

REPORT ITU-R M.2084*

**Satellite detection of automatic identification
system messages**

(2006)

1 Introduction

In the early 1990s, the International Association of Maritime Aids to Navigation and Lighthouse Authorities (IALA) first proposed the development of a universal shipborne system to improve the maritime safety and efficiency of navigation, and to help protect the marine environment. Subsequent to that proposal, the International Maritime Organization (IMO), the ITU, and the International Electrotechnical Commission (IEC) adopted a new navigation system now known as the Automatic Identification System (AIS) to help achieve these goals. The primary purpose of the AIS is to facilitate the efficient exchange of navigational data between ships and between ships and shore stations to significantly improve safety of navigation and promote improved control and monitoring of maritime events. The technical characteristics of the current AIS system using time division multiple access (TDMA) techniques in the VHF maritime mobile band are described in detail in Recommendation ITU-R M.1371.

As described in that Recommendation, the AIS is designed to operate autonomously and automatically to exchange short messages among ships, coast stations, and navigational aids within a 20 to 30 nautical miles (NM) (27 to 56 km) range primarily using a self-organizing form of TDMA. Messages include data such as ship identification, location, course and speed.

Under requirements of the International Convention for the Safety of Life at Sea (SOLAS), the installation and use of AIS is mandatory on all ships of 300 gross tons or more engaged in international voyages. In 2008, all ships of 500 gross tons or more engaged in national voyages should also be equipped with AIS. AIS equipments designed for this mandatory carriage requirement are designated as Class A units. A lower power version intended for voluntary carriage, called Class B, is under development. Since its introduction, the AIS has proven very successful in meeting the original goals set by the IALA.

Recently, a need has evolved for the capability to detect and track ships at distances from coastlines that are larger than can be accomplished by normal terrestrial VHF communications. Requirements of these long-range applications such as better handling of hazardous cargo, improved security, and countering illegal operations suggest a need to detect approaching ships at distances of 200 NM (370 km) from shore and beyond.

This Report introduces satellite detection of AIS as one means of accomplishing long range ship detection. The report addresses its technical feasibility, examines satellite capacity under various conditions and examines possible methods for improving satellite capacity. The remaining portions of this document are organized into eight subsections as follows: operational and technical characteristics of AIS, overview of satellite detection of AIS, link budget analysis, intra-system interference analysis (Class A only, Mixed class A and Class B, and non-uniform ship distribution), compatibility with incumbent mobile systems, techniques for improving performance and sharing, and summary.

* This Report should be brought to the attention of the International Maritime Organization (IMO), the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), and the International Maritime Radio Association (CIRM).

2 Operational and technical characteristics of shipborne AIS

To assist in functionally describing and understanding the nature of satellite AIS detection, the basic characteristics of conventional terrestrial AIS as described in Recommendation. ITU-R M.1371 are summarized in the following paragraphs.

AIS functions as a ship-to-ship and ship-to-shore communication system in which AIS-equipped ships periodically transmit short fixed-length TDMA messages including data such as identification, location, course, speed, and other status information. The associated AIS receivers aboard ships and shore stations detect this information from all nearby ships, thus providing a comprehensive picture of the local environment to supplement radar and other navigation aids.

The TDMA signal structure is based on a one minute frame divided into 2 250 time-slots with each message nominally occupying one time-slot. In the normal mode, these identification messages are periodically transmitted alternately on two VHF maritime channels that have been designated for this purpose. Ship location is obtained from an on-board electronic position-fixing device. TDMA timing is obtained from the GNSS receiver built in the AIS station. With the two channels, the total capacity of AIS is 4 500 one-slot messages/min.

AIS is designed around an access scheme called self-organizing TDMA. Through this technique, the system functions without a central TDMA controller, as is typical in fixed-assignment TDMA schemes. By continuously sensing the AIS signals in the local environment and “announcing” its next intended transmission slot, coordination is achieved by all participating ships in the local environment and conflicts in use of a given time-slot are minimized. Other TDMA access schemes are also used for certain message types.

