GUIDANCE RATIONALE FOR FUTURE AREA DEFENCE MISSILE SYSTEMS

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ABSTRACT

Future generations of Anti Surface Ship Missiles (ASSMs) will place increasing demands upon naval defensive weapon systems. This article addresses guidance issues associated with the Support Defence Missile System (SDMS) and brings together a picture of a single ASSM engagement by an SDMS missile. Interactions between the complex range of factors which contribute to the attainment of robust levels of performance are discussed.

Introduction

This article is concerned with guidance issues relating to future generations of medium range surface to air guided weapon systems. Although many of the techniques described herein can be generally applied to both land and sea based systems, this article takes as an example the Support Defence Missile System (SDMS) which is currently the subject of collaborative feasibility studies. This forms an air defence layer operating inside the outer protective boundary formed by Combat Air Patrol and provides cover to ships in company as shown in FIG. 1.

For a particular threat direction, the boundary of cover provided will be symmetrical about the threat axis as illustrated. An incoming seaskimming Anti Surface Ship Missile (ASSM) is shown attacking a consort positioned near the edge of the protected zone and a defending missile is launched from the SDMS ship. An essential feature of the system is its ability to intercept crossing targets in the manner illustrated and this paper is largely concerned with the conditions and constraints that the achievement of crossing performance places upon the design of system elements.

The interception range is limited by practical considerations such as missile cost and size and the detection range of the ship's radar. Hence for ships under attack near the boundary of cover, large crossing angles are to be expected between missiles and their targets. Future ASSM target types will

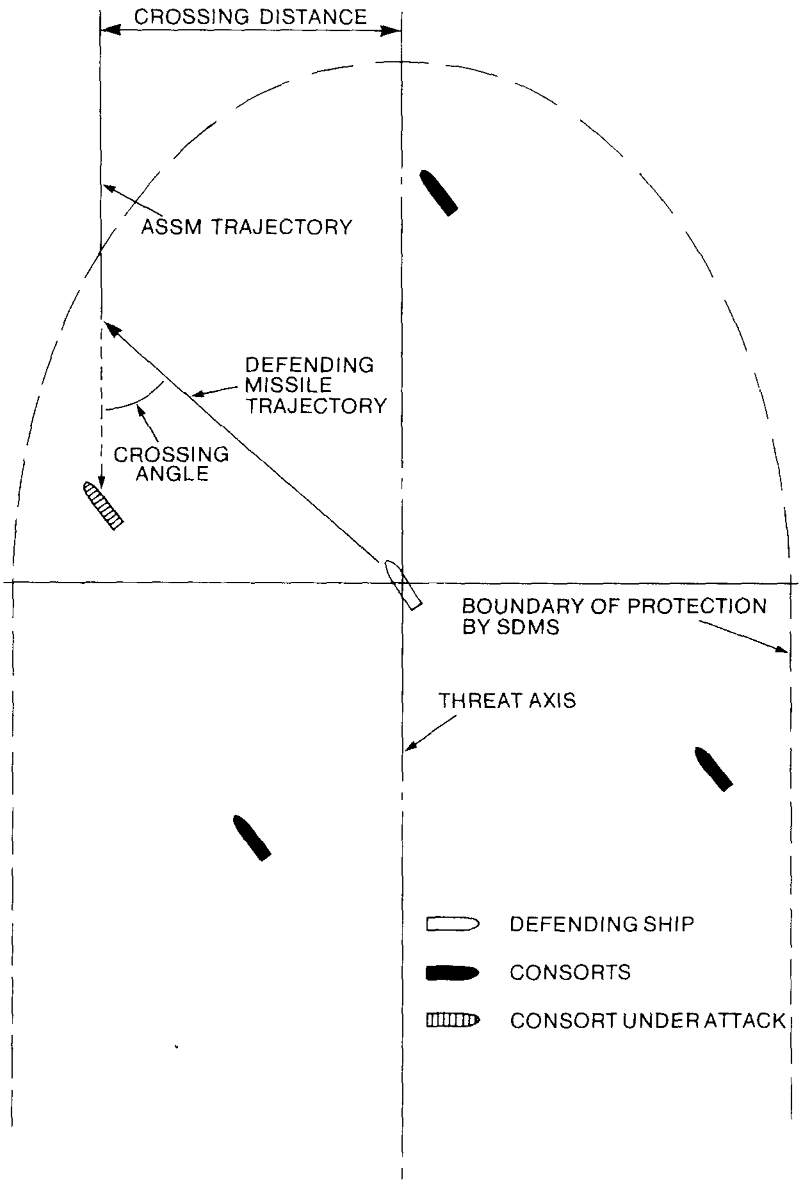


FIG. 1—COVERAGE PROVIDED BY SUPPORT DEFENCE MISSILE SYSTEM (SDMS)
ASSM: Anti Surface Ship Missile

prove increasingly difficult to counter due to their high speed, ability to perform evasive manoeuvres aimed at defeating the defences of the ship under attack, and the possibility of near simultaneous arrival from directions spread in azimuth. The attainment of desired performance levels under such conditions is dependent upon the successful integration of many conflicting factors which govern the design and performance of the weapon system.

The key elements of the weapon system are a multi-function phased array radar (MFR) and a complement of vertically launched missiles. The system is configured to allow for simultaneous engagement of a number of targets and an artist's impression of SDMS being used 'in anger' to its full capability is shown in FIG. 2.

Clearly, the situation depicted here is very complex in terms of the demands made upon the weapon system. Its evolution must embrace the development of robust solutions to problems such as multiple track formation, threat evaluation and the optimal allocation of limited weapon resources.

