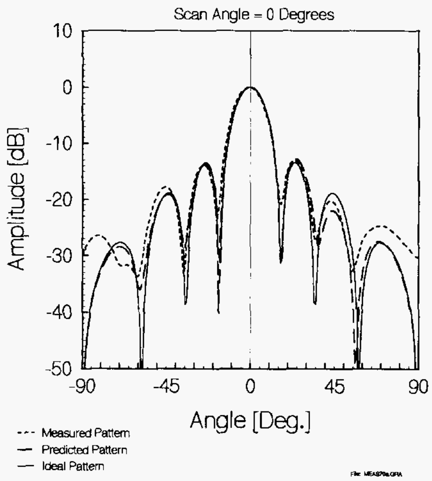


Figure 15a. Unscanned beam.

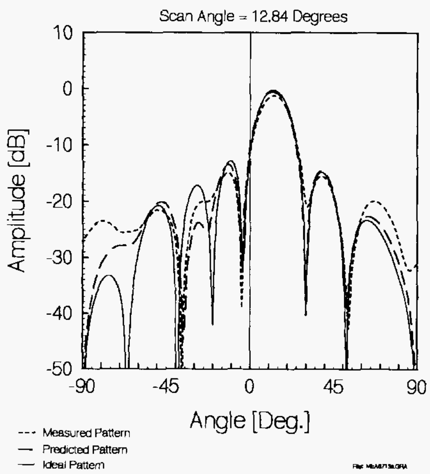


Figure 15b. Scanned beam.

This array was also used to investigate the transient behavior of coupled oscillators in an effort to understand better the modulation characteristics of such arrays. It seemed clear that if all of the oscillators were frequency modulated, the array would effectively transmit the modulated signal provided the tuning curves of the oscillators were sufficiently similar. However, it was also conjectured that modulation of less that the entire array, say only one or two oscillators, might also yield acceptable results. Thus, it became important to verify the theory concerning transient behavior. This was done by square wave modulating individual oscillators of the seven element array and observing the phase response using the diagnostic system. The result of these observations is shown in Fig. 16 where the phase differences between the oscillators are plotted as a function of time after switching the tuning voltage of one oscillator. Fig. 16a shows the result when an end oscillator is switched whereas Fig. 16b shows what happens when an interior oscillator is switched in tuning frequency. The qualitative agreement with the theoretical prediction is evident in each case. Details of this experiment can be found in [25].

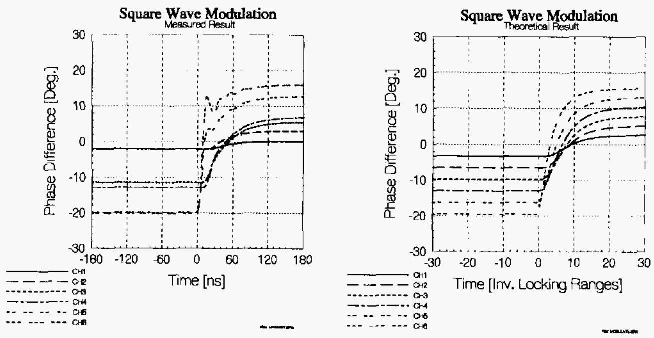


Figure 16a. Transient response with one end oscillator detuned.

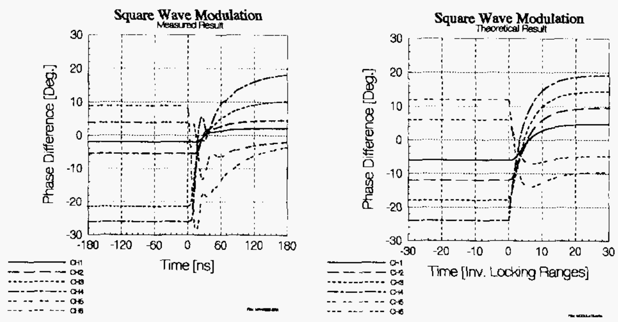


Figure 16b. Transient response with one interior oscillator detuned.

