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Information Branch

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TECHNICAL PAPER

AUTOMATIC RENDEZVOUS AND DOCKING: A PARAMETRIC STUDY

I. INTRODUCTION

Automated rendezvous and docking is a technology goal which has been identified for Teleoperator Maneuvering system (TMS), Orbital Transfer Vehicle, and space station applications [1,2]. In this study, the performance of a video-driven system [3], employing the same type of data as a remote human pilot, will be investigated under a wide variety of conditions, including target attitude misalignments and angular rates. Since previous studies have already established the feasibility of automatic docking, quantitative determination of the system's abilities and characteristics will be emphasized; the sources of limitations will be identified and possible improvements suggested.

This report will first explain the functioning of the various components of the system, such as the sensing devices, image analysis algorithms, goal setting logic, and control laws. The techniques used to model each of these elements in the digital computer simulation are then described. The remainder of this document is devoted to the discussion of simulation results and is divided into three sections: docking performance, fuel/time efficiency, and noise-related effects. The first of these establishes the range of initial conditions within which a successful docking is likely to result, using data from the digital simulation. It also identifies system characteristics which limit this range and suggests possible improvements. The second section examines the relationships between fuel/time requirements and target conditions; patterns of behavior resulting in waste are identified and corrective measures proposed. Finally, the effects of system noise are investigated; the various mechanisms by which noise degrades performance and efficiency are discussed.

II. POSITION AND ATTITUDE SENSING SCHEME

The technique currently under investigation uses a docking pattern consisting of three individually distinguishable lights or reflectors attached to the target spacecraft (Fig. 1). They can be differentiated from one another by color, shape, or a timing sequence, and switched on or illuminated by the chase vehicle. To facilitate unambiguous determination of attitude, one of them must be placed on a short post above and between the other two. The chase vehicle is equipped with a forward-looking digital imaging sensor capable of clearly resolving the target light images throughout the entire rendezvous and docking trajectory. Its output is fed to an image-processing algorithm which computes and identifies the centroids of each image; this function can be performed by either computer software or specially designed hardware. Observed relative attitude and position is then calculated from the centroid coordinates using a mathematical procedure based on geometric projection. A detailed explanation of the derivation of these equations can be found in References 4 and 5.

III. CHASE VEHICLE CONTROL SYSTEM

A. Position/Velocity Control

One such measurement is taken every 1.25 msec and fed to the Kalman filter, which smoothes the position data and derives translational rates. It also maintains a state covariance matrix, which is indicative of the accuracy of the current filter output. Random variations in measurements and thrust magnitude are considered in its computation. The information thusly derived is then passed on to the system's goal-setting logic, which effectively determines the shape of the entire docking trajectory. An "aim point" toward which the spacecraft flies is established for each phase of the maneuver, as a function of the measured range to the target. At the beginning of each computation cycle, a "goal box" is defined about this point, and appropriate translation commands are issued to place the vehicle within the box by the end of the cycle.

B. Attitude Control

The chase spacecraft attitude control system has two largely independent functions it must perform. First and foremost, it must keep the docking target image within the field of view of the imaging sensor, which is not steerable independently of the chase vehicle itself. This objective is acheived by constantly issuing pitch and yaw commands to keep the image as close to the center of the field of view as possible. This same technique also works reasonably well during the final approach phase of the maneuver, since proper alignment of docking target and sensor will automatically align the docking fixtures if the various devices are strategically positioned. Additionally, proper relative roll alignment must be attained before docking can, in most cases, be successfully attempted. This system establishes roll alignment as soon as possible and maintains it for the entire duration of the maneuver. Roll control is implemented by simply issuing commands as necessary to keep the relative alignment within certain tolerance limits.

For both attitude and position control, the same basic quadratic phase plane digital switching logic is used. Given the velocity, time limit, thrust range, and acceptable final position limits for a given axis, the algorithm determines whether or not a command should be issued to the respective control channel. Actual implementation of these commands is carried out by thruster selection logic and tables.

IV. THE COMPUTER SIMULATION

A block diagram of the all digital simulation used in this study is shown in Figure 2. The programs represented by most of the blocks are constructed much as they would be in the actual flight software. A mathematical model of the chase vehicle including its thrusters is used to determine its true motion and provide simulated inertial measurement unit information. Utilizing this and a similar target spacecraft motion model, the centroids of the target pattern light images as seen by the chase vehicle sensor are computed. Random numbers having a Gaussian distribution are then added to these coordinates to simulate the effects of electrical noise and other uncertainties. This data is fed directly into the image interpretation program, which computes "measured" relative attitude and position and sends it to the Kalman filter just as an actual system would.

The criteria for a successful docking were chosen to correspond to the characteristics of the Remote Manipulator System (RMS) grapple fixtures. That is, the end of the docking probe must be within the fixture and at an angle of less than 15 deg from perpendicular. The simulation continues to run until this condition is met or a preset time limit is exceeded.

V. RESULTS

A. Docking Performance

One of the primary goals of this study was to establish the range of initial conditions within which a successful dock would be highly probable. To achieve this objective, a large number of runs were made from the design-maximum initial range of 300 m, gradually increasing the parameter of interest until successful docking was no longer possible, while holding all other parameters to a constant (usually zero) value. Since range may be an important factor affecting the performance of an automatic system, this procedure was repeated for initial distances of 50 and 100 m. The results are summarized in Figures 3a and 3b, from which several important conclusions can be drawn. One surprising result is that the system can tolerate higher target pitch and yaw rates as the initial range is reduced. One reason for this behavior is that the target does not have time to rotate very far from its initially aligned state before the chase vehicle arrives if the initial range is fairly small. If the range is large, however, the target lights may rotate out of view before the chase gets close, thus making a successful dock unlikely. Also, a tendency has been observed (Fig. 11) for the chase spacecraft to overshoot the target when rates are high and the initial range large. This phenomenon is a result of the chase vehicle rotating itself into an attitude such that the relatively weak Y or Z thrusters must be used for braking rather than the more powerful X thrusters which initially accelerated it. In cases where the initial range is large, a high forward velocity is developed, rendering these small thrusters incapable of slowing the vehicle soon enough. Unfortunately, this situation is largely unavoidable, since it must orient itself so that the sensor is aimed at the target at all times. The undesirable effects, however, could be avoided if the control system could anticipate early in the maneuver if this situation would later arise. In these cases, braking could begin earlier to compensate for the reduced thrust available. One possible implementation of this approach would be the inclusion of a Kalman filter for accurately deriving target attitude rates and thereby predicting chase vehicle attitude prior to arrival. Since this same difficulty is responsible for limiting the maximum initial target angles, such an improvement would be most worthwhile. In fact, the chase vehicle would theoretically be capable of continuing on its original course almost totally unaffected, even if the target were to disappear from view.

The system possesses two qualities which effectively place limits upon the permissible target roll rate. The first of these is the roll control limit cycling range, which increases with the target roll rate. For those docking fixtures requiring accurate roll alignment at the moment of contact, this effect will limit the acceptable target roll rate to a relatively small value. Even if the docking fixture does not require roll pre-alignment, there are secondary effects induced by this phenomenon which can influence pitch and yaw performance; these will be discussed later. This limit cycling is clearly evident in Figures 4, 5, and 6, which show relative roll versus time for target roll rates of 1, 2, and 3 deg/sec, respectively. The first of these shows relative roll cycles between +3 and +15 deg during the final phase of the maneuver. As roll rate increases, so does the cycling range, with maximum relative alignment reaching 25 and finally 35 deg. Even larger misalignments occur when the roll information from the sensor (shown as a dashed line in the figures) is heavily corrupted by noise due to great distance from the target. These errors are not a problem as far as meeting docking conditions is concerned, but do result in considerable propellant wastage.

Another important aspect of target roll rate is its effect upon chase vehicle pitch and yaw control capabilities. It has been noted that sudden deviations from previously accurate docking axis alignment begin to occur as the two spacecraft closely approach each other. Examples of this phenomenon are shown in Figures 7, 8, and 9, wherein docking takes place from a distance of 300 m, with an initially aligned target having a roll rate of 1, 2, and 3 deg/sec, respectively. From these figures, it is obvious that both a low and high frequency component are present in the deviations. The latter is due to the normal limit cycling of the pitch and yaw control and has no significant effect upon system performance, due to its limited peak-to-peak swing. The predominant low frequency component, however, is of greater amplitude and can, in some cases, drive the docking axis far enough out of alignment to prevent docking. Its instantaneous magnitude has been determined to be related to the instantaneous relative roll misalignment when the two vehicles are close together. Evidence for this cross coupling can be found by comparing Figures 4, 5, and 6, representing relative roll versus time, with their respective counterparts in Figures 7, 8, and 9. Such a comparison will reveal that the worst docking axis misalignments coincide with the worst roll alignments, once 100 sec or so have passed. A check of the corresponding distance versus time graphs has revealed that the spacecraft are less than 65 m apart by this time. The times of best alignment also coincide; even the slopes of the curves are clearly related. Since the relative roll curve contains only a single low frequency sawtooth wave component, we know that the pitch and yaw do not significantly affect roll control.

Unfortunately, it turns out that this behavior is an inherent property of the control scheme itself. It is designed to keep the chase vehicle sensor pointed at the target at all times by adjusting pitch and yaw such that the target image is always centered in the field of view, as shown in Figure 10a. For various reasons previously discussed, this is an appropriate technique for use at large distances from the target. During the latter portion of the maneuver, however, it can result in actions which would actually reduce the probability of a successful dock. Under the conditions depicted in Figure 10b, where the docking axes are otherwise perfectly aligned, a roll misalignment results in an offset of the target image from the center of the field of view. Consequently, the control system will issue unnecessary pitch and yaw commands which will degrade the pitch and yaw alignment that originally existed.

Fortunately, several modifications are possible which would likely eliminate or reduce these effects. The simplest of these would be a reduction in the roll control deadband. Here, the roll misalignment would always be limited to a value which would hold the roll-induced side effects to a more tolerable level. One disadvantage of this approach would ordinarily be an increase in fuel consumption due to more frequent roll thruster firings. If, however, the deadband is controlled by the goal-setting logic and reduced as the chase vehicle closes in, the increase should be minimal. Alternatively, the target offset could be subtracted out so that the chase vehicle always points toward the docking fixture rather than the target. The use of a completely different technique at extremely close range is also a worthwhile option, which will be discussed later.

B. Fuel and Time Requirements

In order to determine how efficiently the automatic docking system performs under a wide variety of conditions, fuel consumption and time required to dock were investigated for a large number of test cases. Examination of this data reveals interesting trends which reflect the manner of control system response to target rates, random noise, and large initial misalignment angles. Although the system performs reasonably well in its present form, areas in which productive improvements could be made have been identified.

In general, fuel consumption and time requirements minimization are conflicting objectives for any spacecraft, whether automatically or manually controlled. That is, any time reductions achieved by attaining a higher average velocity during the trip will be at the expense of additional fuel needed to accelerate and decelerate the chase vehicle. It is meaningful, however, to optimize the system such that the product of time and fuel will be held to a minimum. There are several techniques applicable to an automatic docking system in pursuit of this goal, requiring only slight increases in computational resources. In almost all cases, both the fuel and time requirements tend to increase with the initial docking axis misalignment for a given initial range. This is primarily because the system is currently programmed to fly a curved trajectory in such cases, which require additional fuel for Y and Z axis accelerations and attitude adjustments. Similar increases in these requirements occur concurrently with pitch or yaw rate, for much the same reasons. Also, these rates can result in the chase vehicle wasting fuel by "hunting" for proper docking axis alignment, as can be seen in Figure 12, wherein the vehicle spends 150 sec attempting to align the docking fixtures. Figure 13 shows that 17 kg of fuel were used in the process. This oscillatory motion occurs because the attitude control system responds to a given rotation of the target spacecraft by initially rotating the chase spacecraft in the opposite direction. The source of this behavior can be understood by examining Figure 10c, which depicts the image seen by the docking sensor under close-range pitch misalignment conditions. For clarity and compactness, these drawings were made as if seen by a sensor having a field of view wider than that currently modeled in the simulation. The principles they illustrate, however, are valid nonetheless. In this illustration, the target spacecraft is shown centered vertically in the field of view with a +45 deg pitch misalignment. It is clear that an appropriate response would be for the chase vehicle to also pitch in the same direction to reduce the docking axis misalignment. With the present attitude control scheme, however, it will actually pitch in the opposite direction to re-center the docking target image, thereby actually worsening the alignment. It is true that maintaining target visibility is an important consideration but, at close range, docking axis alignment should be made the top priority. Such a change would not only reduce fuel consumption and time requirements, but also probably permit better docking at higher angular rates.

