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THE TALOS GUIDANCE SYSTEM

The Talos guidance system evolved from a series of development efforts within the Bumblebee and Talos programs — specifically, the first beamriding system and the first semiactive interferometer homing system. The guidance system that evolved was virtually unjammable, and it provided the missile with capabilities against manned aircraft, antiship missiles, surface ships and boats, and radar targets.

INTRODUCTION

When the Bumblebee Program was conceived, missile guidance technology was in its infancy. The early guidance development work was based on pulse radar technology since pulse radars were well developed by 1945. The first guidance concept was that a radar beam, following the target, could be used to guide the missile to the target. It was determined early, however, that the maximum allowable miss distance could not be achieved by such a "beamriding" system at ranges beyond approximately 10 nautical miles. When the target intercept range for the missile was increased, the guidance concept was revised to use beamriding for the midcourse phase with semiactive homing for the terminal phase. This resulted in a guidance system that produced very small miss distances, essentially independent of intercept range. During the later Talos years, the major guidance effort was focused on the homing system. This effort resulted in a monopulse homing system that was virtually unjammable and an antiradiation missile seeker that enabled the missile to home on radar targets.

MIDCOURSE GUIDANCE

In a beamriding system, departure of the missile from the axis of a conically scanned radar beam causes deflection of the aerodynamic surfaces to return the missile to the beam axis. Basically, the missile must determine the vector that indicates the angular direction and distance to the scan axis. The distance is determined by observing the amplitude of the modulation produced by the conically scanned beam, and the angular direction is determined by the phase of the amplitude modulation with respect to the scan frequency reference signal.

The beamriding system for Talos was the result of a joint effort by APL and Farnsworth Television and Radio Corp. It employed a conically scanned radar beam (Fig. 1) and, together with a sinusoidal variation of the pulse repetition frequency, provided the missile-borne receiver with the signals needed to measure missile angular distance and direction perpendicular to the nutation axis of the guidance beam (Fig. 2). The missile was roll stabilized in flight by a free gyro so that the error signals would be directed to the proper aerodynamic steering surface.

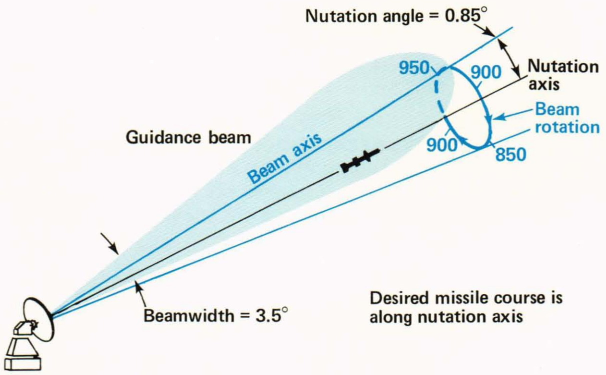

Figure 1 — The guidance beam for the beamrider missile was conically scanned at 30 hertz with a clockwise rotation, as viewed from behind the radar antenna. The radar pulse rate, nominally 900 pulses per second, was varied by ±50 pulses per second in synchronism with the conical scan.

The guidance transmitter radiated pulse groups at a nominal rate of 900 pulses per second. Each group consisted of three pulses that were coded by interpulse timing to identify the guidance beam to the missile. Nutation position information was transmitted by frequency modulating the pulse group rate at the nutation frequency (30 hertz) with a deviation of ±50 groups per second. The maximum pulse group rate occurred for a nutation position that was up and left. On board a ship, an inertial system was required to compensate the pulse group modulation for roll and pitch.

A simplified block diagram of the beamrider receiver is shown in Fig. 3. Microwave pulses were detected and passed through a decoder to produce one pulse for each valid code group. The decoded pulses were then applied to a 30-hertz amplitude detector, a 30-hertz frequency modulation detector, and a beacon transmitter. Outputs from the frequency modulation detector were used as references for the

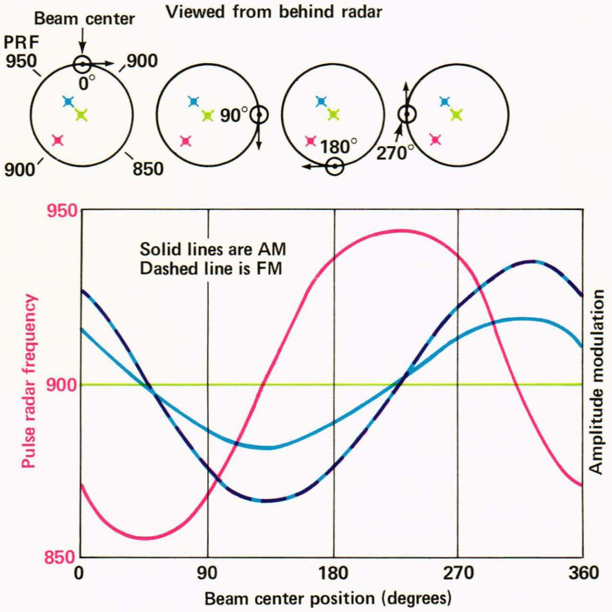

Figure 2 — Signal modulations detected by the beamriding receiver were processed to determine missile position with respect to the guidance beam. Angular direction and distance from the scan axis were determined by comparing the phase and amplitude of the 30-hertz amplitude-modulated signal with the frequency-modulated reference signals.

steering channel phase comparators. The phase comparators were used to resolve the in-phase component of the amplitude modulation detector output to obtain steering-error signals for each wing plane.

As a flight progressed, the direction of the guidance beam was programmed by the fire-control computer to cause the missile to fly the desired midcourse trajectory. Missile range was determined by automatically range tracking the missile-borne beacon pulses. That range was used by the fire-control computers to control the beam program and compute the time at which a homing enable pulse code was transmitted to the missile, permitting target acquisition by the homing system.

Subsonic beamriding along a fixed beam was accomplished by a guidance test vehicle in January 1947. The first supersonic beamriding Talos was demonstrated in 1950.

TERMINAL GUIDANCE

A terminal-guidance phase following the midcourse beamriding phase had been envisioned from almost the beginning of the development program. The task was to devise a homing system that would be compatible with the constraints imposed by the ramjet diffuser and that would rapidly acquire the target without requiring accurate missile-to-target line-of-sight positioning information. The goal of intercepting small targets at long range (about 100 nautical miles) placed a premium on high receiver sensitivity as well as on good target resolution.

The interferometer homing system was chosen for terminal guidance for the following reasons:

1. Widely spaced body-fixed antennas were compatible with ramjet inlet constraints.
2. The body-fixed antennas were simple compared with a gimballed dish antenna.
3. Rapid target acquisition was possible without the need for missile-to-target angle data.
4. It was desired to have the largest possible aperture and, hence, the most accurate measurement of the line-of-sight angular rate.

The basic principle of the interferometer system is illustrated in Fig. 4. Two widely spaced antenna elements of an interferometer have a composite antenna pattern consisting of a series of peaks and nulls. The peaks and nulls are moved by a phase shifter, resulting in amplitude modulation of the target signal. A discriminator tuned to this modulation frequency provides an output that is proportional to the angular rate of the target line of sight. If the target line-of-sight rate with respect to an inertial reference is maintained at zero, a proportional navigation homing trajectory to the target is executed. It is therefore only necessary to control the missile turning rate so that the line-of-sight rate is maintained at zero to effect an intercept.

