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Suggested Modifications to Optical Sensor Algorithms in JANUS

H. H. Bailey, L. G. Mundie, H. A. Ory

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Optical sensor algorithms in the JANUS(T) ground combat simulation do not include a repeated detection criterion for target acquisition and weapon firing, nor do they provide for the effects of false detections. As a result, targets detected with very low probability, such as those at ranges near the performance limit of the sensor, will often give rise to acquisition and weapon-firing decisions when rare single detections result from coverage by many sensors and time cycles. This Note reviews the detection algorithms for optical sensors implemented in JANUS(T), identifies some approximations that can lead to overoptimistic estimates of target acquisition probabilities when the calculated detection probability is small, and suggests an acquisition criterion that alleviates the problem.

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Suggested Modifications to Optical Sensor Algorithms in JANUS

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Prepared for the
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PREFACE

This Note reviews the detection algorithms for optical sensors implemented in the JANUS(T) engagement model, identifies some approximations that can lead to overoptimistic estimates of target acquisition probabilities when the calculated detection probability is small, and suggests an acquisition criterion that alleviates the problem. Various implementations that differ in the amount of additional computing burden required are described for the acquisition criterion.

The results should be of interest to anyone involved in applications of the JANUS(T) engagement model.

The research was carried out as part of the Joint Close Support Study, and this Note is part of a series of publications documenting that work. The project was jointly sponsored by the Director of Defense Research and Engineering, the U.S. Army, and the U.S. Air Force and was conducted by all three of RAND's federally funded research and development centers (FFRDCs): National Defense Research Institute (Office of the Secretary of Defense, and Joint Chiefs of Staff); the Arroyo Center (Army); and Project AIR FORCE (Air Force).

SUMMARY

The target acquisition algorithms implemented for optical sensors in the JANUS(T) ground combat simulation, unlike radar sensor algorithms, are found to include no requirement for repeated detection as a condition for target acquisition declarations and weapon firing, nor any consideration of possible false detections. As a result, targets detected with very low probability, such as those at ranges near the performance limit of the sensor, will often give rise to acquisition and weapon firing decisions when rare single detections result from coverage by many sensors and time cycles. A stronger criterion is needed for target acquisition and weapon firing than just a single detection, to avoid overestimating the number of acquisition and weapon firing events for long range targets.

An acquisition criterion is suggested, similar to that used with radar sensors in JANUS, **in which two detections out of three successive scans are required to accomplish acquisition and fire weapons.** This criterion is effective primarily in the region of small detection probability, where the corresponding acquisition probability approaches a square law dependence on the detection probability. This lowers acquisition when the detection probability is small and greatly reduces the number of weapon firings at long range.

Various methods for implementing the acquisition criterion in JANUS have different effects on the computational load. JANUS is interactive, and it is desirable to minimize the computing load and execution time. A direct implementation, similar to the way that radar sensors are currently modeled, stores detection results for two previous scans, and **detection during the current scan is counted as acquisition if detection also occurred on one of the two previous scans.** This implementation involves specifying search sectors and scan rates for each sensor, accumulating sensor scanning time over JANUS cycles until it equals the time required for the sensor to cover its assigned search sector, then evaluating target detection for the completed scan. It thus requires more computation than the current algorithms and storage of many more variables, including detection results for two previous scans for each sensor and target combination. A variation of this approach avoids storage of results by evaluating acquisition based on the probability of two detections out of three scans as approximated

by repeated application of the results from the current scan to simulate those that would be obtained from successive scans.

An indirect implementation applies the acquisition criterion to the JANUS procedure for setting threshold resolution requirements for accessibility of targets to detection, which otherwise is based on a single detection requirement. The current JANUS procedure involves drawing a random number between 0 and 1 and inserting it into the relationship, expressed in a data table, between sensor resolution and the time-independent part of the detection probability to determine the threshold resolution required for accessibility of a given target to detection by a given sensor. The indirect application of the acquisition criterion involves replacing the current data table by one that expresses the relationship between sensor resolution and an acquisition probability expression derived from the time-independent part of the detection probability. Additional computation and data storage are not required for this indirect approach.

If computing resources permit, the full direct implementation of the acquisition criterion for optical sensors is recommended. If variable storage must be minimized, then the variation described for the direct implementation is recommended. If no additional computing burden can be tolerated, then the indirect implementation is recommended. Even this indirect approach would greatly improve the modeling of target acquisition and weapon firing.

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I. INTRODUCTION

Optical sensor algorithms in the version of the JANUS ground combat model currently in use include no repeated detection criterion for target acquisition and weapon firing, and no provision for the effects of false detections. A single detection, even though a rare and isolated event, can result in a weapon firing decision. The probability of such an event can be appreciable when the detection probability is accumulated from many sensors over an extended duration. It can lead to an overestimate of sensor and weapon performance at long ranges. Here we examine whether a repeated detection criterion is needed as a basis for acquisition and weapon firing, what its effects would be, and how such a criterion could be implemented.

JANUS(T) is an interactive, two-sided, closed, stochastic ground combat simulation developed and maintained by the U.S. Army Training and Doctrine (TRADOC) Systems Analysis Activity (TRASANA), which is now called the TRADOC Analysis Center (TRAC), at White Sands Missile Range, New Mexico. It is derived from the Lawrence National Laboratory prototype model JANUS. Most air and ground systems that participate in offensive and defensive operations are represented, with emphasis on those that participate in maneuver and artillery operations on land. [1] JANUS(T), hereafter referred to simply as JANUS, is widely used for operational effectiveness analyses, at RAND as well as other locations.

It is characteristic of models that approximations are involved in the representation of systems and their performance, and in the overall description of operations. Because JANUS is interactive, computations must be sufficiently rapid to allow simulation time not greatly different from real time. Some of the model's approximations are designed to improve the speed of computation. Usually the approximations are consistent with the scenario assumptions, but it is always necessary to examine whether a given scenario produces circumstances in which particular approximation errors are emphasized that might affect the results significantly.

Consider an example in which ranges between sensors and targets are usually sufficiently long that detection during any sensor scan is a low probability event, but many sensors are involved over many scan periods. The cumulative single detection probability can become large and can result in weapon firing decisions based on single

detections. For example, simulation of standoff weapons emphasizes the accuracy of the detection algorithm in circumstances that may be quite different from those for which it was derived. As a case in point, algorithms for imaging sensors in JANUS are based on a detection model that was derived under conditions where detection probabilities were much larger than occur during simulations of combat near the range limit of the sensors.