The RF and data technical parameters of AIS are summarized in Table 1. As described in the Table, the basic message length is 256 bits with the last 24 bits serving as a buffer to accommodate propagation and repeater delays, timing jitter and extra bits due to bit stuffing. Typically, the last 20-bit positions are empty. The characteristics of antenna and associated transmission line parameters to be installed on AIS equipped ships are not defined in the basic ITU Recommendation but are added herein to more fully define the AIS characteristics. In practice, two types of antennas are in common use, a $1/2 \lambda$ dipole and a $5/8 \lambda$ end-fed monopole with gains ranging from 2 to 4.5 dBi. In order to be conservative for this study, the $1/2 \lambda$ dipole is assumed having a maximum gain of approximately 2 dBi with a simple cosine-squared elevation gain pattern. The transmission line type and length varies with the installation. For purposes of this paper, a 3 dB loss is assumed to account for cable and other miscellaneous losses associated with the AIS ship transmitter. The default data packet bit structure is shown in Table 2.

TABLE 1
Overview of shipboard AIS technical parameters

AIS parameters	Values
Frequencies	161.975 and 162.025 MHz
Channel bandwidth	25 kHz
Platforms	Class A ships, Class B ships, coast stations, navigation aids
Power	12.5 W (Class A); 2 W (Class B)
Antenna type ⁽¹⁾	$1/2 \lambda$ dipole
Antenna gain ⁽¹⁾	2 dBi with cosine-squared vertical elevation pattern; Minimum gain = -10 dBi
Cable loss ⁽¹⁾	3 dB (estimated)

TABLE 1 (*end*)

AIS parameters	Values
Receiver sensitivity	–107 dBm for 20% packet error rate (PER) (minimum) –109 dBm for ≤20% PER (typical)
Modulation	9 600 bits GMSK
Multiple access mode	TDMA (self-organizing, random, fixed and incremental)
TDMA frame length	1 min; 2 250 time-slots
TDMA slot length	26.7 ms; 256 bits (see Table 2)
Message types	22 types
Message length	1 to 5 slots with 1 slot being the dominate type
Periodic message interval	2 s to 6 min transmit intervals (see Table 3)
Required <i>D/U</i> protection ratio	10 dB at PER = 20% ⁽²⁾

(1) Typical parameters not defined in Recommendation ITU-R M.1371.

(2) Parameter specified in IEC 61993-2.

TABLE 2

Default data packet bit structure

Power ramp up	8 bits	
Training sequence	24 bits	Necessary for synchronization
Start flag	8 bits	
Data	168 bits	Default length
Cyclic redundancy code	16 bits	Necessary for error detection
End flag	8 bits	
Buffer	24 bits (typically, the last 20-bit positions are empty)	Necessary to accommodate bit stuffing, propagation and repeater delays, and jitter
Total	256 bits	

To accommodate the various functions performed by AIS, 22 message types are defined in the standard, which can be grouped into four categories: dynamic, static and voyage, safety and administrative, and data. The dynamic messages, transmitted periodically, comprise the largest volume of traffic in the AIS environment. One key variable is the rate at which the different platforms transmit these periodic messages. For several platform types a range of reporting intervals are defined in the standard depending on the ship dynamics such as speed and course. Table 3 summarizes the message reporting intervals for the various platforms.

As will be shown later, the message reporting interval plays an important role in the performance of satellite detection of AIS. As shown in Table 3, the reporting interval for Class A ships varies over a wide range from every 2 s to every 3 min depending on the dynamic status of the ship. In order to determine a long term average transmission interval for Class A ships, it is necessary to have an estimate of the distribution of the ships among the various dynamic status situations. Table 4 lists the status categories, their respective reporting interval and an estimate of the percentage of ships in each category at any given time. From this data, an overall estimate for the reporting interval was determined.