THE FIRST TALOS HOMING SYSTEM

Guidance concepts consisting of body-fixed, widely spaced antennas to be used as a radar interferometer were proposed almost simultaneously by the Defense Research Laboratory (DRL) of the University of Texas and the Massachusetts Institute of Technology. Both concepts used widely spaced antennas but different methods of signal processing. Because the basic system proposed by DRL (which employed an independent interferometer channel for each wing-control plane) was judged to be more consistent with the state of the art, the first Talos homing system was based on that concept.

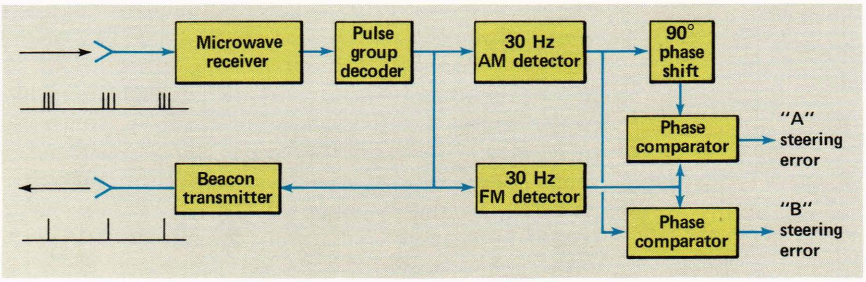

Figure 3 — The beamrider receiver detected and processed guidance beam signals to generate commands for the missile control planes and the radar beacon responses.

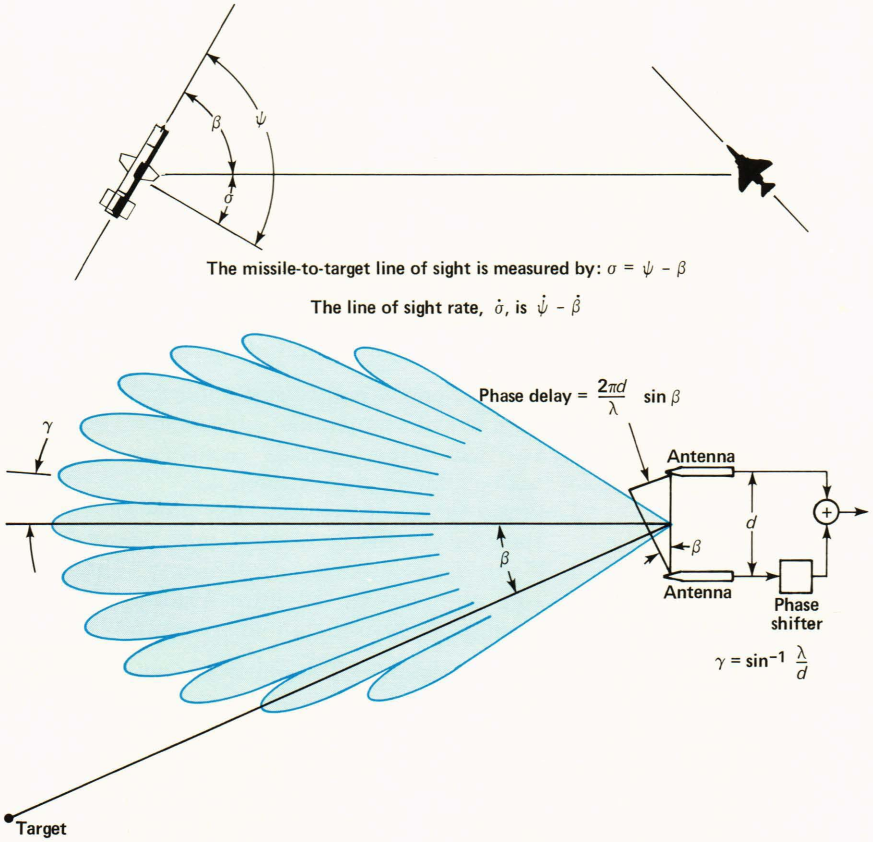

Figure 4 — Interferometer parameters and symbols used in the article are defined in this figure.

The receiver (Fig. 5) used a scanning interferometer system. Target signals at the antenna were:

$$\begin{aligned} X_1 &= A_1 \sin \omega t \\ X_2 &= A_2 \sin (\omega t + \theta) \qquad (1) \\ &= A_2 \sin \left(\omega t + 2 \frac{\pi d}{\lambda} \sin \beta \right) , \end{aligned}$$

where ω is the microwave frequency and θ is the electrical phase difference at the antennas. A_1 and A_2 are the amplitudes, which may be different, but the scanning process was essentially insensitive to that difference. The scanning phase shifter advanced the phase of X_2 by $\Phi(t)$ as follows:

$$\Phi(t) = \omega_S t + \Phi , \qquad (2)$$

where ω_S is the scan frequency and Φ is the initial phase shift. The X_3 can be written as

$$X_3 = A_2 \sin \left[\left(\omega + \omega_S + 2 \frac{\pi d}{\lambda} \dot{\beta} \cos \beta \right) t + \Phi \right] . \qquad (3)$$

The addition of X_3 and X_1 gives X_4:

$$\begin{aligned} X_4 &= A_1 \sin \omega t \\ &\quad + A_2 \sin \left[\left(\omega + \omega_S + 2 \frac{\pi d}{\lambda} \dot{\beta} \cos \beta \right) t + \Phi \right] . \qquad (4) \end{aligned}$$

X_4 can be seen to be a carrier signal at ω and is amplitude modulated at

$$\omega_S + 2 \frac{\pi d}{\lambda} \dot{\beta} \cos \beta . \qquad (5)$$

The heterodyne process in the receiver changed the carrier from microwave to a lower frequency but did not affect the modulation and, therefore, did not change the basic $\dot{\beta}$ information. It is also apparent that because the desired information was the frequency of the modulation, changes in amplitude of the signal had no direct effect upon the measurement of $\dot{\beta}$. Decoupling of body motion to provide the line-of-sight rate measurement ($\dot{\sigma}$) was accomplished by use of a body-mounted rate gyroscope where the gyro output frequency modulated an oscillator to produce a carrier frequency (ω_0) with a deviation proportional to the missile body turning rate ($\dot{\psi}$). The term N in the gyro channel was an estimate of cos β. A fixed value of N for all flight conditions proved to be unsatisfactory. Therefore, Talos had a selection of two values based upon the crossing component of the target speed. That value was set into the missile at the time of launch. Double modulation eliminated the scan-