C. Effects of Noise

As previously discussed, a Gaussian random number generator was used to simulate electrical noise and other random disturbances in the system; apparently, this noise has a greater effect on fuel consumption than any other parameter yet investigated. This is clear from Figure 14, which contains fuel and time requirements data for several runs made with and without random noise from an initial range of 300 m. In every case, the fuel consumption increased dramatically (106.43 percent average rise) when the noise was included. Additionally, more time was needed to complete the maneuver in most cases. The mechanism responsible for the former was found to be random thruster firings brought about by noise-contaminated target attitude measurements, as shown in Figure 15. This plot was made while docking with a perfectly aligned nonrotating target from a distance of 300 m. It shows that these measurements are practically meaningless in their unprocessed form at distances greater than about 80 m, often deviating as much as 50 deg from the correct value. Because the chase vehicle is designed to approach the target spacecraft along its docking axis, accurate knowledge of its attitude is essential throughout the entire trajectory. Normally, the chase uses its Y and Z thrusters to approach the docking axis, while employing the powerful X thrusters to accelerate toward the target. Since the measured target attitude varies erratically, however, many unnecessary Y and Z firings are made which actually cancel each other, resulting in the waste of considerable fuel. Figures 16a and 16b show the total number of X, Y, and Z translation commands issued during a dock with an aligned nonrotating vehicle, the former representing a run made with the noise and the latter without. In the noiseless case, fewer Y and Z commands than X commands are issued; also, the regular intervals at which the firings occur indicate that they are due entirely to normal limit cycling. When noise is introduced, the number of firings on all axes increases dramatically, and occur practically continuously, as the smooth cumulative firing curves indicate. It has been noted from these figures that the number of X-thruster commands also increased, although not as much as did the Y- and Z-firings. Since the forward (X) velocity of the chase vehicle is controlled primarily as a function of range and range rate, it is possible that the noise remaining in the

Kalman filtered signal may be partially responsible. Another possible cause is the suboptimal path taken by the vehicle when the noise is present, as shown in Figure 18. Although the number of X-firings during the run did not increase as much as did the Y and Z, this is just as significant because the X-thrusters are larger and consume more fuel. As for the chase vehicle attitude control, it is interesting to note that no attitude adjustments commands at all were needed when noise was not present (Fig. 17a), but quite a few were required when it was added (Fig. 17b). Examining Figure 17b in detail reveals only normal limit cycling on pitch and yaw control but an abnormally linear roll firing curve. Since pitch and yaw control require only a knowledge of relative target azimuth and elevation, measurements relatively unaffected by sensor noise, these channels operate normally during its presence. Roll measurements, however, are heavily contaminated as Figure 15 indicates, resulting in the issuing of many unneeded roll commands and heavy fuel consumption. One possible solution to this problem would be the removal of the roll error signal from the control loop when its accuracy is inadequate for efficient operation. The chase spacecraft could be held at a constant roll attitude by the inertial reference system until the range had decreased and the measured roll accuracy improved. At this point, closed-loop roll control would begin, and the chase vehicle, having a powerful roll acceleration, would match the rate of the target and achieve alignment before contact occurs.

IV. DYNAMIC GRAPHICS SYSTEM

Many of the system characteristics described thus far were originally discovered through the use of a computer graphics package developed specifically for use in multi-body dynamic simulations. This software provides a realistic perspective depiction of both spacecraft, as viewed from any vantage point the user selects, including on board the moving chase vehicle. Figures 19, 20, 21, and 22, photographs taken from the screen of a Tektronix 4027 color graphics terminal, are typical of the images it creates. Although these illustrations are in black and white, color is normally used to distinguish certain spacecraft features which might otherwise be difficult to identify. Attitude of the chase vehicle (on the left in Fig. 23) is never ambiguous, even though it is represented by a simple box, because each side is a different color. Figures 20, 21, and 22 are frames taken from a single simulation run with a target pitch rate of 1.1 deg/sec and an initial chase vehicle range of 100 m. As the chase vehicle moves in closer to the target, the viewpoint is also brought nearer to assure maximum resolution. Figure 23 shows the chase vehicle approaching a stabilized target which was initially misaligned in yaw by 75 deg. In this figure, the docking target lights, as well as the arrows representing the inertial coordinate frame axes can be clearly seen; normally these items would all be of different colors. A videotape of four complete simulations has been prepared and has proven useful in understanding the system and demonstrating its feasibility.

VII. CONCLUSIONS

This study has demonstrated that the three-light automatic docking technique works, even under relatively difficult conditions. The ability of this system to accommodate initial docking axis misalignments and rolling or tumbling targets has been well established, and shown to be dependent upon initial range. The amount of noise present in the system, in addition to the target conditions, was found to influence both the time and fuel required for the docking maneuver. By analysing data from runs made at the edge of the system's operating envelope, factors limiting rate and misalignment tolerance have been identified. Modifications which would both improve performance and decrease fuel consumption have been devised and suggested for future investigations.

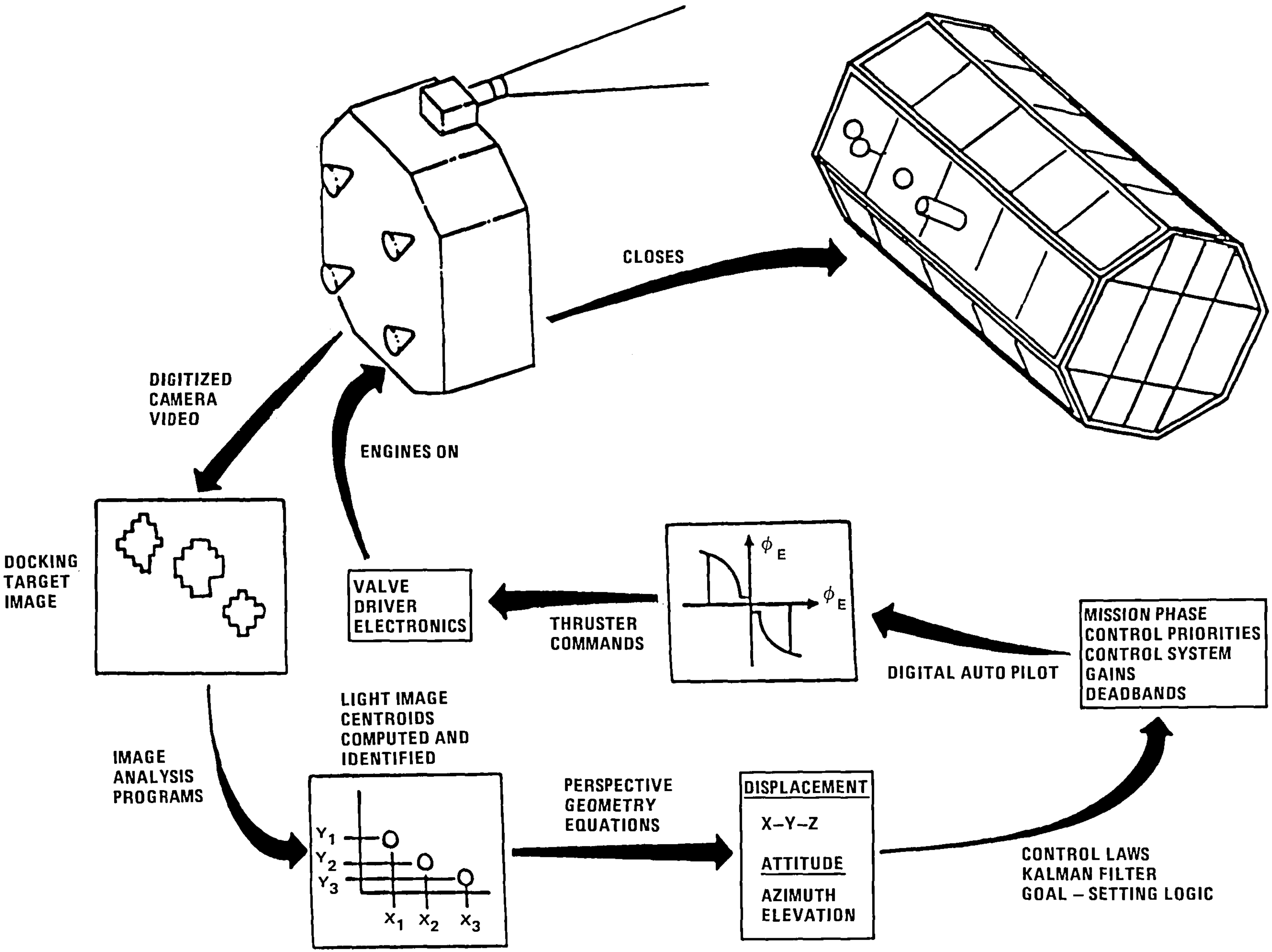

Figure 1. Video docking system.

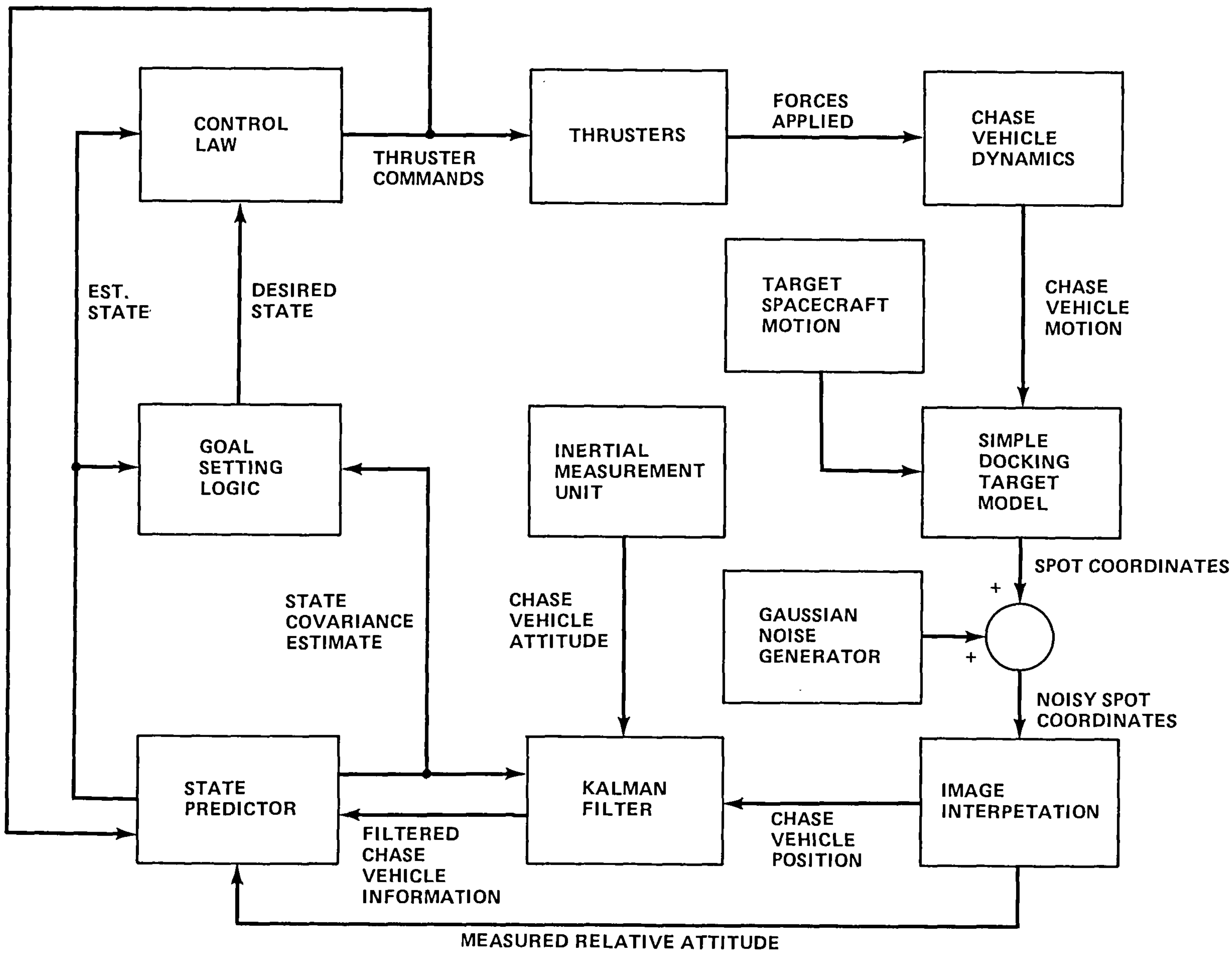

Figure 2. Three-light docking simulation block diagram.

