locations on a regular basis can still be achieved. To achieve ship location updates every 12 hours, it is necessary to successful decode only one of the more than 360 messages received (~0.3%) from a given ship during this period. This is explained in more detail later.

The two frequencies that have been designated as channels within the maritime mobile service for the terrestrial AIS function are not allocated on an exclusive basis. Rather, these channels and adjacent channels are allocated and used throughout various regions of the world for other mobile service applications including VHF public correspondence stations (VPCS) in the maritime mobile service and land mobile radio systems. Unlike conventional terrestrial AIS systems that can co-exist with other co-frequency transmitters through geographical separation, the satellite antenna beam covers a large geographical area, thereby receiving transmissions by multiple AIS ship transmitters simultaneously, as well as mobile systems operating inland. Satellite AIS must be able to successfully operate in the interference environment resulting from existing services. The performance of satellite AIS operating with existing services is examined in Section 9.

Table 5 takes into account the above discussion to summarize the characteristics of the AIS satellite used for this study.

TABLE 5

Assumed Characteristic of AIS Satellite Link

AIS satellite parameters	Values
Satellite	
Constellation	1 to 6 satellites
Altitude	950 km
Inclination	82.5 Deg
Period	104 Min
Earth Footprint	3 281 km radius (at the horizon)
Antenna	
Gain (G_{MB})	6 dBi
Beamwidth (θ_{3dB})	100 Deg
Pattern	$G_{MB} - 12 (\theta / \theta_{3dB})^2$
Polarization	Near circular
Circular to Linear Polarization Conversion Loss	3 dB
Receiver	
Noise Figure at LNA input	3 dB
Required E_b/N_o for BER = 10^{-5}	13 dB including implementation loss
Line/filter losses prior to LNA	2.5 dB
Sensitivity at LNA	−118 dBm for 1% packet error rate (PER) −120 dBm for 20% PER
D/U Protection Ratio (for co-channel, coincident-in-time signals)	15 dB for 1% PER 10 dB for 20% PER
Desired ship location update period	Single satellite overpass, 4 hours, and 12 hours

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4 Link budget analysis

One of the most basic performance measures of any satellite communication system is a link budget. For the case under study, it consists of a calculation of the received power at the satellite from one ship and a comparison with the satellite sensitivity. If the received power exceeds the sensitivity, i.e. has a positive margin, successful communication can be achieved. Using the parameters previously defined herein for AIS ship transmitters and AIS satellite receivers, a link budget was developed for the AIS ship-to-satellite path. Table 6 describes the applicable geometry and power calculations for detection of AIS messages from Class A ships.

TABLE 6

Ship-To-Satellite Link Budget at Maximum Range

Parameters	Values
Geometry	
Satellite Altitude (km)	950
Minimum transmit elevation angle (Deg)	0
Satellite antenna off-axis angle (Deg)	60.5
Maximum Slant range (km)	3 606
Maximum Surface range (km)	3 281
Power	
Transmit Power (dBm)	41.0
Transmit Gain (dBi)	2.0
Transmit Cable & Miscellaneous Losses (dB)	3.0
Free Space Propagation Loss at maximum range (dB)	147.8
Polarization Mismatch Loss (dB)	3.0
Satellite antenna gain at the horizon (dBi)	1.6
Satellite RF Line/Filter losses (dB)	2.5
Received power at satellite (dBm)	–111.7
Satellite sensitivity (dBm) for 20% PER	–120.0
Net Margin (dB)	8.3

One factor that was explored in more detail was the propagation loss at very low take-off angles from the ship antennas. For most satellite communications systems, it is normal to design the system for some minimum elevation angle above the horizon at the earth terminal, such as 3 or 5 degrees, to account for technical factors such as fading and/or regulatory limitations. For the present study, it was found that these factors are not applicable for VHF earth-to-satellite propagation over sea water. Using a radio propagation model designed for earth-to-satellite propagation loss predictions, a curve, given in Fig. 1, was developed showing the estimated median propagation for a satellite at 950 km altitude.[2] The curve was developed based on average maritime temperate meteorological and sea state conditions. The resulting lobbing structure in the data results from the periodic enhancement and fading of the signal due to in-phase and out-of-phase

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2 See http://flattop.its.bldrdoc.gov/if77.html.

addition of the reflected path from the water's surface. As seen in the data, nominal free space propagation conditions apply within a couple of dB all the way to the optical horizon with propagation losses rapidly increasing beyond that distance.

FIGURE 1

Earth-to-Satellite Propagation Loss over Sea Water at 162 MHz (Satellite at 950 km Altitude)

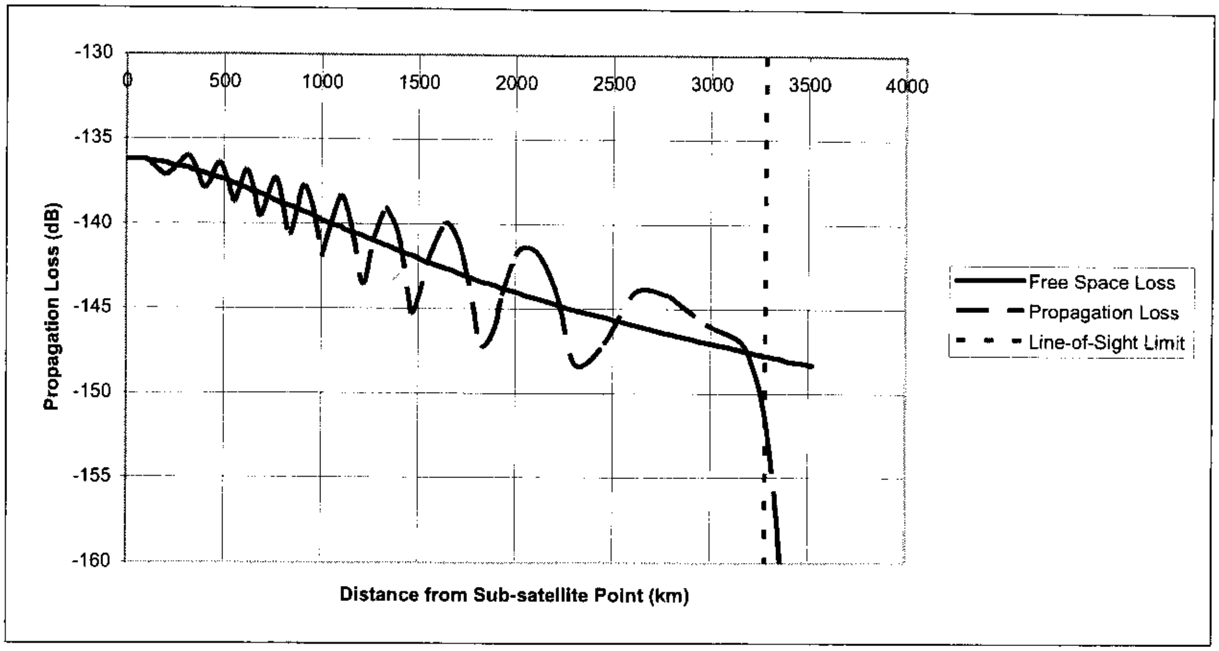
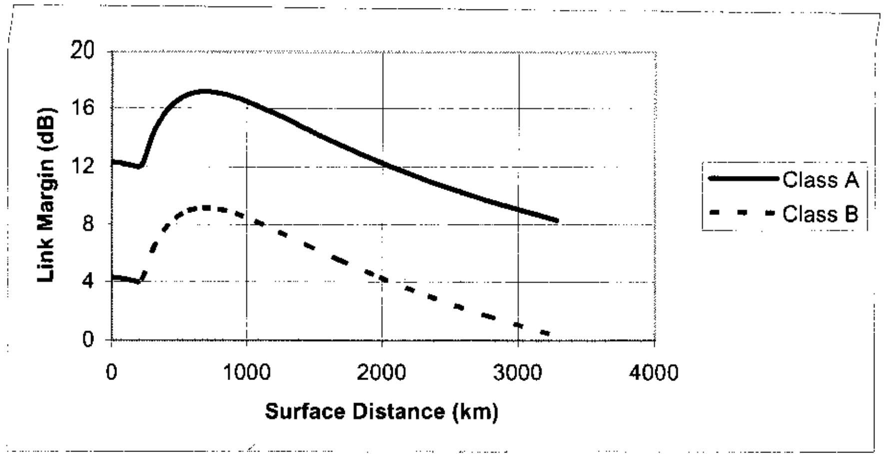


Figure 2 expands upon the result derived in Table 5 to describe the net margin as a function of distance from the sub-satellite point on the Earth to the horizon. For this calculation, free space propagation is used to the Earth horizon without including the in-phase/out-of-phase fading structure shown earlier. The partial null directly under the satellite is a result of the null in the antenna gain of the dipole antenna used for the AIS ship antenna. Since the link budget technical parameters for Class B ships are basically identical to Class A, except for the reduced power, a parallel curve representing Class B reception at the satellite is also shown.

FIGURE 2

Ship-To-Satellite Link Margin vs. Surface Distance from Sub-satellite Point



It can be concluded from these results that adequate link margin exists to detect and decode both Class A and Class B AIS signals by satellite at most ship locations within the satellite footprint.

5 Intra-system interference analysis (class A only)

Although the link budget shows that adequate link margins for detection of a Class A ship AIS message anywhere within the satellite footprint, a significant limitation on system detection performance occurs because of intra-system interference. In the discussion that follows, three methodologies are described that quantify the limitations on system performance due to intra-system interference.