TABLE 3
AIS message reporting intervals

AIS platform	Reporting interval
Dynamic information:	
Coast station	3 1/3 to 10 s interval (10 s nominal)
Class A ship	2 s to 3 min interval (approximately 7 s average) (see Table 4)
Class B ship	5 s to 3 min interval (30 s nominal)
Search and rescue aircraft	10 s interval
Aid to navigation	3 min interval
Static and voyage information	6 min interval
Safety & administrative messages	As required
Data message	As required

TABLE 4
Class A shipborne mobile equipment reporting intervals

Ship's dynamic conditions	Nominal reporting interval	Percent of total
Ship at anchor or moored and not moving faster than 3 knots	3 min	28
Ship at anchor or moored and moving faster than 3 knots	10 s	
Ship 0-14 knots	10 s	30
Ship 0-14 knots and changing course	3 1/3 s	12
Ship 14-23 knots	6 s	30
Ship 14-23 knots and changing course	2 s	
Ship - 23 knots	2 s	
Ship - 23 knots and changing course	2 s	
Average for all ships	~7 s interval	

3 Satellite detection of AIS

In concept, satellite detection of AIS would involve use of one or more satellites in low earth orbit (LEO) to receive and decode AIS messages, and relay the resulting information via satellite feeder links to appropriately located earth stations. Satellite altitudes in the range of 600 to 1 000 km are typical for LEO satellites. A functioning satellite AIS detection system is not currently in place and the operational and technical parameters for such a system have not been defined. Consequently, it is necessary for purposes herein to assume reasonable and technically achievable parameters.

An initial demonstration system will consist of a single (LEO) satellite in polar orbit at an altitude of 950 km. For later operational systems, it is envisioned that a relatively small constellation of LEO satellites would be used; consequently satellite coverage of a given ship location will not be continuous. Full global coverage and the use of a modest number of earth stations necessitate the

need to use store and forward techniques for the received AIS data. However, for detection and monitoring of ships up to several thousand nautical miles from a coast, the large satellite footprint on the Earth allows real time download of data during the visibility period of the satellite.

Several key technical factors distinguish satellite AIS detection from conventional ship-to-ship and ship-to-shore AIS detection, specifically receiver sensitivity, antenna gain pattern, and reliability requirements. Measured data reported for AIS shipborne receivers show that off-the-shelf receivers are typically more sensitive than the receiver sensitivity required in the AIS specifications. Using low noise amplifiers (LNAs) and optimum detection schemes, further improvement in AIS satellite receiver sensitivity is possible. Countering these improvements, however, is the need for larger than optimum receiver bandwidths to accommodate Doppler shifts of up to about ± 3.5 kHz. Taking these factors into account, a baseline sensitivity of -118 dBm for a 1% packet error rate (PER) and -120 dBm for a 20% PER are used herein for the AIS satellite receiver.

The initial satellite system will use a wide beam satellite antenna. Broadbeam antennas used on LEO satellites can generally be categorized into two groups. One commonly used type is one in which the peak gain is directed omni-directionally towards the horizon with lower gain towards the sub-satellite point. With this type of antenna, the change in antenna gain with off axis angle partially compensates for the changes in propagation loss resulting in a lower variation in signal level as off-axis angles vary. The other antenna category is of a more conventional type with peak gain directed towards the sub-satellite point. For purposes of this study the latter type is assumed having a peak gain of 6 dBi and a -3 dB beamwidth of 100° . For the gain pattern of the main lobe, a model often used in ITU-R studies is used herein as follows:

$$G(\theta) = G_{MB} - 12(\theta/\theta_{3dB})^2$$

where:

- $G(\theta)$: satellite antenna gain (dBi) at off axis angle θ (degrees)
- G_{MB} : satellite antenna main beam gain (dBi)
- θ_{3dB} : satellite antenna -3 dB beamwidth (degrees)

