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Millimeter-Wave Missile Seeker Aimpoint Wander Phenomenon

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Aimpoint wander is the tendency of the apparent source of microwave radiometer echoes to shift laterally, suddenly and unpredictably, during the closing flight of a tracking seeker. The phenomenon is shown from flight test records to be completely explained by the observed presence of sudden variations in echo intensity, such as are well known to be caused by low-order interference of the radiometer echo from complex targets. The origin of the echo intensity excursions is presumed to be low-order interference between flat surface and corner features on tanks, trucks, and other targets. Aimpoint wander during terminal homing primarily requires the presence of some relative lateral motion of the tracker, due either to aerodynamic buffeting or deliberate manipulation of the closing flight path.

Introduction

THIS paper examines the behavior of an active microwave tracking seeker antenna. In brief, the axis of the seeker dish is observed to depart from any line of sight, as though the origin of the echoes which serve as input signals to the seeker, were not fixed on the target, but rather shifted positions abruptly, and at more or less random intervals during the flight. These shifts are observed to be much greater than those normally associated with electrical or gyroscope noise.

The phenomenon in question was studied by the authors by use of a number of flight tests of active millimeter-wave seekers, in a general program in which the tracking performance of the seekers was being tested. The tests were carried out between November 1975 and May 1976; and a report was written at the University of Florida, summarizing the results, in the same year. The following paper is a condensation of the same results, with sufficient background information included to clarify, it is hoped, a number of features of the data, that have not heretofore been clearly understood.

As is the case with all observed phenomena, the data obained which describe an observable object, are functions both of the characteristics of the object, and also of the device by use of which the data are obtained. In the aimpoint wander study, the primary observable item is a target—normally a metal object like a truck, tank, or aircraft. By reason of the fact that its material composition is metal, it is always seen to have a reflecting power for microwaves larger by roughly an order of magnitude, than that of equal areas of the background. Furthermore, because of the fact that most real targets are characterized by features generating specular reflection of the incident microwave radiation—such as the corners of open truck bodies, corners where a tank turret intersects the carriage, etc.—many targets have "cross sections" that act as an array of small corner reflectors. Such reflectors have the property of reflecting any microwave signal back in the same direction from which the signal came. As a result, targets of practical interest may have cross sections that are somewhat larger than a smooth and rounded metal shape would have.

The seeker used to detect the target is basically an "optical" device. It is often a Cassegrainian telescope having a characteristic diffraction pattern of about 2 λ/d angular width, where λ is the wavelength of the radiation and d is the diameter of the antenna. However, the wavelength of the seeker microwave source, in contrast with the situation in optical devices that use white light, is relatively narrow-band. Various parts of the target may therefore generate echoes that interfere either positively or negatively, to an extent much greater than is observed in most familiar optical systems. Finally, the seeker is steered, in its tracking motions, by a servosystem having certain properties originating in the nature of the signal-processing circuitry. The interaction of the circuitry with the input signal produces the aimpoint wander in a manner readily understood.

There is a great deal of interest in the detection of targets against a ground-clutter background.[1-9] A number of these references, specifically Refs. 2, 3, and 7, focus on the peculiarities of a target—resonant structures, small specularly reflecting surfaces, etc.—which may produce a distinctive target signal. Other references are directed at signal-processing algorithms or special radar signal characteristics[4,5,8,9] for use in discrimination against the clutter background signals. Two references[6,8] take note of the well-known characteristics of target signals to fluctuate because of glint.

There are a large number of studies of the radar (or radiometric) cross sections of different types of terrain.[10-18] These range over a variety of types of terrain, frequencies of microwaves, and angles of observation. They disregard the matter of contrast with targets, in some cases because the nature of the vegetation, or strength of clutter signal are of primary interest.

In the nonexhaustive (but typical) referenced work, the interaction of the peculiarities of the incoming signals with the circuitry of the tracking servo is not introduced. Indeed, no study of the aimpoint wander phenomenon itself has been found in the literature by the authors.

Geometrical Optics of a Microwave Seeker Dish

Any small target on the ground, having a cross section sufficiently large will produce a signal in the seeker receiver circuitry approximately described as to its intensity, as related to the angle between the seeker axis and the line of sight to the target, by the equation for the Fraunhofer diffraction pattern for a circular aperture

$$I(x) = I_0 [2J_1(x)/x]^2 \tag{1}$$

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Here the intensity I is seen to be proportional to I_0, the value it will take when the line of sight coincides with the antenna axis, $x=0$. The parameter $x=k\xi/R$, where ξ is the angle between line of sight and seeker antenna axis, R is the seeker-to-target range, and k is chosen to insure that $I(x)$ will take the value 0 when x has the value of the first zero of the Bessel's function, $J_1(x)$. An excellent approximation to Eq. (1), often used for convenience, is the Fraunhofer expression for diffraction due to a slit

$$I=I_0(\sin x/x)^2 \tag{2}$$

The curves of Fig. 1 show the intensity I as described by Eqs. (1) and (2). It is at once clear that the two expressions are virtually the same within the central lobe of the curves. They differ in the amplitude of the sidebands. (A fit has been forced at the point $I=\frac{1}{2}I_0$.)

All point sources of radiation from the ground will produce intensities I described essentially by Eq. (2). This means that any seeker operated from a tower and caused to pan slowly across the terrain, will record a signal which when plotted as a function of time can never show a feature any narower in contour than that indicated in Eq. (2), and Fig. 1. A very strong echo will exhibit a peak I_0 that is correspondingly large but its width will be just the same as that of a weaker echo with smaller I_0.