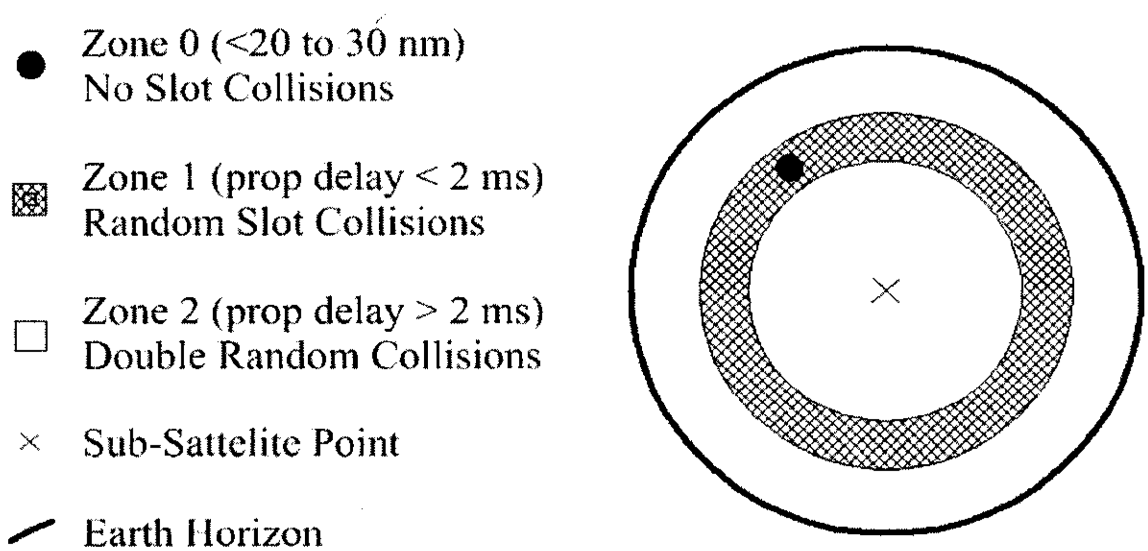
Analytic Approach. As previously described, the self-organizing TDMA (SOTDMA) scheme used for AIS assures the coordination of timeslot usage so that minimal timeslot conflicts result among ship and shore units in a given local geographic area. Such is not the case for AIS satellite detection. The satellite sees many such local areas within the antenna beam. Since there is, in general, no coordination between local areas, timeslot collisions will occur between many signals received at the satellite. When a time slot collision occurs, depending on their respective power levels, both messages could be lost. As the rate of occurrence of these time slot collisions increases, the probability of successfully detecting and decoding a given ship AIS message decreases.

These time slot collisions can be viewed in terms of a single desired AIS message (D), and one or more undesired AIS messages (U). Whenever a timeslot collision occurs and the aggregate D/U power ratio is less than the required 10 dB, loss of that message will result. Initially considering only Class A ships, Fig. 2 showed that the ratio of the maximum AIS signal received to minimum AIS signal received to be about 9 dB. Consequently, for any timeslot collision that occurs, the D/U will fail to achieve the required 10 dB value resulting in the loss of most packets. Potential receiver processing techniques are described later that may reduce the loss of packets.

Under certain conditions, the loss of two packets will occur during slot collisions. Figure 3 illustrates this point. In the figure, the outer circle represents the footprint on the Earth's surface and the centre of the circle is the point directly below the satellite. The much smaller black area represents a local AIS coordination area. Consider the reception of a message from a ship located in that local area. AIS messages from other ships located in that same local area will be coordinated in time due to the SOTDMA architecture; consequently no time slot collisions will occur either locally or at the AIS satellite receiver. However, ship messages located outside that local area in the larger shaded area will not be coordinated and will result in random occurrence of timeslot collisions and loss of a percentage of the desired messages. As long as the difference in propagation delay to the satellite from the various ship locations in this zone is less than about 2 ms, the GPS time synchronization assures that time slots will effectively align and only one time slot is impacted. The 2 ms delay corresponds to the 20 empty bit positions at the end of an AIS message. In areas outside of the shaded zone, represented by the enclosed white areas, larger differences in propagation delay to the satellite will result in overlapping of timeslots and the resultant loss of two slots.

FIGURE 3

Illustration of Time Slot Collision zones



If one considers only Class A ships and assumes the idealized situation where the geographic distribution of ships is uniform within the satellite field of view, a simple analytic methodology can be used to calculate the statistics associated with this form of intra-system interference.

First, consider the trivial case of a single message being received at the satellite from a given ship and there exists only one other ship in the environment. The probability of packet collision and probability of successful detection are given by

$$Q_{1,1} = k * D_C / 2$$

$$P_{1,1} = 1 - (k * D_C) / 2$$

$$P_{1,1} = 1 - (k * (\tau / \Delta T) / 2)$$

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where

$Q_{1,1}$ = Probability of timeslot collision (Desired message from 1 ship; periodic undesired messages from 1 other ship)

$P_{1,1}$ = *Probability of at least one successful detection without collision (1 desired* message; periodic undesired messages from 1 other ship)

D_C = Transmit duty cycle of the undesired ship messages

k = 0, 1, or 2 for interfering messages from ships located in zones 0, 1, or 2

ΔT = Average message transmission interval (seconds)

τ = Message length (0.0267 seconds).

The factor of 2 included in the above equation accounts for the fact that AIS ship messages are alternated between the two AIS frequencies.

As an example, using a ΔT of 7 seconds and a competing ship message from zone 2 yields

$$P_{1,1} = 99.6\%.$$

Expanding this example to the case of a single message being received at the satellite from a given ship with N total ships in the environment, the probability of successful detection of the signal without time slot collisions is given by

$$P_{1,N} = (P_{1,1})^{N-1}.$$

For the general case where M messages are transmitted by a given ship during a period of satellite visibility, the probability of successful detection of at least one of the transmitted messages during the period of visibility is given by

$$P_{M,N} = 1 - [1 - (P_{1,1})^{N-1}]^M$$

where

M = $T_{vis} / \Delta T$

T_{vis} = Time period of satellite visibility

Under the assumption that the ships are uniformly distributed within the satellite antenna footprint, it is clear that that some ships may be located in each of zones 0, 1, and 2. The relative location and size of these zones varies with each received message. Given the very small size for zone 0, undesired messages from this zone have minimal impact on overall satellite detection performance and can be ignored. Consequently, an average value for k would be between 1 and 2. For the case of a uniform ship distribution within the satellite footprint, it was found that an average value for k of about 1.6 accurately describes the intra-system interference. Continuing with the above example using k = 1.6 yields the following two results.

$$P_{1,1000} = 4.8\%$$

$$P_{100,1000} = 99.3\%$$

The analysis methodology described above is consistent with other studies completed on this subject.[3] Figure 4 gives an example curve for the simple case of a single satellite and single overhead pass of the satellite.

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[3] Hoye, Gudrun K., et al, *Space-Based AIS for Global Maritime Traffic Monitoring*, Kjeller, Norway: Norwegian Defense Research Establishment (FFI), undated.

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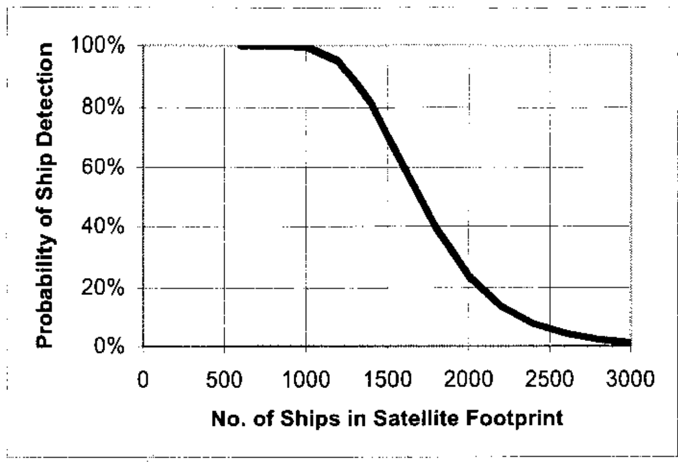
FIGURE 4

Satellite Detection Statistics



The calculations described above represent the probability of detecting a given ship during a specified satellite visibility period. An alternative and possibly more useful statistic would be the percentage of the ships detected. Since it is reasonable to assume that the detection probability is independent from one ship to another, then the average number of ships detected (S_{ave}) is given by

$$S_{ave} = N \cdot P_{M,N}$$

Expressing this in terms of the percent of the total ships detection results in a curve identical to the results shown in Fig. 4 with the ordinate scale labelled percent of ships detected .

A third statistic of interest is the probability that, during the given visibility period, all the ships in the satellite footprint will be detected. This much more stringent criterion is defined by the following:

$$P_{All} = (P_{M,N})^N$$

Because of the extremely high value of the exponent, this curve is effectively all or nothing. That is, with a probability of individual detection very close to 1.0 then 100% of the ships will be detected. But when the probability of individual detection drops below 1.0, then the probability of detecting 100% of the ships quickly drops to near zero.

In considering the above discussion, it becomes clear that many of the transmitted messages can be corrupted and lost by time slot collisions and still achieve the desired goal of updating ship locations during a given satellite visibility period.

