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# The Operational Assessment of Submarine Communications Options

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*Abstract*

*The aim of this paper is to demonstrate how the intelligent application of simple methods can be used to provide rapid and effective comparisons of options for $C^3I$ systems. Two studies of submarine communications options are described. In the first, a simple effectiveness model proved adequate to identify the dominant criterion for selection amongst a diverse range of options; in the second, quantification of the impact on performance of a number of policy variables provided decision-makers with the information that they needed.*

## Introduction

The selection of methods for submarine communications presents a number of special problems, particularly in the balance between capacity requirements and other needs such as covertness. This paper describes two studies whose objective was to compare alternative communications system options for submarines. These studies show how relatively simple Operational Analysis techniques can assist with the choice in this situation; they also illustrate some of the changes over the past five years, and the continuities, in assumptions made about the future operational environment.

The first study was aimed at supporting a decision between a wide range of communications options. The study was conducted right at the end of the Cold War era, but still assumed the submarine roles and modes of operation appropriate to that era. The second study, which was concerned with a more narrowly focused choice, took place more recently, when the expected roles of the submarine and its operating environment had changed significantly - though fortunately, the results of the two studies were compatible.

Because $C^3I$ systems have only an indirect impact on military operations, it is difficult to convert estimates of system *performance* into the measures of operational *effectiveness*. Performance is measured by parameters such as data rates, while operational effectiveness is the impact of the performance of the system on operational success. It is operational effectiveness, rather than performance, which is used for cost-effectiveness comparisons.

The methods and models used to assess effectiveness in the work described here are relatively simple, avoiding the use of large-scale battle models. Indeed, one of the aims of the paper is to demonstrate that in appropriate cases such methods can give considerable insight into the relative merits of alternative options, without the need for complex models.

The next section of the paper describes some of the special characteristics of submarines and their modes of operation which influence and constrain their use of communications. This is followed by descriptions of the two studies and their findings. The final section then draws some general conclusions on the assessment methods appropriate to this type of problem.

## Submarine Operations and Communications

The primary *raison d'etre* of submarines is their covertness; while they are operating below the surface, they are difficult to detect, and very difficult to locate with any accuracy, unless they themselves take some action which helps the searcher. This covertness arises from two sources. Firstly, most forms of electromagnetic radiation do not penetrate water to any significant depth. Secondly, the use of the main alternative detection method, sound waves (sonar), is complicated by the non-uniformity of sea water and the resulting refraction effects; in particular the well-known phenomenon of the 'surface duct', where the temperature gradient in the sea means that a submarine below a certain depth is virtually undetectable from the surface.

Covertness allows a submarine to operate, unsupported, in waters where a surface ship would not survive at all, or only as part of a large force. The submarine can attack enemy surface ships, and can operate close in-shore, to collect intelligence or to lay mines for example. Also, because of the duct phenomenon, a submarine operating below the duct layer may well be the best platform for detecting an enemy submarine.

A fundamental problem with submarine communications is that all the available communications modes will compromise covertness in some way. This problem can arise in two ways. Firstly, any form of transmission from the submarine will make it liable to detection and location by the enemy. Secondly, any antenna raised above the surface is liable to detection (for example, by airborne radar). This means that, for some communications modes at least, even reception makes the submarine vulnerable to detection.

Another potential disadvantage of at least some communications modes is that they require the submarine to come to periscope depth, and thus above the surface duct layer. This will disrupt any search they are conducting for enemy submarines.

All these problems result in submariners being reluctant to communicate, especially when this entails transmission *from* the submarine. Modes of submarine operation have evolved which do not rely on communications, and thus enable the submarine to operate autonomously, under the ultimate control of a shore-based command authority.

Nevertheless, there are significant operational benefits in enabling submarines to communicate. There may be information available to the submarine command authority ashore which will be of value to the submarine: for instance, the location of potential targets, or potential threats. Conversely the information collected by the submarine from its own sensors may be of value to other platforms, if it can be passed to them quickly enough. An extreme case of this is 'third-party targeting', where information about the position of (say) a ship is sent from an aircraft to the submarine so that the submarine can launch a weapon against it without having detected the target with its own sensors.

