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Bank-To-Turn Control Technology Survey for Homing Missiles

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1. SUMMARY

Satisfying projected mission requirements will require missiles with capabilities exceeding those of current systems. Preliminary analysis has indicated that bank-to-turn control may provide the needed improvement in missile performance. This report summarizes the advantages of bank-to-turn steering, reviews the recent and current programs that are actively investigating or considering bank-to-turn steering, and assesses the status of the critical technology areas associated with bank-to-turn control.

2.1 EXPANDED SUMMARY

Increasingly severe mission requirements and the potential for improved performance offered by bank-to-turn (BTT) steering are generating renewed interest in BTT control. Table 2.1 lists the current programs which are actively investigating BTT control or are considering BTT control for one or more of the competing configuration designs. The most detailed BTT studies have been done for the short range air-to-air mission, which requires extremely high lifting capability. Recent investigations funded by Eglin AFB have demonstrated the feasibility of BTT control and have shown that an off-the-shelf servo and seeker meet the system requirements. These studies have led to the Technology Integration of Missile Subsystems (TIMS) program. In addition, a BTT airframe is the required baseline configuration for the Air Force sponsored Ramjet Interlab Air-to-Air Technology (RIAAT) program.

Long range missions such as the Air Force ASALM (Advanced Strategic Air Launched Multi-Mission Missile) and the Navy AIAAM (Advanced Interceptor Air to Air Missile) and SOJS (Standoff Jammer Suppression) programs are considering BTT control because of its compatibility with ramjet engine inlet designs. The first phase of the ASALM program, a propulsion demonstration, is into the flight test stage. Both Phase II primary contractors are pursuing the critical problem areas of integrating BTT control into a tactical weapon. BTT is attractive for air-to-surface missions because of the increased lift to drag ratio obtained by eliminating the yaw lifting surfaces. Both the Medium Range Air-to-Surface Missile (MRASM) and the Advanced Conventional Standoff Missile (ACSM) are in the very early stages of concept definition.

Table 2.2 lists the critical technology areas and the status of current investigations. Because the requirements and constraints are different, the status is broken down into short range and long range missions. Body rate coupling, which can be severe for BTT systems with RF seekers, is not a problem for infrared seekers. In addition, the sideslip constraint is not as severe for rocket engines as for ramjets. These factors probably contribute to the short range mission having been studied in greater detail. Analysis is progressing for the longer range, ramjet propelled, radar guided missiles.

Depending on airframe aerodynamics, turn coordination can be a difficult

Table 2.1

Current programs investigating or considering BTT steering

Program Name	Application	Sponsor	Contractors	Development Status	Comments
TIMS	Short Range Air-to-Air Missiles	Eglin AFB	-	Continuing Technology Development Effort	Formerly called ILAAT. Outgrowth of Eglin BTT Studies
RIAAT	Moderate to Long Range Ramjet Propelled Missile	Eglin AFB and Wright-Patterson AFB	Hughes TASC	BTT contract let Summer 1979	BTT investigation is an add-on to Ducted Rocket Engine development effort.
AIAAM	Long Range Air-to-Air	Navy (NWC-China Lake)	Hughes McDonnell/ Douglas	Concept Definition	Probably Ramjet propelled
ASALM	Long Range Air Launched Strategic Missile	Wright-Patterson AFB	Martin/ Marietta McDonnell/ Douglas	Concept Validation	Phase I - Propulsion Demonstration Test Vehicle flown Oct. 1979 Phase II - Tactical Integration Study (TIS)
SOJS	Long Range Surface-to-Air, Jammer Suppression	Navy	-	Concept Definition	Funding halted for FY 80.
MRASM	Medium Range Air-to-Surface Missile	Joint Navy/AF	FSI	Concept Definition	Large Tactical Targets Planned to have land and sea missions
ACSM	Long Range Air-to-Surface	Eglin AFB	Vought	Concept Definition	-----

Table 2.2

Status of critical technology areas

Critical Area	Status * (short range missiles)	Status (medium to long range missiles)	Comments
Guidance Performance	Good performance has been demonstrated via simulation.	Performance has not yet been completely established.	Long range case may require trajectory shaping or transition to STT during terminal homing.
A/P Design	Recent studies have designed pitch, yaw and roll autopilots separately.	No generally accepted approach to coordinated autopilot design exists. Designs used have required "trial and error" iteration.	Coordinated autopilots, when required, depend strongly on specific airframe configuration and flight condition.
Sensitivity to Body Rate Coupling	Not a problem for high lift airframes with infrared seekers	Methods to relieve this sensitivity are currently being investigated by several organizations.	Body rate coupling must be considered for short range missiles with RF or strap down sensors.
Subsystem Requirements	Adequacy of off-the-shelf seeker, actuator and digital autopilot has been demonstrated via hardware-in-the-loop simulation.	Detailed investigations of subsystem requirements have not been completed.	One long range Air-to-Surface missile exhibited severe coupling due to seeker coulomb friction.

* The short range missile envisioned here is the configuration used for the Eglin AFB investigations (References II-10, II-11, and II-12).

design task but can probably be done satisfactorily. The body rate coupling problem is as yet unsolved. This and the out-of-plane motion induced by BTT steering may require a hybrid bank-to-turn/skid-to-turn system for the final portion of terminal homing.

3. INTRODUCTION

Bank-to-turn steering may provide improved performance for future missile systems. For example, a missile can be designed to have very high lifting capability in one direction. This lift vector can then be directed using BTT control. In addition, the ramjet engine chin inlet configuration is believed to provide a greater range capability than other inlet configurations. BTT control is required to satisfy the sideslip constraints imposed by chin inlets. Despite these facts, there are unanswered questions concerning BTT system stability during homing, guidance performance, autopilot and guidance logic design and subsystem requirements which must be investigated before BTT steering can be considered a viable method of control for high performance missiles.

This report surveys the current status of BTT control technology. A literature search has been conducted and a variety of technical organizations have been contacted. The objectives of this survey are to identify missions and programs for which BTT steering has been or is being investigated, to identify potential problem areas, and to assess the progress of the various studies which are investigating these problems. It is hoped that this survey will serve as a reference point for future BTT investigations.

The following section provides a brief background discussion of BTT steering. Then, the various missions for which BTT control is applicable are categorized in Section 5. As each of these missions is discussed, the relevant programs which have investigated BTT control are described. A more detailed description of some of the problem areas is contained in the appendixes, along with a complete bibliography.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

4. BACKGROUND

Missile systems designed to meet the threats of the future will require capabilities far in excess of those currently available. In many cases the potential advantages of bank-to-turn (BTT) steering, listed in Table 4.1, may provide the improved capability.

TABLE 4.1

POTENTIAL ADVANTAGES OF BTT STEERING

- Increased lifting capability in one plane without weight and drag penalty of orthogonal surfaces
- Enhanced aerodynamic stability characteristics
- Compatibility with ramjet engine inlet designs

For example, adequate protection of aircraft requires an air-to-air missile with very large lifting capability, especially if the missile must intercept a target behind the launch aircraft. Such a capability might be achieved by using a planar airframe with large wings to provide lift in one direction but without the weight/drag penalty of orthogonal lifting surfaces. In addition this configuration would satisfy the constraints of wing launch systems. BTT control would be required to direct the acceleration or lift vector of such a configuration.

