System Design and Assessment Notes
Note 35
December 14th, 1995

High Power Microwave Hazard Facing Smart Ammunitions

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1. Introduction

The battle field of the present and even more the one in future will be characterized by the use of weapon systems with a high degree of electronics, computers and sensors, designed and built to keep not only the man out of the loop!?
But the higher the technology used for smart weapon systems, the more these systems are endangered by numerous sources of hazard. One of those sources is the threat caused by induced or natural electromagnetic fields. These threat factors can be generated by natural, civil and military environment.

In principle there are two main applications which must be considered in military applications: Firstly, weapon systems, that is, high power microwave sources as well as intelligent electromagnetic radiation systems to defeat ammunition on the battle field and secondly, the hardening of the own smart ammunition systems and missiles against the interference sources created by the different types of electromagnetic fields.

The following will discuss the possible electromagnetic coupling effects on smart ammunition and missiles and their typical interference caused on the electronics and sensor level. Real time 6-DOF simulations show the flight mission which may be compromised depending on the coupled electromagnetic fields.

The German MOD has established a research programm where smart ammunitions with different seeker systems are investigated in respect of the coupling effects on smart ammunition caused by high power microwaves.

2. Smart Ammunition Systems

Smart ammunitions typically have a number of electronics, sensors, electromechanics and mechanics on board which are necessary for a controlled, autonomous flight for a successful mission. The smart ammunition and missile technology distinguish between semi autonomous and autonomous guided ammunition and missiles. The advance in the electronic and sensor technology

is mainly represented by a change from analog to digital operated systems with a high degree of computerization with processor technology.
The future belongs to the autonomous fire and forget systems where an active or passive seeker system is on board. The man should be out of the loop in direct combat situations.
In principle ammunition and missiles can be classified as follows (ref. figure 2-1):

- unguided ballistic ammunition/missiles;
- programmed flight of ammunition/missiles; the data for the nominal flight path are stored in the mmissile's computer;
- semi autonomous guided ammunition/missiles controlled via radio, wire, laser spots (laser designator), laser beams, video systems etc., the control and guidance data are transmitted to the missile from the firing station in an interactive manner;
- autonomous guided, fire and forget ammunition and missiles with different search and detection sensors (IR, mmW, and the lik like) on board; the powerful, miniaturized computers control the target search and target discrimination algorithms select the the target and guide the missile to the target (target track with final homing);

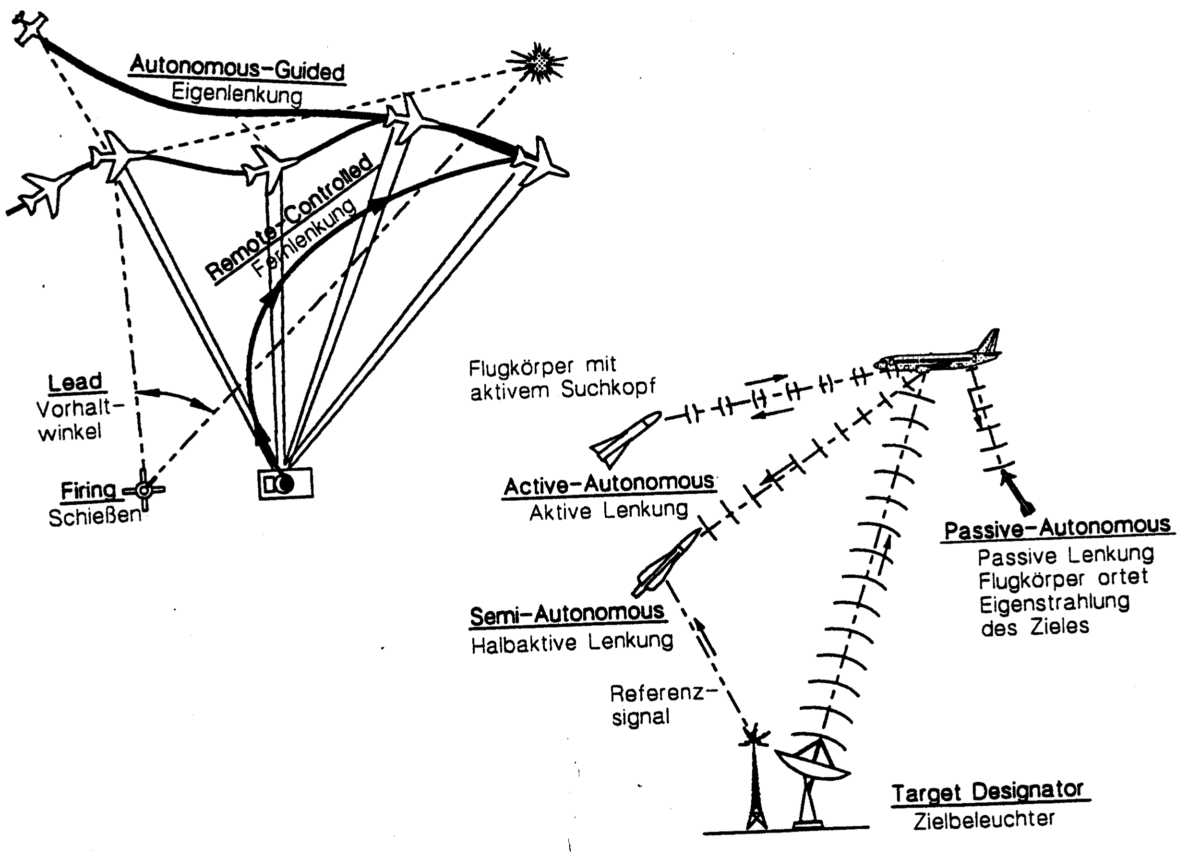


Figure 2-1: Flight Path and Information Loop for various Ammunition and Missile Systems

3. Back and Front Door Couplings

Smart ammunition systems normally do have intended and inadvertent path's of micro wave transmissions. An intended path of micro wave transmissions (***Front Door***) is - for example - the subsystem *mmW-seeker-section with the antenna system or the IR-seeker*.
Nearly all smart ammunitions need wings for the aerodynamic lift and for stabilization. Furthermore control fins are necessary to guide and maneuver the system with the goal to hit the searched and tracked target. Barrel or tube launched systems require folded wings and fins which are deployed after launch. This means that the body has to be designed with a number of slots. For initialization of the missiles before launch, umbilicals are necessary. All these described system-specific designs are called "***Back Door***" coupling possibilities (ref. figure 3-1).