The problem of selecting the 'right' communications fit for a submarine is influenced by a range of factors: the limited space available inside the pressure hull, limitations on piercing the hull for extendible antennas, and on external fittings which may disrupt hydrodynamic flow and generate noise. However, the fundamental aim is to achieve the right balance between passing useful information and not compromising covertness.

## The First Study - Selection of Communications Methods[1]

The first study was carried out in 1989, at the end of the period when the Soviet threat was the dominant consideration in UK defence planning. The aim of the study was to help to select the communications fit of a new class of submarine then being planned, and a very wide range of options was available. These covered frequency bands ranging from VLF to EHF. VLF is a popular mode for submarine communications, since it will penetrate a significant distance through water, while EHF was at that time an experimental band for satellite communications. The wavelengths under consideration thus ranged from tens of kilometres down to about one centimetre, with a corresponding range of potential data rates. The antenna types included various masts and dishes, floating wires and towed buoys.

The study investigated the best options for a number of types of submarine operation, but the case described here is that of **Area Operations**, where the submarine operates independently of other units, under the control of a shore authority. In a typical operation, the submarine is searching for 'targets' - enemy surface ships or submarines - using its own sensors, typically passive sonar. The main requirements for communication are:

- for the shore authority to pass information to the submarine on the possible location of targets (together with orders about such matters as operating areas and Rules of Engagement);
- for the submarine to pass back information about the targets it has located and the actions it has taken.

Although there were many different options to be assessed, the ability of each option to meet the requirements could be characterised by just three input parameters:

(1) The rate at which it could pass information. Though the different frequency bands allow correspondingly different data rates, the key differences in fact result from the antenna characteristics. Some antenna types (e.g. floating buoys) allow communication while the submarine is at its normal operating depth, and thus provide continuous communications. Others, such as mast-mounted antennas, require the submarine to come to periscope depth, thus interrupting the use of its sensors. These can only be used periodically - typically every few hours. This rate determines the age of the information when the submarine receives it and hence its value as an aid to target location.

(2) The impact on sensor effectiveness of any requirement to come to periscope depth. When the submarine comes up to communicate, effectiveness of its passive sensor will be lost for some time, until the submarine has returned to its operating depth and had time to settle.

(3) The loss of covertness resulting from their use. For *reception* by the submarine the dominant consideration is the form of the antenna; in general wire antennas floating on or just below the surface score better than masts or dishes poking above it. For *transmission* by the submarine the dominant consideration is the detectability of the signal; in general terms, EHF satellite communications score well, because a dish antenna enables a very narrow beam aimed at the satellite to be used.

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[1] This study was carried out by Director of Science (Sea) in collaboration with CORDA, the defence analysis subsidiary of BAeSEMA Ltd. It was sponsored by the Director of Operational Requirements (Sea).

These three parameters were combined into a single overall measure of effectiveness of a communications system: the number of targets which the submarine could expect to encounter and report back to its controller before it would be detected and located itself from its use of the system.

In order to quantify the effects of (1) and (2), we built a search model, which represented the submarine searching for randomly placed moving targets using its own sensor, guided by information on possible target locations passed by the communications system. This information could be:

- inaccurate, in the sense that there were errors in the original information;
- incomplete, in the sense that not all the targets present were included;
- out-of-date in terms of target positions, both because of delays in acquiring the information by the shore controller and because of delays in the communications system.

The parameters (1) and (2) were represented in the model by the age of the information provided and by periods during which the submarine sensor was inoperative, respectively. When the submarine detected a target, it moved to intercept it. The output of the model was the target encounter rate: the number of targets which the submarine detected and intercepted per unit time, as a function of these various parameters.

This model enabled us to draw a number of interesting conclusions, not all of direct relevance to the primary objective of the study; for instance it could be used to investigate the trade-off between the range of the submarine's own sensors and the completeness and accuracy of the picture about target locations sent to the submarine. Figure 1 shows the target encounter rate as a function of the sonar range for unaided search, and for search aided by an external picture which is 50% and 100% complete respectively. Figure 2 shows the percentage increase in encounter rate as a function of range for a 50% complete picture; as one would expect, the benefit declines as the sonar range increases.