For cruciform configurations, angle-of-attack (and hence, lifting) capability is often limited by roll-yaw aerodynamic stability considerations. This constraint can be relieved by rolling or banking the airframe to an orientation which has optimum aerodynamic stability characteristics. Intercepting long range standoff jammers (SOJ) significantly improves the effectiveness of inner defense weapons when defending surface targets against air attack. Ramjet engines appear to be the only propulsion system capable of providing the long ranges and high speeds required to intercept SOJs. BTT control will be required to achieve satisfactory ramjet engine performance for many of the proposed inlet designs. As a final example, air-to-surface glide weapons designed to achieve long ranges require an airframe with as little drag as possible and reasonably high lift. Here again a winged, planar configuration can be used with BTT control to null azimuth heading errors.

In addition to its potential advantages, BTT control introduces some problems which must be carefully examined. Table 4.2 compares some of the design considerations for skid-to-turn (STT) and BTT steering. In an STT system, acceleration commands are broken into orthogonal (cartesian) components for steering. Thus the achieved maneuver lies in or very close to the desired plane of maneuver. However, in a BTT system, the acceleration vector can be directed out of the desired plane of maneuver while the missile airframe rolls to its preferred orientation. This out-of-plane component can potentially cause some degradation in performance. If the acceleration command is small, the preferred orientation is ill defined and guidance noise can cause excessive, undesirable roll motion.

Homing missiles require some mechanism (e.g., a seeker) to generate guidance signals. These signals are inevitably corrupted by body motion, for example, due to radome aberration errors or incomplete seeker stabilization. The coupling from body motion to guidance closes the so-called parasitic loop and can lead to system instability. Preliminary investigations have indicated that BTT control is less tolerant of body rate coupling than STT systems are. This problem, in fact, appears to be one of the major limitations of BTT systems.

In addition, BTT control may alter subsystem requirements. If sideslip angles must be constrained, a cross-coupled autopilot must be designed to coordinate the bank maneuver. Seeker tracking and slew rate capability and also signal processing must be compatible with an airframe that could roll up to several hundred degrees per second. Unmatched or varying polarization effects add another variable to the BTT guidance problem which does not exist for STT systems. Other areas where BTT control may affect requirements include pointing a communications antenna, gyro and servo specifications, adaptive autopilot techniques and guidance policy implementation.

As indicated in Table 4.2, some of these potential problem areas are discussed in greater depth in Appendices A through E.

Table 4.2

Comparison of fundamental considerations for STT and BTT steering

	STT (Cruciform, Roll Stabilized)	BTT	Discussed in Appendix
Guidance Performance	• Maneuvers remain in desired plane • Response time dependent on pitch autopilot	• Bank maneuver causes airframe to leave desired maneuver plane • Response time depends on pitch and roll autopilots	--
Guidance Logic	• Pitch and yaw systems can be independent	• Bank command undefined for small pitch accelerations • Additional noise reduction may be required for these cases	A
Autopilot	• Pitch and yaw systems identical	• Turn coordination required if side slip is to be constrained • Requires compensation for aerodynamic and kinematic cross coupling	B
Seeker	• Slew rate requirements determined by stabilization requirements and/or search pattern design • Antenna polarization matched to radiation	• Slew rate capability must be compatible with missile bank motion • Low frequency signal processing requirements may differ from STT • Polarization mismatches decrease antenna gain and may increase radome error for semi active systems • Polarization changes may alter aim point for active systems against large targets	C
Body Rate Coupling	• Pitch and yaw rates couple into guidance signals • System may tolerate linear instability	• Pitch, yaw and roll rates couple into guidance signals • BTT systems appear to be more sensitive to body rate coupling	D
Roll Yaw Aerodynamic Coupling	• Coupling can limit angle of attack for some orientations	• BTT systems can maintain orientations which minimize coupling	--
Communications Antenna	• Orientation fixed at all times	• Orientation changes as missile banks	--
Analysis	• Problem can usually be simplified by assuming two independent steering channels and a roll channel	• Complex coupling requires three dimensional analysis • Simulations are required	E

5. MISSIONS FOR WHICH BTT CONTROL IS APPLICABLE

The missions for which BTT steering is applicable can be divided into four categories:

Short range air-to-air

Moderate range against air targets

Long range against air targets

Air-to-surface.

Table 5.1 lists these missions along with the basic airframe requirements and the programs which will be discussed in the following subsections.

5.1 Short Range Air-to-Air Missions

The application of BTT steering to the short range air-to-air mission has probably been studied in greater depth than the other missions. These studies have been funded primarily by Eglin AFB, Florida. Historically, however, the Eglin technology studies can be traced to two studies supported by the Navy and the Army. In 1970, Froning, et al., [II-5]* under contract to the Naval Weapons Center at China Lake, investigated the feasibility of BTT steering for highly maneuverable tactical air-to-air missiles. He concluded that BTT is a viable steering method and that BTT response times can be as fast as those for STT. The Froning study included a coordinated autopilot design, but the problems associated with body rate coupling were apparently not realized. Another report [II-6], also by McDonnell-Douglas, investigated BTT for a re-entry vehicle interceptor. The concept used an elliptically shaped body and investigated both external burning and jet interaction control. This study was funded by the Army Advanced Ballistic Missile Defense Agency under project UpSTAGE.

Froning [II-7], with support from Eglin AFB, then drew upon the technologies described in those two reports to determine the feasibility of exploiting SAM technology to develop a low-cost, high-performance air-to-air missile. The promising technologies investigated included very high-lift airframe technology in conjunction with BTT control. He also felt that the high-lift airframe would enable the use of pursuit guidance and thus a low-cost, all-weather

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* References are contained in the bibliography at the end of the report.

Table 5.1

Missions for which BTT steering is applicable

MISSION	REQUIREMENTS	RECENT PROGRAMS	COMMENTS CONCERNING MISSION
1. Short Range Air to Air	High Maneuverability High Speed Short Range	Eglin BTT studies ILAAT TIMS	Rocket propulsion Turn coordination probably not required If IR seeker meets guidance requirements, body rate coupling problem greatly reduced.
2. Moderate Range	High Maneuverability	SM Improvement Program RIAAT AIAAM	Air Targets Ramjets used for some candidate configurations Probably requires coordinated autopilot Body rate coupling of concern during RF homing guidance
3. Long Range	Long Range Moderate to High maneuverability	ASALM SOJS	Air Targets Ramjet engine required Coordinated autopilot required Communications antenna probably required
4. Air to Surface	Long Range Low Drag Low Maneuverability	GBU-15 MRASM ACSM	Subsystem requirements probably less severe than previously discussed anti-air applications.

radar seeker with fixed antenna. In a follow-on study [II-9] Froning "synthesized and analyzed advanced maneuvering air-to-air configurations that incorporated: Aimed cylindric and mass-focused directed energy warheads, active radar and passive infrared seekers, pursuit, lead-pursuit and proportional navigation, and bank-to-turn control of a highly maneuverable airframe." Proportional navigation was found to perform better than the pure pursuit guidance. Another follow on program was recommended to refine the most promising configurations, more extensive subsystem development, etc.

These recommendations were accepted by Eglin AFB, and in 1976 Emmert, et al., at Rockwell began a several-year study of BTT control [II-10, II-12]. The result of the first study [II-10] was a control system definition for a BTT autopilot. The baseline airframe used by Emmert was similar to one of those used by Froning. An IR seeker was assumed. Emmert's autopilot design does not include roll-yaw control cross coupling to minimize sideslip but does include a self adaptive dithering autopilot to adjust to varying flight conditions. His design produced "exceptional short range performance" using available components. The only discussion of body rate coupling is in a brief section investigating the applicability of a strap-down seeker. The allowable rate coupling for the pitch system only led him to conclude that "strap-down sensors could not be easily integrated with the BTT flight control system." (No consideration was given to roll-yaw loop, body-rate coupling problems.) A follow on study [II-12] performed detailed stability and control system element requirements and system performance. The major conclusion was that subsystem requirements could be satisfied with state-of-the-art components. It was recommended that these results be verified with a hardware-in-the-loop simulation.