The performance requirements of AIS satellite detection are also significantly different than the terrestrial counterpart. Conventional AIS, like most communications systems, aims to successfully receive and decode most of the associated transmitted messages with moderate to high reliability. For purposes of monitoring ships using satellite detection of AIS, high communications reliability is not required. For ships within a few hundred nautical miles of a coast, updates of the ship locations every hour may be sufficient and for ships further at sea, location updates every four hours or even every twelve hours may be sufficient. As will be shown later, intra-system interference results in the loss of a very large percentage of received AIS ship messages. For example, for a single satellite overpass, up to 99% or more of the AIS ship messages can be lost and the goal of updating ship locations on a regular basis can still be achieved. To achieve ship location updates every 12 h, it is necessary to successfully decode only one of the more than 360 messages received ($\sim 0.3\%$) 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 § 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 (km)	950
Inclination (degrees)	82.5
Period (minutes)	104
Earth footprint	3 281 km radius (at the horizon)
Antenna	
Gain (G_{MB}) (dBi)	6
Beamwidth (θ_{3dB}) (degrees)	100
Pattern	$G_{MB} - 12 (\theta/\theta_{3dB})^2$
Polarization	Near circular
Circular to linear polarization conversion loss (dB)	3
Receiver	
Noise figure at LNA input (dB)	3
Required E_b/N_0 for BER = 10^{-5} (dB)	13 including implementation loss
Line/filter losses prior to LNA (dB)	2.5
Sensitivity at LNA (dBm)	−118 for 1% packet error rate (PER) −120 for 20% PER
Protection ratio (for co-channel, coincident-in-time signals) (dB)	15 for 1% PER 10 for 20% PER
Desired ship location update period	Single satellite overpass, 4 h, and 12 h

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 (degrees)	0
Satellite antenna off-axis angle (degrees)	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 for 20% PER (dBm)	-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°, 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.¹ The curve was developed based on average maritime temperate meteorological and sea state conditions. The resulting lobing structure in the data results from the periodic enhancement and fading of the signal due to in-phase and out-of-phase 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 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's 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.

¹ See <http://flattop.its.blrdoc.gov/if77.html>.

FIGURE 1

Earth-to-satellite propagation loss over sea water at 162 MHz
(Satellite at 950 km altitude)