The next array built was a minimal size planar array of nine 2.8 GHz oscillators coupled on a Cartesian lattice in a 3 by 3 square. This was thought to be the first planar agile beam array based on coupled oscillators but was actually predated by the 4 by 4 array of Isper, et al. [16]. The array, which has not radiating aperture, is shown in Fig. 17 together with a control box with precision potentiometers with which to adjust the tuning of each oscillator. The inset shows the circuit board and the oscillators. The coupling is accomplished via microstrip lines at each oscillator connected with coaxial transmission lines via SMA connectors. A phase diagnostic system was included based on the same principles as that of the seven element linear array. It was basically a linear diagnostic system "snaked" through the planar array so as to measure phase differences which could be integrated in a LabView program to provide a display of the planar aperture phase distribution.

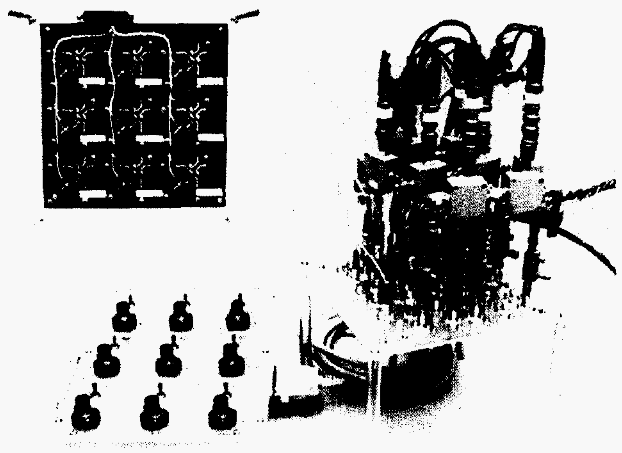


Figure 17. Nine element array.

The aperture phase distributions displayed on the virtual instrument are shown in Fig. 18. This array is described in detail in [26].

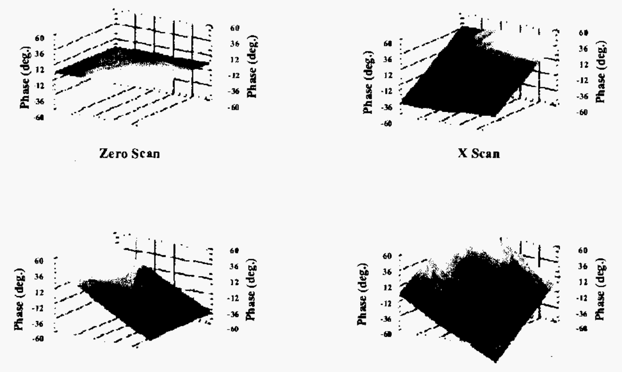


Figure 18. Nine element array aperture phases.

The above 3 by 3 oscillator array was then outfitted with frequency triplers at each oscillator output and an X-band radiating aperture appropriate to the tripled frequency, 8.4 GHz. This array is shown in Fig. 19 both on the bench and on the antenna range and its radiation patterns and corresponding aperture phase distributions are shown in Fig. 20. The line stretchers were used to equalize the electrical line lengths from the triplers to the radiating elements. Details of this array together with more extensive measurements are presented in [27].

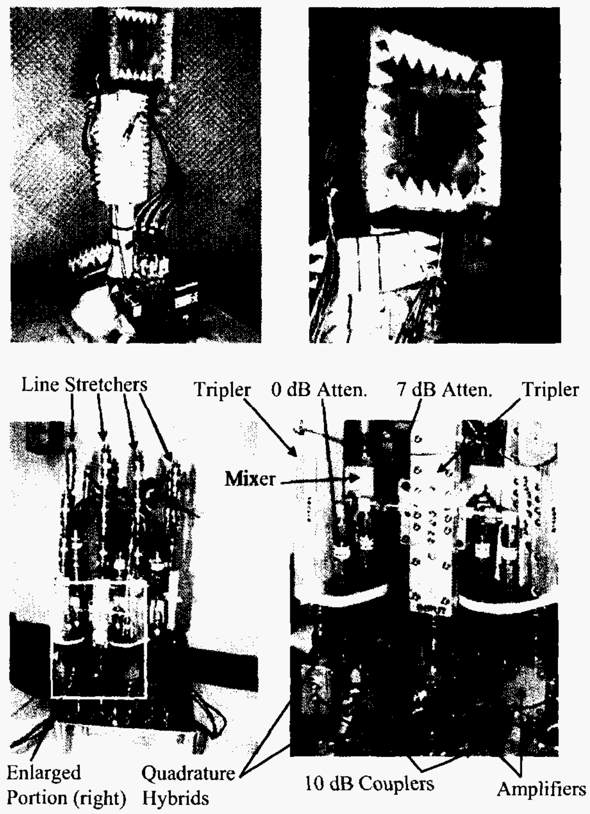


Figure 19. Nine element frequency tripled array.