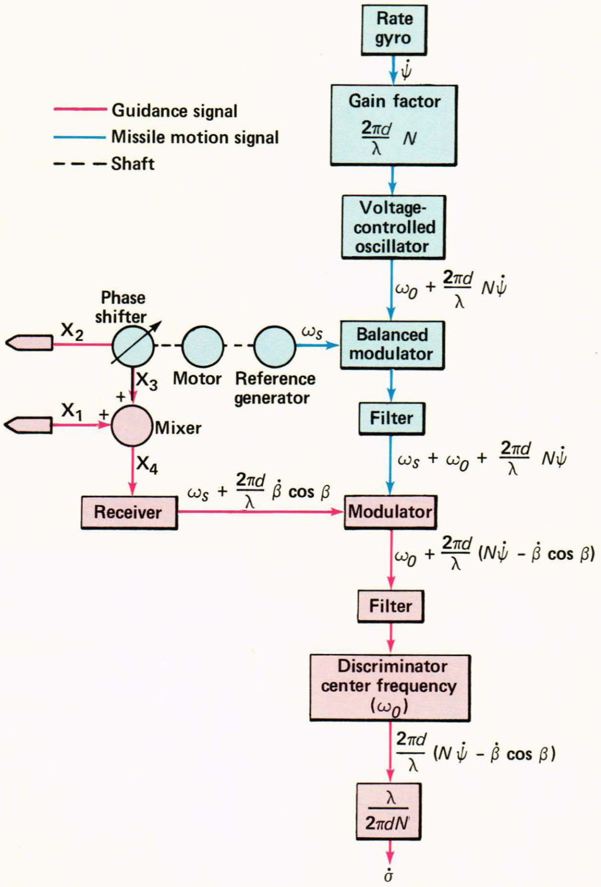

Figure 5 — The first Talos homing receiver (1950) used a scanning interferometer. The system shown here was for a single control plane. An identical system was used for the orthogonal control plane. Output from a body-mounted rate gyro was used to decouple the effect of body motion on the interferometer signals. The term N was an estimate of cos β. The output from the discriminator was a signal proportional to $\dot{\sigma}$.

phase shifter frequency (ω_S) from the final term and allowed a frequency discriminator tuned to ω_0 to provide an output that was proportional to $(2\pi d/\lambda)$ $(N\dot{\psi} - \dot{\beta} \cos \beta)$. The discriminator output, neglecting biases, was approximately proportional to the desired $\dot{\sigma}$. This form of signal processing was used in a number of test flights and for the first Talos production receiver.

STABLE PLATFORM PHASE FOLLOW-UP SYSTEM

Two major problems associated with the first Talos homing system were the following:

1. A bias resulted from any offset between the voltage-controlled oscillator and the discriminator center frequency,
2. A stable gyro gain factor equal to $(2\pi d/\lambda)N$ was difficult to maintain.

Both problems were solved by the Stable Platform Phase Follow-Up System (STAPFUS).

The scanning interferometer using STAPFUS is shown in Fig. 6. As before, a motor drove the phase shifter and a reference generator. A single-degree-of-freedom free gyro was coupled to a synchro-resolver to make phase corrections for missile body motion. The gear ratio between the gyro and resolver provided a constant gain factor for the gyro coupling. The difference in phase between the reference signal and the interferometer signal was obtained by the rotor shaft position in a phase-following servo. A potentiometer driven by the phase servo provided an output that, when differentiated, was a measure of the desired line-of-sight rate. Differentiation after the phase-subtraction process eliminated bias. A simple initializing circuit was provided to ensure that the potentiometer started at the zero position. There was no inherent bias in the system because the source of the bias had been eliminated.

Shortly after the incorporation of STAPFUS into the missile system, it was realized that a phase detection of the two signals driving the phase servo could provide an excellent indication of the presence of a signal suitable for steering, especially in a home-on-jammer mode. For this reason, a phase detector was eventually included in a major receiver design program to support home-on-jammer operations.

STAPFUS proved to be an extremely precise measurement system; after it was incorporated into the Talos missile, the majority of the intercepts resulted in direct hits (Fig. 7).

DEVELOPMENT OF THE CONTINUOUS WAVE INTERFEROMETER HOMING SYSTEM

During the 1950's, the microwave pulse-interferometer homing system was developed, and capability against medium-to-high-altitude targets was successfully demonstrated. During that period, the application of Talos to low-altitude targets, particularly over land, was being explored. In that situation, the target-tracking radar, operating at low elevation angles, illuminated the earth's surface and resulted in a large clutter signal that obscured the target (Fig. 8).

The technique developed in the Talos Program to permit low-altitude operation made use of the familiar Doppler effect. Because of the incoming target's velocity, its reflected radar signal is slightly higher in frequency than is the return from the clutter, which is stationary. This frequency separation is the unique signal characteristic that permits rejection of the undesired clutter signals. Tracking the target Doppler signal with a narrow bandpass filter effectively eliminates the massive clutter signals. A typical spectrum of the Doppler signals received by the missile in flight is shown in Fig. 9.

Attention was first given to the excellent work by Raytheon on the Lark (DPN-15) and the Sparrow (DPN-24) homing systems. The initial work on the continuous wave (CW) interferometer for Talos used much of the circuit design of those systems. Six flight

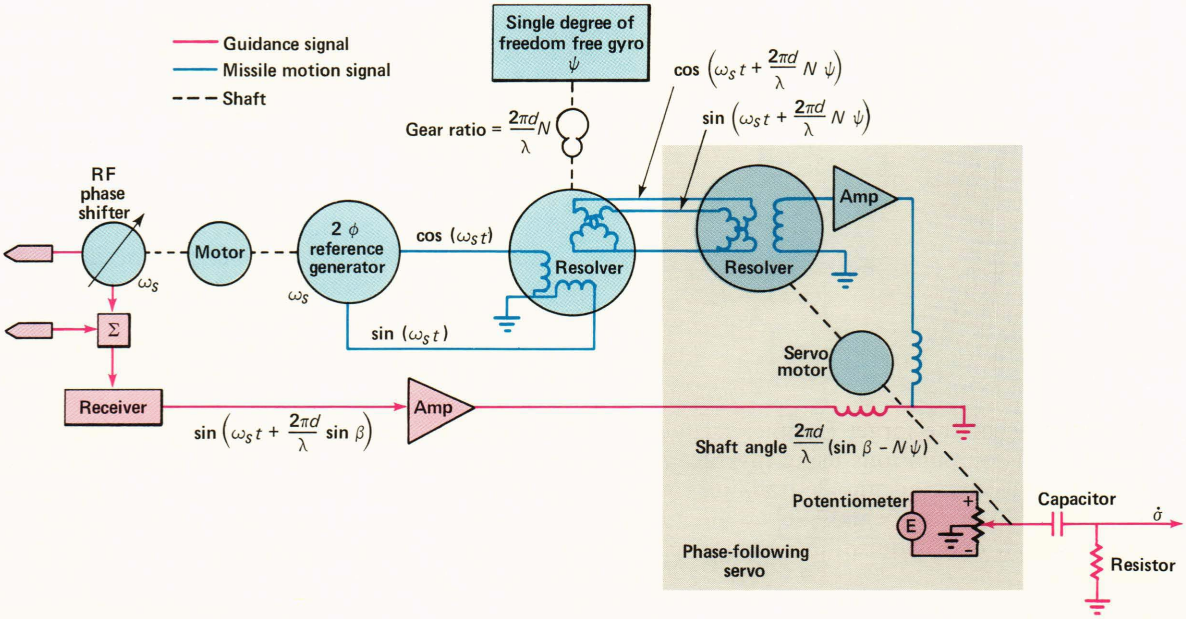

Figure 6 — STAPFUS was a more precise method for decoupling body motion from the scanning-interferometer output. The figure shows a single control channel. A synchro-resolver mechanically coupled to a free gyro (stable platform) was used to shift the phase of the reference generator. A phase-following servo positioned the resolver shaft at an angle that corresponded to $(2\pi d/\lambda)(\sin \beta - N\psi)$. That shaft was also coupled to the arm of a potentiometer. The output from the potentiometer was differentiated by a resistor-capacitor network and resulted in a signal proportional to $\dot{\sigma}$.