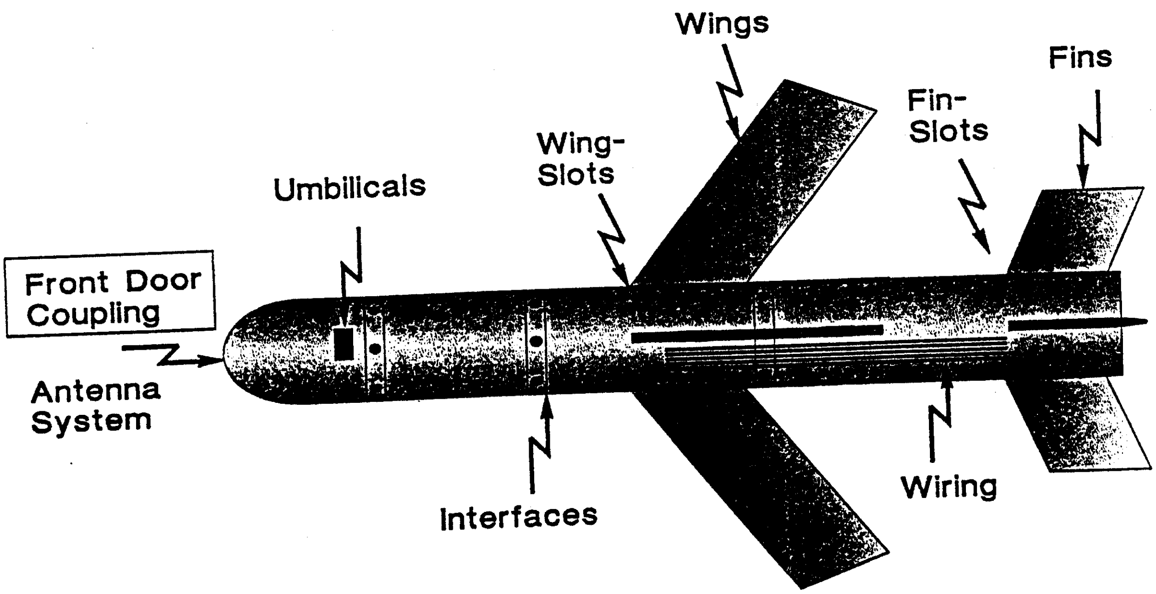


Figure 3-1: Back and Front Door Coupling

These systemspecific extremities, slots, umbilicals, antennas and wirings but also the body of the missile itself must be considered as antennas which respond to the electrical field.
The wing and fin slots respond best to the magnetic field component, whereas the wings and fins respond best to the electrical field component. The coupled electromagnetic field, or the current induced by the electromagnetic field, is lead to the inside of the ammunition over the fins, wings and slots affecting electronical components depending on the frequency, field strength, polarization, modulation frequency and modulation degree of the propagated electromagnetic field.

The critical resonances due to the outer dimensions of the ammunition can be estimated in advance. It must be distinguished between

- outer body resonances due to
  - missile length ($\lambda/2$-antenna)
  - missile circumference ($\lambda/2$-antenna)
- resonance possibilities due to
  - slots in the structure of the missile
  - wings and fins of the missile

The slots can be considered as (λ/2)-antennas where the electromagnetic field can cause resonance in the missile. The best coupling effect can be achieved when the H-field is oriented in parallel to the slots. The control fins also act as antennas. The best coupling effect can be achieved when the E-field is oriented in parallel to the fins. This is also true of the wings. The control fins normally extend into the inside of the missile, where the fin control actuators with the control electronics are located. In this case the fin length must be considered as (λ/4)-antennas. The surface current induced on the fins is transmitted via the fin root to the inside of the ammunition and acts there as a secondary radiation source on the wiring and electronics. The same effect occurs when the wings have a connection inside the missile body. This is normally the case when folded wings are used. Another possible design version has the wings mounted directly on the surface of the missile structure. Now the length of the wings or fins must be considered as (λ/2-antennas). The coupled surface current on the wings is now passed on to the missile's body.

4. The Guidance and Control System of Smart Ammunitions

The missile guidance and control components are tasked with guiding the missile after stabilization to a target area and acquiring a target with subsequent final homing. The guidance and control loop of smart ammunition is designed with different layers of control loops which have different tasks. These control loops are more or less sensitive to electromagnetic radiation interference and can lead to the loss of the target.

The complex guidance and control system of smart ammunition shows hierachical structure and exists of a number of cascaded control loops, the most interesting one being the ***guidance loop***, the ***control loop*** and the ***track loop***.

