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The Intrinsic Variability of Detection Range and Its Implications

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Abstract

The range of first detection of an approaching target is among the most important parameters defining sensors and defensive surveillance systems. A demonstration of capability typically consists of staged approaches of a target under realistic conditions in order to 1) assess detection range for mission planning, 2) show that the range of first detection occurs at notably greater range than competing systems, or 3) show that it exceeds a minimum performance specification. In port protection, for instance, it is common to demonstrate the performance of a sonar for the detection and tracking of underwater intruders by staging the approach of divers, or to demonstrate the performance of a radar for the detection of a fast boat by heading a boat toward the radar. The importance of detection range holds equally for combat systems.

Like most quantitative observations, the observation of detection range is subject to random variability. That is, the same value is neither observed nor expected on repeated trials. It will vary instead depending in part on the constantly changing environmental conditions that affect a sensor's performance, and in part on the changing target-strength of the target owing to its construction, aspect, and speed, and in part on any intrinsic randomness in the nature of the detection process itself. The intrinsic uncertainty is the subject of this paper.

At the limits of detection, a sensor system is by definition "straining" its utmost to distinguish a target in noisy or cluttered scene. Its probability of detection in a small time period is relatively low, for if it were high, one would not be speaking of the range limits of detection. Here it is shown by analysis that this in turn implies that there is a high intrinsic random variability in detection range that is not due to environmental or target strength uncertainties. Defensive response measures against a target must, as a minimum, be robust against this intrinsic variability in detection range. The interpretation of observed detection range must also take this intrinsic variability into account, when comparing one system against another or against performance specifications.

Introduction

The designer of a detection system is likely to have prior requirements or goals for three key performance parameters: for 1) the false alarm rate, 2) the probability of detection, and 3) the detection range. These initial design goals are of little practical interest after the sensor system has been built. The important question, rather, is what the parameters turn out to be in reality, in the final product while operating under realistic conditions. Detection trials must therefore be staged. In port protection, for instance, it is common to assess the performance of a sonar for the detection of underwater intruders by staging the approach of divers (see Fig. (1)), or to assess the performance of a radar for the detecting fast small boats by heading a distant boat toward a radar. In any case, one assesses an existing detection system empirically, by staging the approach of target-like contacts toward the sensor under realistic conditions.

The three performance parameters are not independent. Whatever its design, every sensor system has some form of detection sensitivity adjustment, either preset by the factory or adjusted on location by the sensor operator. *Increasing* the detection sensitivity generally *increases* all three performance metrics. The adjustments are typically made by trial and error, until a functional tradeoff is reached between a tolerably low number of false alarms on the one hand, and plausibly high probability of detection and detection range on the other. Indeed, the outer limits of detection coverage may be defined as the maximum distance from the sensor beyond which an operationally viable balance can no longer be found. The dependencies between the three performance parameters must be considerd when speaking about the high variability observed in detection range.

