CORRELATION OF GPS RECEIVER CHANNEL TRACK CONTINUITY WITH AIRCRAFT STRUCTURAL MASKING

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ABSTRACT

A GPS receiver with antennas located in an aircraft-mounted pod will be subject to signal blockage due to masking of the GPS satellite constellation by the aircraft structure. Analysis of aircraft flight test data involving a wing-mounted GPS antenna has shown that most of the receiver's loss-of-lock occurrences can be correlated with the optical shadow of the aircraft. Shadow regions of various tactical aircraft are used to estimate the extent of tracking outages for GPS pod antennas with the full 18-satellite constellation.

INTRODUCTION

Test and evaluation applications of the Global Positioning System (GPS) involving aircraft participants will entail the use of equipment configurations that must be attached to the vehicle as are normal stores. For tactical/strategic aircraft, these attachments must not compromise the operational configuration. Thus, small AIM-9-sized pods containing GPS receiver-processor and associated interface units are being developed by the Range Applications Joint Program office (RAJPO), AD/YIR, Eglin Air Force Base, Florida. The GPS instrumentation packages will provide both a source of vehicle position/state vector data and a means of transmitting these data to a remote collection facility for processing, control, and display.

Although the use of wing-station pylons for GPS pod mounting avoids aircraft modifications, it does not always afford the GPS pod antennna an unobstructed view of the sky for multiple satellite signal reception. Since signals from four satellites must be received for a three-dimensional navigation solution, the extent of aircraft structural blockage of the GPS satellite constellation was the subject of a recent GPS pod antenna masking test conducted by the Air Force at the U.S. Army Yuma Proving Ground, Arizona. The purpose of this test was: (1) to evaluate the performance and volumetric coverage of a GPS pod antenna designed by Cubic Defense Systems to operate mounted on an AIM-9-sized instrumentation pod and (2) to gather information on the ability of the five-channel GPS X-set receiver (developed by Magnavox under the GPS Phase I program) to maintain signal track on the satellite constellation when using various GPS antenna locations on the vehicle. This paper addresses the wing-station pod antenna results, correlating receiver channel tracking outages with the attitude and heading of the aircraft during a series of maneuvers.* These findings then permit the development of a methodology for predicting conditions under which satellite signal outages may occur for other aircraft configurations when the 18-satellite constellation is deployed.

TEST DESCRIPTION

The GPS equipment was provided by the USAF Space Division and consisted of a Magnavox 5-channel X-set integrated with a Litton P-1000 gimballed inertial navigation system (INS), a digital magnetic tape-recording system, an engineering display unit (EDU), a receiver control display unit (CDU), and a GPS antenna/preamplifier assembly, the latter installed in an AIM-9 sized pod. The aircraft used was an F4-J. As shown in Figure 1, the X-set, INS, and recorder were installed in a 300-gallon fuel-tank-type pod that was carried on the aircraft centerline (belly position). The EDU and CDU were located in the back seat of the test-bed aircraft for X-set monitoring and operation during the mission. The pod antenna was mounted on the outboard side of the left wing's inboard pylon (the test aircraft had no outboard pylon), with a temporary cable routed to the receiver antenna switch. The test flight profiles used consisted of barrel rolls and circular turns 360° (flown left and right) at constant bank angles of 15°, 30°, 45°, and 60°.

The data recorded by the belly-pod recording system included: aircraft roll, pitch, and heading, and GPS receiver track status for each of four channels (i.e., Costas [carrier loop] track, code loop track, search for signal, and AGC level). These data, along with the GPS satellite positions (transformed post-test to local elevation and azimuth angles), permitted analysis of the angular regions about the antenna in which satellite signal lock was interrupted due to masking.

DATA ANALYSIS RESULTS

The data tapes were analyzed using a data reduction program on the VAX 11/780 computer that monitored the track status of each of the four X-set channels (each of which tracked a preassigned satellite), transforming the satellite positions (in earth-centered, earth-fixed coordinates) into an aircraft elevation and azimuth coordinate system for each

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occurrence of a loss-of-lock (Costas loop) event. Using a polar coordinate system centered at the aircraft wing-pod antenna location, these points were then plotted and oriented so that the plane of the wings was parallel to the zero elevation plane; i.e., an azimuth angle of zero was aligned in the aircraft's nose direction. During the maneuvers of a 40-min sortie, approximately 120 loss-of-lock events were found and thus plotted (Figure 2).

