Feasibility Study of Far-Field Methods for Calibrating Ground Station Delays: An Interim Report

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This interim report presents the results of a study to survey and arrive at cost/performance estimates of various methods of implementing far-field calibrations of ground station delays. Both direct and indirect methods for far-field calibrations are discussed.

I. Introduction

This is an interim report of a study to survey and arrive at cost/performance estimates of the various methods of implementing far-field calibration of ground station delays.[1] Determination of ground station delays is of vital importance in the overall ranging accuracy problem. Ideally, the calibration scheme should involve a radiator of electromagnetic waves in the far field of the antenna thus minimizing the effects of multipaths, particularly those involving antenna structural elements. Experimental verification of this approach was performed by Otoshi and Brunn (Ref. 2) utilizing the Viking Spacecraft as the signal sources. While the results were promising, the essentially one-shot nature precludes using such spacecraft over extended periods of time for a deep experimental investigation of the significant factors causing the station delay uncertainties.

This study will address itself to both the direct and indirect approach. The direct schemes will involve placing a transponder at or beyond the classical far-field distance (Ref. 3) given by $2D^2/\lambda$ where the antenna diameter D and wavelength used λ are in the same units. Just precisely where the transponder is located will depend on other factors as well as depending on what platform is used to transport the transponder. The indirect approach will be dependent on finding a valid means of transforming measurements made utilizing a transponder located in the near-field region to those results obtainable if it were possible to locate the transponder in the far field.

[1] The initial report on this study has been presented in Ref. 1.

II. Antenna Parameters

The criterion of whether a source is located in the far field of an antenna is determined if the antenna-source distance R exceeds

$$R = 2D^2/\lambda$$

where D is the diameter and λ is the wavelength received by the antenna measured in the same units. This relationship defines the condition where a wave incident on the antenna does not deviate more than $\lambda/16$ across the aperture. The source is considered to be a point source thus radiating a spherical wave, and it is this curvature that is mismatched to the plane of the antenna aperture.

The antenna diameters of greatest interest are 26 and 64 meters. Frequencies of interest are 2295 and 8415 MHz. Table 1 shows the far-field distance for the two antenna diameters at the two frequencies.

It is immediately evident that a collimation tower can be used in the far field effectively at 2295 MHz with a 26-m antenna, but it cannot be used for a 64-m antenna. At 8415 MHz, neither the 26-m nor the 64-m antenna's can utilize collimation towers located in the far field because of the tower height required for a reasonable elevation angle of greater than 5 deg.

III. Far-Field Platforms

Discounting the situation of investigating sources of antenna delay variations solely of a 26-m diameter antenna at 2295 MHz, it is clear from Table 1 that the transponder must be attached to some type of free-moving platform because of the great distance and height required. A problem of considerable complexity is presented, that of determining with sufficient accuracy the near-instantaneous location of this platform. Range to a collimation tower is easier and less expensive to determine and can be repeatedly surveyed to reduce range errors. The aircraft, balloon, and satellite approaches discussed in the next three sections all require an independent ranging system.

A ranging scheme has been suggested using a tracking laser system (Ref. 4) similar to those used in connection with extremely precise tracking of geodetic satellites. Results from the NASA LAGEOS Project, which requires the precise ranging and tracking of a satellite in earth orbit, indicate that accuracies of better than 5 cm are possible.

The rationale of using lasers is to operate at a wavelength sufficiently far removed from microwaves to avoid those effects deleterious to microwaves but not to lasers. Lasers in turn have problems, particularly clouds, so any advantages won in one area may be lost in becoming more weather dependent.

These high-performance laser trackers are very expensive because of their ability to track rapidly moving targets with great precision. Depending on the degree of computer control and various safety equipment desired, the cost of a laser tracker can exceed $250,000.

A. Aircraft

A high-performance jet-powered aircraft can be used as a transponder platform. The outstanding advantage of an aircraft is the positive control of the transponder both as to its position and operation. Precise maneuvers can be executed along a flight path thereby somewhat easing the range determination problem. Further, the danger of losing a transponder or suffering a malfunction is eased since the entire system is retrievable at anytime.

The main disadvantage of the aircraft is the maximum altitude (Ref. 5) achievable being limited to about 13.5 km (8.39 miles). This altitude translates into an elevation angle of about 12 deg with a slant range of 65 km. A 26-m diameter antenna operating at 8415 MHz could satisfactorily use the aircraft-mounted transponder since the elevation angle is about 18 deg for the necessary far field slant range of 40 km at an altitude of 13.5 km. A 64-m diameter antenna requires a minimum far-field slant range of 238 km resulting in a 3-deg elevation angle, which is below the present operating limit set by transmitter and land-mask considerations.

