# TDRSS MULTIPLE ACCESS RECEIVING PHASED ARRAY SYSTEM*

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## SUMMARY

A 30-element phased array, with remote beamforming and multiple access signal design, is the basis for a new multiple access concept to be used by the Tracking and Data Relay Satellite System (TDRSS). System tradeoffs evolved a control and calibration concept which parallels modern estimation theory in dynamic systems and reduces the complexity of adaptive control while maintaining the necessary accuracy. A system dynamic model propagates “open loop” estimates of optimal weight vectors based on user satellite ephemerides derived from tracking data. A sampled-data closed loop adaptive control system periodically updates the beam-steering vector to eliminate parameter drifts and modeling errors, and to maintain the weight vector near optimum. The concept is primarily useful in the specified noninterference environment, though some nulling capability is possible.

## INTRODUCTION

The TDRSS Multiple Access (MA) return link uses a spaceborne 30-element phased array and remote beamforming, together with PN spread-spectrum modulation, to provide simultaneous multiple access relay services for 20-user satellites at S-band. (Refer to Figure 1. ) The system must provide 85%- 100% orbital coverage with three geosynchronous satellites for user orbits between 200 km to 2000 km altitudes. The available bandwidth is 6 MHz and user EIRP’s are constrained by CCIR flux density limits. To limit self-interference in the multiple access system, user EIRP’s are also allocated proportional to the data rates, which vary from 100 bps to 50 kbps. The users cover a 26° field of view (FOV) from geosynchronous altitude of the relay satellites.

The limited user EIRP’s require about 30 dB of antenna gain and 3 dB noise figure receivers on the TDRS to support the data rates. But an antenna with a 26° FOV has only about 16 dB of gain. An array of 30 16-dB helices with remote beamforming and tracking

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produces the required 30 dB gain with a steerable 5° beam which provides some spatial discrimination in the multiple access system.

PN code modulation of the user signals over the 6 MHz bandwidth is easily accommodated by the array design at 2287.5 MHz center frequency since the percentage bandwidth is only 0. 26%. This PN spectrum spreading serves five functions: (1) It reduces the user flux density to obey the CCIR guidelines. (2) It reduces self-interference in the multiple access system by providing processing gains of 17.8 dB to 44.8 dB, depending on the user data rate. (3) Narrowband interference sources are rejected by the same degree of processing gain. (4) Accurate range measurements are possible by code phase comparison on a two-way link. (5) User identification for adaptive beamforming.

Remote bearnforming in the ground station removes the control complexity and weight from the spacecraft, but requires phase-coherent telemetering of the thirty element channels to each of 20 remote beamformers. (Refer to Figure 2. ) Phase coherence can be maintained, for short periods, in a coherent frequency division multiplexing downlink which uses 7.5 MHz channel spacing over a 225 MHz band at K-band (13.5 GHz) if a pilot-tone technique is used to estimate and compensate for path-length variations due to relay satellite motion. However, even at K-band, diurnal ionospheric time-delay variations introduce a linear phase-gradient across the array element channels. Random phase and gain drifts due to spacecraft parameter variations further degrade the accuracy of beamforming. Thus, some form of adaptive control is desirable.

## TRADEOFF ISSUES

Full-time adaptive control using the analog control loops with one loop/element would require 600 analog loops in a 30-element, 20-user system. So many independent analog loops could cause system problems with loop phase shift calibration, multiplier offsets and other imbalances to degrade the S/N below the few tenths dB allowed, in addition to being extremely expensive to implement.

Time-sharing of correlation loops and a digital microprocessor for control and adaptive algorithm implementation reduces drift and offset problems and reduces the complexity count by greater use of LSI. The degree of time-sharing depends upon the convergence rate and velocity lag effects of adaptive loops in tracking moving users at low S/N across the field of view. This could be satisfactorily resolved in TDRSS with one time-shared adaptive loop/user for a total of 20 time-shared adaptive loops, each using a dedicated microprocessor to implement the algorithm.

At the opposite extreme, an open-loop system uses ephemerides derived from tracking data to generate line-of-sight look angles and, from the antenna geometry, beam-steering vectors. With appropriate calibration, a system dynamic model could propagate beamsteering vectors for a considerable time, of the order of 15 minutes to an hour without recalibration. Such “open-loop” control further reduces the complexity since it depends more upon software and programming. However, convenient propagation of the optimum weight vector depends upon a simple noise environment as we will show later.