The outline of the F-4J "optical shadow" is included on Figure 2 to correlate satellite loss-of-lock locations with a simple aircraft masking profile. This shadow may be thought of as being cast by a point source of light at the wing-pod antenna location. In practice, the "shadowgram" was obtained in the laboratory, using an accurately detailed scale model of the aircraft. In this procedure, the aircraft model was mounted on an elevation-over-azimuth gimbal support provided with angular readout mechanisms. The whitened tip of the model's antenna pod was illuminated by a low-power Helium-Argon laser (for convenience) and the model rotated until the illuminated "antenna" was obscured from the fixed laser line of sight. The angles corresponding to observation extinctions were recorded, then plotted in Figure 2. The accuracy of this procedure is estimated to be about 1°.

Although RF diffraction phenomena are complex and difficult to predict in detail, the shadow method was investigated as a gross tool to predict vehicle masking of satellite signal reception. As seen in Figure 2, the occurrence of satellite loss-of-lock events correlates well with the shadow projection. The several spurious loss-of-lock points "randomly" distributed in angular regions outside the shadow are thought to be due partly to the data reporting mode of the equipment, which reports a change in receiver channel track status only every 4 s. These delays may also account for the distribution, of loss-of-lock events within the central region of the shadow. Thus, the aircraft angular rates experienced during maneuvers could easily result in decorrelation of aircraft attitude and some loss-of-lock events due to the potential of data latency. It can also be seen that loss-of-lock data are sparse in the shadow regions corresponding to the nose (upper right) and left wing tip (lower left) projections. This was found to be due to the relative paucity of satellite/vehicle attitude combinations that would result in the satellite being tracked through these angular regions. The lack of these data is unfortunate, since they would have added empirical information about the "softening" of the optical shadow by RF refraction around these structural surfaces. Nonetheless, the relatively good correlation of loss-of-lock events within the optical shadow suggests that it could be used as a mechanism to forecast worst-case masking effects for other aircraft and other satellite constellation positions.

MASKING PREDICTIONS

Shadowgrams were prepared for two additional representative tactical aircraft, the F-16 and F-14, based on using wing-station pod antennas on the outmost pylon locations. The F-16 represented a benign shadowing case with the pod antenna on the left wing tip, whereas the F-14 represented a stressing configuration due to the pod location being close to the fuselage. Figure 3 shows these aircraft configurations and typical GPS pod locations. The shadowgrams for the F-4J, the F-16, and the F-14 were used together with a projected 18-satellite constellation to derive masking predictions for pod configurations in various attitudes, especially wings-level flight.

A computer program was used to model the 18-satellite constellation configuration and predict the satellite positions and the number of satellites that might be seen above the 5° horizon at Yuma. The number of satellites visible over a 24-h period is plotted in Figure 4, and it can be seen that the pattern is repetitive in 12-h cycles. In particular, Figure 4 indicates that only 5 satellites may be visible about 40% of the time. This condition represents a typical situation with which a GPS pod-mounted receiver must cope. As an illustrative example, the elevation and azimuth locations of five visible satellites at an arbitrary 0600 hours were plotted in local tangent plane polar coordinates (Figure 5). Using the shadowgram of the F-4J (seen in Figure 2), the number of satellites visible to the pod antenna were plotted (Figure 6) as a function of aircraft heading by rotating the shadow overlay. As can be seen, all five possible satellites are unmasked only for fairly narrow heading angle regimes; more typically, only four are visible.

The aircraft shadow also was mathematically transformed in polar coordinates to represent a 45° bank (Figure 7). This shadowgram was overlayed on the satellite position plot and rotated to effect different headings, producing the satellite masking plot of Figure 8. In this case, the masking is seen to be more severe in that several heading angles resulted in only three (and sometimes two) satellites being visible to the pod antenna. In practice, an aircraft would not maintain a constant bank angle for prolonged periods. Typically, an air combat maneuver will occur in only a few seconds, resulting in momentary blanking of multiple satellites.

In similar fashion, shadowgrams for the F-16 and F-14 aircraft were prepared in the wings-level format (Figure 9a and b, respectively). The F-16 produces only a thin shadow that is about 10° high (elevation) and 170° in length (azimuth). The F-14, on the other hand, casts a shadow that extends about 60° in elevation (an additional 20° of shadow is below the -10° horizon plotted in Figure 9) and wraps around about 205° in azimuth, when the pivoted wings are extended for subsonic flight. Thus, the possibility of greater satellite blockage is expected for this aircraft. Figure 10 plots the wings-level F-14 satellite blockage as a function of heading angle for the example satellite positions used. Although it does not seem that fewer satellites are visible for the F-14 (Figure 9) than for the F-4J (Figure 6), the larger shadow of the F-14 suggests greater chances of satellite blockage under various satellite geometries and aircraft attitudes. However, the F-14 blockage in level flight may be less severe than its shadow would indicate, because much of the fuselage shadow extends below the horizon; furthermore, the extended wing obstruction may be sufficiently thin to preclude excessive RF masking.