One such study, also supported by Eglin, was done in 1977 by McDonnell-Douglas [II-11]. The objective of the program was to demonstrate the ability of a Raytheon RAYSCAN infrared sensor to guide a BTT missile. This objective was met.

In 1978, a hardware-in-the-loop simulation was developed at Eglin AFB to investigate three subsystems: a digital autopilot, infrared seeker and pneumatic actuator. Based on the results of this BTT hardware demonstration program, it was concluded that a BTT air-to-air missile system is feasible and that performance is superior to existing short range air-to-air weapons. The results of these simulation studies are reported in the open literature [(I-10, I-11)].

The BTT investigations described above were formally concluded and the results transmitted to the ILAAT (Inter-Lab Air-to-Air Technology) program, which is now called TIMS (Technical Integration of Missile Subsystems). This program is defining system level performance requirements and doing trade studies to determine how best to meet these requirements. Bank-to-turn control is a requirement for these studies.

Two points should be made concerning the Eglin studies. First, after the Froning studies, no attempt was made to coordinate the steering maneuvers; that is, no attempt was made to minimize sideslip while banking. The reason for this is that the short range missile will be rocket - not ramjet - propelled and therefore will not have inlet imposed sideslip constraints. The requirement to limit sideslip angle in order to constrain the sideslip induced roll moment is usually less severe than the limit imposed by ramjet inlets, especially for the low angles-of-attack achieved by the high-lift airframe. Second, the effects of body rate coupling were generally not considered. There are two reasons why it may also be appropriate not to consider body rate coupling for this case. The high-lift airframe would not have large rotation rates in pitch and the altitudes considered have atmospheric pressure high enough to keep angles of attack reasonably small. Thus the gain through the airframe of the body-rate coupling (parasitic) loop is small. The second reason body-rate coupling is small is that these short range missiles were assumed to have infrared seekers, which do not have the level of radome aberration error associated with radar seekers.

5.2 Moderate Range Missions Against Air Targets

There are at least three programs which either have recently considered or are considering bank-to-turn control for moderate range missions against air targets. These are the Navy Standard Missile Improvement Program, the Air Force Ramjet Interlab Air to Air Technology (RIAAT) Program, and the Navy

Advanced Interceptor Air to Air Missile (AIAAM) Program.

5.2.1 SM Improvement Program

One limitation on the maneuverability of the Standard Missile is the angle of attack constraint imposed by roll-yaw aerodynamic coupling. This constraint is less severe for maneuvers where the missile is oriented such that the acceleration vector lies midway between the control surface panels, a so-called combined plane maneuver. One method suggested to relax the roll-yaw constraint is to roll the missile such that steering maneuvers always occur in the combined plane.

A preliminary investigation was conducted into a version of BTT control which would simultaneously steer the missile using both steering channels and roll to the preferred orientation. These investigations revealed several problems which would require in-depth analysis, including the body rate coupling, guidance filter mechanization, and uplink antenna orientation. In addition, laboratory tests indicated that radome errors may be increased when the polarization of the semiactive seeker is not aligned with the incoming radiation. The BTT alternative was discarded because schedules did not permit the several detailed investigations which would be required before the performance improvements could be realized.

5.2.2 RIAAT

In September of 1978, the Air Force Aero Propulsion Laboratory initiated a 55 month, $17M to $18M program to develop ducted rocket technology. Currently a fixed-fuel-flow study is underway with a variable-fuel-flow ducted rocket to be investigated in the future. The system is designed to be compatible with the AMRAAM forebody and will be a propulsion variant for AMRAAM.

The RIAAT program is an amendment (approximately $1M) to the propulsion development program. Its objective is to develop armament technology for integration into a ducted rocket air-to-air missile in the post AMRAAM time period. The contract was let in the summer of 1979, and the system is not yet defined. However, it will be bank-to-turn at least through midcourse with a possible handover to STT during the last few seconds of terminal homing. Due to inlet constraints and the probable use of a radar seeker, the studies will investigate coordinated autopilots and body rate coupling effects.

5.2.3 AIAAM

The Advanced Interceptor Air-to-Air Missile (AIAAM) program is funded by NAVAIR through the Naval Weapons Center at China Lake. Since the source selection process was in progress when the program office was contacted for this survey, the funding levels could not be determined. As with the RIAAT program, the missile configuration is not yet defined nor have system requirements been specified. It will be an air breather, but the decision between liquid fuel, solid fuel or ducted rocket has not been made.

At least one configuration being considered is symmetric about just one plane. This and ramjet inlet considerations make BTT control a prime candidate. However, BTT has not yet been made a requirement. Preliminary investigations by China Lake and by contractors (McDonnell-Douglas and Hughes) have revealed potential problems associated with body rate coupling and coordinated autopilot design. These have led to the consideration of a hybrid BTT/STT system for use during the terminal portion of flight. In-depth investigations of these effects and other subsystem interactions will be required before the viability of BTT control for this mission can be determined.

5.3 Long Range Missions

5.3.1 ASALM

Both the Air Force and the Navy are supporting programs for a long range mission against air targets. Ramjet engines will be necessary to provide the required ranges (greater than 200 nautical miles) for these missions. One of the missions of the Air Force Advanced Strategic Air Launched Multi-Mission Missile (ASALM) is the suppression of enemy Airborne Warning and Control (AWACS) aircraft. The ASALM program is divided into two phases. The objective of Phase I is to develop and demonstrate the capability of a ramjet-propelled configuration. The competitive contract was won by Martin-Marietta, and the first propulsion test vehicle, a chin inlet ramjet, was flown in October, 1979. Phase II is a Tactical Integration Study (TIS), with the objective to develop the technology to move the program into Engineering Development of a tactical weapon. Both of the primary aero-mechanical contractors (McDonnell-Douglas and Martin-Marietta) have investigated a chin inlet configuration which would require bank maneuvers up to 180°. Both contractors have designed detailed coordinated autopilots and have investigated noise suppression techniques for low angle-of-attack maneuvers (see Appendix A). Both contractors also are concerned about the body rate coupling problem. Various techniques to relieve this stability problem include trajectory shaping, filtering those frequencies where instabilities occur, and a hybrid STT/BTT system near intercept.

5.3.2 SOJS

The Navy long range program is a raid suppression mission called Standoff Jammer Suppression (SOJS) (formerly LRDMM). The purpose is to aid medium range and inner defenses by intercepting jamming equipment or forcing them to operate at ranges where they would be less effective.

Anti-Shipping Missile (ASM) launch aircraft and the ASMs themselves are secondary targets after the standoff jammers. In addition some of the fundamental problems related to guidance and control of long range missiles are being studied under the Navy Wide Area Guidance and Control program. A leading candidate configuration for these long range missions is the chin inlet ramjet. This will satisfy the range and speed requirements and still have sufficient space for effective guidance equipment. The chin inlet configuration requires BTT control and the associated problems are being investigated under the Wide Area Program.

