NANO-SATTELITE DEMONSTRATION MISSION: THE DETECTION OF MARITIME AIS SIGNALS FROM LOW EARTH ORBIT

SMALL SATELLITE SYSTEMS AND SERVICES SYMPOSIUM

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ABSTRACT

In April 2008, COM DEV Ltd. launched an 8 kg nano-satellite, called NTS, for the purpose of demonstrating the capability of detecting maritime Automatic Identification System (AIS) signals from space. In particular, the experiment was designed to demonstrate that high-performance detections of these signals can be achieved. To date, this satellite has achieved the highest detection rates for AIS ever demonstrated, and, a follow up mission is expected to increase this capability further. This paper discusses the performance of NTS, and the prospects of using satellites such as this for maritime monitoring, environmental protection, safety and data fusion.

1. INTRODUCTION TO AIS

Terrestrial AIS is a signalling system between ships and ships and shore-stations that uses two VHF narrow band (25 kHz) channels at 161.975 MHz and 162.025 MHz. The signal transmitted is a Gaussian Minimum Shift Keying (GMSK) modulated carrier and the use of a Self-Organized Time Division Multiple Access (SOTDMA) protocol. The protocol makes use of short time slots that partition a one-minute 'frame' that allows for up to 4500 time slots per frame to be sent. Fig. 1. shows a schematic of the time division of the two AIS channels, each with 2250 slots of 26.7 ms each. Fig. 2. shows the makeup of messages transmitted in a single slot.

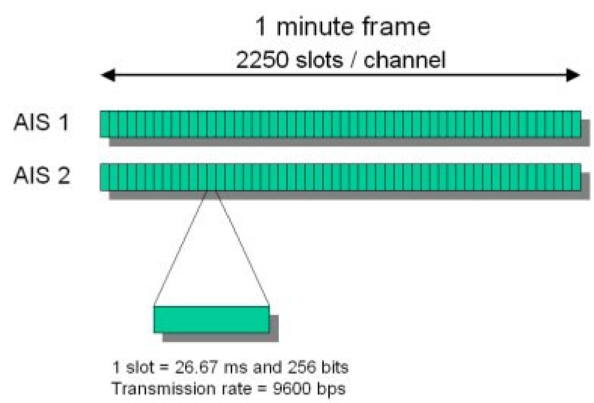

Fig.1. A one minute SOTDMA time frame of AIS messages from the two AIS channels make up a total of 4500 available slots.

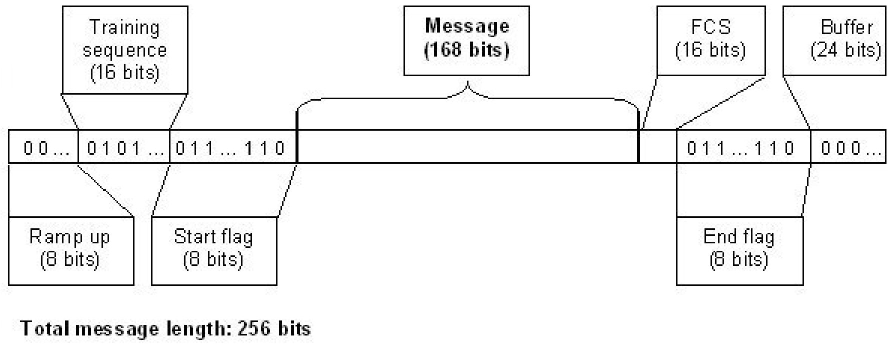

Fig. 2. Each AIS message contains a the message content, automatically transmitted by the ships, as well as housekeeping sections such as start flags, frame check sequence (FCS) and end flags.

Ships alternatively transmit on AIS channel 1 and 2, and the TDMA protocol ensures that no signal transmissions ‘collide’ for the local ‘cell’ of ships. In theory, a large number of ships can be accommodated using this scheme without congestion. The signal transmission range is typically about 50 nautical miles and this characterizes the size of a cell of ships that are self-organized. Ships at distances greater than 50 NM from other ships need not be coordinated using this TDMA protocol, because the time slots can be re-used due to low signal strength from far away ships.