The cost of developing an aircraft-based transponder platform depends on many factors. Methods of mounting as well as the type of aircraft selected all strongly influence the cost. Special techniques must be employed to minimize bothersome reflections that can cause a multipath error. The total cost of an aircraft-based program can be quite low if leased aircraft are used. Some planes suitable for this application are available for about $1,000/h.

Use of powerful laser ranging systems on manned aircraft is always cause for concern. An unmanned jet-powered aircraft is being developed for military use that can be useful for transporting a transponder package. The USAF Compass Cope (Ref. 6) can carry a payload of 500 kg to a height above 18 km. One of the projected uses of Compass Cope by the USAF is as a communications relay.

B. Balloons

Balloons have in the past been used to calibrate antenna systems and constitute a relatively inexpensive means of lifting lightweight targets or transponders to moderate heights. The lifting of relatively sophisticated instrument packages such as a ranging transponder and associated equipment requires a fairly large balloon system, certainly much larger than those Rawinsonde systems routinely used by the Weather Bureau.

The Stratoscope Project (Ref. 7) utilized a free balloon system capable of lifting 3600 kg of equipment to a height in excess of 25 km. These balloons are expensive, quite difficult to launch, and require a considerable amount of special handling equipment as well as a highly trained operations crew. Further, use of these large balloons is highly weather dependent and recovery of the transponder for subsequent flights is problematical at best. Flight paths of the balloon can often be quite unpredictable as with any free flying craft.

An interesting possibility, however, is the powered balloon. This is a free flying but powered balloon and therefore has a limited maneuvering capability. Such a craft should be able to hover over the same sub-earth point making a suitable transponder platform for a 64-m antenna at 2295 MHz, but would still be of little use at 8415 MHz.

The cost of balloon systems for all but the very small weather balloon would be expected to be rather expensive, about $25,000 each, and are not reusable. Powered balloons would cost more than free balloons but would be less likely to be lost along with the transponder package than a free balloon.

C. Satellites

A satellite can be used as a transponder platform provided it does not move at high angular velocities. Geostationary satellites are in orbit such that they appear to the antenna as essentially fixed in the sky. Because of this fact, such a transponder platform will be available anytime of the day and could be placed so that favorable elevation angles can be achieved. The orbital height is determined by the physical constants of the earth and is about 36,000 km in altitude above the earth, nearly a tenth of the distance to the moon. Accurate ranging of the transponder platform at these distances becomes considerably more difficult than at aircraft or balloon ranges if the goal of determining this distance with an accuracy of better than 50 cm is to be achieved. Accuracies in the region of 40 cm have been achieved at lunar distances, but only after the accumulation of considerable data.

Costs of satellite systems have been determined and a Cost Estimate Relation (CER) derived by Hadfield (Ref. 8). Applying these CERs to a geostationary satellite in the 140-kg weight class, the cost estimate is about $5,000,000. These CERs are relatively insensitive to the type of electronics flown in the satellite and one may assume that a ranging transponder is not extraordinarily complicated nor sophisticated enough to alter these CERs.

An interesting variant to using satellites in this range delay problem is to use the ALSEP (lunar package transmitter) as a far-field source and use a delay comparison method. The delay of a horn antenna is measured and is compared with a medium size (9-m diameter) antenna such as the ARIES antenna while both are aimed at a collimation tower located in the far field of the medium sized antenna. The derived delay for the medium sized antenna is now used to view ALSEP simultaneously with a 26-m or 64-m antenna while located adjacent to the large antenna. The outputs of both antenna are then suitably processed, thus yielding a difference in delays through the respective antenna microwave optics. The delays through the major electronic components in the implementation of this method will be determined using existing techniques (Ref. 9).

IV. Near-Field Methods

The previous sections describing the various far-field methods have shown that except for the ALSEP bootstrap, all of these approaches require an independent means of accurately determining distances preferably without the use of microwave systems. The laser ranger needed is quite complex and therefore expensive since it must be agile enough to track distant and often rapidly moving targets.

A collimation tower by its very nature provides a very stable platform and whose distance can be determined by modern conventional surveying to a high order of accuracy. Here again lasers can be used but they will not be tracking systems and therefore will be much less expensive.

Collimation towers are relatively inexpensive and a number of them can be erected at various distances. For a 26-m diameter antenna, a far-field and near-field tower can both be erected (Ref. 10) and studies performed to arrive at suitable models that allow near-field measurements to be transformed to those simulating far-field measurements. The cost of a 30-m collimation tower of the type used as broadcast antennas with an equipment elevator can be erected for about $20,000 (Ref. 11). The exact total cost will depend on its location with such factors as earthwork requirements, type of surface material, safety equipment, and other logistical factors.

At Goldstone, the various elevation angles are listed for both the existing 2-m collimation tower (Ref. 12), and the proposed 30-m collimation tower in Table 2.

