

AD-E300 030

DNA 4092F

AD A 0 49203

DDC FILE COPY

# DESIGN CONSIDERATIONS FOR A MICROWAVE SCINTILLATION EXPERIMENT

Stanford Research Institute  
333 Ravenswood Avenue  
Menlo Park, California 94025

15 March 1977

Final Report for Period 16 September 1976-15 March 1977

CONTRACT No. DNA 001-76-C-0389

APPROVED FOR PUBLIC RELEASE;  
DISTRIBUTION UNLIMITED.

THIS WORK SPONSORED BY THE DEFENSE NUCLEAR AGENCY  
UNDER RDT&E RMSS CODE B32207T462 L25AAXHX63801 H2590D.

Prepared for  
Director  
DEFENSE NUCLEAR AGENCY  
Washington, D. C. 20305

DDC  
RECEIVED  
JAN 31 1978  
B

Destroy this report when it is no longer  
needed. Do not return to sender.



UNCLASSIFIED

(18) DNA, SBIE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  |                                                                                                          |  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|----------------------------------------------------------------------------------------------------------|--|
| <b>(19) REPORT DOCUMENTATION PAGE</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  | <b>READ INSTRUCTIONS<br/>BEFORE COMPLETING FORM</b>                                                      |  |
| 1. REPORT NUMBER<br><b>DNA 4092F, AD-E300-030</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |  | 3. RECIPIENT'S CATALOG NUMBER                                                                            |  |
| 4. TITLE (and Subtitle)<br><b>DESIGN CONSIDERATIONS FOR A<br/>MICROWAVE SCINTILLATION EXPERIMENT.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  | 5. TYPE OF REPORT & PERIOD COVERED<br><b>Final Report for Period<br/>16 Sep 76-15 Mar 77</b>             |  |
| 7. AUTHOR(s)<br><b>Edward J. Fremouw, Roy A. Long<br/>Boyd C. Fair, Alan A. Burns<br/>Roland T. Tsunoda</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |  | 6. PERFORMING ORG. REPORT NUMBER<br><b>SRI Project 5786</b>                                              |  |
| 8. PERFORMING ORGANIZATION NAME AND ADDRESS<br><b>Stanford Research Institute<br/>333 Ravenswood Avenue<br/>Menlo Park, California 94025</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  | 8. CONTRACT OR GRANT NUMBER(s)<br><b>DNA 001-76-C-0389</b>                                               |  |
| 9. CONTROLLING OFFICE NAME AND ADDRESS<br><b>Director<br/>Defense Nuclear Agency<br/>Washington, D.C. 20305</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | 10. PROGRAM ELEMENT, PROJECT, TASK<br>AREA & WORK UNIT NUMBERS<br><b>NWET Subtask<br/>L25AAXHX638-01</b> |  |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |  | 12. REPORT DATE<br><b>15 Mar 77</b>                                                                      |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | 13. NUMBER OF PAGES<br><b>12565p</b>                                                                     |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | 15. SECURITY CLASS (of this report)<br><b>UNCLASSIFIED</b>                                               |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | 15a. DECLASSIFICATION/DOWNGRADING<br>SCHEDULE                                                            |  |
| 16. DISTRIBUTION STATEMENT (of this Report)<br><br><b>Approved for public release; distribution unlimited.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |  |                                                                                                          |  |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |                                                                                                          |  |
| 18. SUPPLEMENTARY NOTES<br><br><b>This work sponsored by the Defense Nuclear Agency under RDT&amp;E RMSS<br/>Code B32207T462 L25AAXHX63801 H2590D.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  |                                                                                                          |  |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br><b>GHz Scintillation<br/>mm-Wave Propagation<br/>Equatorial Ionospheric Irregularities<br/>Volcanic Eruptions<br/>High-Explosive Detonations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  |                                                                                                          |  |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><b>The plasmaspheric irregularities that produce radiowave scintillation at<br/>frequencies above 1 GHz near the geomagnetic equator, and the signal perturba-<br/>tions that they impose, are of considerable importance to DNA responsibilities.<br/>This report describes possible experimental approaches to understanding the<br/>phenomenon of microwave scintillation that could be conducted during the forth-<br/>coming period of increased solar activity. We take it to be axiomatic that the<br/>key measurement is of GHz scintillation itself, although consideration is given<br/>to corollary measurements. Because GHz scintillation is less common than VHF-</b> |  |                                                                                                          |  |

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

332500

*[Signature]*

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (Continued).

UHF scintillation, and because understanding the phenomenon would be fostered greatly by observation throughout the complete evolution of GHz-scintillation events, the recording of signals transmitted for a geostationary satellite is stressed.

One of the salient results of the Wideband satellite experiment has been the demonstration of the close relationship between the measured signal phase and the plasma structure that produces scintillation. For this reason, we consider it essential that the prime experiment include measurement of phase scintillation. Several approaches to obtaining the necessary coherent signals radiated from a geostationary satellite are considered; they include a dedicated launch, a dedicated satellite on a "piggy back" launch, a payload on a multiple-experiment SAMS0 satellite, and the use of a satellite already in orbit. Because of time constraints and a paucity of planned launches, only the first (dedicated launch) and the last (operational satellite appear viable.

An ideal but very expensive (\$10 million plus launch costs) program employing the existing but unlaunched ATS-F' satellite is described; a preferred, less expensive (\$8 million plus reduced launch costs) approximate realization of the ideal experiment, employing a dedicated launch (with potential for sharing of costs by use of excess launch-vehicle and satellite capability), is suggested; and a relatively modest alternative (costs of several hundred thousand dollars) using the operational ATS-6 satellite is pointed out. Application of the preferred approach to assessment of mm-wave propagation effects of nonplasmaspheric origin, which is of potential concern to DNA, also is addressed. As corollary elements of an overall attack on the question of plasmaspherically produced GHz scintillation (employing any of the three viable geostationary-satellite alternatives), we suggest (1) that observations of the Wideband satellite continue as solar activity builds, and (2) that DNA coordinate the activities of its atmospheric-effects research community with the NASA team developing the Equion program, which is to provide extensive in-situ satellite measurements of the equatorial ionosphere.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## TABLE OF CONTENTS

|                                                                    |    |
|--------------------------------------------------------------------|----|
| LIST OF ILLUSTRATIONS . . . . .                                    | 2  |
| LIST OF TABLES . . . . .                                           | 3  |
| I INTRODUCTION . . . . .                                           | 5  |
| II THE IDEAL EXPERIMENTAL PROGRAM . . . . .                        | 7  |
| A. Objectives and Background . . . . .                             | 7  |
| B. Geostationary Satellite Observations . . . . .                  | 9  |
| C. Observations from a Low-Orbiting Satellite . . . . .            | 19 |
| III SATELLITES CONSIDERED FOR USE IN THE EXPERIMENT . . . . .      | 23 |
| A. Approaches Considered . . . . .                                 | 23 |
| 1. Dedicated Satellites . . . . .                                  | 23 |
| 2. Cooperative Launches with Other Satellites . . . . .            | 26 |
| 3. SAMSO Multi-Experiment Satellites . . . . .                     | 26 |
| 4. Satellites of Opportunity . . . . .                             | 27 |
| B. Summary of Alternatives . . . . .                               | 30 |
| IV SUGGESTED EXPERIMENTS . . . . .                                 | 32 |
| A. An Embodiment of the Ideal Program . . . . .                    | 32 |
| B. An Alternative Employing Existing Satellites . . . . .          | 42 |
| V APPLICATION TO PROPAGATION PROBLEMS IN THE TROPOSPHERE . . . . . | 48 |
| VI CONCLUSION . . . . .                                            | 59 |
| REFERENCES . . . . .                                               | 61 |

|                                 |               |                                     |
|---------------------------------|---------------|-------------------------------------|
| ACCESSION for                   |               |                                     |
| NTIS                            | White Section | <input checked="" type="checkbox"/> |
| DDC                             | Buff Section  | <input type="checkbox"/>            |
| UNANNOUNCED                     |               | <input type="checkbox"/>            |
| JUSTIFICATION _____             |               |                                     |
| BY _____                        |               |                                     |
| DISTRIBUTION/AVAILABILITY CODES |               |                                     |
| Dist.                           | AVAIL.        | and/or SPECIAL                      |
| A                               |               |                                     |

## LIST OF ILLUSTRATIONS

|    |                                                                                                                                                 |    |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1  | Example of an Equatorial Wideband Pass . . . . .                                                                                                | 8  |
| 2  | Phase Correlation Coefficient Between Two Pairs of UHF<br>Signals During the Scintillation Event Shown in<br>Figure 1 . . . . .                 | 11 |
| 3  | Frequency Dependence of Phase Scintillation Event<br>Shown in Figure 1 . . . . .                                                                | 12 |
| 4  | Frequency Dependence of Uncertainty in Measured<br>Standard Deviation of Phase Because of Fluctuations<br>in the Reference Channel . . . . .    | 14 |
| 5  | Range-Time-Intensity Plot of Enhanced-Backscatter<br>Plumes Observed with the 50-MHz, Large-Array Radar<br>Located at Jicamarca, Peru . . . . . | 16 |
| 6  | Current Trend in Local Time of Wideband Equator<br>Crossings . . . . .                                                                          | 21 |
| 7  | Observing Geometry to Geostationary Satellite in<br>Geopotential Well at 105° Longitude . . . . .                                               | 36 |
| 8  | Method of Generating Frequencies Listed in Table 3 . . . .                                                                                      | 40 |
| 9  | Basic Frequency Play for Augmenting the Present<br>Wideband Receiver Design . . . . .                                                           | 41 |
| 10 | Computed Attenuation Compared to Measured Signal-<br>Strength Fluctuations from DICE THROW . . . . .                                            | 51 |
| 11 | Attenuation Resulting from Absorption and Excess Phase<br>Shift as a Function of Integrated Dust-Density . . . . .                              | 52 |

# LIST OF TABLES

|   |                                                                                           |    |
|---|-------------------------------------------------------------------------------------------|----|
| 1 | Ideal Transmission Spectrum . . . . .                                                     | 10 |
| 2 | Link Budget for Employment of ATS-F' . . . . .                                            | 18 |
| 3 | Characteristics of the ETS-2 Satellite . . . . .                                          | 24 |
| 4 | Satellite Approaches Considered . . . . .                                                 | 31 |
| 5 | Observing Geometry for Geostationary Satellite at<br>105° W (Geopotential Well) . . . . . | 35 |
| 6 | Suggested Transmission Spectrum . . . . .                                                 | 37 |
| 7 | Link Budget for Suggested Experiment . . . . .                                            | 39 |
| 8 | Observing Geometry for Geostationary Satellite (ATS-6)<br>at 140° W . . . . .             | 46 |
| 9 | Link Budget for MM-Wave Transmitter . . . . .                                             | 58 |

## I INTRODUCTION

This is the final report on a six-month study of experimental approaches to measuring microwave scintillation. The primary objective of the project was to outline an experiment for definitive measurements of plasmaspherically produced scintillation at frequencies above 1 GHz. Our design considerations were directed at (1) quantitatively characterizing the signal statistics that result from GHz scintillation in terms useful for engineering application, and (2) revealing the altitude and nature of the plasma conditions that give rise to the phenomenon. A secondary objective was to assess the importance to DNA responsibilities of corollary microwave-propagation data that might be collected in the measurement operation.

Four principal tasks were carried out to meet the primary objective. The first was to survey the satellites from which signals for definitive measurement of GHz scintillation could be transmitted. The satellites considered included some already operating and some that could be in operation within the next few years. The second task was to choose a geostationary satellite from those considered. The third was to assess the value and feasibility of employing a low-orbiting satellite to complement the geostationary-satellite observations. The final task was to choose observation sites near the geomagnetic equator, and to establish antenna and receiver-frequency configurations for those sites.

Our approach to the experiment design was first to outline the elements of an experimental program that would be ideally suited to the pursuit of an understanding of plasmaspherically produced GHz scintillation. (This ideal program is described in Section II.) We then surveyed the instrumental resources available for such an endeavor, concentrating primarily on satellites that could transmit the relevant signals. (The satellites identified and considered are described briefly in Section III.)

NOT  
Preceding Page BLANK - FILMED

We then chose one geostationary satellite and one low-orbiting satellite upon which to base a possible realization of the desired experiment.

The suggested experiment is put forth in Section IV-A, followed by an outline of a less definitive but much less costly alternative in Section IV-B. Section V points out applications that might be made of the desired experiment to propagation effects of other than plasmaspheric origin that would be important to DNA. Finally, we present our recommendations in Section VI.

## II THE IDEAL EXPERIMENTAL PROGRAM

### A. Objectives and Background

The objective of the program is to understand microwave scintillation, a phenomenon that has been observed mainly between 1 and 6 GHz near the geomagnetic equator, mostly in years of high solar activity (Taur, 1973).<sup>\*</sup> We take it to be axiomatic that the central element in the desired experimental program is a quantitative measurement of microwave scintillation itself. Further, we desire to establish the complex-signal statistics attendant to such scintillation and to locate and describe the plasma-spheric irregularities that produce the effect. It would be ideal also to measure several large-scale, or background, plasma characteristics during the development and the existence of the irregularities.

Nearly all observations of microwave scintillation have been made using signals from geostationary satellites (Craft, 1971; Skinner et al., 1971; Craft and Westerlund, 1972; Taur, 1972 and 1973) or sources even at a higher altitude (Christiansen, 1971). This fact plus the fact that well-developed diffraction effects (that is, the very existence of intensity scintillation) at such high frequencies require considerable propagation distance, prompted the hypothesis that microwave scintillation is produced in electron-density irregularities located in a vast plasma-spheric region that extends to great heights, possibly as high as several earth radii (Booker, 1975).

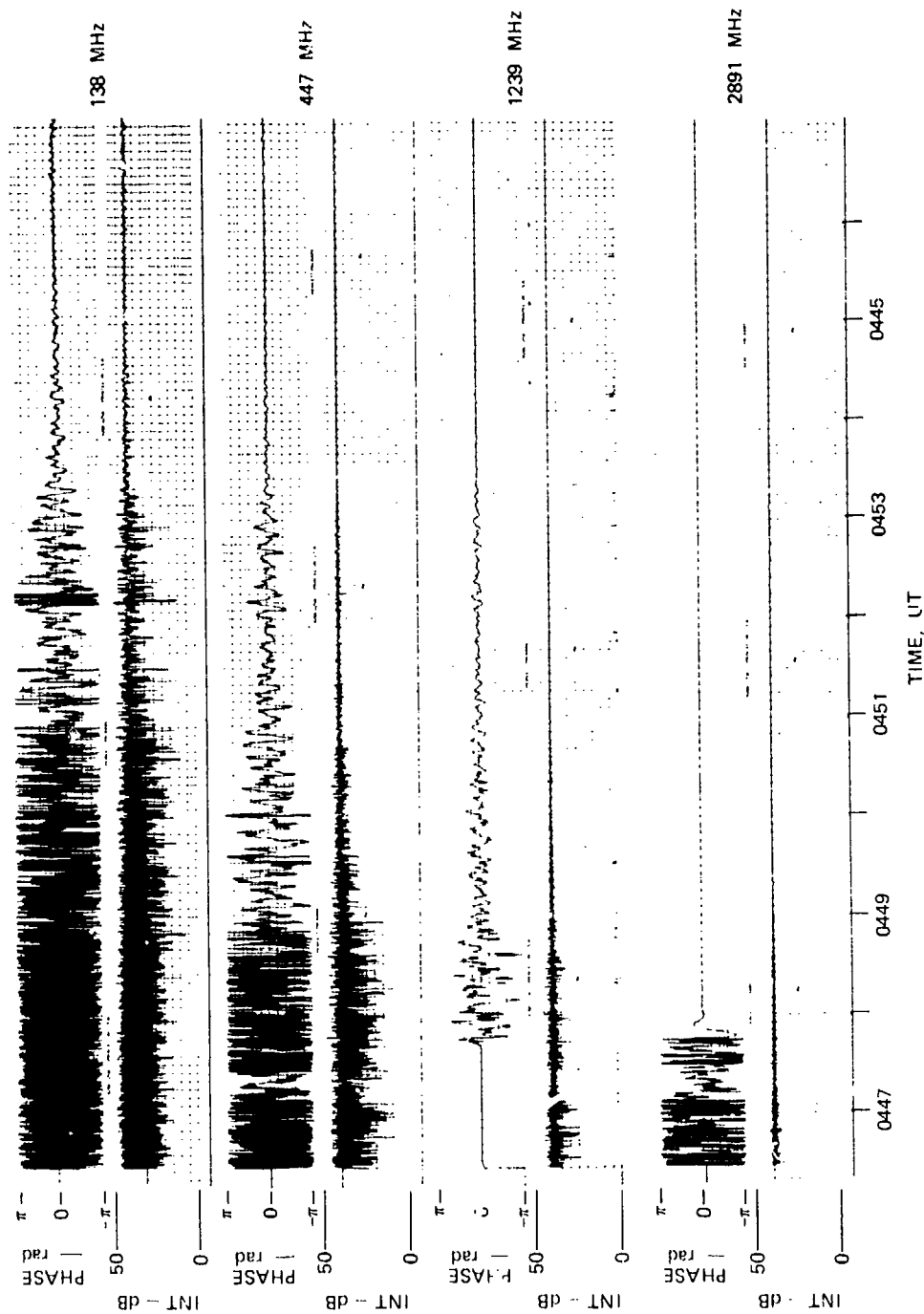
It now has been demonstrated unequivocally that irregularities above 1000 km are not a necessary condition for production of GHz scintillation (Fremouw, Cousins, and Durfey, 1977). That is, scintillations of several dB have been observed on the 1.2-GHz and 2.9 GHz signals transmitted from the Wideband satellite, which is in a 1000-km orbit. An example is presented in Figure 1.