The final factor to be defined is the satellite visibility time period. For the representative 950 km satellite altitude being considered herein, the period of visibility for a single directly overhead pass of a satellite is approximately 16.8 minutes. However, most satellite overpasses will not occur directly overhead but rather at some lower elevation angle, depending on the satellite orbit inclination and the latitude of the ship location. Through use of a commercially available satellite analysis model, average satellite visibility periods were derived as a function of ship latitude and

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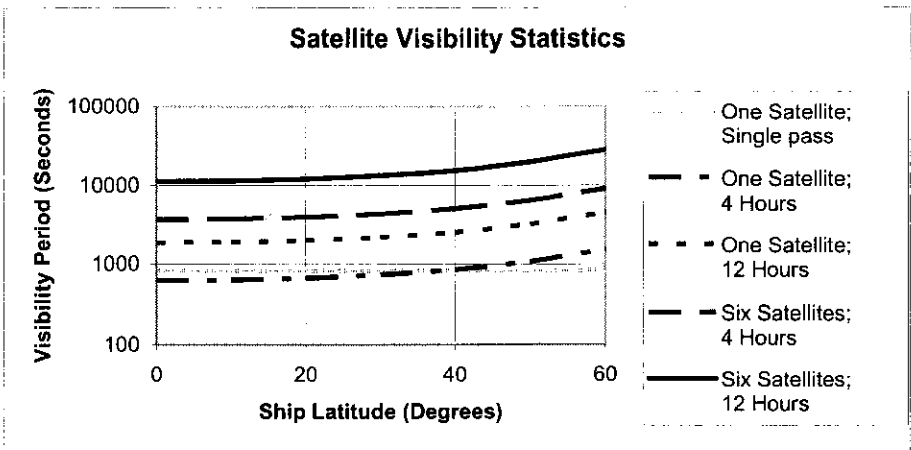
observation period as shown in Fig. 5.[4] Values for a single overhead pass as well as average values over longer extended observation periods of time such as 4 and 12 hours are given. Multiple satellite coverage is also considered for a six-satellite constellation, where the satellites are *adequately spaced to avoid overlapping of footprints on the earth.*

FIGURE 5

Satellite Visibility Statistics
(Satellite in Polar Orbit at 950 km Altitude)



For simplicity, most of the examples presented herein are for a ship latitude of 40° North. Table 7 gives the specific visibility values for a ship located at 40° North.

TABLE 7

Satellite Visibility Statistics
(Satellite in Polar Orbit; Target Ship at 40° North Latitude)

Satellite Constellation	Single Overpass	4-Hour Observation	12-Hour Observation
1 Satellite	818 seconds	853 seconds*	2 560 seconds
6 Satellites	818 seconds	5 118 seconds	15 360 seconds

* For the single satellite constellation, the 4-hour observation period represents a long term average, noting that there can be periods of over 9 hours without satellite visibility.

The analytic methodology and satellite visibility statistics can now be combined to describe the percentage of ships detected and the probability of detecting all ships. Figure 6 shows the results for a typical satellite overpass. Throughout the remainder of this report, these curves will be used as the baseline for AIS satellite detection of Class A ships. Figure 7 compares the results for other observation periods and a multiple-satellite constellation with the baseline curve.

4 Throughout this report the term "observation period" is used interchangeably with "ship location update period", both of which refer to a period of time in which it is desired to obtain at least one update of a given ship's identification and location. The term "visibility period" refers to the total number of seconds within the observation period that a line-of-sight path exists between a given ship and the satellite.

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FIGURE 6

AIS Satellite Detection
Baseline Curves for Single Satellite & Single Overpass

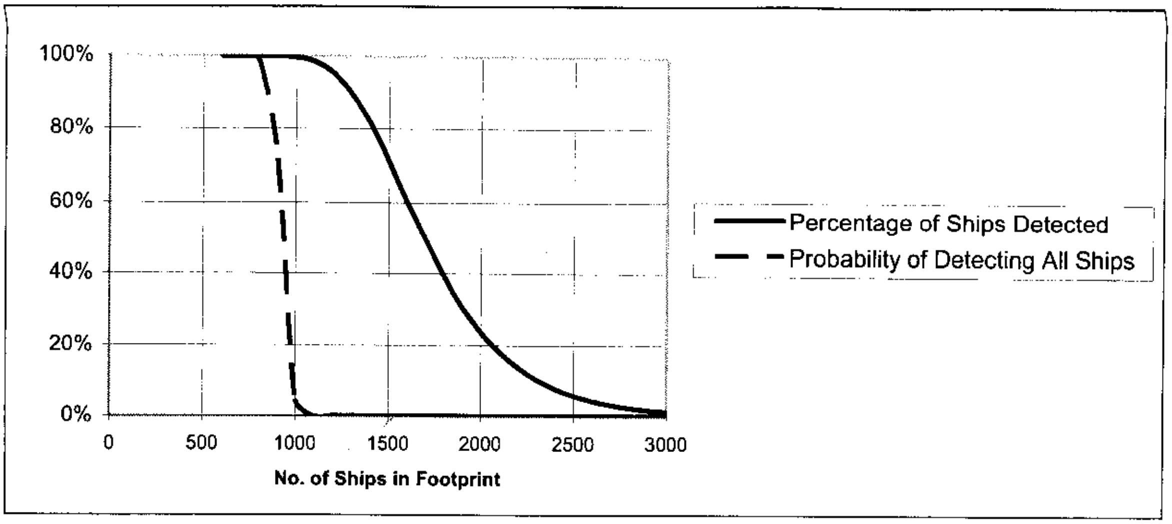
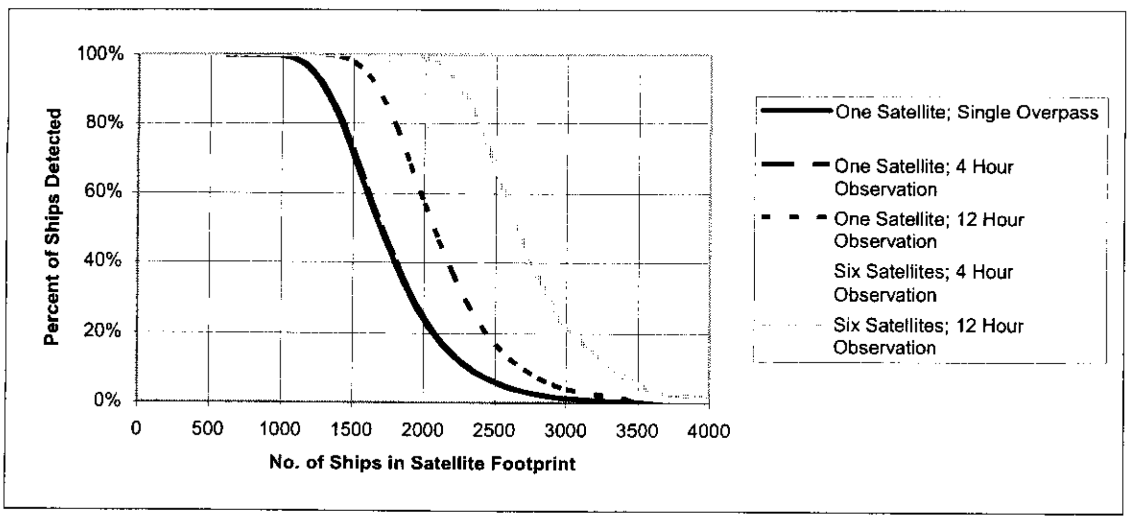


FIGURE 7

AIS Satellite Detection
(One and Six Satellite Scenarios)



For purposes of this study, the capacity of the satellite is defined at two points, the point at which 80% of the ships in the satellite antenna footprint are detected and where 100% are detected. Consequently, for the cases described above, Table 8 summarizes the satellite capacity for the various cases studied.

TABLE 8

Calculated Satellite AIS Detection Capacity
(Polar Satellite at 950 km Altitude; Ship at 40° Latitude; 80% Detection)

Satellite Constellation	Capacity Definition	Single Overpass	4-Hour Observation	12-Hour Observation
1 Satellite	80%	1 420 Ships	1 430 Ships*	1 790 Ships
6 Satellites	80%	1 420 Ships	2 018 Ships	2 381 Ships
1 Satellite	100%**	738 Ships	753 Ships	797 Ships
6 Satellites	100%**	738 Ships	1 052 Ships	1 382 Ships

* For the single satellite constellation, the 4-hour observation period represents a long term average, noting that there can be periods of over 9 hours without satellite visibility.

** Capacity calculated at 99.9%.

Simulation Method. An alternative approach was undertaken to investigate AIS satellite detection capacity limitations using Monte Carlo simulation methods. Using a Microsoft Excel® spreadsheet, a database was created where each record included technical parameters representing a ship located within the satellite footprint. By randomizing the key transmit parameters of each AIS unit and repeatedly calculating the resulting aggregate power received at the satellite in a given time slot, statistical results can be obtained in the same format as in the earlier analytic method. The key assumptions of the Monte Carlo simulation method developed for this study are as follows:

– Ships are uniformly distributed in a circular geographic area with a 3 281 km radius centred on the sub-satellite point
– Ships randomly transmit on AIS channel 1 or 2, and on one of the 2 250 time slots
– Each Class A ship transmits at the power and average time slot interval described earlier.

In addition to computing the aggregate power at the satellite, it is also necessary to compute the propagation time delay from each simulated ship in order to appropriately consider the time slot collision factor. In order to properly aggregate the interfering power received in a given desired-signal time slot under conditions of varying propagation time delays, the desired signal time slot was further subdivided into sub-time slots. For this study it was found that using ten sub-time slots provided sufficient accuracy, i.e. use of a larger number of sub-time slots did not significantly change the results. The first and last of the ten sub-time slots, twenty bits in length, represents overlapping time slots involving the 20 empty bits in the buffer. The other eight sub-time slots are 27 bits in length for a total of 256 bits. If the aggregate power in any of these middle eight sub-time slots results in a D/U of less than 10 dB, then a lost message is declared.

Figure 8 was developed through the use a Microsoft Excel® spreadsheet implementation of this methodology. The curve shows several data point calculations using the simulation method compared with the baseline values given in Fig. 5 showing close agreement.