The main disadvantage of using collimation towers is that measurements must be made at low elevation angles. Antenna structural sag as well as ground reflections may pose problems. A reflection abatement program forms an integral part of this near-field method. As mentioned earlier, the near-field method depends upon finding a valid means of transforming measurements made with the transponder located in the near field to those results obtainable if it were possible to locate the transponder in the far field. In concept it would appear that the same transformation technique used in near-field gain measurements can be applied. This approach needs to be investigated thoroughly by an antenna expert and may prove to be a new separate theoretical area of study that needs to be supported and funded.

V. Conclusions and Recommendations

Table 3 summarizes the various methods for far-field ground station delay calibration methods described in this report. It provides a quick reference for purposes of cross comparisons of the salient characteristics, advantages and disadvantages of the various methods.

The study of range-delay calibrations and their uncertainties is an important topic and should be approached by various routes. The moderate sized (26-m) antenna appears to be a very important element in this study since it is quite feasible to construct a transponder platform in the near field and one in the far field. Comparison of measurements taken with this system will verify the validity of antenna range-delay models with minimum expense. If extensive testing on this range yields an acceptable model, one may extend it to the larger (64-m) antenna, erect a collimation tower that necessarily must be in its near field, and commence study of important factors contributing to its delay uncertainties.

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References

1. Sato, T. "Feasibility Study of Far-Field Methods for Calibrating Ground Station Delays", in *The Deep Space Network Progress Report 42-37,* pp. 55-56, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1977.

2. Otoshi, T. Y. and D. L. Brunn, "Multipath Tests on 64-m Antennas Using the Viking Orbiter -1 and -2 Spacecraft as Far-Field Illuminators", in *The Deep Space Network Progress Report 42-31,* pp. 41-49, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1976.

3. Hollis, J. S., "Antenna Measurements", *Microwave Journal,* pp. 39-46, Feb. 1960.

4. Couvault, C., "Help Aboard Key to Laser Mission Goals", *Aviation Week and Space Technology,* pp. 36-43, May 12, 1975.

5. Jane's *All the World's Aircraft,* McGraw-Hill, 1976.

6. O'Lone, R. G., "Compass Cope Seen in Anti-Tank Role", *Aviation Week and Space Technology,* pp. 60-62, June 13, 1977.

7. Ashbrook J., "The Latest Flight of Stratoscope II", *Sky and Telescope,* Vol. 39, No. 6, pp. 365-367, June 1970.

8. Hadfield, B. M., "Satellite-System Cost Estimation", *IEEE Transactions on Communications,* Vol. COM-22, No. 10, pp. 1540-1547, Oct. 1974.

9. Komarek, T. and T. Otoshi, "Terminology of Ranging Measurements and DSS Calibrations", in *The Deep Space Network Progress Report 42-36,* pp. 35-40 Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1976.

10. Rusch, W. V. T. and P. D. Potter, *Analysis of Reflector Antennas,* Academic Press, 1970.

11. Walker, A. P. Ed., *NAB Engineering Handbook,* pp. 2-41-2-43, McGraw-Hill, 1960.

12. Jackson, E. G., private communication.

Table 1. Far-field distance as a function of frequency and antenna diameter

Antenna diameter, m	$2D^2/\lambda$, km	
	2295 MHz	8415 MHz
26	11	40
64	65	238

Table 2. Elevation angles to collimation towers

Collimation tower location	DSS 13, 26 m		DSS 14, 64 m	
	Target location	Target elevation angle, deg	Target location	Target elevation angle, deg
Near field				
Existing tower $0.14\left(\frac{2D^2}{\lambda}\right)$	2 m from ground on 176-m high hill	6.6	–	–
Proposed tower $0.10\left(\frac{2D^2}{\lambda}\right)$	30 m from ground that slopes −2.2 deg; near same azimuth as Tiefort Mtn.	0.92	30 m from ground on 70-m hill at azimuth of 50 deg	0.88
Far field				
Existing tower Tiefort Mtn. $1.8\left(\frac{2D^2}{\lambda}\right)$	2 m from ground on Tiefort Mtn.	0.5	–	–

Table 3. Advantages and disadvantages of methods

Method	Advantages	Disadvantages
Aircraft	Positive control of operation and of flight path; relatively inexpensive if leased aircraft used	Good only for S-band on 64-m antenna; needs laser ranger
Balloon, free	Can reach higher altitude than aircraft	Good only for S-band on 64-m antenna; needs laser ranger; requires good weather for launch
Balloon, powered	Same performance height as free balloon; limited maneuver capability, can hover over a sub-earth point	Good only for S-band on 64-m antenna; needs laser ranger
Satellite, geosynchronous	Continuously in position; in far field for both S- and X-band of 64-m antenna	Very expensive, satellite and launch cost greater than \$5M; needs laser ranger
Near-field collimation tower	Continuously in position; least expensive, \$20k per tower; easier to determine distances; does not need laser ranger	Works at low elevation angles; needs near- to far-field transform; will require ground reflection abatement