---

<sup>\*</sup>References are listed at the end of this report.

16 DECEMBER 1976

ANCON PASS 35-12



LA-3786-4

FIGURE 1 EXAMPLE OF AN EQUATORIAL WIDEBAND PASS SHOWING PHASE AND INTENSITY SCINTILLATIONS AT L BAND AND S BAND (bottom two panel pairs). Note change of phase reference from L Band to S Band just before 0448 UT.

## B. Geostationary Satellite Observations

Despite the observation of GHz scintillation from low orbit, it remains our judgment that in a concerted effort to understand the phenomenon, the primary measurement ought to be made by means of transmissions from a geostationary satellite. We believe this for two reasons. First, the Wideband observation does not preclude a contribution from irregularities above 1000 km. More important, a geostationary satellite would permit continuous observations through a designated ionospheric locale. Continuous observations are crucial if (1) we are to understand the production dynamics and the evolution of scintillation-producing irregularities and if (2) we are to document the signal-statistical ramifications that various evolutionary states might produce.

We consider the use of a geostationary satellite for observing scintillation to be most important from the plasma-physics point of view. It has been quite well established for some time (Craft and Westerlund, 1972; Taur, 1972) that equatorial microwave scintillation occurs almost exclusively during the five or so hours that precede local midnight (with rare occurrences as late as 0300 local time) and that sudden onsets near the time of sunset on the F layer are quite common. Only the use of a geostationary satellite can ensure observation of such onsets and of the nightly evolution of scintillation conditions.

In an ideal geostationary-satellite experiment, one would employ a multifrequency coherent beacon such as that used in Wideband but that provides additional transmissions at higher frequencies. A transmission spectrum considered virtually ideal is presented in Table 1.

The frequencies listed in Table 1 are based on the spectrum employed for Wideband. In fact, the VHF and UHF signals and the L-band carrier are identical to the corresponding Wideband signals except for a one-kHz shift in the fundamental frequency (11.473 to 11.474 MHz) to avoid mutual interference. The L-band sidebands are included to permit measurement of the total electron content (TEC) by the  $\Delta_2\phi$  technique (Burns and Fremouw, 1970). The sidebands would be generated by simple modulation of the L-band carrier at four times the fundamental frequency. The

Table 1  
IDEAL TRANSMISSION SPECTRUM

| Designation         | Frequency<br>(GHz) | Harmonic Number<br>(of 11.474 MHz) |
|---------------------|--------------------|------------------------------------|
| VHF                 | 0.138              | 12                                 |
| UHF                 | 0.413              | 36                                 |
| L Band              | 1.193              | 104                                |
|                     | 1.239              | 108                                |
|                     | 1.285              | 112                                |
| S Band              | 3.718              | 324                                |
| K <sub>p</sub> Band | 11.153             | 972                                |
| K <sub>a</sub> Band | 33.458             | 2916                               |

S-band signal in Table 1 is somewhat higher than the S-band signal on Wideband, to provide more uniform sampling of frequency (on a logarithmic scale), especially above 1 GHz.

In the experiment summarized in Table 1, the prime measurements would be of intensity and phase scintillation at 1.2, 3.7, and 11.2 GHz, using a 33.5-GHz phase reference. The signals at 413 and 138 MHz would be used primarily to relate the microwave scintillation results to past results, such as those from Wideband. The advantage of performing  $\Delta_2\phi$  measurements at the L band rather than at UHF, as in Wideband, is that, in the former method, the higher frequencies are less apt to be decorrelated during extreme scintillation events. That decorrelation of phase across narrow bands at UHF does occur during such events has been established from Wideband measurements, as reproduced in Figure 2.

The general trend for phase statistics to be more reliably interpretable in terms of plasmaspheric structure, when one employs simplified propagation theories such as the phase-screen model, is illustrated in Figure 3, which also is taken from Wideband measurements. The figure shows the frequency dependence of the standard deviation of phase during

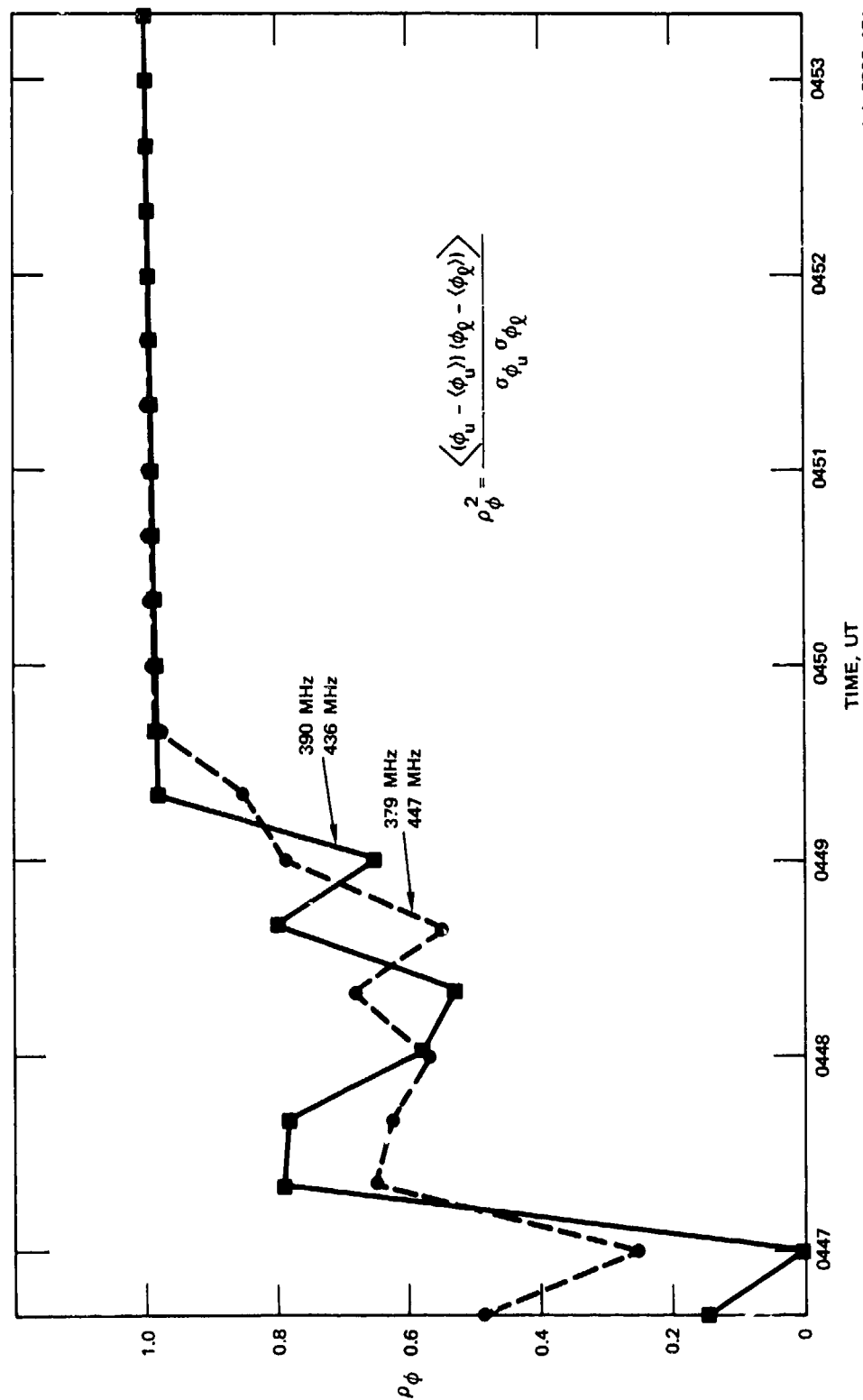


FIGURE 2 PHASE CORRELATION COEFFICIENT BETWEEN TWO PAIRS OF UHF SIGNALS DURING THE SCINTILLATION EVENT SHOWN IN FIGURE 1

LA-3793-151

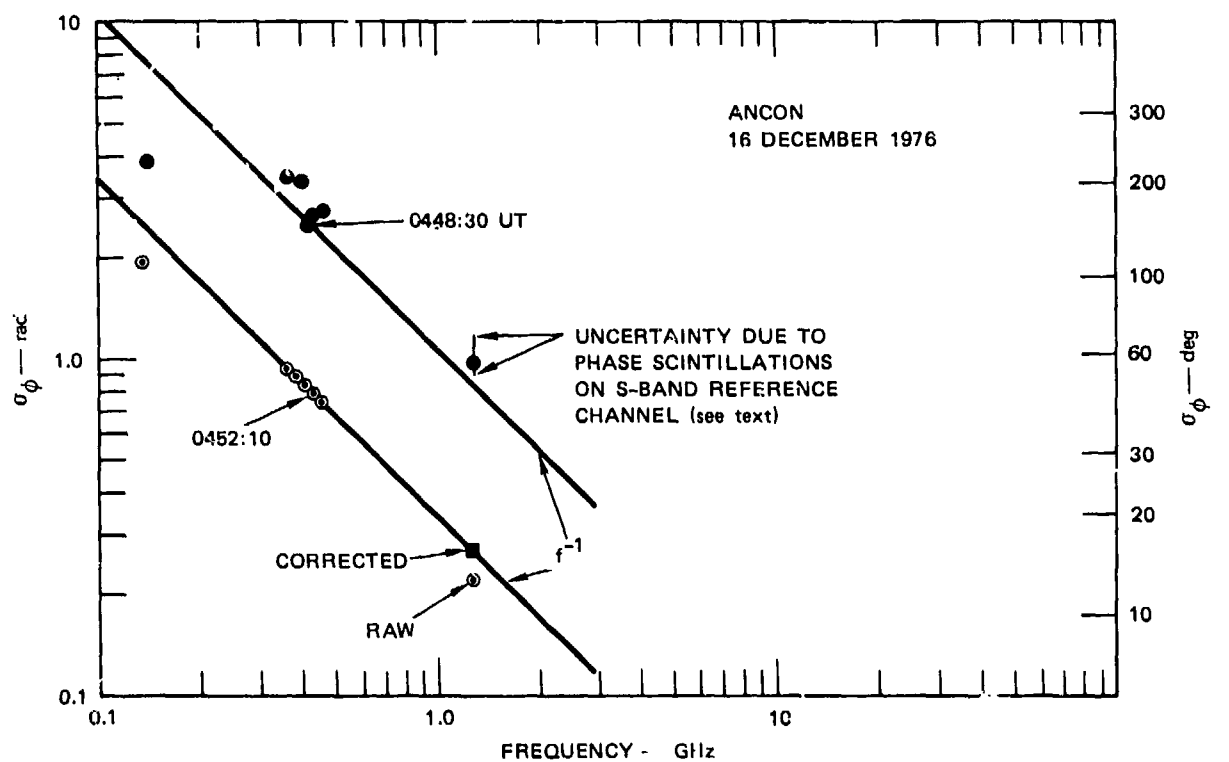


FIGURE 3 FREQUENCY DEPENDENCE OF PHASE SCINTILLATION DURING TWO 20-s PERIODS OF THE SCINTILLATION EVENT SHOWN IN FIGURE 1. Also illustrating uncertainty due to phase fluctuations on the reference channel.

two twenty-second periods of the Wideband pass illustrated in Figure 1, compared with the  $f^{-1}$  dependence predicted by a strict phase-screen model. In the less disturbed of the two periods, the L-band and UHF points adhere almost completely to the predicted behavior, but the VHF point falls beneath the theoretical curve. In the more disturbed period, the VHF point still is more depressed, and the UHF points are scattered. (In both cases, the phase-screen theoretical dependence has been passed through the central UHF point.)

In addition, Figure 3 illustrates (by means of the uncertainty bar on the L-band data point) one of the fundamental limitations of differential measurements of dispersive phase. The phase,  $\phi_m$ , measured at the

output of a coherent receiver is derived from the measurement frequency's true phase,  $\varphi$ , and that of the reference frequency,  $\varphi_r$ , as

$$\varphi_m = \varphi - \varphi_r/n \quad (1)$$

where  $n$  is the ratio of the reference frequency to the measurement frequency. Given an  $f^{-q}$  dependence of phase scintillation, the measured standard deviation will be related to the true standard deviation by

$$\sigma_{\varphi_m} = \sigma_{\varphi} \left[ 1 - n^{-(q+1)} \right] \quad (2)$$

if phase fluctuations on the two frequencies are fully correlated, and by

$$\sigma_{\varphi_m} = \sigma_{\varphi} \left[ 1 + n^{-2(q+1)} \right]^{1/2} \quad (3)$$

for complete decorrelation.

The uncertainty bar in Figure 3 represents the difference between Eqs. (2) and (3), evaluated for  $q = 1$ , for a measurement frequency of 1.239 GHz and a reference frequency of 2.891 GHz, as are employed in Wideband. The uncertainty that results from reference-phase fluctuations, for the same underlying frequency dependence, is compared in Figure 4 for Wideband and the spectrum given in Table 1. The latter spectrum would extend the range of very small uncertainty out to S band and would provide more accurate measurements even at  $K_p$  band than are obtained at L band in the present experiment. Furthermore, the  $K_a$ -band reference frequency would provide an opportunity for measuring effects of propagation on the intensity and polarization of a mm-wave signal.