In terms of the study objective, this model allowed us to draw two major conclusions. The first concerned the relationship between the encounter rate and the periodicity with which communications were possible by a particular method. The results are illustrated in Figure 3. The conclusion is that, over the range of values provided by the different options, the encounter rate depends only weakly on the typical delay in passing the information. The variation in rate is less than 20% over the full range of values considered, and in practice differences of this size are likely to be masked by other sources of uncertainty.

The second conclusion was that the loss of sonar operation while the submarine comes to periscope depth did not have a significant effect on the total encounter rate. This was because the distance moved during this period by the relatively slow-moving targets assumed in the study was small compared to the sensor range, and hence relatively few targets were lost.

Hence the conclusion drawn from the model result is that parameters (1) and (2) above - frequency of information update and loss or not of sonar coverage - do not strongly discriminate between the communications systems. The measure of effectiveness was thus largely driven by the expected time for the submarine itself to be detected, which was estimated using naval judgement, and this *did* differ strongly between candidate systems. It was thus on the basis of covertness that the study recommendations were made - including the use of EHF satcom for transmission from the submarine.

## The Second Study - Selection of Satcom Frequencies[2]

The time now moves on to 1994, and the focus shifts from the overall requirements of the submarine to the need to match the submarine's requirements with the design of SKYNET 5, the next generation UK satellite communications system, which must meet the needs of a multiplicity of users.

Currently UK surface ships use satellite communications in the SHF band, but UK submarines use the UHF band. This is because UHF is particularly easy to install and use within the constrained environment of a submarine and has been favoured in the past by the US Navy. During the Cold War period, the ability to interoperate with the US submarine fleet was regarded as essential.

However, UHF has a number of disadvantages, including lack of covertness, low data rates, vulnerability to interference and jamming, and the size and weight it adds to the satellite. Therefore the likelihood is that both the US and UK will move away from it in the future.

The primary operational band for SKYNET 5, as for the current UK satellites, is likely to be SHF; however, advances in technology mean that it is feasible to provide an EHF capability. This then raises the question: should UK submarines move to SHF or to EHF? This is an important decision both in the context of the submarine fleet and, since this would be one of the major users of EHF, in the context of the decision whether to fit EHF to SKYNET 5 at all. This decision has not in fact yet been taken; the study described here was one contribution to the decision process.

Since the end of the Cold War, the relative importance of different submarine roles has changed; in particular, greater importance is now attached to **support operations**, where the submarine cooperates with a surface force. Two types of support operation are distinguished:

- **associated support**, where the submarine operates independently under the control of the shore authority, but may be tasked to provide contact information to, and receive intelligence from, a surface Task Group Commander (CTG);

- **direct support**, where tactical control rests with the CTG, who may task the submarine directly.

Good communications are fundamental to support operations. If submarines are to become part of a fully integrated force then they need the appropriate communications for their effective deployment. Coordination of the submarine with the supported units requires that:

- the same tactical picture is available for the submarine and supported units;

- data such as contact reports and firing solutions can be exchanged in near real-time between the submarine and the supported units (possibly beyond line-of-sight);

- voice communications (possibly beyond line-of-sight) are available for clarification and discussion between the submarine and supported units.

Thus support operations are more demanding in their communications needs, both in terms of duplex data rates and of timeliness requirements, than the area operations of the first study.

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[2] The study was conducted by the Naval Studies Department of the Defence Research Agency in collaboration with CORDA. It was sponsored by the Director of Operational Requirements (Sea).

They are also more demanding in terms of *interoperability*, since there is a need to communicate with surface ships, possibly of more than one nation, as well as with the shore.

Important criteria in the selection of the best frequency for submarine communications are therefore:

(1) Whether a particular frequency can meet the capacity and timeliness requirements for communications of these types of operation. Because satellite communications are important to many types of military operation, and because the satellite itself forms a single critical node in the system, they are likely to be subjected to jamming; hence the ability to meet requirements in a jamming environment must be assessed.

(2) Interoperability: the ability to communicate with all the units, both UK and allied (in particular US) with which the submarine may need to operate.

(3) Covertness: as discussed above.

Factors which affect how these criteria are met include:

- The choice of terminal equipment on the submarine; in particular the modem which converts the information to be communicated into the signal sent over the satcom bearer. For both SHF and EHF bands there are a number of options under consideration, which differ in performance and cost.

- Physical constraints on the fitting of equipment to the submarine. This limits in particular the diameter of dish antenna which can be fitted, with implications for both achievable data rates and covertness.