FIG. 3a: MAXIMUM TARGET RATES FOR A SUCCESSFUL DOCKING VERSUS INITIAL RANGE. (RATES IN DEGREES PER SECOND; ALL AXES ASSUMED INITIALLY ALIGNED.)

TUMBLE AXIS	INITIAL RANGE (METERS)		
	300	100	50
YAW	.5	.8	1.1
PITCH	.5	1.1	1.1
ROLL	1.5	1.5	1.5

Figure 3a. Maximum target range for a successful dock.

FIG. 3b: MAXIMUM TARGET AXIS MISALIGNMENT FOR SUCCESSFUL DOCKING. (ALL OTHER AXES ARE ASSUMED ALIGNED; NO RATES PRESENT.)

NONALIGNED AXIS	INITIAL RANGE (METERS)		
	300	100	50
YAW	60^{o}	75^{o}	70^{o}
PITCH	45^{o}	60^{o}	80^{o}
YAW AND PITCH	30^{o}	60^{o}	65^{o}
ROLL	180^{o}	180^{o}	180^{o}

Figure 3b. Maximum target axis misalignment for a successful dock.

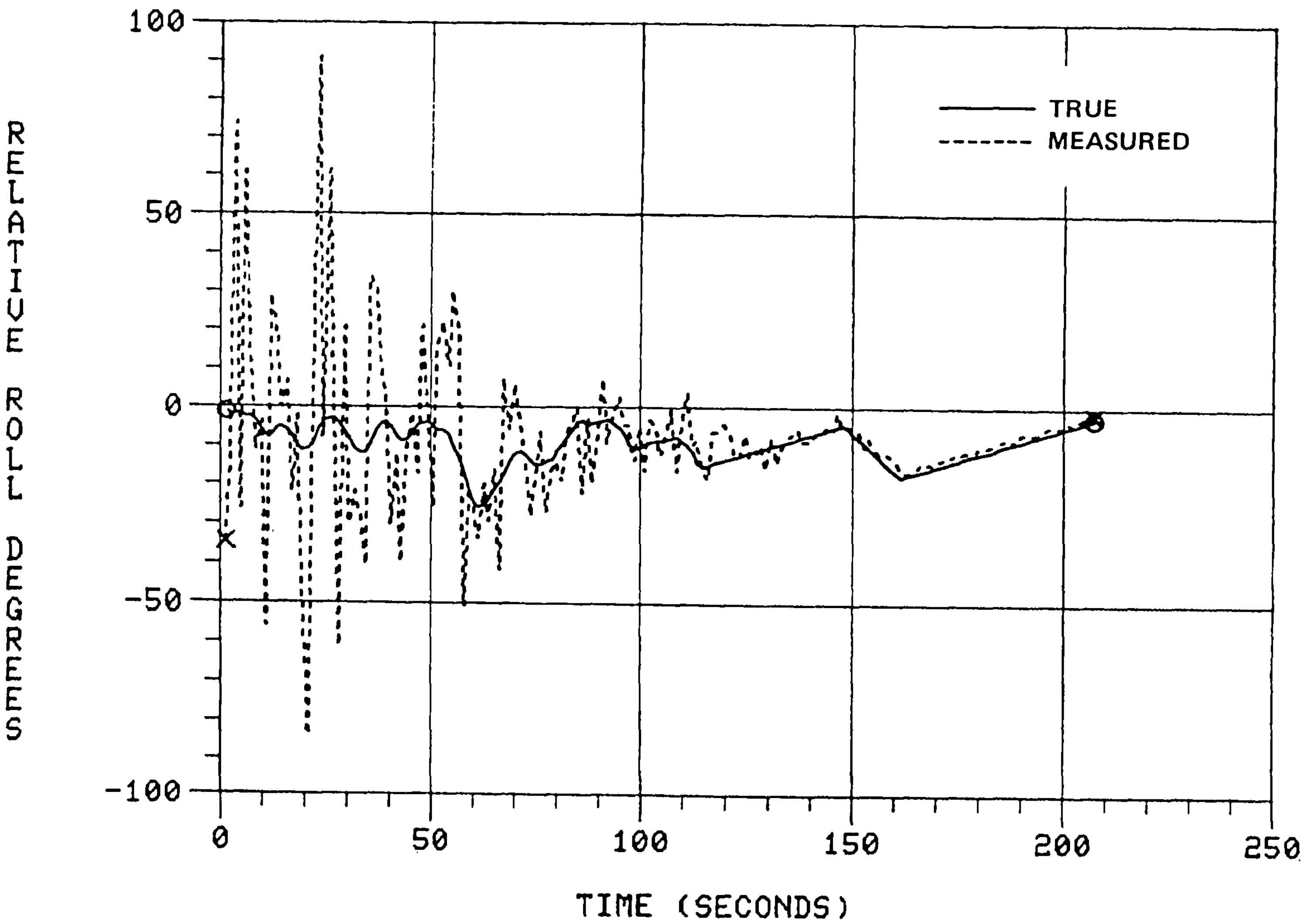

Figure 4. Relative roll versus time with 1 deg/sec roll rate.

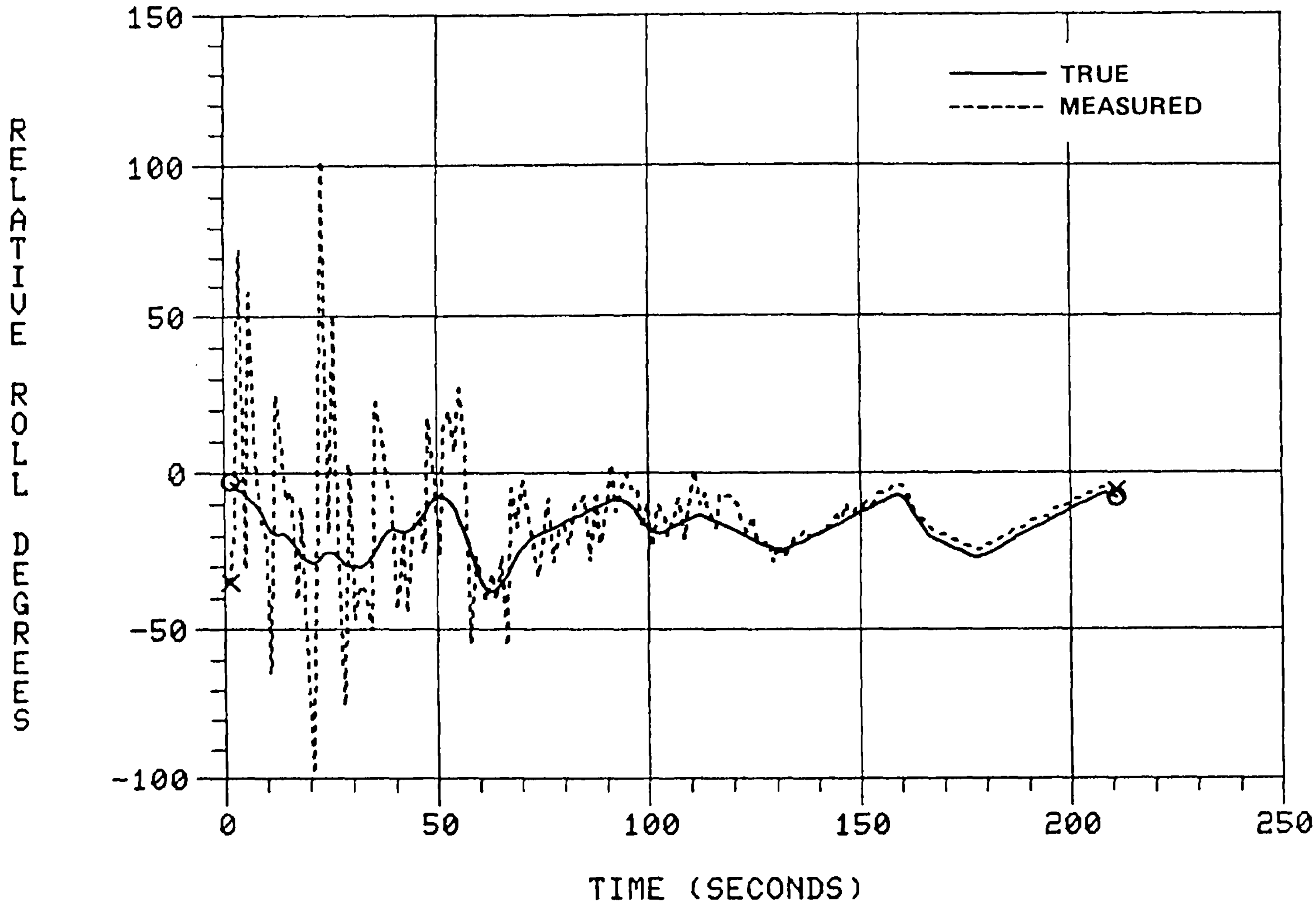

Figure 5. Relative roll versus time with 2 deg/sec roll rate.

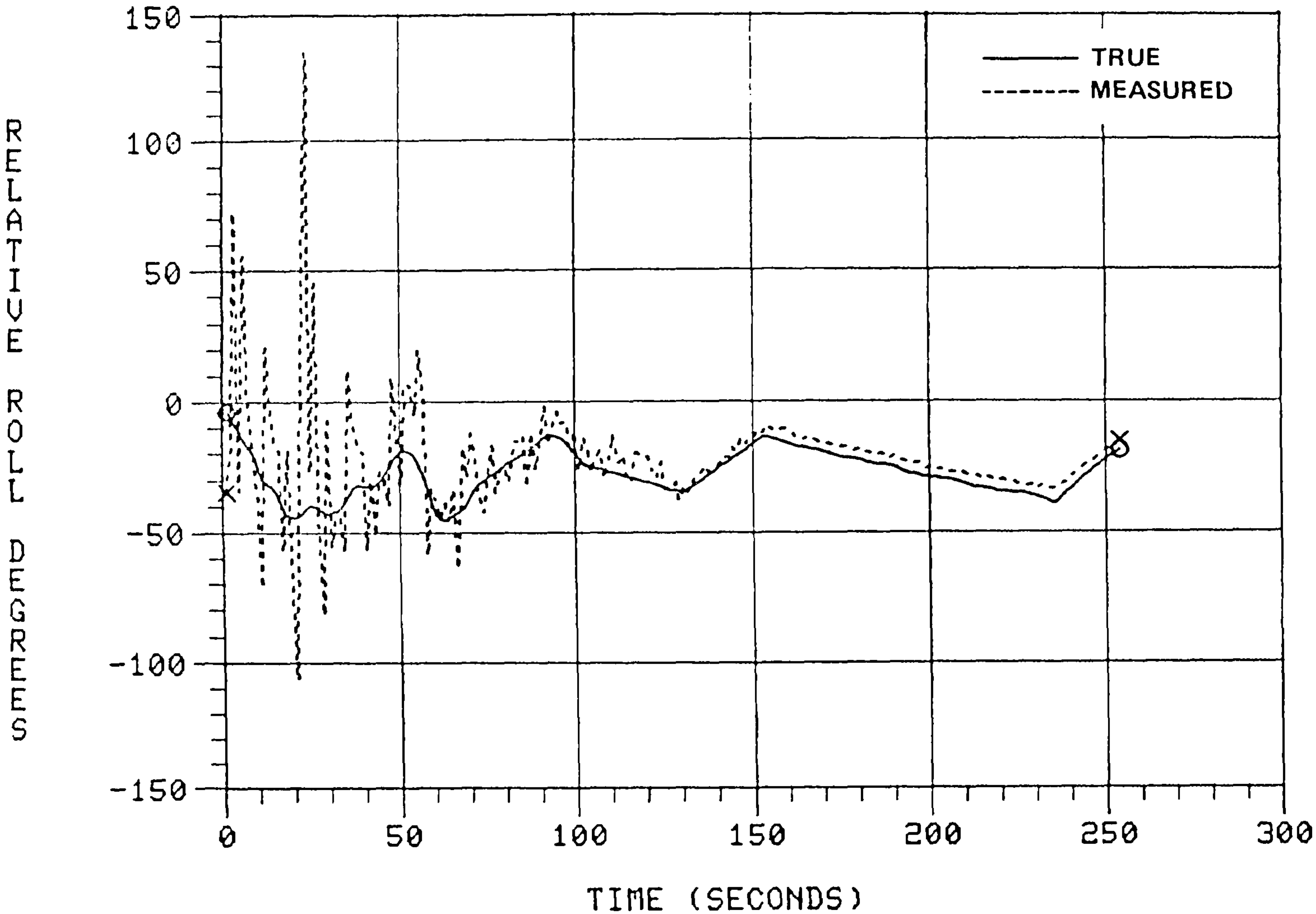

Figure 6. Relative roll versus time with 3 deg/sec roll rate.