In addition to providing essentially an ideal frequency selection for the measurement of plasmaspherically produced scintillation, the spectrum in Table 1 establishes a basis upon which to build a mm-wave propagation experiment. The  $K_a$ -band reference signal would provide an opportunity for measuring effects on intensity and polarization at a

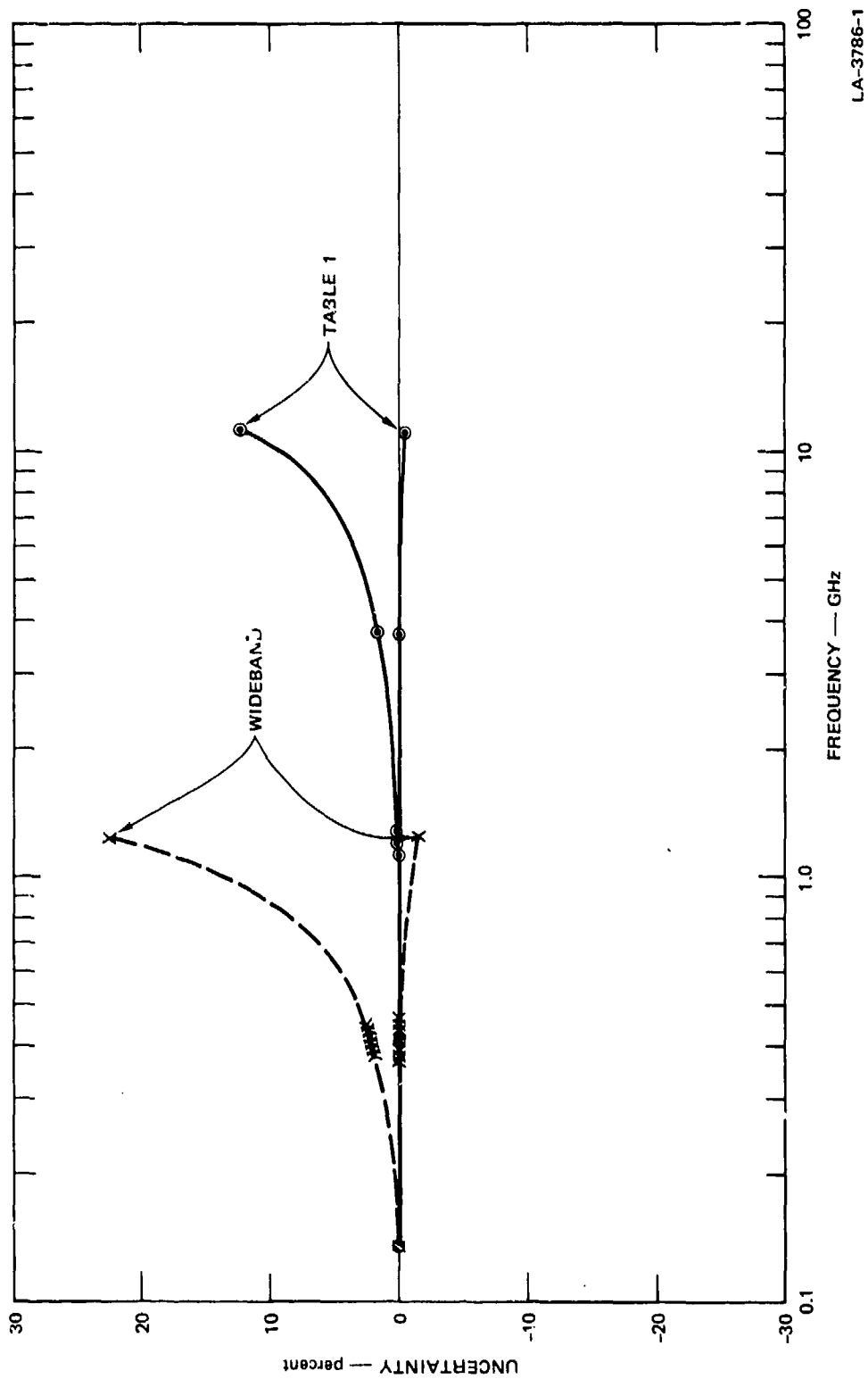


FIGURE 4 FREQUENCY DEPENDENCE OF UNCERTAINTY IN MEASURED STANDARD DEVIATION OF PHASE DUE TO FLUCTUATIONS IN THE REFERENCE CHANNEL, COMPARED FOR WIDEBAND AND FOR THE TRANSMISSION SPECTRUM SHOWN IN TABLE 1

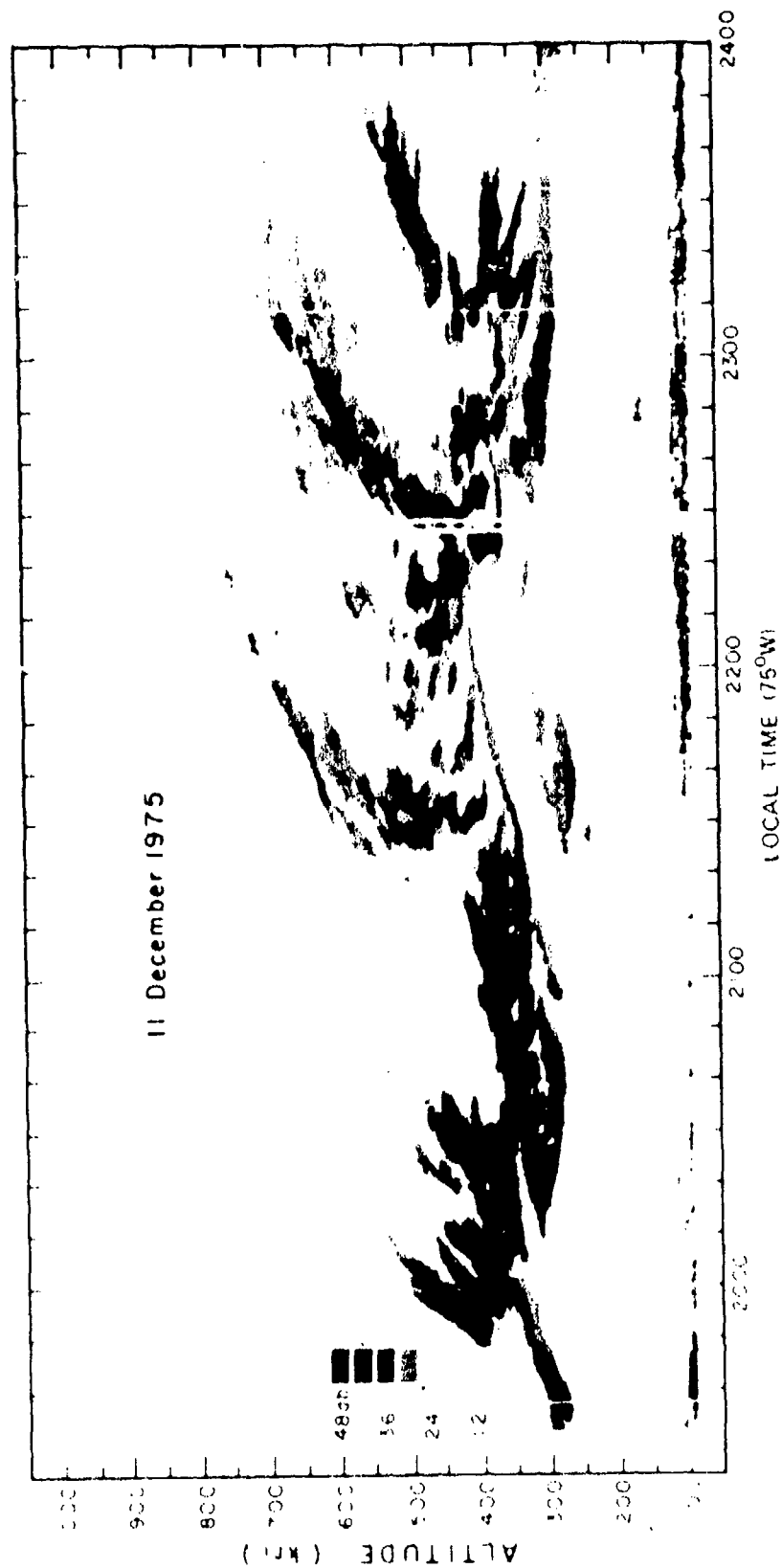
wavelength of 9 mm. Additional frequencies, phase-coherent if desired, could be added to provide measurements at shorter wavelengths.

Several factors influence the choice of an observation site, but for an ideal experiment, one consideration is paramount: the utility of the 50-MHz backscatter radar at Jicamarca, Peru. This instrument has been the key element in understanding the nature and production mechanism of meter-scale irregularities in the equatorial electrojet of the E layer (Farley, 1974). More recently, attention has been directed to F-layer backscatter returns at Jicamarca (Woodman and LaHoz, 1976; Basu et al., 1977), which at times reveal large, plume-like regions of irregularity, an example of which appears in Figure 5. The propensity of the plumes to occur between F-layer sunset and about local midnight suggests strongly that they are directly related to the production of equatorial scintillation, including that observed at GHz frequencies.

For the ideal experiment, therefore, one would like to receive the satellite signals from a point in Peru such that the line of sight would traverse the F layer near the region over Jicamarca. A geostationary satellite near 75°W longitude and an observation site a few km to the geomagnetic south of Jicamarca, on the eastern outskirts of Lima, would be ideal, and even the present Wideband site at Ancon, would suffice. Alternatively, a satellite placed somewhat farther west would provide a favorable geometry for observations from Huancayo (See Section IV-A).

One of the advantages of a geostationary-satellite beacon experiment is that measurements of irregularity drift can be made in a straightforward fashion by employing spaced receivers. For highly field-aligned structures, however, it is extremely difficult to measure the north-south component of drift velocity. The most profitable spaced-receiver measurement, therefore, would be made using an east-west baseline. Because numerous spaced-receiver observations have been made in equatorial regions at VHF (Koster, Katsriku, and Tete, 1966) and UHF (Hopkins, 1977), it is recommended that future observations be made at L band.

Because the L-band, Fresnel-zone size in the F layer (for a satellite at geostationary altitude) is on the order of 300 meters, a baseline of at least this length should be employed for spaced-receiver measurements



LA-3786-2

FIGURE 5 RANGE-TIME-INTENSITY PLOT OF ENHANCED-BACKSCATTER PLUMES OBSERVED WITH THE 50-MHz, LARGE-ARRAY RADAR LOCATED AT JICAMARCA, PERU (McClure and La Hoz, 1976)

of intensity-pattern drift. Detrending of phase data would permit similar measurements of the fine-scale phase pattern; raw records would provide measurements of angle scintillation. Spaced-receiver measurements of phase at L-band would yield data directly applicable to the planning and operation of L-band synthetic aperture radars, such as that planned for SEASAT. A single baseline would suffice, because phase measurements at one antenna provide information about the shape of the spatial spectrum of a drifting pattern; the second antenna, in effect, calibrates the spatial scale.

Because the suggested L-band interferometer observations would be unique and could employ simple, non-tracking antennas, we suggest that a north-south baseline also be employed, in addition to the east-west one, to detect any east-west-aligned structure that may exist in the irregularities responsible for GHz scintillation. For these measurements, the longest convenient baseline should be employed, and should be at least 1 km in length.

There exists today a satellite ideally suited for employment in the experiment described in this section. It is the ATS-F' satellite built by Fairchild for NASA, as a follow-on to ATS-6, and subsequently turned over to the Air Force. ATS-F' is virtually identical in configuration to ATS-6; its dominant feature is a 9-meter parabolic reflector that would be unfurled on orbit for use with antenna feeds for most of the frequencies listed in Table 1. The dish has been ground-tested and found usable up to 8 GHz; it is envisioned that K-band horns would be added for the highest two frequencies in Table 1.

A link budget for the ideal experiment, employing ATS-F', is given in Table 2. The transmitted powers are based on SRI's experience with Wideband and other DNA experiments, for example, the Dust and Debris project. The ground antenna assumed is a 3.7-meter dish, such as the one employed at Kwajalein and Poker Flat for Wideband, except that the K-band signals are assumed to utilize an aperture only half that diameter. Note that the greatest signal-to-noise ratio occurs at L band, so that still smaller antennas could be used for interferometer measurements.

Table 2

## LINK BUDGET FOR EMPLOYMENT OF ATS-F'

|                             | VHF       | UHF       | L-Band    | S-Band    | K <sub>p</sub> -Band | K <sub>a</sub> -Band |
|-----------------------------|-----------|-----------|-----------|-----------|----------------------|----------------------|
| P <sub>T</sub> (dBm)        | 27        | 24        | 20        | 20        | 20                   | 20                   |
| G <sub>T</sub> (dBi)        | 16        | 26        | 35        | 33        | 32                   | 32                   |
| Path loss (dB)              | -167      | -177      | -187      | -197      | -207                 | -217                 |
| S/C alignment (dB)          | 0         | 0         | -2        | -2        | -2                   | -2                   |
| G <sub>R</sub> (dBi)        | <u>11</u> | <u>20</u> | <u>30</u> | <u>37</u> | <u>44</u>            | <u>54</u>            |
| P <sub>R</sub> (dBm)        | -113      | -107      | -104      | -109      | -113                 | -113                 |
| T <sub>rec + ant</sub> (°K) | 5000      | 600       | 400       | 500       | 2000                 | 3000                 |
| BW (Hz)                     | 30        | 30        | 30        | 30        | 30                   | 30                   |
| P <sub>N</sub> (dBm)        | -147      | -156      | -158      | -157      | -151                 | -149                 |
| SNR (dB)                    | 34        | 49        | 54        | 48        | 38                   | 36                   |

The total cost of deploying ATS-F' for the ideal experiment would be very high, on the order of \$50 million. Of this, however, by far the major cost, about \$40 million, would be for launch on a Titan IIIC vehicle. We suggest that DNA consider investigating interest of the Air Force in such a launch, which clearly should then be made available for the addition of other experiments to ATS-F'. In particular, it would seem that observations of solar radiations, solar-wind conditions, and magnetic conditions near the earth's magnetosheath (since synchronous altitude is near 5.6 earth radii) should be considered from the perspective of developing an understanding of the solar-geophysical phenomena that trigger scintillation. For example, Jain and Singh (1977) have found that prolonged and isolated magnetic storms clearly are correlated with the vertical motions of the equatorial F<sub>2</sub> layer. In turn, the

altitude of the  $F_2$  layer is believed to be associated with the onset and intensity of scintillation (e.g., Farley et al., 1970; Hudson and Kennel, 1975). Furthermore, any experiment employing ATS-F' should include instruments designed to extend the state of the art of mm-wave communications.

### C. Observations from a Low-Orbiting Satellite

Given a geostationary satellite such as the one described in Section II-B, it is reasonable to ask whether complementary scintillation observations by means of a low-orbiting satellite would be cost-effective and, if so, at what orbital inclination. Three inclinations come to mind: (1) strict equatorial, (2) an inclination of about ten degrees, so that the satellite would be essentially in the geomagnetic equatorial plane during a portion of each day, and (3) nearly polar.

The underlying reason for considering a low-orbiting beacon satellite is to assist in accurately locating the plasmaspheric irregularities that produce GHz scintillation. It has been demonstrated repeatedly in the Wideband experiment that phase measurements provide a more direct signature of scintillation-producing irregularities than do intensity measurements. For simple location of such irregularities in latitude and longitude, however, the advantage of phase measurements over intensity observations does not warrant the cost of orbiting an additional satellite and placing numerous receiving stations around the equatorial belt. A much more cost-effective job of (horizontal) location can be performed by using satellites of opportunity to observe intensity scintillation at existing ground stations, such as the Intelsat net (see Section III-A-4).

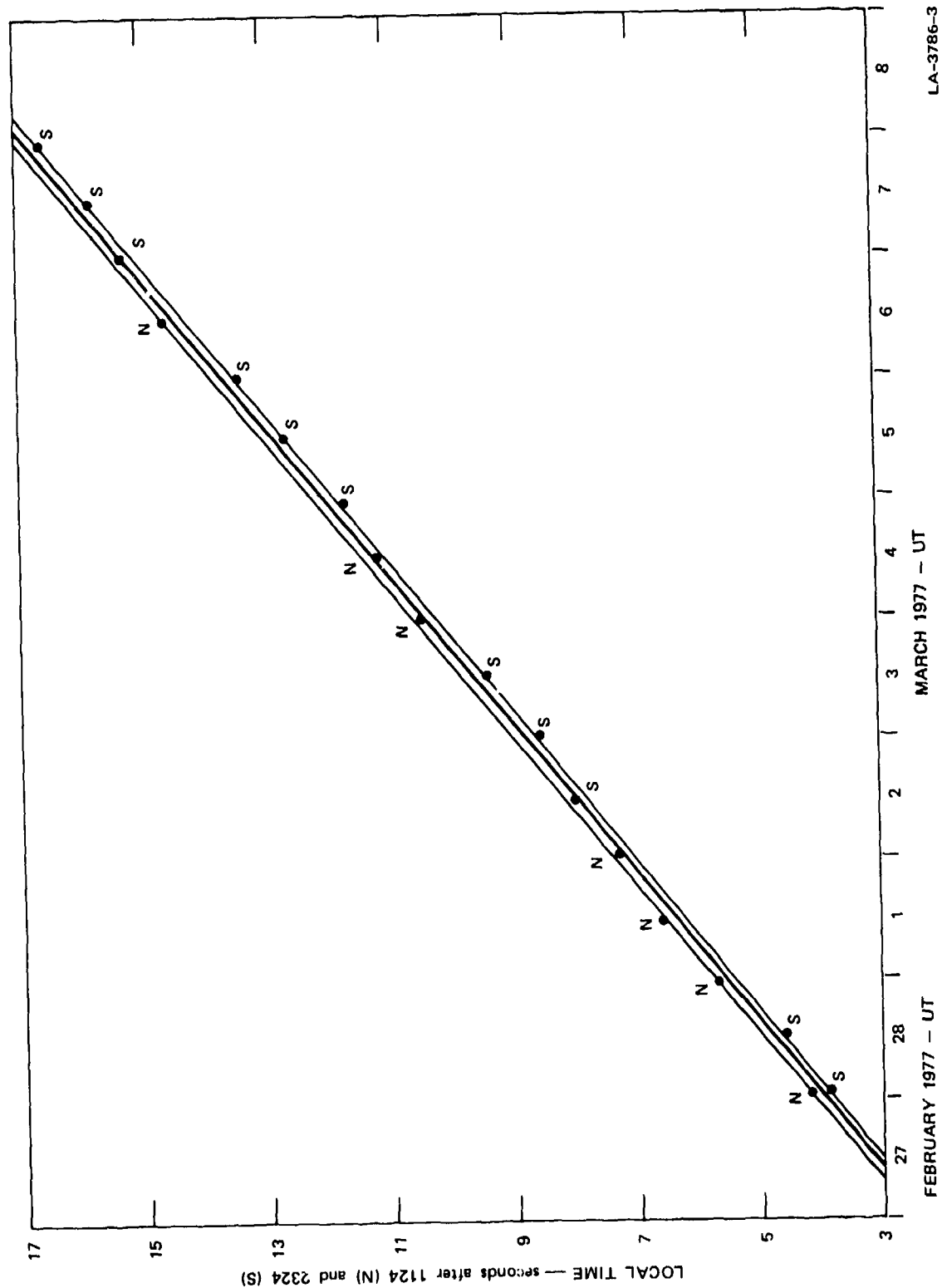
For determining the height of scintillation-producing irregularities, interferometer measurements of a low-orbiting beacon are very useful. Indeed, such measurements are being conducted with the Wideband satellite. Assuming continued good health of the Wideband satellite, there is little reason to suggest orbiting another high-inclination beacon satellite. The current trend in local time of equator crossing by the Wideband

Satellite is illustrated in Figure 6, and shows a lag rate of 1.6 seconds per day, or about ten minutes per year. At the present rate, the equator crossings will occur very close to noon and midnight at the epoch of the next solar maximum, which currently is predicted for early 1981. Thus, occasional observations of GHz scintillation and F-layer plume structure should be possible by means of Wideband in the same epoch envisioned for the geostationary-satellite observations described in Section II-B.