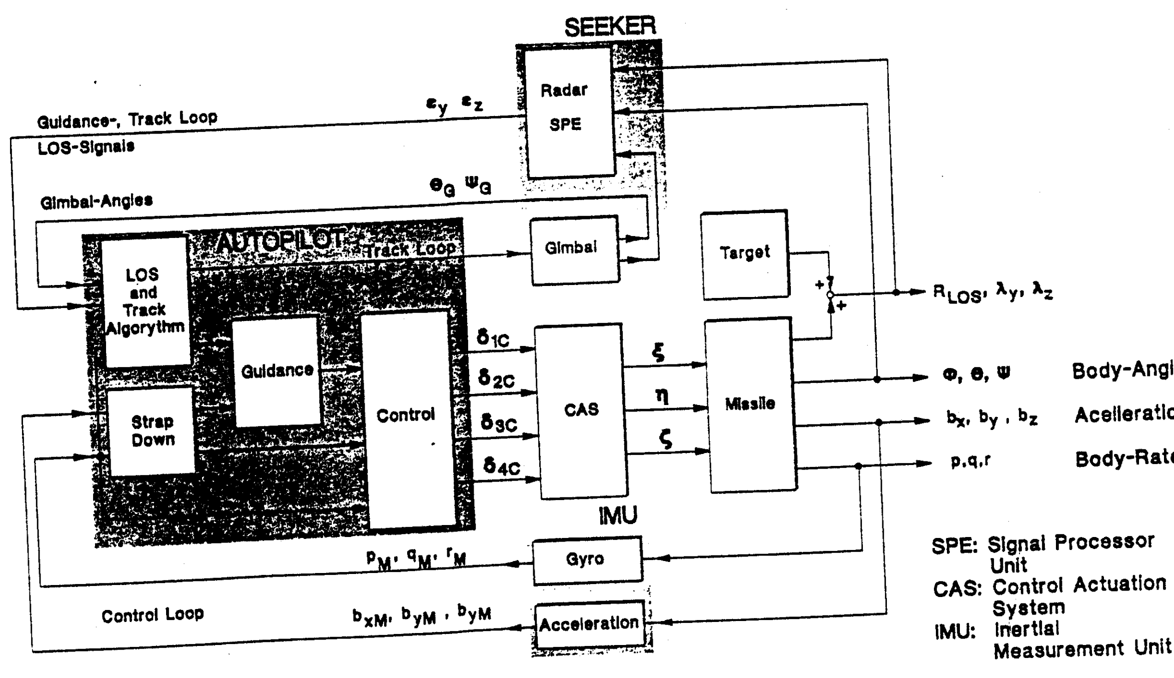


Figure 4-1: Structure of a Complex Guidance and Control System

Control Loop

The control loop is tasked with ensuring IPAS roll control in the three axes (roll, yaw and pitch).This includes: Stabilizing the roll movement (attenuation); Achieve and maintain an inertially predetermined flight attitude (attitude hold); Controlled angle of incidence of ammunition for ensuring the required accelerations.
The computation of the actual flight attitude deviations from desired values is effected by means of the signals supplied by the IMU. The discrepancies as determined will be translated into appropriate actuation signals d1c, d2c, d3c, d4c by the control algorithms and transmitted to the control actuator system.

Since perturbations of both the IMU signals and the actuator system would be passed into the control loop directly, they present a potential hazard to the control loop function.

Guidance Loop

The guidance loop is superposed to the control loop described earlier. It is responsible for the IPAS Center of Gravity movement (trajectory).
For orientation during the navigation phase the guidance loop makes use of the position and velocity data computed by the strap-down algorithms out of the IMU signals. Deviations from the desired trajectory are eliminated by the guidance regulator due to appropriate acceleration commands to the control loop. Any interference on the level of the inertial sensor system will produce navigation errors which, depending on nature and value of those factors, may cause the ammunition to miss the target area.

After target acquisition the guidance signals will be computed based on the target miss distance data ey and ez as measured by the seeker (deviations from the aimpoint in the seeker field of vision). In order to minimize the miss distance values also in the case of rapidly moving targets the proportional navigation is used as a guidance method. The line of sight rate data needed for this guidance law (change IPAS to target line of sight) are estimated by means of a special algorithm (LOS algorithm).

In addition to the measured target miss distance values oG and wG of the seeker frame system the IPAS roll data pm qm rm are processed. Accordingly, any interference of the IMU signals would cause an error in the estimation of the line of sight rate and, hence, improper operation of the guidance loop.

Tracking Loop

During the end game, a constant line of sight is required between the seeker and the target. Therefore, seeker frame system-to-target tracking is required. Since the position of the aimpoint in the seeker field of vision, which is only +/- 1.5 degrees (linear range) is determined by both the target movement and the IPAS in-flight movement, the tracking algorithm must use the roll rate measured via the IMU. The processing of roll rate measurement data subject to interference will, however, cause malfunctions to the seeker tracking process which may, in the worst case, result in target loss and, hence, IPAS end game failure.

5. Interferences of Investigated Radiated Smart Ammunition with Electromagnetic Fields

Interference investigations were conducted with the smart prototype ammunition IPAS (Smart Antitank Submunition). The figure 5-1 illustrates the smart ammunition.

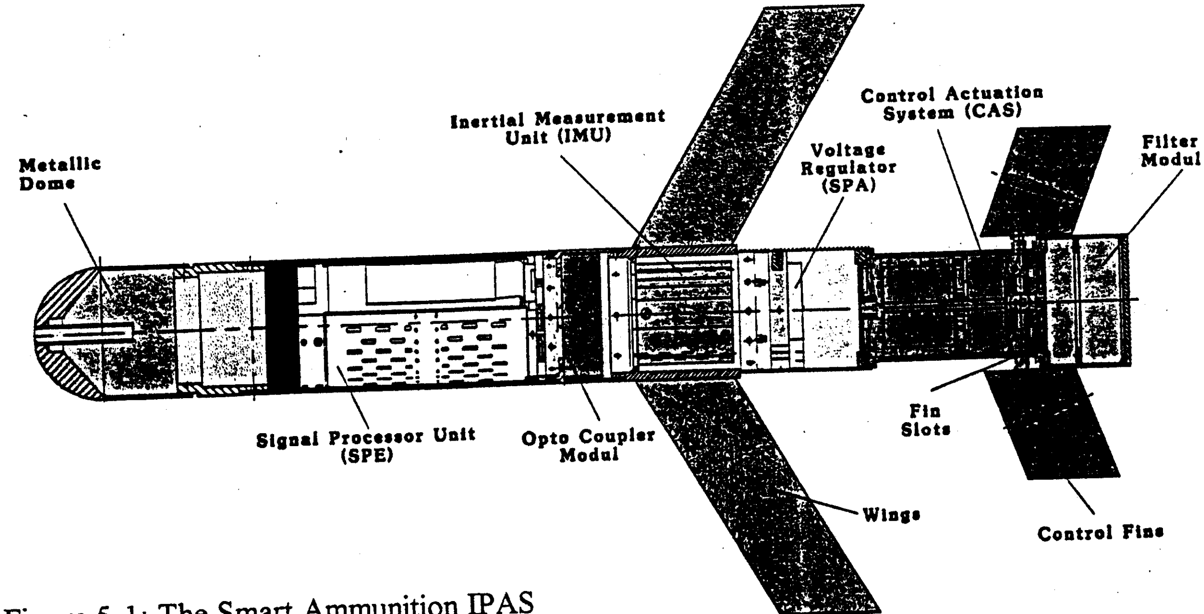


Figure 5-1: The Smart Ammunition IPAS

For the first investigation step the system was operated without the seeker. The front door coupling effect was prevented by using a metallic nose instead of the dome. This ensured that only the back door effects due to the fins, finslots, wings and missile structure could be investigated. The interferences on the electronics due to electromagnetic field radiation were measured. Real time 6-DOF simulations showed performance limitations for the ammunition (fig. 5-2, test set up).