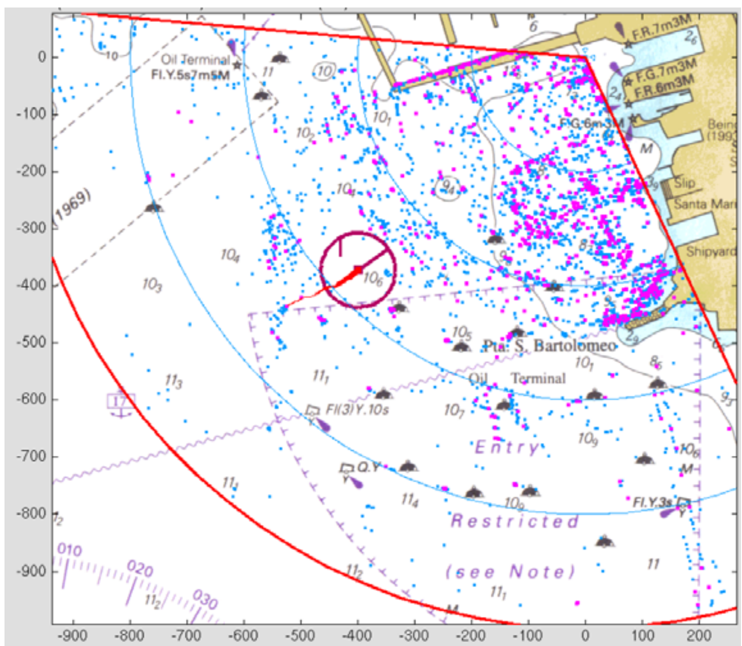

Fig. (1) Example of diver detection by commercial sonar (QinetiQ Cerberus sonar). The diver (circled, label 1), swimming unaided toward the sonar (upper right) was detected in this case at a range of about 700 m. The water depth was about 10 m.

Detection Range as Measurement

There is apparently no widely accepted definition of detection range when assessing the performance of one candidate sonar against another or against minimum performance specifications, or when setting an expected outer limit to sonar coverage during operations. The detection range of a system might be defined as the average r_{avg} of many detection ranges r_D observed during a sequence of N staged target approaches toward the sonar. Or, with additional analysis it might be defined as the detection range would be the distance at which some specified proportion—50 % or 90 %—of distant approaching targets would be detected. In any case, experimentalists will point out that a quantitative measurement of any property is meaningless if it does not have an express or implied uncertainty bound assigned to it, and they are correct to do so because the unadorned statement of a parameter's observed numerical quantity permits no generalizations or inferences to be drawn from it. We must also know something about the uncertainty bounds that the measurement entails in order to generalize beyond the observation itself.

For simplicity, let the average r_{avg} of N observed detection ranges r_D constitute our definition of the measured detection range. To make the analysis concrete, moreover, let us consider an application from port protection; namely, the automatic detection of the approach of a distant diver (as in Fig. (1) above) using a monstatic active diver-detection sonar with transmission signals (pings) consisting of frequencies between 80 kHz and 120 KHz, which includes most commercial diver-detection sonars in fact.

Let the uncertainty in our measured detection range r_{avg} be expressed using an estimate of its standard deviation $\pm\sigma_{ravg}$. We need to know these uncertainties when comparing sonar A with sonar B. For if the differences between their measured detection ranges is comparable to or less than the sum of the standard deviations of their measured average detection range, then we will be unable to conclude which of the two sonars is better. $r_{avg}{}^{A}$ may be greater than $r_{avg}{}^{B}$ owing to random uncertainties in the measurement process and not to the capabilities of each system. The strength of any inferences about overall performance generally weakens as the uncertainties $\pm\sigma_{ravg}$ in measured r_{avg} become large.

To estimate the uncertainty $\pm\sigma_{ravg}$ in measured detection range r_{avg} we need a better understanding of what takes place during the observation of detection range r_D. Sonar designers and modellers use signal processing and environmental properties to predict the detection range r_D for a single target, or perhaps of r_{avg} for a class of targets. We shall not do this here. We shall only use the observables available from a detection range experiment, such as the observed detection ranges $r_{D,}$ the target's range of entry into the sensor's field of view *R0*, the sonar ping rate, and so forth, and we shall draw our inferences about the detection process from these alone. The inner workings of the sonar under test, the prevailing propagation conditions, and the diver target strength all remain unknown to us, as they typically do in fact, in performance evaluations as in actual operations.

Given that there is a diver approaching in the field of view of the sonar, the sonar system gathers information about the underwater scene in the vicinity of the approaching diver at a constant rate determined in large part by the ping rate of the sonar. Prior to detection, information is gathered in effect by a series of "looks" made by the sensor acquired at regular intervals. The time interval T between looks is presumably somewhat larger than the time interval between consecutive pings of the sonar; the two need not be the same. If the diver enters the field of view of the sonar at range *R0* and travels at constant speed v

toward the sonar, and if the sonar correctly registers a detection of the diver after *n* looks have been taken at the scene, then the detection range is

$$r_D = R0 - nvT \;. \quad (1)$$

It is an empirical fact that the number of looks *n* before detection is a random variable. Sometimes a diver is detected sooner (at greater range), sometimes later (shorter range). There is a degree of random unpredictability in the observed result. It is this random variability that concerns us here, particularly when repeated observations are made under controlled conditions—that is, under much the same environmental conditions, and much the diver target strength, insofar as these are possible in practice.