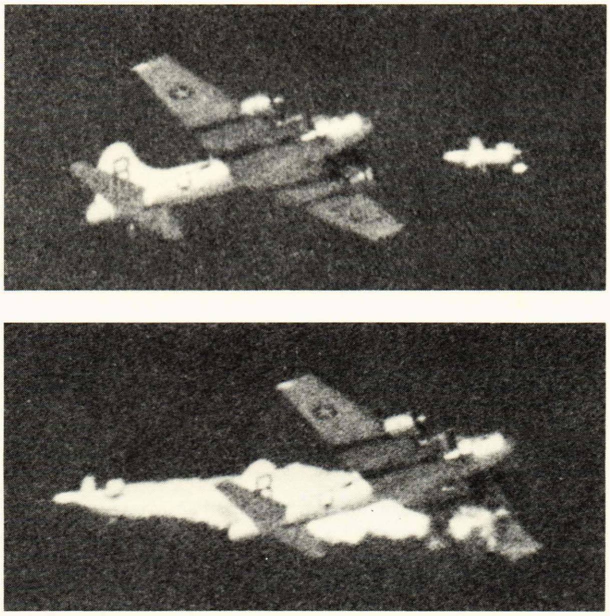

Figure 7 — Miss distances were reduced significantly following the introduction of STAPFUS. The B-17 target shown in this figure was destroyed by a direct hit. The warhead was not used in this test.

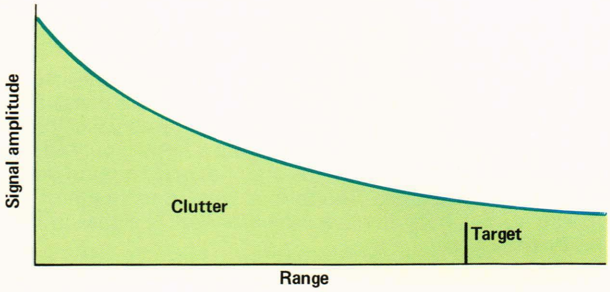

Figure 8 — Pulse radar signals from a moving target can be obscured by large, stationary reflecting surfaces such as the sea or land masses.

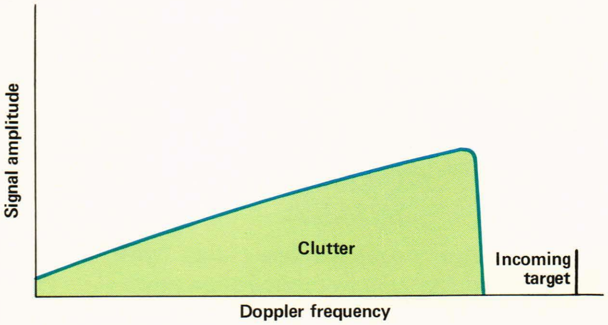

Figure 9 — Continuous wave (CW) radar signals from a moving target can be detected by filtering at the Doppler frequency.

tests were made during 1955-56 using the Sparrow homing-system design but modified for an interferometer antenna system. These tests revealed or confirmed the existence of characteristics that would need to be significantly improved to meet the goals set for the Talos homing system.

The Talos CW homing receiver was designed around the following features:

1. The superheterodyne receiver used quartz-crystal filters to establish a stable and narrow

bandpass that would remove the clutter signals from the target signal.

2. The klystron local oscillator, used in the conversion of the microwave input signals to an intermediate frequency, was controlled by phase-locking the klystron to the illuminator signal from the fire-control radar. That was essential if the target signal was to be kept within the narrow passband (100-hertz bandwidth) of the receiver. The phase-lock loop also provided a convenient way to offset the klystron frequency for automatic tracking of the target Doppler signal.
3. A prediction of the target Doppler frequency, based upon computations using measurements from the target- and missile-tracking radars, was transmitted to the missile to aid in the target search and acquisition function of the receiver. This feature reduced the initial Doppler search bandwidth from 50 kilohertz to 3.5 kilohertz and provided target acquisition in less than 2 seconds in most cases.
4. The solid-state circuit design provided low package volume, stability of adjustment, and immunity to vibration and shock.
5. The missile-to-target angle-measuring system of the interferometer was retained because of its precision and other advantages for the Talos ramjet configuration.

With the timely availability of cavity-stabilized, high-power (1 to 5 kilowatts) klystron amplifiers for the CW radar illuminator, the missile could operate against small aircraft at a range of 100 nautical miles, which coincided with the improved range of the ramjet at that time.

Figure 10 is a block diagram of the phase-locked klystron loop and the ground-aided acquisition loop. The klystron was electrically pretuned prior to launch to the approximate frequency of the illuminator. Automatic frequency control pull-in occurred at the time the ship-based CW illuminator began radiating, about 15 seconds before intercept. The target Doppler frequency, f_D, was computed using radar data and transmitted to the missile by a 400-kilohertz plus f_D frequency modulation on the illuminator frequency. That estimate of the Doppler was used in the ground-aided acquisition loop to establish the initial frequency for the voltage-controlled oscillator. In that way, the klystron frequency was very close to the correct value, and only a minimal search was required to acquire the target.

Figure 11 includes the front receiver with its narrowband quartz crystal filters and discriminators, and the Doppler tracking loop. The loop served to control the voltage-controlled oscillator and, therefore, the klystron in order to keep the target signal in the center of the receiver's narrow bandpass. As long as tracking of the target Doppler signal was maintained, the interferometer angle data could be processed by the STAPFUS system to steer the missile.

The SAM-N-6c1 Missile with its CW homing receiver had some fundamental characteristics that contributed to the missile's capabilities in a countermeasures environment. First, there was limited exposure to the hostile environment as a result of the narrowband characteristics of the seeker and the short (6 to 10 second) homing time. Second, the high-speed phase-tracking loop in STAPFUS provided a nominal angle-tracking sensitivity (volts per degree per second) when it was tracking, independent of the signal-to-noise ratio. Finally, inherent in the Talos phase-interferometer angle processing was the capability to resolve signals from two or more separate sources (for example, from multiple noise jammers) if there was a small power difference (≥ 2 dB) between them.