Even without definitive interferometer observations, comparison of the magnitude of phase scintillation observed on the L-band signal transmitted by Wideband with that measured on the L-band signal transmitted by the geostationary satellite should provide an estimate of the contribution made to GHz scintillation by irregularities above 1,000 km. Meanwhile, the DNA community should remain alert to any scintillations that may be reported on the geostationary-to-low-orbit data links utilized by NASA's Tracking and Data Relay Experiments, as described by Tsunoda and Burns (1977).

For interferometer observations, an essentially equatorial orbit may be advantageous because the line of sight then would be scanning across field-aligned irregularities. For this purpose alone, however, it would be difficult to justify the cost of such a launch. On the other hand, if such a satellite were to include a capability for in-situ measurements of electron density and its gradients, electric field and its gradients, and possibly ionospheric constituents, then it might be cost-effective. In this case, an inclination of about 10 degrees would be most productive.

With such an inclination, the satellite would orbit essentially in the geomagnetic equatorial plane during a portion of each day, scanning through all local times in the process. For an observation station at a particular longitude, there would be a period of some weeks each year when the alignment of the orbit with the geomagnetic equatorial plane would occur during the station's local nighttime hours. The season in which the alignment would be properly timed for a given longitude could be selected by properly choosing the orbit's line of nodes, accounting for orbital precession.



Such an orbit could provide a great deal of in-situ data on equatorial irregularities, since a daily sampling in the geomagnetic equatorial plane would occur. As described above, the orbit also could be tailored to provide favorable circumstances for beacon observations during a portion of the year at a pre-chosen location. For instance, one presumably would choose to perform such observations in Peru in October and November, a period of maximum occurrence of GHz scintillation (Taur, 1972). In addition, one could use a portable receiving station that could be moved to different locations which become favorable during the course of a year.

A low-orbiting satellite with a 10-degree inclination is presented within the context of "The Ideal Experimental Program" because it could contribute much to understanding of equatorial irregularities. As will be described briefly in Section IV, plans already are underway for a similar endeavor, namely NASA's Equion program (Morse, 1977). It is suggested that DNA concentration on a geostationary satellite, plus maintenance of the existing research capability afforded by the polar-orbiting Wideband satellite, could be coordinated with the NASA effort to achieve nearly the ideal overall program for understanding microwave scintillation. One might envision also a limited number of rocket probes to make in-situ measurements at altitudes beneath that of the low-orbiting satellite.

### III SATELLITES CONSIDERED FOR USE IN THE EXPERIMENT

#### A. Approaches Considered

A number of approaches have been considered for meeting the primary objective stated in Section II-A. These various approaches are contained in four categories: (1) use of a dedicated satellite designed and launched for this experiment, and controlled to optimize the execution of the experiment; (2) use of a dedicated satellite placed in geosynchronous orbit by using available space on scheduled launches (that is, a "piggyback" satellite); (3) use of a beacon payload designed for this experiment and integrated into a multiple-experiment satellite coordinated by the Air Force Space and Missiles Systems Organization (SAMSO); and (4) use of signal sources from satellites of opportunity. Each approach is discussed in the following subsections.

##### 1. Dedicated Satellites

For the ideal experiment (Section II), we proposed use of the ATS-F' satellite. We estimated an experiment cost on the order of \$10 million plus the costs of launch and integration on a Titan IIIC vehicle. A means of reducing the total cost would be to use a less expensive launch vehicle than the Titan IIIC. Satellites recently have been inserted into geostationary orbits using the less expensive Thor/Delta launch vehicle.

A dedicated satellite that would allow most of the objectives of the ideal experiment to be met could be built by copying Japan's Engineering Test Satellite, ETS-2, with slight modifications. This spacecraft was designed and built by Aeronutronic-Ford in Palo Alto, California, and launched on a vehicle built by McDonald-Douglas that is very similar to the Delta 2914 launch vehicle. The satellite was launched in February 1977 and has achieved its desired geostationary orbit. Its characteristics are listed in Table 3.

Table 3  
CHARACTERISTICS OF THE ETS-2 SATELLITE

|                            |                                                                                             |
|----------------------------|---------------------------------------------------------------------------------------------|
| <u>Orbit</u>               | Geostationary (Active Station Keeping)<br>$0 \pm 1^\circ$ latitude, $130^\circ$ E longitude |
| <u>Downlink Signals</u> *  |                                                                                             |
| (1) Telemetry:             | 136.1121 MHz, 2/8 W                                                                         |
| (2) Transponder            |                                                                                             |
| Frequencies:               | 2.1159 GHz (up); 1.7043 GHz (down)                                                          |
| Power:                     | 4 W                                                                                         |
| Bandwidth:                 | 8.2 MHz                                                                                     |
| (3) Propagation Experiment |                                                                                             |
| Coherent Frequencies:      | 1.705, 11.50875, 34.52625 GHz                                                               |
| ERP:                       | +28, +46, +50 dBm                                                                           |
| Earth Coverage:            | (34 GHz beamwidth $\approx 2^\circ$ )<br>$35.5 \pm 7.5^\circ$ N, $50.4 \pm 7.5^\circ$ E     |

\*Power system will not support all transmitters simultaneously.

For the microwave scintillation experiment, the following modifications would be made:

- A UHF beacon transmitter and antenna system would be added. A desirable\* frequency--426.25 MHz--already exists in the coherent beacon synthesizer (item 3 in Table 1). It is possible that the VHF telemetry transmitter (item 1 in the table) is, or could be made, coherent (with item 3 also).
- The S band (1.705 GHz) signal would be modulated to provide a coherent triplet of frequencies for measurements of total electron using the  $\Delta_2\phi$  technique.
- The antennas would be aligned to illuminate the equatorial region instead of the region around  $35^\circ$ N illuminated by the ETS-2 satellite. East-west beam

---

\*Desirable for frequency sampling; see Table 1.

steering could be performed by command to the antenna despin system or by moving the spacecraft. Slight north-south adjustments in beam position could be made by tilting the spacecraft.

The ETS-2 copy described above could be built for about \$12 million in about two years. The cost of the launch would be about \$8 million.

A spacecraft much simpler than the ETS-2 satellite could be built using gravity-gradient stabilization. Although a completely successful gravity-gradient-stabilized geosynchronous satellite has yet to be built, the technology now exists to do it. Early spacecraft designs utilizing gravity-gradient stabilization employed extendable tubular booms such as those used in the existing wideband satellite. Flexing of these booms caused by uneven solar heating was found to result in librational instability. For low-altitude (700-1,000 km) orbiting satellites, the extent of the libration is about 10 degrees, but at geosynchronous altitudes the libration is much greater. More modern spacecraft that use gravity-gradient stabilization employ scissors booms, which are unaffected by solar heating. The libration on low-altitude-orbiting satellites that employ these booms can be made to be a fraction of a degree. Although spacecraft that have scissors booms have not yet been flown at geosynchronous altitudes, the results are predictable.

The Applied Physics Laboratory of Johns Hopkins University could build a gravity-gradient-stabilized spacecraft with minimum design effort by utilizing and adapting existing designs. In order to obtain stability at geosynchronous altitude, the center of solar pressure must be coincident with the center of mass of the spacecraft. For this reason, the spacecraft would be divided into two similar parts and separated by the extendable booms. Solar cell panels would be deployed from or applied to both sections. A multiple-antenna system using a fabric dish at the low frequencies and horns at the high frequencies would be located on the spacecraft surface that faces Earth.

Another feasible simplification would be to eliminate an active station-keeping system on the satellite. Without active station keeping,

the satellite will drift in longitude because the earth's gravitational field is not uniform. The intent in this case would be to have the satellite trapped in one of the geopotential wells (see Section IV-A). For this purpose, a thruster system would be included in the satellite to correct its velocity so that it would be trapped in the desired geopotential well. The satellite then would slowly oscillate east and west of that location over a period of a few years. Additional details on the use of this kind of satellite for the proposed experiment are given in Section IV-A.

The simplified gravity-gradient-stabilized spacecraft would cost between \$7 and \$8 million to build, test, and interface. It would be launched by a Delta 2914 vehicle, and would only use about one-half of the 750-lb. maximum capability of that vehicle. Launch using a Delta 2914 costs about \$8 million.

## 2. Cooperative Launches with Other Satellites

Occasionally, launches occur in which the space and weight budgets for the vehicle are not completely used by the satellites being launched. Such an opportunity will exist in 1978 with the launch of the 777 satellites. The weight budget easily would allow a satellite of the gravity-gradient type to be launched in "piggy back" fashion. The space available would require design of a special satellite that would fit the available space. Unfortunately, the time scale for the forthcoming launches of the 777 satellites is too short to allow time for the design and construction of a satellite meeting our requirements, and follow-on satellite systems planned for launch in later years do not have space for the additional "piggy back" satellite. Other launches with sufficient space left over have not been found. As a result, this approach currently is not considered possible.

## 3. SAMSO Multi-Experiment Satellites

The Air Force Space and Missiles Systems Organization (SAMSO) provides a regular schedule of launches in which a number of small experiments are combined into a large satellite system. Most of these launches

are for low-altitude orbits. A synchronous satellite of this class now is being discussed for launch in 1982 or 1983. The current schedule would put the time of the launch after the period of solar maximum, even if no slips occurred in the schedule. Our experience with P72-2 (Wide-band I) and other combined-experiment spacecraft leaves us very pessimistic about this approach.

#### 4. Satellites of Opportunity

The characteristics of a large number of satellites that are either in orbit or planned for the next few years have been reviewed to see if any one (or more) of the satellites could be used for this experiment. The restricting factor, of course, is the limited number of coherent frequencies that are transmitted by any satellite. None of the satellites has a transmission spectrum that approaches the ideal spectrum shown in Table 1. However, because some useful data can be obtained from even a limited spectrum, we discuss some of the more interesting satellites in this subsection.

As discussed by Tsunoda and Fremouw (1976), ATS-6 potentially is one of the most useful of those available for this experiment. ATS-6 contains a transponder that, in a phase-locked mode, can be made to transmit simultaneously a coherent pair of microwave frequencies to a ground station. In this mode, the transponder coherently translates the uplink C-band signal (6.35 GHz) to two frequencies, 3.75 and 1.55 GHz, both of which simultaneously are transmitted earthward. The signal at 3.75 GHz originally was intended for ranging purposes, while the signal at 1.55 GHz was originally intended for radio relay to low-flying aircraft as part of the Position Location and Aircraft Communication Experiment (PLACE). Although the reference frequency (3.75 GHz) is not as high as we would like (see Table 1), the coherent pair still would provide valuable data on microwave scintillation.

ATS-6 also contains a radio beacon that transmits coherently at 40, 140, and 360 MHz. Although they are not coherent with the higher-frequency pair, they still could be used to relate the microwave scintillation results to past results. Another advantage of ATS-6 is its

ability to conduct an altitude partitioning experiment, as described in detail by Tsunoda and Burns (1977). By utilizing radio relay links between ATS-6 and low-orbiting satellites (such as GEOS-C, NIMBUS) and between ATS-6 and ground stations, the altitude at which the irregularities that produce microwave scintillations are imbedded can be determined. Further details concerning ATS-6 as part of a useful experiment are given in Section IV-B.

The Lincoln Experimental Satellites (LES) also can provide a pair of coherent CW transmissions, one at 250 MHz and the other near 37 GHz. However, they must be turned on and commanded into a special mode, a constraint not conducive to a routine monitoring operation. The LES satellites also have a telemetry transmitter at S band that can be made coherent with the other frequencies, but the modulation cannot be disabled. It might be possible to devise a scheme that effectively would remove the modulation (for example, a technique of this kind was successfully employed in the Wideband program, in which the modulation on Transit satellite transmissions was removed). If such a scheme could be devised, the coherent set of three frequencies would enhance considerably the usefulness of the LES satellites for a microwave experiment.

At present, two LES satellites are in operation, LES-8 and LES-9. Both were launched to synchronous altitude on 11 March 1976. The orbits are nearly circular, and are inclined from the equator by 23 degrees. LES-8 was stationed near 105° W and LES-9 was stationed at 40° W. It is reported, however, that LES-9 is being moved westward to 67° W by 1 April 1977. Both LES-8 and LES-9 can be viewed at reasonably high elevation angles from Jicamarca (54.6 degrees to LES-8, 71.8 degrees to LES-9). Alternatively, a receiving site could be located so that the ionospheric penetration point would be directly over Jicamarca (see Section IV for the observing geometry for a geostationary satellite at 105° W longitude). This pair of satellites can be used to separate temporal and spatial variations in microwave scintillations at similar frequencies. Their ionospheric penetration points (at an altitude of 350 km) from Jicamarca are separated by 2.5° in

longitude, or 10 minutes in local time. Another consideration is the apparent movement of the LES satellites because of their orbital alignment with the ecliptic plane rather than the equatorial plane. Their position will change as much as  $23^\circ$  in latitude during a period of 6 hours. This movement can be exploited because LES-8 trails LES-9 by about a quarter of a cycle. It may be possible to determine the degree of correlation in scintillations as a function of latitudinal as well as longitudinal separation.

The only other satellite that has a usable coherent pair of frequencies above 1 GHz is the Japanese ETS-2 satellite described in Section III-A-1. (See Table 3.) The K-band signal covers only the immediate region around the islands of Japan, and is not useful for any equatorial measurements. The X-band and S-band signals, however, could be received at Kwajalein (at an elevation angle of  $45.3^\circ$ ) when they are turned on. Although its reference frequency for this case (11.5 GHz) would be higher than that available from ATS-6, it has a further disadvantage in that the observing geometry cannot include the region near the Jicamarca radar.

None of the numerous other satellites operating above 1 GHz that were investigated for the proposed experiment has a coherent pair of frequencies. Most operate either in the commercial 6 GHz (uplink)/4 GHz (downlink) band, or in the military 8 GHz (uplink)/7 (downlink) band. These include the Intelsat, ANIK, DSCS, NATO-IIA, B, and SKYNET satellites. Others, which operate at other frequencies, include the CAS-C, GOES/SMS, and COMSTAR satellites. This group of satellites can be used for morphological studies, utilizing particularly the Intelsat network. Currently, 17 operational Intelsat satellites are distributed in longitude (see Tsunoda and Fremouw, 1976) and being used by COMSAT to investigate the characteristics of microwave amplitude scintillations. Dr. D. J. Fang of COMSAT has expressed a willingness to cooperate with us on any current or future study of GHz scintillations.

## B. Summary of Alternatives

The various approaches described in this subsection are summarized in Table 4. When costs are shown, they include only the costs of the satellite and the launch, which override all other costs in the case of dedicated satellites. Considering the characteristics, advantages, and limitations of the payload for each of the approaches included in Table 4, we suggest two alternatives to the ideal experiment described in Section II. The preferred alternative is an approximate realization of the ideal experiment, using a gravity-gradient-stabilized satellite and a dedicated launch (which could, however, support other experiments). This approach, described in Section IV-A, could be used to field a mm-wave experiment directed at nonplasmaspheric propagation effects, as addressed in Section V. A lower-cost alternative to the preferred experiment for measuring plasmaspherically produced scintillation is described in Section IV-B; it would employ ATS-6.