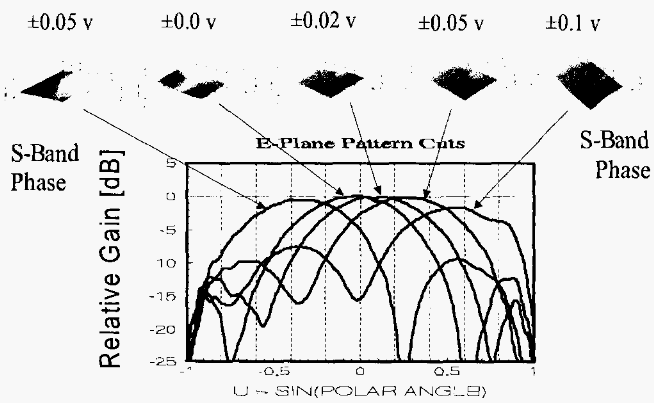


Figure 20. Nine element array aperture phases.

As a next step in the development of this technology, a 5 by 5 element S-band array was constructed again embodying a phase diagnostic system using mixers as phase detectors as shown in Fig. 21. Here the radiating aperture was integrated with the array as shown in Fig. 22. The array on the measurement range is shown in Fig. 23 and an example measurement is shown in Fig. 24.

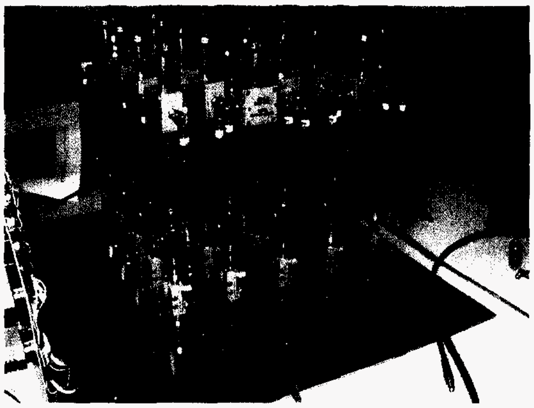


Figure 21. 25 element array phase diagnostic system.

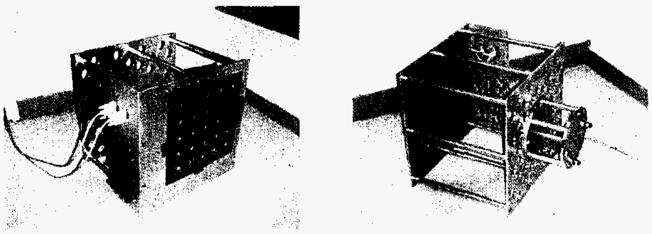


Figure 22. 25 element array with integrated radiating aperture. (Phase diagnostic system removed.)

Figure 23. 25 element array on measurement range.

The phase diagnostic system for this array was made so that it could be removed and the array operated without it. However, it was found that removal of the diagnostic system changed the calibration of the array. Therefore, it is planned that all future arrays will embody a permanently installed (built-in) diagnostic system. Details concerning this array and its performance are provided in [28].

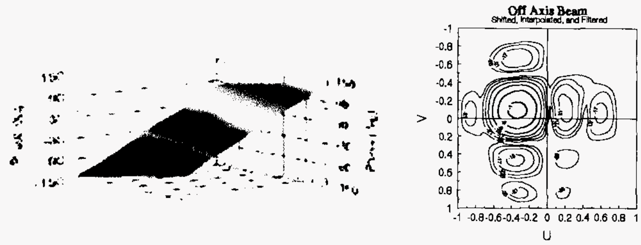


Figure 24. Beam scanned to (u, v) = (-0.35, 0.1) while phase distribution implies (u, v) = (0.305, 0.083).