During some JANUS simulation exercises, target detection and weapon firing actually were observed at ranges longer than expected for the sensors being modeled. Calculations based on JANUS algorithms also produced small, single-look detection probabilities, on the order of 1 percent, at similar long ranges. An appreciable detection probability, which in JANUS is essentially the acquisition probability, resulted when the small, single-look detection probability accumulated over many sensors and time cycles. With actual sensors, acquisition at small, single-look detection probabilities would require difficult discrimination against the effects of noise and clutter, which are not represented in the JANUS model. However, if noise and clutter effects had been represented, they might well have given a comparable number of false detections. Therefore, we investigated possible modifications to the JANUS optical sensor algorithms that would represent rare detection events more realistically.

This Note examines the representation of imaging sensors in the JANUS model and suggests modifications that would improve the accuracy of target acquisition calculations in long range combat circumstances. Section II reviews the imaging sensor detection algorithms and their implementation in JANUS and identifies some of their limitations. Section III presents modified algorithms with a stronger criterion for target acquisition and weapon firing and illustrates their effects. Various methods, differing in the amount of computational burden they impose, are suggested for their implementation in the JANUS model. Conclusions and recommendations for implementing the acquisition criterion are summarized in Sec. IV.

II. CURRENT IMAGING SENSOR ALGORITHMS

The best experimental data on the probability of target acquisition by a human observer, through direct vision or by observing sensor imagery displayed electronically, are probably those obtained by the Army's Night Vision Laboratory (NVL), now called the Center for Night Vision and Electro-Optics (CNVEO), at Ft. Belvoir, Virginia. Their results have been extended to broader conditions than those of the original experiments reported in Johnson's classic paper, [2] and were incorporated into a model that is usually referred to as the NVL model. [3–4] This model, widely used for analyses of sensor performance, provides the basis for the representation of imaging sensors in JANUS. It expresses the detection probability as the product of two terms—P_1, the probability of detection with unlimited observation time, which depends primarily on resolution and contrast, and P_2, a time-dependent term that takes account of search sectors, fields of view, and coverage during a scan time.

TIME-INDEPENDENT TERM

The first term, P_1, expresses the experimental observation that, with unlimited observation time, the probability of detection is a function of C, the number of resolvable modulation cycles (or line pairs, or resolution cells) present within the critical (usually minimum) dimension of a target image. The resolution is dependent on sensor quality, target contrast, and propagation effects. P_1 is also a function of the background clutter, type of target, and the kind of decision to be made (detection, recognition, etc.). These latter factors are combined into a parameter, M, which scales the resolution requirement; it is the value of C required to yield a specified value (usually 0.5) for P_1, for whatever types of clutter, target, and decision are specified.

Examples of M can be cited to give a feeling for its magnitude. As noted, the number of line pairs achieved in resolution must equal M for a 50 percent detection probability given unlimited observation time. M is often considered to be a fixed scale value, which, for the example of a small armored vehicle, is set as 1 for detection against a reasonably uniform background, 2 for detection in medium clutter, 4 for recognition, and 6.4 for identification. Actually, M should be thought of as a parameter to which a

number must be assigned in setting requirements, but for which few guidelines can be provided. It can be argued that a weapon-firing decision is intermediate between mere detection and full recognition, and therefore in many cases a value of M = 3 is appropriate; this perception level is sometimes called classification. The approximate nature of defining M is implicitly acknowledged by the common use of small integers to describe a continuous variable.

In the NVL model, P_1 is represented as a function of the ratio C/M and expressed by the following empirical equation:

$$P_1 = \frac{(C/M)^{2.7 + 0.7(C/M)}}{1 + (C/M)^{2.7 + 0.7(C/M)}} \tag{1}$$

The expression satisfies the requirement that when C = M, then $P_1 = 0.5$. The data to which this equation is a fit are very approximate. Variability is caused by background clutter, observer skills, target type, detection criteria, and other factors. Also, it is in the nature of these empirical data that small departures from zero or unity are difficult to observe and quantify; therefore, accuracy is probably greatest in the midrange of values. Other empirical functions can also be used to represent P_1. We note in passing that an expression derived in unpublished work by H. Bailey agrees with the previous expression more closely (within about 2 percent) than can be easily distinguished by comparison with the approximate experimental data:

$$P_1 = 1 - \exp[-(0.84C/M)^{2.4}] \tag{2}$$

This form may be more convenient for use in some analyses.

To determine the value of P_1 in a given situation, one must assign a value to M appropriate to the conditions of the situation and determine the number of resolution cycles across the minimum target dimension, C, achieved by the sensor under the prevailing conditions.

For a sensor that resolves only in angle, the resolution is given by the relation:

$$C = r\,\Theta \tag{3}$$

where r is the resolution of the sensor, usually expressed as the effective number of resolvable line pairs (sometimes called cycles) per milliradian, and Θ is the angular subtense at the sensor, in milliradians, of the critical (usually minimum) dimension L of the target. For a target at range R, Θ is simply L/R. The value of r depends on the type and quality of the sensor.

In the visual region, the sensor resolution in line pairs per milliradian is given approximately by:

$$r = m[1.22 \ln(C_s) + 4.09] \tag{4}$$

where m is the magnification employed, ln designates the natural logarithm, and C_s is the apparent contrast of the target against the background as observed at the sensor, given in ref. [5] as:

$$C_s = C_t / \{1 + SG [\exp(\epsilon_v R) - 1]\} . \tag{5}$$

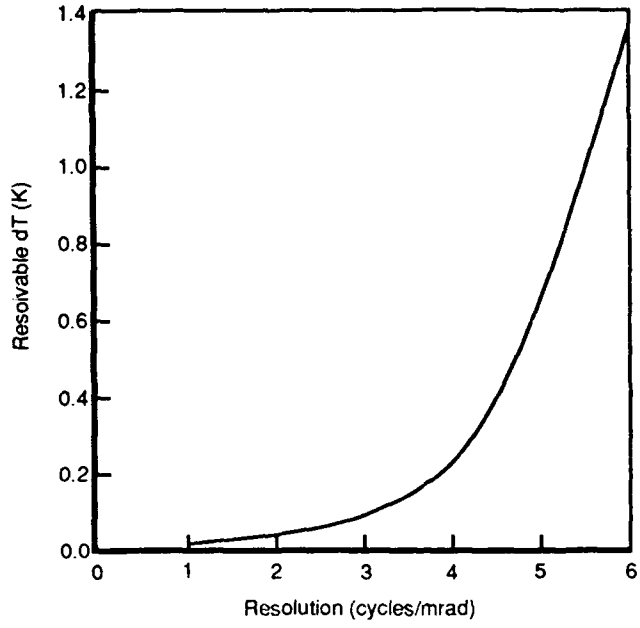
Here C_t is the contrast between target and background as observed at the target, SG is the ratio of sky brightness to background brightness, and ϵ_v is the atmospheric extinction coefficient in the visual region. ϵ_v varies from 0 to 1. SG varies from 1.4 to 7 for desert backgrounds, with brightness not much less than the sky, and from 5 to 25 for forest backgrounds, with brightness much less than the sky, for example.

For infrared sensors, r is a function of the apparent temperature difference, dT_s, between the target and the background, as measured at the sensor. The relation between r and dT_s is given by the minimum resolvable temperature (MRT) curve, which is measured experimentally and is usually provided by the sensor manufacturer or a government testing laboratory. Figure 1a presents such a curve for a nominal Forward-Looking Infrared (FLIR) sensor; Fig. 1b presents the corresponding minimum resolvable contrast (MRC) curve for a nominal television sensor, which can be related to Eq. (4). In JANUS, the MRT curve is represented by tabulated values from which r is interpolated for a given dT_s. dT_s is related to dT_t, the temperature difference at the target, by:

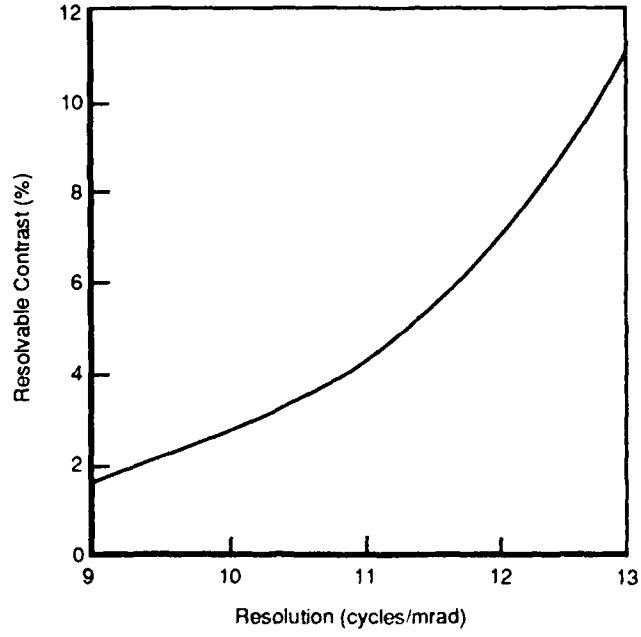
$$dT_s = dT_t \exp(-\epsilon_{ir} R) \tag{6}$$

where ϵ_{ir} is the atmospheric extinction coefficient in the infrared spectral bandpass of the FLIR.

For ground-mapping radars, which measure range and azimuth rather than horizontal and vertical angles, the purely geometric concept of a resolution cell is adopted. This is an area given by the product of an azimuthal and a range resolution, $(R\Theta)(ct/2)$, where Θ is the antenna beamwidth in azimuth, c is the velocity of light, and t is the pulse duration. This geometric concept does not include any intensity or contrast requirement, as does the effective resolution described above for optical sensors. For



(a) Minimum Resolvable Temperatures (MRT) curve for a nominal FLIR sensor



(b) Minimum Resolvable Contrast (MRC) curve for a nominal television sensor

Fig. 1—Examples of sensor resolution performance curves

radars, contrast is replaced by a signal-to-noise or a signal-to-clutter ratio (depending on which is dominant), and the probability of detection is calculated rigorously for a specified false detection rate, P_{fd}. Note that, in the optical imaging case, P_{fd} is selected implicitly and subjectively by an observer as he assesses what he considers to be the effective or usable resolution, whereas for radars this quantity must be entered explicitly. For optical imaging sensors, it is not known what value is typically selected. It may often range between 10^{-3} and 10^{-6} depending on the observer's visual acuity, his motivation at the time, and other factors. In radar calculations, a value at the more conservative end is commonly used, such as $P_{fd} = 10^{-6}$, but not necessarily so.

Considerations up to this point presuppose a line of sight (LOS) between the sensor and the target. Actually, there may be interferences from terrain or smoke, and these are handled by the JANUS model. JANUS includes a detailed terrain model that is used to evaluate whether a line of sight exists between the sensor and the target. An obscuration factor is incorporated into P_1 as a multiplying factor, dependent on the LOS conditions. Smoke obscuration, which is more dynamic, is addressed in a similar manner, but the obscuration factor multiplies the time-dependent term.

TIME-DEPENDENT TERM

The time-dependent term in the detection model is given by:

$$P_2 = 1 - \exp[- (C/M) (t/6.8)] \tag{7}$$

Here t is the amount of time that the target is within the sensor's field of view, termed the observation time. The C/M factor in the exponent can be thought of as describing the efficiency with which the observation time can be utilized; greater resolution facilitates detection. The experimentally determined constant, 6.8, presumably relates to the number of fixation points within a typical field of view. If one field of view is observed within the cycle time of 2 sec, at which JANUS operates, the effective amount of time that the eye fixates on a particular target is 2/6.8 sec, close to the classical fixation interval or glimpse time of 1/3 sec.

In JANUS, if a total search sector (SS) is to be covered by a sensor with a field of view (FV) then the time available for looking in each field of view is:

$$t_J = 2 (FV/SS) \tag{8}$$

where the subscript J indicates that this expression is specialized to the JANUS cycle time. Substituting this value of t into Eq. (7) yields the expression:

$$P_{2J} = 1 - \exp[-(C/M)\,(2/6.8)\,(FV/SS)] \qquad (9)$$

where the second subscript again refers to JANUS specialization. As mentioned earlier, P_{2J} is also multiplied by another factor to account for whether smoke obscures the line of sight between sensor and target, but this aspect is peripheral to the present discussion.

