

COHERENT MULTIPLE TONE TECHNIQUE FOR GROUND BASED SPS PHASE CONTROL*

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1.0 Introduction

The ground based phase control concept has been under study at LinCom as an alternative approach to the reference SPS phase control system (See Refs. 1,2,3). The details of the ground based phase control system study are documented in Ref. 4. In this short paper we summarize the coherent multiple tone technique used for the ground based phase measurement waveform design and phase control system.

2.0 Ground-Based Phase Control Concept

The ground based phase control system achieves beam forming by adjusting the phases of the individual transmitters on board SPS. The phase adjustments are controlled by ground commands. To specify the correct amount of adjustments, the phases of the power beams from each individual transmitter arriving at the rectenna center must be measured, the appropriate corrections determined (to ensure that all power beams arrive at the same phase) and relayed to the SPS. The proposed scheme to be considered is sequential in nature, i.e., the phase measurement is performed one at a time for each individual transmitter at approximately one-second intervals (measurement time allocated is 10 μ sec). The phase corrections are updated once every second. A 10-bit phase quantization for the corrections giving 0.35° resolution is envisioned. The uplink command data rate is on the order of 10 Mbps. The functional operation of the ground-based phase control concept is summarized in Fig. 1. As evident from the figure, the key issues that need to be addressed are:

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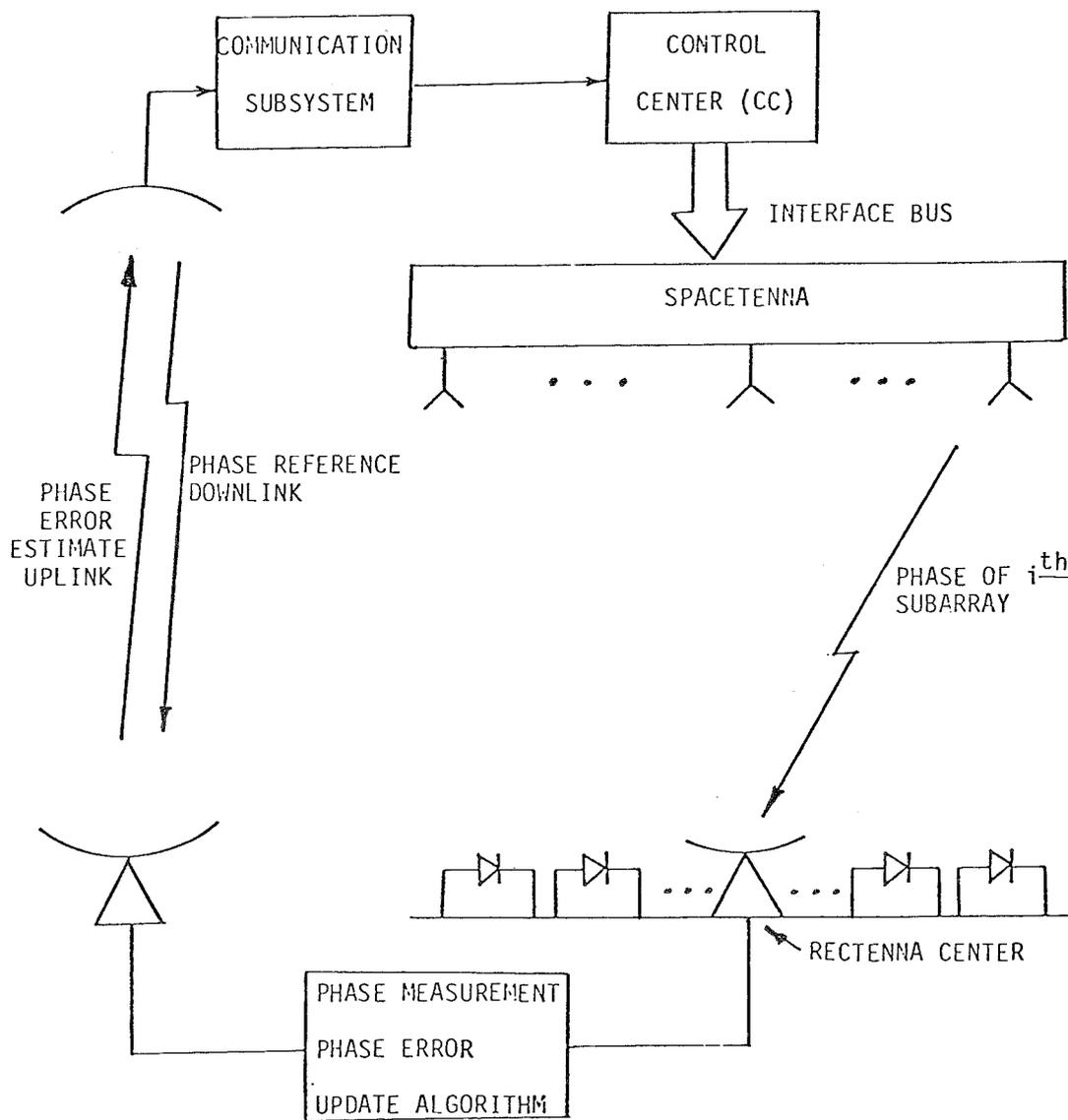