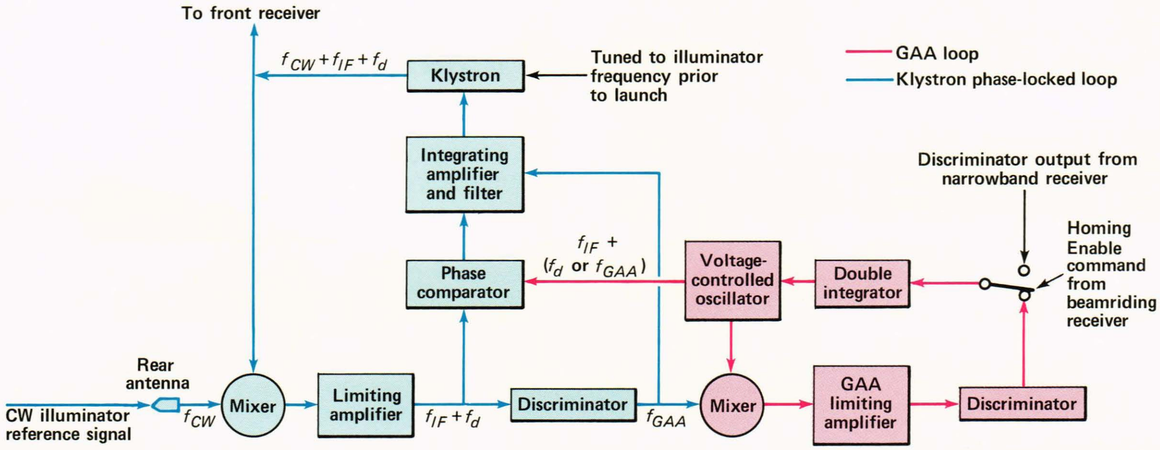

Figure 10 — The rear reference receiver used a phase-locked klystron and a ground-aided acquisition (GAA) loop. The klystron frequency was coarsely corrected by the discriminator to the frequency of the illuminator signal, followed by exact frequency control by the phase-locked loop. The voltage-controlled oscillator frequency was offset from the intermediate frequency by the f_{GAA} loop and caused the klystron frequency to be offset precisely for the target signal entering the front receiver (see Fig. 11).

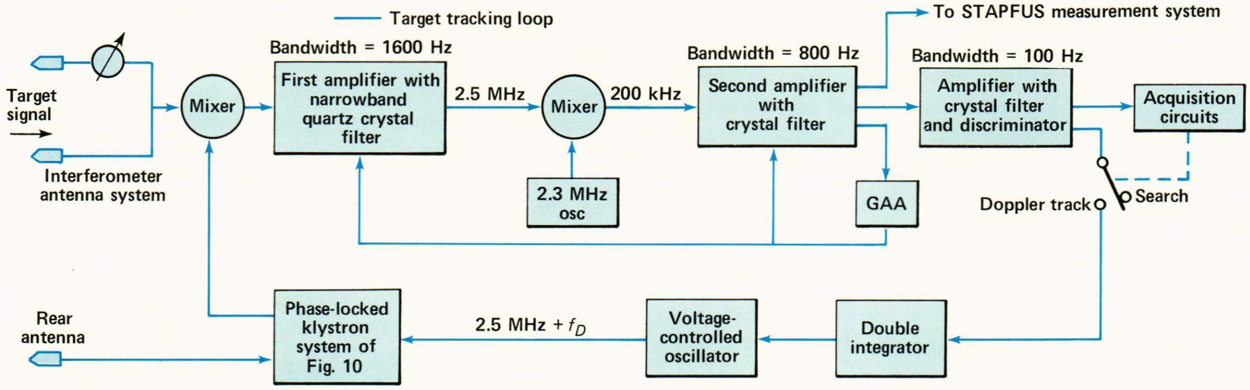

Figure 11 — A target signal having a Doppler frequency equal to f_{GAA} would pass through the amplifiers and narrow-bandpass quartz crystal filters and be detected by the acquisition circuit. Upon detection, the discriminator output readjusted the frequency of the voltage-controlled oscillator to keep the target signal in the center of the receiver bandpass. The narrow-bandpass filters removed the land and sea clutter signals entering the antennas.

As the flight test program proceeded, it became of interest to determine if the CW guidance system would perform well against surface targets. In this application, the target signal and the sea clutter signals do not have a useful Doppler frequency separation. But the combination of the 800-hertz and 100-hertz filter bandwidths maintained a signal-to-clutter ratio suitable for guidance. Figure 12 shows the massive destruction of a destroyer escort vessel as the result of a direct hit by a Talos missile.

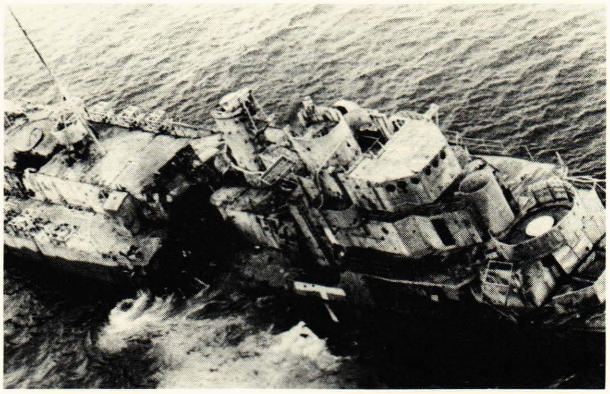

Figure 12 — Talos with the CW interferometer guidance had an inherent capability against surface ships and boats. The capability to engage these targets at ranges well beyond the radar horizon and in the presence of extensive land clutter required only minor changes to the missile and to the shipboard fire control system. The missile for this intercept did not have an active warhead.

MONOPULSE* HOMING SYSTEM

The original SAM-N-6c1 Missile performed extremely well against many types of jamming — its capabilities far exceeded those of any other missile of its day. However, its RF sequential lobing (scanning) angle processing, its slow automatic gain control, and its time-consuming Doppler search routines limited its capabilities against some types of deception countermeasures.

One of the principal objectives of the monopulse seeker design was to enable the missile to win any one-on-one encounter with an aircraft employing any conceivable AM and/or FM noise or deception jamming, even if the designer of the jammer had full knowledge of the Talos guidance system. By the mid-1960's, a seeker emerged that was virtually unjammable by an attacking aircraft. However, the system was not introduced to the Fleet until 1971 because of the high-priority antiradiation missile effort.

Two different monopulse receiver concepts were initially examined. APL examined the concept that took the intermediate frequency (IF) signals associated with antenna pairs and, after the narrowband filtering, multiplexed them into a common IF. Meanwhile, Bendix pursued the idea of the parallel channel, that is, two IF's in parallel for each guidance plane. With the solid-state technology that existed in the early 1960's, the parallel-channel concept became the most attractive: it lent itself to the use of hard-limiting IF's (no automatic gain control; phase tracking appeared satisfactory; the four IF's could be packaged within the same volume occupied by the two IF's in the original CW homer; and it would provide a simpler design than would be possible with a multiplex receiver.