Table 4

## SATELLITE APPROACHES CONSIDERED

| Approach                                           | Approach Characteristics                                            | Advantages                                            | Limitations                                                                                     | Conclusions                                     |
|----------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------|
| <u>Dedicated</u>                                   |                                                                     |                                                       |                                                                                                 |                                                 |
| ATS-F'                                             | Ideal spectrum                                                      | Ideal spectrum, arbitrary longitude                   | \$10 million plus launch costs                                                                  | Too expensive unless shared                     |
| ETS-2 (copy)                                       | 4 or 5 coherent frequencies                                         | Arbitrary longitude                                   | \$12 million plus launch costs                                                                  | Reasonable choice                               |
| Gravity-gradient-stabilized satellite              | Augmented Wideband satellite                                        | \$8 million plus launch costs (potential for sharing) | Geopotential well                                                                               | Preferred experiment                            |
| <u>Piggy-back Satellite</u>                        |                                                                     |                                                       |                                                                                                 |                                                 |
| Gravity-gradient-stabilized satellite on 77 launch | Augmented Wideband spectrum                                         | Less expensive than dedicated launch                  | 777 satellite launches occur too soon; not enough time for design and construction of satellite | Not a viable approach                           |
| <u>Multi-Experiment Satellites</u>                 |                                                                     |                                                       |                                                                                                 |                                                 |
| Dedicated payload                                  | Ideal spectrum or augmented Wideband spectrum                       | Less expensive than dedicated satellites              | First launch scheduled after sunspot maximum; schedule slippage possible                        | Not an attractive approach                      |
| <u>Satellites of Opportunity</u>                   |                                                                     |                                                       |                                                                                                 |                                                 |
| ATS-6                                              | 2 coherent microwave frequencies and 3 coherent VHF-UHF frequencies | Operational; visible from Jicamarca                   | Low viewing angle from near Jicamarca                                                           | Low-cost alternative to preferred experiment    |
| LES-8, LES-9                                       | 3 coherent frequencies                                              | Well situated; two satellites at similar frequencies  | May not be usable for routine monitoring operation; modulation on S band                        | Potentially useful; could be considered further |
| ETS-2                                              | 2 coherent frequencies                                              | Operational                                           | Foreign satellite (Japan); cannot be viewed from Jicamarca                                      | Not considered a serious candidate              |

#### IV SUGGESTED EXPERIMENTS

##### A. An Embodiment of the Ideal Program

As described in Section II, a comprehensive study of equatorial scintillation can be made by means of a program that would (1) be centered around transmission of the spectrum presented in Table 1 from the ATS-F' geostationary satellite, (2) incorporate observations of the polar-orbiting Wideband satellite, (3) be coordinated with NASA's Equion in-situ satellite in low-inclination orbit, and (4) be augmented by a number of rocket probes of the equatorial F layer. All elements of the foregoing ideal program are feasible, and most could be performed at reasonable cost. Unfortunately, however, the central element itself would be extremely expensive.

In Section II-B, we suggest consideration of a shared program that would employ ATS-F'. We recognize, however, the improbability of establishing the necessary inter-agency coordination to accomplish such an ambitious undertaking in time for the 1981 solar activity maximum. In this section we describe a less expensive approach to placing a multi-frequency coherent beacon into geostationary orbit. Although this approach would require development of a satellite for the purpose, it would employ a much less expensive launch vehicle (a Thor/Delta) than that required for launch of ATS-F' (a Titan III C). In addition, the beacon payload would incorporate the existing spare Wideband payload, but would require some compromise in transmission spectrum.

Aside from its 9-meter dish, an important asset contained in ATS-F' is its capability for station-keeping and relocation. This capability would provide maximum flexibility in the choice of observation sites. But this also is a major element of the weight and complexity of the satellite. We suggest in this section the use of a lighter, simpler satellite that could be made to remain within an acceptable longitudinal

sector by taking advantage of the well-known shape of the earth's gravitational field.

A satellite injected into synchronous orbit does not remain fixed over a given longitude, as would occur if the only force acting on it were that from a uniform gravitational field. Instead, such a satellite drifts in longitude because of non-uniformities in the gravitational field. The satellite moves toward a longitude of minimum potential energy and oscillates about that longitude if the satellite's kinetic energy is less than the depth of the geopotential well.

There are two dominant geopotential wells in the earth's gravitational field, one at  $75^{\circ}$  E and the other at  $105^{\circ}$  W. The latter, of interest here, will trap a satellite if the satellite's drift velocity is less than 0.4 degree/day. For  $\pm 45^{\circ}$  excursions in longitude about the stable point, the oscillation period will be on the order of three years. For  $\pm 60^{\circ}$  oscillations, the period is closer to four years.

We suggest inserting a satellite developed for microwave-scintillation measurements into the geopotential well located at  $105^{\circ}$  W longitude. The observing geometry to such a satellite from several possible receiving sites is summarized in Table 5. The list of possible receiving sites includes those locations from which the satellite at  $105^{\circ}$  W can be viewed through the disturbed equatorial ionosphere with a reasonably high elevation angle, in addition to those sites favored by other considerations.

An overriding consideration in the selection of both a satellite location and a receiving site, as discussed in Section 1, is the inclusion of the Jicamarca radar into the observing geometry. It is highly desirable to have the radar provide plasma diagnostics along the propagation path from the satellite to the receiving station. It can be seen from Table 3 that a satellite in the geopotential well at  $105^{\circ}$  W longitude can be viewed from Jicamarca at an elevation angle of 55 degrees. With this viewing angle, the ionospheric penetration point (at an altitude of 350 km) is located approximately 200 km northwest of Jicamarca, and within  $0.8^{\circ}$  of the magnetic dip equator. But because the

Jicamarca radar beam cannot be steered to such a low elevation angle, a preferred receiving site would be one that has a line-of-sight path to the satellite that penetrates the ionosphere directly over Jicamarca.

The coordinates of such a preferred site are shown in Table 5, together with the ionospheric penetration point, which, by definition, has the coordinates of Jicamarca. As noted in the last column, the ionospheric penetration point is within  $0.34^\circ$  in latitude from the magnetic dip equator. The observing geometry is shown graphically in Figure 7. The expanded view in the inset in Figure 7 shows the locations of three of the larger towns near the preferred site, P. Of the three towns, Huancavelica appears to be best suited for the desired geometry. The ionospheric penetration point from there would be located approximately 40 km northwest of Jicamarca and within 20 km of Ancon, a Wideband receiving site. Tsunoda and Burns (1977) showed that irregularities in the equatorial ionosphere are statistically nonuniform over distances greater than 100 km in latitude. Therefore, the 40 km separation distance should be small enough that the plasma diagnostics obtained with the radar will be representative of those at the ionospheric penetration point. Either of the other two towns also satisfies this requirement.

Consideration should be given also to Ancon, Lurin, and Huancayo as possible receiving sites. Ancon has the advantage of being an operating Wideband receiving station. Because of its proximity to Jicamarca, its viewing angle and ionospheric penetration point are similar to those of Jicamarca. Lurin is included because the Wideband station at Ancon may be moved to Lurin this year. Huancayo is slightly better situated than Lurin and Ancon because its ionospheric penetration point is closer to Jicamarca. However, the penetration point still is approximately 150 km away from Jicamarca, somewhat farther than the desired maximum separation of 100 km. Huancayo would be preferred from a practical point of view because it is also the site of a geomagnetic observatory. Ancon, Lurin and Huancayo are within  $2^\circ$  of the magnetic dip equator.

Table 5  
OBSERVING GEOMETRY FOR GEOSTATIONARY SATELLITE AT 105° W (GEOPOTENTIAL WELL)

| Name             | Station         |                  |                  |                | Ionospheric Penetration Point (h = 350) |                  |                                                |
|------------------|-----------------|------------------|------------------|----------------|-----------------------------------------|------------------|------------------------------------------------|
|                  | Latitude<br>(°) | Longitude<br>(°) | Elevation<br>(°) | Azimuth<br>(°) | Latitude<br>(°)                         | Longitude<br>(°) | Latitude of Dip<br>Equator (°)<br>(h = 400 km) |
| Jicamarca        | 11.95 S         | 76.87 W          | 54.61            | -68.83         | 11.23 S                                 | 78.76 W          | 12.06 S ( $\Delta\text{lat}=0.83$ )            |
| Preferred Site*  | 12.72 S         | 74.80 W          | 52.14            | -69.28         | 11.90 S                                 | 76.87 W          | 12.29 S ( $\Delta\text{lat}=0.34$ )            |
| Ancon            | 11.45 S         | 77.08 W          | 55.03            | -69.46         | 10.76 S                                 | 78.94 W          | 12.04 S ( $\Delta\text{lat}=1.28$ )            |
| Lurin            | 12.26 S         | 76.86 W          | 54.47            | -68.35         | 11.52 S                                 | 78.75 W          | 12.06 S ( $\Delta\text{lat}=0.54$ )            |
| Huancayo         | 11.05 S         | 75.33 W          | 53.34            | -71.41         | 10.38 S                                 | 77.33 W          | 12.23 S ( $\Delta\text{lat}=1.85$ )            |
| Christmas Island | 1 N             | 157 W            | 30.51            | 90.78          | 0.94 N                                  | 152.5 W          | 11.43 S ( $\Delta\text{lat}=2.37$ )            |
| Kwajalein        | 8.72 N          | 192.27 W         | 5.95             | 90.41          | 8.4 N                                   | 179.09 W         | 2.63 N ( $\Delta\text{lat}=5.77$ )             |

\* Station at which line-of-sight to satellite passes overhead at Jicamarca at 350 km altitude.  
 $\Delta\text{lat}$  = difference between latitude of penetration point and latitude of dip equator.

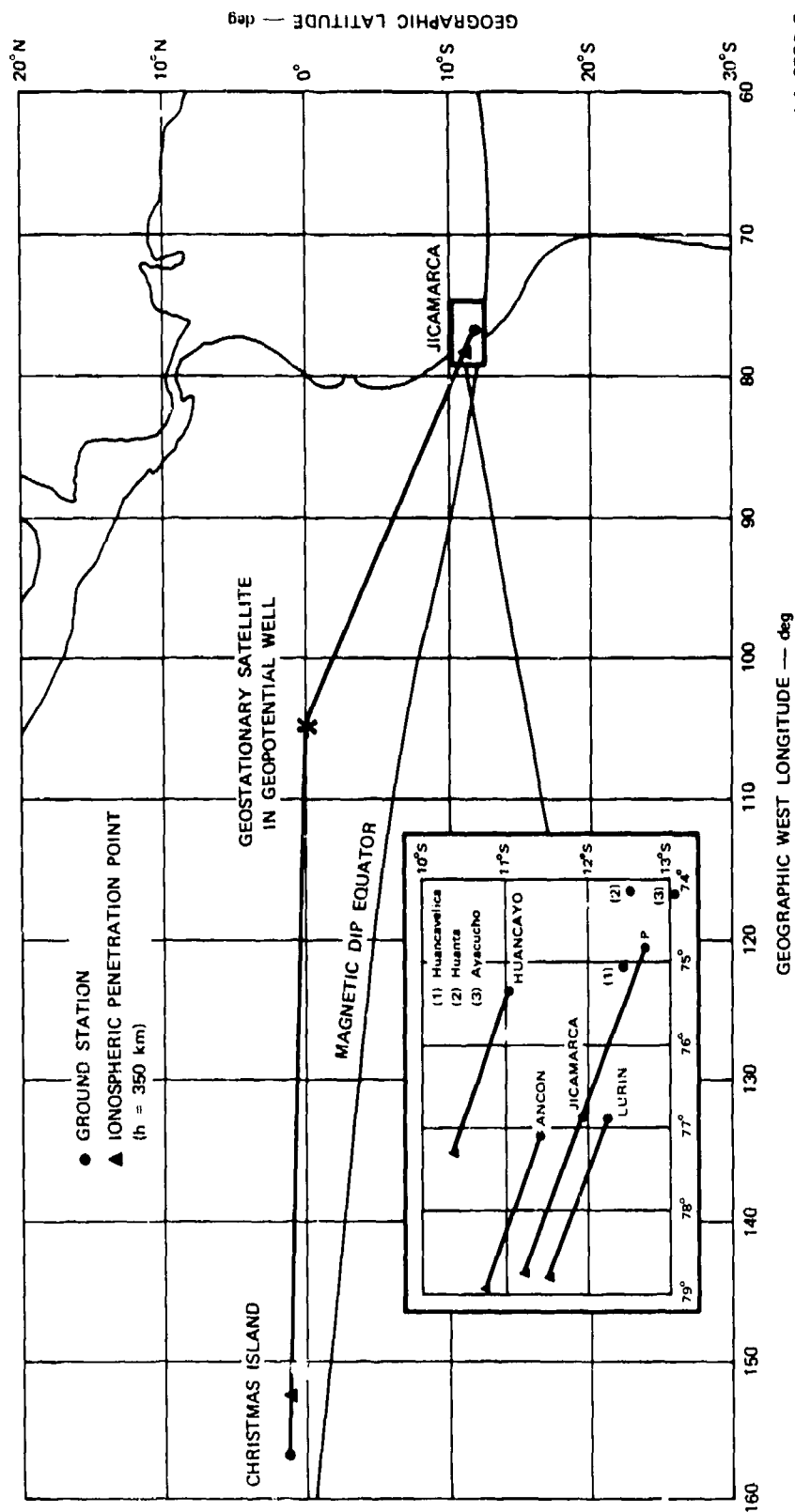


FIGURE 7 OBSERVING GEOMETRY TO GEOSTATIONARY SATELLITE IN GEOPOTENTIAL WELL AT 105°W LONGITUDE

Other than these sites in Peru, the only other possible receiving site would be Christmas Island, located west of the geopotential well. However, its viewing angle is not nearly so good as those from South America. Its ionospheric penetration point also is farther from the magnetic dip equator than are the corresponding points from receiving sites in South America. Kwajalein, which is the location of another equatorial Wideband receiving station, can be seen from Table 5 to be too far west to receive any consideration as a receiving site.

A principal consideration in configuring the satellite to be used in the suggested experiment is the choice of an antenna assembly to radiate the desired coherent signals. The frequencies suggested for the experiment are presented in Table 6. The suggested spectrum, to some degree, approximates the ideal spectrum presented in Table 1, and could be generated by augmenting the existing spare Wideband beacon.

Table 6  
SUGGESTED TRANSMISSION SPECTRUM

| Designation         | Frequency<br>(GHz) | Harmonic Number<br>(of 11.474 MHz) |
|---------------------|--------------------|------------------------------------|
| VHF                 | 0.138              | 12                                 |
| UHF                 | 0.379              | 33                                 |
|                     | 0.390              | 34                                 |
|                     | 0.402              | 35                                 |
|                     | 0.413              | 36                                 |
|                     | 0.424              | 37                                 |
|                     | 0.436              | 38                                 |
|                     | 0.448              | 39                                 |
| L. Band             | 1.239              | 108                                |
| S Band              | 2.891              | 252                                |
| K <sub>e</sub> Band | 13.631             | 1,188                              |

Unlike the ideal spectrum, the suggested spectrum would make TEC measurements possible at UHF instead of at L band. An improvement of 3 dB could be achieved in the UHF signal-to-noise ratio by providing only first-order sidebands, as discussed in conjunction with Table 1, rather than three sideband orders, as shown in Table 6. A simple modulator could be employed to provide a single pair of sidebands. The overriding fact, however, is that a space-qualified electronics package exists that would provide the 7 UHF spectral lines shown in Table 6. To modify the package by replacing the present modulator with a new, simpler one would require a significant amount of testing and requalification, which we do not believe would be justified by the small improvement in the signal-to-noise ratio that would be obtained.

The antenna assembly envisioned for use in the suggested experiment is a deployable two-meter parabola illuminated at UHF, L band and S band. The reflector would be used also as a curved ground plane over which crossed VHF dipoles would be placed. Because the use of this dish at K band would result in too narrow a beamwidth, the K-band antenna would be a conical horn having a 10 degree beamwidth and would be mounted separately on the spacecraft.

Although this configuration does not preserve the common phase achieved with the Wideband satellite, separate antennas are acceptable for this experiment because of the fixed geometry that results from geosynchronous orbit. Differential phase shift between the K-band signal and other radiations caused by spacecraft rotation is expected to be small and to have a period of approximately 24 hours, and therefore easily detrended.

The link budget for the suggested experiment is presented in Table 7. For all frequencies except the K band, the receiving antenna assumed is the one presently used for Wideband observations at Ancon. For the K band, the antenna assumed is a 2-meter dish with 40-percent efficiency.