EVALUATION PROCEDURE

JANUS is a stochastic model in which outcomes of events are determined by random draws against their probabilities of occurrence, rather than being described by a statistical average. Although the model for detection probability has the form of a product of conditional probabilities, the outcomes of P_1 and P_2 are evaluated separately and then multiplied. If the outcome from P_1 is zero, then no detection is possible, no matter what the value of P_2. If the outcome from P_1 is unity, then the outcome from a random draw against the value of P_2 determines whether detection occurs.

Evaluation of P_1 is actually implemented indirectly in JANUS, in a manner that reduces the amount of computation required. Also, the value of M used to evaluate P_1 is always taken as 3.5 (insofar as the internal data table that is used is constructed using this value); this value provides sufficient recognition to support a weapon-firing decision; no other recognition requirement is included in the JANUS model. For each target and sensor combination, the indirect procedure involves making a random draw against the range of values of P_1, 0 to 1. According to Eq. (1), a given result corresponds to a particular value of C/M and for the value M = 3.5 used to justify the weapon firing decision, corresponds to a particular value of C. That value of C is identified as a threshold value, such that during each cycle time, if the value of C calculated in the JANUS PAIRS subroutine (based on Eq. (3)) exceeds the threshold, then the given target is accessible to detection by the given sensor; otherwise it is not. The random draw that determines the threshold C is performed only once during initialization, and the thresholds are not changed during a particular JANUS run. This procedure is implemented in the JANUS INITACQ subroutine, and the data table PAIRSVAL is entered with the result of the random draw to extract the threshold value of C. Use of this procedure provides stochastic results while requiring computation of target

accessibility only once. Thus, it minimizes the computational load and improves the speed of execution.

P_2 is evaluated at each time cycle according to Eq. (9), using particular values of variables appropriate to the situation at the time and a nominal value of M = 2, which assumes detection against medium clutter. Some adjustments are applied in particular cases, such as for a moving target or one that has just fired, but these adjustments are not germane to the current discussion. In the process, the resolution, C, achieved under current conditions is evaluated. If the value of C is less than the threshold value, then the target is not accessible to detection. If the value of C equals or exceeds the threshold value, then a random draw is made against the value of P_2, and the outcome determines whether the target is detected. If detected, the target is added to the target list for the sensor (subject to other conditions that can be ignored here), and no further detection criteria must be satisfied to initiate weapon firing.

This procedure is repeated each JANUS time cycle. Assuming for convenience that P_2 maintains a constant value, the average cumulative detection probability for a given target within the search area of a given sensor over N time cycles is

$$P_d(N) = \begin{cases} 0 & \text{if } C < C_{threshold} \\ 1 - (1 - P_2)^N & \text{if } C \geq C_{threshold} \end{cases} \tag{10}$$

If a given target is within the search area of n sensors over N time cycles, the probability that $C_i \geq C_{threshold}$ for any sensor i is P_{1_i}, and the average number of effective sensors n_{eff} for which $C_i \geq C_{threshold}$ is the sum of the P_{1_i} over the n sensors. The cumulative detection probability for n sensors and N cycles, assuming that P_2 remains constant, is then:

$$P_d(n,N) = 1 - \prod_{i=1}^{n}[1 - P_{d_i}(N)] \tag{11}$$

$$= 1 - [1 - P_2]^{Nn_{eff}}$$

Of course, P_2 does vary, and there are correlations among P_1, P_2, and C; however, the above equations illustrate the general dependence of P_d on n and N. The numbers of

sensors and time cycles can be large, so $P_d(n,N)$ can grow to an appreciable value, even for such small values of P_d as might occur near the sensor's range limit.

All the burden of establishing target recognition sufficient for firing is carried by P_1, and only a single detection is required to enable tracking and weapon firing. No special criteria are imposed to avoid possible false detections; indeed, JANUS includes no provisions for false detections or their consequences.

III. SUGGESTED ACQUISITION CRITERION

RATIONALE

Target detection based on a single look is probably not an adequate criterion for initiating the firing of a weapon. Successive looks at a sensor image of the real world in real time are not identical, for a wide range of reasons. The target may be moving with respect to the clutter. The target may be nominally at rest but moving slightly (such as a hovering helicopter) so that, if the observed contrast is marginal, motion of as little as a single pixel through the clutter could alter the perceived shape of a target. There may be motion internal to a target, such as moving guns or rotors, or internal to the clutter, such as wind-caused foliage movement. The sensor may be moving with similar consequences. There is always some detector or receiver noise, even though in a well-designed system these are seldom limiting or even noticeable. There is always some electronic noise in a display, which usually is noticeable. The observer's visual system has its own noise, quantum noise at low light levels, electrical noise in the retina and nerves, and changing perception thresholds because of motivation or extraneous inputs. Illumination and thermal conditions vary. At the margin of barely detectable targets, all of these phenomena may be operating. One is not looking at a static photograph, and experienced observers will seldom trust a single glimpse; rare detection must be confirmed by repetition to be trusted.

Radar engineers and operators concerned with detecting isolated targets (e.g., aircraft) at long range (usually limited by receiver noise) have developed an acquisition criterion of at least two detections out of three successive antenna scans. Indeed, this criterion is incorporated in the JANUS model for radar sensors. The details are somewhat different for optical sensors, but a similar criterion of two detections out of three successive looks is appropriate. Perhaps the criterion should be a slightly different ratio, such as three out of five, but in general the numerator probably should be greater than one and the denominator less than ten.

Until better experimental data become available, we suggest addition of an acquisition criterion for optical sensors based on a requirement for two detections out of three successive scans. This criterion would increase the complexity of the model, so three possible implementation methods, suggested below, entail different degrees of

complication. A direct implementation involves storage of detection results from two previous scans and comparison with the current result; this is similar to the current radar algorithms. A variation of this method avoids the storage requirement by computing the probability that two detections would occur within three successive scans, based on the result from the current scan. An indirect implementation minimizes modifications to the JANUS program. No additional variables or computations are required, only substitution of values derived from a repeated detection requirement for those currently in the JANUS PAIRSVAL data table mentioned above.