5.4 Air-to-Surface Missions

5.4.1 GBU-15

Long range glide weapons require large lift to drag ratios. These can be achieved with a planar, winged airframe which uses BTT steering to null heading errors. One program which has investigated BTT control for this application is the GBU-15 Planar Wing Weapon. During a study for the Air Force, Hughes developed and evaluated alternate BTT autopilot configurations in terms of dynamic response and guidance performance. It was found that the BTT configuration, because of the airframe's greater maneuverability in the pitch plane, required considerably less range to null a heading error than an STT configuration. However, the BTT system was more sensitive to noise, windgusts, and, especially, seeker coulomb friction, and these effects reduced the accuracy of terminal guidance below that of STT. The coulomb friction seemed to be a major problem, significantly increasing miss distance unless maximum roll rates were reduced to about 60 deg/sec. Also, tests on the electro-optical seeker* indicated high sensitivity to body roll rates, especially when the seeker had a yaw gimbal angle. A combined BTT/STT system was also considered. This configuration showed promise, but its performance was not completely evaluated.

5.4.2 MRASM

Another air-to-surface missile program which is considering BTT steering is the joint Navy/Air Force MRASM (Medium Range Air to Surface Missile). The objective of the MRASM is to destroy large tactical targets such as runways, bridges and aircraft on the ground at ranges up to 200 miles. There is also a potential antishipping role. About $2.3M has been released for this study, with a large portion of this going for warhead development. The program is currently in system definition stage. Speed regime, guidance, propulsion and airframe have not been determined. However, some of the configurations under considerations would use BTT steering.

5.4.3 ACSM

The Air Force Advanced Conventional Standoff Missile (ACSM) is also in the early stages of system development. This missile is meant to have greater range than MRASM. Although configuration decisions have not yet been made, BTT is the baseline if no terminal seeker is to be used. Problems encountered in the GBU-15 program may dictate a STT system. However, the ACSM program is only in the conceptual stage and many studies remain. Advances in seeker technology may solve the problems encountered several years ago.

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* The seeker used was a Rockwell International Corporation unit, part number HGO 20501-201-00.

APPENDIX A

GUIDANCE LOGIC

Guidance logic involves the question of how to use guidance information to command a BTT system. This can be broken down into the problems of forming a roll command and of forming a steering command.

Various methods have been used to form the bank or roll command. It is usually assumed that the seeker provides guidance information in two orthogonal channels. For example, if $\dot{\sigma}_p$ and $\dot{\sigma}_y$ are the line-of-sight (LOS) rates in the body fixed pitch and yaw channels, then the roll error can be shown to be

$$\Delta\phi = \tan^{-1}\frac{\dot{\sigma}_y}{\dot{\sigma}_p} \quad .$$

This quantity can then be used to form the roll command. Other methods to form the roll command would be to use commanded acceleration components rather than LOS rate components, or to use a ratio as an approximation to the arc tangent.

The above discussion ignores the complexity required to always roll through the minimum excursion to achieve the desired orientation. There are various ways to realize this minimum excursion logic, and these depend on whether the maximum excursion is 180° (e.g., to keep a chin inlet windward when the maneuver direction changes), 90° (e.g., a planar configuration which can pull negatives angles-of-attack) or 45° (e.g., a cruciform configuration trying to achieve a combined plane steering maneuver).

STT control may be called cartesian control since the accelerations are commanded as components in two orthogonal planes. Following this analogy, BTT control can be called polar control [II-5]. Here the acceleration magnitude is the pitch command and the angle is the bank or roll command. In any cartesian-to-polar conversion there is a singularity: the angle is undefined if the magnitude is zero. In a practical BTT system the singularity creates a problem at small but non-zero LOS rates because noise on the guidance signals increases the variation in roll error angle. This is illustrated in Figure A.1, which is similar to a figure from Reference II-5. The top portion of the figure illustrates the situation where the noise component of LOS rate is small relative to the true LOS rate. In this case the roll uncertainty or roll vari-

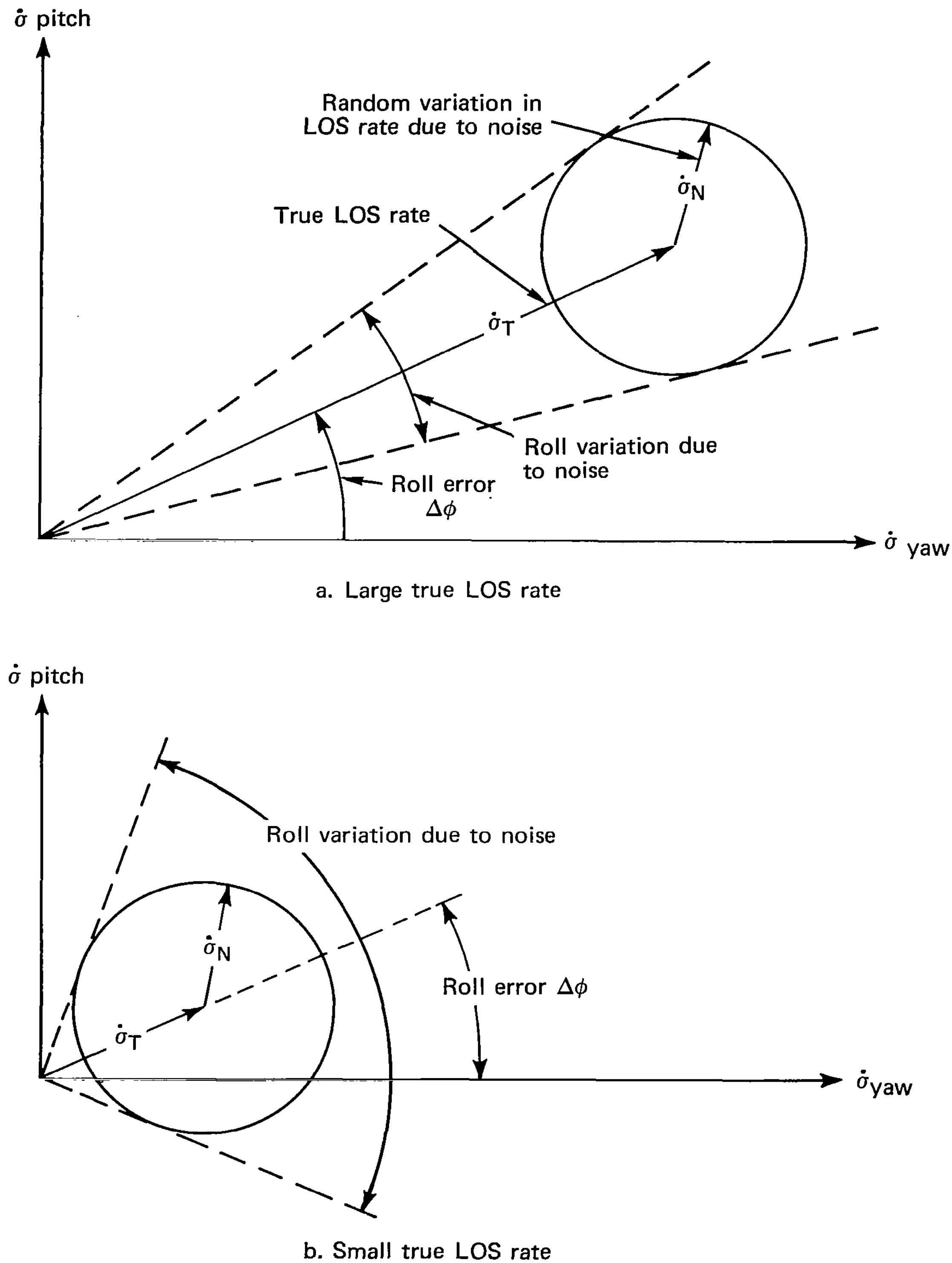

Fig. A.1 Variation of roll noise with LOS rate magnitude.

ation due to the noise is small. However, if the true LOS rate is small, the noise component is relatively larger and can cause large variation in the roll command, as illustrated in the lower part of Figure A.1.