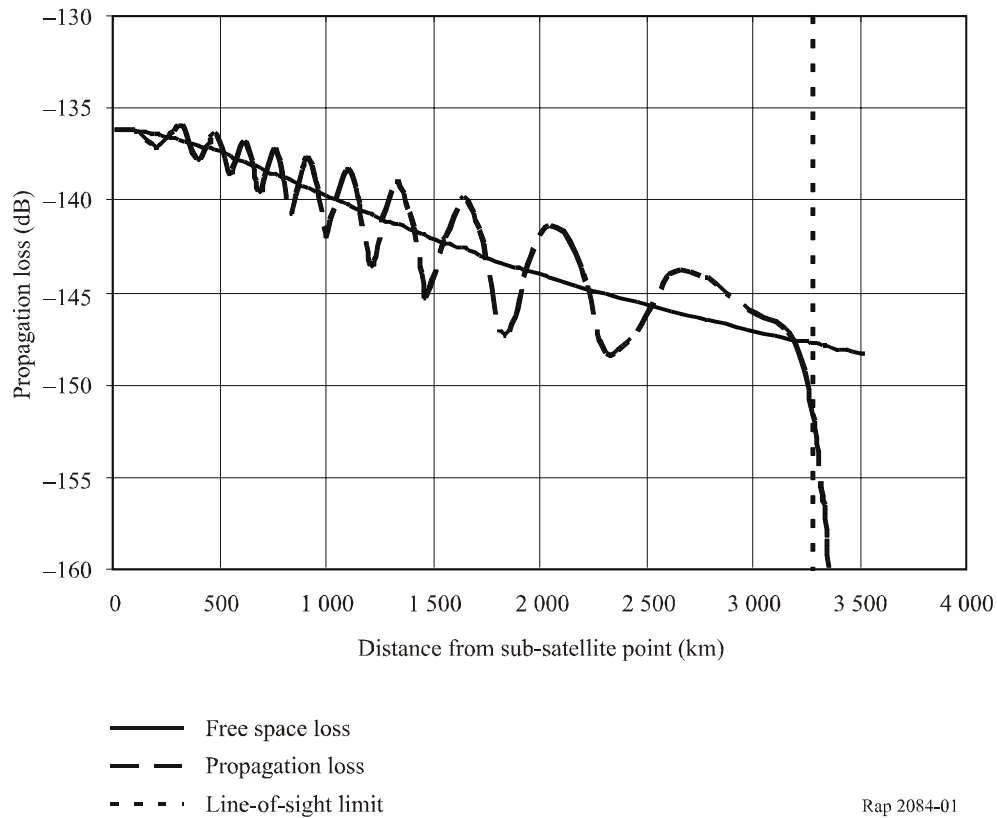
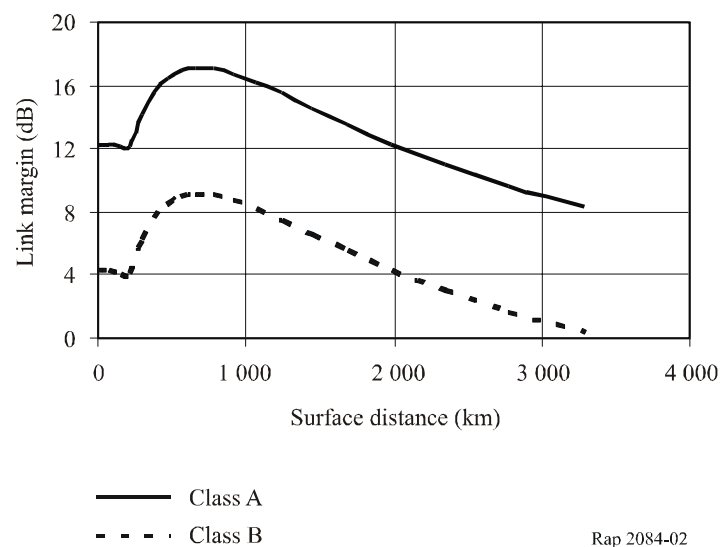


FIGURE 2

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.

5.1 Analytic approach

As previously described, the self-organizing TDMA (SOTDMA) scheme used for AIS assures the coordination of time-slot usage so that minimal time-slot 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, time-slot 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.

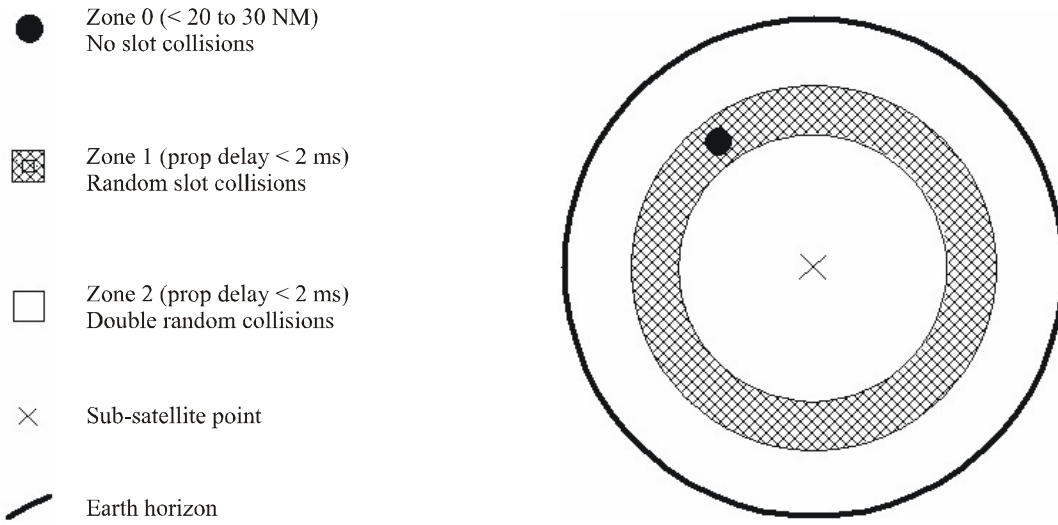
These time-slot collisions can be viewed in terms of a single desired AIS message (D), and one or more undesired AIS messages (U). Whenever a time-slot collision occurs and the aggregate D/U power ratio is less than the required 10 dB, loss of that message will result. Initially considering only Class 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 time-slot 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 time-slot 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 time-slots and the resultant loss of two slots.