- Environmental conditions: signals in the EHF band are subject to a greater degree of attenuation by the atmosphere. Under conditions of very heavy rainfall, the signal may be lost completely, although there is controversy about how often this will happen in practice.

- The mode of operation of the satellite. In general, communications satellites can operate two different types of antenna: 'earth cover', where the satellite beam covers virtually the entire hemisphere visible from the satellite, and 'spot beam', where the beam is focused into a spot a few hundred kilometres in diameter. A spot beam will provide a stronger signal, and thus support a higher data rate, and is less vulnerable to jamming. It may also be steerable over the earth's surface. However, there will be a limited number of spot beams available on SKYNET 5, leaving significant areas of the earth unserved. The spot beams must also be shared amongst all its users - which potentially include the whole of the UK's defence forces.

Ideally, a study to compare the merits of the competing frequency bands should assess them in terms of their contribution to the success of the operation; that is, in terms of a measure of effectiveness which quantifies this contribution, as was done in the first study described above. However, the time constraints of the study, the uncertainty of the data, and the lack of suitable tool for modelling support operations meant that this approach was not feasible. Hence it was necessary to assess the alternatives in terms of their performance characteristics; that is, in terms of the three criteria discussed above: capacity, interoperability, and covertness. In practice, this gave good discrimination between the options, but the final choice remained (and remains) with the MOD decision-makers.

In terms of *interoperability*, no clear-cut differentiation could be achieved, because of uncertainties about future USN intentions and the potential divergence between RN and USN plans. In any case there are alternative methods of meeting interoperability requirements, besides a universal use of the same frequency and associated equipment. For example, interoperability can be achieved at a price by a dual equipment fit to surface ships, where the space constraints are less severe than on submarines, or by shore-based translation systems called 'gateways'.

In terms of *covertness*, EHF provides superior performance, for three reasons. In the first place, the higher frequency band gives a narrower beam for a given antenna size; this is illustrated in Figure 4. This figure also shows the positions of some other satellites relative to the possible location of one of the SKYNET 5 satellites. This means that the beam is less likely to illuminate satellites other than SKYNET 5; it also makes it more difficult to detect the beam from terrestrial platforms, such as aircraft. Secondly, for the first few years of SKYNET 5 operation at least, there are likely to be far fewer satellites in orbit *capable* of intercepting EHF signals. Finally, the greater bandwidth available at EHF increases the effectiveness of the signal processing techniques which are used to make it more difficult both to detect the signal and to use it to locate the submarine.

The bulk of the work in the study was devoted to comparing the ability of the different options to meet the communications capacity requirements. The comparisons were based on the ability to meet the operational information exchange requirements (IERs), which were estimated for three operational settings:

- independent anti-submarine warfare (ASW) operations;
- associated support to an Amphibious Task Group;
- direct support to a UK/US Task group in open ocean.

These three settings are not comprehensive but they are illustrative of the range of operations an RN submarine might undertake in the future and therefore serve to indicate the type of information exchange which will be required in the SKYNET 5 era.

The estimates of capacity requirements for each setting were derived by identifying all the types of IER (e.g. voice nets, datalinks) and the capacity required for each, and then summing these. Since this effectively assumes that all the IERs must be met simultaneously, the result is an upper bound for the capacity requirement, but this estimate was found to be adequate for assessing the relative merits of the competing options.

The requirements were divided into:

- a *baseline* capacity requirement which is common to all three settings; this is represented by the IERs needed to support independent ASW operations;
- a *supplementary* requirement, corresponding to the additional needs of the support operations.

These requirements were then compared with the capacities which would be available from the various options. For each frequency, the only difference between the options was the modem used; all other details both on board the submarine and on the satellite were identical for each band. The capacities were estimated for earth cover and spot beams, for a range of jamming threats, using assumptions about the satellite payload characteristics: antenna gain, satellite power and signal processing capabilities, for example. The capacities were estimated for three modes of communication:

- submarine to shore only;
- two-way communications between submarine and shore;
- direct two-way communications (i.e. not via a shore-based gateway) between a surface ship and a submarine.