The most recent experimental work concerned a receive concept testbed originally designed under Ballistic Missile Defense Organization (BMDO) funding and damaged in fabrication. This was a circuit board with fifteen L-band oscillators [Modco CM1398MST] coupled with transmission lines. The purpose was to use the oscillators to provide local oscillator signals to be mixed with simulated element-received signals to demonstrate intermediate frequency (if) combining as envisioned for a receive array. Funding recently became available to repair this damaged board and conduct the "if" combining experiment. The apparatus is shown in Fig. 25.

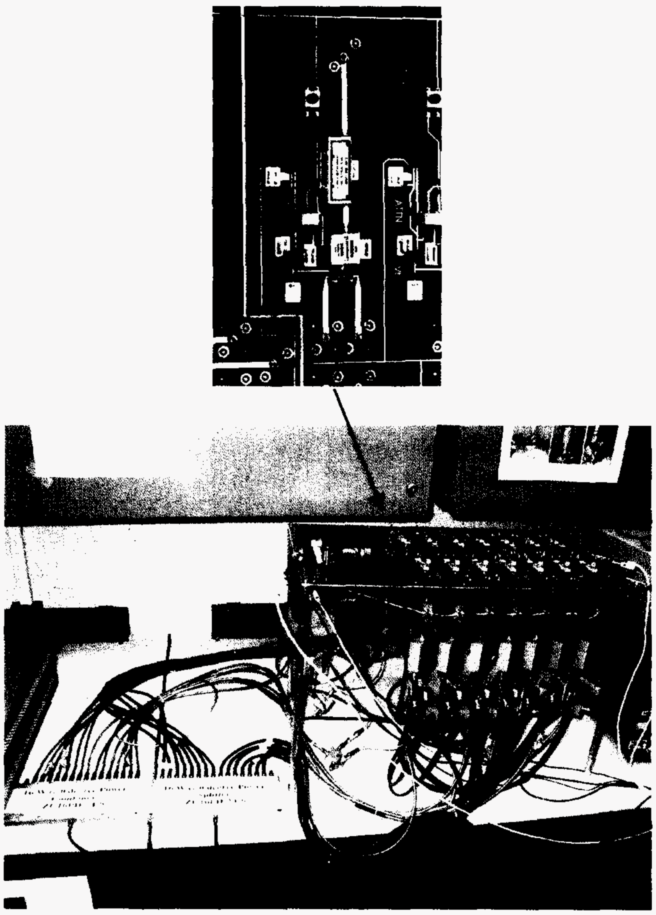


Figure 25. 15 oscillator receive concept testbed.

Visible in the photograph are two 16-way power dividers. One of these divides a 1.950 GHz signal from a laboratory signal generator to simulate signals received by the aperture elements under broadside illumination. In this case only eight signals are used and these are connected to mixers whose 1.265 GHz local oscillator signals are supplied by every other oscillator (alternate oscillators) in the fifteen element array. As mentioned earlier, this extends the scan range over that attainable by using adjacent oscillators because adjacent oscillators can only have 90 degrees of phase between them whereas alternate oscillators can achieve nearly 180 degrees of phase difference. The mixer outputs at the intermediate frequency 685 MHz are combined by the other power divider. The output of this is the received signal measured in the experiment.

With a broadside incident signal simulated with the power divider, measurement of the if output while scanning the array by detuning the end oscillators provides data for the plot of the beam shape shown in Fig. 26. Note that this is not the beamshape normally measured on an antenna range with a fixed scan angle. Rather, this is the beam shape that would be relevant to a signal acquisition sequence in which the signal incidence angle is fixed and the beam is scanned to find it.