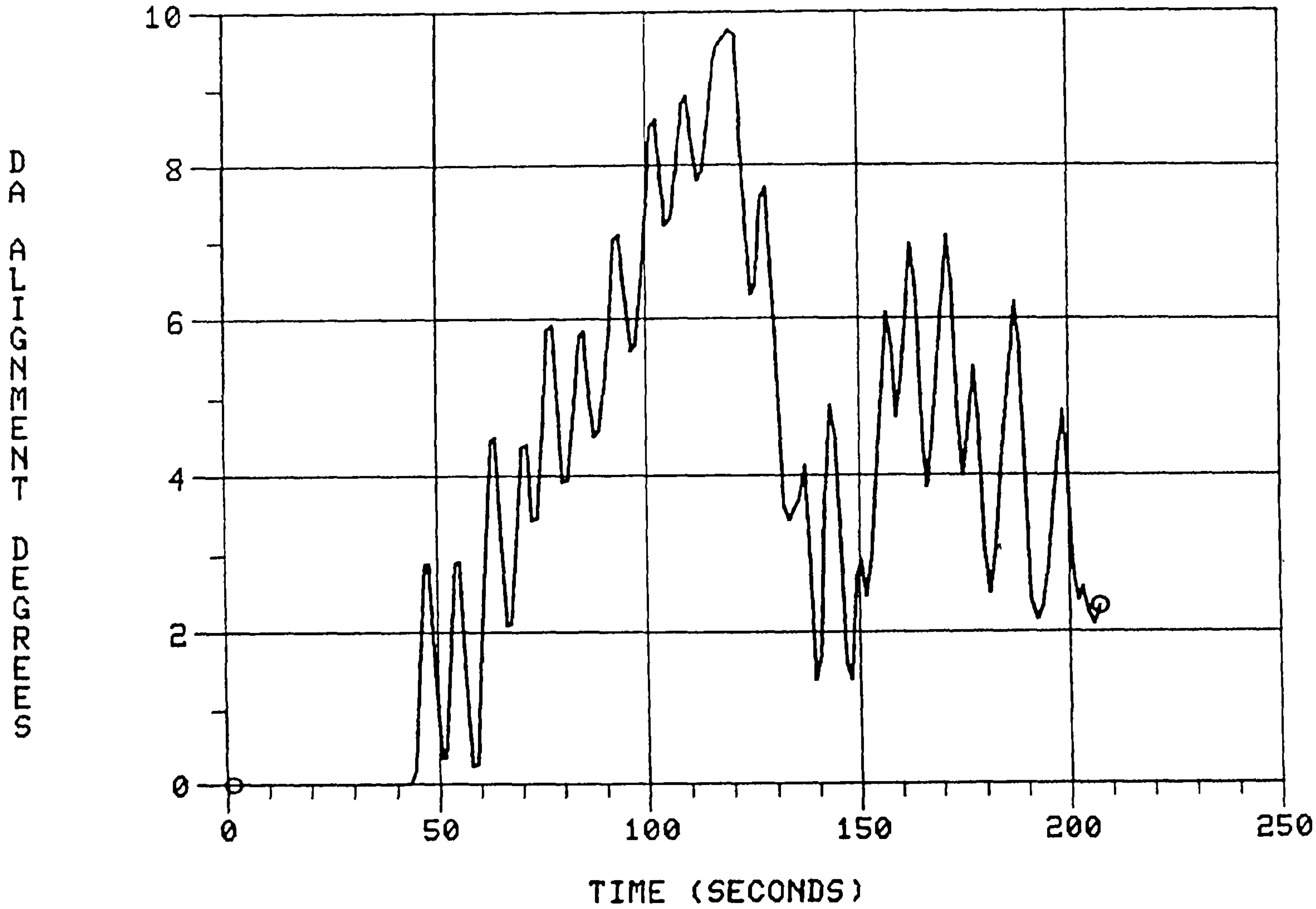

Figure 7. Docking axis alignment versus time with 1 deg/sec roll rate.

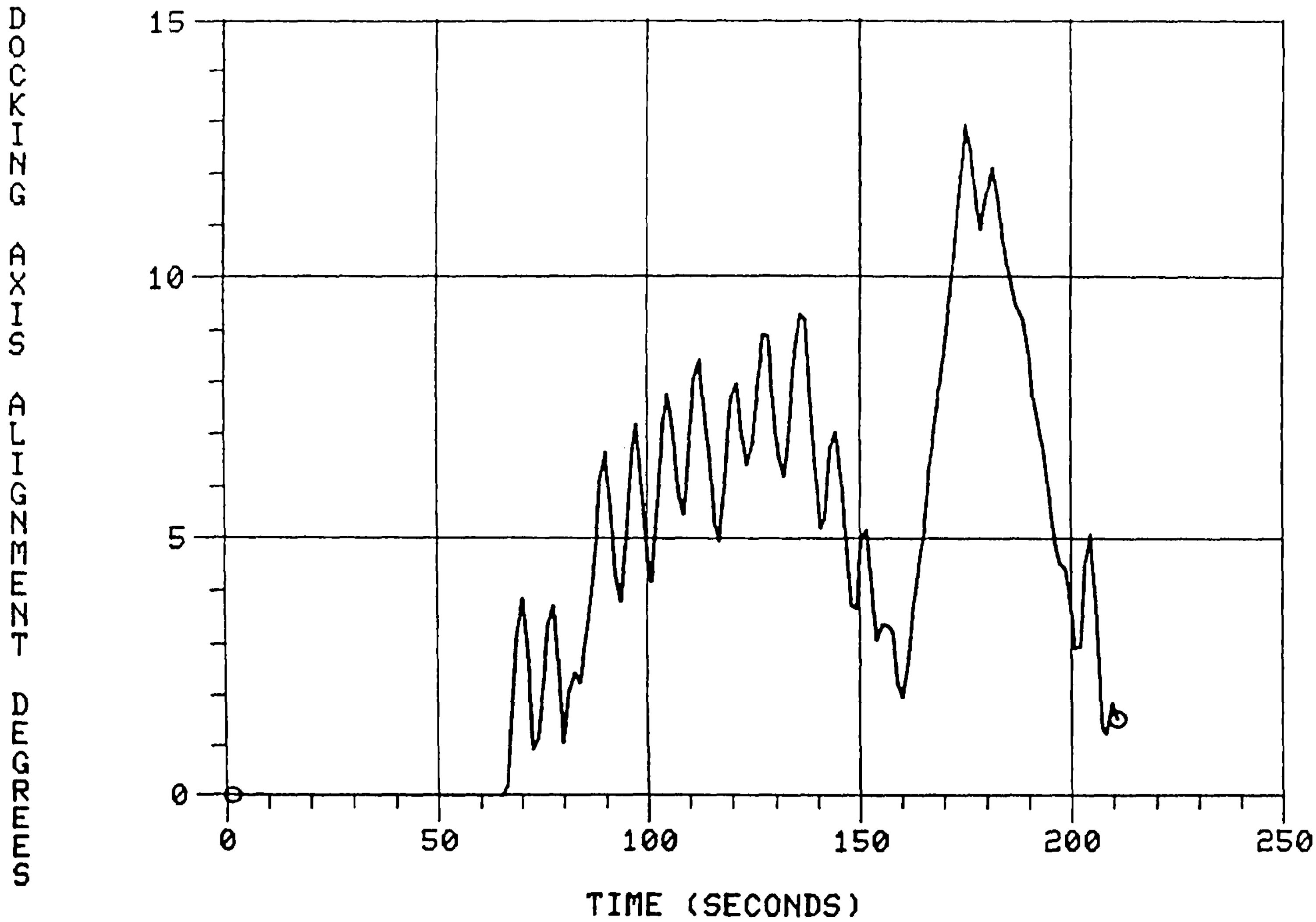

Figure 8. Docking axis alignment versus time with 2 deg/sec roll rate.

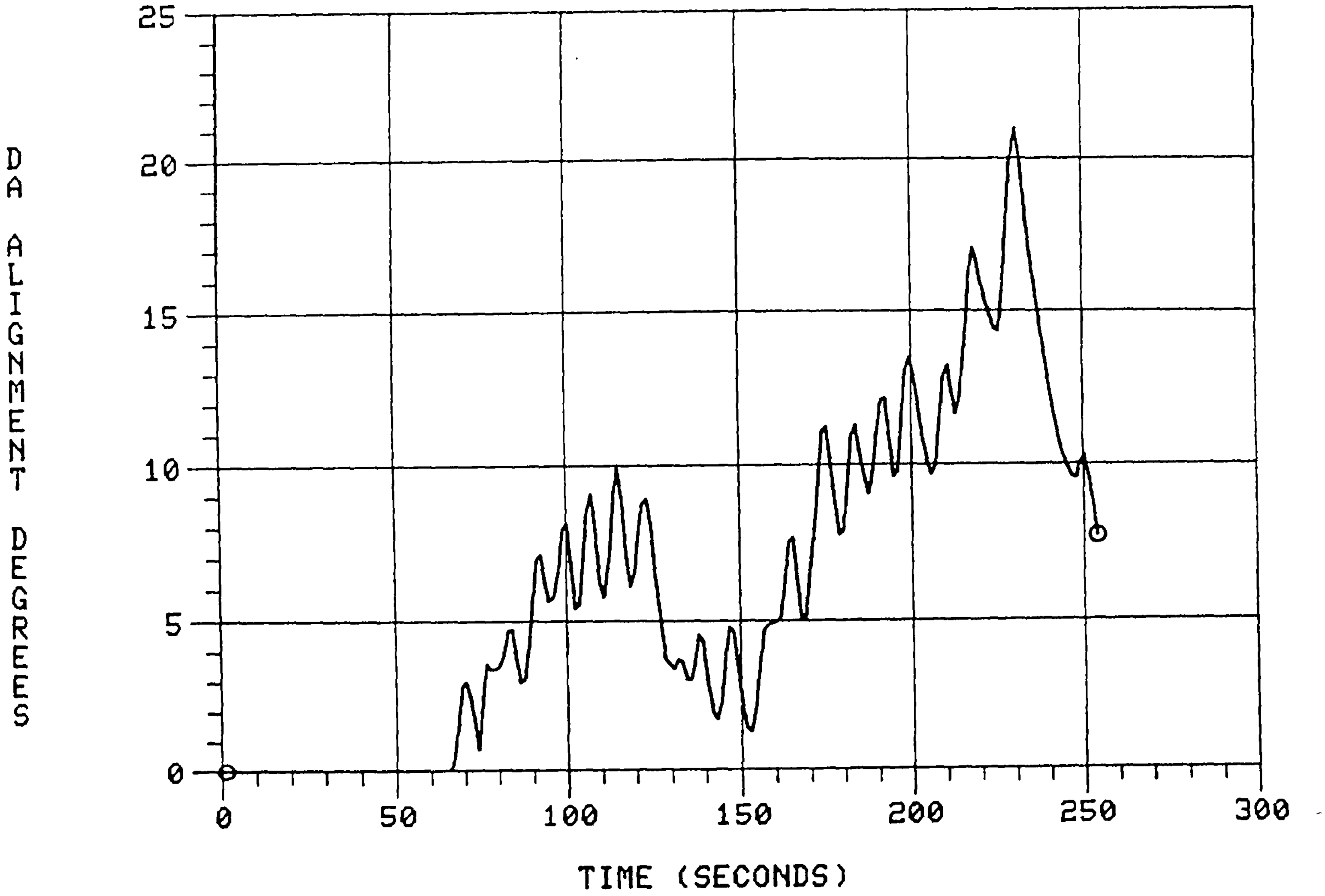

Figure 9. Docking axis alignment versus time with 3 deg/sec roll rate.