Let the probability of making a detection given a single look be *p*—call it the *single-look* probability of detection. The single-look probability of detection must be distinguished from the overall (or *saturated*) probability of detection for the sensor system, which is the outcome of many accumulated single looks at the target while the target is approaching. The saturated probability of detection can be high, even when the single-look probability *p* is very low.

If *p* is constant along the path travelled by the diver before detection, then it can be shown that the average number of looks n_{avg} before detection is equal to 1/*p*, and the expected or average detection range is

$$r_{avg} = R0 - n_{avg} vT = R0 - vT / p \;. \quad (2)$$

There is evidence that, for the monostatic active sonars used for diver detection operating in the 80 kHz to 120 kHz frequency range, the single-look probability of detection *p* is typically a slowly varying with range if the seafloor is flat and of constant make up. Although the diver (target) echo increases with decreasing range, that is, the seafloor reverberation in the vicinity of the diver also increases with decreasing range, and it does so at much the same rate. The principle was pointed out theoretically in [1], and empirically by an expert sonar developer and operator during sea trials [2], and it was confirmed informally by a sonar modeller [3]. Sudden changes can occur for *p* in complex environments (steep slopes, rock outcroppings, etc.), or by the system design if the detection sensitivity of the sonar is made to jump discontinuously in range, but these are more the exception than the rule and can be ignored here.

Equation (2) brings two very general properties to light despite its assumptions. First, the expected detection range r_{avg} increases as the single look probability *p* increases, much as one would expect. Better performing sonars ought to have higher *p* and higher r_{avg}. Secondly, the observed and average detection range (equations (1) and (2) above) depend on the entry range *R0* of the target into the field of view of the sensor. Indeed, if *p* is roughly constant with range, then greater entry range *R0* results in greater expected detection range, at least up to the point where *R0* either exceeds the maximum range-scale setting of the sensor, or reaches the point where the echo signal is overwhelmed by system and environmental noise. The dependence of detection range on *R0* is often forgotten during tests of sonars whose performance is reverberation limited, as in diver detection. When assessing the outer limits of performance, the starting range should be equal or greater than the maximum range scale setting recommend by the manufacturer of the sensor. When assessing detection range it is necessary to control (or at least simply record) the starting range of the target in the field of view of the sensor. The range scale setting and ping rate should likewise be recorded.

If p is roughly constant with range over the path travelled by the diver before detection, then it can be shown that the standard deviation of a set of observed diver detection ranges under controlled conditions (roughly the same $R0$, v, T, environment, and target strength) will be

$$\sigma_r = vT\frac{\sqrt{1-p}}{p} \approx vT\left[\frac{1}{p} - \frac{1}{2} + \frac{1}{8}O(p)\right] \approx R0 - r_{avg}\,. \qquad (3)$$

The (Taylor) series approximation in (3) applies as p becomes small; the point being that the standard deviation σ_r of observed detection ranges becomes large as p becomes small. The fact that small p engenders high variability in detection range holds more generally, even when p changes with range, provided that the size of p remains small.

Before estimating p from empirical data, it should be clear that p is *not* a system design parameter. It probably never featured in the sonar system design, for instance. It is rather an effective parameter inferred from our observations of detection range in order to roughly characterize the random process of detection that must hold sway during the sequence of repeated occasions for detection (“looks”) that the sonar carried out with the diver in view and its detection was immanent (i.e., was expected at any moment by the experimenter).