To solve this problem, some sort of threshold, or hysteresis, or reduced roll gain is required in the roll command. In fact all three of these methods have been proposed. For any of these, either no command or a small command is the input to the roll system until the pitch system has developed some acceleration. This has the disadvantage of initially maneuvering in the wrong direction (before the airframe begins to roll) and also of increasing the roll and, therefore, steering response times.

There are also a number of methods to form the steering (pitch) commmand. The most straightforward is to command pitch with the magnitude of the LOS rate vector (square root of the sum of the square of the components) times the appropriate guidance gain, and to command yaw with zero. This method to command the steering system may lead to excessive out-of-plane motion for missiles with slow roll systems. One variation which will reduce out-of-place motion is to reduce the gain on the pitch command until the missile pitch orientation is within some tolerance of the commanded maneuver direction. Of course, this technique tends to increase the steering time constant. Another method which can be used for symmetric configurations is to command both pitch and yaw simultaneously with roll. This is especially useful for a cruciform configuration being commanded to a combined plane maneuver. The steering maneuver can be initiated in the correct inertial direction as the airframe is rolled to preferred orientation. Of course any of these methods must be analyzed to insure they satisfy the requirements and constraints for both the mission and the missile subsystems for which they are being considered.

APPENDIX B

AUTOPILOT

If a BTT missile has stringent sideslip constraints, for example due to engine inlets, some sort of turn coordination will be required. Without this coordination, any achieved angle-of-attack might be rolled directly into sideslip angle. The coordination must nullify the aerodynamic, control and kinematic cross coupling among the roll, pitch and yaw systems.

One way to design a coordinated BTT autopilot would be to write the transfer function from roll control surface deflection to sideslip (see, for example, II-8) including all cross coupling, and then to generate yaw control surface deflection which would cancel or compensate the cross coupling effects. Another way to achieve the same result would be to utilize decoupling techniques from linear systems theory [I-7]. Regardless of the approach, however, the cross coupling terms are functions of angle-of-attack and various aerodynamic parameters which vary with flight condition. In addition, a controller which performs adequately when the missile banks and accelerates from zero may not do so if an angle-of-attack is present and the maneuver plane is to be tilted. Designing a coordination system which maintains adequately small sideslip for all flight conditions and all possible maneuvers is a difficult task requiring analysis, insight and probably detailed simulation.

APPENDIX C

SEEKER REQUIREMENTS

The seeker is an important missile subsystem. Its functions are to track a target, remain spatially stabilized or go into a search mode if target track is lost, and to provide a guidance signal. In order to satisfy the tracking and stabilization functions, the seeker slew rate capability must be compatible with the banking motion of the missile, taking into account the possibly large look angles. The impact of banking maneuvers on track loop requirements must also be assessed. Detailed seeker analyses would have to model inertial coupling between the two seeker channels and the effects of friction, which seemed to cause a substantial problem for the GBU-15 weapon.

Reference II-12 documented an investigation in which seeker requirements were determined by simulating the equations describing seeker operation. In addition, Reference II-11 described hardware tests with infrared seekers in a hybrid simulation. These investigations were all part of the Eglin studies and are applicable to air-to-air missiles. The conclusion was that existing infrared seekers could satisfy the requirements for BTT steering.

Some roll stabilized radar seekers generate line-of-sight (LOS) rate ($\dot{\sigma}$) by adding the seeker gyro output ($\dot{\theta}$) to the derivative ($\dot{\varepsilon}$) of the error between the seeker pointing direction and the target direction, i.e.,

$$\dot{\sigma} = \dot{\theta} + \dot{\varepsilon}.$$

This is done for each seeker axis. It can be shown that this operation makes the measurement of $\dot{\sigma}$ independent of the seeker track loop dynamics. A disadvantage of this method is that the differentiation can amplify noise. In addition, the differentiation is electronic and is performed on a signal measured in seeker coordinates. This operation, and indeed all seeker low-frequency signal processing, must be analyzed to determine its appropriateness when the missile and seeker are no longer roll stabilized but can bank at a rate of several hundred degrees per second.

Polarization effects must also be investigated in light of missile banking maneuvers. For a semiactive, linearly polarized seeker with linearly polarized radiation, the seeker gain goes to zero when the polarizations are 90° apart. This can occur, for example during a 90° bank. Potentially more serious are the changes in radome aberration error as the relative polarization of the seeker and incoming radiation change. If the radome is tailored for a given polarization, other angles may result in larger aberration errors.

Polarization effects may also pose a problem for the case of an active seeker against a large target (e.g., a ship). If the reflectivity of the target depends on the polarization of the signal, the aim point may change as the missile banks. This rapid change in aimpoint might be interpreted by the guidance system as a spike in LOS rate, the result of which could cause the missile to miss the target.

These polarization effects are not well understood, and there is admittedly some conjecture in the above descriptions. However, they do represent another problem which should be thoroughly understood before BTT steering is considered an acceptable control method.

APPENDIX D

BODY RATE COUPLING

Figure D.1 illustrates the elements of a homing missile guidance loop. The target-missile engagement geometry is measured by an on-board sensor (seeker). This measurement of geometry is then transmitted to the guidance computer for processing. Most current missiles use some form of proportional navigation guidance. The geometry information consists of a measure of the rotation rate of the missile-to-target line-of-sight (LOS) and the missile-target closing rate. The guidance computer filters the LOS rate measurement and computes a lateral acceleration command proportional to this rate. The requirement for a measure of LOS rate is not limited to conventional proportional guidance; modern guidance methods based on optimization techniques are usually similar, perhaps with a time varying guidance gain or an additional term to account for target accelerations.

As illustrated in Figure D.1, the measurement of LOS rate is invariably corrupted by body rotation rates. These undesirable perturbations on LOS rate can result from imperfect sensor stabilization or unmatched signal processing gains. However, for RF systems the primary source of these unwanted perturbations is radome aberration error. A body-rate-induced perturbation on the guidance signal causes a perturbation in the commanded and achieved accelerations and, hence, additional body rate. This "parasitic" loop can cause system instability and/or degraded performance.