Figure 1. Ground Based Phase Control System Concept with Major Functional Blocks.

- (1) measurement waveform design and selection,
- (2) phase measurement pilot reference design and selection,
- (3) uplink phase corrections command link format and design, and
- (4) system synchronization techniques.

3.0 Two-Tone Phase Measurement Scheme with Coherent Subcarrier

In the basic two-tone measurement scheme, two side tones at $f_0 \pm \Delta f$ are transmitted from the satellite to the ground receiver. A phantom carrier can be reconstructed from the sidetones by passing the signal through a squaring circuit. The output will then have a CW component with frequency $2f_0$ and a phase component equal to $(\phi_1 + \phi_2)$, where ϕ_1 and ϕ_2 are the channel induced phase shifts at $f_0 + \Delta f$ and $f_0 - \Delta f$, respectively. This phase shift is very close to double the one that would have occurred if the downlink signal were a single sinusoid at frequency f_0 . If we divide the $2f_0$ component by two, we obtain the average phase $\frac{\phi_1 + \phi_2}{2}$. Unfortunately, the divide by two circuit results in a $0^\circ - 180^\circ$ ambiguity.

4.0 Four-Tone Phase Measurement Scheme

The four-tone measurement scheme given in Fig. 2 is a simple modification of the two-tone scheme. Basically, we first use frequencies at $f_0 \pm 2\Delta f$ for phase error measurement with introduces π ambiguity. Then we use frequencies at $f_0 \pm \Delta f$ for ambiguity resolution. The scheme works as follows. The transmitted signal at the input to the transmitting antenna is (neglecting multiplicative constants)

$$s_1(t) = \cos\left[\omega_0\left(1 + \frac{\ell}{N}\right)t + \left(1 + \frac{\ell}{N}\right)\theta_i + \frac{2\pi k \ell}{N}\right] \\ + \cos\left[\omega_0\left(1 - \frac{\ell}{N}\right)t + \left(1 - \frac{\ell}{N}\right)\theta_i - \frac{2\pi k \ell}{N}\right] \quad \ell = 0, 1, 2$$