DIRECT IMPLEMENTATION

Direct implementation of the two out of three acquisition algorithm would require considerable change from the way JANUS currently implements optical sensors. JANUS evaluates detection by a random draw against the detection probability calculated for each time cycle, which implicitly assumes a scan rate adequate for sector coverage within a time cycle. The observation time that is allocated to each target location may be quite small. Actually, the time required for a sensor to complete a full scan is usually longer than a single JANUS time cycle. Nevertheless, although it does not exactly replicate sensor operations, the JANUS procedure linearly approximates the more exact representation of detection probability, and that is sufficiently accurate as long as the calculated detection probabilities are small. For larger detection probabilities, the JANUS procedures somewhat overestimate the detection probability. However, the linear approximation is often adequate for determination of the single-look detection probability.

The linear approximation is not adequate for application of the two out of three acquisition criterion, because this criterion is essentially nonlinear and must be applied to a complete detection cycle over the full sensor scan period, not just a fragment. To apply it properly, JANUS procedures must utilize the correct representation of sensor observation time in the detection equations described earlier. Search subsectors must also be assigned within JANUS so that when they are covered at the scan rate of the sensor, the correct amount of time will be spent observing the target. Typically, the total threat sector could be divided by the number of sensors to determine the search subsector for an individual sensor. If the number of sensors is large enough, a larger subsector could be assigned with sectors covered by more than one sensor. Particular assignments

would depend on particular scenarios but in general should be realistic. The time required to complete a scan is given by the search subsector divided by the scan rate of the sensor.

Detection should not be evaluated until a scan is completed for whatever search sector the sensor covers. That usually takes longer than a JANUS cycle, so that the observation time entering into the exponential time factor of Eq. (7) is the actual amount of time the target is within the sensor field of view during the scan.

$$t = t_s\,(FV/SS) = FV/\alpha \tag{12}$$

where t_s is the scan time for coverage of the search subsector at the sensor scan rate, α, and the two are related by $t_s = SS/\alpha$. This observation time differs from that in Eq. (8) by the use of t_s rather than the JANUS 2 sec cycle time. Then, if the value of resolution, C, for the current circumstances exceeds the threshold, a random draw would be made against the detection probability based on a complete scan, as calculated according to:

$$P_2 = 1 - \exp[-(C/M)\,(t_s/6.8)\,(FV/SS)] \tag{13}$$

$$= 1 - \exp[-(C/M)\,(FV/6.8\alpha)]$$

The result would then be compared with the stored results of earlier detection scans. If the current scan plus one of the two previous scans achieved detection, then the target would be acquired. Two flags would be associated with each sensor and target combination, one flag to store the results for each of the two previous scans, and the flags set according to detection results as each scan is completed. If a given scan does not achieve detection, flag settings are shifted backward one scan and compared again in the next scan.

Some aspects of this model for optical sensors involve license that is not involved in the corresponding model for radar sensors. The performance of radar hardware is determined according to operational settings made by the operator. By contrast, optical sensor scanning rate and sector coverage are often controlled by human observers who can and do introduce variations in the scanning rate and sector coverage. This can aid or hinder the search process, according to the circumstances. However, for modeling purposes, this source of variability is ignored and the optical sensors are assumed to search in a regular manner that is more amenable to analytical modeling.

The approach outlined here is a direct implementation of the two out of three acquisition criterion and is very similar to the procedure currently used in JANUS for radar sensors. It does increase the number of variables involved in JANUS calculations, including the two detection flags for each sensor and target combination, the particular sensor search subsector (which must be redefined each time the sensor moves), the sensor scan time, and the accumulated search time. Additional computations are involved in accumulating search time and comparing it with the sensor scan time, and in comparing results from successive scans; this is somewhat offset by the smaller number of evaluations of detection probability for each sensor scan time rather than for each JANUS cycle. Setup effort is increased slightly by the increased number of parameters. This implementation is recommended if computing resources are available to support it.

VARIATION ON DIRECT IMPLEMENTATION

If the increased number of variables is a critical problem, a slight variation of this procedure would avoid the requirement for using two flags to store detection results for each sensor and target combination. It probably would be sufficient to calculate a fictitious two out of three acquisition probability for each scan time, on the assumption that the probabilities of detection are unlikely to change much during three successive sensor scans. An acquisition probability, P_a, could be calculated for each scan as follows:

$$P_a = P_1P_2(1 - P_3) + P_1P_3(1 - P_2) + P_2P_3(1 - P_1) + P_1P_2P_3 \qquad (14)$$

$$= 3P_d^2 - 2P_d^3$$

where $P_{1,2,3}$ are the detection probabilities on the first, second, and third simulated scans, respectively, and each is equal to the calculated value of P_d for the current scan. Although it reduces the number of variables, this variation slightly increases the amount of computation required. This implementation of the acquisition criterion is recommended if the number of variables must be constrained, but the computation load is otherwise acceptable.

Equation (14), as plotted in Fig. 2a, also illustrates the effect of the two out of three criterion. P_a is equal to P_d when $P_d = 0.5$. For smaller values of P_d, P_a is smaller than P_d, and for larger values of P_d, P_a is larger than P_d. The ratio of P_d to P_a increases as

P_d becomes small, as can be seen in Fig. 2b. Thus, the greatest effect of applying the acquisition criterion is to reduce drastically the acquisition probability when the detection probability is small, especially when the effect is compounded by multiple looks by a given sensor, or looks by multiple sensors, or products of looks and sensors. This corresponds to drastic reduction of acquisition at very long ranges.

For illustration, consider the following average cumulative probabilities of detection and acquisition:

nN	$P_d(n,N)$	$P_a(n,N)$
1	.010	.0003
10	.096	.003
100	.634	.030
1	.050	.007
10	.401	.070
100	.994	.517
1	.100	.028
10	.651	.247
100	1.000	.942

evaluated according to:

$$P(n,N) = 1 - (1 - P)^{nN} \tag{15}$$

for cases in which P_d takes on the values of .01, .05, and .10, and the number of looks is the product of the number of sensors, n, that can observe the target and the number of scan cycles, N, performed during the period while the target is in the search subsector.