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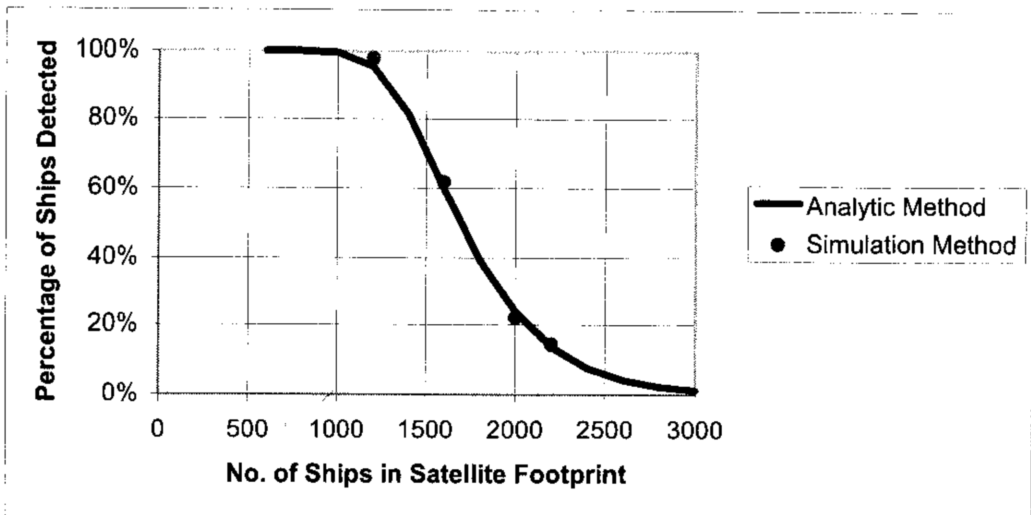
FIGURE 8

AIS Satellite Detection
Baseline Curve Using Simulation Method



Stochastic Method. A third methodology to develop statistics for detection of Class A ships is described by Tunaley.[5] In this method, the arrival time at the satellite of the AIS messages from the ships is considered as a random variable having a Poisson distribution. The expressions derived from this approach have the same general form as the earlier analytic method except the term $P_{1,N}$ is replaced with the following expression:

$$P_{1,N} \approx e^{(-\lambda\ \tau\ /\ 2)}$$

where

λ = $k \cdot (N-1) / \Delta T$

k = Factor to account for the double slot collision factor as described earlier (1.6)

τ = AIS Message Length (26.7 ms)

N = Number of Ships

ΔT = Message Transmit Interval.

For the case of Class A transmitters in a uniform ship environment, it is easily found that the results using this method are essentially identical with the analytic method described earlier in this subsection. This can be explained by noting the following approximation for the exponential function as follows:

$$e^{(-x)} \approx 1 - x \quad \text{for} \quad x << 1$$

By appropriate substitution of this approximation and rearranging of terms, it is found that the analytic and stochastic methods result in identical equations for low transmission duty cycles.

[5] Dr. J.K.E. Tunaley, *A Stochastic Model for Space-Borne AIS*, Undated.

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The near identical results derived using three different analysis methodologies sufficiently validates the results derived herein. In the discussion that follows, analysis results for various scenarios will be compared with the baseline values derived above. Given the equivalence among the three analysis approaches, only one analysis method is used that is most convenient for describing any given scenario.

6 Intra-system interference analysis (mixed class A and class B)

Detecting a Class A ship in an environment consisting of both Class A and Class B ships can now be investigated. The stochastic method described above is convenient for examining this case. Because of the lower power of the Class B units, not every time slot collision results in the loss of a message. For example, it can be seen from Fig. 2 that an AIS message from a single Class B ship located far from the sub-satellite point colliding with an AIS message from a Class A ship located near to the sub-satellite point would result in a D/U approaching +17 dB. This well exceeds the interference criteria of 10 dB and consequently this Class A message would still be correctly received. However, multiple overlapping of such signals may occasionally aggregate to the point where loss of signal for this example would occur. Consequently, the simple analytic procedure described earlier cannot be used, since it assumes that every collision results in message loss.

In order to use the stochastic methodology, some modifications are necessary. Specifically, the λ factor is replaced by the following

$$\lambda = k_A (N_A - 1) / \Delta T_A + k_B (N_B) / \Delta T_B$$

where the subscripts refer to the appropriate parameters for Class A and B. The constant, k_A, is the same value as k in the earlier equation. The constant k_B, however, can initially be only roughly estimated. It accounts for the fact that only a portion of the Class B slot collisions cause message loss, depending on relative power levels at the satellite receiver. One technique to provide a more accurate estimate of constant k_B, is to exercise the simulation model described earlier for a single data point. These results were used to derive a value of 1.2 for k_B.

Figures 9 though 11 show the probability of detecting a Class A AIS message in a mixed Class A and Class B environment under various conditions.

FIGURE 9

Detection Probability in a Mixed Class A & B Environment (One Satellite; Single Satellite Overpass)[6]

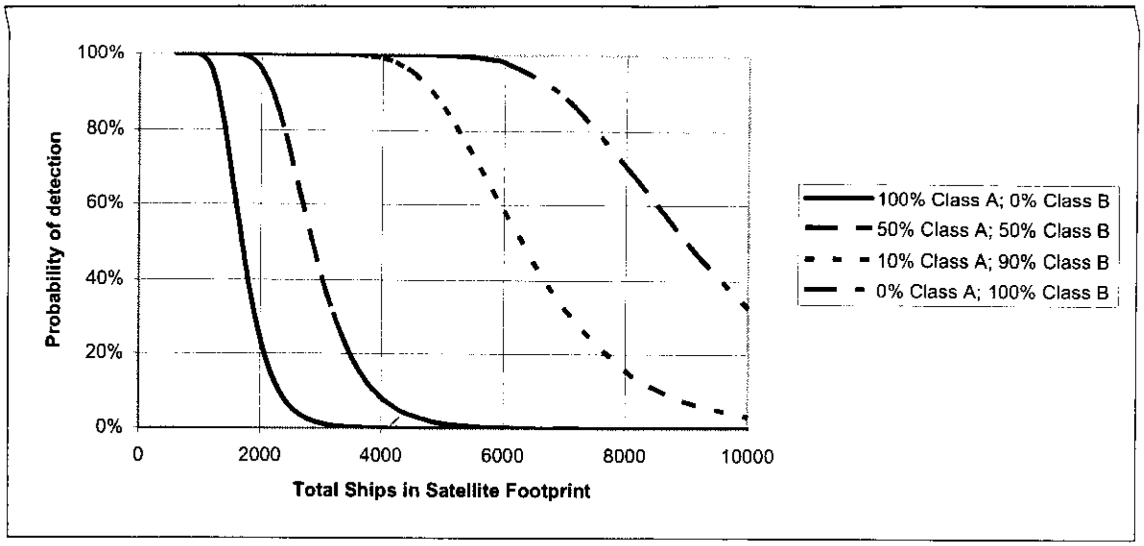
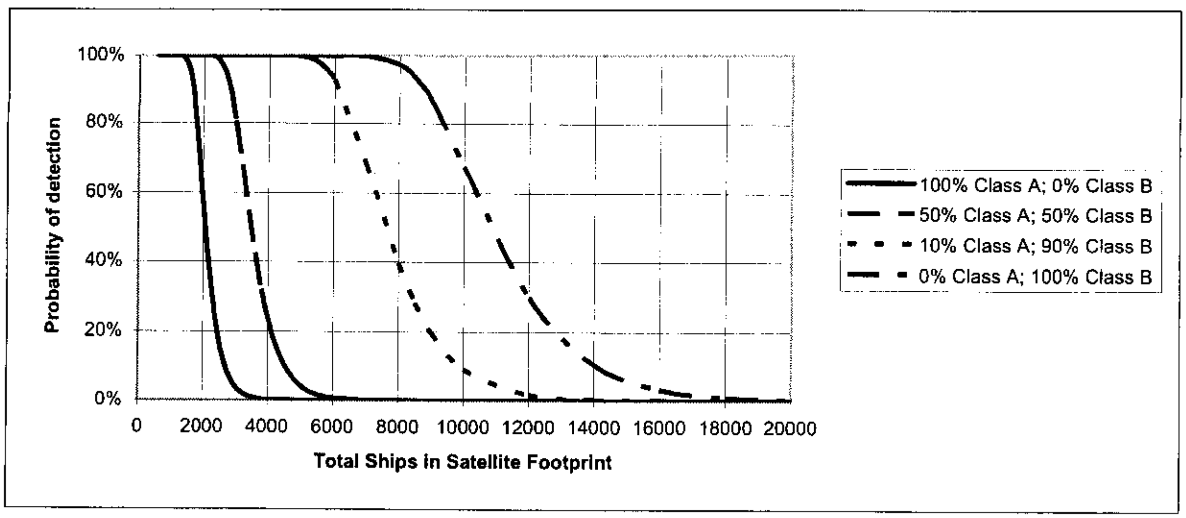


FIGURE 10

Detection Probability in a Mixed Class A & B Environment (One Satellite; 12 Hour Observation Period)



[6] In Figures 9, 10 and 11, the curve labelled "0% Class A; 100% Class B" refers to a hypothetical limiting case where the target is a single Class A ship and all remaining ships in the environment are Class B.