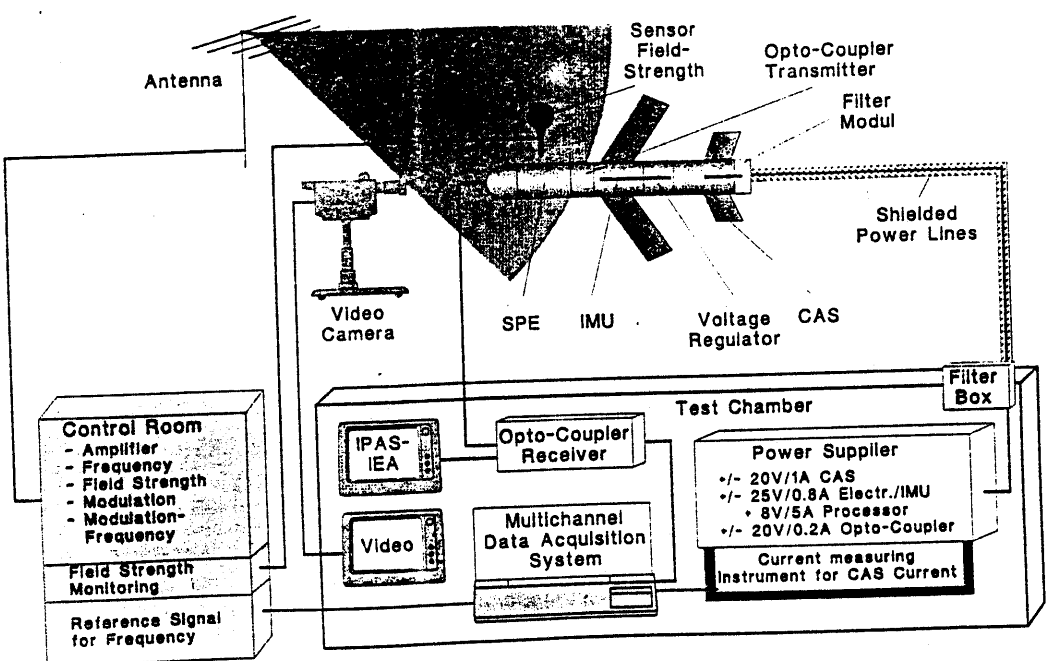


Figure 5-2: Test Set-Up for the Susceptibility Tests with the Activated IPAS

During the radiation tests the investigated ammunition was activated. All relevant guidance and control signals were transmitted via an optocoupler device and recorded. The power supply lines were also decoupled from the missile. No flight abnormal additional devices interfered the system during radiation.

The figure 5-3 illustrates the procedure for the susceptibility investigations with the activated system. During the irradiation phase the IPAS was holded in a defined flight position, in this case the ***final homing*** was selected.

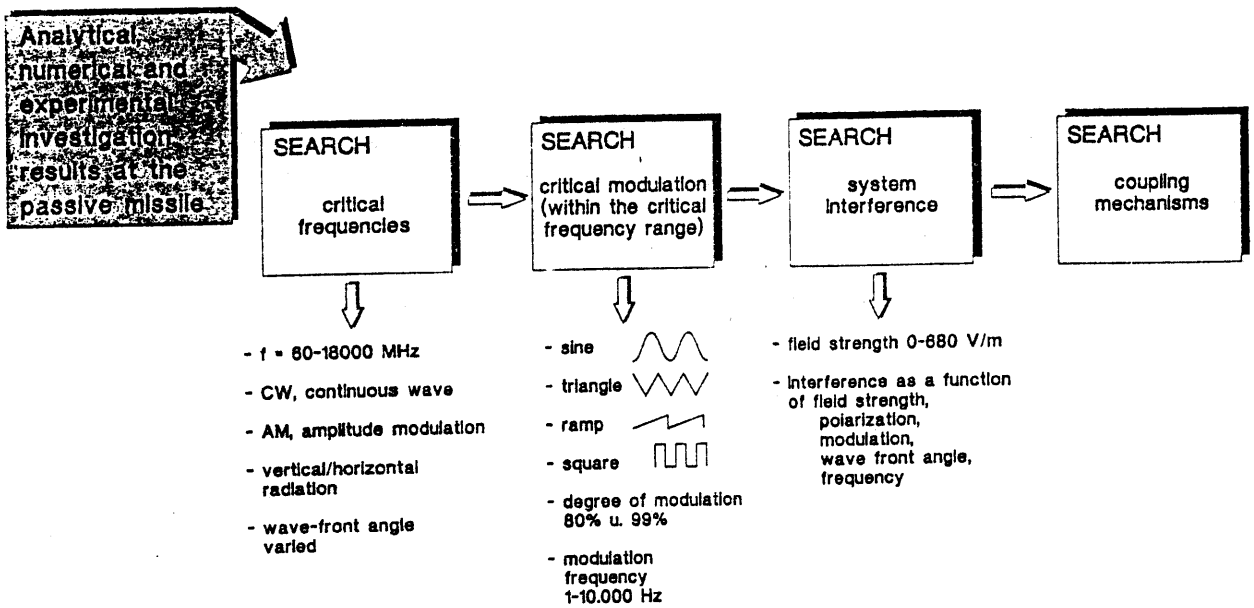


Figure 5-3: Procedure for the Susceptibility Tests with the Activated IPAS

The experimental radiation investigations with the activated IPAS showed, that this ammunition could be affected by interference only via the control fins and the slots in the structure for the control fins. The kind of modulation and the modulation frequency played the essential role for the missile electronic's susceptibility to interfere. The fins act like one side short-circuited dipoles. Due to the negligible fin slot dimensions nearly the whole system interference was caused through the resonances of the fins. The signal interference of the missile show a rather big damping working forwards from the rear (CAS) to the front of the missile.

Without any modulation of the carrier frequency the electronics of the system couldn't be interfered at all. The radiation frequency is the carrier of the interference energy and resonates with the structures of the system whereas the modulation frequency resonates with the working frequencies of the guidance and control signals of the system and cause the real degradation of the system performance.

The following system signals were subject to interference: the fin deflection signals of the control actuation system, the gyro and acceleration signal of the IMU (Inertial Measurement Unit) and the digitalized acceleration and gyro signals inside of the Signal Procesor Unit (SPE).

The figure 5-4 shows the response levels for the four independly fin defeflection signals of the CAS and the corresponding total current. The maximum current is limited to 6.5A per fin control loop.The fins #2 and 4 show interferences already at a fieldstrength of 20 V/m whereas the fin #1 and 3 are less sensitive. The fins #2 and 4 are parallel to the E-field. In this position the both fins can resonate best. At fieldstrengths of 220 V/m the current in the servo loop reaches the maximum value of 6.5 A and will lead after 3 to 5 sec to a burn-out of the power amplifier.