SUMMARY AND CONCLUSIONS

GPS satellite track continuity data from a recent GPS pod antenna flight test have provided relatively good correlation with an optically projected aircraft shadowgram of the F-4J test aircraft, although additional data are needed to verify this relationship at the wing-tip extremities. Shadowgrams of the F-4J, the F-14, and the F-16 used in conjunction with a projected computer “snapshot” of a representative worst case for the full 18-satellite configuration (i.e., only 5 satellites visible above the 5° horizon) indicates that four satellites should be available for the GPS navigation solution for most wings-level aircraft headings. However, the F-14 may experience more transient signal outages during maneuvers than the other aircraft considered due to its larger shadow. Consequently, inertial aiding designs should be capable of propagating the navigation solutions when fewer than four satellites are available. In addition, high-dynamic maneuvers such as those used in air combat can cause significant masking. Although these satellite signal interrupts should be transitory, lasting only a few seconds, they will necessitate fast satellite signal reacquisition performance to maximize GPS measurement data availability for the navigation solution.

ACKNOWLEDGMENTS

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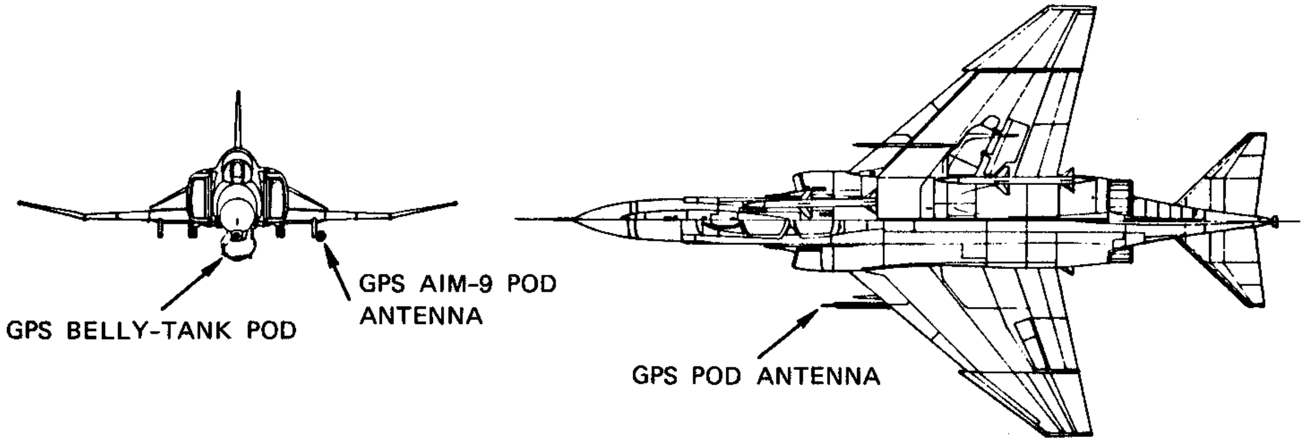