One requirement for the Talos monopulse seeker was that it be compatible with the existing STAPFUS. STAPFUS, as discussed earlier, required a scan reference (ω_S) and a scan ($\omega_S + (2\pi d/\lambda) \sin \beta$) signal. As illustrated in Fig. 13, the Talos monopulse receiver was designed to provide those two signals. The receiver can be likened to the scanning receiver, with the exception that a pseudo scan was introduced at IF following narrowband filtering. That was accomplished by offsetting the frequencies of the second IF amplifiers by an amount equal to the pseudo scan. To ensure that the pseudo scan would not be vulnerable to electronic countermeasures (ECM), the scan

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*The word "monopulse" is often used to describe a missile guidance system that employs simultaneous lobe comparison and may or may not employ pulses. For Talos monopulse, the signals were CW.

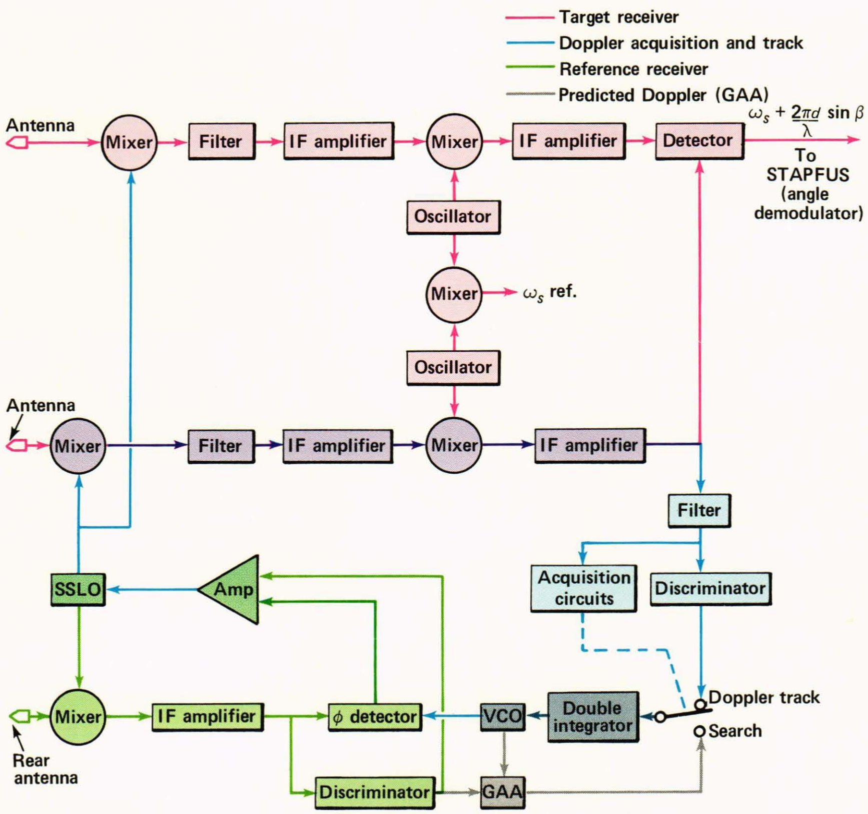

Figure 13 — The monopulse seeker was a refinement of the original CW seeker. The target and/or jammer signals were processed through a two-channel receiver (per guidance plane). Narrowbanding occurred almost immediately following the microwave mixers. The intermediate frequency (IF) amplifiers were hard limited on receiver noise. The Doppler tracking loop was closed through the microwave local oscillator and the first mixer. Predicted Doppler information provided by the ship was used to aid target search. The home-on-jamming mode employed the same narrow bandwidth and angle processing circuits used for tracking the target echo.

reference was chosen to be greater than the bandwidth of the narrow input filters. There was also a conversion of the scan signals and the scan reference signals to the lower frequency signals required by STAPFUS.

The Doppler search routines in the original CW seeker were deficient in that target reacquisition was slow or in some cases could be prevented entirely. Two contributing characteristics were the relatively slow sweep-repetition rate and the total reliance on memory for positioning the sweep. The original search patterns had been designed to provide a high first-look acquisition probability under minimum-signal-level conditions. That limited the maximum search speed that, in turn, was in conflict with the electronic counter-countermeasures requirement for fast reacquisition. Reacquisition must be fast since a jammer can cause the seeker to lose acquisition repeatedly throughout the homing phase. A compromise was sought for the monopulse seeker wherein the sweep speed was increased to a point where the single-look probability for the small signal case was lower than before but, after a second or two, was comparable because of the increased number of looks. Late in the homing phase, when the target signal-to-noise ratio was relatively high, the probability of single-look acquisition was essentially unity and, thus, the desired fast reacquisition was achieved. The problem of positioning the Doppler search center was alleviated by using the predicted Doppler information provided by the ship during the homing phase. The new search routines ensured continuous STAPFUS angle tracking under virtually all conceivable electronic countermeasures conditions and made the system far more tolerant of Doppler prediction errors.

The control of critical guidance functions was based on the coherency of the angle data. That provided a way to resolve a signal emanating from essentially a point source forward of the missile (target skin echo or a jammer) from other signals such as sea clutter, scattered chaff, receiver noise, and so on. There was no need for a detector dedicated to the home-on-jammer (HOJ) mode. The only circuit dedicated to HOJ was the HOJ timer, which delayed guidance switchover from midcourse to homing in cases where acquisition of the target echo was not achieved immediately. That was to prevent immediate HOJ on a standoff jammer. The guidance control logic is shown in Fig. 14.

TESTS OF THE CW AND MONOPULSE HOMING SYSTEM

Extensive laboratory testing of the CW and monopulse homing systems was conducted by the countermeasures group at the Naval Ordnance Laboratory, Corona, Calif. The results of that evaluation provided convincing evidence that the Talos missile with the monopulse seeker would be virtually undefeatable by any self-protection noise or deception jammer. Twenty-five of the 26 valid flight tests of the

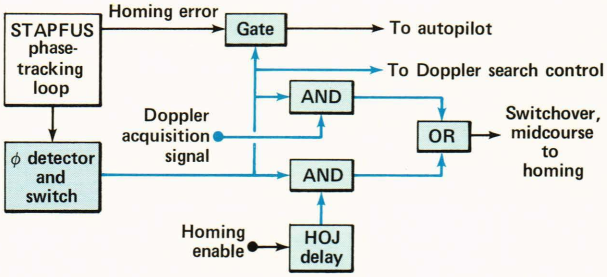

Figure 14 — Guidance-control logic used to implement guidance switchover from midcourse to homing, to gate the steering information once homing began, and to control Doppler-search routines was based on the coherency of the angle data. The signal used for that was obtained from a phase detector that monitored the STAPFUS phase-tracking loop.

Unified missile were successful. Of the 25, nine were with the monopulse seekers against a broad selection of electronic countermeasures types and parameters. Two of the successful tests were against multiple jammers, one of which is shown in Fig. 15.

An interesting observation can be made about how self-protection jamming affected the guidance accuracy (miss distance) of the Talos monopulse missile (see Fig. 16). Note that the Talos performance against the jamming targets was superior to that against the nonjamming targets. This is understandable when one recognizes that a jammer generally provides point-source enhancement of the target; that is, it literally provides a beacon that the missile can home on.