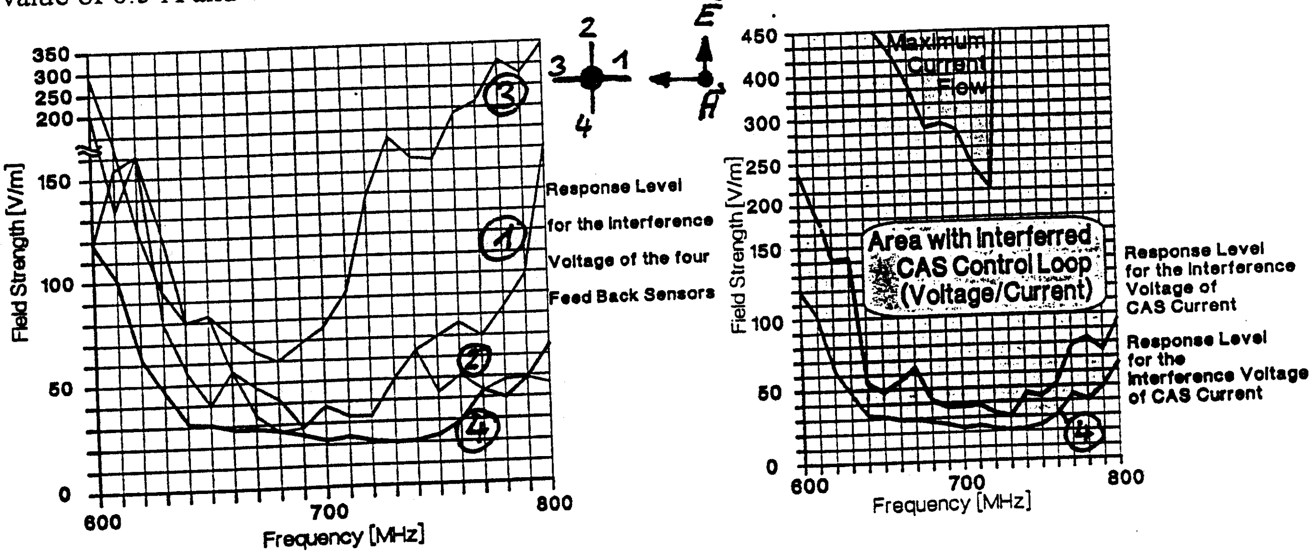


Figure 5-4: Response Levels for the four Fin Deflection Signals and Current of the CAS

The figure 5-5 shows the interference of the fin deflections signals and the total current of the CAS as a function of the frequency and fieldstrength. Again, without the modulation of the carrier frequency, no interference could be detected. The fin defelection signals #2 and 4 already show a rather big. signal-interference at fieldstrenth values of about 200 V/m, where at the most critical frequency of about 720 MHz the maximum current could be detected. The fin defection signals #1 and 3 are much less sensitive due to their wrong adjustment to the E-field vector.

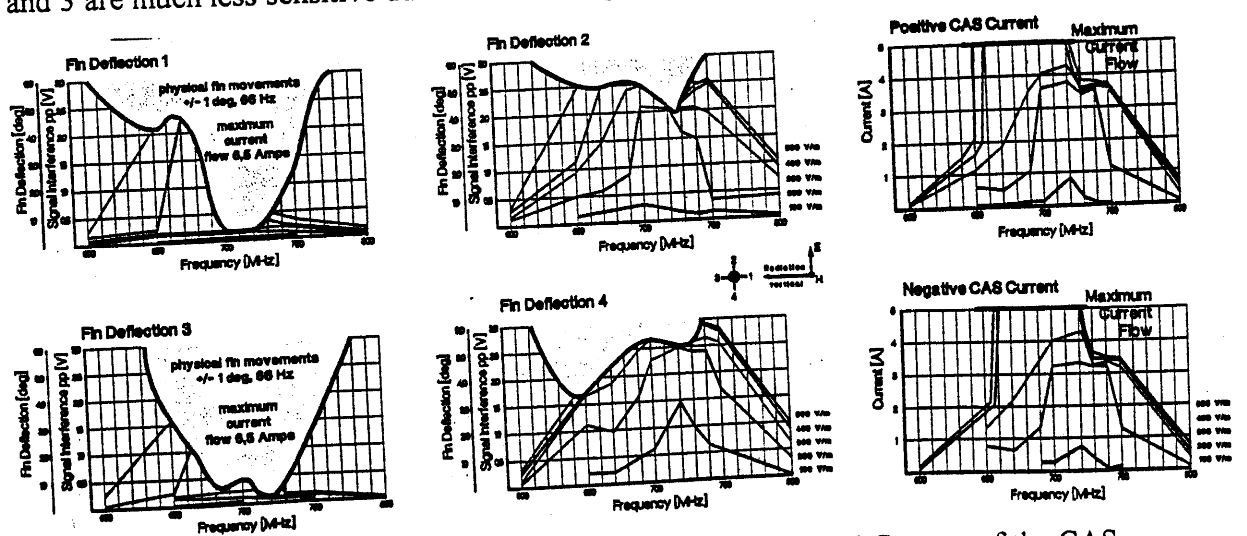


Figure 5-5: Interference of the Fin Deflection Signals and the total Current of the CAS

The figure 5-6 shows the interfered IMU-signals and the corresponding digitized signals used for the guidance and control process with the SPE (signal processor unit).
The IMU signals are much less sensitive than the fin signals. This is due to the location of the subsystem inside the missile. The coupled electromagentic field is much more damped at this position.