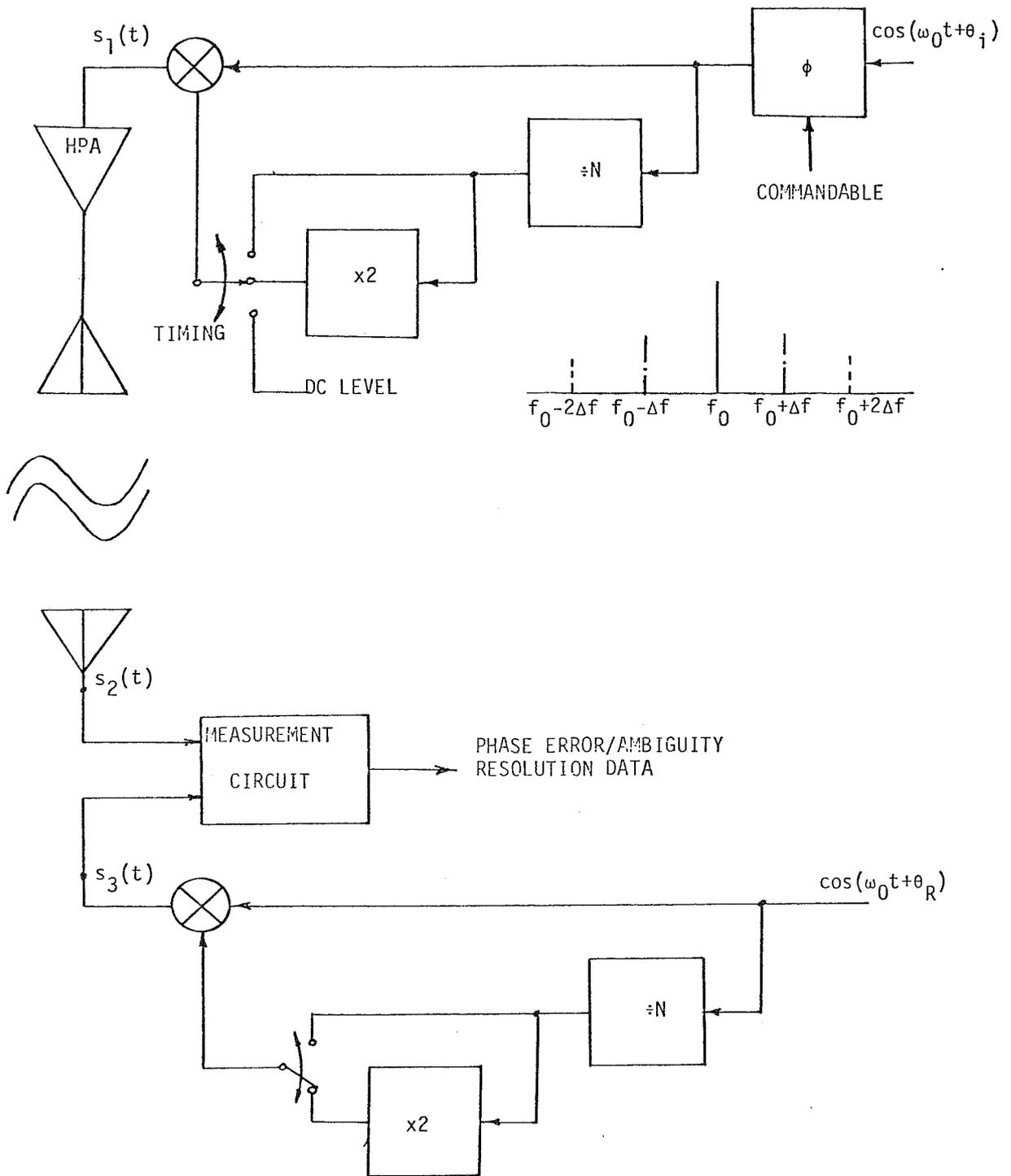


Figure 2. Four-Tone Phase Measurement Scheme.

where θ_i includes the commandable phase shift, $\frac{2k\pi}{N}$ is the ambiguity introduced by the divide by N circuit, $f = \frac{f_0}{N}$, and $\ell = 0,1,2$ depending on whether the PM is in the power mode (1), ambiguity resolution mode (2), or phase error measurement mode (3). At the receiver on the ground,

$$s_2(t) = \cos\left[\omega_0\left(1 + \frac{\ell}{N}\right)t + \left(1 + \frac{\ell}{N}\right)\theta_i + \frac{2\pi k\ell}{N} + \varphi_+(\ell)\right] \\ + \cos\left[\omega_0\left(1 - \frac{\ell}{N}\right)t + \left(1 - \frac{\ell}{N}\right)\theta_i - \frac{2\pi k\ell}{N} + \varphi_-(\ell)\right]$$

where $\varphi_+(\ell)$ and $\varphi_-(\ell)$ are the phase shifts introduced by the channel.

The reference signal $s_3(t)$ is given by

$$s_3(t) = \cos\left[\omega_0\left(1 + \frac{\ell}{N}\right)t + \left(1 + \frac{\ell}{N}\right)\theta_R + \frac{2\pi \ell m}{N}\right] \\ + \cos\left[\omega_0\left(1 - \frac{\ell}{N}\right)t + \left(1 - \frac{\ell}{N}\right)\theta_R - \frac{2\pi \ell m}{N}\right]$$

where θ_R is the phase of the ground reference, and $\frac{2\pi m}{N}$ is the ambiguity introduced by the ground divide by N circuit. If the operations are synchronized, we can then measure up to modulo 2π at the output of the measurement circuit, the phases

$$\varphi_+(\ell) + \left(1 + \frac{\ell}{N}\right)(\theta_i - \theta_R) + \frac{2\pi \ell}{N}(k-m) = \phi_+(\ell) + 2\pi M_+(\ell) \quad (1)$$

$$\varphi_-(\ell) + \left(1 - \frac{\ell}{N}\right)(\theta_i - \theta_R) - \frac{2\pi \ell}{N}(k-m) = \phi_-(\ell) + 2\pi M_-(\ell) \quad (2)$$