DEVELOPMENT OF MULTIMODE/ MULTIBAND HOJ SYSTEM

The long-range capabilities of Talos made it a desirable weapon to engage standoff jammers or to force them to remain at great distances. However, there was a guidance problem. If the Fleet's surveillance and fire control radars were jammed so as to deny good information about the location of the jammers and the jammers were indeed at long ranges, the midcourse guidance could not be programmed to put the missile close enough to the jamming aircraft for reliable semiactive homing.

The principal objective for the multimode multiband HOJ homing system was to enable the missile to home on jammers in S, C, and X bands. If the missile could home on one of the jammers, the midcourse guidance requirements could be relaxed. All of the semiactive and on-frequency HOJ capabilities of the monopulse homing system were to be retained. A secondary objective was to enable the missile to home on radars operating in those bands. Finally, the homing system had to be compatible with existing Talos missiles, with easy retrofitting possible. Changes to the midcourse guidance were also defined that would have extended the missile's range. Two complete guidance kits were fabricated, but the system was not introduced into the Fleet because of the planned deactivation of Talos.

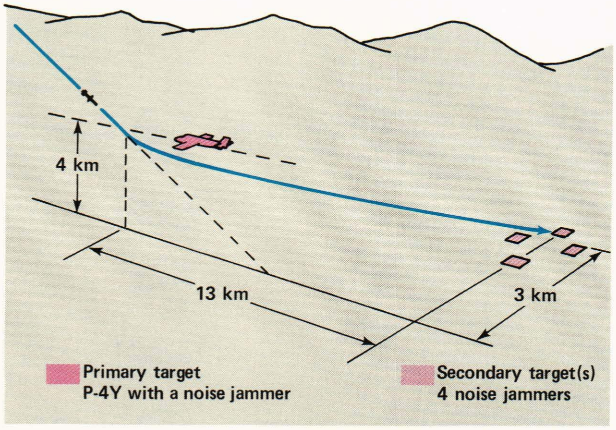

Figure 15 — Multiple jammer flight tests were conducted to demonstrate dichotomous angle-tracking capabilities inherent in the Talos interferometer guidance system. Briefly, if signals from multiple sources were present simultaneously, the missile would track one of them if a power differential of 2 decibels or greater existed within the narrow bandwidth of the receiver. In practice, the missile would nearly always intercept one of the targets. For the multiple jammer test illustrated here, the primary target was a P-4Y aircraft with a noise jammer. After achieving a near miss on the aircraft, the missile successfully intercepted the westernmost jammer on the ground.

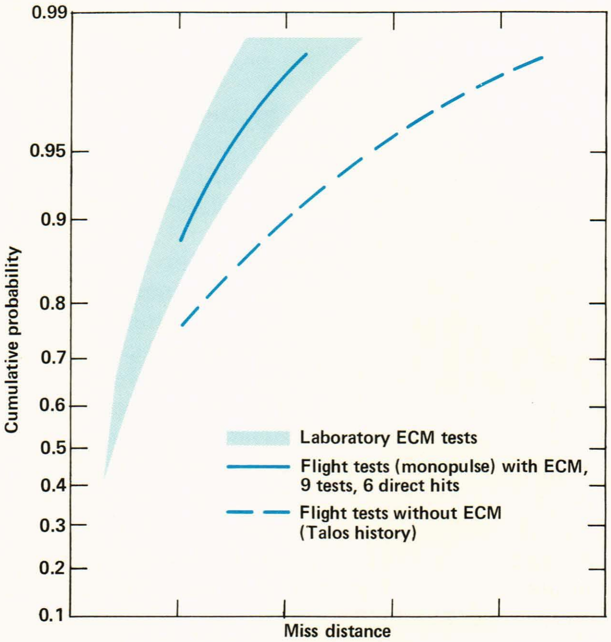

Figure 16 — The effect of self-protection electronic countermeasures (ECM) on miss distance is illustrated. The curves were derived from miss distance data obtained from laboratory ECM tests conducted at the Naval Ordnance Laboratory, Corona, Calif., from the monopulse flight tests against jamming targets, and from historic test data of Talos flight tests against nonjamming targets. Note that the performance against the jamming targets was superior to that against the nonjamming targets.

A simplified block diagram of the homing system is shown in Fig. 17. The basic system was the semiactive monopulse seeker. The principal modifications

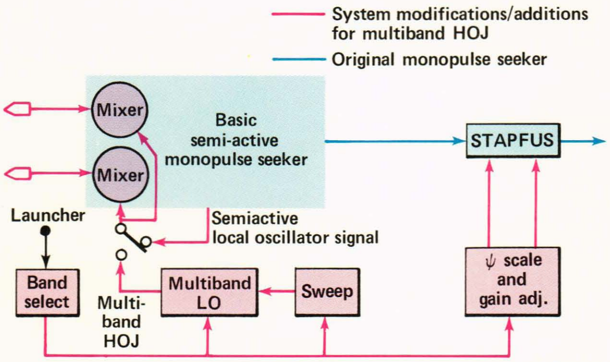

Figure 17 — The multiband HOJ system was basically an expansion of the semiactive monopulse homing system. The microwave portions of the original system were changed to provide the desired wideband operation. Frequency selection (typically 30 or 200 megahertz bandwidth) was by digital message prior to launch. Conventional semiactive homing could be activated in flight.

involved new, wideband antennas and microwave mixers and the addition of a wideband local oscillator. (The original local oscillator was used for semiactive homing.) A missile body motion ($\dot{\psi}$) and guidance gain scaler was added to adjust for the sensitivity of the interferometer to wavelength (frequency).

The multiband HOJ design was based on the simple concept that if the narrow Doppler filters of the semiactive system were excited by an intermittent signal (blinking ECM or pulse radar) at a sufficiently high rate, the output of the filters would be uninterrupted CW signals from which excellent angle information could be obtained. To ensure that the target signal could excite the Doppler filters without having to resort to the complexities of additional target recognition, acquisition, and automatic frequency control tracking circuits, the microwave local oscillator was swept at an appropriate rate over the RF band of interest. The result was a wideband seeker, the bandwidth of which was determined by the extent of the local oscillator sweep. Typically, the width of the band was either 30 or 200 megahertz. If multiple signals were present in the selected band, guidance favored the strongest signal.

The selection of the RF frequency for the multiband HOJ operation was accomplished via a digital message to the missile. Semiactive homing could be initiated in flight (if desired) in the same way as for a conventional antiair engagement.

Since it was assumed that the multiband HOJ feature would be used when target range was unknown, it was planned for the missile to fly at the fuel-conserving cruise altitude until seeker logic initiated homing. Homing always started at that altitude. For the engagement of a radar target (on land or a ship) at long range (over the horizon) but whose general location was known, a midcourse trajectory employing a terminal dive was used.

Flight hardware was fabricated, but there were no flight tests of the multimode/multiband HOJ system. In 1965, however, there were successful flight tests against radar targets at the White Sands Missile Range with Talos missiles using the same guidance concept as in the multiband HOJ system.