The order of magnitude of p can be estimated from one or more observations of the detection range. Readers can do this with their own diver-detection range data. A number of detection range observations (Table (1)) were made experimentally under controlled conditions [4] using a commercially-available (90 kHz monostatic active) diver-detection sonar. The divers always started from the same range ($R0$ = 324 m), and they swam toward the sonar at roughly 1 knot (v = 0.514 m/s) at mid water depth. The starting range $R0$ was well within the serviceable field of view of the sonar. The ping rate of the sonar was T = 3 sec. This was not a test of ultimate performance, but a test of detection variability under controlled conditions. The average observed detection range was r_{avg} = 242.1 m. Substituting this into (2) and solving for p gives p = 0.019 for the effective single-look probability of detection, assuming that it was constant over the ranges of diver approach. Alternatively, inserting the standard deviation σ_r of the observed detection ranges into (3) and solving for an effect (constant) p gives an estimate p = 0.038. In either case the magnitude of p is small—perhaps surprisingly small. The overall (*saturated)* probability of detecting the diver at any point along his or her approach will nevertheless be high if many looks on the diver are accumulated during the approach. The observations of detection range in Table (1) are typical of what one finds with commercial diver-detection sonars [5,6,7]; that is, the diver must approach in the field of view of the sonar for a length of time that is much greater than the ping period of the sonar before its detection is registered. One can debate whether or not p is constant with range, but there is no way to argue from the data (or experience) that p is very much larger than the values estimated here.

The reason why the single-look probability of detection p is small is because in practice security forces cannot tolerate more than a few false alarms each day. The detection sensitivity of the sonar must therefore be reduced to keep false alarms very low under realistic operation. Reduced detector sensitivity is especially needed at the outer limits of sensor performance, where detection is by definition challenging for the sensor and where the false alarm rate is the sensitivity-setting's chief determinant. The single-look detection probability p is reduced to low values at the same time, and the variability (4) in the observed detection ranges r_D therefore becomes high. In effect, the more the sensor strains to achieve coverage at ever longer ranges, the more variable the observed detection ranges will be. What emerges, then, is a picture of how the goals of low false-alarm rates and high overall (saturated) probability of detection are won at the cost of high inherent variability in detection range.

Observed Detection Range (m)	212.4	178.8	253.2	276.2	271.6	270.3	295.3	212.7	289.7	172.0	250.0	265.1	199.7
Average	242.1 m	± 22.5 m											
Standard Deviation	40.3 m	± 19.3 m											

Table (1) Observed detection ranges for repeated diver approaches starting from *R0* = 324 m. The uncertainties reported for average and standard deviation were estimated from theory.

Assessing detection performance

High random variability in r_D means that many repeated observations (distant target approaches) are required under the same operating conditions in order to estimate the average (expected) r_{avg} with accuracy. The standard deviation of average of N observations with standard deviation σ_r in (3) is

$$\sigma_{r_{avg}} = \frac{\sigma_r}{\sqrt{N}} \approx \frac{R0 - r_{avg}}{\sqrt{N}} \tag{4}$$

Both r_{avg} and the accuracy $\pm\sigma_{ravg}$ of its measurement are of utmost importance when comparing one sonar against another, or when comparing a given sonar against minimum performance requirements. It may be that the number of divers is simply too small to conclusively rank the observed performance of two different sonars, or to judge a sonar in light of minimum detection-range requirements.

In Table (1), for instance, it was found that for N=13 divers approaching a commercial (monostatic active) diver detection sonar, equation (4) gives in an estimated accuracy

σ_{ravg} of ±22.5 m on the observed average detection range of 242 m. About N=52 staged diver approaches would be required to reduce that to ±10 m (assuming that the effect of environmental conditions were roughly constant over the long time required to stage so many diver approaches). If N=3 repeated diver approaches were used, on the other hand, as some have used for technical demonstrations, then the estimated accuracy would have been about ±50 m for this sonar—an almost 100 m uncertainty band—which would leave little to be said about sonar performance relative to other candidate sonars or to minimum performance requirements.

False Impressions

When sonar manufacturers' are asked "What is the detection range of this sonar?", they presumably answer with the best ranges that they have observed, with the sensor operating at its longest range scale settings. The analysis tells us that there is little that can be inferred about the expected detection range in practice from a few "best-case" observations of detection range. Although the reported detection ranges have no doubt been observed under realistic conditions, they were almost certainly occasions when the random variability of detection range happened to give a quick (long-range) detection, while the expected (average) detection range r_{avg} will in fact be at much shorter distance. The manufacturer should instead be asked at what range some given percentage (perhaps 50 or 90 %) of targets are expected to be detected. A more informative answer can be expected. If a manufacturer reports the *expected* detection range (r_{avg} in effect) for a given range-scale setting *R0*, then the inherent variability in detection range expected is given roughly by (3), which, as the data in Table (1) shows, can be significant, even under controlled conditions.