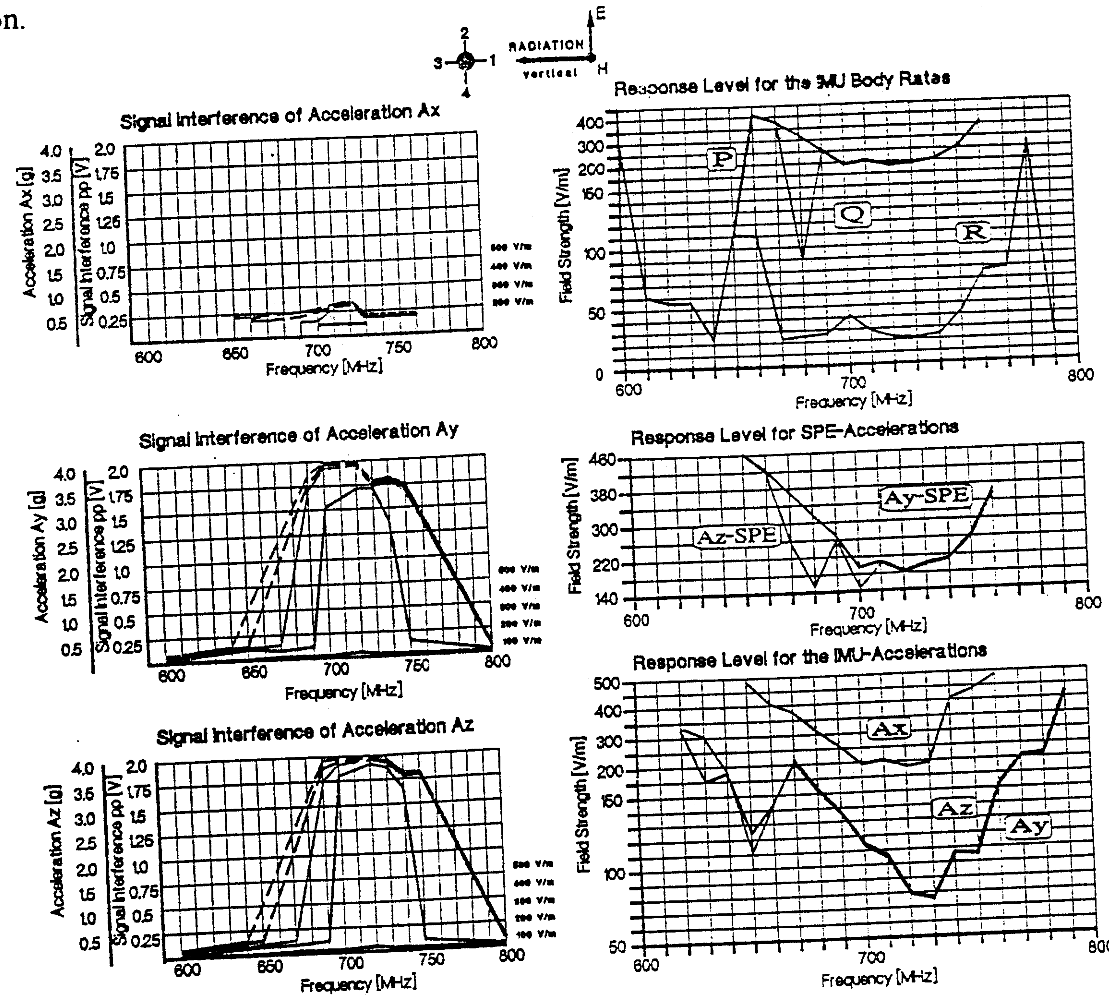


Figure 5-6: Response Level for the IMU-Signals (anloge and digitized)

6. Comparison of different Investigation Aspects

First of all the investigation test results measured at the activated ammunition were compared with investigation test results measured at the passive ammunition - resonances on wiring and cavity responses at different locations inside the missile - and also the theoretical and numerical investigation results.

The predictions due to the outer dimensions of the ammunition matched the measured interferences on the level of the system electronics to a very large extent. But not all predicted and measured resonances at the passive ammunition cause an interference with the system electronics. Only system tests with activated electronics can quantifiy the predicted interference potential. The figure 6-1 illustrates the comparision of the test results of the the different experiment conducted with the passive and activated system.

The performance degradation of the flight path of the system due to the measured signal interfernces must be evaluated by the system simulation.

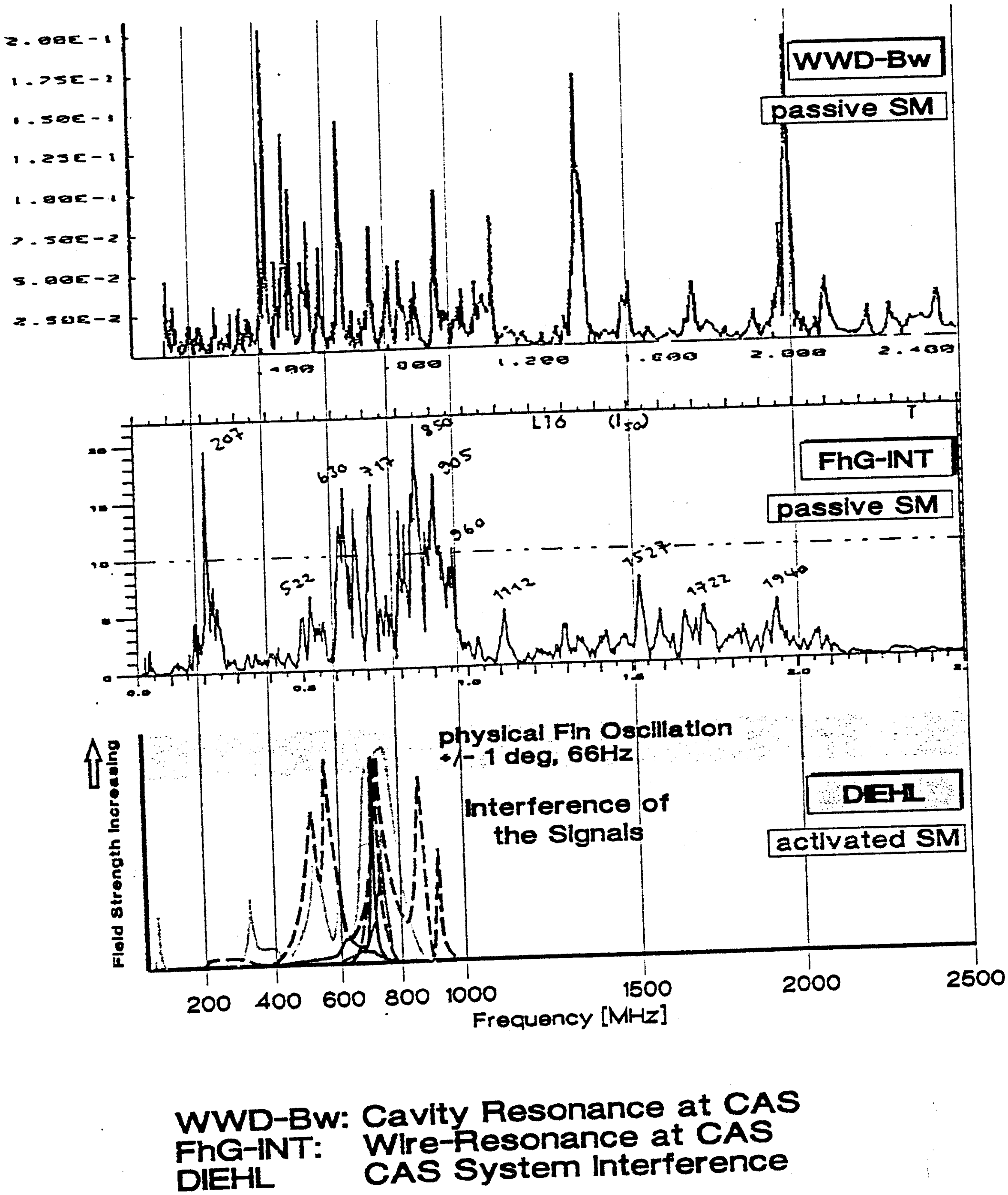


Figure 6-1: Comparison of the Test Results of the various Experimental Investigations