The numbers of looks and sensors for which the comparisons are given above are modest compared with the numbers of sensors and durations of time usually represented in JANUS simulations. When P_d is small, the effect of the two out of three criterion for acquisition is striking; $P_a(n,N)$ can be smaller than $P_d(n,N)$ by more than an order of magnitude. These numbers indicate that if determined directly by P_d there would be a 0.63 probability of weapon firing (assuming the weapon could handle the target) after 100 scans, even though detection occurs only one time out of a hundred, on the average, which would not provide a reasonable basis for acquisition and track. The simple accumulation of detection probability without taking account of noise and clutter is not a

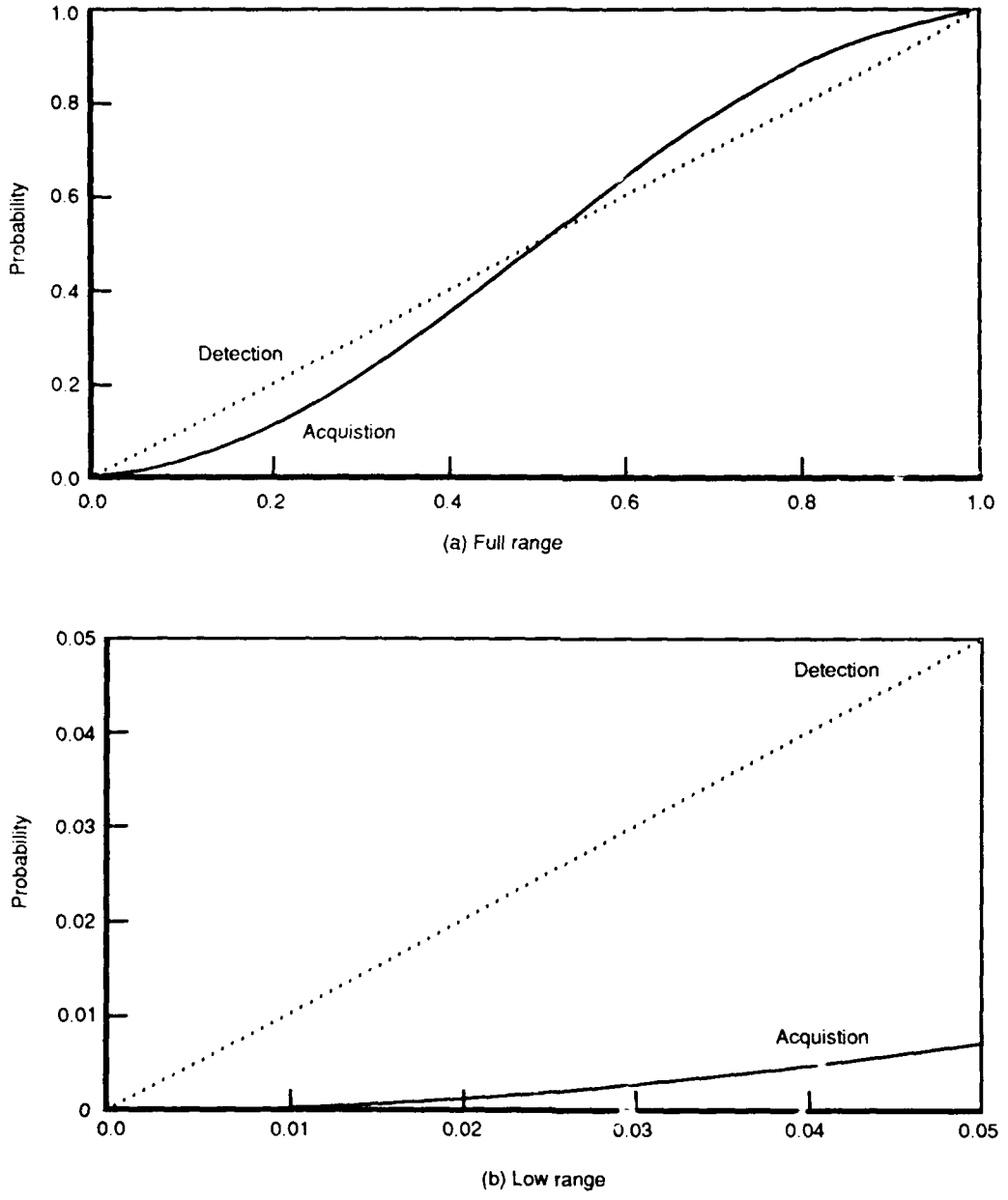


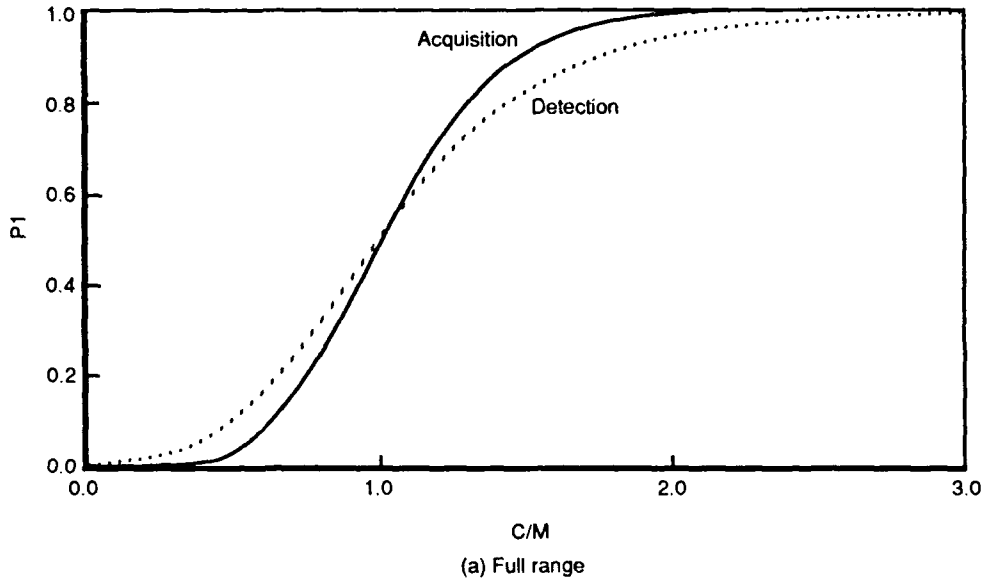
Fig. 2—Relationship between detection and acquisition probability based on a requirement for two detections out of three successive scans

reasonable representation of acquisition, tracking, and firing processes. If the two out of three acquisition criterion is applied, which has an effect equivalent to discrimination against noise and clutter, the probability of weapon firing is only 0.03, a twenty-fold reduction.