The results are summarised in qualitative form in Tables 1 - 3. These tables characterise performance using the following categories:

**High** the available capacity is adequate to meet the baseline plus the supplementary requirement.

**Medium** capacity is adequate to meet the baseline requirement only.

**Low** some useful capacity is provided, but not enough to meet the baseline requirement.

**None** no useful capacity is provided.

These results can be summarised as follows:

- EHF Option 1 is the most robust solution, giving at least a minimal level of performance under all circumstances for both earth cover and spot beams - although other options give better performance in some circumstances (e.g. in a spot beam or under low threat conditions).

- EHF Option 2 is the only one which can meet the full communications requirement, but needs a spot beam to do it, and even then will fail under the worst jamming conditions.

- SHF Option 2 gives the best performance for communicating with the shore if only earth cover is available, providing jamming is low; though note that EHF Option 1 at least gives the submarine sufficient capacity to *ask* for a spot, in all circumstances.

Thus the analysis of capacity strongly favours EHF. Option 1 is preferred if robustness of the solution is important, and Option 2 is preferred if meeting the IERs is vital and a spot beam can be guaranteed.

This analysis presented the results in terms which the military sponsors of the study could easily assimilate and use to assess the impact of their judgements of such issues as the level of jamming threat that the system must be able to resist.

## Conclusions

The main conclusion to be drawn from these studies is that it is possible to gain considerable insight into the relative value of alternatives by relatively simple methods. This is in spite of the fact that the links between performance and operational value for $C^3$ systems are more indirect and difficult to quantify than for weapon systems. In particular the type of 'thresholding' effect found in the first study, where differences in performance outside a particular range have very little effect on operational effectiveness, is not uncommon in $C^3$ systems. If they can be identified, they are a very valuable tool in system assessment. In the second study, a simple analysis of system performance was sufficient to assess the impact of policy assumptions and differentiate between system options.

However, this type of approach is only likely to be successful if the analyst starts with a good insight into the conduct of military operations and the ways in which $C^3$ system performance will affect them.