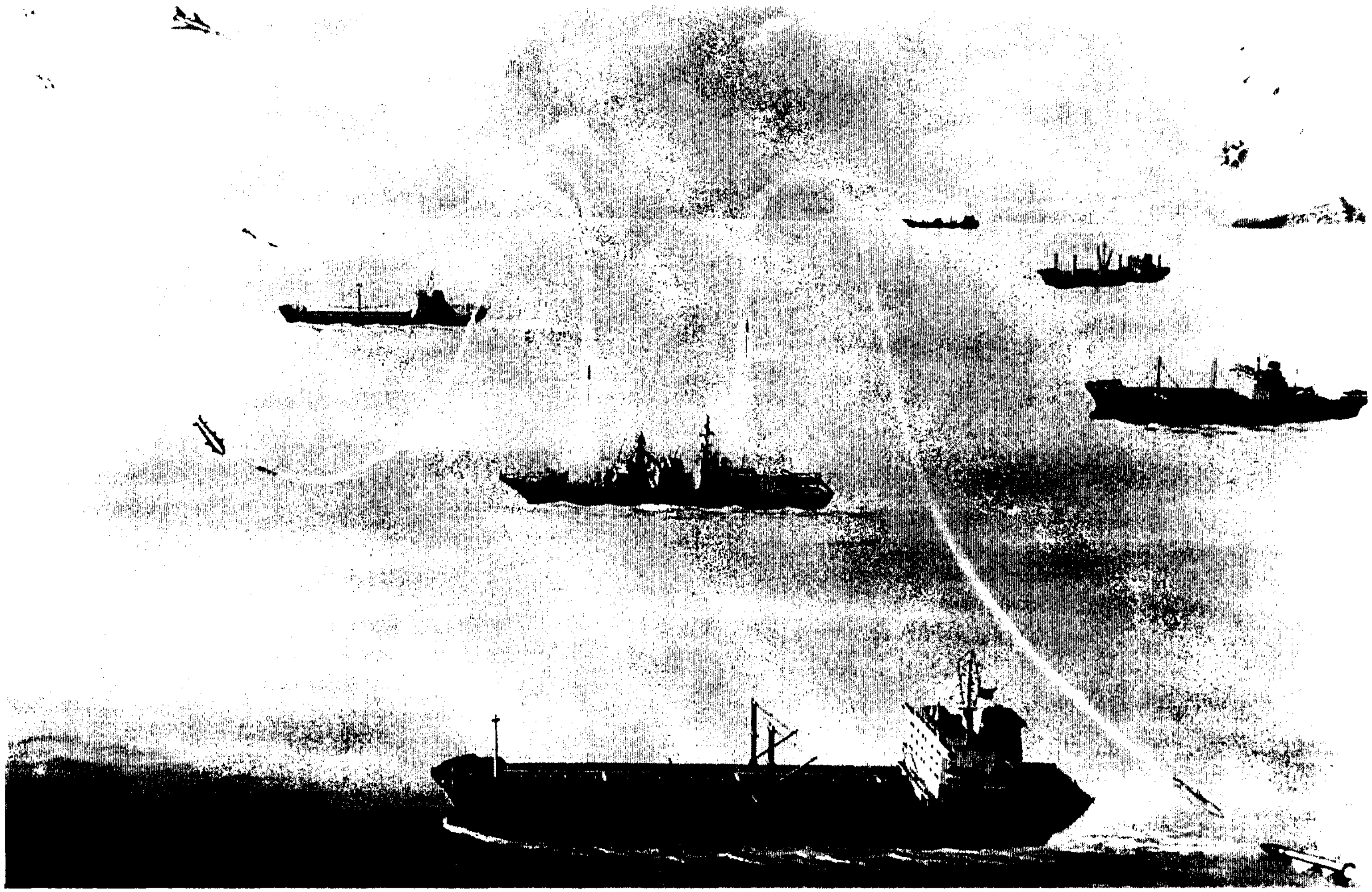


FIG. 2—SDMS—AN ARTIST'S IMPRESSION

To enable the study of such areas in depth it is necessary to first investigate the factors involved in achieving a successful target engagement by a single missile and to study the guidance issues involved. The following sections of this article are intended to form a basis for the understanding of these factors and their interactions.

Guidance Considerations

The need for multiple channels of fire against the types of target we have discussed above drives us towards the use of a guidance law based on the principle of Proportional Navigation (PN). Its advantages over the simpler Line of Sight (LOS) guidance method are well understood[1] and in our application the adoption of PN enables the use of a seeker within the missile with the benefit that measurement errors reduce as the target is approached. The seeker may either be active in its operation (by virtue of transmitting its own RF pulses) or semi-active (relying on illumination provided from the ship).

Studies to date have assumed the seeker to be active, thus freeing the weapon system from channel of fire limitations imposed by the need for target illuminators sited on the ship. However, a combination of limitations in existing technology and packaging constraints within the missile will limit the seeker power and hence its acquisition range. Therefore in all but the shortest range engagements the system is dependant upon a mid-course guidance phase operative up to the point where control of the missile can be handed over to the seeker.

Before discussing the implementation of the mid-course and handover phases, let us affirm our objective with regard to terminal performance. FIG. 3 is an artist's impression of the final stages of an engagement with the missile depicted as pulling a high 'g' manoeuvre, combining components in both its pitch and yaw planes. Such behaviour is to be expected as the missile

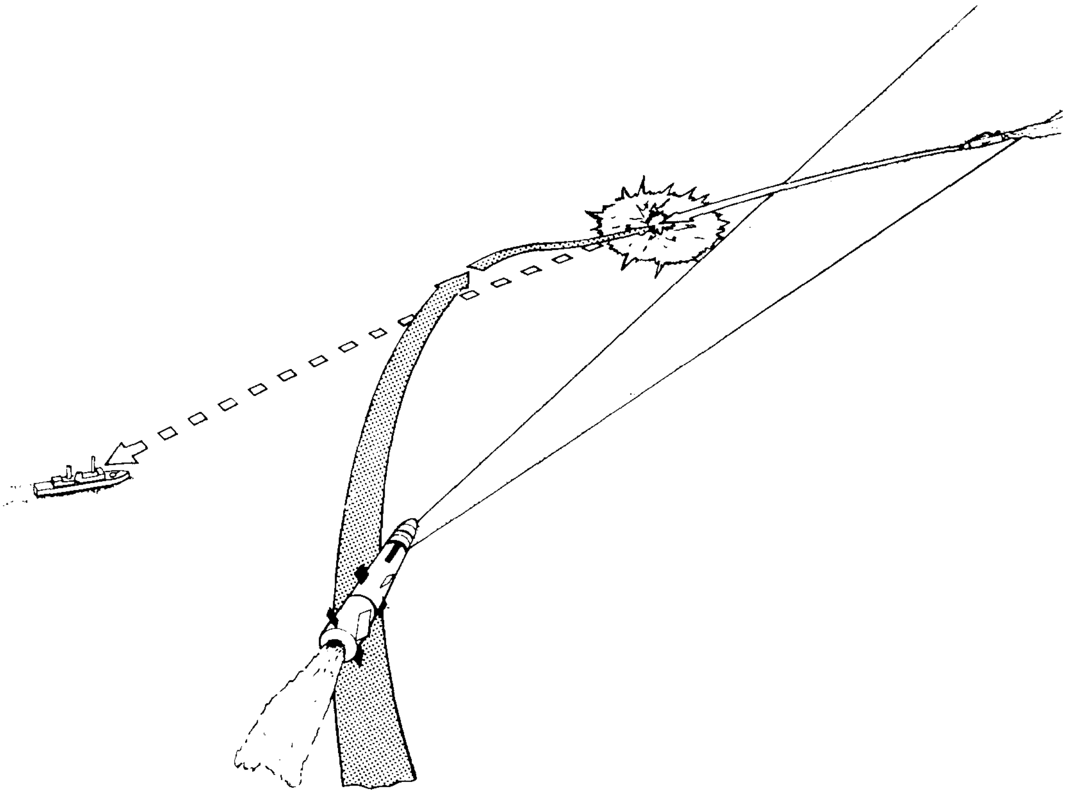


FIG. 3—ARTIST'S IMPRESSION OF THE FINAL STAGES OF AN ENGAGEMENT. THE INCOMING (TARGET) MISSILE IS ON THE RIGHT; THE DEFENCE MISSILE IS IN THE FOREGROUND

closes on the target but some artistic license has been used in producing Fig. 3. A virtual head on, direct hit as shown will not generally occur since a range of factors will, in most engagements, conspire to produce a near miss rather than a hit, as is discussed later.