Resolution of this tradeoff conflict depends upon the fact that a single adaptive loop, time-shared between the 30-element channels of a single user’s beamformer can converge to the optimum weight vector for a known source location. The corresponding beamsteering vector can be derived as shown later. Thus, it is possible to derive an accurate beam-steering vector from a single user channel’s adaptive loop. Furthermore, in the coherent frequency division multiplexing system used to transmit the array element signals from the spacecraft to the ground, the entire RF path length from the array antenna elements through the coherent downlink and ground station to a 20-way power divider preceding the 20 beamformers is common to all user channels. Thus, except for a small portion of the RF path, in the individual temperature-controlled bearnformers, calibration of a single user channel allows the correction of all user channels coming from a given relay satellite.

Thus evolved a phased array control and calibration concept in which the known system dynamics model is used to propagate best estimates of the beam-steering vectors and a relatively narrowband time-shared adaptive loop provides periodic updates based on observations of the optimum beam- steering vector and the corresponding optimum weight vector, to reset the “initial conditions” of the open-loop dynamic model.

## ANTENNA ARRAY THEORY

The far-field amplitude pattern of an array of n identical elements is proportional to the inner product

$$\underline{\xi}^{\dagger}\underline{w} = (\underline{\xi}, \underline{w}) \tag{1}$$

where the beam-steering vector $\underline{\xi}$ has elements

$$\xi_i = \exp(-j\,\vec{k}\cdot\vec{P}_i) \tag{2}$$

and $\underline{w}$ is the array weight vector with the i<u>th</u> element, $w_i$. The propagation vector, $\vec{k}$, has magnitude $2\pi/\lambda$ at wavelength $\lambda$, and $\vec{P}_i$ is the i<u>th</u> position vector. The dagger (†) denotes conjugate transpose.

The array S/N, the ratio of Hermitian forms

$$\frac{S}{N} = \frac{|(\xi, w)|^2}{(\underline{w}, \Phi \underline{w})} \leq (\underline{\xi}, \Phi^{-1} \underline{\xi}) \tag{3}$$

is maximized for the weight vector choice

$$\underline{w} = \Phi^{-1} \underline{\xi} \tag{4}$$

by Schwarz's inequality. This is the "matched filter" solution for a signal in colored noise. Here, $\Phi$ is the spatial coherence matrix of array element signals.

## STATE VARIABLE DESCRIPTION

When system dynamics of user motion and parameter drifts are considered, the problem of control and calibration for the MA phased array return link parallels modern estimation theory for dynamic systems. This theory is characterized by dynamic models in a state variable description. (Refer to Figure 3.)

The beam-steering vector serves as a state vector and characterizes the desired user beam. The optimal weight vector satisfies the Wiener-Hopf equation and maximizes the S/N. It is linearly related to the beam-steering vector and could be similarly taken as a state-variable description, but the propagation of $\underline{w}$ is more difficult than $\underline{\xi}$.

The process model is characterized by a difference equation

$$\underline{\xi}_k = F_k \underline{\xi}_{k-1} + \underline{q}_k \tag{5}$$

where $F_k$ is a diagonal complex transition matrix whose elements are found from the antenna element coordinates $\{x_i, y_i\}$ and the change in look-angle direction cosines $\{\Delta\ell x, \Delta\ell y\}$. Thus

$$F_{ii}(k) = \exp\left[\frac{2\pi j}{\lambda} \begin{pmatrix} \Delta\ell_x(k) & \Delta\ell_y(k) \end{pmatrix} \cdot \begin{pmatrix} x_i \\ y_i \end{pmatrix}\right] \tag{6}$$

The vector, $q_k$, is a normal zero-mean random variable process. Thus, the sequence $\{\underline{\xi}_k\}$ and the corresponding weight vector sequence $\{\underline{w}_k\}$ are random processes and cannot be known exactly.

The best <u>open-loop</u> estimate of $\xi_k$ is its conditional mean

$$\hat{\underline{\xi}} = E\{\underline{\xi}_k | \hat{\underline{\xi}}_{k-1}\} = F_k \hat{\underline{\xi}}_{k-1} \tag{7}$$

based on the previous best estimate, since $q_k$ is normal, zero-mean and uncorrelated, by assumption. The best policy is to treat the previous estimate as if it were exactly the correct value and to propagate the beam-steering vector according to the known transition matrix, $F_k$.

However, because the error covariance matrix and the process noise covariance matrix are positive definite, the error grows with time and recalibration becomes necessary.