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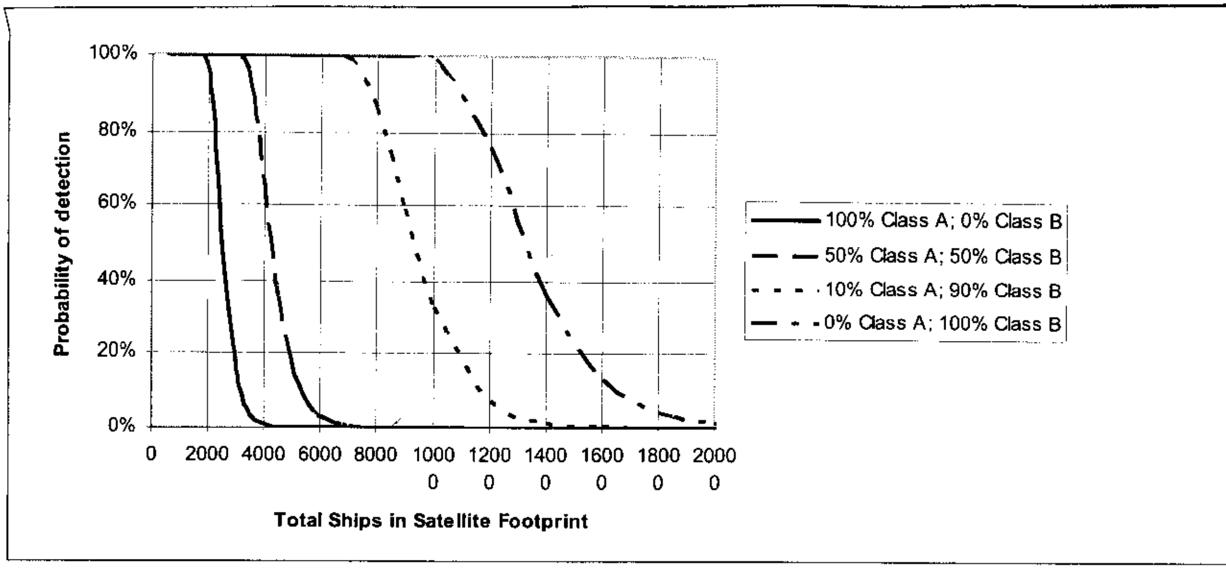
FIGURE 11

**Detection Probability in a Mixed Class A & B Environment
(Six Satellites; 12 Hour Observation Period)**



7 Intra-system interference analysis (non-uniform ship distribution)

The Class A only and the mixed Class A & B environments discussed above were both developed under the assumption of a constant, uniform geographic distribution of ships within the satellite antenna footprint. While this assumption simplified the calculation of the probability of detection, actual ship environments may not be adequately represented by this simplifying assumption. To examine this issue further, a modified simulation methodology was further developed for this study to consider non-uniform ship distributions, more typical of actual environments. However, doing so introduces a number of additional variables to be addressed, including:

- Total number of AIS-equipped ships in the world.
- Geographic location of the desired target ship (latitude and longitude).
- World-wide geographic distribution of AIS-equipped ships.
- Satellite ground track information.

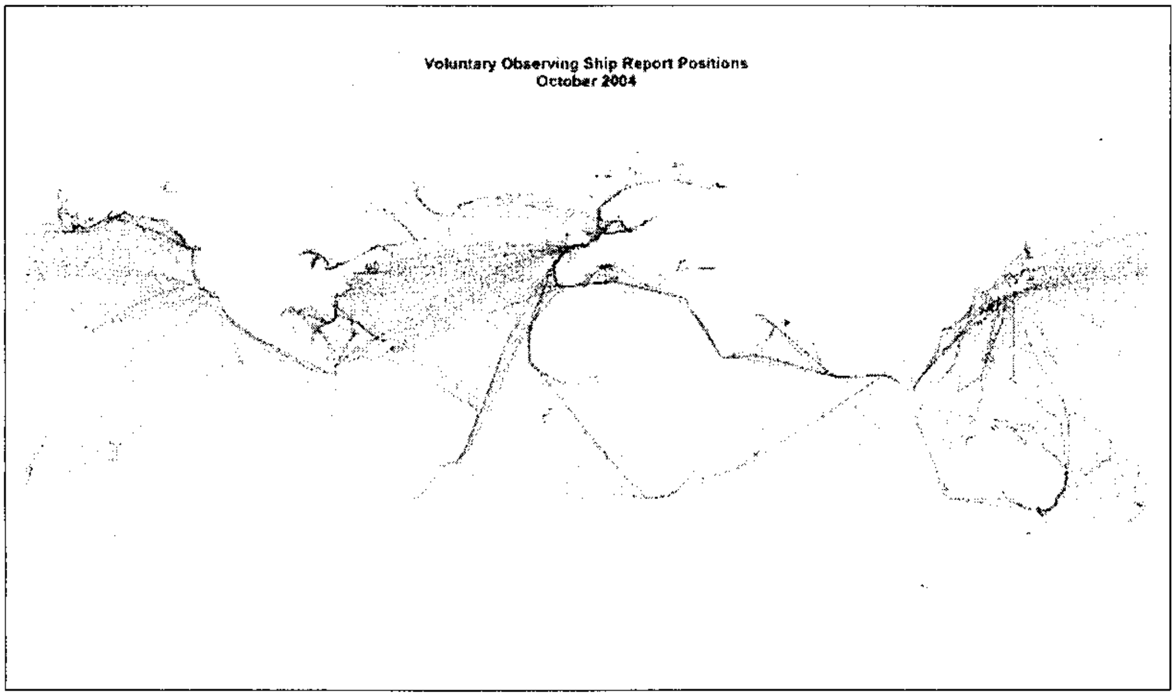
It was not possible for this study to obtain an authoritative count of the number of AIS-equipped ships that are active in the world. In addition to the required carriage under the SOLAS treaty, a growing number of larger, privately owned yachts and working vessels are being implemented with AIS Class A units. From a variety of sources, estimates ranged from about 50 000 to over 80 000. For purposes of this study, an estimate of 70 000 Class A equipped ships in the world is used for the year 2005.

The location of the target ship, quite obviously, has a large influence on the probability of detection. For example, a ship located far from the heavily-used shipping routes may be detected with near 100% certainty. This would not be the case for a ship located near more densely used areas. For this study, a target ship located at four arbitrary locations was used: 1 000 km off the coast from the cities of New York and Los Angeles in the United States, one near the centre of the Gulf of Mexico, and one in the mid-Atlantic were chosen.

Describing the geographic ship distribution is somewhat more challenging. One useful representation of world-wide ship densities can be derived from voluntary weather observations reported by ships at sea. One available set of data for the month of October 2004 contained over 80 000 weather observation reports, including associated latitude/longitude data, from approximately 800 ships. This distribution is shown in Fig. 12. As can be seen from this data, the density of the locations is significantly higher in coastal areas and major shipping routes, and relatively lower over the broad ocean areas, as would be expected. The relative distribution of ship locations in this data is assumed to provide a reasonable worldwide representation of Class A ships. This distribution would not adequately represent future Class B distributions since these are expected to be largely confined to coastal areas.

FIGURE 12

Example Worldwide Distribution of Class A ships



Using this database, an initial step can be taken to study the detection of Class A ships using a more realistic worldwide distribution of ships.

Analysis of non-uniform ship distributions can be accomplished using this data and a Monte Carlo simulation process similar to that described above with the following additional changes:

- A random subset of the ship locations contained in the weather observation data is used rather than uniformly distributed locations within the satellite footprint.
- The satellite location is stepped along a representative satellite orbit passing over the target ship in accordance with the assumed satellite orbit parameters.

Figures 13 through 16 show the resulting probability of detection of a Class A ship as a function of the number of worldwide Class A equipped ships for the four test points identified earlier. Note the change in the abscissa to indicate the total number of Class A equipped ships in the world.

FIGURE 13

Detection Statistics using Worldwide Ship Data
(Target Ship Located 1 000 km off Coast of Los Angeles CA, USA)

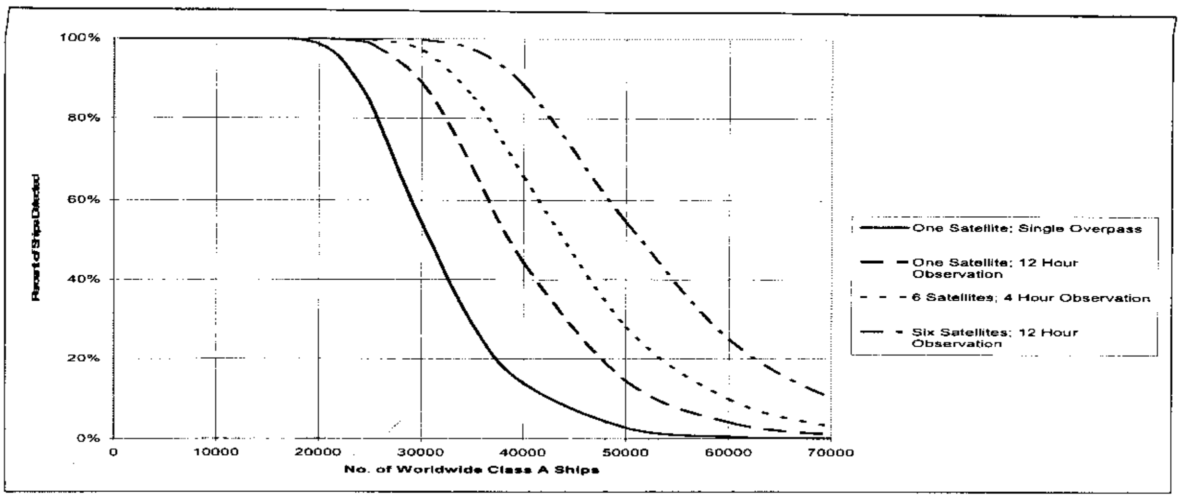


FIGURE 14

Detection Statistics using Worldwide Ship Data
(Target Ship Located 1 000 km off Coast of New York, NY, USA)