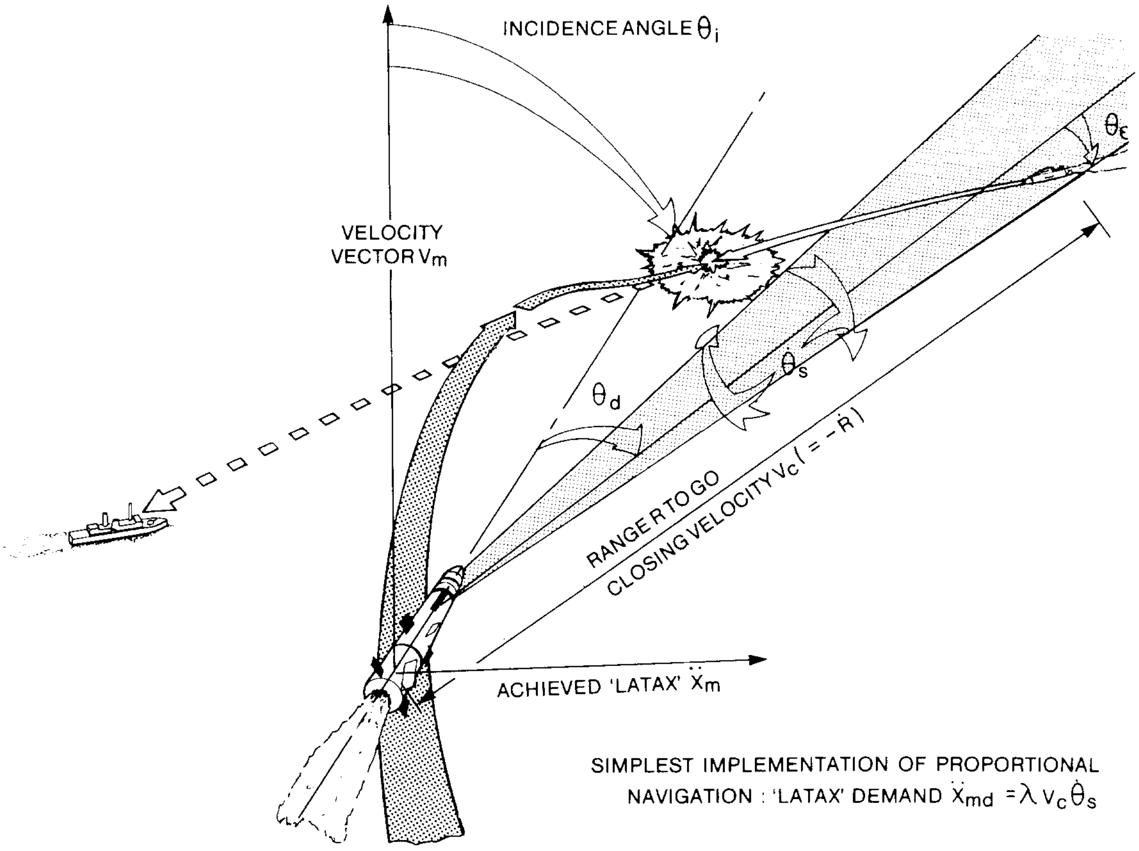


Fig. 4—Terminology associated with Proportional Navigation. The axes, angles, etc., are shown here applied to the scene in Fig. 3.
The Velocity Vector lies along the missile track.
The chain dotted line lies along the missile axis.
The line which is at an angle θ_d to the missile axis lies along the sightline joining the missile to the target.
θ_ϵ is the angle made by the target with the sightline boresight.
Achieved 'Latax' lies at right angles to the Velocity Vector.

Fig. 4 defines some of the terminology associated with proportional navigation (PN). The PN law demands a lateral acceleration ('latax') from the missile based on the product of three terms. These comprise the sightline rate in inertial space $\dot{\theta}_s$, the closing velocity V_c between missile and target resolved along the sightline, and a constant λ, normally referred to as the kinematic gain. The choice of a value for λ is necessarily a compromise. On the one hand, a high value can result in excessive fin activity and induced drag due, amongst other factors, to thermal noise at handover. A low value will result in sluggishness and restricted ability to cope with target manoeuvres. In both cases, miss distances will be adversely affected.

Having selected a suitable value for λ we now need to consider how estimates of V_c and $\dot{\theta}_s$ can be derived. During the terminal phase, V_c is obtainable from the seeker doppler but before the seeker can be laid on, a reasonable prior estimate of V_c is needed. Moreover, such an estimate is required throughout the mid course in order that the PN law can be implemented over this phase of the missile's flight regime.

Similar considerations apply to the derivation of an estimate for $\dot{\theta}_s$. For the arrangement shown in Fig. 5 of a conventional seeker combined with a strapdown inertial measurement unit (IMU), it can be seen that rotation rates of the seeker dish relative to the missile centreline can be obtained from instruments sited on the seeker gimbal axes. In order to derive the sightline rate $\dot{\theta}_s$ in inertial axes, the missile motion must be isolated from this by subtracting the parameters q and r (angular rates about the pitch and yaw axes respectively) available from the IMU.

During the mid course, the method of derivation of estimates for V_c and $\dot{\theta}_s$ is not so clear cut. The technique depends upon the missile possessing reasonably accurate knowledge of its positional co-ordinates and those of the target during the engagement and the method is discussed later.

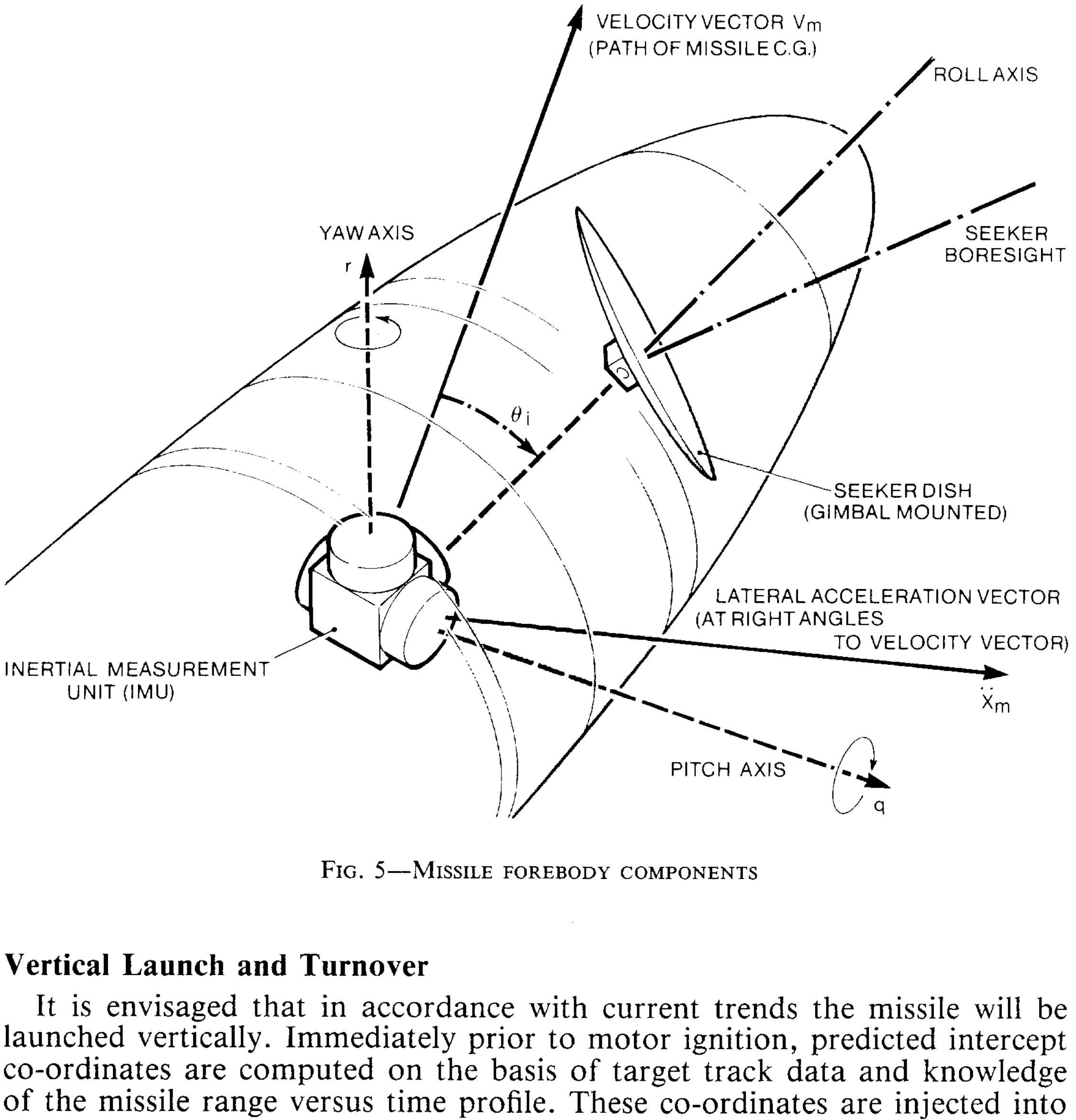


Fig. 5—Missile forebody components

Vertical Launch and Turnover

It is envisaged that in accordance with current trends the missile will be launched vertically. Immediately prior to motor ignition, predicted intercept co-ordinates are computed on the basis of target track data and knowledge of the missile range versus time profile. These co-ordinates are injected into the missile software.

Following launch the missile's velocity vector is turned through an angle which depends upon target elevation and the ship's roll angle at launch. Fig. 6 shows the type of trajectory which would be expected against a sea skimmer attack and compares initial range versus time performance against a missile of identical mass and thrust profile, launched directly at the threat from a conventional trainable launcher.