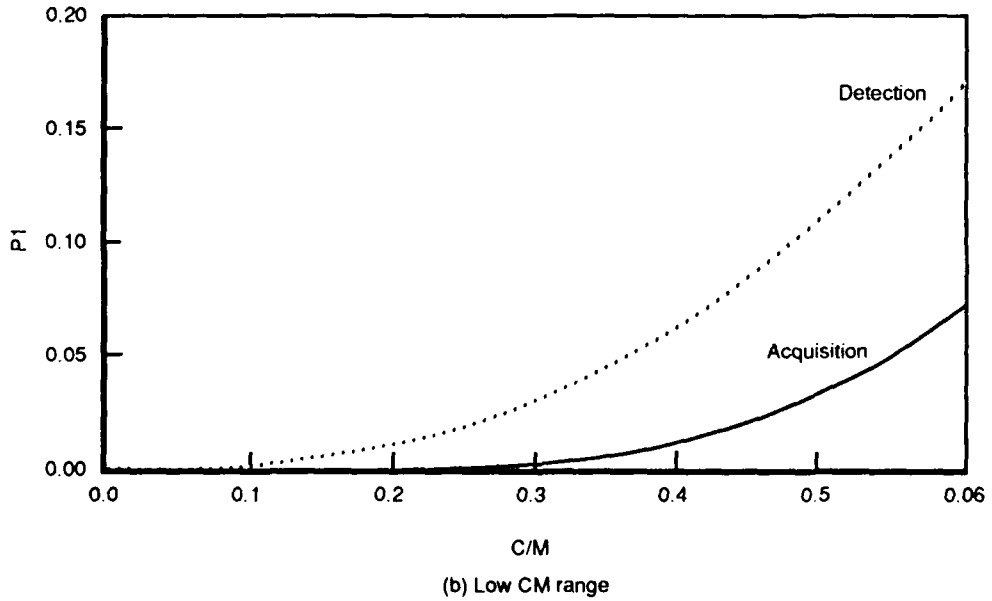
Direct implementation of the two out of three criterion would require rewriting parts of the JANUS program. The general logical approach currently used for radar sensors could be followed, with different equations used to represent the optical sensors and minor differences associated with factors specific to optical sensors, such as smoke, weapon firing, etc. Although the required program changes appear to be minor, they must also accommodate the logic and interactions associated with various other subroutines. Further, any changes would also require corresponding changes to the JANUS support program used to initialize a JANUS scenario and that used for program maintenance. Although not difficult, the task would also not be trivial.

INDIRECT IMPLEMENTATION

An alternative indirect implementation method is possible that would apply the acquisition criterion in a limited way, while not increasing the number of variables or adding to the amount of computation in JANUS. The acquisition criterion could be applied to the time-independent part of the expression for detection probability, similar to the way JANUS currently implements the requirement for a weapon-firing decision. One could determine the threshold value of C for each combination of sensor and target by first obtaining a value from a random draw between 0 and 1, then applying the result against the relationship between P_{1a} (rather than P_{1d}) and C/M, where P_{1d} is the same as P_1 given by Eq. (1) and P_{1a} is derived from P_{1d} according to the relationship expressed in Eq. (14). The resulting threshold C/M and corresponding threshold C (retaining the value of M = 3.5) would be that required for acquisition according to the two out of three criterion rather than for simple detection. These relationships are illustrated in Fig. 3; Fig. 3a covers the full range, and Fig. 3b shows an expanded portion for the lower range between 0.0 and 0.2, of P_{1d} and P_{1a}. In the midrange of values, there is very little difference in the curves for P_{1d} and P_{1a}, and they intersect when (C/M) = 1. For very low values of P_1, the values of C/M that correspond to P_{1a} are greater by a large factor than the values of C/M that correspond to P_{1d}. In these cases, the acquisition criterion sets much larger threshold C values than does the simple detection criterion, and these are



(a) Full range



(b) Low CM range

Fig. 3—Relationship between the time-independent part of the detection probability and the resolution cycle ratio, C/M

much more difficult to satisfy for targets at long range. Thus, long range targets are much less likely to be evaluated as accessible to detection and acquisition according to the acquisition criterion. The more stringent criterion greatly reduces the number of effective sensors for long range targets. Also, for targets that are evaluated as inaccessible, compounding of detection probability over large numbers of cycles has no effect; the targets remain inaccessible and undetected.

The indirect implementation does not apply the full force of the acquisition criterion; nevertheless, it should greatly reduce the occurrences of acquisition and weapon firing for targets with low detection probability, such as at long range. Implementation in JANUS requires only the replacement in the PAIRSVAL table of the current threshold values of C based on the relationship between P_{1d} and C with new threshold values of C based on the relationship between P_{1a} and C. Table 1 presents values of $C_{threshold}$ based on the acquisition criterion that are appropriate for inclusion in the JANUS model; values of $C_{threshold}$ based on Eq. (1), as currently used in JANUS, are also shown for comparison. In both cases, the value of M = 3.5 is used to scale from C/M to $C_{threshold}$. Use of the threshold C values based on the acquisition criterion in the JANUS PAIRSVAL table is recommended if it is necessary to accommodate limited computing resources.

SUMMARY OF IMPLEMENTATION OPTIONS

The essential modification requirements for the various implementations of the two detections out of three scans acquisition criterion are summarized below.

Direct Implementation

The direct implementation method provides the full effect of the acquisition criterion. The modifications required to JANUS include:

1. Specify search subsectors for each sensor and update them after each movement of target or sensor and specify a corresponding scan time based on the sensor scan rate.
2. Define and initialize to zero two flags for each sensor and target combination. One flag is set if target detection occurred in the previous scan, and the other if target detection occurred in the next previous scan. After