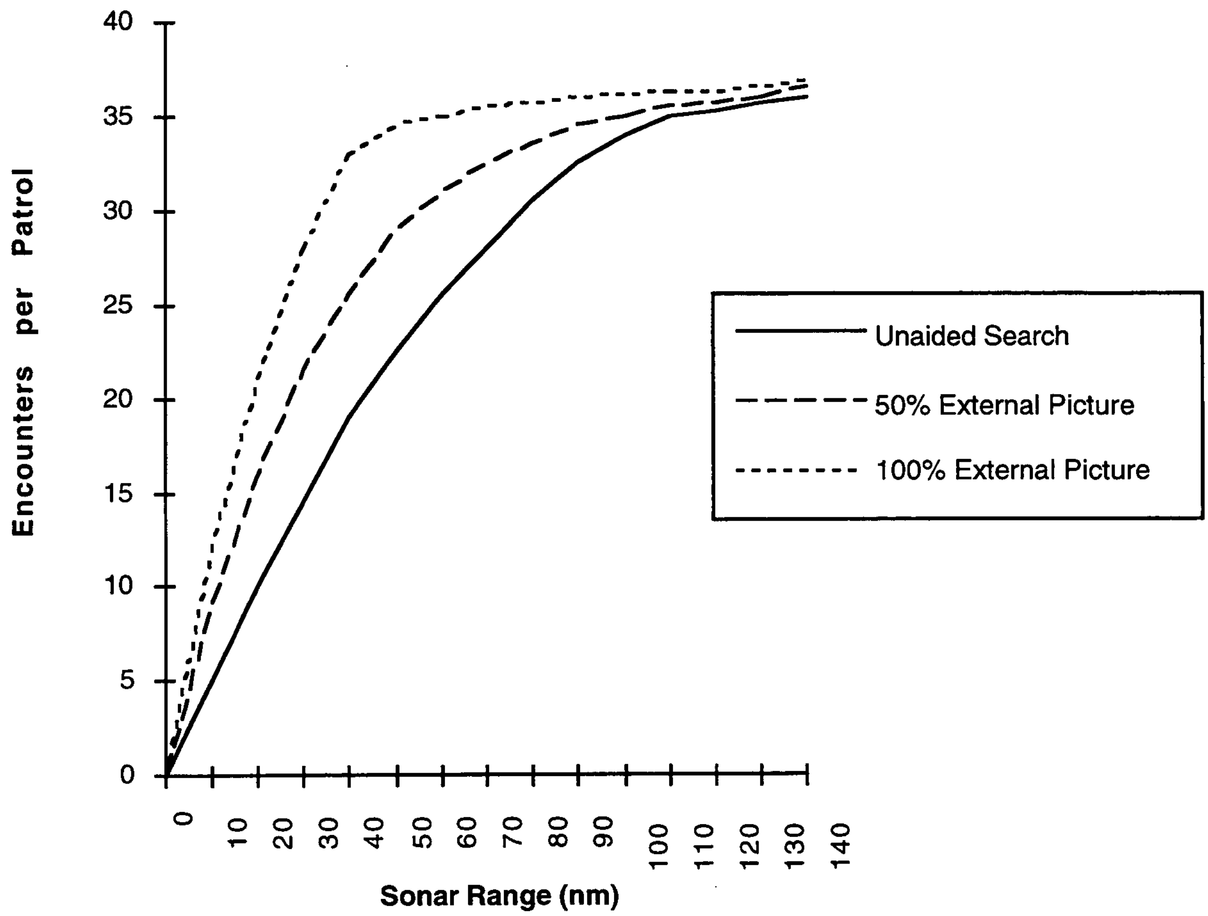



**Figure 1: Effect of Picture Completeness**

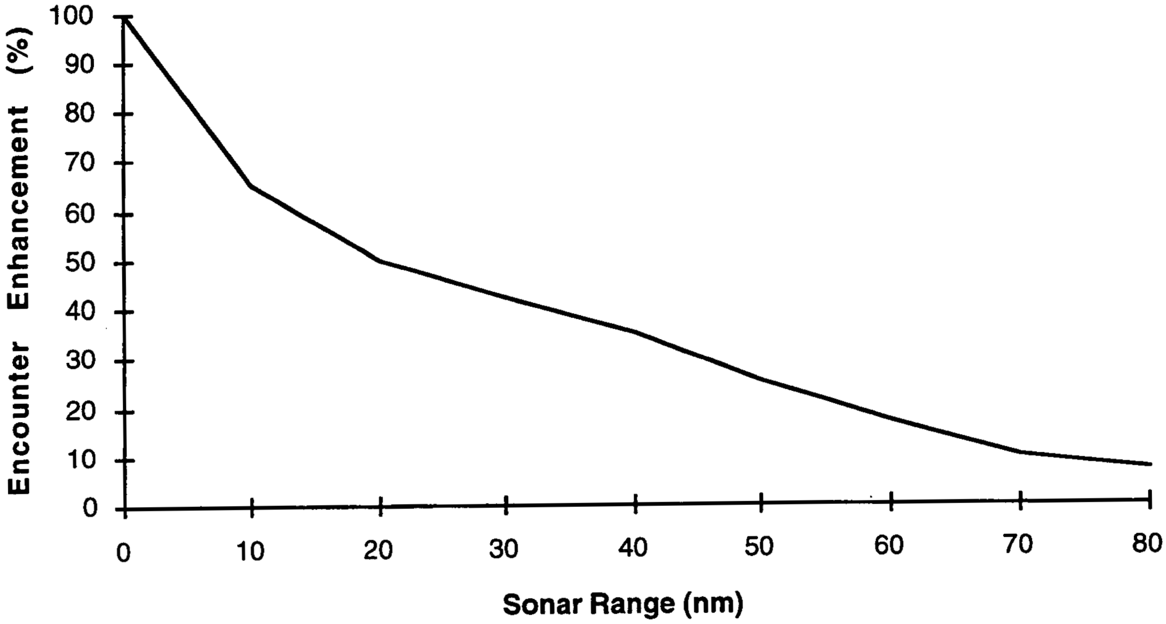