To implement the suggested experiment, we anticipate a modification of the existing Wideband spare beacon in a fashion very similar to the modification employed for the DNA Dust and Debris program. For that

Table 7

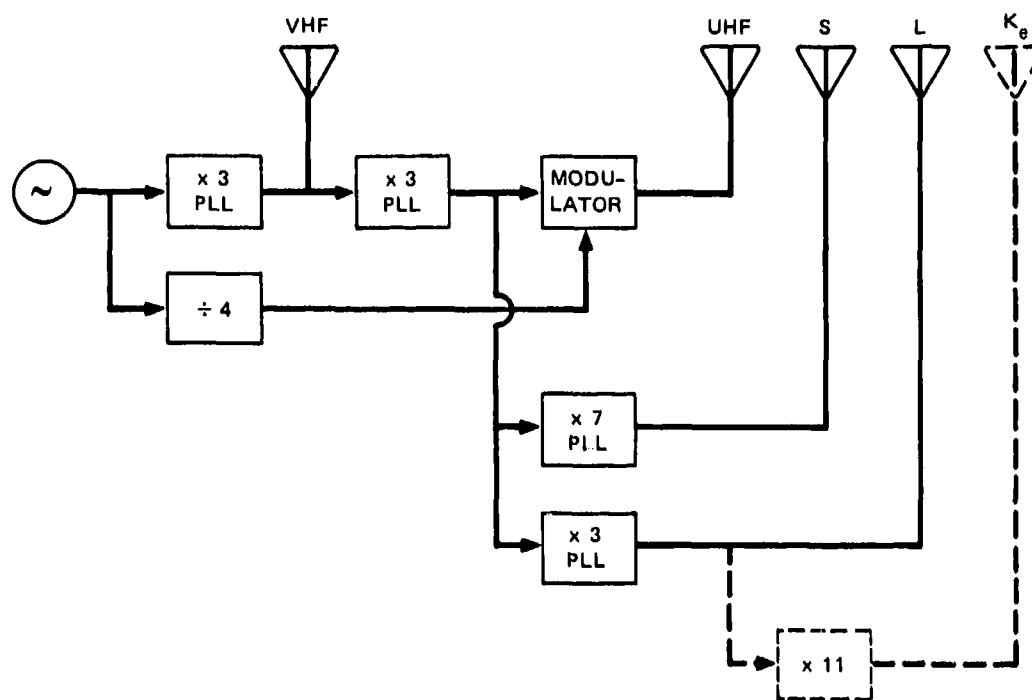
## LINK BUDGET FOR SUGGESTED EXPERIMENT

|                          | VHF       | UHF       | L-Band    | S-Band    | K <sub>e</sub> -Band |
|--------------------------|-----------|-----------|-----------|-----------|----------------------|
| P <sub>T</sub> (dBm)     | 27        | 24        | 23        | 20        | 23                   |
| G <sub>T</sub> (dBi)     | 6         | 15        | 24        | 24        | 24                   |
| Path loss (dB)           | -167      | -177      | -187      | -194      | -207                 |
| G <sub>R</sub> (dBi)     | <u>19</u> | <u>28</u> | <u>38</u> | <u>45</u> | <u>44</u>            |
| P <sub>rec</sub> (dBm)   | -115      | -110      | -102      | -105      | -116                 |
| T <sub>sys</sub> (°K)    | 5000      | 600       | 400       | 500       | 2000                 |
| BW (Hz)                  | 30        | 30        | 30        | 30        | 30                   |
| P <sub>noise</sub> (dBm) | -137      | -146      | -148      | -147      | -141                 |
| SNR (dB)                 | 22        | 36        | 46        | 42        | 25                   |

program, use of an X-band phased-locked-loop multiplier was investigated and found to be impracticable. Instead, step-recovery diode (SRD) multipliers were purchased and used both for the transmitter (10188 MHz) and for local oscillators (9362 MHz) in the receiver. These units consist of three stages of RF amplification (with AGC) that drive a single SRD that produces all the harmonics of the input frequency. The generated frequency comb passes through an isolator to an interdigital filter that selects the desired output frequency. The Dust and Debris multipliers produce +20 dBm at the output frequency. A times-five X-band multiplier was measured and found to exhibit a phase shift of 20 degrees at the output frequency for a 30 °C temperature change or a 3-dB input-power variation.

A multiplier design of the foregoing type offers advantages of proven design, known characteristics, and multiplication by any integer. For the suggested experiment, a times-eleven multiplier would be space-

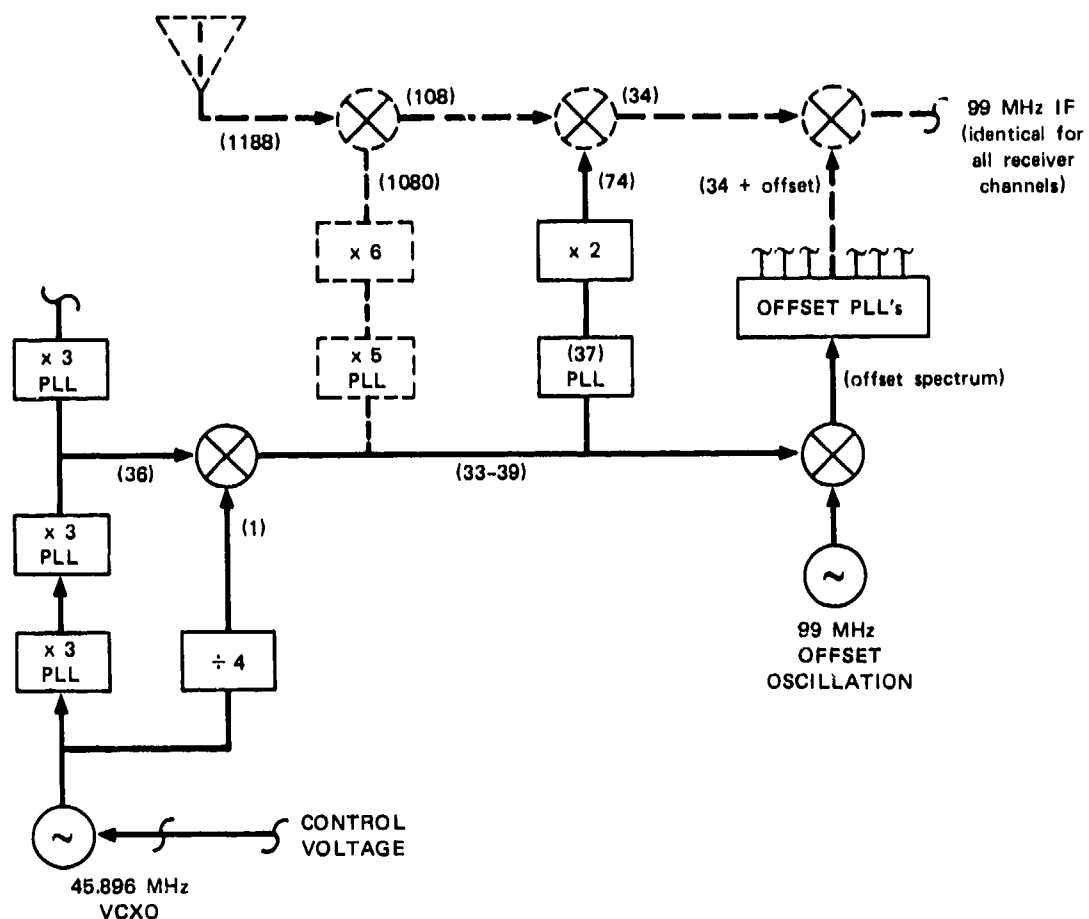
qualified and added to the existing spare Wideband transmitter as shown in Figure 8. Such a multiplier would weigh between three and four pounds, occupy a volume of approximately forty cubic inches, and consume approximately five watts of dc power.



LA-3786-6

FIGURE 8 METHOD OF GENERATING FREQUENCIES LISTED IN TABLE 3. Solid lines indicate existing hardware; dashed lines indicate elements to be developed. PLL denotes phase-locked-loop multipliers.

A similar design would be employed for a times-six multiplier, to follow a times-five, phase-locked multiplier (as shown in Figure 9) in the frequency synthesizer of the receiver, which otherwise would be essentially identical to the synthesizer employed in the Wideband receivers. The IF circuitry that would follow the first mixer in the K-band channel would be identical to that in the L-band channels of the present Wideband receivers. Because we anticipate that simultaneous observations of Wideband and the geostationary beacon will be desired, the suggested experiment must employ frequencies shifted slightly from



LA-3786-7

FIGURE 9 BASIC FREQUENCY PLAN FOR AUGMENTING THE PRESENT WIDEBAND RECEIVER DESIGN FOR USE IN THE SUGGESTED EXPERIMENT. Dashed lines represent new elements to be added to the existing design, elements of which are illustrated by solid lines. PLL denotes phase-locked-loop multipliers, and numbers in parentheses denote multiples of 11.474 MHz.

those transmitted by Wideband. The shift would be accomplished by employing for the suggested experiment a fundamental frequency offset 1 kHz from that of Wideband, namely 11.474 MHz instead of 11.473 MHz. This can be accomplished in the spare Wideband transmitter simply by changing the basic-oscillator crystal and retuning the four phase-locked multipliers. A similar shift would be incorporated in the frequency synthesizer for the new receiver. The other sections of the Wideband receiver design can accommodate the frequency shift without modification, as can the existing Wideband antenna-feed design.

Attempting to use the K-band channel of the suggested receiver as the phase reference for the measurement poses a potential problem. The added frequency multiplication results in a higher loop gain, which might cause instabilities within the reference loop. Some redesign of the reference-loop amplifier (Fremouw et al., 1974) may be necessary to accommodate the K-band reference frequency.

In summary, we suggest that a gravity-gradient-stabilized satellite be developed as a platform for the existing spare Wideband beacon transmitter, which would be augmented by a channel for transmitting a phase-coherent K-band reference frequency. This would extend the present capabilities of Wideband for measurement of complex-signal scintillation to S band and for measurement of intensity scintillation to above 10 GHz. More importantly, the launch of the suggested satellite to geostationary altitude near a longitude of 105° W, by means of a Thor Delta rocket, would provide a capability for continuous observation of microwave scintillations through the equatorial plasmasphere at a fraction of the cost of the ideal experiment described in Section II.

The principal costs incurred with the suggested experiment would result from the development of the spacecraft and the procurement of the launch vehicle. As described in Section III, the Applied Physics Laboratory of Johns Hopkins University could build a suitable gravity-stabilized spacecraft for a cost of between \$7 and \$8 million. The testing and integration of the spare Wideband beacon payload, augmented with a suitable K-band source, would add another \$1 million to the costs of the program. The satellite required for the suggested experiment would make use of only about 350 pounds of the 750 pounds (maximum) payload-weight capacity of the DELTA 2914. This opens the opportunity to share the DoD launch costs of about \$8 million with another satellite program.

#### B. An Alternative Employing Existing Satellites

The preferred experiment, described in Section IV-A, is perhaps the simplest possible embodiment of the ideal microwave-scintillation experiment. Nevertheless, it would require launch of a geostationary satellite

specifically for the experiment. A less ambitious alternative is described in this section, employing existing and planned satellites.

The experimental program envisioned in the context of this section would comprise the three major elements contained in the ideal program: (1) a coherent-beacon experiment employing a geostationary satellite (ATS-6); (2) a coherent-beacon experiment employing a high-inclination satellite (Wideband); and (3) correlative experiments employing a low-inclination satellite (Equion). These three elements are considered in reverse order, in the remainder of this section.

Equion is a satellite-borne experiment being considered by NASA for quantitative one-year exploration of the equatorial F layer in the early 1980's (Morse, 1977). It is envisioned primarily as an integrated set of in-situ measurements designed for sensing irregular plasmaspheric structure, the prime measurements being of ion-density and electric fields and their gradients. Consideration also is being given, however, to incorporating a coherent beacon in the Equion payload.

There are obvious geometric limitations to simultaneous direct probing of and transmission through the same plasmaspheric region. A transmission experiment has a contribution to make to the Equion experiment, however, in the form of "added dimensions." That is, any in-situ measurement provides only a one-dimensional scan of a structured plasma. A transmission experiment, by its nature, integrates along one dimension. The scan it provides, therefore, is tantamount to the average of many in-situ scans at different altitudes, so the two types of experiments are inherently complementary. Furthermore, reception of the beacon signal with antennas spaced orthogonally to the scan direction produces information on gradients in a dimension that is inaccessible to in-situ probes.

As mentioned before, Equion is a NASA program. It is suggested here only that DNA coordinate its efforts with those of the NASA team. To the extent that such coordination takes place, Equion can represent one element of a productive three-pronged investigation into the phenomenon of plasmaspherically produced microwave scintillation.

The second element of the experiment would consist of continued observation of signals from the Wideband satellite. Because Wideband is in polar orbit, it is complementary to Equion for the task of locating scintillation-producing irregularities. It also provides scans through the irregular structure that are essentially orthogonal to those of Equion (that is, along the lines of a magnetic field rather than across them). This complementary geometry would provide an opportunity to sort out further the dimensions of plasmaspheric structure, by means of both the first-order and second-order statistics of the observed signals.

The main element of the reduced experimental program suggested here would be observation of signals from the ATS-6 geostationary satellite. ATS-6 transmits mutually coherent signals at 40, 140, and 360 MHz in addition to sidebands suitable for absolute determination of TEC.

The foregoing frequencies, radiated from the NOAA ionospheric beacon, unfortunately are too low for direct observation of GHz scintillation. There are other transmitters on board, however, that do radiate signals above one GHz. Furthermore, a means has been described (Grubb, 1975) for generating two such signals that would be mutually coherent.

The suggested procedure is to transmit a 6.15-GHz signal to the ATS-6 transponder, operated in an available phase-lock mode. In this mode, an on-board synthesizer, operating at a fundamental frequency of 150 MHz, is phase-locked to the uplink. The synthesizer produces signals at 24.00 times and 9.33 times the fundamental frequency, which then are mixed with the fundamental. The result is transmission of mutually coherent signals at 0.610 and 0.252 times the uplink frequency, or 3.75 and 1.55 GHz.

The ratio of the two coherent frequencies generated in the foregoing manner is 2.42, independent of the exact uplink frequency. Furthermore, phase scintillations on the uplink appear as range changes on the output signals, contributing nothing to the measured dispersive phase. The 2.42 ratio is similar to that between the L-band and S-band signals radiated from Wideband (2.33). Consequently, the uncertainty in the L-band phase-scintillation index because of phase fluctuations on the

reference channel would be nearly the same as that encountered with Wideband. (Actually, it would be slightly less.) That is, from Eqs. (2) and (3),

$$0.99\sigma_{\varphi_m} \leq \sigma_{\varphi} \leq 1.20\sigma_{\varphi_m} \quad . \quad (4)$$

ATS-6 currently is located at 140° W. Pertinent parameters of observing geometry from several locations are tabulated in Table 8. Useful observations could be made from any of the locations listed. Unfortunately, the F-layer horizon of ATS-6 in its present location falls just short of Jicamarca. The nearest penetration point (at an altitude of 350 km) that could be achieved would be separated from Jicamarca zenith by about 60 km. Thus, one might consider observations from Kwajalein or Christmas Island. There is still some preference for observations from one of the sites in Peru, however, for two reasons. First, present knowledge of scintillation morphology suggests a greater likelihood of observing numerous microwave scintillation events in Peru than in the Pacific Ocean sector; and, second, the backscatter radar at Jicamarca is likely to play a significant role in the Equion program, so that coordination with NASA experiments would be facilitated greatly by the choice of an observation station in Peru. Further, there is some possibility of negotiating with NASA to make a small eastward change in the location of ATS-6.

The experiment suggested in this section admittedly is less than ideal, because of the lack of coherence between the three frequencies of the ionospheric beacon, on the one hand, and the two frequencies of the GHz transponder, on the other. Nonetheless, ATS-6 does offer an opportunity for useful observations of microwave scintillation.