Figure 1 - F-4 Aircraft with GPS Equipment Locations

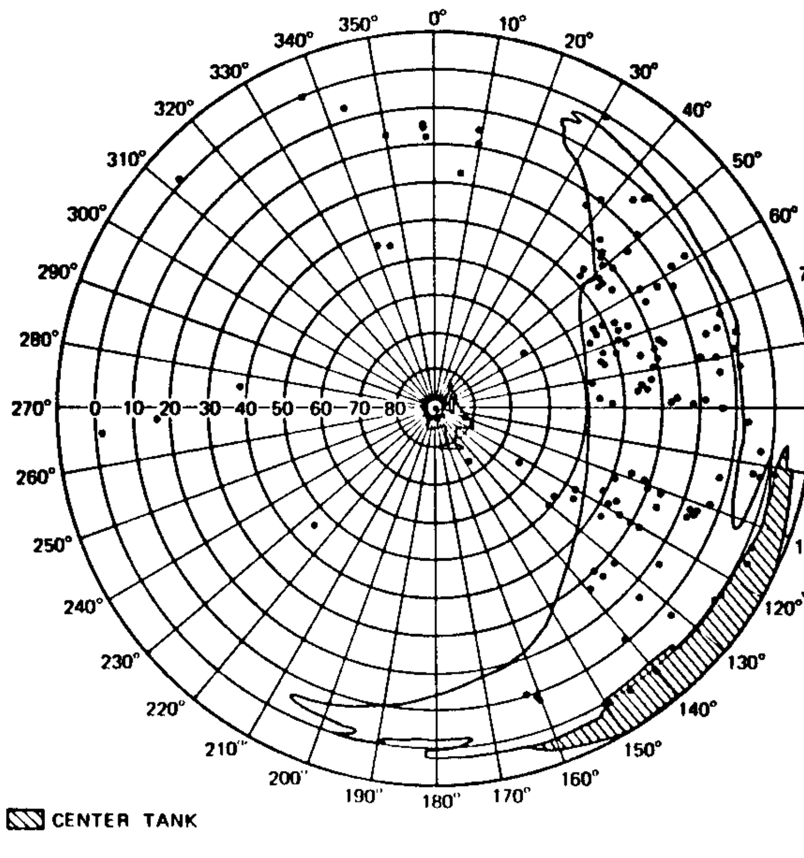

Figure 2 - Loss-of-Lock in Relation to F4-J Aircraft Optical Shadow From AIM-9 Pod Mounted GPS Antenna (Mission 4075)