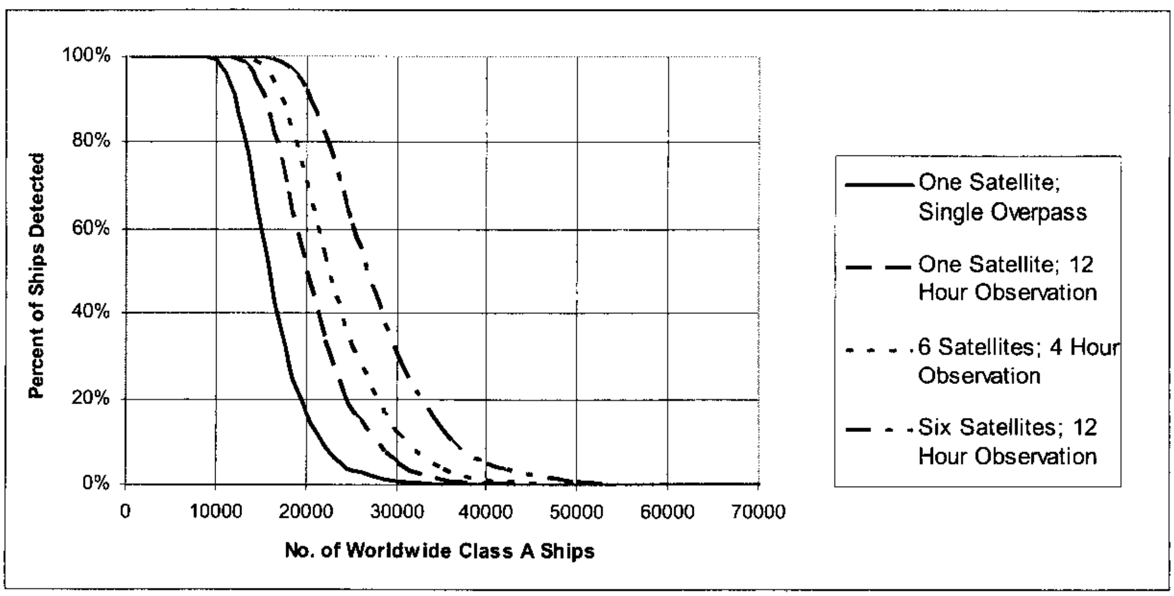


FIGURE 15

Detection Statistics using Worldwide Ship Data
(Target Ship Located in the Gulf of Mexico)

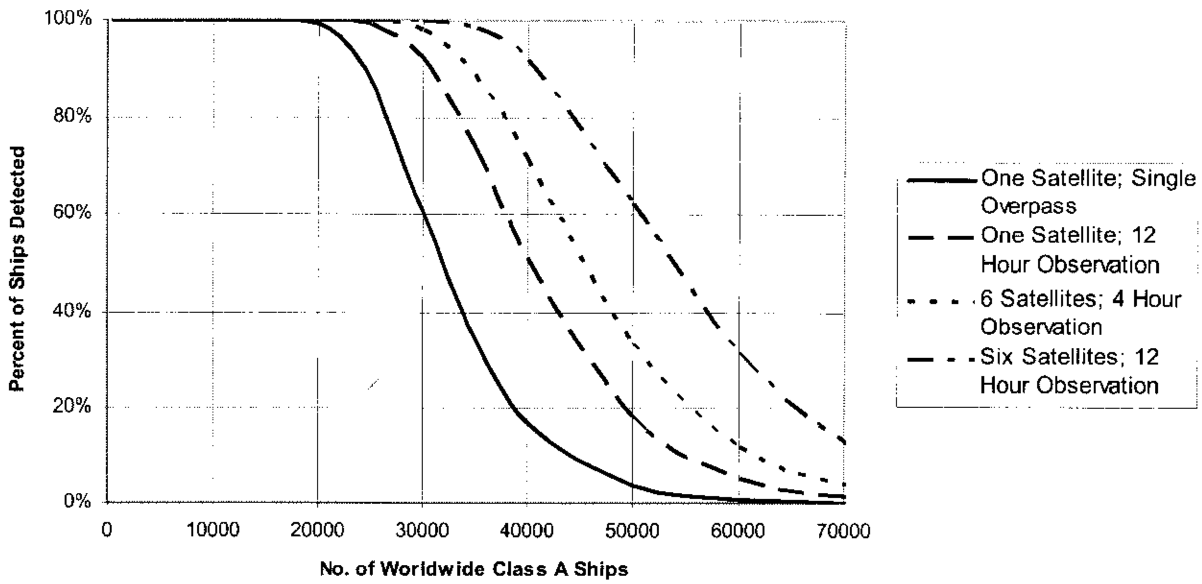
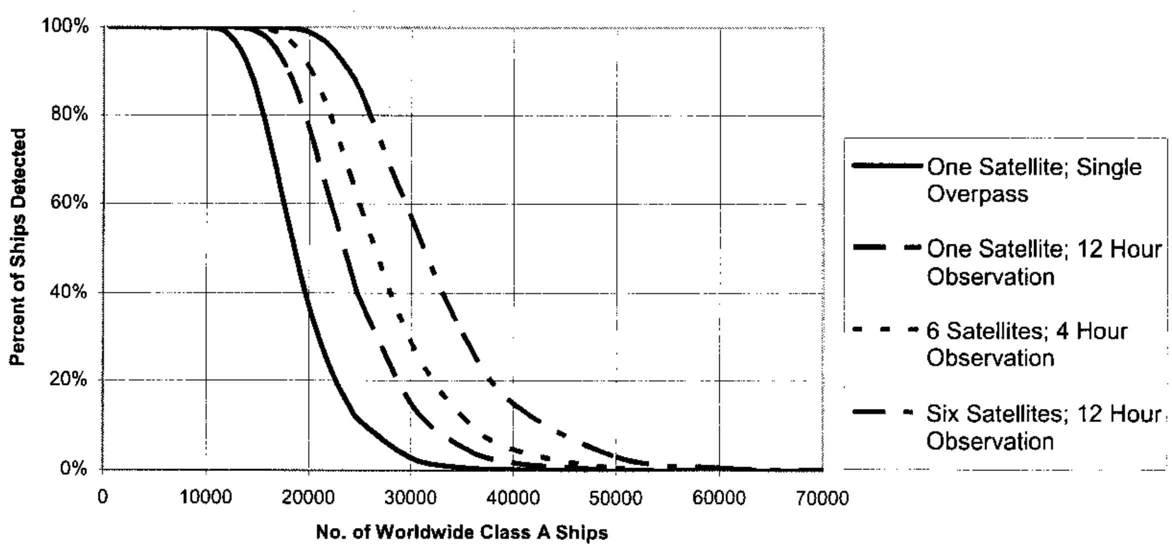


FIGURE 16

Detection Statistics using Worldwide Ship Data
(Target Ship Located in the mid Atlantic Ocean)



8 Candidate techniques to enhance satellite capacity

The analysis results presented herein demonstrate the technical viability and capacity limitations of using satellite detection of AIS to provide a long range ship monitoring capability. Using various satellite scenarios and estimates of the worldwide density of AIS Class A equipped ships, the study suggests that ship densities in certain geographic areas, especially the North Atlantic, can exceed the projected satellite ship-handling capacities. Further studies were undertaken to examine various concepts and techniques to increase the satellite AIS capacity to better accommodate these expected larger ship densities. To examine these various techniques, it is usually sufficient and more convenient to address the issue from the standpoint of a uniform ship distribution. The capacity improvements possible using a worldwide ship database will, on a percentage basis, be very similar to the results derived herein using uniform ship distribution. Four possible techniques are described below.

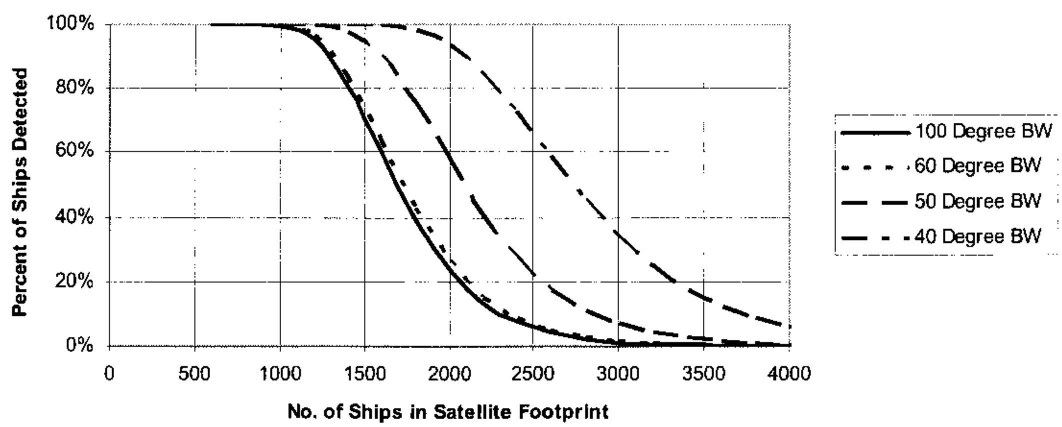
Satellite Antenna. The AIS satellite antenna assumed for this study is a broadbeam antenna (100 degree beamwidth) with the peak gain directed towards the sub-satellite point. Use of an antenna having a narrower beamwidth was examined to determine if use of such an antenna could provide an effective increase in satellite capacity. Reducing the antenna beamwidth lowers the number of competing AIS ship messages at the satellite at any given moment. The lower number of AIS messages, in turn, raises the detection probabilities, effectively increasing the satellite capacity.

Two factors, however, tend to moderate the potential capacity increases. First, even though the –3 dB beamwidth is reduced, the sidelobe gain towards the horizon may still be sufficient to detect competing ship AIS messages at or near the horizon. Second, with a smaller satellite footprint, the satellite will be visible from a given target ship for a shorter time period. From the equations given in Section 5, it is seen that a shorter satellite visibility period tends to decrease satellite capacity.

Figure 17 shows the combined effects of these three competing factors. As shown narrowing the antenna beamwidth to 60 degrees or less raises the satellite capacity. This increase in capacity, however, could come at a large cost since a smaller antenna beamwidth inherently requires a larger satellite antenna, which may not be compatible with a small LEO satellite concept.