The GHz-frequency pair would provide direct measurement of complex-signal scintillation under highly disturbed plasmaspheric conditions; the three lower frequencies provide a similar capability under less disturbed conditions; and the full set of frequencies would permit full determination of intensity-scintillation characteristics across a

Table 8  
OBSERVING GEOMETRY FOR GEOSTATIONARY SATELLITE (ATS-6) AT 140° W

| Name             | Station         |                  |                  |                | Ionospheric Penetration Point (h = 350) |                  |                                                |
|------------------|-----------------|------------------|------------------|----------------|-----------------------------------------|------------------|------------------------------------------------|
|                  | Latitude<br>(°) | Longitude<br>(°) | Elevation<br>(°) | Azimuth<br>(°) | Latitude<br>(°)                         | Longitude<br>(°) | Latitude of Dip<br>Equator (°)<br>(h = 400 km) |
| Jicamarca        | 11.95 S         | 76.87 W          | 17.98            | -84.01         | 11.09 S                                 | 84.27 W          | 11.06 S ( $\Delta lat=0.03$ )                  |
| Ancon            | 11.45 S         | 77.08 W          | 18.25            | -84.20         | 10.63 S                                 | 84.39 W          | 11.04 S ( $\Delta lat=0.41$ )                  |
| Lurin            | 12.26 S         | 76.86 W          | 17.93            | -83.86         | 11.38 S                                 | 84.28 W          | 11.06 S ( $\Delta lat=0.32$ )                  |
| Huancayo         | 11.05 S         | 75.33 W          | 16.50            | -84.82         | 10.25 S                                 | 83.21 W          | 11.27 S ( $\Delta lat=1.02$ )                  |
| Christmas Island | 1 N             | 157 W            | 70.01            | 93.27          | 0.94 N                                  | 155.98 W         | 1.03 S ( $\Delta lat=1.97$ )                   |
| Kwajalein        | 8.72 N          | 192.27 W         | 29.67            | 96.69          | 8.15 N                                  | 187.62 S         | 4.43 N ( $\Delta lat=3.72$ )                   |

$\Delta lat$  = difference between latitude of penetration point and latitude of dip equator.

large spectral range (0.04, 0.150, 0.360, 1.55, and 3.75 GHz). Most important, the geostationary orbit already attained by ATS-6 would permit continuous monitoring of the production and full evolution of scintillation-producing irregularities at a small fraction of the cost of other approaches.

Two elements of the experimental program suggested in this section are common with the preferred program described in Section IV-A. The third element would involve costs of the following order of magnitude: \$85,000 for a ground station, assuming that a three-to-four-meter GFE dish could be obtained; \$90,000 per year for ground-station operation; and \$125,000 per year for data processing and examination.

## V APPLICATION TO PROPAGATION PROBLEMS IN THE TROPOSPHERE

One of the objectives of the study reported here was to investigate the importance and feasibility of collecting data on the effects of SHF propagation from the troposphere and the stratosphere that would bear on DNA responsibilities. Several problems exist that are important to DNA for which data on non-plasmaspheric propagation are insufficient or non-existent. Propagation problems can arise over a wide area following a series of surface nuclear detonations for instance, resulting from turbulence, thermal effects, hydrometeor formation, and dust and debris loading.

There is a current trend to move away from UHF toward millimeter wavelengths for proposed and implemented communications and radar systems, partly to achieve wider bandwidths, narrower beamwidths, and so forth, and for satellite systems, partly to avoid nuclear-induced propagation problems of plasmaspheric origin. Because of this, it becomes important to determine the types of nuclear-induced propagation degradation that can affect the shorter wavelength signals. Under the extreme conditions following low-altitude nuclear detonations, one would expect a substantial worsening of the tropospheric propagation factors known to affect SHF signals adversely.

The original intent of this part of the study was to determine what useful data tropospheric propagation could be collected as an adjunct to the primary experiment concerning the plasmasphere. It is not surprising, however, that each objective is, largely, inconsistent with the other. The root of the inconsistency lies primarily in the location of ground stations, and to some degree in the types of measurements that are most useful. But with the addition or presence of at least one millimeter-wave (K-band) coherent transmission to a geostationary platform the satellite-borne portion of the experiment would be useful for both plasmaspheric and neutral-atmospheric measurements.

A fairly large number of experiments--including satellite observations--involving propagation effects above 1 GHz have been undertaken in recent years. Of particular interest are the effects of rain and other forms of atmospheric water. Rain was the most-often named propagation factor found in a 1974 survey (Thompson, 1974) of the factors for which more information was needed by the designers of systems for the 1-40 GHz band. The refractive index structure (inversions and turbulence) had the next-highest number of mentions. There is a substantial lack of experimental data concerning the statistics of short-term scintillation of tropospheric origin. Most of this research has conformed to at least one part of the following overall scenario: first, propagation experiments are performed to measure attenuation, scintillation, depolarization, diversity gain, and so on as functions of more-easily measured parameters such as rainfall rate and refractivity; second, statistical data such as geographical extent, duration, intensity, variability, and so forth are gathered on the more easily measured parameters. The resulting information, often presented as maps, are used by designers to define and specify systems parameters.

Although more experimental data concerning natural propagation conditions definitely are needed, particularly for frequencies above 10 GHz, a study of ordinary, naturally-occurring tropospheric propagation factors appears to fall outside the responsibilities of DNA. A DNA program on the measurement of tropospheric propagation should consider extreme propagation conditions, such as those occurring following a nuclear detonation or a series of such detonations. Because of the ban on atmospheric testing, one must make measurements of tropospheric-propagation by using either the relatively small-scale, high-explosive simulation tests that are conducted every several years, or find naturally-occurring conditions of extreme propagation that can be related to the nuclear environment. A parallel situation occurs in the investigation of the plasma sphere, where the effects of naturally-occurring scintillation and of artificially-disturbed\* regions are studied.

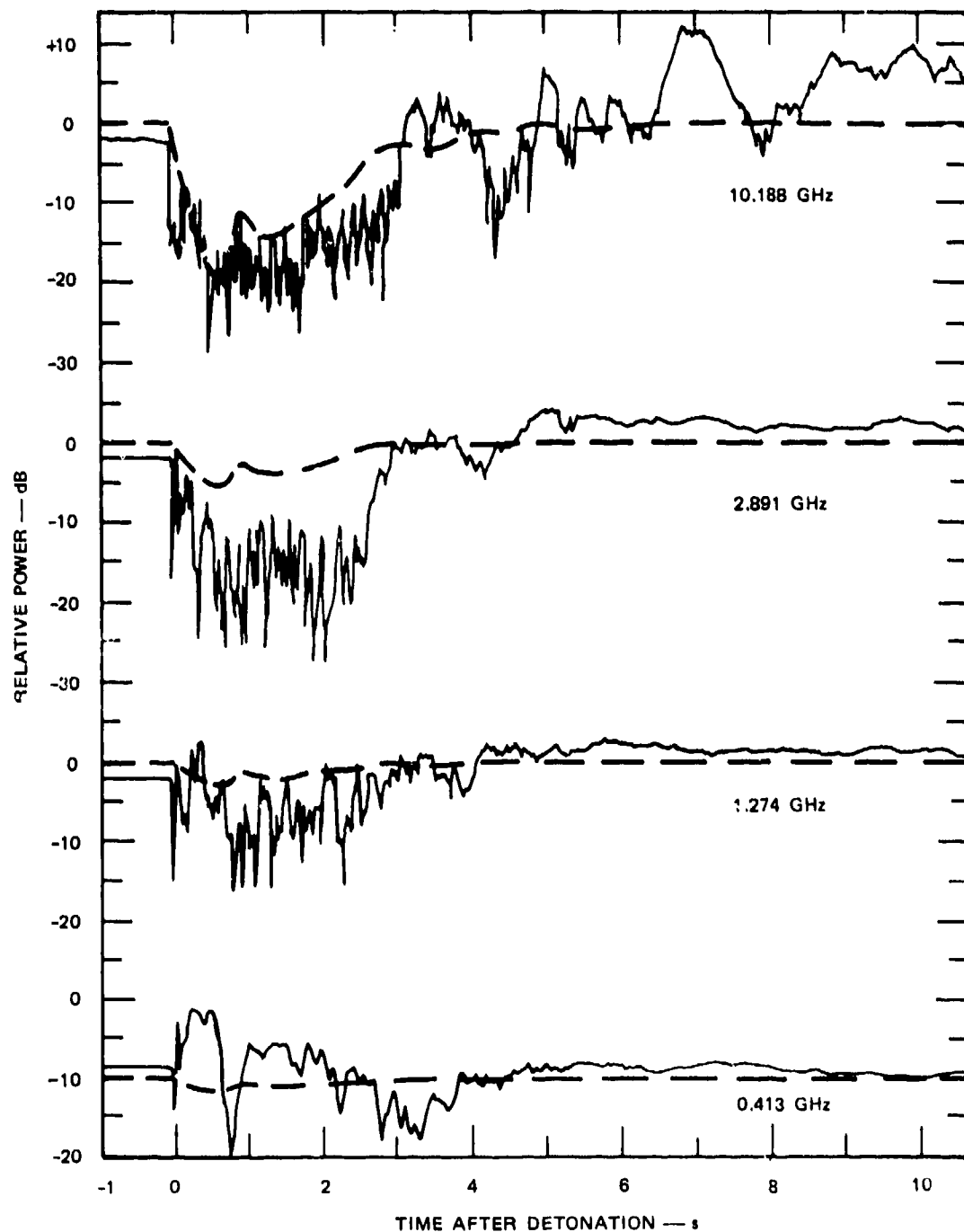
---

\*For example, by releases of barium.

Under DNA sponsorship, SRI conducted in October, 1976, a UHF/SHF transmission experiment during the DICE THROW high-explosives test (Burns, 1977). That experiment was designed to measure the effects of the dust and debris lofted by the explosion of 628 tons of ANFO (Ammonium Nitrate and Fuel Oil--500-ton TNT equivalent) on signals passing through the cloud. The equipment built for DICE THROW was very similar to that used for the DNA Wideband Satellite Program and provided for twelve signals between 378 MHz and 10.2 GHz to penetrate the volume where the cloud was expected to be along six lines of sight (not all frequencies were used on all paths).

The DICE THROW measurements of amplitude and phase were the first of their kind. Because of constraints imposed by geography, avoidance of blast damage, and the limited extent of the dust cloud, measurements were, by design, confined to low-altitude (10-m and 190-m high), low-elevation paths. Because of unfavorable surface winds on the test date, the dust cloud quickly moved away from the signal paths and only short-term occultations were achieved. However, surprisingly severe effects were observed while the cloud interdicted the low-level (10-m high) signal paths. Figure 10 shows the amplitude record from the low-level path passing directly above ground-zero. Fluctuations in amplitude ranged from +5 to -10 dB at 413 MHz to +15 to -35 dB at 10.2 GHz. Corresponding phase shifts were 4 radians peak at 413 MHz and about 100 radians at 10.2 GHz.

This example is intended to point out the potential severity of propagation effects following a nuclear detonation. Besides phase and amplitude scintillation, other propagation factors such as absorption, depolarization, and reduction of the usable bandwidth (i.e., of channel capacity) could be severe as well, particularly at shorter wavelengths. For example, the computed attenuation (Burns and Winkelman, 1977) that results from absorption alone (that is, not accounting for scattering by the particles) shown as the dashed curves in Figure 10 rises to nearly 20 dB at 10.2 GHz. Figure 11, which presents the absorption and phase shifts at various frequencies as a function of the dust density integrated along a signal path, and for dust that has the dielectric and loss



LA-3972-30

FIGURE 10 COMPUTED ATTENUATION (dashed curves) COMPARED TO MEASURED SIGNAL-STRENGTH FLUCTUATIONS OBSERVED IN DICE THROW PROGRAM

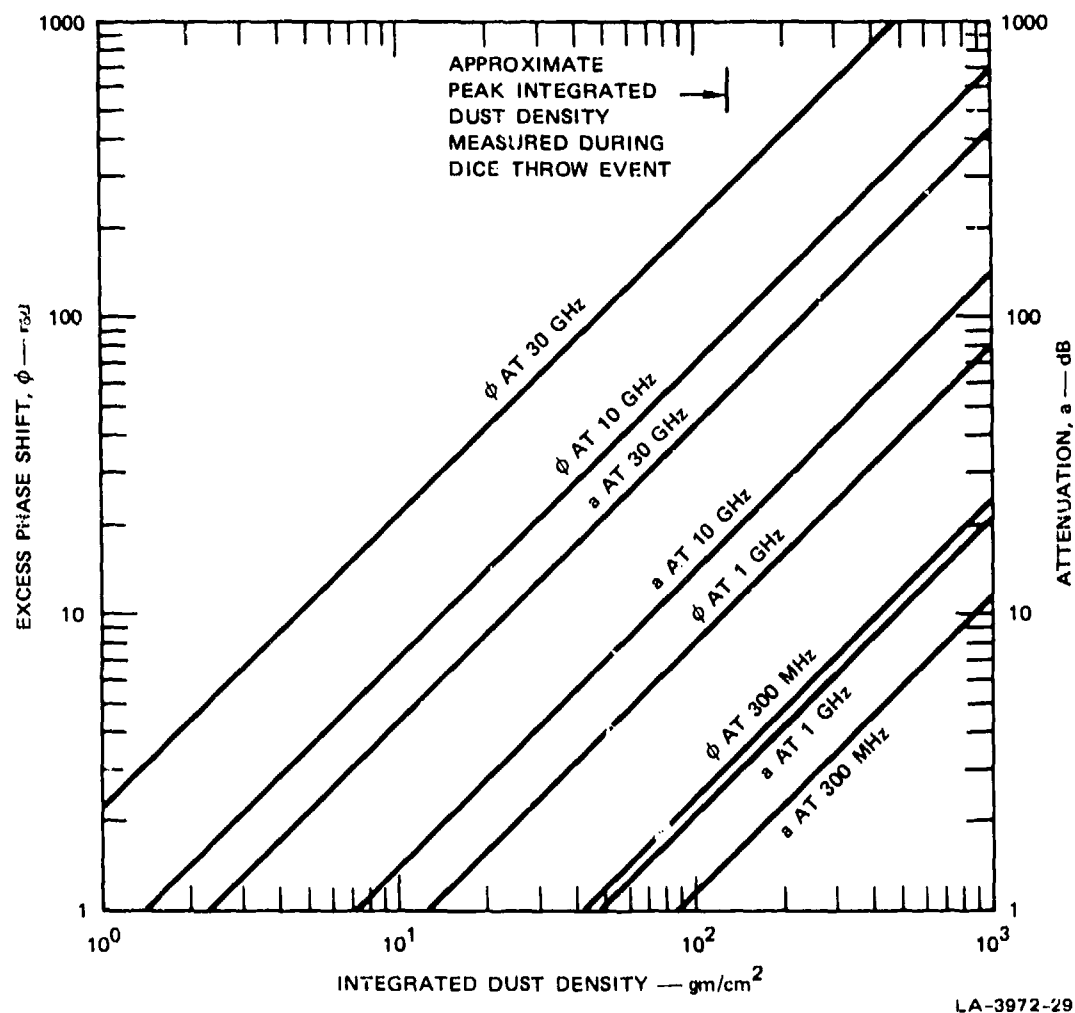


FIGURE 11 ATTENUATION DUE TO ABSORPTION AND EXCESS PHASE SHIFT vs INTEGRATED DUST DENSITY COMPUTED FROM SAND SAMPLE PARAMETERS AT SEVERAL FREQUENCIES

properties measured for DICE THROW, points out two of the potential adverse propagation factors that can become severe at millimeter wavelengths.

All of the propagation factors become more important as microwave systems are extended over path lengths greater than a few tens of kilometers, as in aircraft or satellite applications. At low elevation angles, such a system also can experience very deep fades because of the atmospheric multipath, caused by elevated layers of enhanced or reduced refractivity. Finding ways for dealing with conditions of

extreme propagation degradation is considered crucial for lowering the costs of systems while maintaining adequate reliability and channel capacity.

The nuclear environment provides extreme conditions. In addition to the increased turbulence within and near the nuclear cloud, strong afterwinds, firestorms, and rainout can occur. Furthermore, a large amount of particulate matter (dust) would be lofted and injected into the upper atmosphere by a surface or near-surface burst.

As seen in the DICE THROW test, sufficient concentrations of the particulates can change the refractivity of the ambient atmosphere. For instance, a mass loading of about  $5 \times 10^{-4} \text{ gm cm}^{-3}$  changes the refractivity by 200 to 300 N-units, depending on the specific dielectric properties of the particulates. The ambient refractivity at the surface is about 300 N-units, and falls below 50 N-units above 15,000 m altitude, and turbulent refractivity fluctuations are a small fraction (1-10%) of the ambient refractivity (Millman, 1971). Thus, even mass loadings below  $10^{-5} \text{ gm cm}^{-3}$  could be significant both by enhancing turbulent refractivity variations and in forming stratified layers when sufficient wind shear is present.

Particulates can also cause appreciable signal attenuation by means of scattering and absorption. Depending on the amount of moisture contained by the particles, absorption between 1 and 10 GHz can be several tenths of a decibel for every radian of excess phase shift that is caused by the particulates. Because a particulate mass loading of  $10^{-5} \text{ gm cm}^{-3}$  (about  $2 \times 10^{-4} \text{ gm cm}^{-3}$  was measured in the upper part of the DICE THROW cloud) will, over a 20-km path, cause about 50 radians of excess phase shift at 10 GHz, from 10 to 20 dB of attenuation could result. Even a small dust cloud could have an extreme effect at 30 GHz and above.