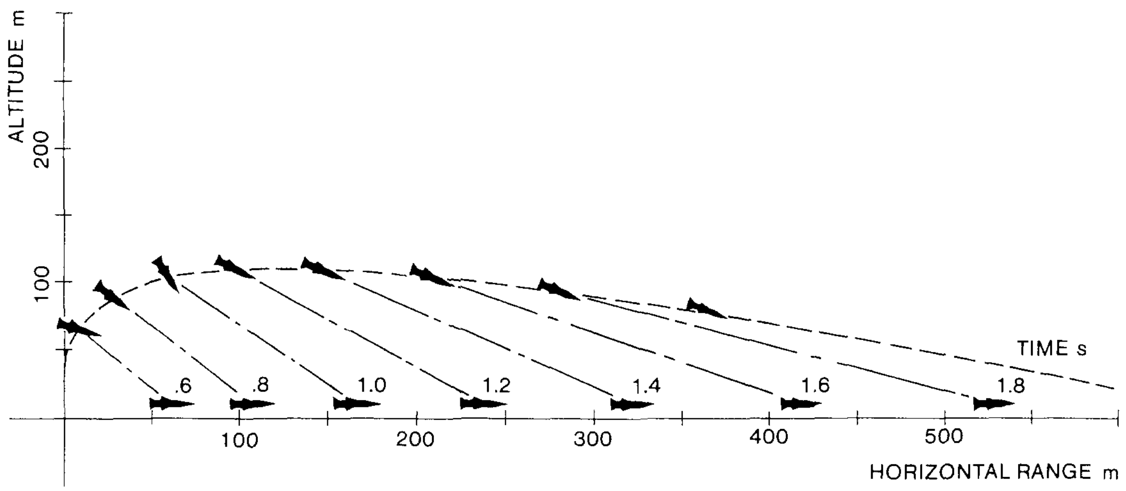


FIG. 6—TYPICAL TURNOVER TRAJECTORY AGAINST A SEA SKIMMER, SHOWING COMPARISON WITH CONVENTIONAL LAUNCH

This phase is achieved using a turnover autopilot which compares the missile's velocity vector and body rates with stored data. Error signals are derived from subtracting achieved rates from demanded rates and used to drive a thrust vector control (TVC) system. It is envisaged that the TVC system would work in conjunction with a separating boost pack, the complete unit being discarded once the turnover manoeuvre is completed.

Following turnover, the missile will be under aerodynamic control and in a position to receive data transmitted from the ship via an uplink. The reception of uplink messages is not considered feasible before boost separation due to the large angles made by the missile body with the direction of transmission evident in FIG. 6. Hence the missile cannot react to changes in the target trajectory that may occur over this period.

Mid-Course Guidance

Let us consider an idealized crossing engagement as shown in FIG. 7. In this case both the missile and target fly in straight lines at constant velocity.

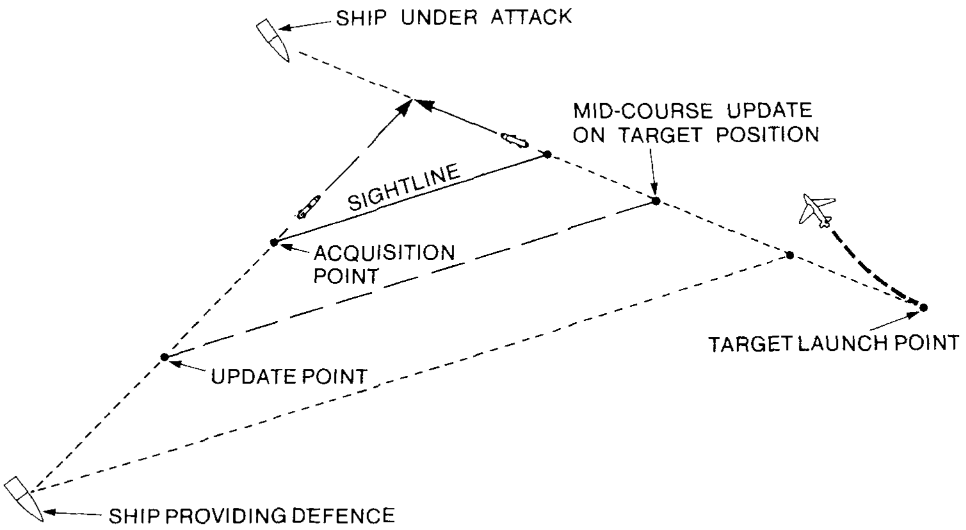


FIG. 7—AN IDEALIZED CROSSING ENGAGEMENT

The pre-launch prediction of the intercept point is assumed to be perfect and hence the sightline rate remains zero throughout. The PN law and missile control surfaces therefore have no work to do.

Complexities start to arise when we realize that the missile velocity will be far from constant. FIG. 6 shows that at the start of the missile flight the build up of horizontal range with time is initially slow and we can therefore see from FIG. 7 that movement at the target end of the sightline will not be matched at the missile end. This will result in anti-clockwise motion of the sightline following launch with the result that, following turnover, the missile will receive a 'latax' demand deviating it to the left of the straight line trajectory shown in the figure.

The missile can estimate the extent of this deviation and corrective action will be taken via the IMU and autopilot. Such corrections will take place during both mid-course and terminal phases as can be seen by reference to FIG. 8. This shows the type of velocity versus time profile which would occur against a target intercepted towards the limit of the missile's kinematic boundary. Where the velocity is less than the mean, the missile will tend to move to the left as before. Where it exceeds the mean, clockwise rotation of the sightline will divert the missile to the right. Fortunately such deviations from a constant bearing course do not cause major problems and there is scope for augmenting the PN law to minimize their impact.

There is, however, another form of unwanted missile deviation with more serious implications. This results from IMU measurement inaccuracies which are functions of the missile manoeuvre characteristics. In this case, the missile is unaware of changes to its course and therefore cannot correct for them.

Turnover manoeuvres as depicted in FIG. 6 are potentially troublesome in this respect since the combination of longitudinal and lateral accelerations attained during this period will cause propagation of IMU instrument errors. Whilst the situation could, to an extent, be ameliorated by the use of ring laser or fibre optic gyros in place of angular momentum units, the availability of such instruments for missile applications cannot be assured within the desired weapon system development timescales.

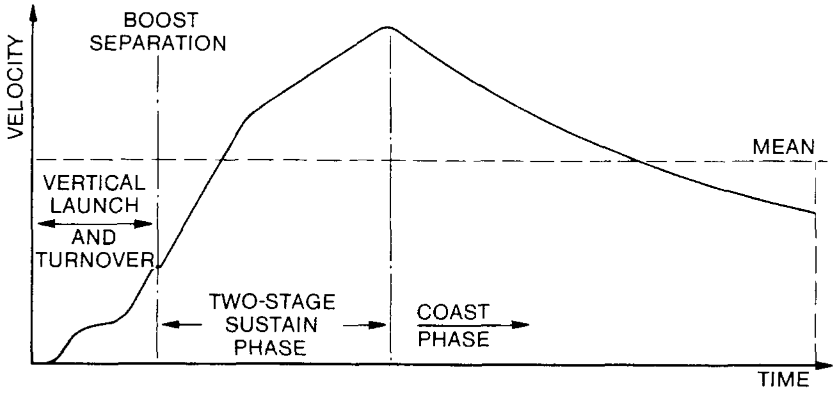


FIG. 8—TYPICAL MISSILE VELOCITY V. TIME PROFILE

There is a further factor which influences the missile's knowledge of its position and attitude. This concerns the accuracy of alignment of the ship's radar, missile launcher and ship's inertial reference (SINS). Whilst methods are available for aligning these elements whilst the ship is docked, conditions at sea will combine to cause misalignment of the axes frames as depicted in Fig. 9. Relevant factors include hogging or sagging of the hull due to changes in load state and seaway conditions, and bending due either to diurnal effects causing differential heating between hull sides or deliberate manoeuvres under large rudder displacements associated with evasive or defensive tactics. The cumulative effect of such factors has proved difficult to quantify but, for the purposes of studies, figures of the order of 1° between SINS, launcher and radar have been assumed.