Typical information transmitted on AIS channels includes the ship’s identification, latitude, longitude, speed, heading, course over ground, rate of turn etc. Certain AIS messages include other information such as destination, crew information or cargo. The AIS standard calls up to 26 different AIS message types [1] that contain varied information.

The following parameters summarize/characterize AIS signals as transmitted and received on the surface of the Earth:

- **Centre Frequency**: 161.975 MHz (AIS channel 1), 162.025 MHz (AIS channel 2)
- **Bandwidth**: 25 kHz per channel
- **Power**: 12.5 Watts (Class A), 2.5 Watts (Class B)
- **Transmission Range**: 50 nautical miles radius (i.e. to the horizon)
- **Modulation**: Frequency modulation, GMSK at 9.6 kbps
- **TDMA Frame and Slot**: 1 minute frame timing extracted from GPS signals, 26.7 ms slot (256 bits)
- **Typical Antenna Mounting**: Vertically polarized monopole or dipole antenna mounted at some height above the ship’s deck, typically to a mast.
- **Propagating Energy of Transmission**: Primarily line of sight and along the surface of the Earth (i.e. perpendicular to the antenna).
- **Carrier to Co-channel Interference Ratio Threshold C/I** : 10 dB
- **Typical Maritime AIS Receiver Sensitivity**: -108 dBm for 20% packet error rate

As can be seen from the signal propagation characteristics and ship antenna mounting, because AIS was designed to be a terrestrial system, the radiated energy from the mast-mounted shipboard antennas will propagate primarily along the surface of the earth to other ships and shore stations and not upwards towards satellites in Earth orbit.

2. SPACE-BASED AIS

By receiving AIS messages (designed for terrestrial transmissions) in orbit, a wide-area maritime surveillance would be possible. Even a single satellite receiving AIS could eventually map the world's shipping traffic over time, obtaining new statistical knowledge of the world's shipping

traffic as clearly demonstrated by COM DEV's NTS mission, presented in this paper, which has been in operation for two years.
However, while the demonstration of the utility of AIS has proceeded quite quickly and smoothly, with AIS being used for maritime traffic awareness, collision avoidance and vessel traffic management, the terrestrial AIS network was never designed for signal reception from earth orbit. This has posed some interesting challenges. Any space based AIS receiving system will have some degree of latency due to the orbits of satellites and locations of ground stations at which satellites download the received data. Thus, AIS signals received in orbit are never intended to provide real-time navigational information, but they are still able to provide excellent situational awareness. A LEO satellite will fly over any given area in a time measured in minutes, thus continued monitoring of any particular area is also not possible. These effects must not be seen as short-comings of the system, because as few as 6 satellites can cover every area of the globe with refresh rates of 2 hours typically (in equatorial regions), and much lower rates at the higher latitudes.
An additional complication arises because the self-organized nature of the TDMA signals between ships is lost when view from the vantage point of low earth orbit (LEO). The very large field of view (FOV) of the satellite allows signals from a vast array of SOTMA 'cells' to be received at the satellite receiver, Fig.3.

Fig. 3. The circles show the typical field of view of a LEO satellite.

Thus, the AIS signals that arrive at the satellite consist of multiply collided (overlapped) TDMA time slots from multiple cells. The problem that is faced by space-based AIS systems is how to deal with these overlapping AIS signals. Solution possibilities include narrowing the field of view (requires very large antenna arrays), waiting for statistically random signal messages that do not have overlaps (long observation time required) or attempting to unravel the overlapping messages (difficult algorithms).
The COM DEV / exactEarth AIS nano-satellite experiment, NTS, relies on sophisticated algorithms that attempt to unravel the overlapping messages.