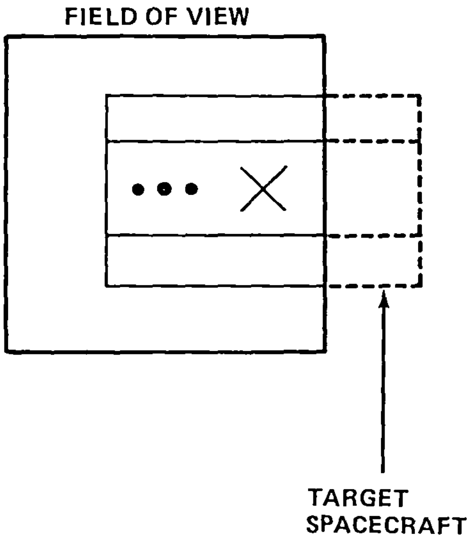

FIG. 10–a: DOCKING TARGET CENTERED IN CAMERA FIELD OF VIEW AT CLOSE RANGE; SPACECRAFT PERFECTLY ALIGNED.

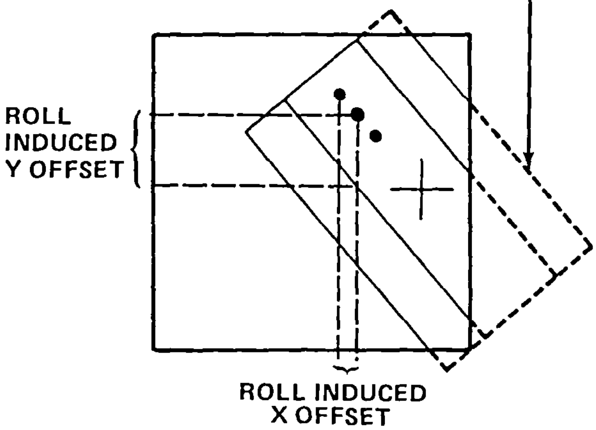

FIG. 10–b: TARGET SPACECRAFT NOW MISALIGNED BY 45° IN ROLL; ALTHOUGH DOCKING AXES ARE STILL ALIGNED IN PITCH AND YAW, THOSE CONTROL CHANNELS WILL RESPOND UNNECESSARILY TO ROLL–INDUCED TARGET OFFSET.

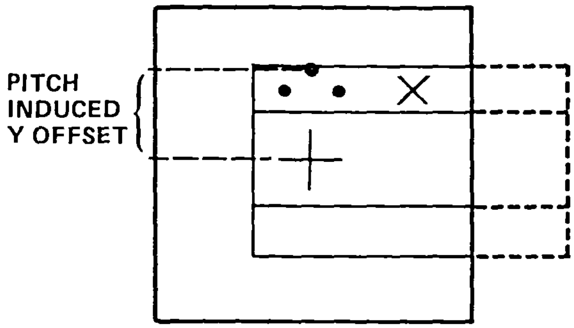

FIG. 10–c: TARGET SPACECRAFT MISALIGNED BY +45° IN PITCH. ALTHOUGH SPACECRAFT NEEDS TO PITCH IN THE POSITIVE DIRECTION TO ALIGN DOCKING AXES, IT WILL DO THE OPPOSITE IN ORDER TO RE–CENTER DOCKING TARGET IMAGE.

Figure 10. Roll-induced target offset.

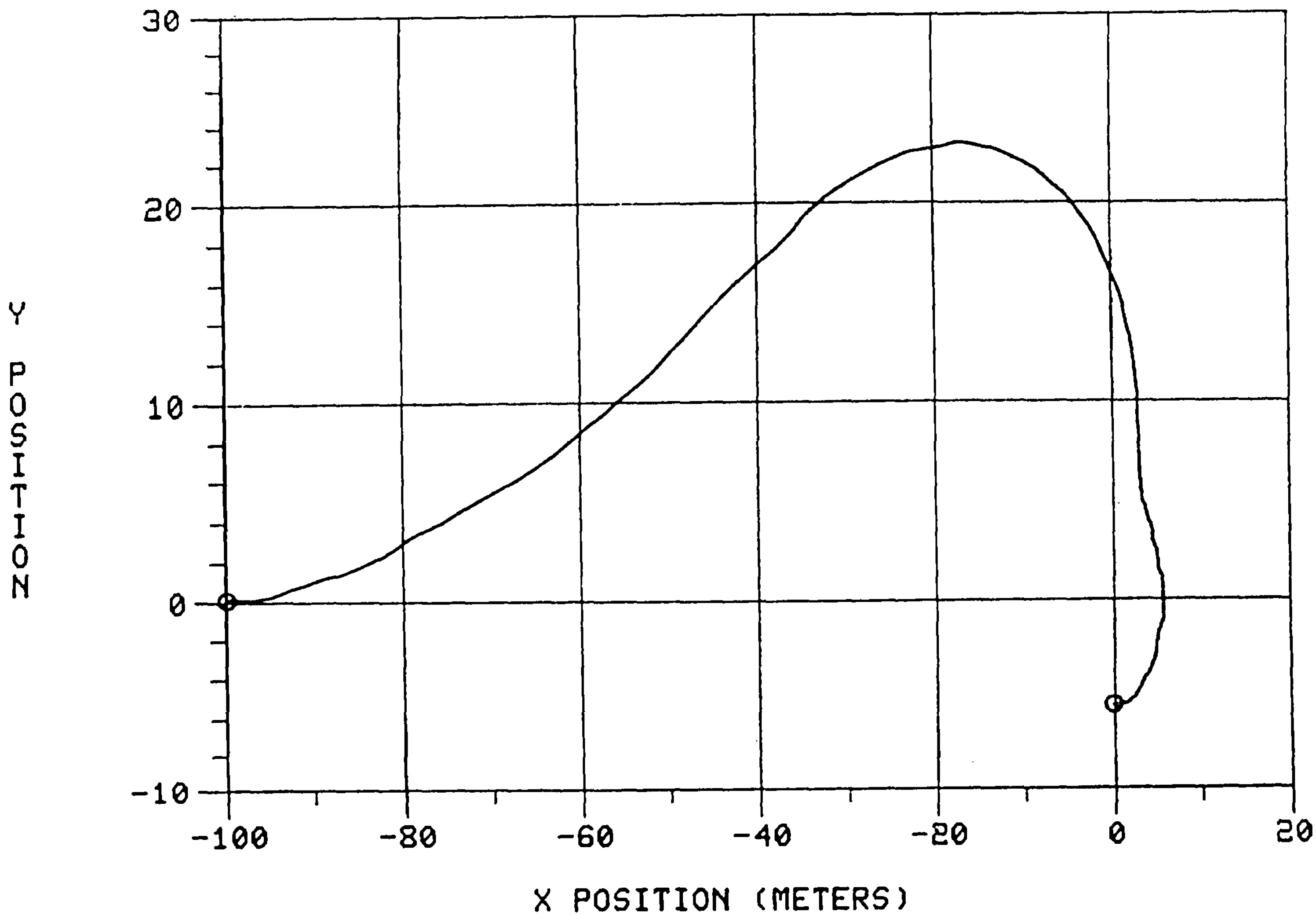

Figure 11. Y versus X position with 1.1 deg/sec pitch rate.

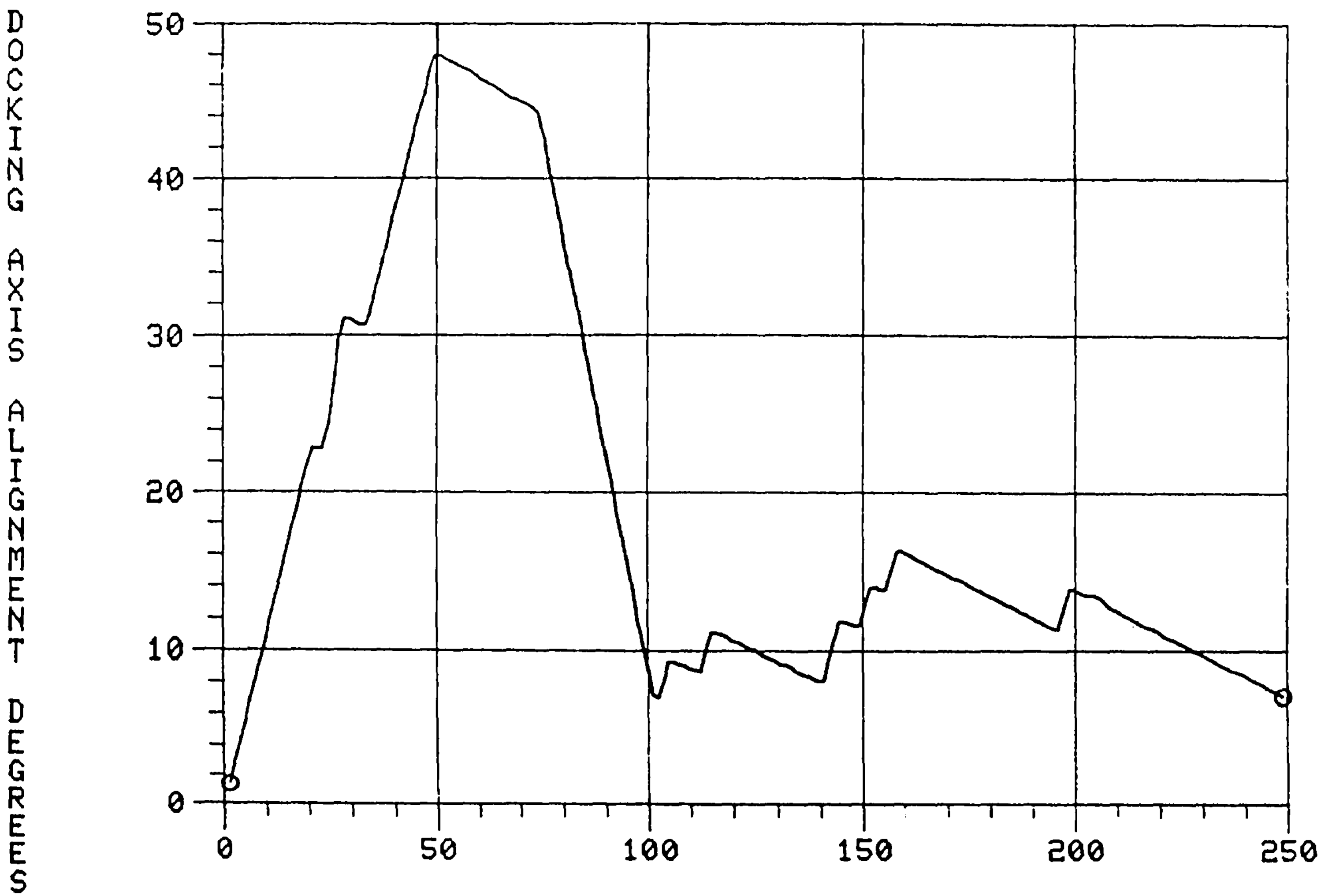

Figure 12. Docking axis alignment versus time with 1.1 deg/sec pitch rate.