DEVELOPMENT OF ANTIRADIATION MISSILE GUIDANCE

Early in the Vietnam conflict, the need for an effective long-range antiradiation missile (ARM) to suppress enemy radars was evident. The Talos ARM program was authorized as a fast-reaction effort to respond to that need. The long-range capabilities and the ease with which the missile could be adapted for new missions made Talos a desirable choice for radar suppression. A feasibility demonstration flight test against an S-band radar target was successfully conducted at the White Sands Missile Range on October 26, 1965, only 35 days after initiation of the effort. Two additional guidance system designs subsequently were developed and flight tested, each progressively more sophisticated. The final design, first deployed on USS *Long Beach*, was completed in 24 months.

A unique operational concept had to be developed for ARM because it was not possible for the ship to track the target and implement missile guidance as it did for the engagement of air targets. For ARM, the target information consisting of geographic location and RF emission characteristics (frequency, pulse-repetition frequency etc.) was provided by appropriate techniques. Ship coordinates were established by means of several navigational techniques, including the Navy Navigation Satellite System. The ship then directed the missile to the vicinity of the target using the beamrider midcourse guidance. As the missile approached the target, the missile was put into a dive and the homing system was activated. Two different terminal geometries were used; one caused the missile to approach the target in an approximate 45° dive, while the other caused the missile to approach from a near-vertical dive.

The principal requirement for the ARM homing system was that it be monopulse, since the low pulse repetition frequency of some target radars was not compatible with the scan frequency used by the earlier semiactive seekers. Also, a system with a high sensitivity was desired that would provide continuous guidance on the low sidelobe levels from the target. Finally, the ARM guidance system had to be compatible with the existing Talos airframe. Modification of existing antiair warfare missiles to antiradiation missiles had to be accomplished by the relatively simple replacement of subsystem modules.

A simplified block diagram of the ARM seeker is presented in Fig. 18. The receiver used two parallel IF amplifiers (per guidance plane) with subsequent in-phase and quadrature processing. A very large instantaneous dynamic range (greater than 120 dB) was achieved by using limiting amplifiers. The differential phase shift between these amplifiers was maintained at a low level by careful attention to circuit design. Good phase tracking was attained with input peak power levels greater than 10 watts.

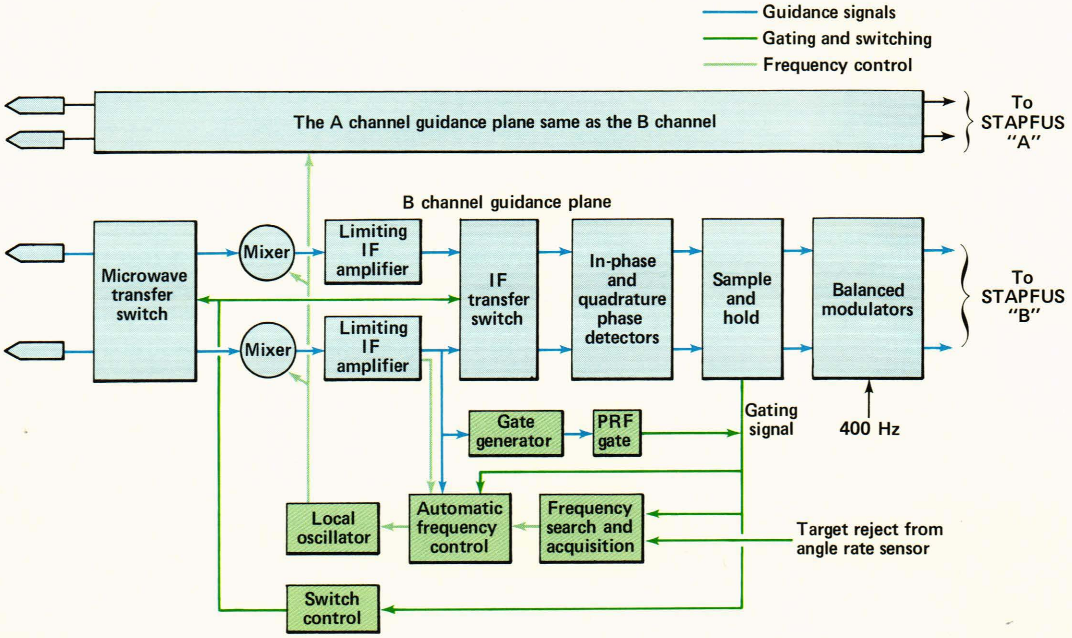

Figure 18 — The Talos Antiradiation Missile (ARM) seeker used two parallel IF amplifiers per guidance plane with subsequent in-phase and quadrature processing. A signal that satisfied the prelaunch frequency and pulse repetition frequency requirements provided the gating signal to the angle channel.

Against very-low-frequency targets (L band), the guidance error associated with as much as 10 electrical degrees differential phase shift between the receiver channels was undesirable. The error was virtually eliminated with the addition of microwave and IF transfer switches that, on a pulse-to-pulse basis, would allow radar pulses to be processed alternately through one channel and then the other. The internally generated errors would then average zero. The measured angle error arising from differential phase shift as a function of signal power level is shown in Fig. 19. The errors with and without the transfer switches operating may be seen.

In parallel with the angle channels was the acquisition and discrimination channel. The receiver was self-gating. A signal that satisfied the radiation and pulse repetition frequency requirements designated at launch would provide a gate to the angle channel. The seeker was able to discriminate between two signals if their operating frequencies differed by 3 megahertz or more. Leading-edge gating was used to minimize the effects of multipath reflections near the target. The angle phase-comparator outputs were multiplied by a 400-hertz signal to provide an amplitude-modulated signal to drive the STAPFUS resolvers.

Geometric discrimination was obtained by the seeker measuring the line-of-sight rate to the target at the time of target acquisition. The ship, via the midcourse beamriding guidance, caused the missile to dive toward a point that was approximately 4 miles beyond the intended target. This resulted in a missile-to-target line-of-sight rate that was in the down direction. If that downward angular rate was not detected during the target acquisition process, the signal was rejected and the seeker continued to search for another target. If the target was accepted, the missile executed a down maneuver to the target. That also enabled the missile to intercept the target at an elevation angle of approximately 90°.

Missile flight tests verified the unique design by exercising the various discriminants. Guidance accuracy was demonstrated with many direct hits (Fig. 20).

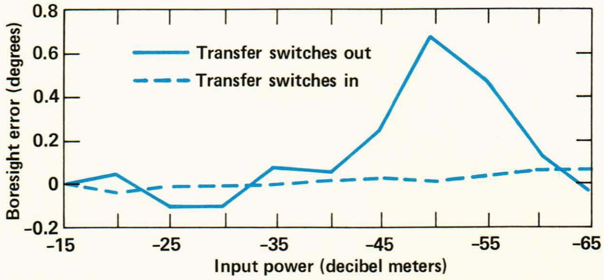

Figure 19 — Angle bias resulting from differential phase shift between the receiver channels was virtually eliminated with the use of radio frequency and of IF transfer switches that operated on a pulse-to-pulse basis.

Figure 20 — A Talos ARM flight test conducted in October 1965 at White Sands Missile Range is illustrated by the sequence of pictures: (a) just before intercept of radar target, (b) impact and warhead detonation, (c) radar target after intercept. The damage mechanism is the warhead explosion plus the kinetic energy of the missile at impact.