Actual echoes as detected by actual seekers show a record of the type indicated only when the record is taken slowly enough to permit electronic noise to be filtered out. In the event any feature should appear to be not in conformity with the pattern required by Eq. (2), it should be concluded at once that the panning motion of the seeker was not smooth, noise was not filtered out, or some other phenomenon occurred which introduced a factor not assumed in the model.

The pattern of behavior as outlined requires that any real target which is not a point, will appear as a *wider* feature than is required by Eq. (2). Two separate point sources of equal strength will be resolved as two separate signals only when their angular separation is somewhat larger than λ/d: that is, $S/R\geq\lambda/d$, where S is the linear distance separating the two sources along a line normal to the range R.

If one were to improvise a model for explanation of aimpoint wander as an actual shift of the antenna axis from one point target to another, lying S apart, wander would be limited to rather short ranges, that is, to ranges such that the two points were actually resolved. Thus if the two equal sources were, say, 3 m apart, and if the wavelength were 0.86 cm, $d=30$ cm, the range at which the tracker would be able to distinguish the two points as distinct from each other would have to be less than $3\times30/0.86=105$ m. In short, complexities of the target itself cannot be plausibly linked to aimpoint wander except at ranges rather closer to the target than present ranges at which guidance is normally terminated. Of course, if course correction could take place within distances less than 100 m, the detailed structure of the target would then be significant.

It should be pointed out that in this analysis thus far, no mention has been made of millimeter wave interference. This matter will now be considered.

The Glint Phenomenon

An interference phenomenon, referred to as "glint," can have such an effect as to influence the conclusions relating to geometrical wander.

Any target, or for that matter, the ground-clutter background of the target, may properly be considered as being made up of an infinite number of point sources. A radar pulse incident upon them is reflected or scattered; the portion of the reflected pulse reaching the receiver is made up of many components which add up to form the input signal to the tracker servocontrols. This addition is not simple; but instead it is essentially a vector addition with relative phase determining whether the sum will be a resultant with amplitude greater than, or less than, the sum of the component amplitudes. Thus a plane surface in the radar footprint normal to the incident radar pulse, will generate an echo with all components from the elemental surface areas adding in phase. They interfere positively with zeroth order interference. Two echo point sources will also interfere positively whenever the distances R_1 and R_2 to the seeker have differences that are exact half wavelengths in absolute magnitude

$$|R_1-R_2|=n\lambda/2 \tag{3}$$

Here n is an integer, and as before, λ is the wavelength.

The considerations above lead to the presumption that the ground, not smooth enough to reflect specularly, will usually reflect as though it were made up of a great number of elements interfering with random phase, but with low order (n small). In this case, the intensity variation of the clutter may be reasonably small, since with any change in aspect angle, as many pairs of elemental sources are likely to be brought into phase as are brought out of phase. In the event the target background, or the target, has some depth along the line of sight, as of course both always do, a narrow-band radar signal will also be characterized by interference of high order n. For this reason, ground-clutter return with narrow-band radar is notorious for showing extreme variations in intensity with change in view angle. A target is correspondingly hard to detect by its echo intensity alone. It is concealed by "glint" from the background.

When seekers use a range of wavelengths $\Delta\lambda$, in each transmitted pulse, and when the intensity of the received pulse is averaged over its entire duration and spectrum, the glint due to interference as described above, may be substantially reduced. In this case, even though low-order interference (n small) may still be present, at least high-order interference (n large) is largely eliminated. The situation is analyzed in Appendix A and illustrated in Fig. 2.

Figure 2 illustrates the situation resulting from the presence of two interfering sources approximately on the line of sight to the seeker, separated by a distance $S=n\lambda$. As S increases

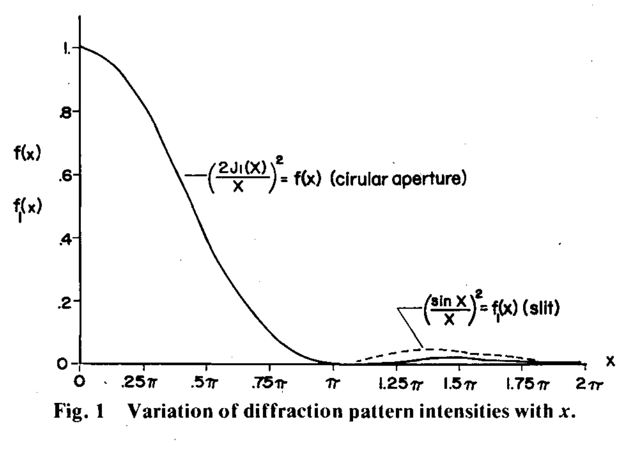

Fig. 1 Variation of diffraction pattern intensities with x.