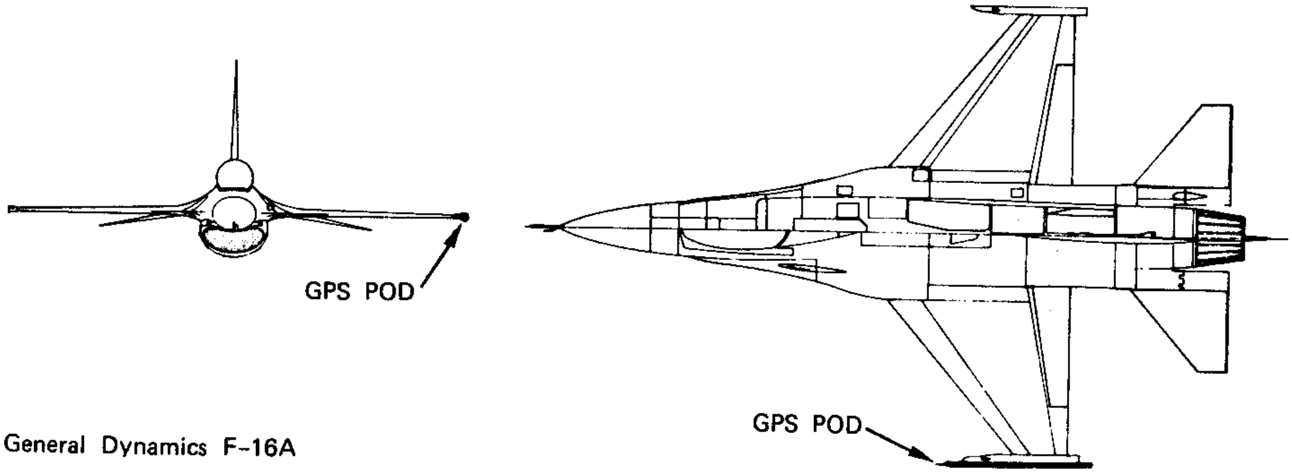

Figure 3a - F-16 Aircraft with Typical GPS Pod Location

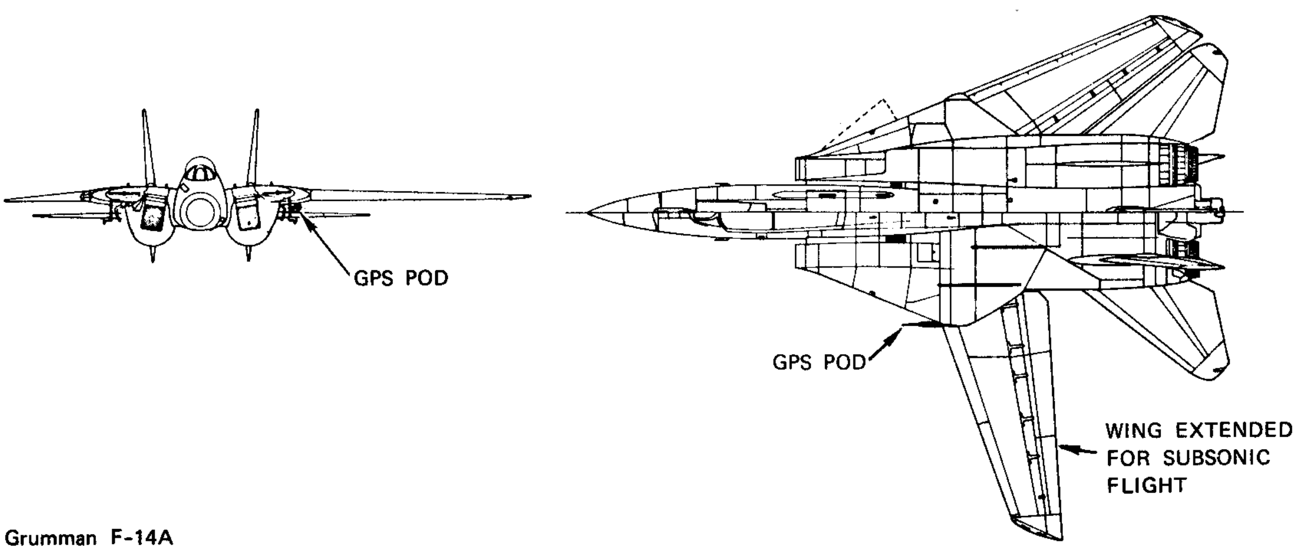

Figure 3b - F-14 Aircraft

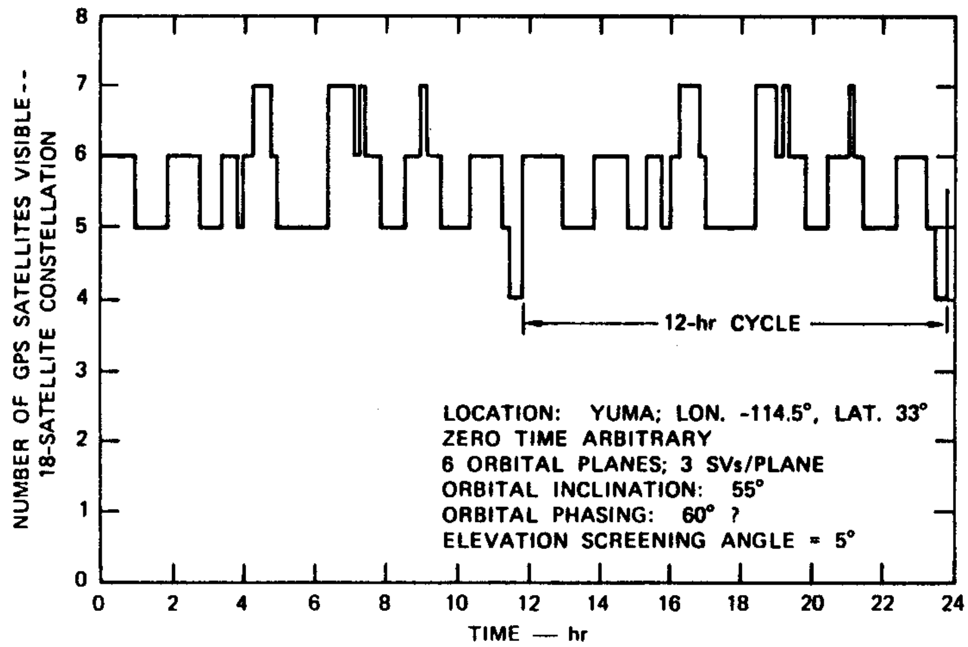

Figure 4 - Number of GPS Satellites Visible at Yuma in an 18-Satellite Constellation of the Type Planned