To observe automatic detection and tracking algorithms in action (one snap-shot given in Fig. (1)) can give the impression that there is a sudden onset of detection capability with range from the sonar. That is, the detection suddenly appears and the track is continued without loss, as if the point of detection signalled the diver's sudden entry into a zone of high detection performance. For analysts familiar with the sonar equation, moreover, the impression reinforces an overly literal vision of the sonar equation in action: that the sonar suddenly detects and locks on to the approaching target at a range completely determined by the environment (transmission loss and reverberation level), target strength, sonar power, and detection threshold, with negligible randomness. That impression, and the extreme effort it sometimes draws from analysts toward environmental and target strength assessment, is false. Track lock does not occur because of a sudden onset of detection performance at a definite range. It occurs rather because the system's signal processing concentrates itself at the moment of first detection into much more efficient modes of inspection in the immediate vicinity of a detection to enable tracking after detection. In reality, a fairly uniform but random capability for first detection is spread across rather wide ranges, perhaps hundred's of meters in the case of diver detection, in which p is small-valued because detection sensitivities are reduced to keep false alarms very low.

Conclusions

Needless to say, detection range is a key performance metric for security planning and system procurement. But its assessment is more complex than most imagine. If detection range is defined as the *expected distance at which an approaching target will be detected under realistic conditions*, then its direct measurement would be the average of detection ranges observed for several staged approaches of similar targets. Also necessary is the random variability of detection range, which determines the minimum number of target approaches required when planning a measurement, and estimates the accuracy of the measured (average) detection range after a measurement has been carried out. The inherent variability of detection range under controlled but realistic operating conditions was estimated above (equation (4)).

Looking beyond the approximations made in the analysis, one discovers the core of a rather general principle of detection range; namely, that *high random variability in observed detection ranges is inevitable at the outer limits of sensor coverage.* The principle holds when1) the detection sensitivity must be severely reduced, especially at the outer limits of detection, in order to keep false alarms low; 2) this reduction results in low single-look probability of detection *p*, often with little effect on the overall (saturated) probability of detection; 3) the low single-look probability *p* in turn produces high random variability in the number of sensor looks taken before detection occurs; and 4) this produces random variability in a chain of related variables: in the time taken before detection, in the distance traveled by an approaching target before detection, and finally in the observed detection range. In brief, the goal of low false-alarm rates is achieved at the cost of high variability in detection range, while the overall (saturated) probability of detection may remain high.

High variability in observed detection range especially applies at the outer limits of sensor performance, where detection is by definition difficult, and where sensitivity must be reduced to keep false alarms low. But the principle applies for some sensors within their field of view as well, such as for the commercial diver detection sonar used in the tests reported here and in tests performed elsewhere [5,6,7].

The high intrinsic variability of detection range at the outer limits of performance makes detection range very difficult to measure or predict in practice. This may be true for submarine hunting and mine hunting as it is for port protection, or whenever there is a coming in range of a distant target. The implication is that the measurement of detection range in the outer limits of performance requires many staged observations of detection range under controlled conditions—many more than may be feasible.

Of course, during real-world operations the observed detection range suffers further variation due to changing and uncertain environmental properties (which in underwater port protection can change on a time scale equal to one quarter of a tide cycle (about 3 hours) in shallow water), and due to changing and uncertain target strength of the target. Response measures must cover the entire range of expected variability produced by the combination of all variability: environmental, target strength, and the intrinsic considered here. The combined variability can be very large in practice.

As the environmental properties and target strength are measured and modeled with ever more accuracy and certainty, moreover, the prediction of long-range detection does *not* become an ever improving forecast, because the origin of the intrinsic variability cited here lies elsewhere; not in the particulars of deterministic propagation conditions and target strength, but in the probabilistic nature of detection. Indeed, there exists a practical limit to the accuracy to which the environment and target strength need to be known for operational forecasts of detection range. One has sufficient information about the environment and target strength once the effect of their remaining uncertainty falls below the intrinsic uncertainty in detection range.

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