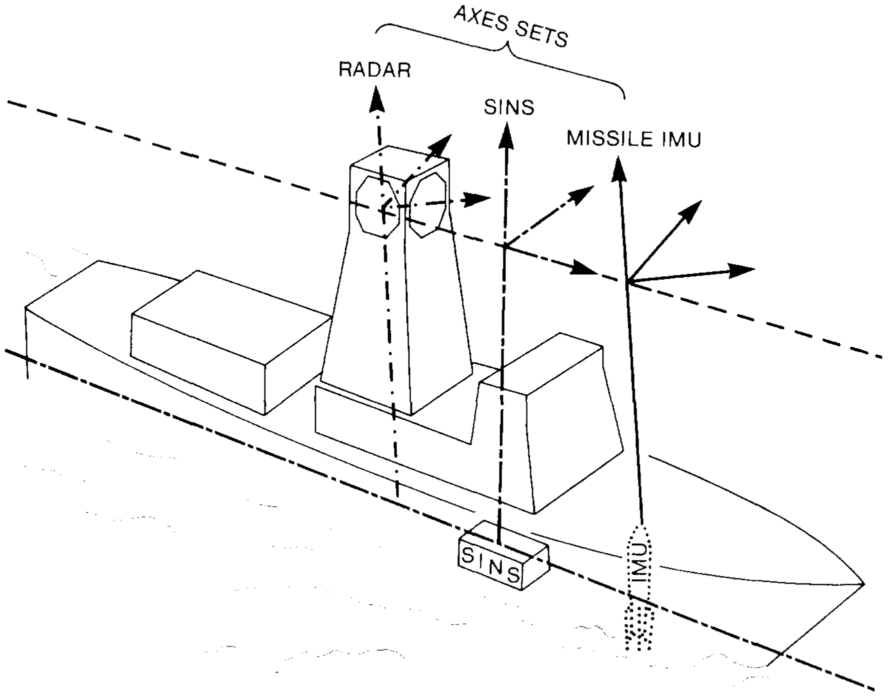


Fig. 9—The alignment problem

We can see from the above that there are two sources of error which combine to produce inaccuracies in the missile's knowledge of its position and attitude, these being IMU and alignment inaccuracies. The most serious consequence of these errors is the possibility of the seeker failing to acquire as illustrated in Fig. 10. In order to highlight this problem the geometry is taken here to be initially 'head on', with the target attacking the launching ship.

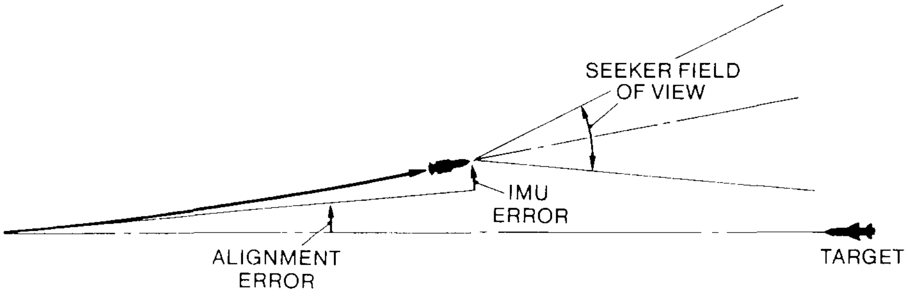


Fig. 10—Failure to aquire due to alignment and IMU errors

If, as implied above, it is non-viable or uneconomic to impose higher standards of ship alignment and IMU quality then an apparent alternative from Fig. 10 is to increase the seeker field of view. There are, however, disadvantages to this approach. We have said above that the constraints of existing technology and packaging with the missile will limit the seeker power and hence its beamwidth can only be increased at the expense of aquisition range. Whilst the trade-off between these two parameters can be chosen such as to maximize the probability of the target falling within the beam, there are other considerations which need to be taken into account.

Any increase in beamwidth will render the seeker more susceptible to enemy electronic countermeasures (ECM) and there is a problem which concerns the missile's ability to 'pull off' heading errors following late acquisition. Large lateral acceleration ('latax') demands will be generated which may be beyond the missile's airframe capability, particularly if the target manoeuvres during this period. In such a case an unacceptably large miss distance will result.

Given that we would not wish to increase the seeker field of view, an alternative solution to the missile heading problem needs to be found. Such a solution has been investigated and is described in the following section.

The 'Track Own Missile' Approach

FIG. 9 depicts a multifunction phased array radar (MFR) of the type advocated for future naval use. In addition to surveillance and air picture compilation duties such devices are intended to possess sufficient capacity for tracking targets and, if necessary, tracking of defensive missiles fired from the ship. This last option offers a potential solution to the missile heading problem depicted in FIG. 10.

The approach taken is to augment IMU data with missile position information obtained from the ship's radar. At first sight, this may appear difficult since the IMU measures angular rates and linear accelerations directly in cartesian axes attached to the missile and derives values for attitude, linear velocity and position through numerical integration. The radar measures linear position and radial range rate in spherical polar co-ordinates which, though attached to the ship, do not exactly correspond to the cartesian frame defined by the ship's master reference for reasons of alignment discussed above.

The overall problem becomes more tractable if one visualizes the missile being progressively 'persuaded' during the mid-course phase to fly in the same frame of reference as the target (i.e. that of the radar). In essence this is the rationale that has been adopted.

Position data from radar measurements are transmitted to the missile via an uplink and transformed into a local geographic cartesian frame used for navigation. We assume that the radar measurement errors in range, elevation and bearing can be characterized in terms of their variances so that these too can be transformed into the missile's navigation frame. Variances associated with error propagation mechanisms in the IMU can be specified by the manufacturer and we can therefore define the statistical variations in all the data available to the missile for navigation purposes. Hence we have sufficient information to formulate a Kalman filter algorithm able to make optimal use of the data available.

A complete description of the filter is beyond the scope of this article, but for a detailed discussion of Kalman filter theory the reader is referred to Jazwinski's book.[2] A notional view of the mode of operation of the filter can be gained by reference to FIG. 11. It can be regarded as that part of the system which lies within the dotted line and is implemented in the form of software within the missile.

In order to explain the sequence of events which occurs let us first assume that missile turnover has been completed and that the boost/TVC pack has been discarded. The mid-course guidance phase has just commenced and the first radar update of missile position is awaited. As mentioned above, angular rates and linear accelerations measured directly by the IMU are integrated to provide estimates of attitude, velocity and position and the expected errors in these quantities are estimated. These data are predicted forward, typically at a rate of 20 Hz. Until the first radar update is received, confidence levels in the accuracy of the data will diminish as time progressess. In other words, the filter's estimates of the error magnitudes grow with time. These magnitudes are characterized by the filter in terms of statistical properties known as covariances.