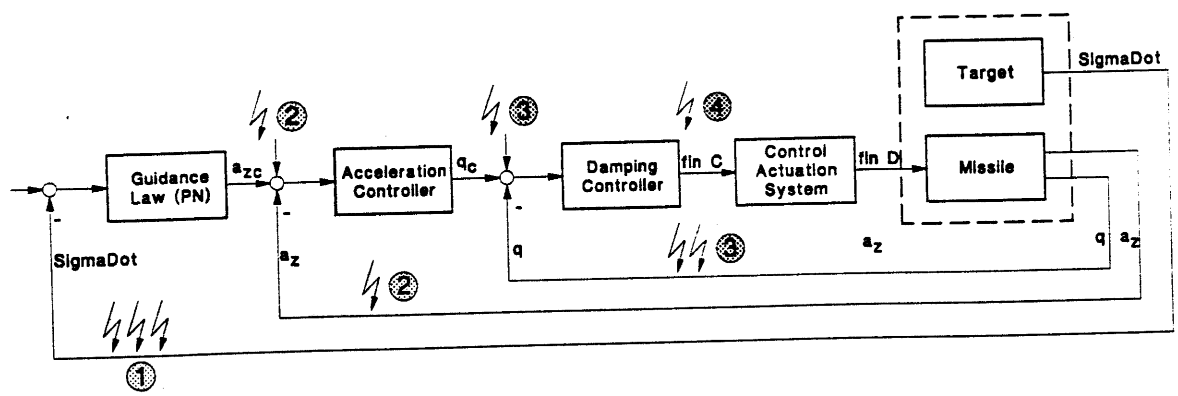
7. System Simulations due to the Interference caused by Low Power Microware

The analytical, numerical and experimental investigations with the passive and powered system has shown a lot of resonances.
The electromagnetic free field causes resonances on the surface of the smart system. Surface currents and -charges interact now with the cavities of the system via the fins and the slots. The coupled interferences to the inside of the system act now as secondary radiation sources on the wirings and electronics of the system with a potential system interference.

The fact is that not all coupled resonances cause an interference in the electronics. The next question which has to be answered is which interferences of the electronics cause a malfunction in the mission success of the system. Therefore, the measured interferences of the various guidance and control signals have to be fed into the 6-DOF (6-Degree of Freedom) flight simulation program to find the real interference of the flight mission in dependence of the outer free field conditions.

The figure 7-1 shows the simplified signal flow of the guidance and control loop with the illustration of the most critical (most sensitive) signal interferences in respect of the flight performance.

The most sensitive signals in the guidance and control loop of the smart ammunition can be found in the track loop or the interference with the gimbal signals which influence the line-of-sight signal and lead to a loss of the target. Follow on investigation with an integrated seeker will verify the influence on the missile's flight path due to the front door coupling effects.



SigmaDot : linie of sight rate from seeker

a_z : acceleration command, Z

q : pitch rate

fin C : Command to pitch fins

①: loss of target

②: Navigation Error

③: Navigation Error/Missile Stability

④: Fin Commands influenced → Missile Stability

Figure 7-1: Simplified Signal Flow of the Guidance and Control Loop of the System

The system simulation was conducted in different steps. The interference was considered for the most sensitive "Final Homing Phase" of the missile's flight path.

Burn-Out of a Power-Amplifier of the CAS

In the final homing phase of the smart system the simulation program considers at about 450 m prior to target impact a burn-out of the power amplifier in the CAS-electronics causing an immediate stop of the maneuverability of the system. The figure 7-1 illustrates the effect of the burn-out of the power amplifier on the mission profile of the smart ammunition.

The oscillating resonances itself on the servo-control-loop hardly interferes with the flight path. But these oscillations cause an increased current flow in the power amplifiers which are designed to withstand the maximum current flow for only a few seconds. Any damage to the power amplifier will immediately interrupt the flight mission.

