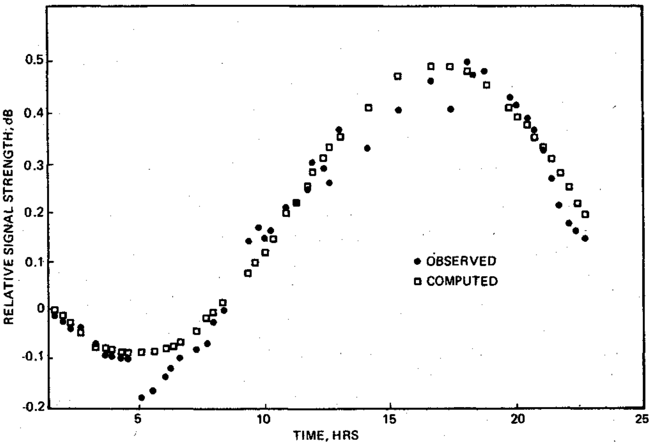

Fig. 2 Observed and computed signal strength variations relative to the first data point for a one-day period.

many times as necessary. The signal strength S is obtained by integrating this quadratic expression.

This data is expected to vary approximately sinusoidally with the spacecraft orbital period, and is therefore curve-fitted to such a function. Once again points more than a specified number of standard deviations from the sine curve are removed, eliminating the noisiest data. The process is helped by selecting stretches of data that show this expected variation. Generally, these stretches are associated with periods of clear dry weather. The data used in the estimation routine is not the absolute signal strength but rather the variation ΔS relative to the first data point. That point is taken from the sinusoidal expression, rather than being the initial measurement itself. A plot of measured ΔS vs time is given in Fig. 2.

The expected signal strength variation ΔS_c corresponding to each of the N measured values not rejected during preprocessing is used to form the residuals required to differentially correct an initial guess of the attitude state vector:

$$\hat{X}_{k+1} = \hat{X}_k + \left(\sum_{i=1}^{N} H_i^T H_i\right)^{-1} \sum_{i=1}^{N} H_i^T(\Delta S_i - \Delta S_{ci}) \quad (4)$$

In these computations the matrix H_i is obtained numerically and again, since the measurements are relative to the first data point, the H matrices are modified by $H_i - H_i - H_1$. In addition, the attitude is adjusted for solar torque precession based on a model which has been shown to predict quite well the long-term attitude motion.[3]

The computed signal variation after six differential corrections is included in Fig. 2. The corresponding differences between observed and computed values, or residuals, are less than 0.1 dB. Ideally, the residuals should be randomly distributed with zero mean, a condition which these results come close to meeting. Tests of this attitude determination scheme were made with data taken in Jakarta during 1978. It was found that the attitude estimates agreed well with those determined using sun and earth sensor data. In all cases the difference was a small fraction of the allowed control band of ±0.25 deg. Thus the somewhat simplified model of the antenna control system, which assumes essentially perfect control, and the lack of modelling for environmental effects such as temperature, atmospheric moisture and ionospheric variations, appear justified.

Conclusions

Although the Palapa-2 communications satellite still has an operating telemetry system, it has nevertheless been demonstrated that the spacecraft attitude can be measured without it. Comparison with standard measurement techniques (data from infrared earth sensors and a sun sensor) shows that the attitude can be determined to well within the control requirement for satisfactory communications. This has been accomplished by measurement at a single earth station. Greater accuracy can be obtained by adding data from a station in the northern part of the antenna pattern such as Manila, where the signal strength variation is out of phase with that experienced in Jakarta.

Acknowledgments

The authors are grateful to M. Eick and R. Blink for the design and implementation of the measurement techniques and devices, J. Janken for his part in making the software operational, and the Indonesian staff at the Jakarta ground station for their assistance in data taking.

References

[1] Sierer, W.H. and Snyder, W.A., "Attitude Determination and Control of Syncom, Early Bird, and Applications Technology Satellites," *Journal of Spacecraft and Rockets*, Vol. 6, Feb. 1969, pp. 162-166.