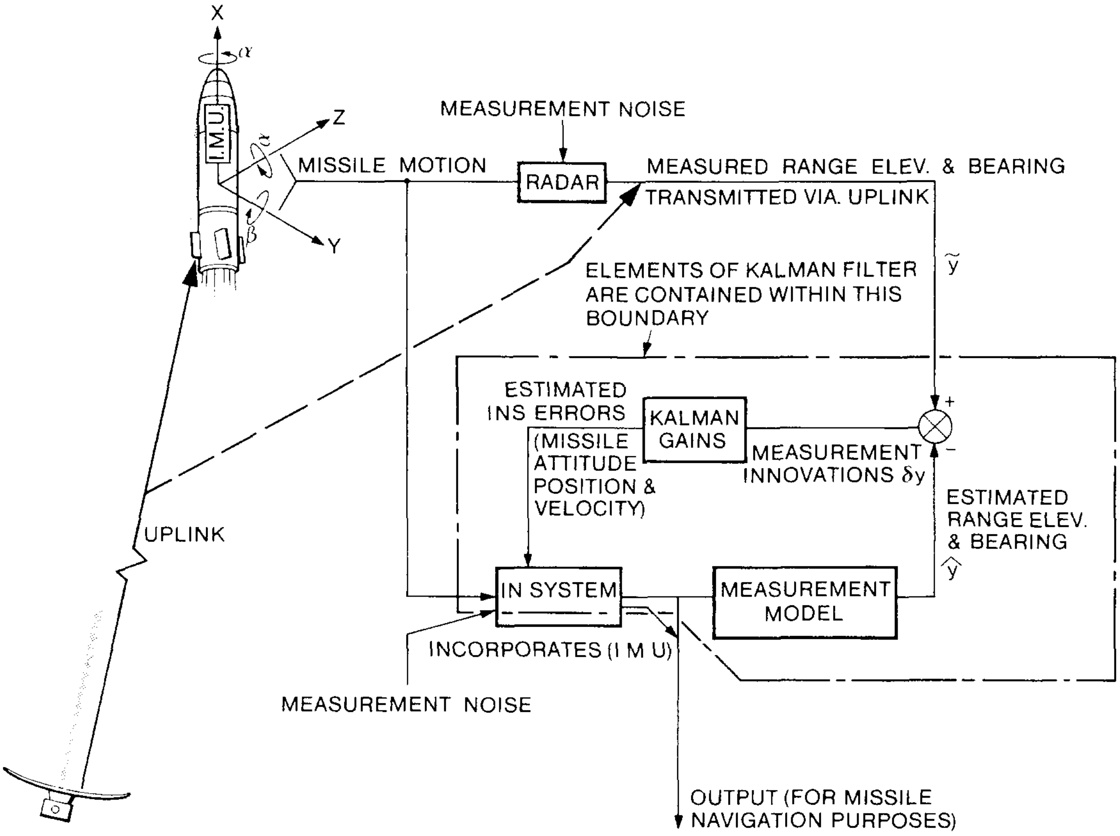


FIG. 11—OPERATION OF THE KALMAN FILTER, ASSOCIATED WITH THE 'TRACK OWN MISSILE' FUNCTION

When an update is received, we can visualize that a radar position measurement will be injected into the loop at the summing junction. In this way, the radar measurements are compared with the estimates of these parameters which the filter has derived from the IMU measurements transformed into the appropriate axis set (this function being performed by the block labelled 'measurement model' in FIG. 11). The differences between these two parameter sets are referred to as the measurement innovations.

Weighting factors are assigned to the measurement innovations by the block marked 'Kalman gains' and the result is used to enhance the missile's knowledge of its attitude, position, and velocity by correcting the IMU. These parameters are now known more accurately than before and the covariance estimates will consequently reduce. In other words the missile knows that it is in possession of more accurate data than before and can quantify its confidence level in that data.

Covariance estimates will subsequently grow due to error propagation within the IMU until the next position measurement update is received from the radar, when once again they will be reduced. After several updates have been received, the covariance estimates will be seen to vary in a cyclic sawtooth fashion and the missile's knowledge of its attitude, velocity and position will vary in a similar manner. Taking the particular example of cross track error (i.e. the difference between where the missile believes itself to be and where it actually is, measured in a direction at right angles to its velocity vector), FIG. 12 shows the form of this quantity with time.

For the parameters assumed in producing FIG. 12, it can be seen that improvements result for use of an update rate as low as 0·2 Hz. In practice, the rate need not be constant for the filter to operate, a feature which is compatible with the expected loading on the MFR, whereby availability for missile measurement purposes at regular time increments cannot be guaranteed.

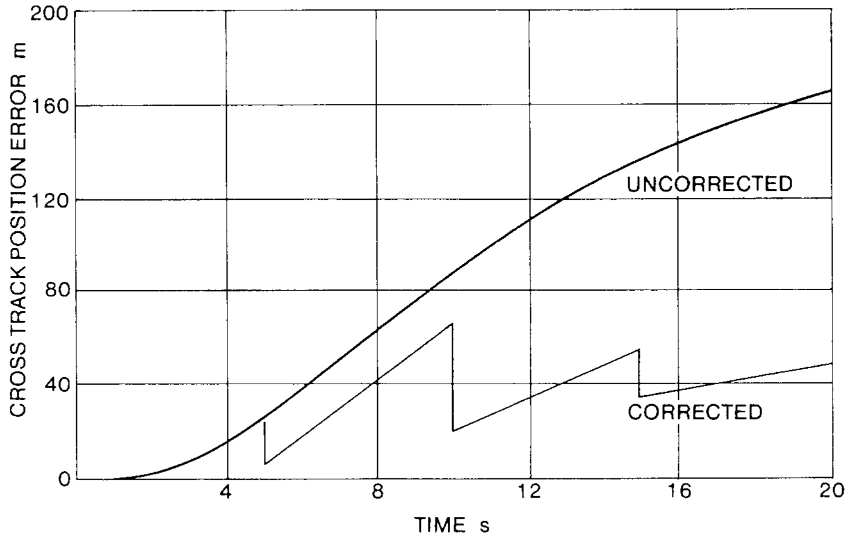


FIG. 12—THE EFFECT OF RADAR POSITION UPDATES UPON CROSS TRACK POSITION ERROR V. TIME

We now need to address the effect of the corrected IMU upon the missile flight path and its probability of acquiring the target. Referring back to FIG. 7, we assumed for simplicity that target and missile velocities were constant, that the target was non-manoeuvring, and that the intercept predictor and the missile IMU operated perfectly. Let us now amend this situation to illustrate the effect of misalignment, IMU error propagation and subsequent correction by the ships radar.

FIG. 13 shows the result. For reasons of clarity only one radar measurement update of missile position is shown. The missile proceeds from the launch ship at a small angle to its idealized straight line course due to alignment

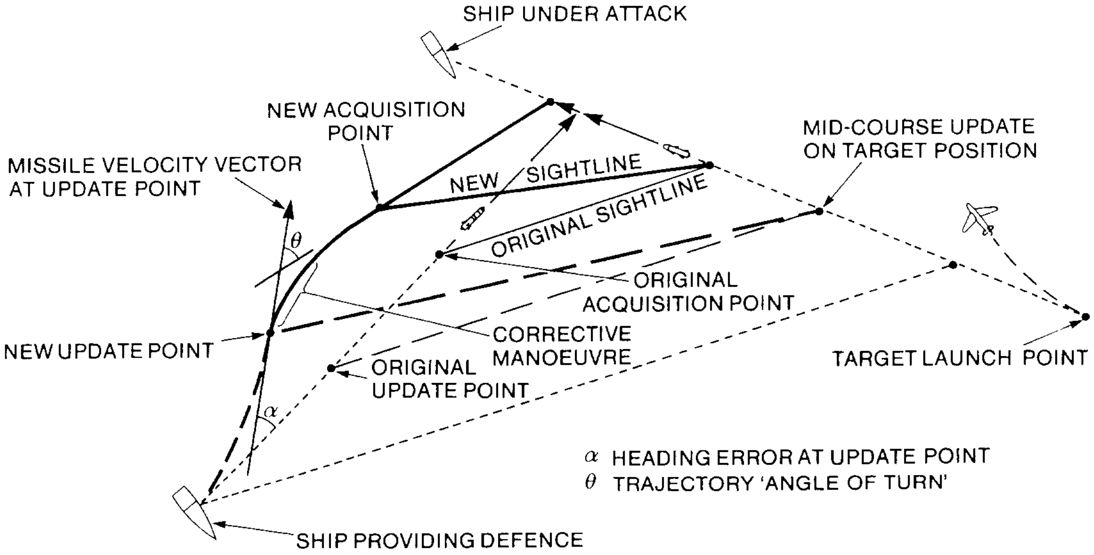


FIG. 13—THE EFFECT OF NAVIGATION ERRORS ON A CROSSING ENGAGEMENT, SHOWING DEVIATION FROM THE IDEALIZED SITUATION OF FIG. 7