## CONTROL AND CALIBRATION CONCEPT

Thus, open-loop estimates can be propagated with a system dynamics transition matrix which is constructed from look-angle and array geometry, once calibration is obtained.

Assume that an adaptive loop is available which derives the optimum weight vector to maximize the S/N, or equivalently, to minimize the mean square error. We may assume that convergence is shown by the reduced norm of the residual error

$$r_k = \hat{\underline{\xi}}_k - \Phi \hat{\underline{w}}_k \tag{8}$$

and that we may obtain estimates of the beam-steering vector by smoothing the correlation product observation

$$\hat{\underline{\xi}}_k \simeq \Phi \hat{\underline{w}}_k \tag{9}$$

when $\underline{\hat{w}}$ is near the optimum. This sets the initial condition for the beam-steering vector model and future estimates can be derived by applying the transition matrix. In this way, phase and amplitude calibration is stored in the initial vector.

According to Eq. (4), the optimum weight vector is obtained from the beam-steering vector by preweighting with the inverse covariance matrix. Since the object of optimum control is to propagate the S/N maximizing weight vector, it would seem that this matrix inverse must always be identified too, and that it would be subject to a dynamic model, since it contains the signals from the multiple access users.

In fact, a well-known matrix inversion lemma can be used to show that, except for a normalization factor which is unimportant in the S/N performance, the primary beamsteering vector terms contained in the matrix inverse cancel in the overall product (4) so that matrix inverse preweighting is not required in a noninterference environment.

In the TDRSS multiple access signal design, the self-interference contributions of other users is negligible because of the large processing gains of the PN code and the careful allocation of user EIRP's to avoid self-interference.

In the case of systems operating in the presence of larger than the specified TDRSS interference, it is possible, in principle, to identify the inverse noise covariance matrix from simultaneous observations of the optimum weight vector and the beam-steering vector for a set of n linearly independent beam-steering vectors or from one moving user occupying n linearly independent positions. This assumes a stationary noise environment. However, the computational load of identification and propagation of the optimum weight vector makes full adaptive control more attractive in the case of heavy interference.

## CONCLUSIONS

By using the additional information in the system dynamics model, computer control of remote beamformers in a programmed track, or open-loop, mode can be used to reduce the control-loop bandwidth of max S/N and LMS adaptive control loops. This is consistent with ideas of modern estimation theory in dynamic systems in which corrections, or updates, are made only on the basis of new information, or innovations. With the reduced bandwidth requirements, it is possible to reduce equipment complexity by time-sharing adaptive loop components and inferring calibrations among statistically related parameters.

The basic idea of incorporating the system dynamic model into an adaptive loop has broad application to the control of phased arrays in dynamic systems, not only to satellites but also to avionics systems in which existing onboard instrumentation can supply motion sensing to predict changing line of sight angles.