FIGURE 17

Detection Statistics for Various Satellite Antenna Beamwidths
(One Satellite; Single Overpass Scenario)

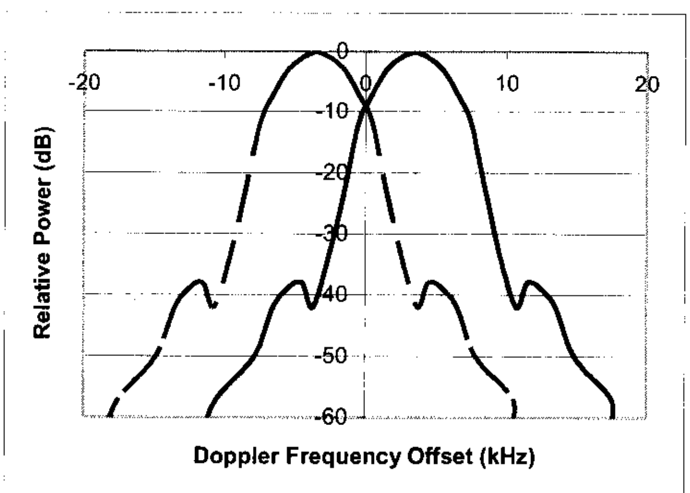


Doppler Tracking. One approach that is being implemented on an early demonstration satellite is the use of Doppler tracking. Because of the Doppler shifts of up to ±3.5 kHz that occur due to satellite motion, the AIS satellite receiver bandwidth must initially be larger than optimum for the GMSK modulation. While the larger bandwidth allows reception of a desired AIS signal under any Doppler shift condition, it also allows reception of all competing ship AIS signals on the same channel under any Doppler shift condition.

A combination of automatic tracking of the desired AIS signal Doppler shift and adjusting the frequency accordingly allows use of a narrower receiver bandwidth and consequently provides some degree of discrimination with other competing ship AIS signals having different Doppler shifts. While the details of the Doppler tracking techniques need not be described herein, the resultant gain in satellite capacity can be examined. Figure 18 shows the typical RF emission spectra of two 9.6 kb/s GMSK signals, one representing a desired AIS signal and the other a competing AIS signal with different Doppler shifts. In this example the desired AIS signal is Doppler-shifted 3.5 kHz lower than the nominal centre frequency and the undesired signal Doppler-shifted 3.5 kHz higher. The difference between the centre frequencies of the two signals is consequently 7 kHz. It is this difference in Doppler shifts that offers the possibility of discriminating against other competing ship AIS messages.

FIGURE 18

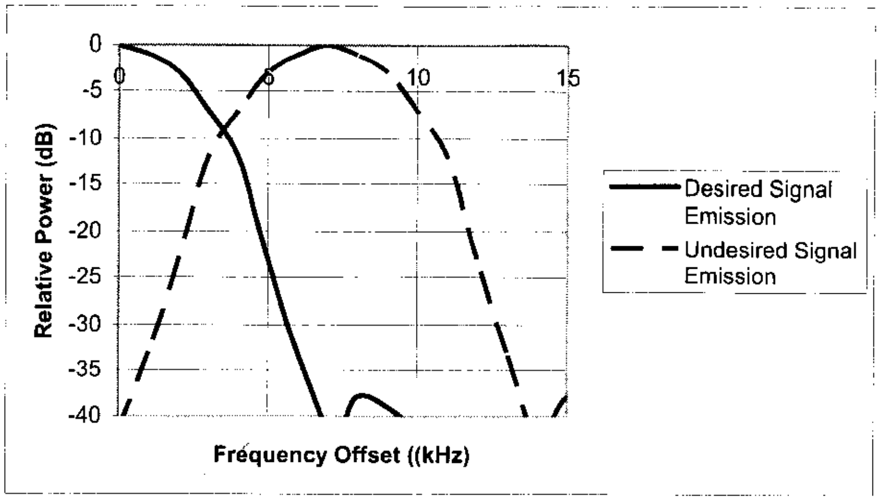
Desired and Undesired AIS Signals at Maximum Doppler Offsets



Through the use of real time tracking of the Doppler shift of a given desired signal, the Doppler frequency offset can be compensated for. Figure 19 shows the same example as above at baseband where the Doppler shift of the desired signal has been determined and compensated for, and the undesired signal is separated in frequency by the difference in Doppler shift – in this example 7 kHz.

FIGURE 19

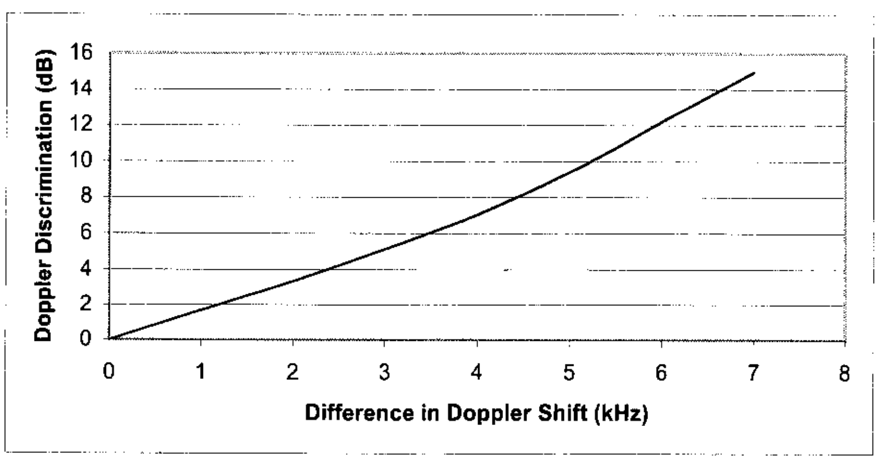
Desired and Undesired AIS Signal at Baseband after Doppler Compensation



By passing the above signal though a narrowband low-pass filter, significant reduction in the interfering signal level can be obtained. However, the above example represents the best case with the greatest Doppler shift difference. Based on ship distributions, the average Doppler shift difference is expected to be about 2.7 kHz. Figure 20 shows the resulting Doppler discrimination as a function of the difference in Doppler shift that has been achieved in a prototype system.

FIGURE 20

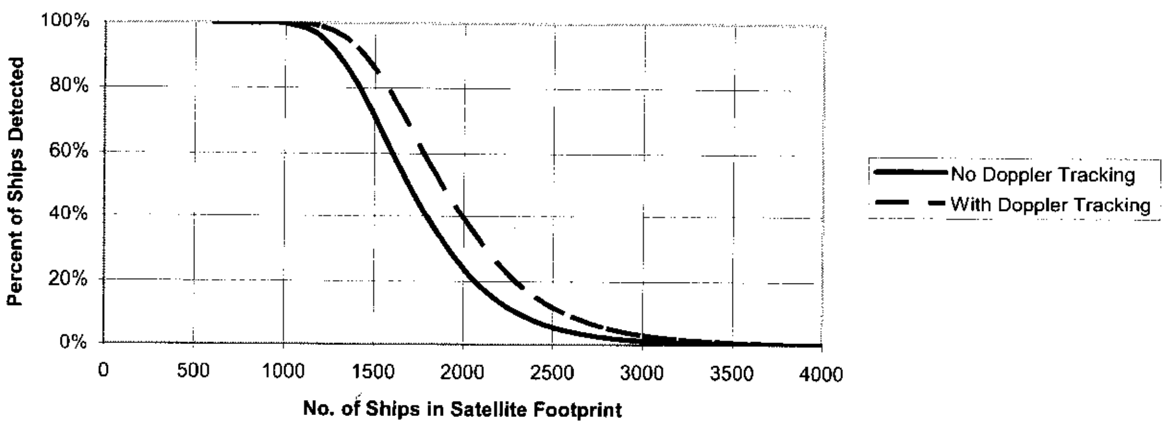
Doppler Discrimination after Narrowband Filtering



To evaluate the effectiveness of this technique, use of the simulation analysis method is required. The simulation model described earlier is further expanded to include a calculation of the Doppler frequency shift for the desired and each undesired AIS and the associated power level is reduced by the amount shown in Fig. 20 for a single satellite overpass. The results are shown in Fig. 21.

FIGURE 21

Satellite Detection Statistics with Doppler Tracking

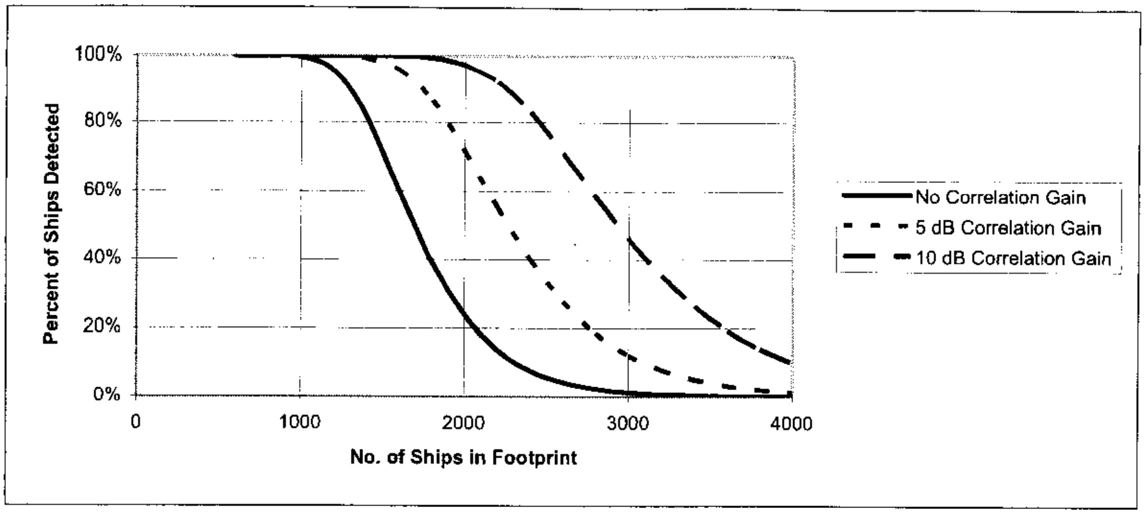


Correlation Processing. Another possible technique to improve satellite capacity would require a modification to the satellite architecture to provide on-board processing or continuous downlinking of the data received on the two AIS channels for processing at an earth station on the ground. This method would take advantage of the fact that the AIS messages transmitted from a given ship have a high degree of correlation from one message to the next. For example, during the 13 minute visibility period of a typical satellite overhead pass, a given ship will transmit about 116 AIS messages. During this period, approximately 60% of the bits in each of these AIS ship message are repeated identically. The MMSI ship identification code is, in particular, repeated with each message. By continuously correlating the two received AIS signals with digitized copies of the signals received during the previous 13 minute period, some degree of correlation gain could be achieved. Given the moderately low data rates of AIS transmissions, use of massively parallel correlator techniques may be possible to permit continuous real time processing of the received downlink data.