[2] Wright, W.H., "Stationkeeping Domestic Communications Satellites," Hughes Aircraft Company, El Segundo, Calif., SCG 50047R, Jan. 1975.

[3] Wright, W.H. and Anzel, B.M., "Telesat Stationkeeping Methods and Performance," AIAA Paper 74-452, 5th Communications Satellite Systems Conference, Los Angeles, Calif., April 1974.

Technical Comments

Comments on "Millimeter-Wave Missile Seeker Aimpoint Wander Phenomenon"

Dean D. Howard*
Naval Research Laboratory, Washington, D.C.

THE subject paper[1] provides interesting experimental results from a "millimeter-wave" missile seeker. However, considerable speculative and misleading discussion is provided to explain a phenomenon that has been extensively covered in the literature. The authors state: "Indeed, no study of the aimpoint wander phenomenon itself has been found in the literature by the authors." However, the authors also use the term "glint" which is a whole category in the International Cumulative Index on Radar System.[2] The glint category has many papers on the general subject of "aimpoint wander" which is called target noise in the IEEE Standard Dictionary of Electrical and Electronic Terms.[3] The subject of "aimpoint wander" is also included in the Radar Handbook[4] as a chapter entitled "Target Noise." The target noise is composed of two sources of angle errors: the amplitude noise (source affecting only conical scan radars as discussed in the subject paper), and angle noise (not recognized by the authors)—a noise-like variation in the apparent angle of arrival of the echo received from a target. Angle noise was first recognized in the early 1950's when it was found that

Received Aug. 10, 1979. This paper is declared a work of the U.S. Government and therefore is in the public domain.

Index categories: Guidance and Control; Missile Systems; Testing, Flight and Ground.

*Tracking Radar Coordinator.

monopulse radar, designed to eliminate angle error caused by amplitude noise, was subject to another source of aimpoint wander.[5]

The terms "glint" and "wander" are associated mainly with target angle noise; but in some usage it could include both angle noise and error caused by target amplitude noise.[3] However, the authors provide lengthy discussion of glint and aimpoint wander as a phenomenon resulting from amplitude noise; yet, they were not aware of angle noise, the major and most difficult component to reduce. Amplitude noise contribution to angle error can be eliminated by use of monopulse tracking or homing, but angle noise is a basic cause of angle error in any tracking or homing system. It can be reduced only by frequency agility or very high resolution techniques which are costly to implement.

Angle noise is a phase-front distortion phenomenon which, similar to amplitude noise, results from the interference between the echoes from the parts of a complex target. However, angle noise is directly dependent on the angular location of each reflecting element of the target having a magnitude proportional to the radius-of-gyration of the distribution of the reflecting areas of the target. Most radar devices find target direction by measuring the angle of the phase-front of a target echo and determine target direction by assuming the target is normal to the phase-front. Although the phase-front of the echo from a point source is essentially flat (at typical target ranges) and normal to the direction of the source, it can be warped by the interference phenomenon when the source is complex. The radar may observe a relatively flat portion of the warped phase-front, but the warping causes it to be tilted so that a normal to the phase-front no longer goes through the target and gives a false measure of the direction of the target.

A simple experiment readily separates the two sources of angle error in a tracking or homing system and demonstrates their characteristics. First, a beacon-type source of radar signal (which could be a pulsed rf signal generator synchronized to the radar prf) may be amplitude modulated at a low frequency (near the conical scan-rate) and connected to a single radiating element. This will cause errors in a conical scan radar when the modulation frequency (or harmonics) falls within the frequency range of the scan frequency plus or minus the servo bandwidth. The angle errors can be severe depending upon the modulation index. However, a monopulse radar will track the source with no error since the point source causes no angle noise or phase-front distortion.