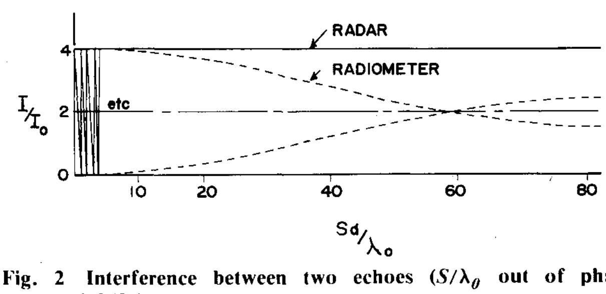

Fig. 2 Interference between two echoes (S/λ_0 out of phase, $\Delta\nu/\nu_0=0.3/35$).

from 0, the intensity of the two interfering sources changes from a peak of four times the intensity of one source alone, to zero, and back again to a maximum, within an increment in S of λ. The envelope of the maxima for the case where λ is a discrete wavelength, with no bandwidth, is then a straight line with ordinate 4. On the other hand, if the wavelength varies linearly with time during the transmitted pulse from $\lambda - \Delta\lambda$ to $\lambda + \Delta\lambda$, the envelope of the maxima will go to 0 at about S equal 60 wavelengths, if $\Delta\lambda/\lambda = 0.01$. In other words, whereas a narrow-band radar will produce glint by positive interference of all orders n, a "radiometer" with $\Delta\lambda$ not equal to zero will produce only low-order interferences. The use of such broader-band pulses exacts a price in the form of lower gain in the superheterodyne receiver, and a longer relaxation time. When a radiometer is used in place of a radar, the background clutter will be substantially reduced in variability. The target itself may still show some glint. Various plane surfaces will produce sudden increases in echo strength when the aspect angle changes by small increments. If there are two or more plane surfaces, or effective corner reflectors due to the intricate geometry of the target, or if there are rounded shapes, and if the distances to the seeker are small, there may be interference between them characterized by a sequence of maxima and minima as the aspect angle changes.

Appendix B shows that when a real target can be approximated by a pair of corner reflectors, there will be almost periodic intensity excursions in the microwave echo at intervals as a tracking seeker flies on a line of constant bearing, not directly toward the target. These excursions are subject to appropriate conditions on the distance ΔS separating the two corners and the range, R. In general, the frequency of the intensity excursions of the echo will increase as the range decreases.

In case the line of flight coincides with the line of sight, excursions of the kind described will not appear with the same regularity. A real target would be expected to be characterized by glint, nonetheless. Some recurrence of the intensity excursion would result, even with flight nominally along the line of sight, if there were any aerodynamic buffeting during the flight, causing lateral or vertical displacements from the line of sight, and if plane surfaces or corners were present to interfere with low orders of interference.

Tracker Response to Intensity Excursions

Terminal homing seekers which provide high missile hit accuracy against moving land vehicles and under windy conditions are normally some form of proportional navigation guidance (PNG). PNG seekers consist of a target sensor and a rotational inertial device. These, with the required circuitry, allow the missile to steer with a side force (for changing path) which is proportional to the inertial line-of-sight rate $\dot{\theta}$. The sensor, in this case the antenna, is rotated to null any angular error ϵ between the sensor and target. This rotation is accomplished by torquing the inertial device, a single two-degree-of-freedom gyro or platform. Figure 3 gives a simplified block diagram for a single axis of the missile guidance loop. (There is an elevation or pitch loop with $\epsilon = \epsilon_{EL}$ and an azimuth loop with $\epsilon = \epsilon_{AZ}$ and $\dot{\theta} = \dot{\theta}_{AZ}$.) It is known that even small amounts of "aimpoint wander" with a frequency within the bandwidth of the missile system will produce a target point miss-distance larger than desired for hard-point targets. Variables which affect the accuracy include missile maneuverability and speed, seeker blind range (AGC dynamic range), and aimpoint wander.

The effect of any sudden intensity excursions on a tracker, whatever the nature of their origin, can be understood if one recalls that trackers are equipped with an automatic gain control (AGC). This device insures that the echo from the target maintains roughly a constant level as the tracker approaches the target.

Trackers generate error signals whenever the antenna axis deviates from the line of sight to the target. Thus if the seeker operates by use of a rapid conical scan about a mean antenna direction, the requisite error signal appears whenever the mean antenna axis departs from the line of sight, only if the AGC does not operate too rapidly. If an intensity excursion is a reasonably sharp pulse, so that it reaches a high level in a time short compared to the characteristic delay time of the AGC, the tracking system misinterprets the intensity excursion as a large angular error. Its response will therefore be a pulselike change in the pointing direction which causes a true wander of the antenna mean axis from the target line of sight. Such a phenomenon would be, on casual examination, the same as though the *aimpoint,* i.e., the true location of the echo being tracked, had suddenly shifted in space. On more detailed examination, the twitch due to an intensity excursion is not quite the same as the wander of an aimpoint, say due to jitter of a laser spot in the case of a laser-guided seeker.

An Experimental Study of Aimpoint Wander

The pattern of behavior outlined above was deduced from a set of data from three different series of flight tests of microwave trackers. No attempts will be made at this point to review in detail all the results of the study; however, two samples of the data analyzed will be presented, which were crucial in forming the basis of the conclusions reached relating to aimpoint wander.

One series of flight tests was made in California by General Dynamics, of their microwave seeker, in their so-called Black Jack program. The seeker is an active one with characteristics listed in Table 1. The mean carrier frequency was 35 GHz. The antenna was a Cassegrainian telescope with an 8.5 in.-diam. main mirror. The secondary mirror was cocked at about 1 deg from the optical axis and spun about that axis at 200 rpm to generate a conical scan of the antenna beam. By this means error signals in pitch and yaw were generated wherever a target lay in the field of view of the seeker, displaced from the mean antenna axis. The error signals were used to steer the direction of the antenna mean axis, that is, the axis of the main mirror which was rigidly mounted on a gyrostabilized platform. The line of sight of the antenna mirror was controlled by torquers on the platform. Its motion was also monitored by a pair of rate gyros also mounted on the platform. In operational use, the flight path of the homing missile guided by the tracker is designed to be altered during the homing flight so as to reduce the parameter $\dot{\theta}$, to zero, thereby providing the conditions requisite for target intercept.