Although further study would be required to determine the degree of correlation gain achievable using this technique, the effective impact on satellite AIS detection capacity can be estimated. Any correlation gain of a desired AIS signal that results via this technique would provide, on a dB-for-dB basis, discrimination against other undesired AIS messages. The result would be that successful detection could occur at lower D/U ratios than would be otherwise possible, effectively reducing the D/U protection criteria from the reference value of 10 dB. Using the AIS detection simulation model described earlier, the effect on detection probabilities of varying the D/U protection criteria can be determined. Figure 21a compares the detection statistics under the assumption that 5 and 10 dB of correlation gain with the reference curve with no correlation gain for a single satellite overpass.

FIGURE 21A

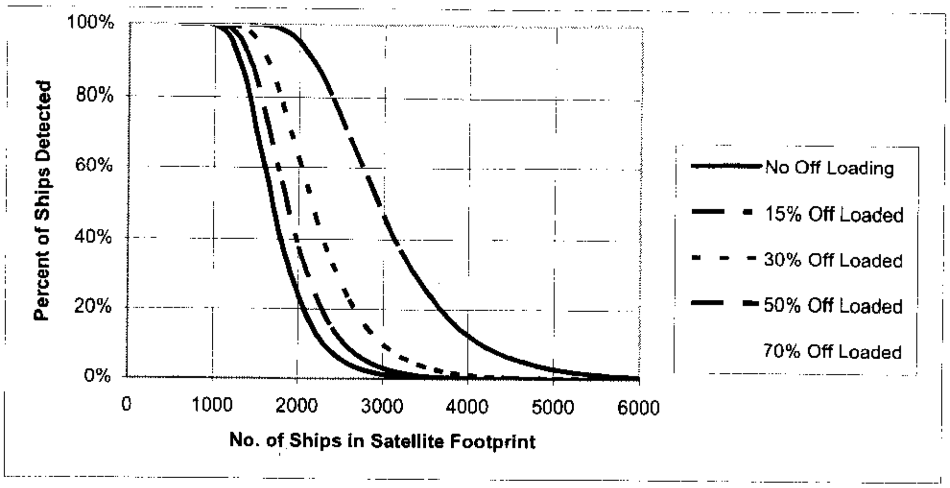
Satellite Detection Statistics with Correlation Processing



Offloading of Coastal Ship Traffic. The AIS architecture provides the capability for an AIS coast station to direct ships within its communication range to automatically shift one of the AIS channels to an alternate frequency in the VHF maritime band. The switch in frequency is transparent to the ship operator and has minimal impact on the normal ship-to-ship and ship-to-shore AIS communications functions. Use of this capability on a routine basis in heavily used coastal areas would reduce loading on AIS satellite detection from coastal ship traffic. Consequently, satellite detection probabilities of AIS messages from ships at sea could improve. One means to test this concept would be to modify coastal stations from the ship distribution database defined earlier in Figure 12 so that only AIS 1 were operable and rerun the simulation analysis. However, identifying and modifying the coastal ships in a database of 80 000 records proved a challenge. It was observed that, because of the very large satellite footprint and the randomizing effects of the satellite motion, simply modifying the same fraction of ships from throughout the database, rather than just coastal ships, gave virtually the same result. Figure 22 shows the resulting detection probabilities using the same non-uniform ship distribution described earlier with various amounts of AIS 2 traffic offloaded during a single satellite overpass. This range of values would include the situations where only ships near major port areas were directed to offload AIS 2 to an alternate channel and all coastal ships offloaded.

FIGURE 22

Satellite detection Statistics with Coastal Offloading of AIS 2



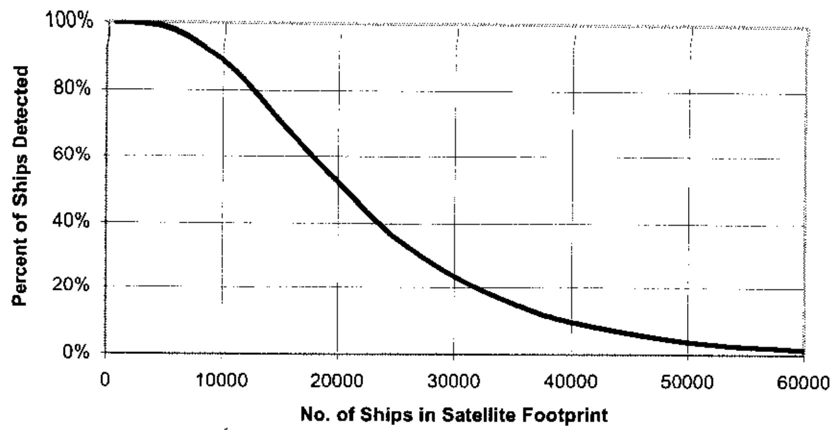
Long Term Studies/Solutions. On a long term basis it may be practical to simultaneously implement several of the techniques described above in order to further enhance satellite detection.

As an alternative long term study, the possibility of using a third AIS channel with the message structure optimized for satellite detection has been introduced within the IMO. The concept has not been finalized with regard to the possible frequency band of operation or specific channel used for a third frequency option. In determining the possible frequency bands or channels for operation, the interference environment resulting from the existing services in those bands must be taken into account in determining the feasibility of accommodating satellite AIS in any given band or channel. Regardless of the frequency band of operation, the use of a shorter message length and longer transmit period can dramatically increase satellite capacity. For example using the analytic method described earlier, a 128 bit message and a 3 minute interval can increase the satellite capacity to over 10 000 ships within the satellite footprint, as shown in Fig. 23. This option would require modification of the installed base and future installations of AIS ship equipment.

 13.11.06

FIGURE 23

Example Satellite with 3rd AIS Channel



9 Compatibility with other incumbent fixed and mobile systems

The two frequencies that have been designated as channels within the maritime mobile service for the terrestrial AIS function are not allocated on an exclusive basis. Rather, these channels and adjacent channels are allocated and used throughout various regions of the world for other mobile service applications including VHF public correspondence stations (VPCS) in the maritime mobile service and land mobile radio (LMR) systems. The VPCS continue to be deployed in certain geographic regions in limited numbers along coastal areas. Most administrations have chosen to assign LMR stations that are at a distance from coastal areas and navigable waterways to assure mutual compatibility between the maritime mobile and land mobile services. However, because the satellite antenna beam covers a large geographical area, transmissions by mobile systems operating inland can still be received at the satellite.

Available frequency assignment records show that the current density of deployment of LMR systems on these AIS channels is less than on other channels in 156-162 MHz and is greatly reduced from the density that is typical for other VHF frequencies allocated for the land mobile service.

The following paragraphs describe the performance of AIS satellite detection when operated with co-channel and adjacent channel mobile systems. The study will initially focus on simple scenarios using a uniform ship distribution followed by several examples using the more realistic non-uniform ship distributions described earlier.

Co-channel Mobile Systems.

The first step in investigating AIS satellite operation with mobile systems is designation of technical parameters of LMR and VPCS systems. Table 10 lists representative technical parameters for VPCS and LMR systems. As seen in this table, both the VPCS and LMR systems may typically employ an effective radiated power (ERP) up to 14 dB higher than the ship AIS transmitters sharing these frequencies. These ERP differences present no compatibility problems among the two terrestrial services as long as the distance separations are adequate. However, this would not be the case for satellite detection of AIS. As described earlier, the footprint on the Earth of a LEO satellite can have a radius of approximately 3 281 km. For several time periods every day, any co-channel mobile system within this radius will have a line-of-sight path with the satellite.

 13.11.06

TABLE 9

Typical VPCS and LMR technical parameters

Parameter	Land mobile base station (wideband)	Land mobile base station (narrowband)	VHF public correspondence coast station
Transmit ERP	37 to 56 dBm (54 dBm typical)	37 to 56 dBm (54 dBm typical)	50 dBm
Modulation	16F3E	11F3E	16F3E
Channelling	25 kHz	12.5 kHz	25 kHz
Antenna Gain	0 to 9 dBd (6 dBd typical)	0 to 9 dBd (6 dBd typical)	
Antenna Pattern	Omnidirectional	Omnidirectional	Omnidirectional

Given the higher ERP of typical mobile systems, negative D/U ratios values can sometimes result from a single co-channel VPCS or LMR located within the footprint of the satellite. A preliminary study indicated that D/U values during these line-of-sight periods for a representative scenario could possibly vary from −17 dB to +5 dB with an average of −6 dB, all of which were below the nominal D/U threshold for practical AIS detection.[7] The average D/U value of −6 dB calculated in that study is consistent with the 6 dB higher effective isotropic radiated power (EIRP) used in that study for the mobile system transmitter as compared to an AIS ship transmitter. Table 10 provides sample calculations from that study for two satellite overpasses for a representative LMR transmitter in the central United States and an AIS equipped ship in the Atlantic Ocean. If these co-channel mobile service transmitters were to be operated on a 100% duty cycle basis, the upfront conclusion would directly follow that satellite detection of AIS is not compatible with other co-channel mobile service applications.

[7] For that study, a simplified methodology was used as follows: Mobile EIRP was constant at 50 dBm over the upper hemisphere; Ship AIS EIRP was constant at 44 dBm over the upper hemisphere; Satellite antenna had constant gain towards the Earth; No polarization discrimination; Free space propagation was used during periods of satellite visibility.

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