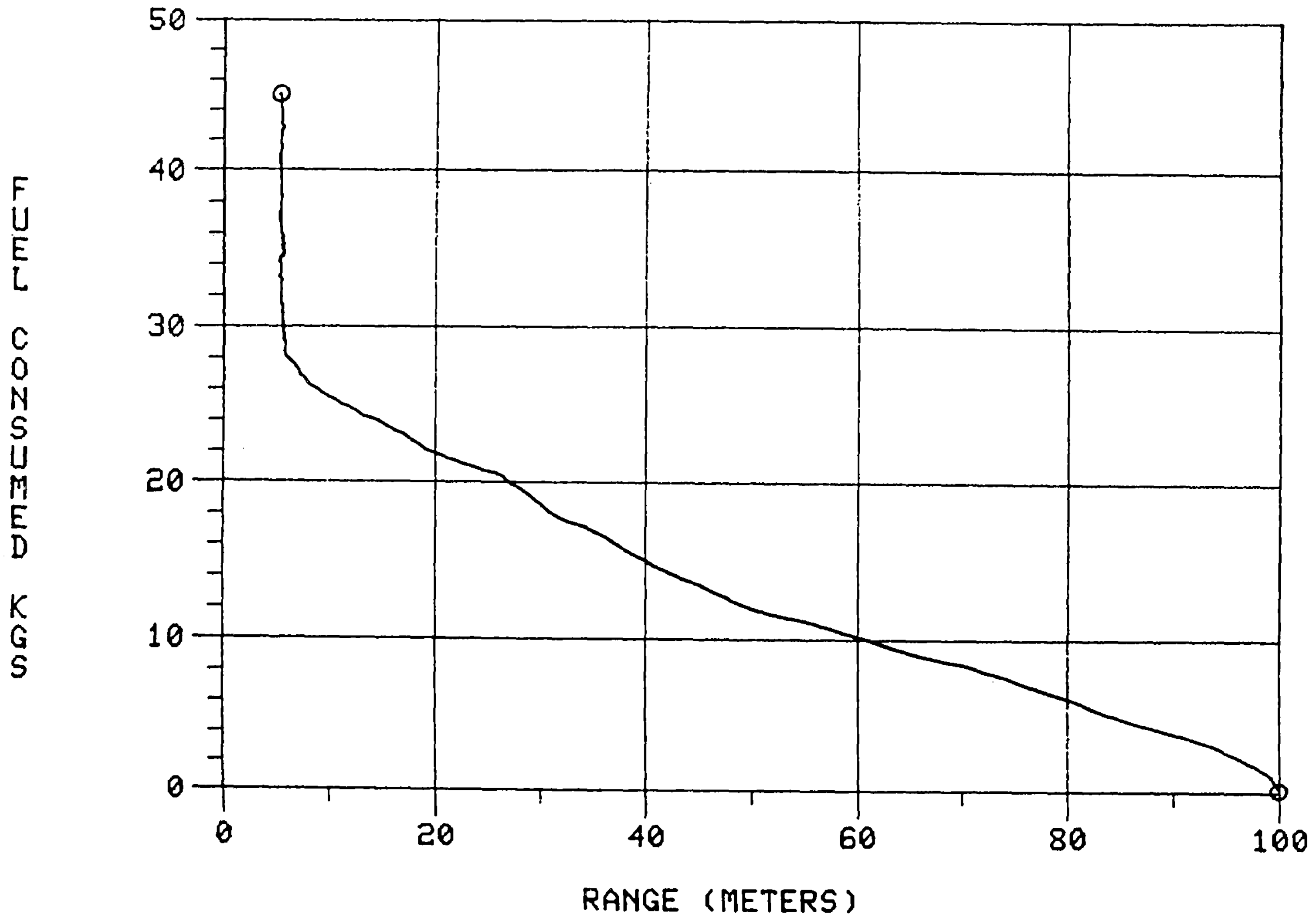

Figure 13. Fuel consumed versus range with 1.1 deg/sec pitch rate.

FROM 300 METERS TARGET PARAMETERS*	NOISE ON TIME	 FUEL	NOISE OFF TIME	 FUEL
60° YAW ANGLE	223.23	53.55	194.87	28.00
45° PITCH ANGLE	239.27	61.02	198.57	25.51
30° PITCH & YAW ANGLES	210.90	54.13	192.40	36.42
.5 DEGREE/SECOND YAW RATE	254.07	59.52	209.67	24.61
.5 DEGREE/SECOND PITCH RATE	203.50	49.10	204.73	22.19
2.4 DEGREE/SECOND ROLL RATE	187.47	44.90	189.93	19.36

*OTHER TARGET ATTITUDE PARAMETERS SET TO ZERO

AVERAGE INCREASE IN FUEL CONSUMPTION WITH NOISE = 106.43%

AVERAGE INCREASE IN TIME REQUIREMENTS WITH NOISE = 10.777%

Figure 14. Effect of noise on fuel and time requirements.

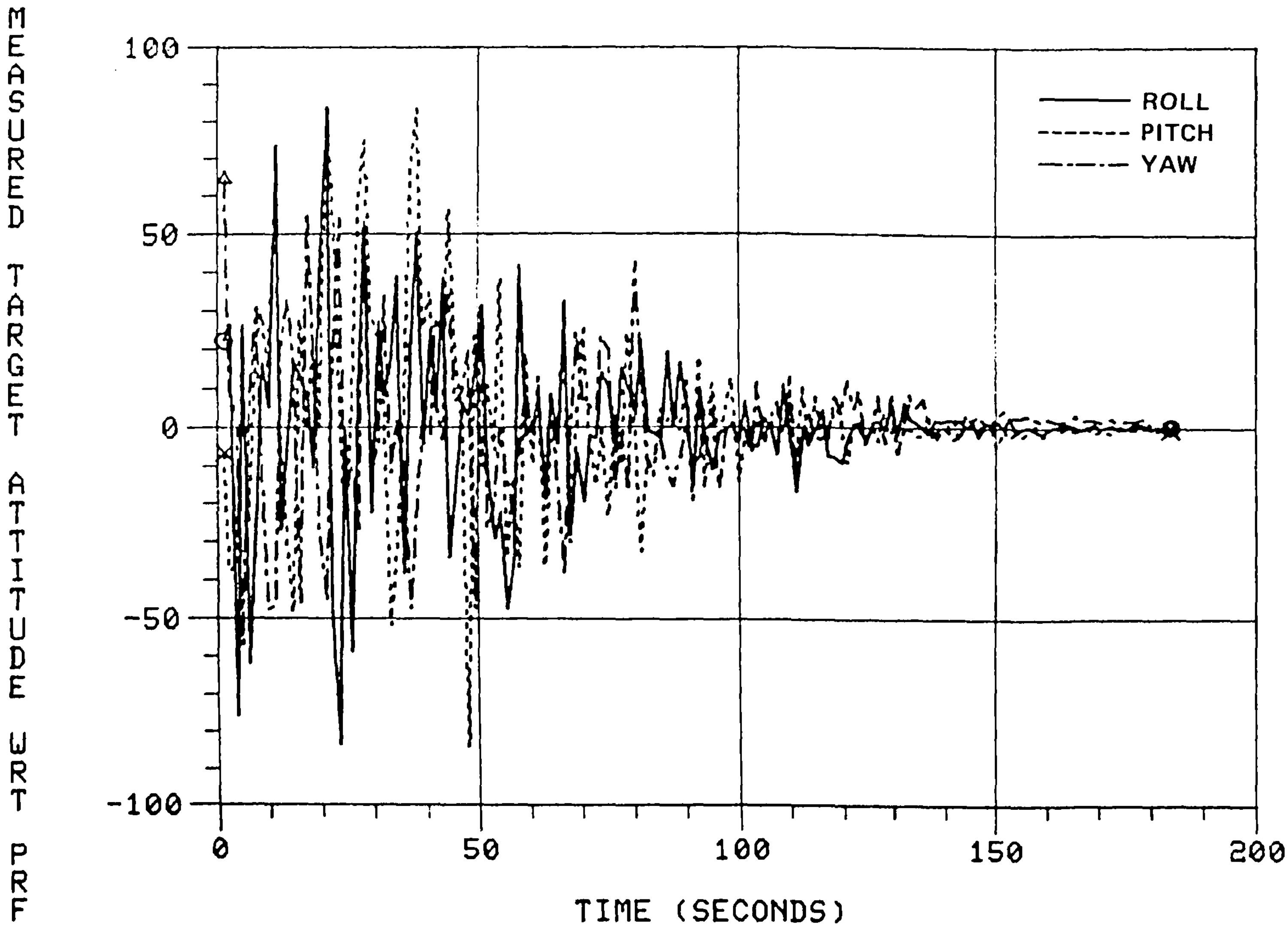

Figure 15. Measured target attitude versus time, noise on.

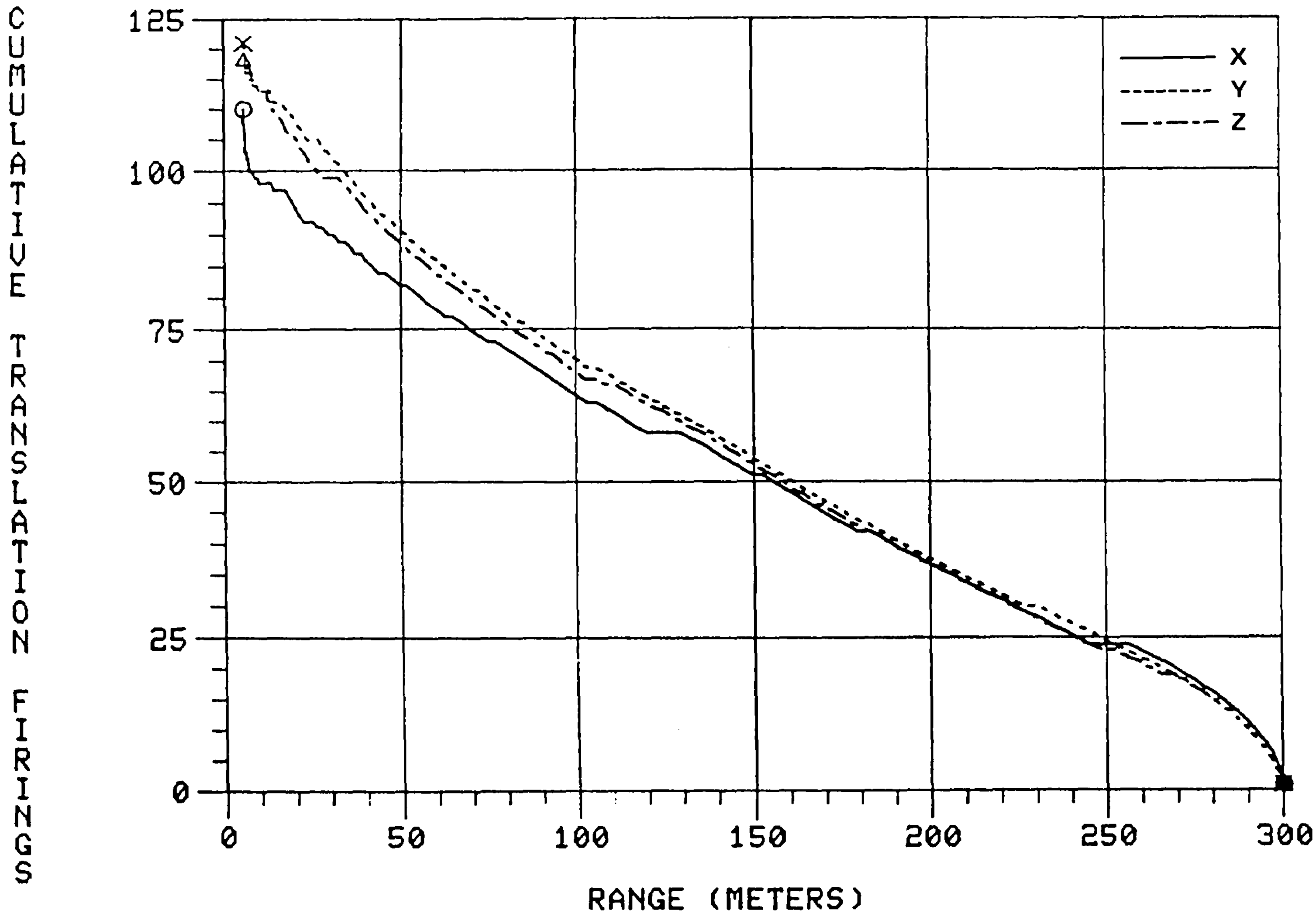

Figure 16a. Translation firings versus range, noise on.