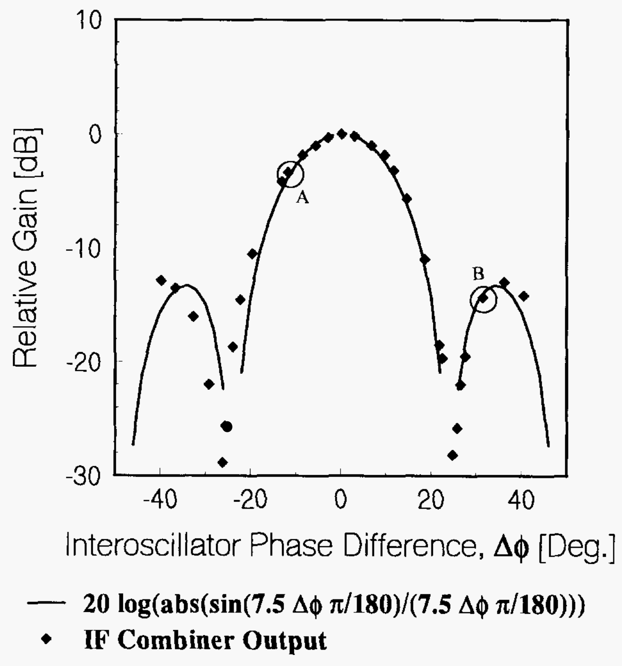
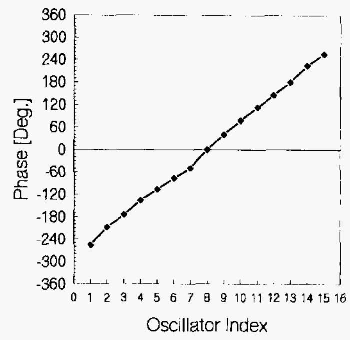
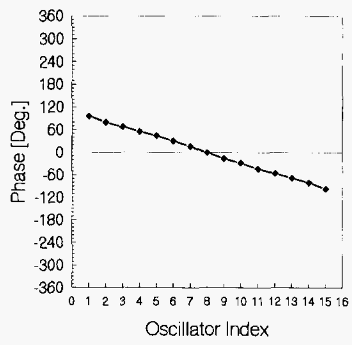


Figure 26. Receive array beam shape.

The oscillator phases corresponding to points A and B in Fig. 26, measured with a diagnostic system similar to those described earlier, are shown in Fig. 27.



Point A



Point B

Figure 27. Phase distributions corresponding to points A and B in Figure 26.

Finally, this apparatus was used to demonstrate in a limited fashion the Kott method of sidelobe cancellation.[18] In this demonstration, the end oscillators were used to generate the interferometer pattern and this was used to cancel a sidelobe of the pattern of the center six alternate oscillators as indicated in Figure 28. The result is shown in Fig. 29. Details of these demonstrations will be found in [29].

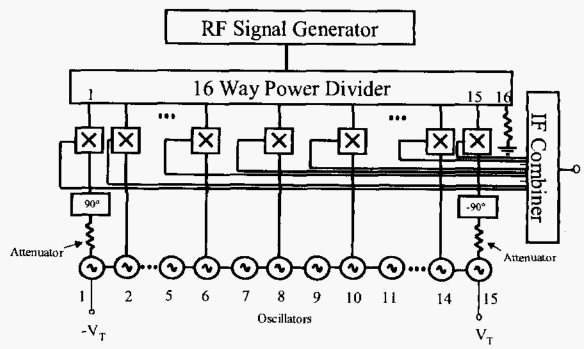


Figure 28. Circuit for demonstration of Kott sidelobe cancellation.

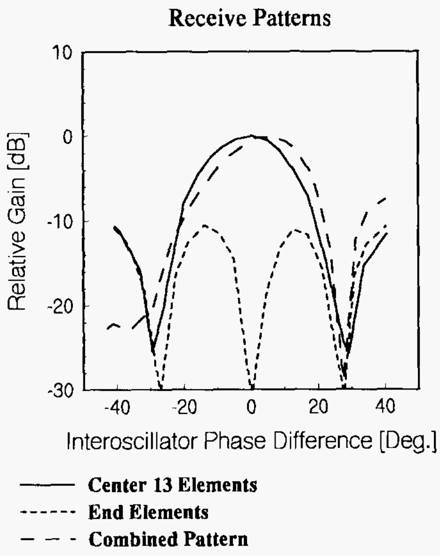


Figure 29. Array and interferometer patterns showing cancellation of the left sidelobe.