The above description can apply to either STT or BTT systems. For STT systems, the roll component of rotation rate is usually small and can be neglected, but the situation is not as simple for BTT. Figure D.2 shows a diagram of the parasitic loop for a BTT system. The input here is the LOS rate in inertial coordinates (the output of the engagement geometry block of Figure D.1). The transformation of this vector to seeker coordinates depends most strongly on the roll angle, as indicated. The line-of-sight rate, perturbed by the parasitic coupling, is transformed to roll stabilized coordinates for guidance filtering. In the absence of parasitic coupling (i.e., $K_R = 0$) filtering in roll stabilized coordinates removes the guidance filter lags from the roll loop. The output of the guidance computer is then transformed back

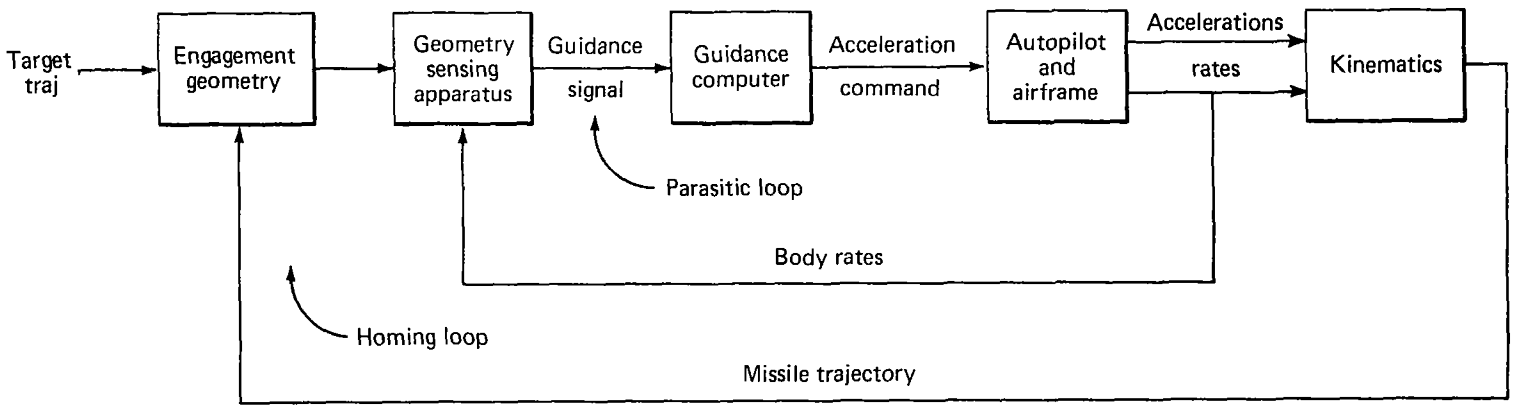

Fig. D.1 Elements of a homing missile guidance loop.

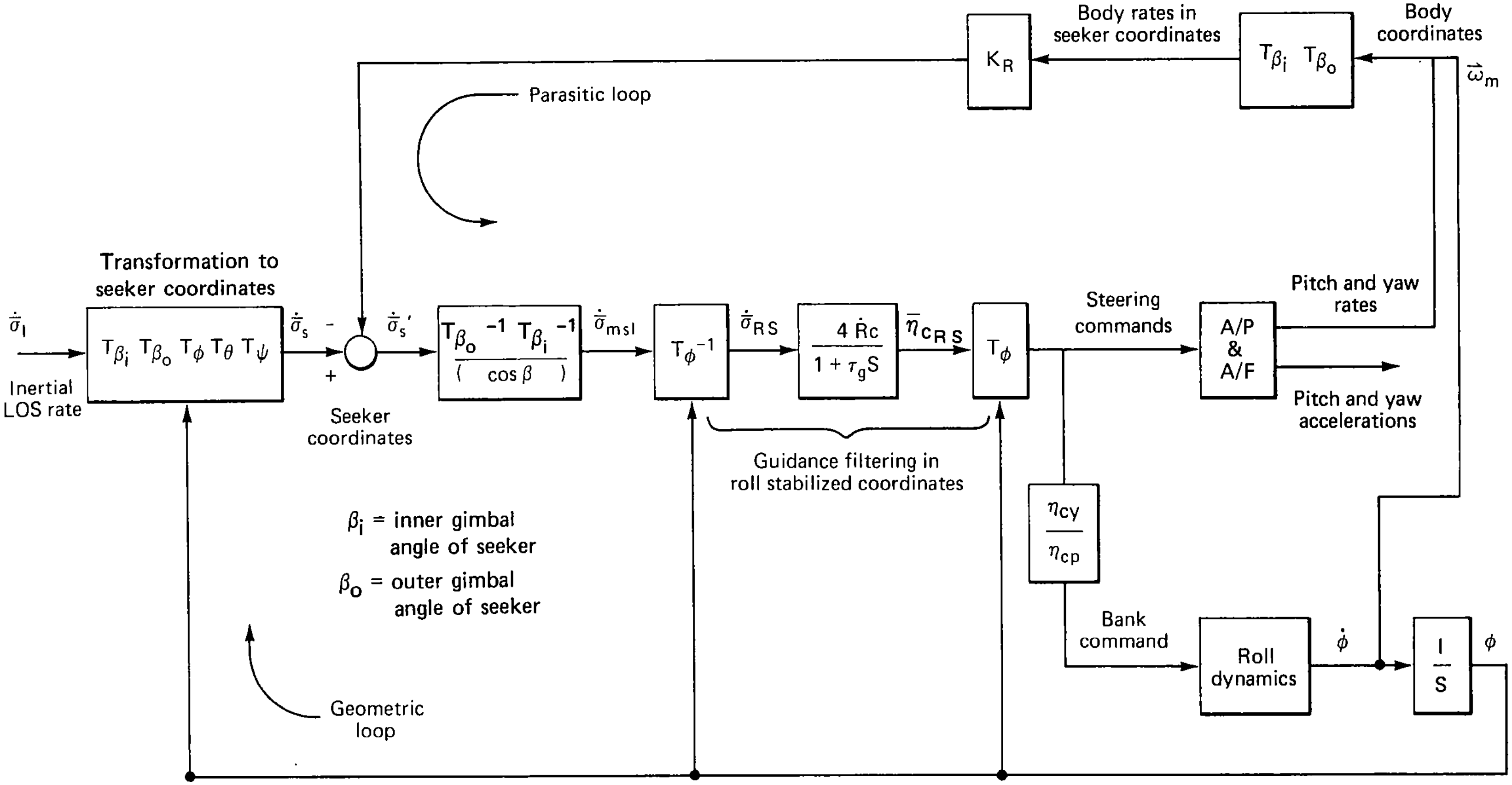

Fig. D.2 Body rate coupling for a BTT system.

to missile coordinates and used to command both the steering (pitch) and the bank systems. Note that the closure of the loop from steering to roll is inherent in BTT systems but is not a part of STT systems. Outputs from both the steering and roll systems form the body rotation rate vector. In Figure D.2 the body rate perturbation is modeled as a linear multiple (matrix K_R) of the rotation rate vector added to the ideal LOS rate.

It is interesting to note that Figure D.2 applies to an STT system as well as a BTT system if the roll command is set equal to zero. In this case the roll rate $\dot{\phi}$ will be zero and the roll angle ϕ will be a constant. Roll stabilized guidance filtering will then be the same as body fixed guidance filtering. Since $\dot{\phi}$ is zero, only the pitch and yaw rates will perturb the LOS rates.

Preliminary analysis has indicated that the additional loop closed from steering to roll renders BTT systems more sensitive to body rate coupling than STT systems. To this writer's knowledge, the problem was first pointed out in Reference I-5, although the severity of the problem was not recognized.

Notice that Figure D.2 has two loops, one from the rotation rates $\bar{\omega}$, including $\dot{\phi}$, through the matrix K_R and a second geometric loop from ϕ to the transformations. The gain of the loop from $\dot{\phi}$ through K_R is inversely proportional to the pitch acceleration command, n_{c_p} since it is in the denominator of the roll command function. For this reason, it is possible to reduce the sensitivity of this loop to body rate coupling by shaping the trajectory during terminal homing so that the pitch acceleration is always substantial. This method may not provide satisfactory performance against maneuvering air targets but may be appropriate against ground or slowly moving surface targets.