**Figure 2: Encounter Enhancement by 50% Complete Picture**

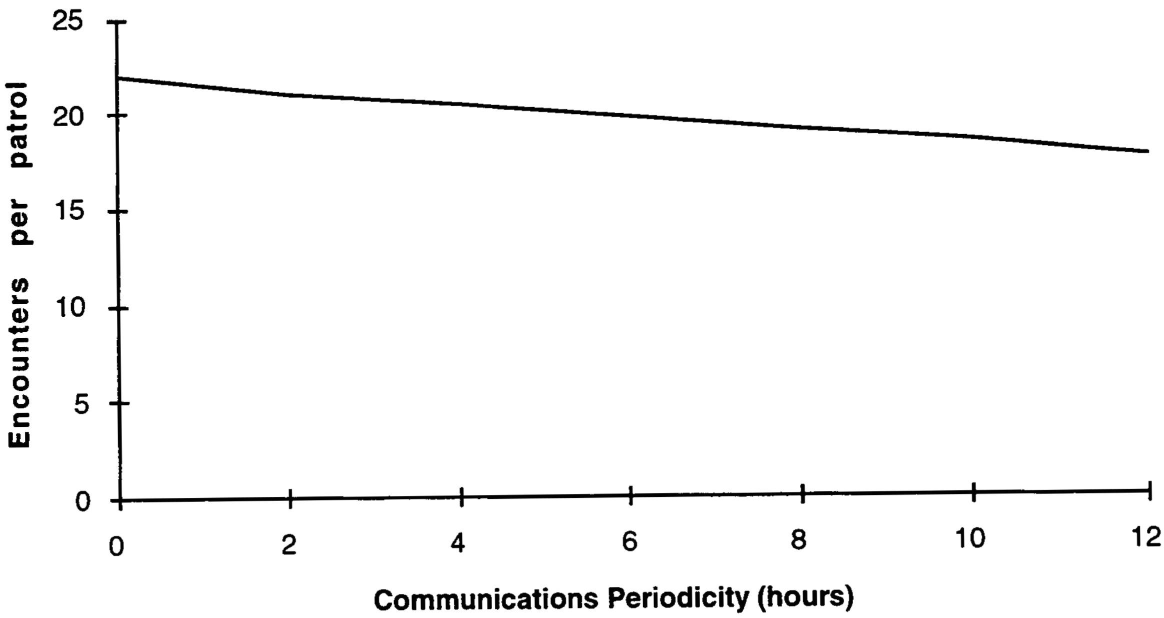
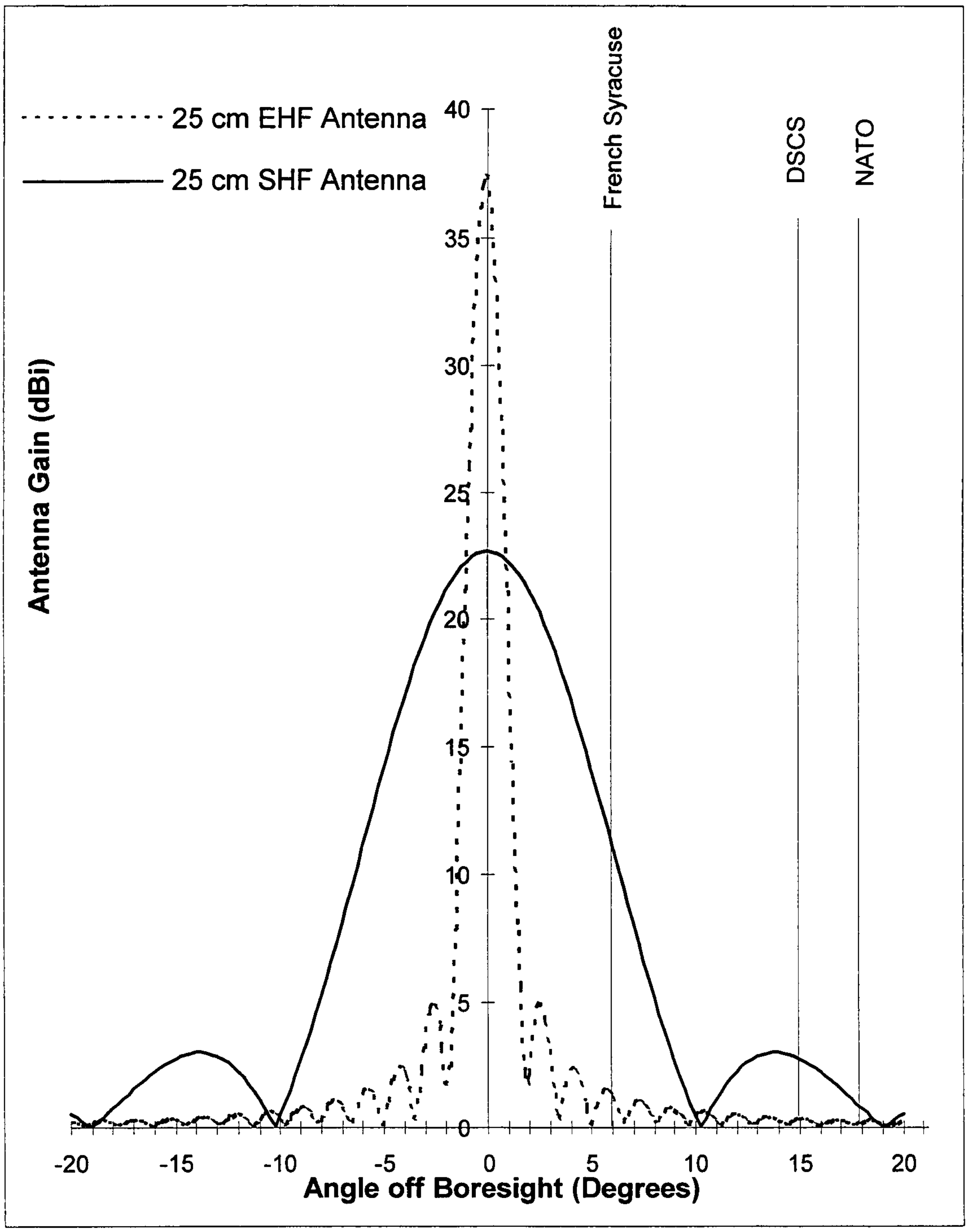