Table 1

THRESHOLD RESOLUTION REQUIREMENTS FOR TARGET ACCESSIBILITY

P_1	Detection $C_{threshold}$	Acquisition $C_{threshold}$	P_1	Detection $C_{threshold}$	Acquisition $C_{threshold}$
0.0050	0.5021	1.1557	0.5050	3.5206	3.5137
0.0150	0.8076	1.4916	0.5150	3.5621	3.5413
0.0250	0.9870	1.6579	0.5250	3.6039	3.5691
0.0350	1.1254	1.7783	0.5350	3.6461	3.5970
0.0450	1.2412	1.8751	0.5450	3.6887	3.6251
0.0550	1.3424	1.9573	0.5550	3.7317	3.6535
0.0650	1.4331	2.0294	0.5650	3.7752	3.6820
0.0750	1.5160	2.0942	0.5750	3.8192	3.7108
0.0850	1.5927	2.1533	0.5850	3.8637	3.7400
0.0950	1.6644	2.2080	0.5950	3.9089	3.7694
0.1050	1.7320	2.2590	0.6050	3.9547	3.7992
0.1150	1.7962	2.3070	0.6150	4.0012	3.8293
0.1250	1.8574	2.3525	0.6250	4.0484	3.8598
0.1350	1.9161	2.3958	0.6350	4.0964	3.8908
0.1450	1.9726	2.4372	0.6450	4.1453	3.9222
0.1550	2.0271	2.4771	0.6550	4.1951	3.9541
0.1650	2.0800	2.5155	0.6650	4.2459	3.9865
0.1750	2.1313	2.5526	0.6750	4.2978	4.0195
0.1850	2.1813	2.5886	0.6850	4.3508	4.0532
0.1950	2.2301	2.6236	0.6950	4.4051	4.0874
0.2050	2.2779	2.6577	0.7050	4.4607	4.1224
0.2150	2.3246	2.6910	0.7150	4.5178	4.1583
0.2250	2.3705	2.7236	0.7250	4.5764	4.1949
0.2350	2.4156	2.7555	0.7350	4.6368	4.2325
0.2450	2.4600	2.7869	0.7450	4.6989	4.2710
0.2550	2.5038	2.8178	0.7550	4.7631	4.3107
0.2650	2.5469	2.8481	0.7650	4.8295	4.3515
0.2750	2.5896	2.8780	0.7750	4.8983	4.3936
0.2850	2.6318	2.9075	0.7850	4.9698	4.4372
0.2950	2.6736	2.9366	0.7950	5.0441	4.4823
0.3050	2.7150	2.9655	0.8050	5.1217	4.5291
0.3150	2.7561	2.9940	0.8150	5.2029	4.5779
0.3250	2.7969	3.0223	0.8250	5.2881	4.6287
0.3350	2.8375	3.0503	0.8350	5.3778	4.6820
0.3450	2.8779	3.0782	0.8450	5.4726	4.7380
0.3550	2.9180	3.1058	0.8550	5.5731	4.7970
0.3650	2.9581	3.1334	0.8650	5.6805	4.8596
0.3750	2.9980	3.1607	0.8750	5.7954	4.9262
0.3850	3.0379	3.1880	0.8850	5.9196	4.9976
0.3950	3.0777	3.2152	0.8950	6.0544	5.0746
0.4050	3.1175	3.2423	0.9050	6.2023	5.1583
0.4150	3.1573	3.2693	0.9150	6.3661	5.2504
0.4250	3.1971	3.2964	0.9250	6.5500	5.3528
0.4350	3.2370	3.3234	0.9350	6.7599	5.4684
0.4450	3.2770	3.3504	0.9450	7.0047	5.6019
0.4550	3.3171	3.3775	0.9550	7.2988	5.7605
0.4650	3.3574	3.4046	0.9650	7.6678	5.9569
0.4750	3.3979	3.4317	0.9750	8.1650	6.2174
0.4850	3.4385	3.4590	0.9850	8.9330	6.6127
0.4950	3.4795	3.4863	0.9950	10.9370	7.6184

each scan, the detection result is placed into the flag for the previous scan, and previous contents of that flag are shifted to the flag for the next previous scan.

3. Specify and initialize a timer for each sensor, use it to accumulate time over JANUS cycles, and compare its contents with the scan time for the sensor. When the timer contents equal the scan time, reset the timer to zero and evaluate the detection probability according to Eq. (13) and the requirement that C exceed $C_{threshold}$. If the detection probability is nonzero, draw against it to determine whether the target is detected. If the target is detected, test to determine whether it was detected in either of the two previous scans. If so, consider the target acquired and post it to the sensor target list if the other conditions are satisfied. If not, shift the contents of detection flags backward one scan and continue.

Variation of Direct Implementation

The variation on the direct implementation provides essentially the full effect of the acquisition criterion. The modifications required to JANUS include:

1. Specify search subsectors for each sensor and update after movement, and specify a corresponding scan time based on the sensor scan rate.
2. Specify and initialize a timer for each sensor, use it to accumulate time over JANUS cycles, and compare its contents with the scan time for the sensor. When the timer contents equal the scan time, reset the timer to zero and evaluate the detection probability according to Eq. (13) and the requirement that C exceed $C_{threshold}$. If the detection probability is nonzero, then compute the acquisition probability according to Eq. (14), and draw against the result to determine whether the target is acquired. If so, post it to the sensor target list if other conditions are satisfied. If not, continue.

Indirect Implementation

The indirect implementation provides a large portion of the effect of the acquisition criterion. The modifications required to JANUS include only:

1. Replace the values of $C_{threshold}$ in the PAIRSVAL data table with $C_{threshold}$ values taken from Table 1.

IV. CONCLUSIONS

The target detection algorithms implemented in the JANUS model for optical sensors include only weak acquisition requirements, and there is no provision against false detections, which are ignored. This permits unrealistic acquisition of targets at very long ranges, based on low detection probabilities, especially when the detection probabilities are compounded over a long search time or a large number of sensors. As a result, firing decisions may be made on the basis of rare single detections. Such effects at long ranges might be emphasized, for example, in simulation of standoff weapons. A stronger requirement based on repeated detections, such as for two detections out of three successive scans, would primarily lessen excessively long range acquisitions and weapon firings.

The acquisition criterion could be implemented by one of the methods described in Sec. III, selected according to the computing resources available:

1. If sufficient computing resources are available, direct implementation of the acquisition criterion is recommended. This would apply the acquisition criterion most strongly and would correspond closely to the way JANUS currently implements radar sensors.
2. If available computing resources cannot accommodate the number of variables associated with the direct implementation, then the variation that approximates the acquisition probability based on only the current detection probability would be nearly as strong as the full direct implementation.
3. If computing resources are severely constrained, the indirect implementation, which imposes the acquisition criterion only on the threshold resolution requirement, is recommended. To accomplish this, the data presented in Table 1 for the threshold C based on the acquisition criterion can be used to replace the current values in the PAIRSVAL table that are based on the single detection criterion. This approach would require minimum effort and, despite its simplicity, would still to a large extent accomplish the objectives of the acquisition criterion.

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