4. CONCLUDING REMARKS

The work at JPL over the past decade has encompassed a wide range of aspects concerning the behavior of coupled oscillator based transmitters and receivers. A large volume of theoretical work dealt with the transient behavior of these systems and the linearized theory leading to the diffusion equation facilitated intuitive understanding of that behavior. Moreover, the limitations of the linearized theory actually led to the discovery of some interesting properties of the fully nonlinear description particularly when the coupling lattice is not Cartesian. A number of experiments involving both linear and planar transmitting arrays and one linear receive array were described. These provided much insight into the practical aspects of actually constructing operational arrays of this type. One practical aspect not specifically addressed by JPL was treated by Shen and Pearson [30]. This concerns the manufacturing variability of components leading to a statistical variability in the free running frequency of the oscillators. In a coupled oscillator array, this leads to phase aberration. A number of interesting results were obtained via the Monte Carlo analysis carried out by Shen and Pearson. In the same time frame, a design optimization approach was proposed by Wang and Pearson to mitigate the impact of such variability.[31]

Recently, a 5 by 5 array was reported by Heath, et al. [32]. This work brought to our attention a phase comparator chip which became available in 2001 and which renders the phase diagnostic system much, much more compact than the one we developed using packaged mixers and hybrids. While the array of Heath,et al. uses such a compact phase measurement system, the radiating aperture was not integrated with the oscillator circuit board necessitating the use of 25 rf cables from the oscillators to the radiating elements much as in the JPL 3 by 3 array. Now, however, it appears possible to both integrate the radiating aperture and compress the diagnostic circuitry resulting in a very compact form factor completely integrated array. Heath has also point out the possibility of generating difference patterns with these arrays.[33]

Thus, it is becoming increasingly clear that the initial technological difficulties with the application of arrays of mutually injection locked oscillators in phase arrays are being overcome one by one and, in retrospect, the overall progress during the past decade has been remarkable. In fact, so numerous are the reported results that it has become nearly impossible, within the confines of a reasonable length paper, to do justice to all of these contributions. Because of this, I have largely confined myself to the JPL work though I have given in now and then to the temptation to describe the related work of others that has influenced my own efforts in one way or another. I must, therefore, apologize if I have inadvertently neglected to mention some of the important work of my colleagues in this field and hope that you will gently remind me of it when we next meet.

5. ACKNOWLEDGEMENTS

The work reported here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA). The earliest conceptual stages of this work were funded by the NASA Advanced Radar Technology Program. Then, beginning with the linearized approximate theoretical formalism, continuing through the seven element linear array development, and portions of the laboratory receive array testbed development, the work was funded by BMDO. The remainder of the work has been funded by NASA under the Cross Enterprise Technology Development Program, the Space Communications Program, and currently the Mars Technology Program and the Interplanetary Network Directorate Technology Program.

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BIOGRAPHY

Ronald J. Pogorzelski *(S'62-M'69-SM'82-F'95) received his B.S.E.E. and M.S.E.E. degrees from Wayne State University, Detroit, MI in 1964 and 1965, respectively, and his Ph.D. degree in Electrical Engineering and Physics from the California Institute of Technology, Pasadena, in 1970, where he studied under Professor Charles H. Papas.*

From 1969 to 1973, he was Assistant Professor of Engineering at the University of California, Los Angeles, where his research dealt with relativistic solution of Maxwell's equations. From 1973 to 1977, he was Associate Professor of Electrical Engineering at the University of Mississippi. There his research interests encompassed analytical and numerical aspects of electromagnetic radiation and scattering. In 1977 he joined TRW as a Senior Staff Engineer and remained there until 1990 serving as Subproject Manager in the Communications and Antenna Laboratory, and as Department Manager and Manager of the Senior Analytical Staff in the Electromagnetic Applications Center. From 1981 to 1990 he was also on the faculty of the University of Southern California, first as Part-time Instructor and then as Adjunct Full Professor. In 1990, he joined General Research Corporation as Director of the Engineering Research Group in Santa Barbara. Since 1993, he has been with the Jet Propulsion Laboratory as Supervisor of the Spacecraft Antenna Research Group and has been a Lecturer in Electrical Engineering at Caltech. In June 2001 he was appointed a JPL Senior Research Scientist.

Dr. Pogorzelski's work has resulted in more than 100 technical publications and presentations. In 1995 he also served as a member of a Blue Ribbon Panel evaluating the Army's Team Antenna Program in helicopter antennas and served for ten-years as a Program Evaluator for the Accreditation Board for Engineering and Technology. He has been active in the Union Radio Scientifique Internationale (URSI) and in the IEEE for several decades. He is the current Chair of U.S. Commission B (Fields and Waves) of URSI and is also a member of U. S. Commissions A and D.