In the tests used to generate the tracking data studied in our investigation, the seeker-tracker was carried on a light single-engine aircraft. The target was acquired manually by the operator of the seeker aboard the aircraft, at as large a range from the target as possible. Thereafter the seeker was locked on the target while the pilot of the aircraft flew along the line of sight, as well as he could judge it. When the closing distance was sufficiently small, he pulled up and flew over the target, concluding that run.

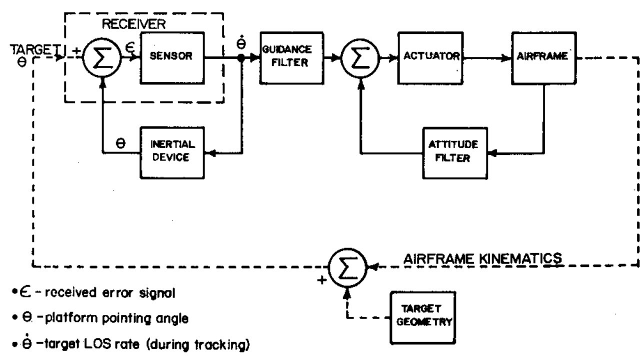

Fig. 3 Guidance loop simplified block diagram for single axis.

Table 1 Characteristics of the Black Jack seeker

1) Carrier frequency, 35 GHz
2) Antenna size, 8.5 in.-diam mirror.
3) Platform – full platform carrying dish, con-scan spinner, rate gyros, and preamplifier
4) Con-scan frequency, 200 rps
5) Angle of scan cone, 2 deg
6) Instrumentation tape records used – pitch and yaw error signals, i.e., the outputs of the receiver operating in a conical scan; rate gyro outputs.
7) Flight test carrier, single-engine Cessna light aircraft

Data taken during the flight were of two types. A vidicon camera was slaved to the platform, and recorded the position of the target during the test. In addition, instrumentation tapes were recorded. In exploiting the data, the actual "aimpoint wander" was read out manually from the TV record, frame by frame. Its accuracy was subject to any possible slop in the linkage between platform and vidicon, TV resolution, and pickoff potentiometer resolution. Also the data from the instrument tapes themselves were plotted and analyzed. The record of input signal ϵ may be looked upon as the record of aimpoint wander, if the "aimpoint" is defined here as the intercept point of seeker axis with the target plane when $\epsilon = 0$.

It may be emphasized again at this juncture that "aimpoint wander," insofar as it is a true variation in the location of the centroid of the echoes originating on the target itself, must by definition be limited in its amplitude to something less than the angle subtended by about half the target, at the tracker. Thus the 3.6 m width of tank could never produce, from itself alone, a wander of more than 1.8 m from the center of the tank. At a range of 550 m, this is equivalent to an angle of 0.19 deg. The same range of wander would exceed 1 deg only at a range of about 100 m.

Figures 4 and 5 have been selected from the data studied as good examples of the phenomena under analysis. Figure 4 shows four channels of the instrumentation tape recorded during one flight, made with a corner reflector as target. The error signals in azimuth and elevation, ϵ_{AZ} and ϵ_{EL} appear as channel numbers 3 and 4 of the figure. These records show as a function of flight time, the product of angular departure by intensity of signal, from target acquisition (ACQ) to the end of the run (EOR). An automatic gain control was used, of course. If its action had been instantaneous, the records would always have been found to be identically zero. Consequently, in order to insure an error signal, the AGC was adjusted to have a delay somewhat greater than a con-scan period of 0.005 s. The amplitude scale of the records in the figure was calibrated by use of measurements in separate tests that were slow enough so that the AGC was operational. If a signal comes in that is not slow, but a fast pulse, the indication of the instrument tape should not be interpreted as a true angular departure unless the indication has a duration of more than about 0.01 s. As for the zeros of the error signal scales, they are of no significance. They are set if possible so that the zero coincides with the mean reading of the error signal. In the event that there is a difference between the zero and the mean, the fact merely indicates an error in calibration.

The first two records of Figs. 4 and 5 are $\dot{\theta}_{AZ}$ and $\dot{\theta}_{EL}$ of the rate gyros mounted on the seeker platform. In the records, a sudden departure from the centroid indicates a twitch in the motion of the platform. Normally such a motion is the result of a response to an appropriate error signal. Thus in Fig. 5, when the record ϵ_{EL} shows a strong error signal, target low, connected to the pull-up at the end of the run, $\dot{\theta}_{EL}$ shows a corresponding substantial rate downward, as the seeker attempts to follow the target, passing beneath the aircraft.

Examination of Fig. 4

A perusal of the data of Fig. 4 led us to the conclusion that aimpoint wander is not significant when the target is a corner reflector. This statement is subject to two provisos. First, it must be understood that some hunting of the tracker line of sight about the mean line of sight to the target is necessary for the proper operation of the tracker. The amplitude of this hunting is estimated at ±0.1 deg or less—it does not significantly degrade the accuracy of the guidance and control of some homing missiles carrying the tracker against hard-point targets. Whether such a hit point error from the mean aimpoint is produced, is determined by the amplitude of the hunting motion and its frequency.