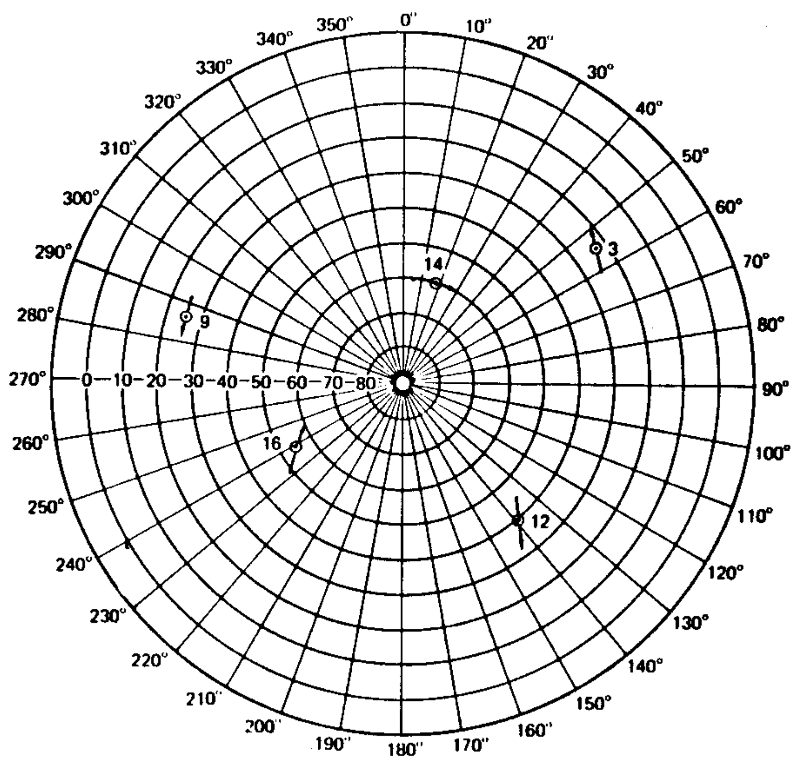

Figure 5 - Azimuth and Elevation of Satellites at 0600 hrs (±15 min; best four-satellite PDOP = 3.02)

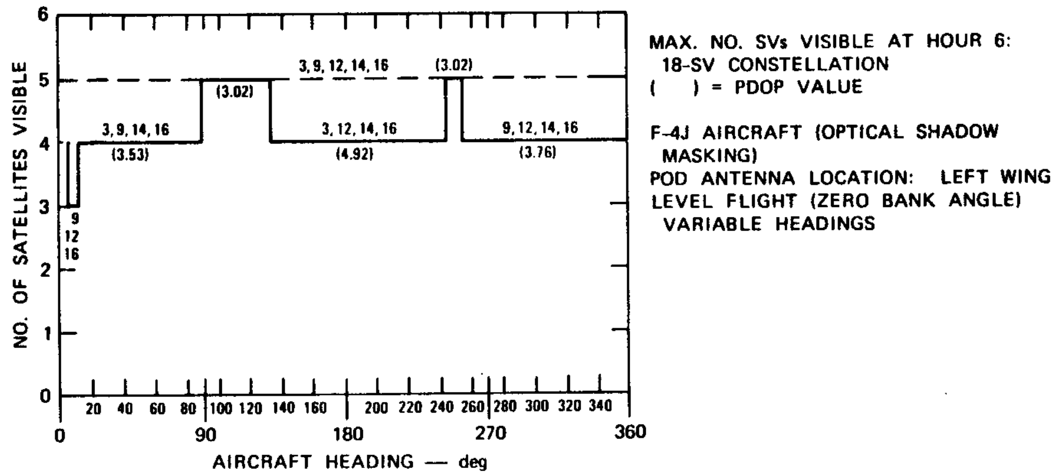

Figure 6 - Number of Satellites Visible in Level Flight (F4-J with pod antenna)