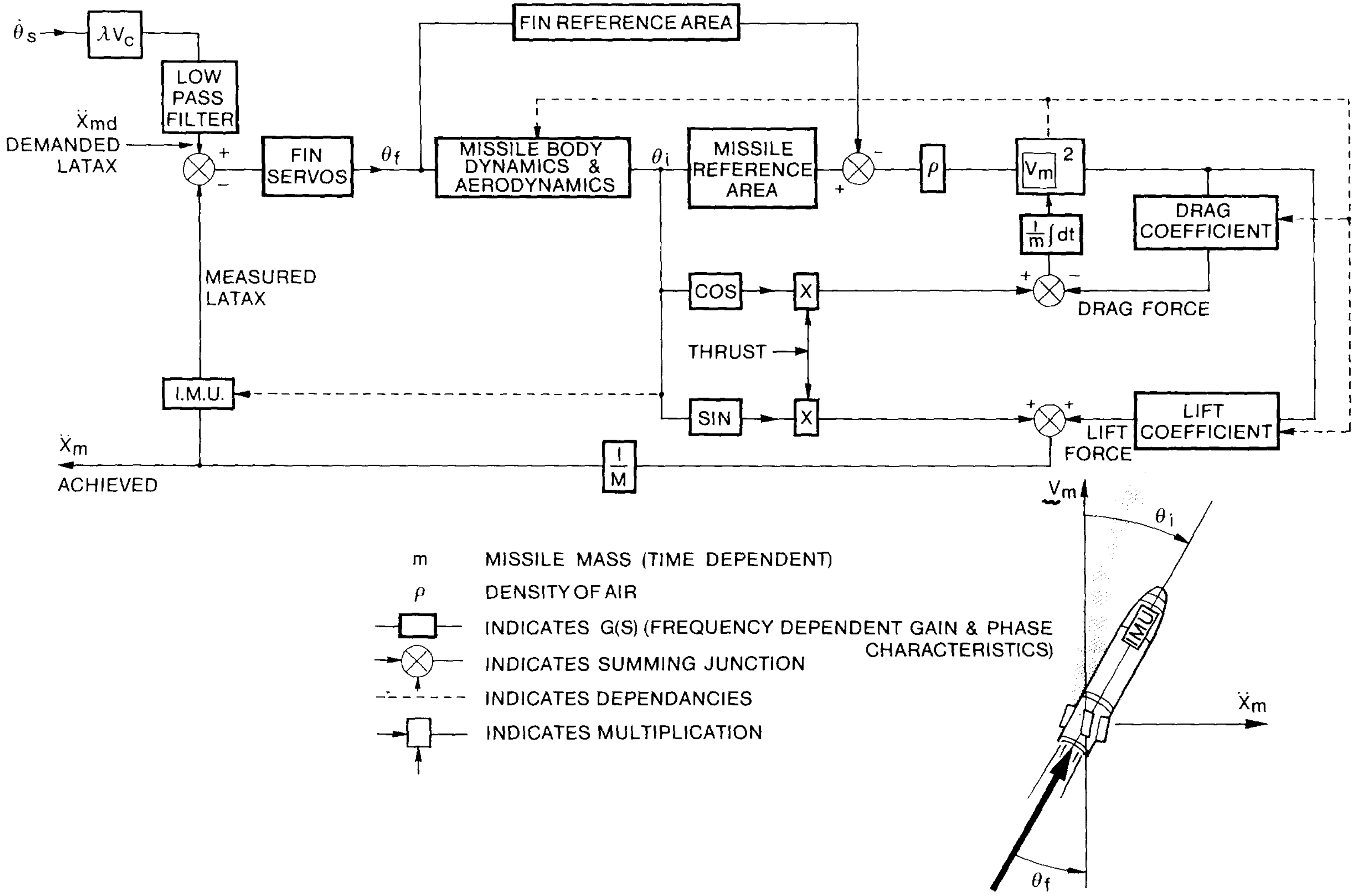


FIG. 14—A LATERAL ACCELERATION AUTOPILOT LOOP

inaccuracies. Error propagation within the IMU subsequently increases this angle to the value α shown. At this point the missile believes itself to be on the straight line course to intercept, but immediately following the uplinked message realizes it has deviated to the left. It registers this in the form of a sightline rate enabling the PN law to demand the appropriate level of lateral acceleration to turn the missile's velocity vector through the angle θ. The sightline rate is thus reduced and the missile's knowledge of its position and that of the target is sufficiently accurate to allow the seeker to acquire.

The cumulative effect of a number of position updates will enhance an otherwise inaccurate system to an extent where the probability of acquisition will be acceptable and high 'latax' manoeuvres during the terminal phase can be devoted to countering target manoeuvres rather than correcting for errors in own missile heading.

Terminal Phase: Factors Affecting Miss Distance

As discussed above, for constant closing velocity resolved along the sightline, 'latax' demands are generated in proportion to observed sightline rates. For a given displacement at either the missile or target end, the sightline will rotate by an amount which is inversely proportional to its length and so we can expect increasing levels of missile 'latax' to occur as the engagement proceeds. Hence we require accurate definition of the missile dynamic behaviour, particularly towards the end of its mission. The relationship between demanded 'latax' and the actual level achieved by the missile becomes important and the parameters which determine this relationship are illustrated in control loop format in FIG. 14.

This relates to a single channel of operation (either pitch or yaw) and for simplicity ignores phenomena such as aerodynamic non-linearities, cross-coupling and the aberration characteristics at the radome through which seeker transmissions pass and are received. Manufacturing tolerances and aerodynamic heating will affect radome refraction characteristics such that there will be differences between measured and actual sightline rates.

Interestingly, there is scope for minimizing the deleterious effects of radome aberration by increasing the 'missile reference area' shown in the forward path of FIG. 14. This area can be increased by the use of large wings which will in turn increase the loop gain, hence reducing both the incidence angle θ_i needed for a given 'latax' level and the time needed to reach that incidence value. This in turn minimizes the amount by which the seeker needs to scan across the radome in order to keep the target within view. There is, of course, a penalty to be paid for this potential means of improving guidance performance and this manifests itself in the form of increased axial drag. In addition, high 'latax' manoeuvres will produce bending moments at the wing roots which the airframe must be designed to withstand.

Further contributions to miss distance arise from the target reflection characteristics at the frequency of the seeker transmissions. The strength of returns from various scattering centres of the target will vary according to the aspect presented to the seeker to produce 'glint' and 'bright spot wander'. Apparent perturbations in the target position will therefore occur.

As mentioned above it is expected that future ASSMs will be capable of deliberate manoeuvres designed to evade ship defences. Such manoeuvres will consume a large proportion of missile 'latax' capability leaving what remains to cope with the adverse effects listed above.

In the case of interceptions which take place near to the kinematic boundary, the missile will have coasted to a velocity much lower than was attained at motor 'burn out'. Against certain target trajectories the combination of low velocity and correspondingly reduced 'latax' capability will result in a 'tail chase' during which seeker look angle limits are reached, with resulting loss of control and consequent large miss distance.

Finally, there comes a point shortly before interception where the missile cannot be guided further. As mentioned earlier in this section, the magnitude of the input signal to the loop of FIG. 14 will tend to increase as the reciprocal of the sightline length. A point will arise when saturation is reached and the fins stay at a fixed displacement for the remainder of the flight.

Simulation of an Engagement

A package which simulates a complete engagement has been developed for MOD use during the past few years. A complete description of its content is beyond the scope of this article but the package includes representations of the factors described above, both statistical and deterministic. This enables the use of single runs to gain an overview of performance against particular types of target trajectories, or batches of Monte Carlo runs to gain a detailed assessment of the range of possible outcomes against a given target resulting from statistical variations in elements such as radar measurement accuracy and IMU performance.