A second proviso is that the wander that appears toward the end of the run, noted by the numbers 3, 2, 1 in the ϵ_{EL} record, be expected at this point. This type of jitter in the vertical

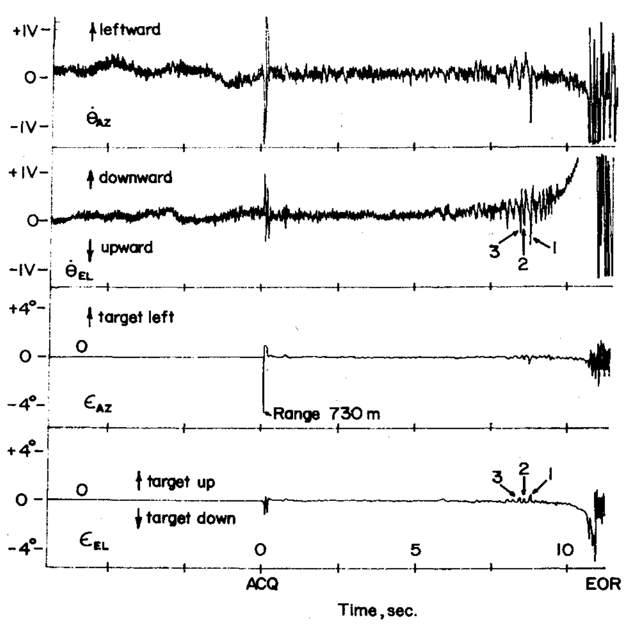

Fig. 4 Millimeter-wave seeker data using corner reflector target (Flight 19, Run 13).

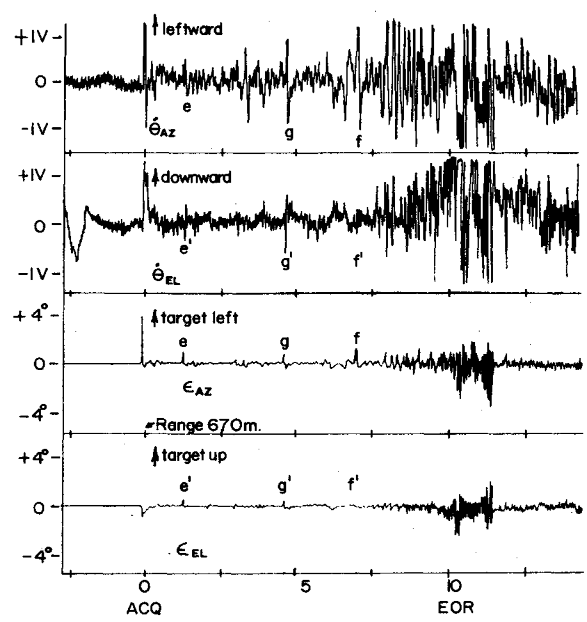

Fig. 5 Millimeter-wave seeker data using M 48 tank with rear aspect (Flight 19, Run 17).

plane, encountered more or less frequently in microwave seeker tests, is known as the "multipath" phenomenon. It comes from the fact that a beam of microwave radiation may be reflected indirectly, i.e., from the image of the target in the ground. Since the ground is normally conducting and since, with microwaves as contrasted to light waves, the ground is smoother, reflection of this type is quite common.

The excursions 3, 2, and 1 show that the tracker suddenly encountered strong signals ϵ_{EL} from the target (target high), as though at this range the seeker was first able to discriminate the target echo from the combination of that echo with the reflection in the ground. Reference to the $\dot{\theta}_{EL}$ record at the same times shows spikes down, indicating upward twitches in the motion of the platform. In other runs with a corner reflector target, the multipath phenomenon produces short bursts of oscillation which appear in the ϵ_{EL} record, with corresponding bursts in the $\dot{\theta}_{EL}$ record. There is some cross-talk with the ϵ_{AZ} and $\dot{\theta}_{AZ}$ records; but no multipath phenomenon is found exclusively in the azimuthal plane, as indeed, was to be expected.

It may be noted that if the relative time epochs are carefully examined at which the spikes appear in ϵ_{EL} and $\dot{\theta}_{EL}$, those in the latter seem to lag those in the former, though by increments on the border of observational precision. Some lag in the servosystem is, of course, expected.

Examination of Fig. 5

An examination of Fig. 5 shows quite a different situation with regard to aimpoint wander when the target is a tank rather than a corner reflector. In the eleven seconds of the run recorded in Fig. 5, with acquisition at 670 m, a number of marked departure spikes are to be seen in the ϵ_{AZ} and ϵ_{EL} records, with corresponding response features in $\dot{\theta}_{AZ}$ and $\dot{\theta}_{EL}$ also appearing. The following peculiarities are noted:

1) The spikes marked e, g, and f appear as heavily damped impulse responses. An upward (leftward) spike in ϵ_{AZ} is immediately followed by an upward (leftward) response in $\dot{\theta}_{AZ}$. This is in turn followed by a much reduced downward excursion (target right) in ϵ_{AZ}, which again is followed by a downward (rightward) response in $\dot{\theta}_{AZ}$. The delays between the error signal and the response are again of the order of 0.01 s. At no time does a spike in $\dot{\theta}$ *precede* a sharp spike in ϵ.

2) When the spikes e and g appear in ϵ_{AZ}, corresponding spikes also appear in ϵ_{EL} (e′ and g′) at the same time. On the other hand, there is no spike f′ in ϵ_{EL} corresponding to f in ϵ_{AZ}.

3) The frequency of the excursions in the records of Fig. 4 is seen to increase as the range to target becomes less. During pull-up, just before the end of the run (EOR), the frequency of spikes becomes very large indeed.

Discussion of the Observations

In relating the observations carried out in the data of Figs. 4 and 5 to wander of the aimpoint, it is clear that these data are not capable by themselves of proving either the existence, nonexistence, or magnitude of such a phenomenon. That is, there is no evidence in the figures as to exactly what point on the targets was the apparent source of radiation reflected from the targets. On the other hand, if the point from which the echo appears to originate should change suddenly, the data of the figures can indicate that change, though its true magnitude is not reliably reported if the change is sudden.