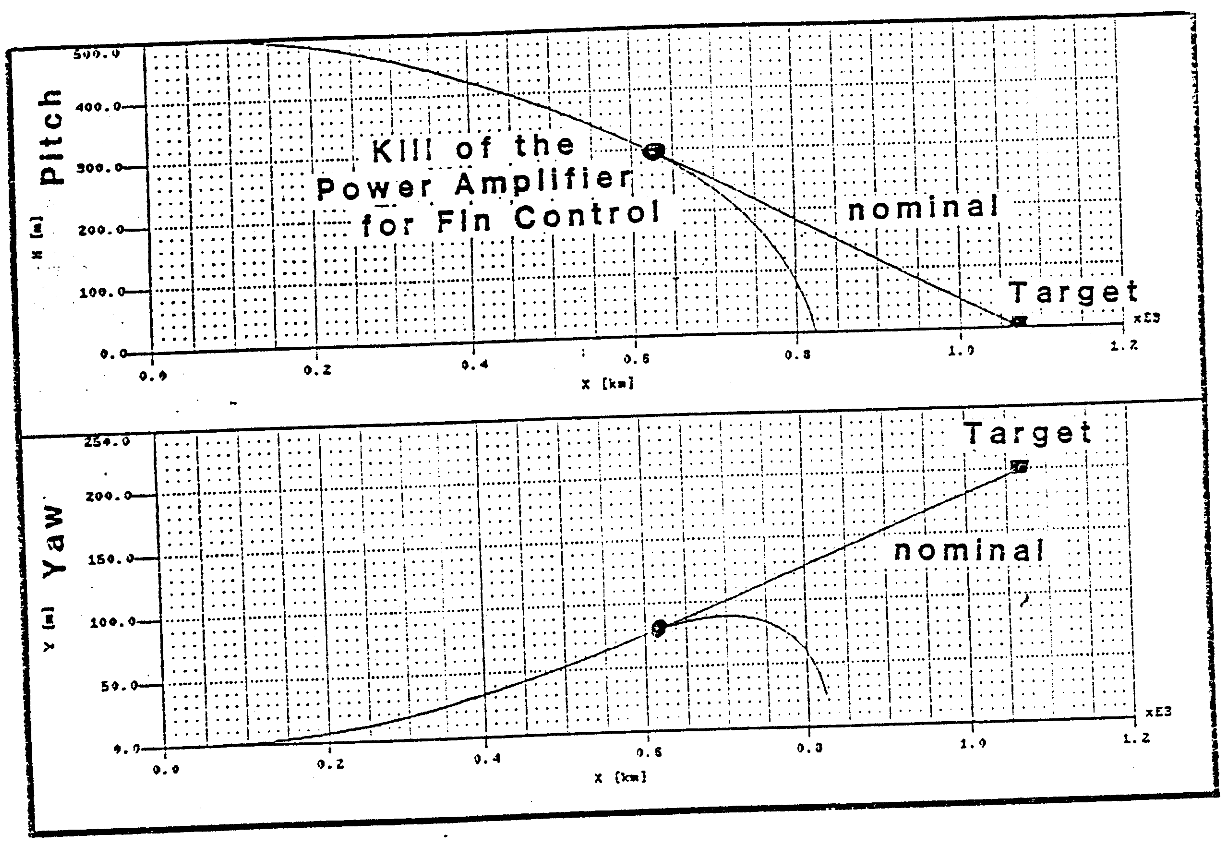


Figure 7-1: Final Homing with the Burn-Out of a Power-Amplifier of the CAS

Consideration of Measured and Assumed Signal Interferences

In the following simulation steps the measured interference signals of the fin deflection signals and the IMU signals, separately and in combination, were considered. Additionally a potential interference on the seeker gimbal angle signals was considered. The seeker was for all simulation runs in the loop. The figure 7-2 shows the flight path degradation due to the measured and assumed signal interferences.

a.) Flight path degradation with measured IMU-signals (body rates and accelerations) only
These signals are the inputs for the guidance and control loop. The oscillating resonances on the IMU signals have hardly any effect on the guidance character of the missile. The strap down in the autopilot integrates the IMU-signals which means that an oscillation will not be recognized as an interference.

b.) Simulation runs with combined interference from CAS and IMU.
The simulation results which considered the interference with the CAS- and IMU-signals showed that the missile's flight path hardly could be degraded in performance. The reason for this effect is that the interferences on the signals have an oscillating character. Much better effects for system interferences can be reached if the signals show offset shifts.

c.) Theoretical interference of the gimbal signal to interfere with the track loop
A closer look at the internal state variables show that the CAS- and IMU-signal interferences have a strong influence on the track loop. The nominal deviation within the sight-of-view is about ±0.15° in comparison to the jammed sight-of-view which reaches the limit of about ± 1.2°. In case the interference causes a deviation greater than 1.2° the target is lost and the flight mission can not be fulfilled. An interference of 3 % on the gimbal signals lead to a loss of the target already.

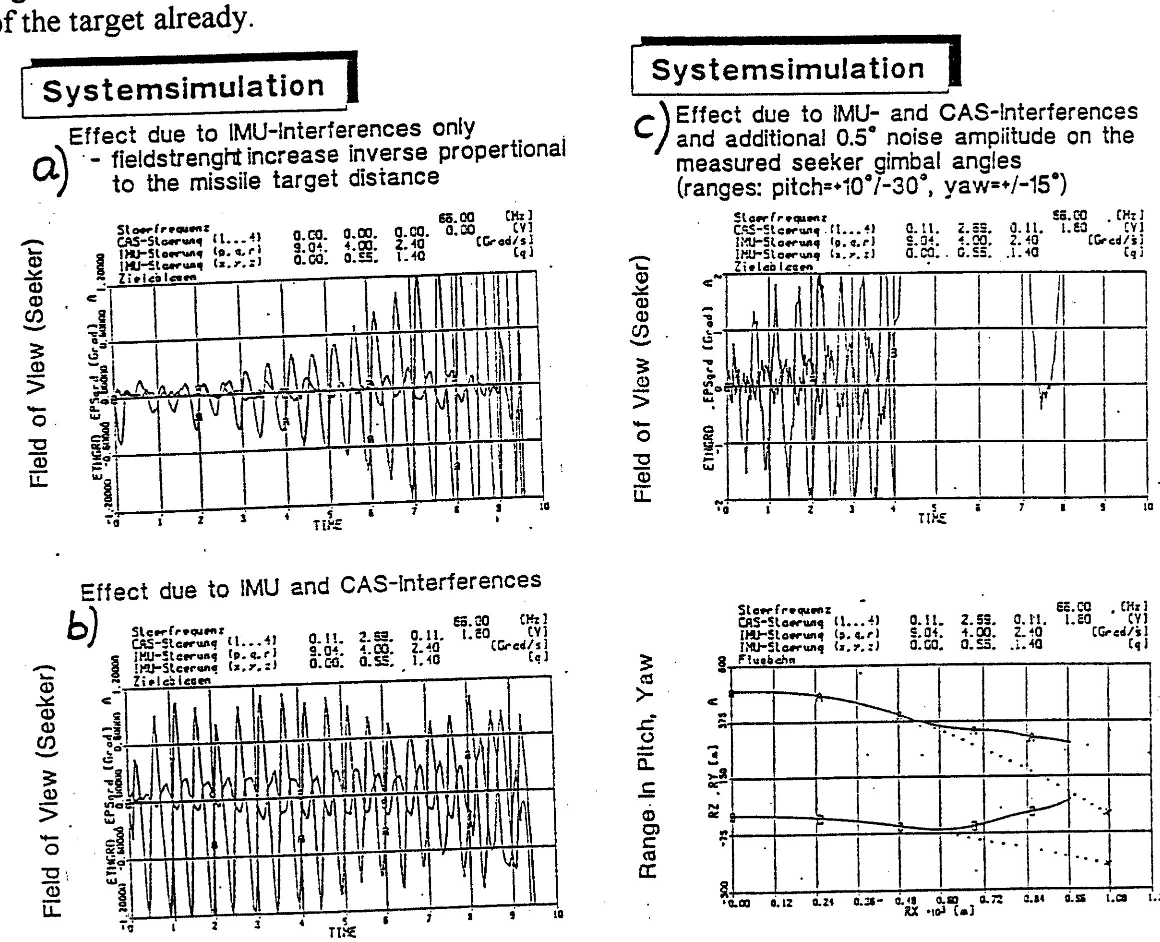


Figure 7-2: Flight Path Degradations due to Signal Interferences