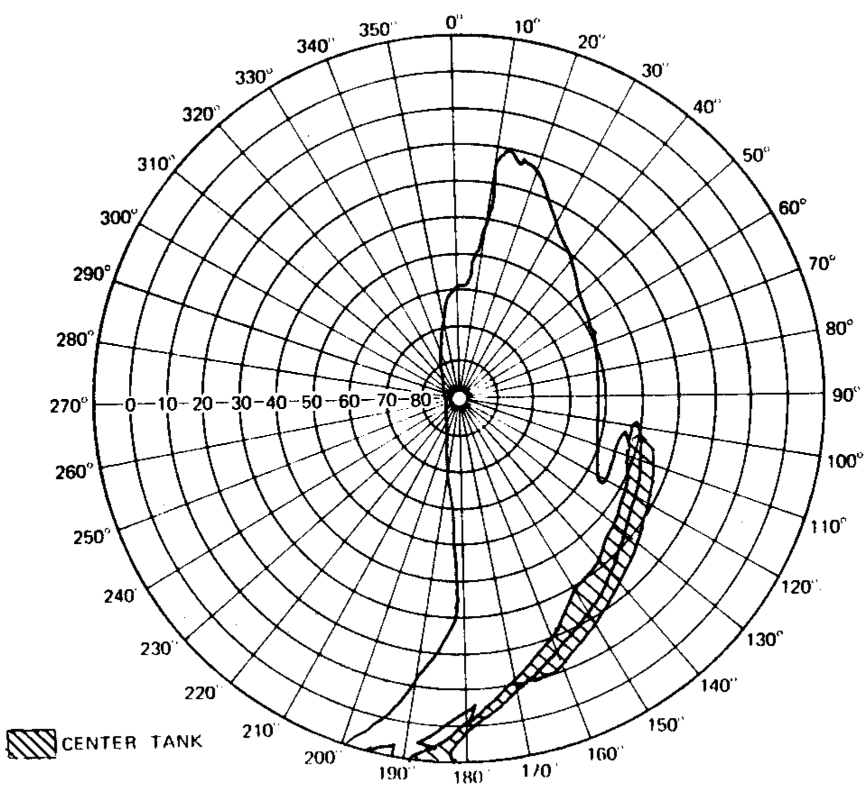

Figure 7 - Optical Shadow of F4-J Aircraft at 45° Bank Angle (left) From Pod Antenna on Left Wing

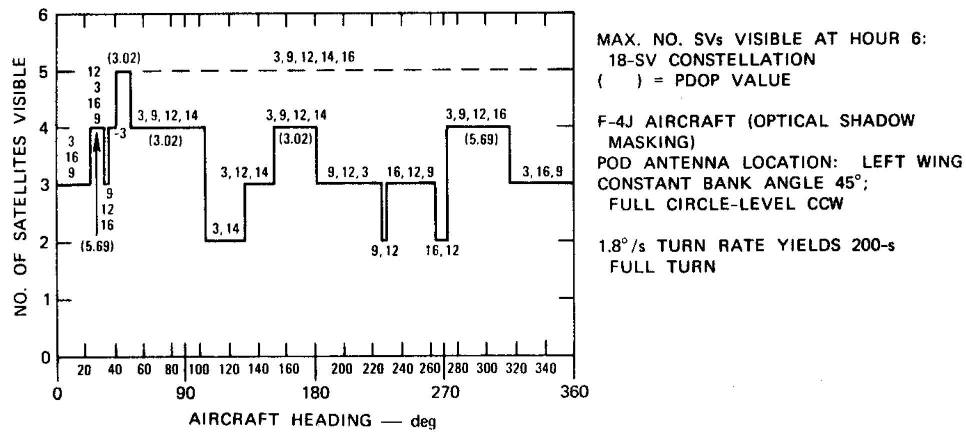

Figure 8 - Number of Satellites Visible in Counterclockwise Full Circle at 45° Constant Bank Angle