Consider first the spike e of Fig. 5. If the calibration were to be accepted at face value, that spike would indicate a sudden shift of about 1 deg in the location from which the target echo comes. The apparent range to the target at e is estimated at 590 m, which means the location of the echo source would have suddenly shifted a distance of $S = 590\pi/180 = 10.3$ m. Since the tank is only 3.6 m wide, in its rear aspect, one would have to conclude that this "wander," if it truly exists, cannot come from the tank, but from the terrain. The same conclusion is to be drawn from the angles of points g and f. To make this conclusion more graphic, Fig. 6 is shown. Here the solid lines mark maximum possible true wander of an aimpoint within the 12 ft width of the tank target of Fig. 6, during the 10.4-s duration of the run of that test. The angle is seen to increase, as one would expect, when the range becomes smaller, but the three features e, g, and f are well outside the anticipated limits. The excursions cannot be classified as any multipath phenomenon, because they appear to occur primarily in azimuth.

If one were to conclude from the data of Fig. 6 that aimpoint wander can be truly greater than the angle subtended by the target itself, then one must inquire why there are so few such excursions.

If one adopts a somewhat more realistic view of the actual operation of a tracker, the excursions e, g, and f of ϵ_{EL} in Fig. 5 are somewhat more plausibly rationalized. If the target were a corner reflector, in this case, it should be considered to act as a single steady source of microwave signal, showing no fluctuation in intensity as the test vehicle flies along the line of sight. Whatever wander there might be in a more complex target, none should appear here—unless, of course, the aimpoint wander actually comes from the terrain. Since, in the ϵ-records of Fig. 4, no spikes appear, one tends to conclude that no aimpoint wander does, in fact, originate from the terrain. In this conclusion, the phenomenon of multipath propagation has been deliberately ignored.

To explain the excursions in the ϵ-records of Fig. 5 one may recall that a complex target like a tank is well known to have a *radar* cross section that varies by large factors when small changes in angle of line-of-sight occur. The same can be anticipated in radiometry, as long as the *order* of interference from the target is small. That is, the features that cause the change in cross section are presumed to be flat areas and low-order interference between effective corners on the target. Furthermore, it must be postulated that some small changes in aspect angle occur during the closing flight. If the flight is presumed to be sufficiently unsteady due to aerodynamic buffeting or small random changes in direction, the echo intensity would be expected to change quite suddenly by large factors. How small such changes in aspect angle should be to account for the excursions is discussed in Appendix B. Two interfering features 3.6 m apart at a 610-m range would show

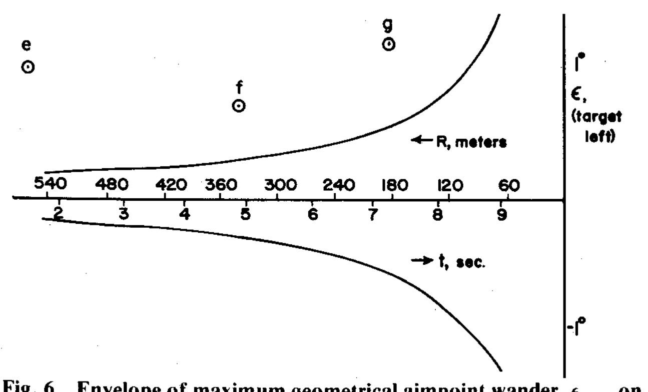

Fig. 6 Envelope of maximum geometrical aimpoint wander, ϵ_{AZ}, on 3.6 m wide tank target.

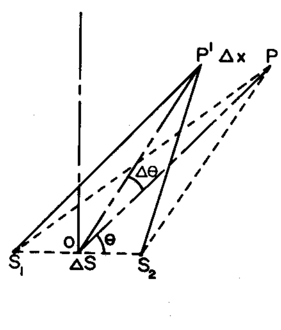

Fig. 7 Geometry leading to recurrent glint in a target simulated by two corner reflectors.

a shift from negative to positive interference with a lateral shift of a little over a foot.

In the event that the intensity of the target signal were to increase suddenly from whatever cause, the result would be a large error signal. This error signal would, of course, presently be reduced as the automatic gain control takes effect. But for a short time, any small angular error in pointing would be amplified by the intensity spike to produce a much magnified error signal. That is, a twitch in the aiming mechanism would be generated from the large error signal, and $\dot{\theta}$ would presently show a spike after the excursion in ϵ appeared. Furthermore, the motions in both planes would be affected, if by chance a small aiming error were present in one plane when the intensity excursion occurred in another.

The result of the motion of the seeker axis in response to the intensity spike in the input channel, would normally be an excursion in the ϵ-record in the direction opposite to the initial spike. In the Black Jack system, the AGC delay time is short enough that this excursion response appears to be already considerably reduced in amplitude: each spike in ϵ is seen, in Fig. 5, to be followed by a smaller but slower excursion in the reverse direction, quite in conformity with the anticipated behavior of the system.