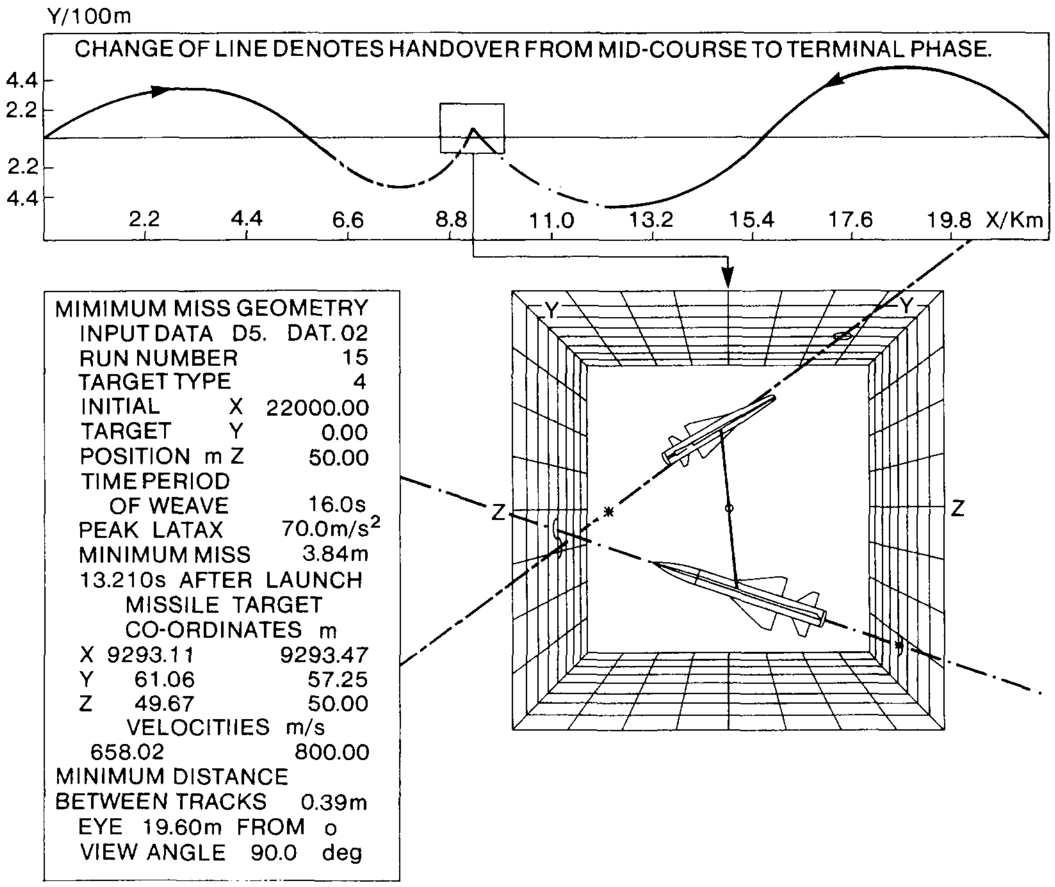
A facility is available for the graphical output of single runs and examples are shown in FIGS. 15 and 16. In each case the target proceeds in from the right hand of the strip graph at the top and in FIG. 15 executes a hypothetical long period weave.The target tracking filter modelled in the simulation predicts interception to occur off the top of the figure since it has no way of knowing the type of manoeuvre the target is subsequently going to perform. Hence the missile is initially sent off in this direction but it is later able to compensate through its navigation law.

In this particular interception the missile acquires the target and the homing head stays within look angle limits. The end result is shown in the 3-D enlargement at the lower right of the figure which depicts the missile positions at the point of closest approach between their mid points. These are shown within a grid which conforms to the walls of an 8 m cube. This particular engagement is almost coplanar, there being little separation between the tracks measured in the Z direction (altitude).

FIG. 16 shows a target trajectory which is again hypothetical. As a result of a dog-leg manoeuvre, the target passes in front of the launch ship in order to home in on another vessel. Its initial crossing range is 8 km and the predictor is led to believe that interception will take place on, or about, this line. The result is that the missile pulls a turn throughout its flight with the tracks finally crossing almost at right angles. A close examination of the terminal geometry shown in the enlargement indicates that the missile is underflying the target with a small dive angle of about 5°.

Each of FIGS. 15 and 16 represents a single sample of results from a batch of fifty Monte Carlo runs. Such batches can be used to predict the range of possible outcomes against particular targets in terms of biases and variances of the various geometrical parameters and the probabilities of occurence of malfunctions such as failure to acquire.

The current version of the simulation does not attempt to model fuze and warhead operation. As with any modelling facility evolved in advance of hardware development, the mathematical descriptions of certain subsystems are necessarily limited but the simulation is nonetheless proving to be a valuable tool in assessing potential performance levels and can be used as a basis for evaluating proposals received from industry in connection with the future development of the Support Defence Missile System.



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  TARGET       Y      0.00
  POSITION  m Z      50.00
  TIME PERIOD
    OF WEAVE          16.0s
  PEAK LATAX       70.0m/s2
  MINIMUM MISS        3.84m
  13.210s AFTER LAUNCH
      MISSILE  TARGET
      CO-ORDINATES  m
  X  9293.11        9293.47
  Y    61.06          57.25
  Z    49.67          50.00
      VELOCITIIES  m/s
   658.02           800.00
MINIMUM DISTANCE
BETWEEN TRACKS    0.39m
  EYE  19.60m  FROM  o
  VIEW ANGLE   90.0   deg
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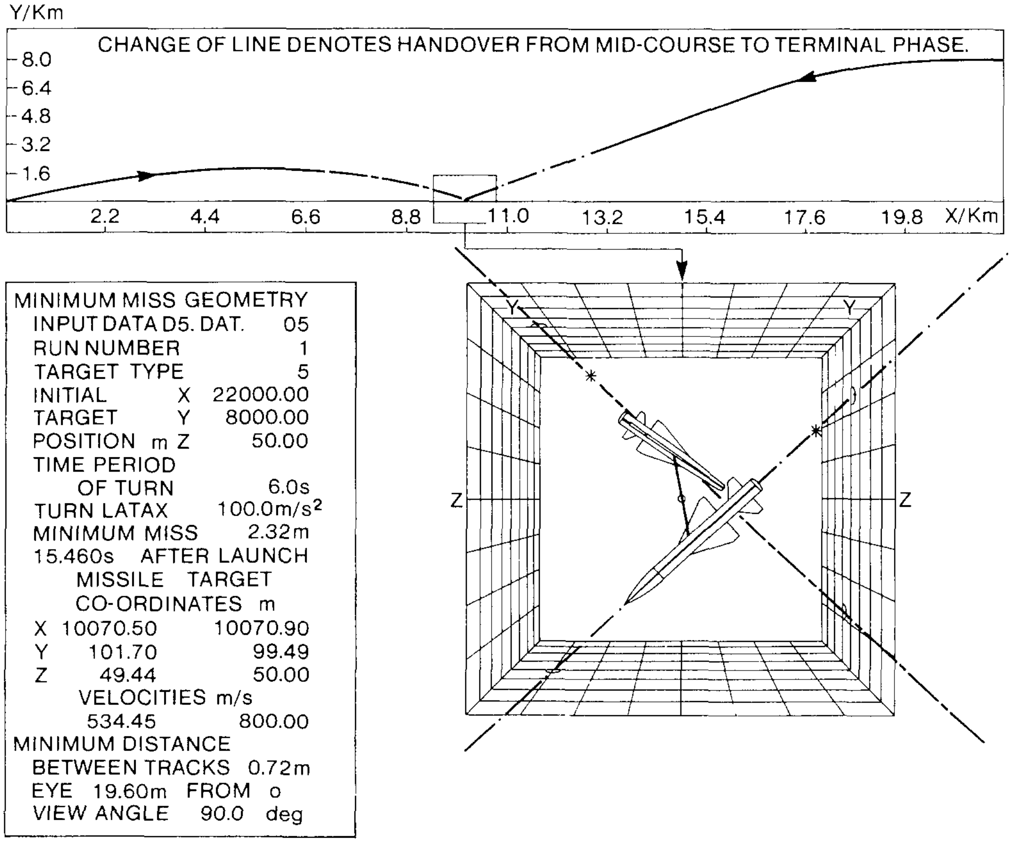
Fig. 15—Predicted performance against a weaving target



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  TARGET       Y   8000.00
  POSITION  m Z      50.00
  TIME PERIOD
    OF TURN            6.0s
  TURN LATAX      100.0m/s2
  MINIMUM MISS        2.32m
  15.460s  AFTER LAUNCH
      MISSILE  TARGET
      CO-ORDINATES  m
  X  10070.50      10070.90
  Y     101.70        99.49
  Z     49.44         50.00
      VELOCITIES  m/s
     534.45          800.00
MINIMUM DISTANCE
  BETWEEN TRACKS  0.72m
  EYE  19.60m  FROM  o
  VIEW ANGLE    90.0  deg
```

Fig. 16—Predicted performance against a dog-leg target

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