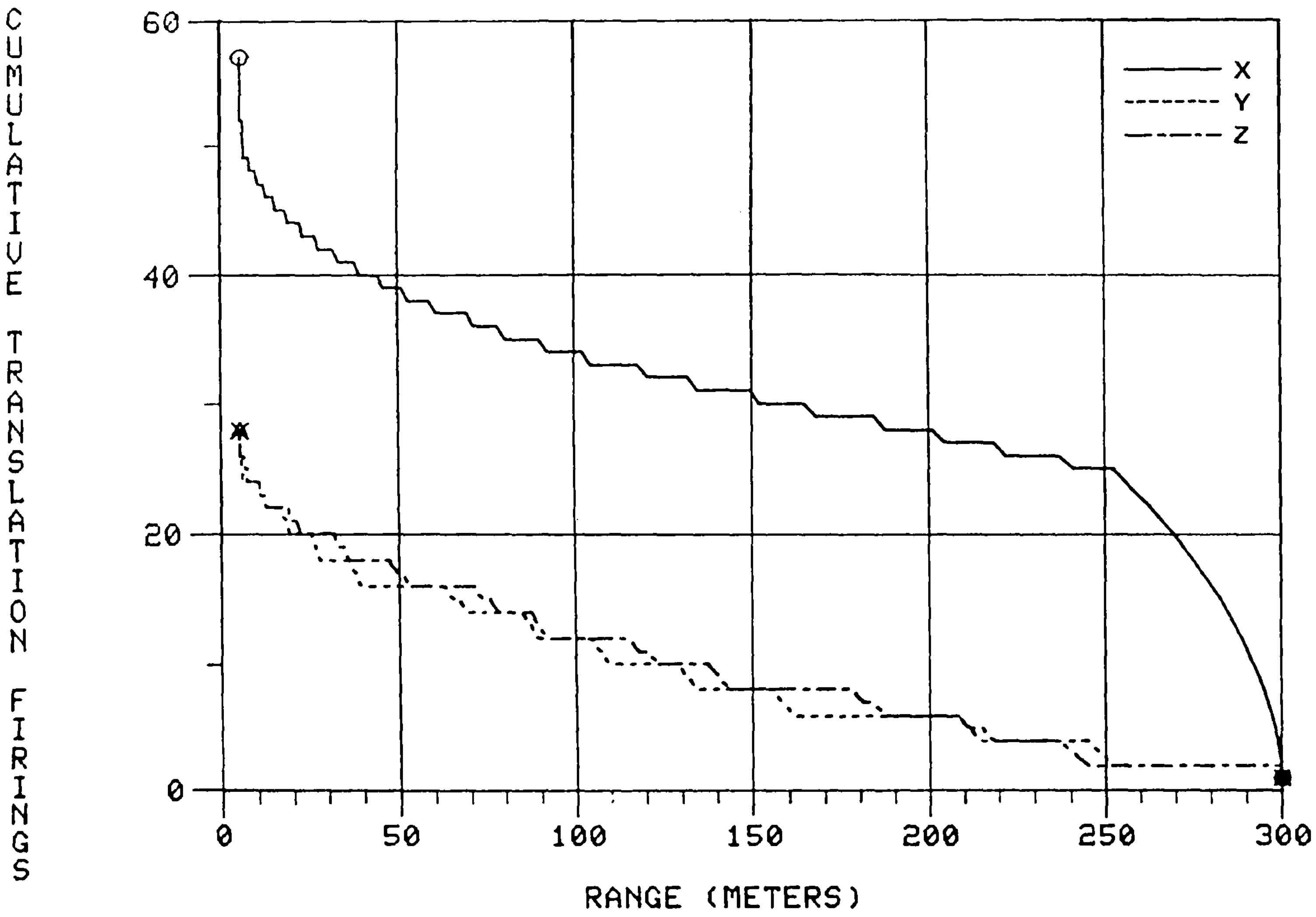

Figure 16b. Translation firings versus range, noise off.

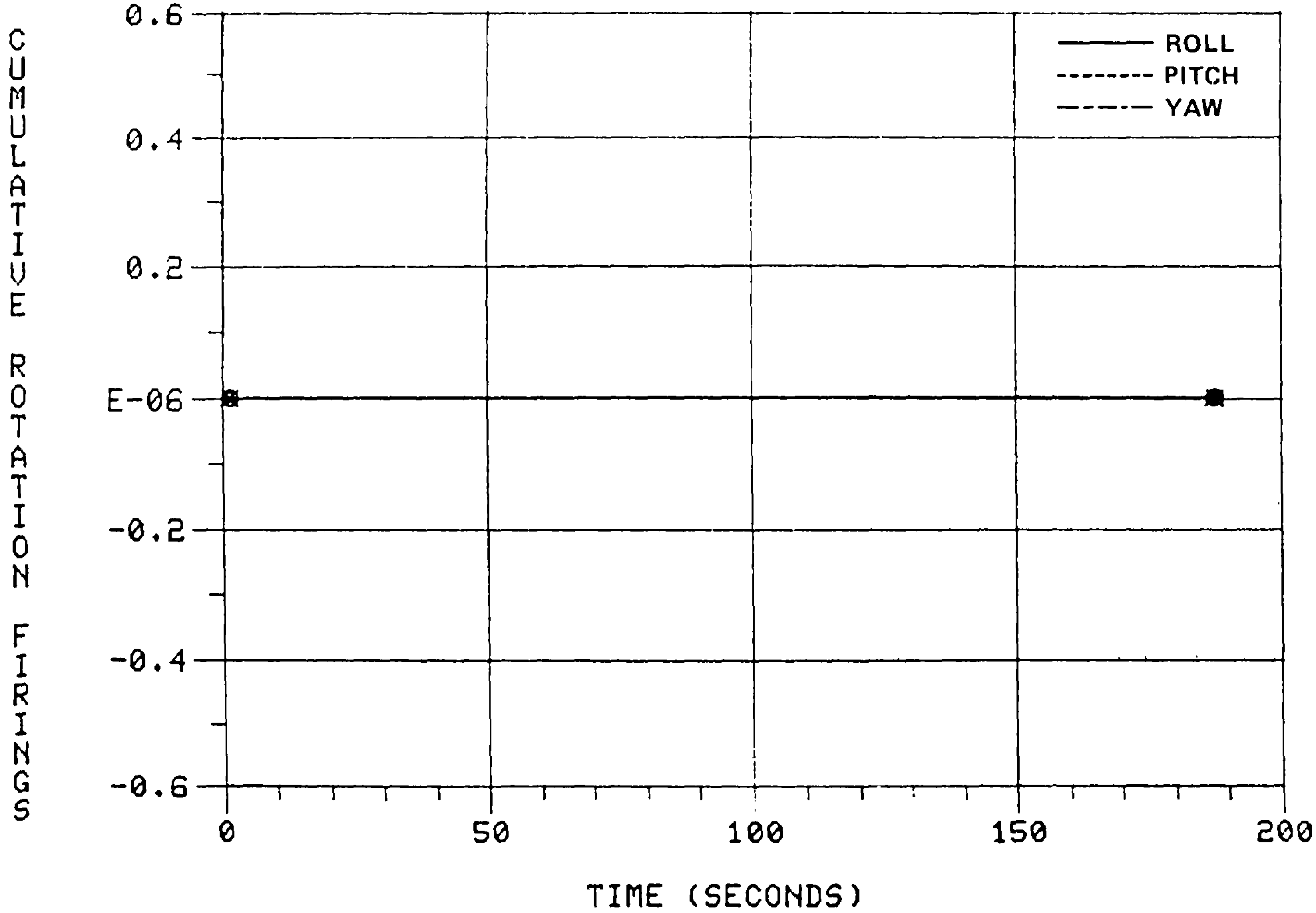

Figure 17a. Rotation firings versus range, noise off.

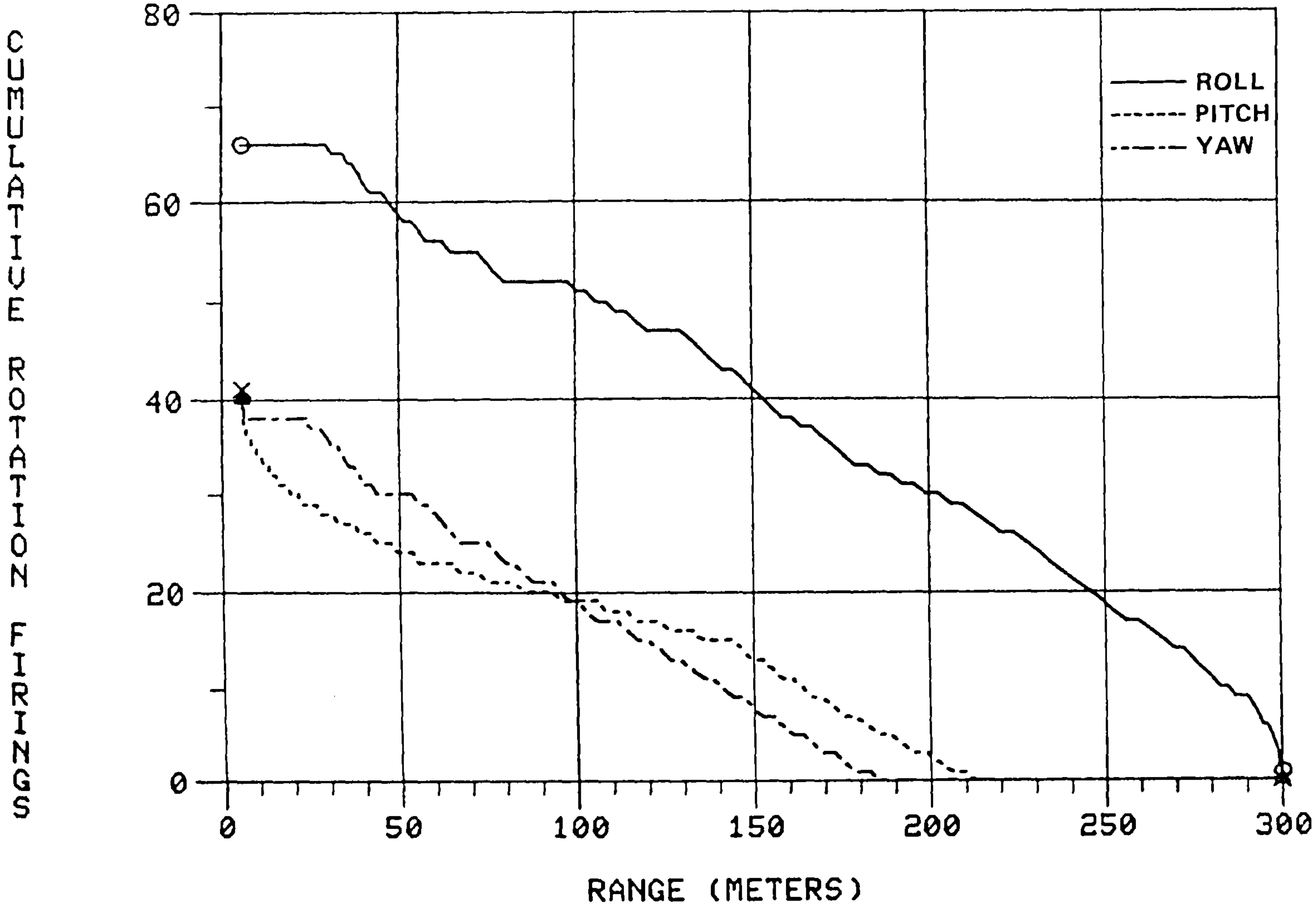

Figure 17b. Rotation firings versus range, noise on.