The point has been made that significant intensity spikes in the tracker input channels are anticipated only if there is some lateral (or vertical) buffeting, or other departure of the flight path from the line of sight. It has also been pointed out that the tests analyzed here were made without a firm control of the homing flight path by the tracker, so that the postulated lateral displacements, if not directly observed, are at least plausibly concluded to exist. This conclusion is supported by the observation that if buffeting exists, the intensity excursions resulting therefrom should show increasing frequency as the range to the target decreases. Also when the pull-up is started at the end of the run, so that flight is no longer along the line of sight, any interference phenomenon in the vertical plane should generate very rapid excursions in the input channels. This prediction is also seen to be realized: the records of Fig. 5 show a buzz in all four channels ϵ and $\dot{\theta}$ during the pull-up. In contrast, the record of Fig. 4 for a corner cube shows only the relatively slow fluctuation ascribable to a failure to track the target precisely during the pull-up.

Conclusions as to the Aimpoint Wander Phenomenon

To summarize the analysis of this study, the following conclusions are drawn.

1) The apparent wander of the aimpoint of microwave trackers of the type considered here is too large to be ascribed to truly geometrical shifts in the origin of microwave echoes at a vehicular target.

2) The speculation that the presence of intensity spikes in the input, possibly due to a low-order interference phenomenon at the target, will account for all the features observed in a record of a flight test, is found to be supported in considerable detail by the data presently available.

3) The fact that a true wander of geometrical origin may also be found to exist is not questioned. It should appear at ranges less than 100 m, for microwave frequencies, and most targets.

4) It is suggested that the pattern of aimpoint wander over a given target may be found for a preselected approach maneuver to be a distinguishing feature for recognizing a target.

Appendix A: Glint in a Radiometer

In a radiometric receiver, the glint phenomenon, always present in a radar echo from the ground, is suppressed to some degree by use of a range of frequencies in the transmitted pulse. The glint in the radar return is ascribed to positive interference between different parts of the antenna footprint. If, for example, two areas within the antenna pattern return echoes from distances that are, say, S apart along the line of transmission, the two echoes will reinforce each other whenever $2S=n\lambda$, where n is any whole number, λ is the wavelength of the radar carrier wave, and the factor 2 comes in because the phase difference is due to the difference in distance traversed in transmission plus reflection. It is at once clear that the number of different values of S, for this example, which would produce glint may be large indeed, in the case of narrow-band radar, since if only a single wavelength λ is used, n may have nearly any value, up to several hundred.

When a spread in frequencies is used as in radiometric seekers, the situation is somewhat altered. Broadening the wavelength band used imposes some penalty on received signal intensity, because receiving circuitry cannot be as narrow-band and the gain of the IF amplifier is therefore impaired. However, if a longer settling time is used, glint is somewhat suppressed because the different wavelengths, produced at different times during transmission, produce interference effects only part of the time for each wavelength during the pulse duration. The average signal is effectively free of glint. It can be shown, however, that some glint may still remain in a radiometric signal, even when the spread in frequencies is used.

As an example, consider two echo signals S_i of equal unit intensity, originating from two locations on a complex target like a tank, so that the path difference between the two beams is S_d. If the two signals are superposed in the receiver, the resulting signal can be written

$$S_{1+2}=e^{j2\pi\nu t}+e^{j2\pi\nu(t-S_d/c)}=e^{j2\pi\nu t}(1+e^{-j2\pi\nu S_d/c}) \tag{A1}$$

The first factor on the right represents the variation with time of the carrier wave. It has a frequency ν of about 35 GHz for Ka-band radiometric seekers. The second factor can be written

$$1+e^{-j2\pi\nu S_d/c}=1+\cos 2\pi\nu S_d/c-j\sin 2\pi\nu S_d/c \tag{A2}$$

This quantity may be viewed as essentially the complex amplitude of the echo signal. Its magnitude is

$$|1+e^{-j2\pi\nu S_d/c}|=\sqrt{2+2\cos 2\pi\nu S_d/c}$$

which varies from a factor 2 when $2\pi\nu S_d/c=2n\pi$, to 0, when $2\pi\nu S_d/c=(2n-1)\pi$, where n is any whole number. Notice that c is the velocity of light. This is a typical interference phenomenon.

Suppose now that ν changes with time by use of a transmitter so "chirped" that the frequency changes from, say, 34.7 GHz to 35.3 GHz during the transmitted pulse duration of, say, 500 ns.

The received signal may be reasonably estimated as the integral over the pulselength, T, of the square of the signal strength S_{1+2}. That is,

$$I=\frac{I_0}{T}\int_0^{500\text{ ns}} S_{1+2}S^*_{1+2}\,\mathrm{d}t \tag{A3}$$

where S^* is the complex conjugate of S. That is,

$$I=I_0\int_0^T(1+e^{-j2\pi\nu S_d/c})(1+e^{+j2\pi\nu S_d/c})\frac{\mathrm{d}t}{T}$$

$$=\frac{2}{T}\int_0^T\left(1+\cos\frac{2\pi\nu S_d}{c}\right)\mathrm{d}t \tag{A4}$$

Now let the frequency be assumed to vary linearly with time from $\nu_0-\Delta\nu/2$ to $\nu_0+\Delta\nu/2$, where $\nu_0=35$ GHz, and

$\Delta\nu/2 = 0.3$ GHz, that is,

$$\nu = \nu_0 - \Delta\nu/2 + \Delta\nu \cdot t/2 \tag{A5}$$

We write $dt = (d\nu/\Delta\nu)\,T$, then

$$I = \frac{2I_0}{\Delta\nu}\int_{\nu_0-\Delta\nu/2}^{\nu_0+\Delta\nu/2}\left(1+\cos\frac{2\pi\nu S_d}{c}\right)d\nu$$

$$= \frac{2I_0}{\Delta\nu}\left[\nu + \frac{c}{2\pi S_d}\sin\frac{2\pi\nu S_d}{c}\right]_{\nu_0-\Delta\nu/2}^{\nu_0+\Delta\nu/2} \tag{A6}$$