**Figure 3: Variation of Encounters with Communications Periodicity**

**Figure 4: SHF and EHF Beam Patterns for 25cm Antennas**



| Option | | Beam | Capacity under different threat levels | | | |
|---|---|---|---|---|---|---|
| Band | Modem | | None | Tactical | Moderate | Heavy |
| SHF | Option 1 | Earth Cover | Low | Low | Low | None |
| | Option 2 | | Medium | Medium | None | None |
| | Option 3 | | None | None | None | None |
| EHF | Option 1 | | Low | Low | Low | Low |
| | Option 2 | | None | None | None | None |
| SHF | Option 1 | Spot | High | Medium | Low | None |
| | Option 2 | | High | High | None | None |
| | Option 3 | | Medium | None | None | None |
| EHF | Option 1 | | Medium | Medium | Medium | Low |
| | Option 2 | | High | High | High | None |

**Table 1: Capacity Available from Submarine to Shore**

| Option | | Beam | Capacity under different threat levels | | | |
|---|---|---|---|---|---|---|
| Band | Modem | | None | Tactical | Moderate | Heavy |
| SHF | Option 1 | Earth Cover | Low | Low | Low | None |
| | Option 2 | | Medium | Medium | None | None |
| | Option 3 | | None | None | None | None |
| EHF | Option 1 | | Low | Low | Low | Low |
| | Option 2 | | None | None | None | None |
| SHF | Option 1 | Spot | Medium | Medium | Low | None |
| | Option 2 | | Medium | Medium | None | None |
| | Option 3 | | Medium | None | None | None |
| EHF | Option 1 | | Medium | Medium | Medium | Low |
| | Option 2 | | High | High | High | None |

**Table 2: Two-way Capacity Available between Submarine and Shore**

| Option | | Beam | Data rates under different threat levels | | | |
|---|---|---|---|---|---|---|
| **Band** | **Modem** | | **None** | **Tactical** | **Moderate** | **Heavy** |
| SHF | Option 1 | Earth Cover | Low | Low | Low | None |
| | Option 2 | | None | None | None | None |
| | Option 3 | | None | None | None | None |
| EHF | Option 1 | | Low | Low | Low | Low |
| | Option 2 | | None | None | None | None |
| SHF | Option 1 | Spot | Low | Low | Low | None |
| | Option 2 | | None | None | None | None |
| | Option 3 | | None | None | None | None |
| EHF | Option 1 | | Medium | Medium | Medium | Low |
| | Option 2 | | High | High | High | None |

**Table 3: Two-way Capacity Available between Submarine and Surface Ship**