The geometric loop is independent of the pitch acceleration. This can be observed by linearizing the feedback path from ϕ to $\dot{\bar{\sigma}}_s$. This feedback will have a term proportional to $[\dot{\bar{\sigma}}_I]$ which cancels the denominator term in the bank command function. Thus trajectory shaping will not affect the dynamics of the geometric loop.

No complete solution is known for the body motion coupling stability problem. Partial solutions which have been investigated include increasing the guidance filtering, selecting the guidance filter and autopilot time constant relationship to minimize the problem, forming the roll command from LOS rates rather than the acceleration commands, and selectively notching out the frequencies where the instability occurs. The first two of these approaches apply also to STT. Forming the roll command from LOS rates shows some improvement for the noise-free case; however, noise considerations and the imposed filtering may alter the results. Notching out the frequencies where instability occurs has the difficulty of knowing where to place the notch filter frequency since radome instability frequencies vary with flight condition and even with the sign of the radome error. Body rate coupling is one of the major problems which must be solved before BTT steering can be considered a viable method for controlling homing missiles with radar seekers.

APPENDIX E

ANALYSIS OF BANK-TO-TURN HOMING ENGAGEMENTS

For STT missiles it is often possible to resolve the motion into two planes and consider the pitch and yaw control systems as independent two-dimensional problems. Using this assumption, guidance performance can be studied using a single plane simulation. This simplification is not possible in the case of BTT control and it is usually necessary to consider the entire three-dimensional problem. Since the resulting equations are nonlinear and difficult to analyze, simulations are required.

Most preliminary BTT guidance studies are made using a simplified model which assumes that sideslip is zero. This assumption permits the use of simplified models, which are desirable so that many performance runs can be made at low cost. Models which represent dynamics in both pitch and yaw planes and also have a means for controlling sideslip have increased complexity.

Graphical presentation of the data is also more difficult for BTT control. Figure E.1 shows a miss distance versus time-to-go plot for a simple, single plane simulation of an STT system. The overshoots and undershoots resulting from autopilot dynamics are readily understood. In three dimensions however, the miss vector could be in any orientation and negative miss has no meaning. Thus, absolute value of miss should be used, as shown in Figure E.2, rendering the figure more difficult to interpret.

For a single engagement a plot of y_{mt} versus z_{mt} (y_{mt}, z_{mt} = missile-target separation along y, z inertial axes) is sometimes useful, especially if missile roll orientation is also indicated. Such a trajectory is shown in Figure E.3 and indicates the orientation of the miss and that the missile is not spiraling into the target. Other polar plots are sometimes useful. For example, a comparison of commanded and achieved accelerations in nonrolling coordinates can help in understanding how turn coordination is affecting the trajectory. Of course, time histories of pertinent system variables are very helpful in reconstructing and interpreting the results. The point to be remembered is that BTT trajectories are inherently three dimensional and require careful examination to insure that the results are not misinterpreted.

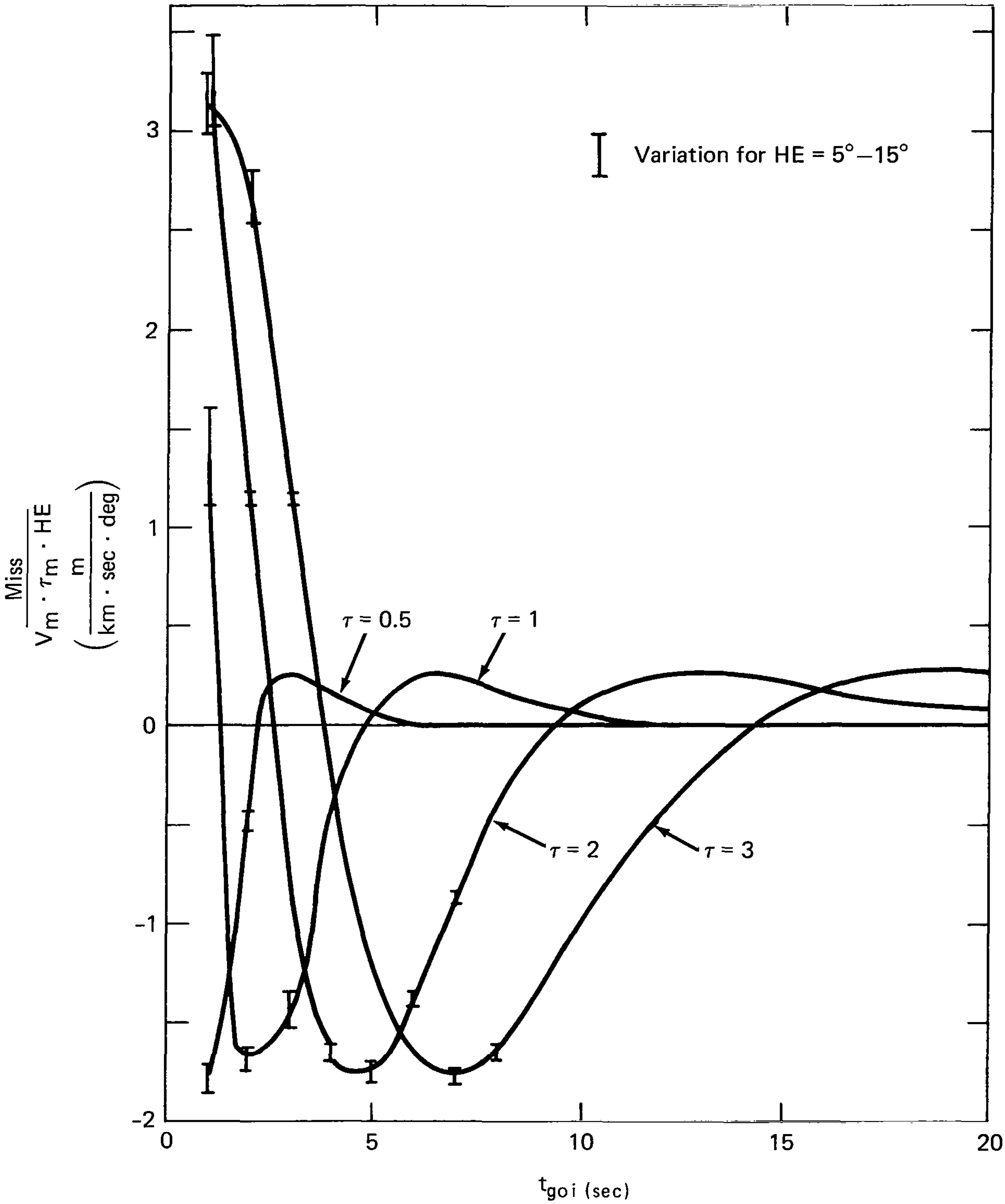

Fig. E.1 **Normalized miss versus time-to-intercept for STT system with time constants of 0.5, 1, 2 and 3 seconds.**