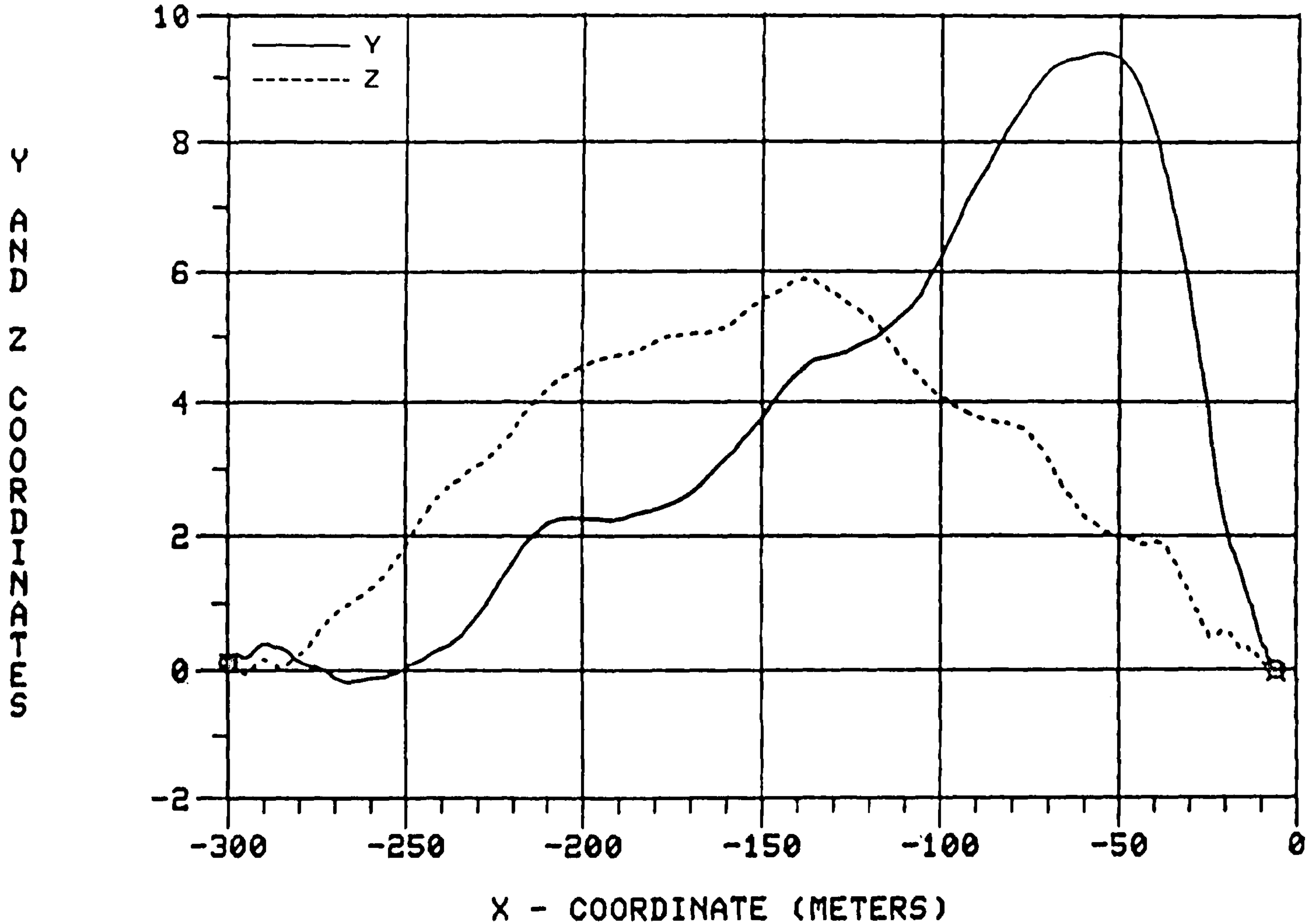

Figure 18. Y and Z versus X position, noise on, target aligned.

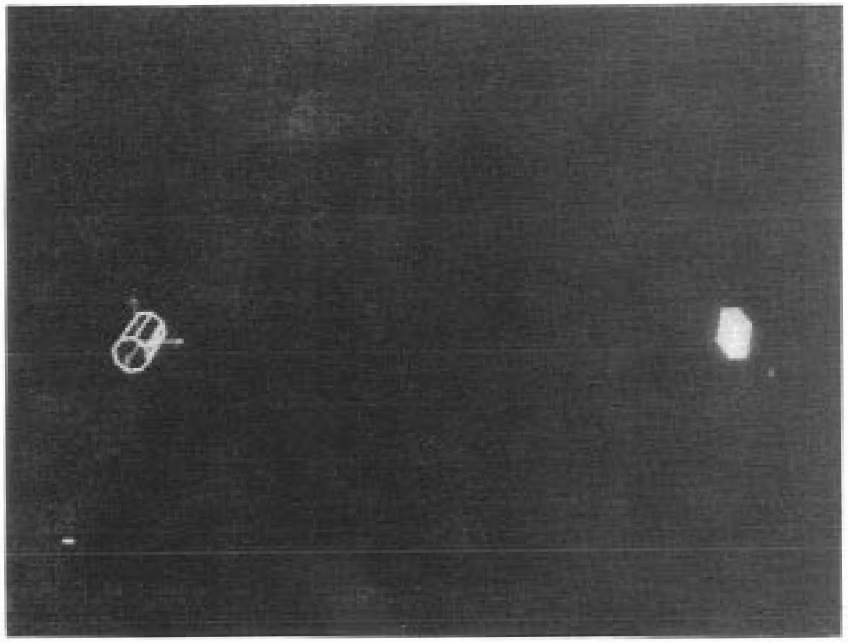

Figure 19. Chase and target vehicles aligned at 100 m.

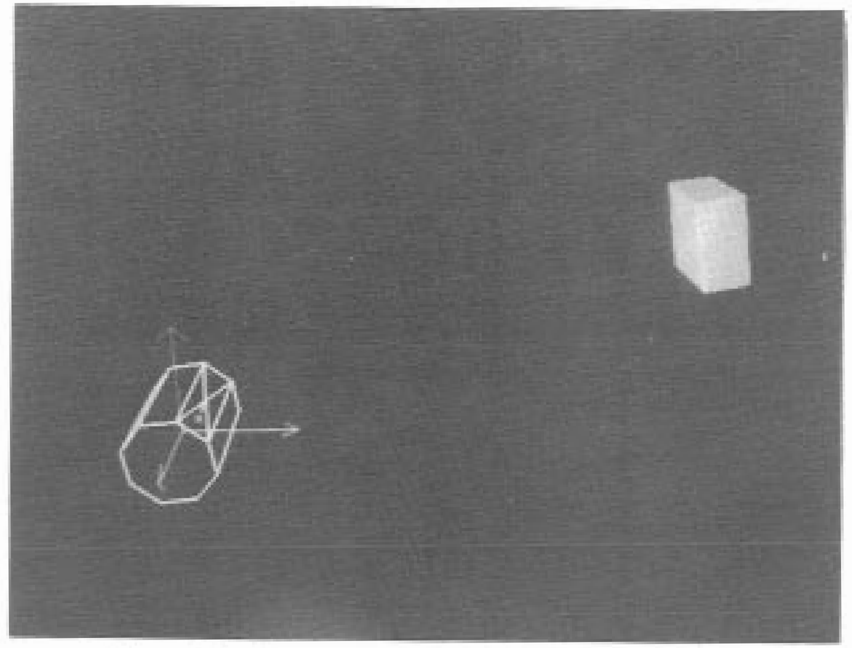

Figure 20. Approaching tumbling target; range = 30 m.

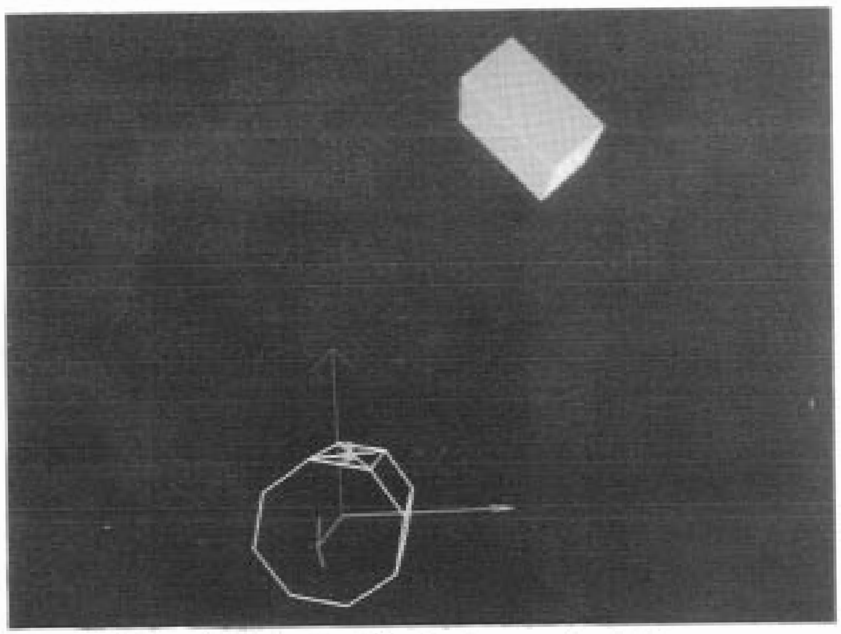

Figure 21. Turning for final approach at 15 m.

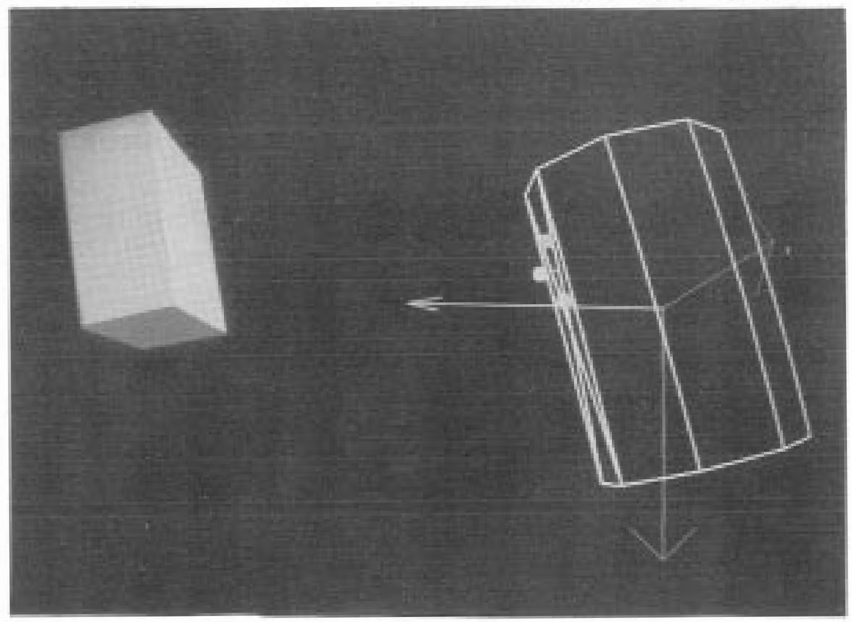

Figure 22. Approaching stabilized target; range = 8 m.

APPENDIX

The chase vehicle considered in this study is a version of the Mark II Propulsion Module, designed by Martin Marietta and adapted for use as an Orbital Maneuvering Vehicle. The utilization of this spacecraft in such a role is described in detail in Martin Marietta Final Briefing TMS-SE-01-07, "Teleoperator Maneuvering System Mark II Propulsion Module Study," September 1983, wherein several different vehicle configurations and mission profiles are discussed. For the purpose of this study, the characteristics outlined in the table below have been assumed. These data are taken from Reference 4.

CHASE SPACECRAFT DATA

SIZE: 5 x 13 x 4.5 METERS (L x W x H), APPENDAGES DEPLOYED FUEL: MONOPROPELLANT HYDRAZINE WITH GN_2 BLOWDOWN			
INERTIAL DATA	FUELED	UNFUELED	
I_{XX} (ROLL)	4240	1910	MOMENTS OF INERTIA ($KG \cdot M^2$)
I_{YY} (PITCH)	5110	2300	
I_{ZZ} (YAW)	5030	2260	
MASS	3700	1800	KILOGRAMS

THRUSTER CHARACTERISTICS				
FORCE DIRECTION	QUANTITY	THRUST (NEWTONS)	TORQUE AXIS	TORQUE ($N \cdot M^2$)
X	2	360	NONE	NONE
Y	4	80	Z (YAW)	30
Y	4	20	X (ROLL)	25
Z	4	80	Y (PITCH)	30

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16. ABSTRACT

A technique for achieving autonomous rendezvous and docking of two orbiting space vehicles is described. Results of a digital computer simulation of the technique are presented and used to evaluate its performance under a wide variety of conditions, including docking with tumbling spacecraft. The interrelationships between initial range, tumbling rates, fuel consumption, and time requirements are explored; factors which limit performance are identified and beneficial modifications proposed.

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