Actually, in (1) and (2), $\phi_+(\ell)$ and $\phi_-(\ell)$ are the measured phases and $M_+(\ell)$ and $M_-(\ell)$ are integers so that the absolute values of $\phi_+(\ell)$ and $\phi_-(\ell)$ can be restricted to π . Note that we are interested in determining $[\varphi_+(\ell) + \varphi_-(\ell)]/2$ modulo 2π . For $\ell=2$, we know from (1) and (2) that

$$\frac{\varphi_+(2) + \varphi_-(2)}{2} = \frac{\phi_+(2) + \phi_-(2)}{2} + [M_+(2) + M_-(2)]\pi - (\theta_i - \theta_R) \quad (3)$$

Now if we can resolve whether $[M_+(2) + M_-(2)]$ is even or odd, we can determine $[\varphi_+(2) + \varphi_-(2)]/2 + (\theta_i - \theta_R)$ modulo 2π . This information is

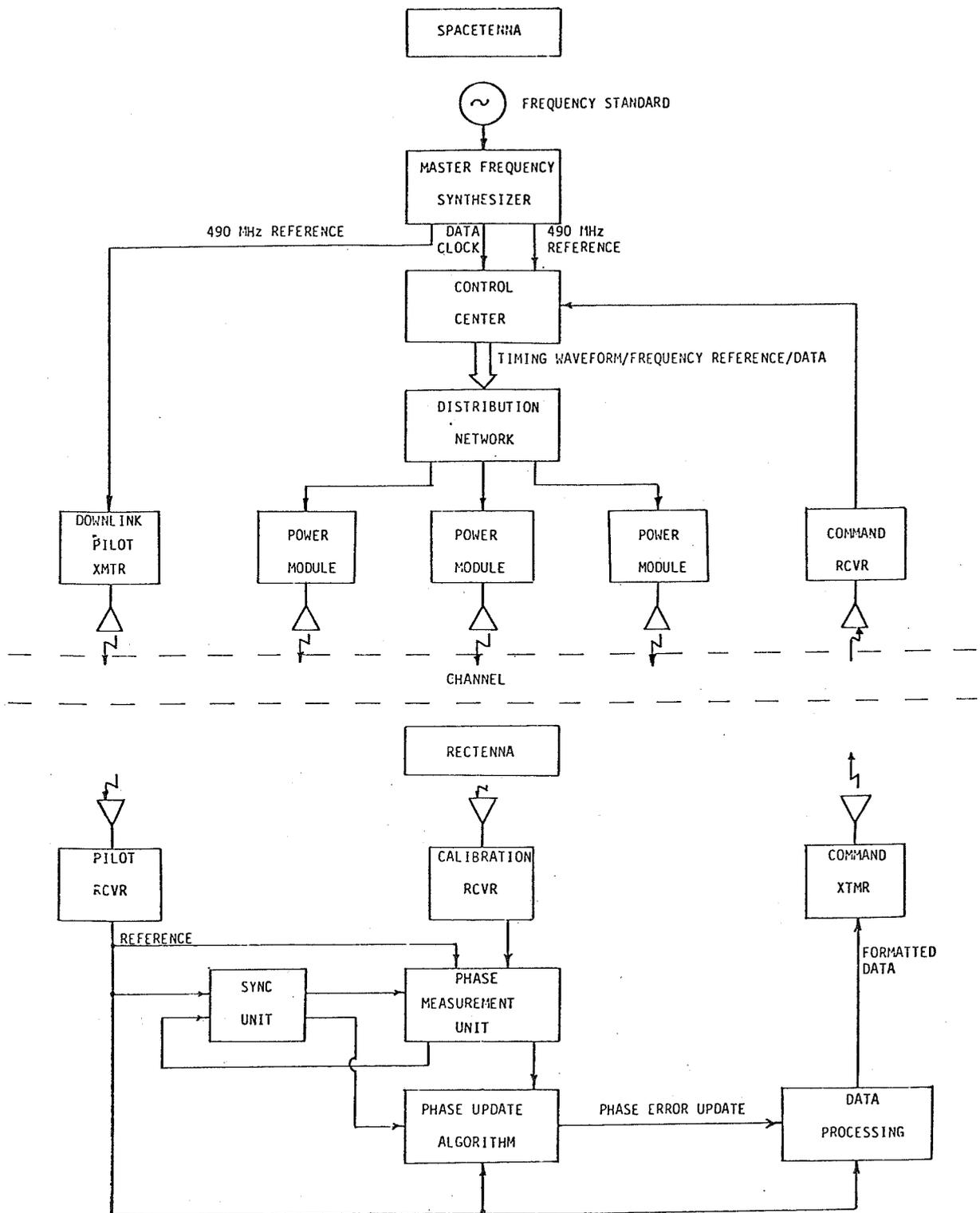


Figure 3. SPS Ground Based Phase Control Functional Block Diagram Showing System Timing Hierarchy.