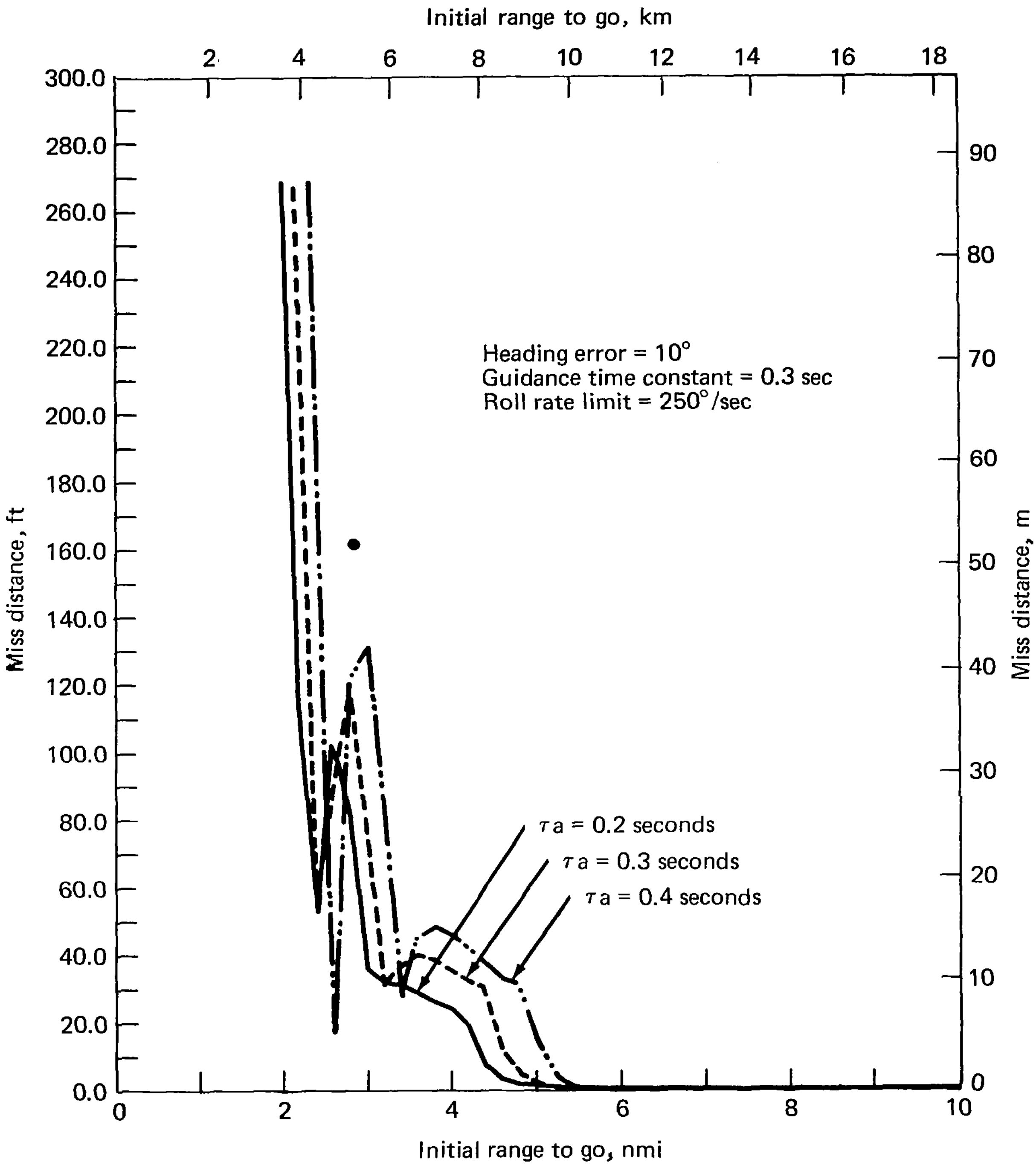

Fig. E.2 Miss distance versus initial range to intercept for a BTT system.

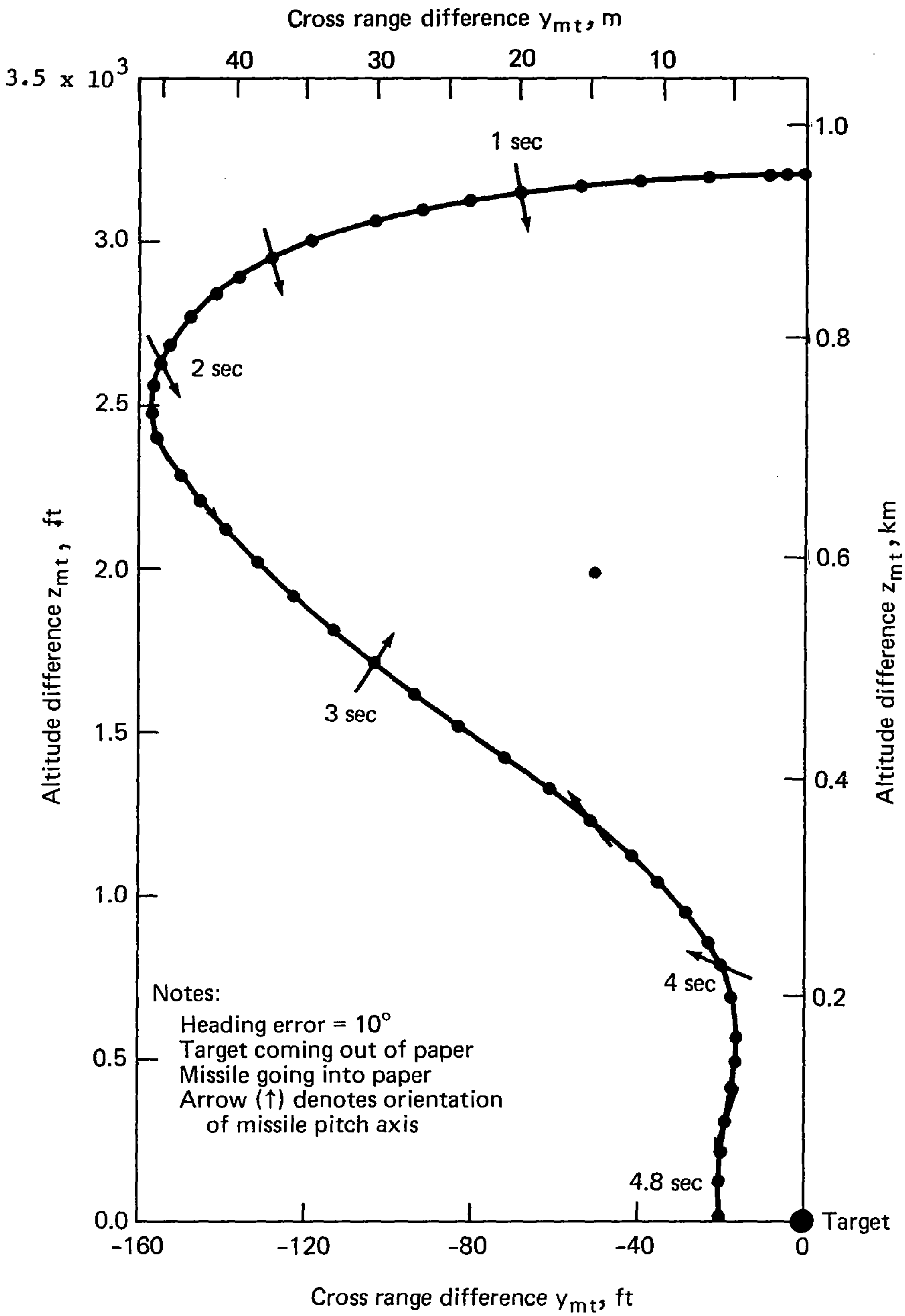

Fig. E.3 Cross range differences versus altitude difference.

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I. Papers from the open literature,

II. Reports from the defense literature.

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16. Abstract

The potential advantages of bank-to-turn control are summarized. Recent and current programs which are actively investigating bank-to-turn steering are reviewed and critical technology areas concerned with bank-to-turn control are assessed.

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