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.

FIGURE 3

Illustration of time-slot collision zones



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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:

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

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

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

where:

- $Q_{1,1}$: probability of time-slot 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 (s)
- τ : message length (0.0267 s).

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 s 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:

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

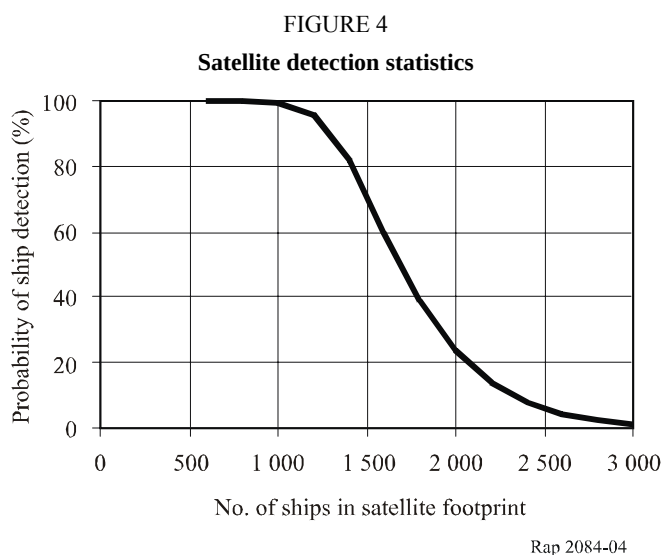
T_{vis} : time period of satellite visibility

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.² Figure 4 gives an example curve for the simple case of a single satellite and single overhead pass of the satellite.



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.

² Hoye, Gudrun K., *et al.* [undated] Space-Based AIS for Global Maritime Traffic Monitoring, Kjeller, Norway: Norwegian Defense Research Establishment (FFI).

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:

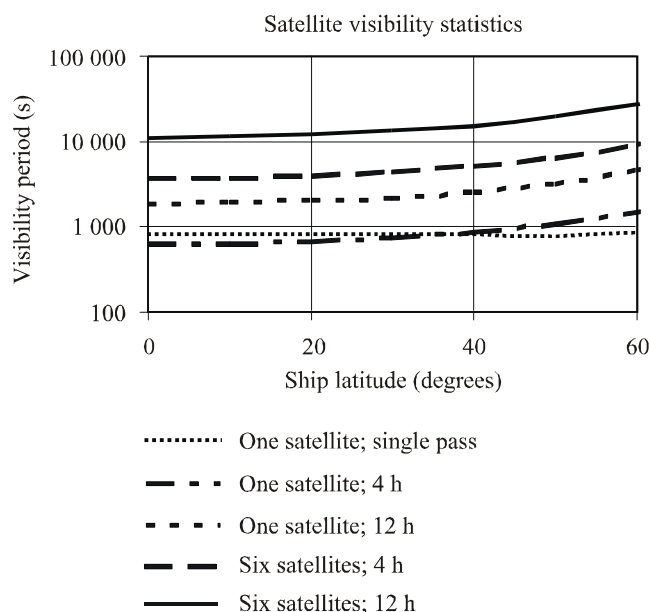
$$P_{All} = (P_{M,N})^N$$

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 min. 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 observation period as shown in Fig. 5.³ Values for a single overhead pass as well as average values over longer extended observation periods of time such as 4 h and 12 h 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)



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³ 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.