That is,

$$I = 2I_0 + \frac{I_0 c}{\pi S_d \Delta\nu}\left(2\cos\frac{2\pi\nu S_d}{c}\sin\frac{\pi\Delta\nu S_d}{c}\right) \tag{A7}$$

Now notice that $\nu_0/c = 1/\lambda_0$. It is at once evident how I changes as a function of S_d. Thus consider S_d varying from 0 to several hundred mean wavelengths λ_0. At first, with S_d small, the value of I is nearly

$$I \doteq 2I_0(1+\cos 2\pi S_d/\lambda_0)$$

That is, I varies sinusoidally from 4 to 0, with a period S_d/λ_0—it goes through a maximum, back to 0, and again to a maximum each time S_d changes by λ_0, roughly 0.857 cm. As S_d becomes larger, the amplitude of the sinusoidal variation of I decreases. Thus

$$I = 2I_0\left|1+\left(\frac{\sin\pi\frac{\Delta\nu}{\nu_0},\frac{S_d}{\lambda_0}}{\pi\frac{\Delta\nu}{\nu_0}\frac{S_d}{\lambda_0}}\right)\cos 2\pi\frac{S_d}{\lambda_0}\right| \tag{A8}$$

Now $\Delta\nu/\nu_0 = 0.6/35$, so that the oscillations with S_d/λ_0 in I reduce to 0 at $S_d/\lambda_0 = \nu_0/\Delta\nu$, or $S_d = 35\,\lambda_0/0.6 = 58.3$ wavelengths, about a half meter. It might be noticed that the distance S_d is twice the distance between interfering elements in a real target, so that elements on a tank cannot interfere if the distance between them, along the line of sight, is greater than about 10 in. (¼ m). The amplitude, as shown in the equation builds up again to a weak maximum of 0.212 at $S_d = 87.5$ wavelengths. In other words, it is possible to have target signal intensities varying quite substantially in a manner that is the same as glint, even when a radiometric seeker is designed so as to reduce glint. The higher orders of interference are essentially eliminated above, say, 20 or so.

Figure 2 shows the manner of variation of the signal intensity with S_d/λ_0. It is clear from the figure that a chirped transmitter will in this fashion tend to reduce glint, but it will never altogether eliminate it. Even if the breadth of the frequency band used should be further increased, there will generally be, on a tank or other complex target, some flat surfaces or rounded smooth ones that will produce specular reflections—positive interferences of order 0—which will result in an echo cross section characterized by sharp spikes of high intensity in different directions, as a missile homes in on the target.

Notice that the presence of interference on the target echo will have the characteristic of changing rapidly by factors of orders of magnitude with small changes in aspect. Thus if two interfering elements like a pair of tail lights, were 3.6 m apart on the target, though nearly equidistant from the seeker, they would produce changes in signal strength from a maxium to zero with an aspect angle change of $\lambda_0/(4\times 3.6\times 100) = 0.00059$ rad. The factor 4 comes from the fact that the two elements are reflectors with changes of $\lambda/2$ for change from a maximum to a minimum. An approaching seeker need be buffeted laterally from line of sight only 0.36 m, at a 610-m range, to detect a signal going from 0 to a maximum, from these two interfering sources. As range decreases, the distance between maxima and minima also decrease in proportion to the range. Buffeting of the seeker carrier will accordingly cause a fluctuation in signal intensity that increases in frequency inversely with range to the target.

Appendix B: Interference Intensity Variations with Target Range

Consider a target as represented by a pair of corner reflectors ΔS apart. A maximum in the microwave echo intensity will be observed whenever the two distances to the seeker from the reflectors differ by a half wavelength, $\lambda/2$, where λ is the mean carrier wavelength. Such will be the case whenever the angle θ between the line of sight OP (see Fig. 7) and ΔS conforms to the condition

$$n\lambda = 2\Delta S\cos\theta \tag{B1}$$

subject only to the additional condition that the order n is small enough to permit interference, if the tracker uses a radiometer. This limitation confines the glint due to interference to corners separated by distances ΔS_L of the order n_L given by

$$\Delta S_L = n_L\lambda/(2\cos\theta) \tag{B2}$$

where n_L would be about 45, for the case of radiometer considered in Appendix A. For $\theta = 0$ deg, the largest value of ΔS which would permit interference would be, for Ka radiation, $\Delta S_L = 17$ cm. As θ approaches 90 deg, of course, ΔS_L could be any distance at all, as long as the illumination by microwaves from the seeker includes both elements.

What is of special interest in this connection is that the seeker will encounter the sudden increase in echo intensity many times as it approaches the target, if its flight permits a change in θ. Thus in tracking of a pair of corner reflectors 15 cm apart so that the order of interference is 30, then θ becomes 31 deg. Again where $n = 29$, $\theta = 34.1$ deg. If the line of flight were parallel to ΔS, the distance between successive signal maxima will be given in terms of the range R by

$$\frac{\Delta x}{R}\sin\left(\frac{34.05+31}{2}\right) = \frac{34.05-31}{180}\pi \tag{B3}$$

Thus if $R = 610$ m, $\Delta x = 3.05\times\pi\times 610/180 \sin 32.5$ deg $= 60$ m. Here Δx is the distance traveled by the tracker between signal interference maxima. At 61 m, the distance Δx becomes less by a factor 10. The frequency of the excursions, for flight at 60 m/s, would be 1/s at the longer range, and 10/s at the shorter range.

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