Angle noise can be similarly demonstrated by dividing the rf beacon source between two radiating elements with adjustable relative phase and relative amplitude. With a small separation between the sources (compared to radar beamwidth), they can be adjusted in relative amplitude and phase to cause very large errors in either a conical scan or monopulse radar. For example, with 180 deg relative phase (as observed at the radar) and a relative amplitude of 0.9, the apparent location of the source will appear approximately 9.5 times the angular span of the two sources from their midpoint. The direction of error is to the side of the larger of the two sources. This angle noise phenomenon demonstration is performed with no modulation (other than radar pulse modulation if used), thus eliminating amplitude noise. With a fixed signal level and fixed values of relative amplitude and phase, the tracking or homing devices will look continuously in the erroneous direction with the direction error as described above. This same phenomenon has even been demonstrated in sonar systems.

The authors draw a false conclusion that the "wander" cannot exceed the span of the target. There is no logic to this conclusion if the wander is caused by amplitude noise because even a point source, modulated appropriately as described above, can cause large errors. Also, I have observed conical scan tracking of a propeller driven aircraft where the scan rate coincided with a propeller modulation frequency harmonic. The angle errors were spectacular, greatly exceeding the target span.

There might be some logic to the expectation that angle noise is limited to the extent of the span of the target. However, theory and measurement of radar tracking of aircraft demonstrate that the apparent location of a target (even exclusive of multipath) can fall far outside the target span. Also, multipath readily demonstrates this phenomenon. For a target composed of an aircraft and its reflected (multipath) image, the apparent angular location can be in error by many times the target span (target-image separation). Furthermore, measured target angle noise on aircraft is typically Gaussian shaped with significant tails extending beyond the extremities of the target.

One effective method for reducing angle noise or glint is to use frequency agility. The authors discuss this approach in Appendix A of Ref. 1. However, this work would have been much more effective if they had taken advantage of the available literature such as the several papers on the subject by G. Ling (see listing under Frequency Agility and Diversity in Refs. 2 and 6). The authors essentially state that if the path distance between interfering reflectors is greater than the velocity of light (c) divided by the bandwidth (assuming $\lambda_0 = cV_0$, where λ_0 is the wavelength at center frequency V_0) the signals from the reflecting elements cannot interfer. This is later qualified by the authors, but as it stands it is a false statement and should not be made. The fact that the statement is incorrect is an important distinction between incoherent frequency agility and coherent use of the bandwidth for range resolution, for example. With the bandwidth used for range resolution, the elements can be resolved and interference prevented, as the reflectors separate further, while with frequency diversity they will continue to interfere.

In summary, I believe some useful assessment of the tracking or homing problems of Ref. 1 could have been made by the authors with a knowledge of the existing literature which is a result of many years of effort by many people. Without this background, the authors have made misleading interpretations and conclusions.

Also, the authors calculate the echo amplitude fluctuations but only speculate on the angle errors they cause. This results in a very weak paper when quantitative analysis rather than speculation is needed.

References

[1] Williams, D.T. and Boykin W.H. Jr., "Millimeter-Wave Missile Seeker Aimpoint Wander Phenomenon," *Journal of Guidance and Control.* Vol. 2, May-June 1979, pp. 196-203.

[2] Barton, D.K., *International Cumulative Index on Radar Systems,*" IEEE, Vol. II, New York, 1978, pp. 29-30.

[3] *IEEE Standard Dictionary of Electrical and Electronic Terms,* John Wiley, New York, 1972.

[4] Skolnik, M.I., *Radar Handbook,* McGraw-Hill, New York, 1979, Chap. 28.

[5] Locke, A.S., et. al., *Guidance,* VanNostrand, New York, 1955, pp. 439-443.

[6] Barton, D.K., *Radars—Vol. 6: Frequency Agility and Diversity,* Artech House, Dedham, Mass., 1977.

Reply by Authors to D.D. Howard

D.T. Williams* and W.H. Boykin Jr.†
University of Florida, Gainesville, Fla.

MR. HOWARD'S criticism of the gap in the literature background of angle noise is quite proper. The authors should have presented such material, even though their conclusions do not involve such a type of aimpoint wander.

Received Nov. 5, 1979.

Index categories: Guidance and Control; Missile Systems; Testing, Flight and Ground.

*Professor Emeritus. Member AIAA.

†Professor of Engineering Sciences. Member AIAA.