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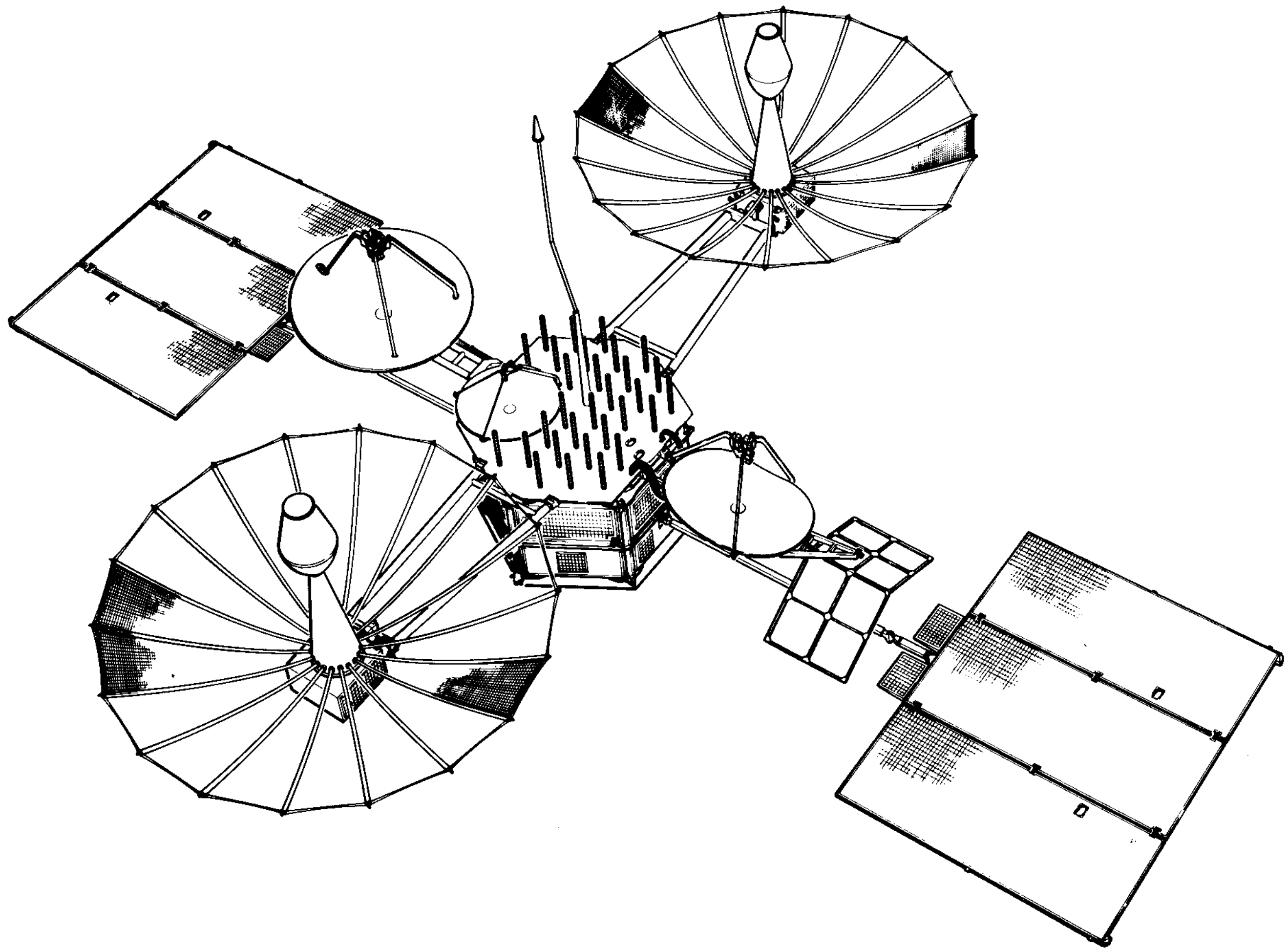