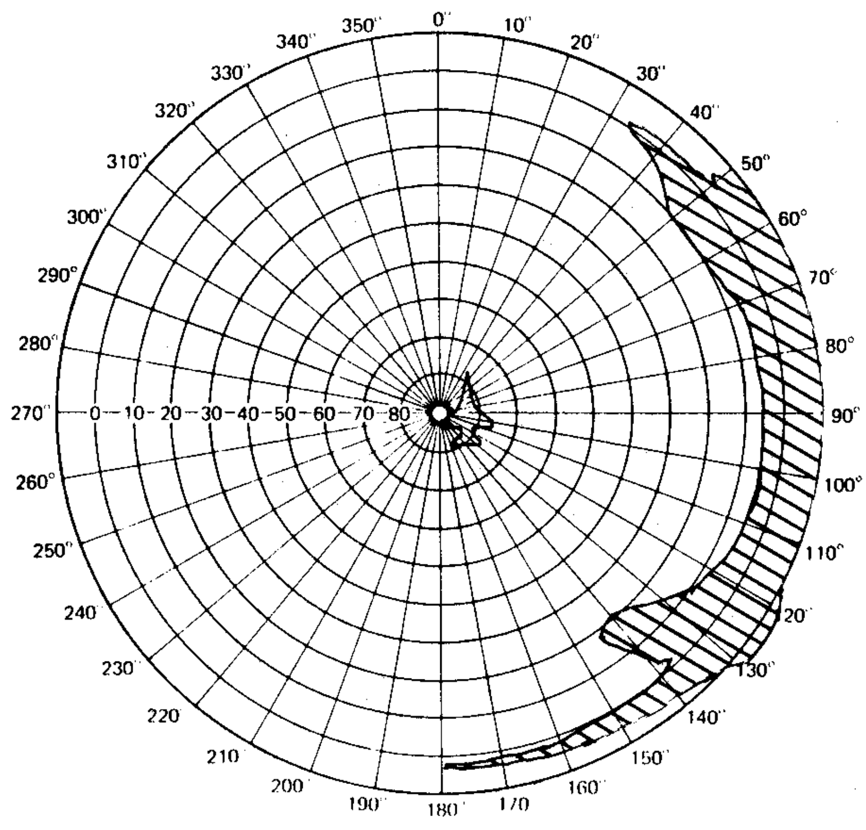

Figure 9a - Shadowgram for F-16 Aircraft with Wing-Tip-Mounted GPS Antenna Pod

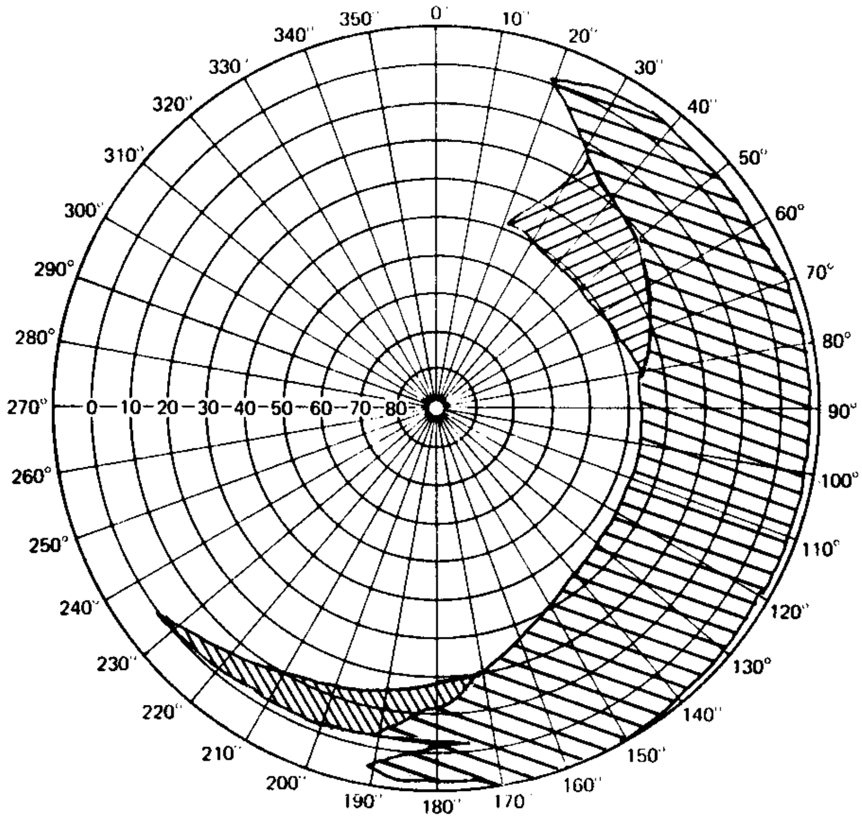

Figure 9b - Shadowgram for F-14 Aircraft with GPS Pod Antenna Mounted as in Figure 3

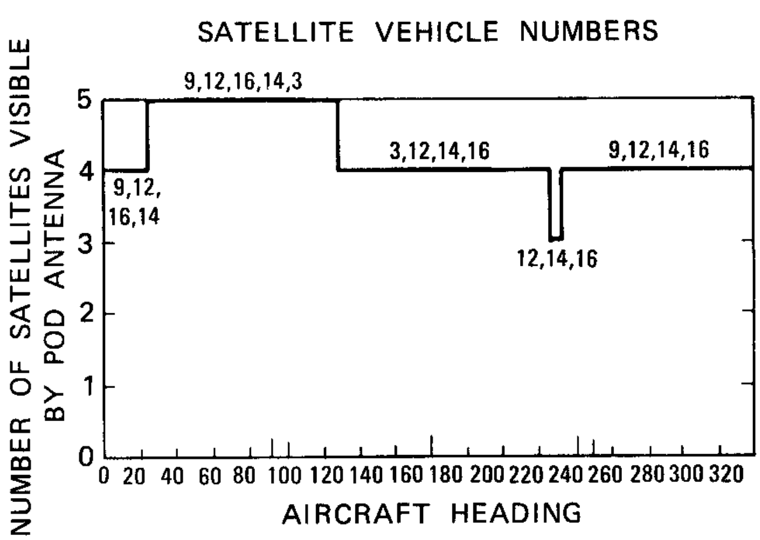

Figure 10 - F-14 Wings-Level GPS Satellite Blockage Estimations as a Function of Aircraft Heading