Because the particulates can act also as condensation nuclei, the moisture factor may become particularly severe. Eventually, water droplets and ice crystals can form, possibly leading to rainout.

Above 10 GHz, system margins normally are established with the expectation of a specified rate of rainfall. But information concerning other propagation factors accompanying rainfall still must be gathered, because margins are necessarily smaller under extreme circumstances. In the nuclear environment, one would have to consider particulates, particularly the larger ones, along with hydrometeors. The other factors are related to smaller-scale structure. These factors are depolarization and polarization diversity; scintillation, multipath, and coherent bandwidth; and frequency, time, and space diversity.

Although the high-explosive simulation tests are fairly small (only about 4-5 kt maximum of material, as estimated from crater, lip and ejecta field volumes, was available to be lofted in the DICE THROW dust cloud, for example), they do provide extreme conditions that in principle may be related--through such means as the AFWL HULL code--to the nuclear environment. A geostationary satellite with a millimeter-wave coherent beacon would be useful for measurements employing radio transmission during the series of simulation tests. The particular advantage of the geostationary satellite source is that the upper parts of the dust cloud could be conveniently probed. It is usually difficult to provide a stable, high elevation-angle signal source. Because no antenna steering would be needed, either the DNA Wideband Satellite Program ground stations or the similar DICE THROW receiving system which are fairly portable, could be used during a test.

Because these tests are conducted only every few years, they in themselves may not warrant a satellite experiment (in other words, the inclusion of a millimeter wave beacon); naturally-occurring extreme conditions should be investigated as well.

Several potential sources of conditions of extreme propagation have been considered. These include large thunderstorms, dust storms, and explosive volcanoes. Of the three, volcanoes are the most promising because they are stationary, can be photographed with relative ease, and in many ways, actually can resemble a nuclear detonation. For example, a recently reported study (Hobbs, Radke and Stith, 1977) of the

St. Augustine eruption series (57 eruptions) of early 1976 noted particulate densities of more than  $10^{-5}$  gm/cm<sup>3</sup> in parts of the cloud. Furthermore, one observed eruption produced a mushroom-shaped cloud that rose to an altitude of 7 km, and had an estimated total particulate mass of more than 40 kt. Another cloud contained an estimated 330 kt of mass. Thus, it appears that plumes from explosive volcanoes could provide propagation factors similar to those associated with nuclear detonations.

The big problem, of course, is finding the right volcanoes. Not only must they be active; they must be explosive. With a geostationary source illuminating the entire visible side of the world, the problem of fielding an experiment is greatly reduced, however, since only a portable receiving station need be put in place. An automatic, continuous monitoring and recording system could be implemented to accommodate the uncertainty in eruption times. The Smithsonian Institute's Bulletin on short-lived phenomena is an ideal early-alarm system for identifying quickly volcanic events.

There are a large number of active volcanoes, and the number of significant, newly active or resurgent volcanoes is generally between 15 and 20 per year. Hobbs et al., (1977) deduced that the average number of eruptions similar to that of St. Augustine, which injected 330 kt of particulates into the atmosphere, is between 80 and 500 per year. Because there were fewer than 60 eruptions during the St. Augustine series, it follows that there are roughly 1 to 10 candidate eruptions per year. Not all of those can be used, however, because of the position of the satellite, problems of accessibility, and other such hindrances. Fortunately, with a geostationary satellite in the geopotential well at 105°W, two active volcanic areas--in the Aleutian chain and in Central America--are, in addition to Hawaii, within the satellite coverage and in many ways are reasonably accessible.

The properties of the particulates emitted by volcanoes are not likely to be similar to those of dust clouds. There tends to be a larger amount of metallic compounds in the volcanoes along with silicates, which more resemble dust clouds. Volatile elements and compounds, namely, H<sub>2</sub>O,

CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S, HF, and HCl, also are abundant. However, the refractivity of even a slightly diffuse cloud is proportional to the factor  $(\epsilon - 1)/(\epsilon + 2)$  and, therefore, is only a weak function of the dielectric constant,  $\epsilon$ , of the constituent materials. Phase shifts caused by clouds are, in general, a far stronger function of the amount of matter present than of the individual characteristics of the materials. Theoretically, however, absorption is directly proportional to the loss tangents of the materials, as well as to the amount of matter. But because one of the objectives of any measurement program would be to verify the connection between the properties of the materials and the properties of the clouds, the specific values for the loss tangents are not directly relevant. One must obtain a reasonable estimate of the properties of the materials, either from actual samples of volcanic emanations, or from knowledge of the relative amounts of each type of compound or material from the eruption. In any rigorous application of the results to a nuclear detonation, the properties of the specific type of material likely to be lofted should be ascertained. Therefore, it is relatively unimportant that particulates from volcanoes probably are not very similar to those of dust and debris clouds.

It thus appears that opportunities for tropospheric measurements under extreme propagation conditions--either natural or man-made--would occur fairly often--in fact, often enough to justify adding a millimeter wave capability to any satellite experiment contemplated and constructing a portable ground station facility for a wide variety of measurements. If desired, routine studies of tropospheric propagation factors could be undertaken as adjuncts to measurements directed at unique, extreme events. A comprehensive geostationary satellite beacon, utilizing a number of coherent frequencies with a good representation above 10 GHz, would be a necessary and extremely useful tool for answering a number of current and future questions about radio propagation.

A minimum tropospheric-oriented millimeter-wave measurement program should include measurements of amplitude scintillation, absorption, spatial coherence and depolarization. But by making the millimeter wave beacon coherent with the lower frequencies, a substantial improvement in

the capability and flexibility of measurement could be achieved at little extra cost. With a completely coherent beacon measurement of phase scintillation becomes possible, and an important diagnostic capability--for making estimates of integrated particulate density analogous to those of total electron content--would become available. A capability for measuring coherent bandwidth also would be desirable in at least one millimeter-wave band, but would require a more elaborate transmitter to generate a comb similar to the UHF spectrum.

Several types of ground-based supporting measurements should be considered also. Photographic coverage of any special events--either HE tests or volcanic eruptions--is essential. A simultaneous experiment using multifrequency radar (including laser radar) experiment would provide important data concerning distributions of particle size and the relative importance of scattering and absorption to signal extinction or attenuation. Because a millimeter-wave radiometer gives information about the absorption component, it can be used also to separate absorption from scattering.

The addition of at least a single coherent tone, in the K band, to the transmitter of the experiment suggested in Section IV-A, would make tropospheric measurement possible. Strong consideration should be given to adding at least one more tone in the 90 to 100 GHz band. Table 9 presents the link calculations for extending the suggested experiment to 30 and 90 GHz. Several frequencies are usable; the two presented here are based on doubling the 13.63 GHz,  $K_e$ -band signal and multiplying the 2.891 GHz signal by 252 to 92.53 GHz. While the 92.53-GHz system presupposes the use of the latest state-of-the-art components, the 30-GHz system is conservative. It is estimated that adding both millimeter-wave frequencies would add around \$1 million to the suggested experiment, with the majority for the 90-GHz system. This rough figure includes costs for modification of the ground station (either one of the existing wideband stations or the DICE THROW system could be used as a portable ground station).

Table 9

## LINK BUDGET FOR MM-WAVE TRANSMITTER

|                       | K <sub>m</sub> -Band | W-Band       |
|-----------------------|----------------------|--------------|
| f (GHz)               | 27.26                | 92.53        |
| P <sub>T</sub> (dBi)  | 23                   | 23           |
| G <sub>T</sub> (dBi)  | 20                   | 20           |
| Path loss (dB)        | -214                 | -225         |
| G <sub>R</sub> (dBi)  | 56                   | 56           |
| Margin (dB)           | <u>-3</u>            | <u>-3</u>    |
| P <sub>R</sub> (dBm)  | -118                 | -132         |
| T <sub>sys</sub> (°K) | 3000                 | 400 (paramp) |
| BW (Hz)               | 30                   | 30           |
| P <sub>N</sub> (dBm)  | -149                 | -158         |
| SNR (dB)              | 31                   | 26           |

In summary:

- (1) A need exists for data concerning propagation factors above 10 GHz in the troposphere and stratosphere, particularly under disturbed conditions, when dust loading and hydrometeor formation are present.
- (2) Both man-made events (HE simulation tests) and natural events (volcanic eruptions) can provide disturbed conditions similar to those generated by nuclear explosions.
- (3) Adding millimeter-wave capability to the experiment suggested in Section IV-A would provide a useful signal source for a variety of measurements of signal perturbations originating in the troposphere.

## VI CONCLUSION

In the foregoing sections of this report we have considered several types of experiments, beginning with an ideal program for meeting the primary objective of understanding microwave scintillation of plasmaspheric origin. Considering the satellites suitable for the purpose and costs of various approaches, we are led to suggest a preferred experiment in Section IV-A. In search of still a lower cost, a less ambitious alternative was presented in Section IV-B. The final consideration was the application of the preferred experiment to the secondary objective of assessing propagation effects of non-plasmaspheric origin that would be of concern to DNA.

SRI's principal recommendation is that DNA now consider undertaking the experimental endeavor described in Section IV-A, for which the cost of implementation is estimated to be between \$8 and \$9 million, spread over the fiscal years 1978, 1979, and 1980, plus launch costs. The preferred program would comprise three elements, of which two involve very little new effort on the part of the DNA research team. The first of these elements is the continued operation of the Wideband satellite experiment as solar activity increases. The second is coordination with the research team developing NASA's Equion program for exploration of the equatorial ionosphere. The third and principal element of the recommended program is the development of a relatively light and low-cost satellite to be used for placing a multifrequency coherent beacon in geostationary orbit.

The geostationary satellite would exploit recent developments in the technology of gravity-gradient stabilization in order to minimize cost and weight, permitting launch on a Thor Delta rocket. Further cost control would be exercised by basing the payload on an existing, space-qualified Wideband beacon transmitter. Thus, the spectrum for the plasmaspheric experiment would consist of the augmented (with  $K_e$  band) Wideband spectrum shown in Table 6. This spectrum would be observed by means of

an augmented Wideband receiver from a station in Peru, located for the purpose of making coordinated observations of the F layer by means of the Jicamarca backscatter radar.

The preferred experiment would provide an opportunity for meeting the secondary objective set at the beginning of this design study. In particular, it would permit, through experimentation, an assessment of the effect of low-altitude atmospheric disturbances on operation of satellite communication systems at today's increasingly high frequencies, including mm-wave systems. It is recommended that a mm-wave capability be added to the preferred experiment and that it be exploited by means of observations through hot and turbulent tropospheric disturbances above volcanoes in the Pacific basin, and through the clouds of debris produced by certain man-made HE detonations.

The foregoing recommendation is the result of a search for the least costly approach to performing definitive measurements of plasmaspherically-produced microwave scintillation and to provide a platform for measurements of mm-wave propagation disturbance of interest to DNA. The major elements of cost stem from the necessity to develop a satellite and to provide a launch to geostationary altitude for this mission. In the time frame set by the coming solar activity maximum, there appears to be no alternative to the described approach (unless major cost-sharing with another program can be arranged), short of falling back to the use of existing satellites.

In the event that costs of the preferred experiment are deemed prohibitive, we recommend uncoupling the experiments directed at plasmaspheric scintillation, on the one hand, from those directed at lower-atmosphere effects on mm-wave propagation, on the other. For the prime (plasmaspheric) experiment, we recommend employing ATS-6, as described in Section IV-B. This approach would result in a measurement of scintillation on a coherent pair of microwave frequencies and on an independently coherent triplet of VHF/UHF frequencies at a cost of hundreds of thousands of dollars instead of millions.

## REFERENCES

- Basu, S., J. Aarons, J.P. McClure, C. La Hoz, A. Bushby, and R.F. Woodman, "Preliminary Comparisons of VHF Radar Maps of F-Region Irregularities with Scintillations in the Equatorial Region," accepted for publication, J. Atmos. Terr. Phys. (1977).
- Booker, H.G., "The Role of the Magnetosphere in Satellite and Radio Star Scintillation," J. Atmos. Terr. Phys., Vol. 37, No. 8, pp. 1089-1098 (August 1975).
- Burns, A.A., "Preliminary Results of DICE THROW Transmission Experiment," Technical Report 1, Contract DNA001-75-C-0206, SRI Project 3972, Stanford Research Institute, Menlo Park, California (January 1977).
- Burns, A.A. and E.J. Fremouw, "A Real-Time Correction Technique for Transionospheric Ranging Error," IEEE Trans. Ant. and Prop., Vol. AP-18, No. 6, pp. 785-790 (November 1970).
- Burns, A.A. and R.E. Winkelman, "UHF/SHE Properties of Dust from the DICE THROW HE Test," Technical Report 2, Contract DNA001-75-C-0206, SRI Project 3972, Stanford Research Institute, Menlo Park, California (February 1977).
- Christiansen, R.M., "Preliminary Report of S-Band Propagation Disturbance During ALSEP Mission Support (November 19, 1969-June 30, 1970)," NASA Report X-861-71-239, Goddard Space Flight Center, Greenbelt, Maryland (June 1971).
- Craft, H.D., Jr., "Some Measurements of Ionospheric Scintillations at 4 GHz and 6 GHz," paper presented at the Spring Meeting of URSI, Washington, D.C. (April 1971).
- Craft, H.D., Jr. and L.H. Westerlund, "Scintillations at 4 and 6 GHz Caused by the Ionosphere," paper presented at AIAA 10th Aerospace Sciences Meeting, San Diego, California (17-19 January 1972).
- Farley, D.T., "Irregularities in the Equatorial Ionosphere: The Berkner Symposium," Rev. Geophys. and Space Phys., Vol. 12, No. 2, pp. 285-289 (May 1974).
- Farley, D.T., B.B. Balsley, R.F. Woodman, and J.P. McClure, "Equatorial Spread F: Implications of VHF Radar Observations," J. Geophys. Res., Vol. 75, p. 7199 (1970).

Fremouw, E.J., M.D. Cousins, and G.K. Durfey, "Wideband Satellite Observations," Bimonthly Progress Report 5, Contract DNA001-75-C-0111, SRI Project 3793, Stanford Research Institute, Menlo Park, California (March 1977).

Fremouw, E.J., D.J. Barnes, R.C. Livingston, M.D. Cousins, B.C. Fair, G.K. Durfey, "Wideband Satellite Experiment--Preparations for Launch," Final Report--Phase III, SRI Project 1972, Stanford Research Institute, Menlo Park, California (November 1974).

Grubb, R., private communication to E.J. Fremouw (1977).

Hobbs, P.V., L.F. Radke, and J.L. Stith, "Eruptions of the St. Augustine Volcano: Airborne Measurements and Observations," Science, pp. 871-873, Vol. 195, No. 4281 (4 March 1977).

Hopkins, R., Report presented at meeting of the Interagency Working Group on Scintillation, San Diego, California (26 January 1977).

Hudson, M.K. and C.F. Kennel, "Linear Theory of Equatorial Spread F," J. Geophys. Res., Vol. 80, p. 4581 (1975).

Jain, S.K., and B. Singh, "Vertical Motions of the L- and Equatorial-Latitude F<sub>2</sub> Layers during Prolonged and Isolated Magnetic Storms," J. Geophys. Res., Vol. 82, p. 723 (1977).

Koster, J.R., I. Katsriku, and M. Tete, Studies of the Equatorial Ionosphere Using Transmissions from Active Satellites, Annual Summary Report No. 1, Contract AF61(052)-800, University of Ghana, Legon, Accra, Ghana (1966).

Millman, G.H., "Tropospheric Effects on Space Communications," AGARD Conference Proceedings No. 70 on Tropospheric Radio Wave Propagation, Part 1 (February 1971).

Morse, F.A., private communication to E.J. Fremouw (March 1977).

Skinner, M.J., R.F. Kelleher, J.B. Hacking, and C.W. Benson, "Scintillation Fading of Signals in the SHF Band," Nat. Phys. Sci., Vol. 232, pp. 19-20 (July 1971).

Taur, R.R., "Ionospheric Scintillation at Frequencies Above One GHz," Technical Memorandum CL-29-73, Contract INTELSAT R&D Task No. 211-4054, COMSAT Laboratories, Clarksburg, Maryland (August 1973).

Taur, R.R., "Ionospheric Scintillation at 4 and 6 GHz," Technical Memorandum, CL-43-72, Contract INTELSAT R&D Task No. 211-4054, COMSAT Laboratories, Clarksburg, Maryland (August 1972).