**Fig. 1 - Spacecraft Configuration**

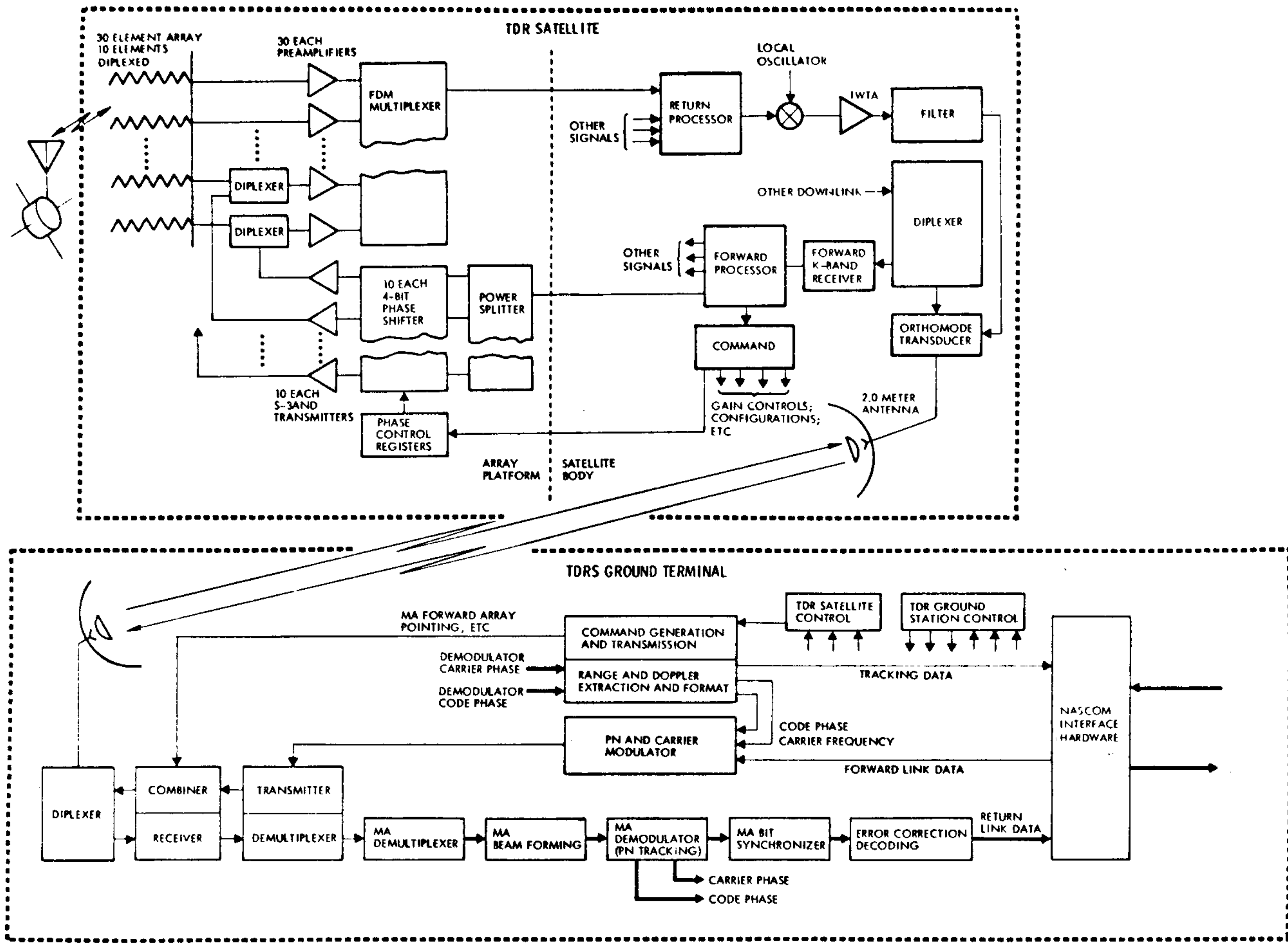


**Fig. 2 - MA Link Processing Simplified Block Diagram**

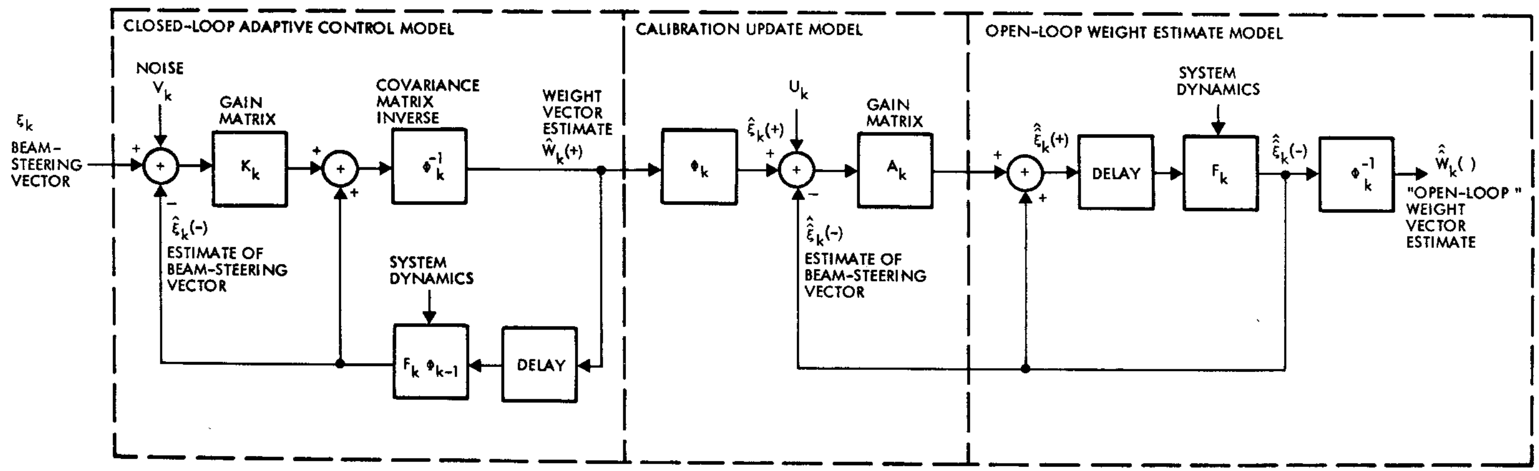


**Fig. 3 - Control and Calibration Concept**