provided by comparing

$$\varphi_+(1) - \varphi_-(1) = -\frac{2}{N}(\theta_i - \theta_R) - \frac{4\pi}{N}(k-n) + \phi_+(1) - \phi_-(1) + [M_+(1) - M_-(1)]2\pi \quad (4)$$

$$\frac{\varphi_+(2) - \varphi_-(2)}{2} = -\frac{2}{N}(\theta_i - \theta_R) - \frac{4\pi}{N}(k-n) + \frac{\phi_+(2) - \phi_-(2)}{2} + [M_+(2) - M_-(2)]\pi \quad (5)$$

If Δf is designed properly ($\Delta f < 50$ MHz) the left hand side of (4) and (5) are nearly equal. See Ref. 4 for a discussion on ionospheric effects. Equating (4) and (5) we have

$$\frac{\phi_+(2) - \phi_-(2)}{2} + [M_+(2) - M_-(2)]\pi \equiv \phi_+(1) - \phi_-(1) \pmod{2\pi} \quad (6)$$

Since we can measure $\phi_{\pm}(2)$, we can determine from (6) whether $[M_+(2) - M_-(2)]$ is odd or even. This then determines whether $[M_+(2) + M_-(2)]$ is odd or even, since $[M_+(2) - M_-(2)] + [M_+(2) + M_-(2)] = M_+(2)$ must be even. With this information, we can solve for $[\varphi_+(2) + \varphi_-(2)]/2 + (\theta_i - \theta_R)$ modulo 2π in (3).

5.0 Baseline System for Ground-Based Phase Control

The implementation of the ground-based phase control concept is determined by the phase control waveform designs employed. Based on our waveform selections, functional subsystems to implement the ground-based phase control concept are identified and functionally represented. The resultant ground-based phase control functional block diagram is depicted in Fig. 3 and includes:

- Satellite Signal Processing
 - Time-Frequency Control
 - Processing Control Center
 - Signal Distribution Network
 - Processing Power Module
 - Downlink Pilot Transmitter

- Uplink Command Receiver
- Ground Based Signal Processing
 - Pilot Beacon Receiver
 - Calibration Receiver
 - Phase Measurement Unit
 - Synchronization Unit
 - Phase Update Algorithm
 - Data Processing Unit
- Uplink Command Transmitter

The ground-based system envisioned employs satellite based frequency/timing reference with an IF frequency of 490 MHz. A 4-tone measurement scheme using frequencies at $2,450 \pm 9.57$ MHz and $2,450 \pm 19.14$ MHz is selected. Each power module devotes 10 μ sec per second for phase correction measurement, representing a minimal loss in total power transmitted. Two frequencies are chosen for the downlink and one frequency for uplink; the downlink pilot signal center frequency is set at 4.9 GHz.

Our preliminary investigation indicates that the effects of power beam interference and thermal noise on the phase measurement error can be controlled to a tolerable level. The ground based system can also function if the ionosphere is nonturbulent in nature and the satellite's tilt rate is limited to $0.5 \widehat{\text{min}}/\text{sec}$.

6.0 Limiting Factors of the Feasibility of Ground-Based Phase Control System

The feasibility of the ground-based phase control concept becomes unclear if the conditions on the ionosphere and the satellite motion are not met. The ground-based phase control system can only correct for random phase fluctuations which have a correlation time that is large

compared with 1.25 sec. The noise components which are faster than 1.25 sec is uncompensated for and result in a degradation on transmission efficiency. Unfortunately, measured ionosphere data which is suitable for the SPS system is not readily available. (Most data are concerned with spatial correlations rather than temporal correlations. Also, most data are measured from low orbit satellites rather than geostationary satellites.) The other limiting factor is the statistical behavior of the random pointing error exhibited by the spaceteenna. Again, the fast component of this error is not corrected for and it contributes to efficiency degradation. At this point, we feel that the development and specification of models for ionospheric phase disturbance and satellite motion is essential. It is hoped that our findings can serve as a guideline for any parallel efforts in studying these two factors.

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