3. SPACE AIS RECEIVER PERFORMANCE

The reception of AIS signals transmitted by the 12.5 watt Class A type transponders on board sea going vessels and from shore base stations has been demonstrated by several companies as well as the US government's TacSat2 mission. That AIS signals might be detected from LEO and thus used for a more global awareness of ship movement was postulated years ago, post September 11 2001, by the US Coast Guard [1], with initial speculation of the possibility dated back perhaps 10 years. In the years since, a few companies and institutions have launched some type of AIS receiver into LEO, including the Naval Research Laboratory, Orbcomm, SpaceQuest, LuxSpace and COM DEV. It is expected that very soon some European AIS receivers and satellites may be tested.
To date, some comparisons have been made between these assets officially and un-officially. COM DEV maintains that NTS out performs all other known space AIS assets.
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Measure of Performance

Several metrics have been considered to characterize the performance of a space AIS receiver. One may try to determine some fraction of Class A AIS transmitting ships that are detected. This procedure is fraught with difficulties primarily because no ground truth exists for the actual number of ships transmitting AIS signals in any particular location, especially ships far out in the oceans, away from ground based receivers. It is proposed here that a better comparison metric is the number of ships detected per unit time, or the number of AIS messages detected per unit time of observation. The messages/unit time counted in this should be the number of verified (frame check verified) messages only, not partial or potential messages.

The global average rate of detection of the NTS nano-satellite is about 15 messages per second. The detection rate can peak at about 35 messages per second in certain areas such as the Atlantic. As the following Table 1. shows, the message rate of (1) a standard terrestrial AIS receiver launched into space, or (2) a modified commercial receiver designed to look at several separate Doppler bands per AIS channel, (3) the NTS demonstration nano satellite and (4) the expected performance of the exactEarth satellite, to be launched shortly, is expected to outperform even NTS.

RECEIVER TYPE	GLOBAL AVERAGE DETECTION RATE (Msg/s)	PEAK DETECTION RATE (Msg/s)
Simple Receiver (1)	2 to 3*	Not tabulated
Complex Receiver (2)	6*	19*
COM DEV NTS (3)	14.8*	35*
exactEarth Satellite (4)	42	TBD

Table 1. Detection rate performance of a simple commercial receiver, a Doppler band commercial receiver, NTS, and the expected performance of an exactEarth satellite. The asterisks indicate measured performance.

The performance of NTS is quite remarkable considering the fact that the nano-satellite is limited to 90 seconds of data acquisition in each capture of AIS signals. NTS downloads raw AIS signal data (I/Q pairs of baseband data) and thus this raw signal can be used to test various receivers and algorithms. This is how the performance of other receivers in Table 1 was determined.
The NTS satellite data is processed using a sophisticated signal processing algorithm designed to untangle messages even from overlapping AIS message slots. The probability of detection is then related to detection rates if a comparison is required to be made between metrics.

The detection probability of a ship depends on a number of factors: (i) how often the ships are transmitting, (ii) the number of ships simultaneously in the field of view (iii) the fraction of the transmitted messages that are actually de-modulated, or detected by the receiver.

The following analysis shows how the probability of detection is related to these factors.

Define:
$N = number\ of\ ships\ in\ FOV$
$r = average\,rate\ of\ ship\ AIS\ transmissions\ (typically\ 10\ per\ minute)$
$T = observation\ time\ interval\ length\ (typically\ 10\ minutes)$
$\gamma =\ prob\ of\ decoding\ a\ message\ at\ satellite\ (fraction\ of\ messages\ extracted)$

Assume that there are *N* ships in the FOV of the satellite. When a message arrives at the satellite, the probability that this message is from a *particular* ship is $\frac{1}{N}$ and the probability that it is <u>*not*</u> from that ship is $1-\frac{1}{N}$. During the observation interval, T, the number of messages arriving at the satellite from all the ships is

$$NumberOfMessages_T = N\ r\ T \tag{1}$$

Thus the probability that, in all these messages, *none* are from that *particular* ship is

$$p = (1-1/N)^{NrT} \tag{2}$$

However, not all of the messages arriving at the satellite are decipherable. That is, only a fraction, γ, of the messages arriving at the satellite are decoded (by either some algorithm or a commercial receiver). Thus effectively, the number of messages arriving at the satellite is reduced by a factor γ and the probability that none of the messages are from that particular ship is

$$p = (1-1/N)^{\gamma NrT} \tag{3}$$

Or equivalently,

$$\ln(p) = \gamma NrT \ln\left(1-\frac{1}{N}\right) \tag{4}$$

For large numbers of ships, $N >> 100$ say, this can be expanded, and to first order

$$\ln(p) = -\gamma NrT\left(\frac{1}{N}+\frac{1}{2N^2}+\ \dots\right) \approx -\gamma rT \tag{5}$$

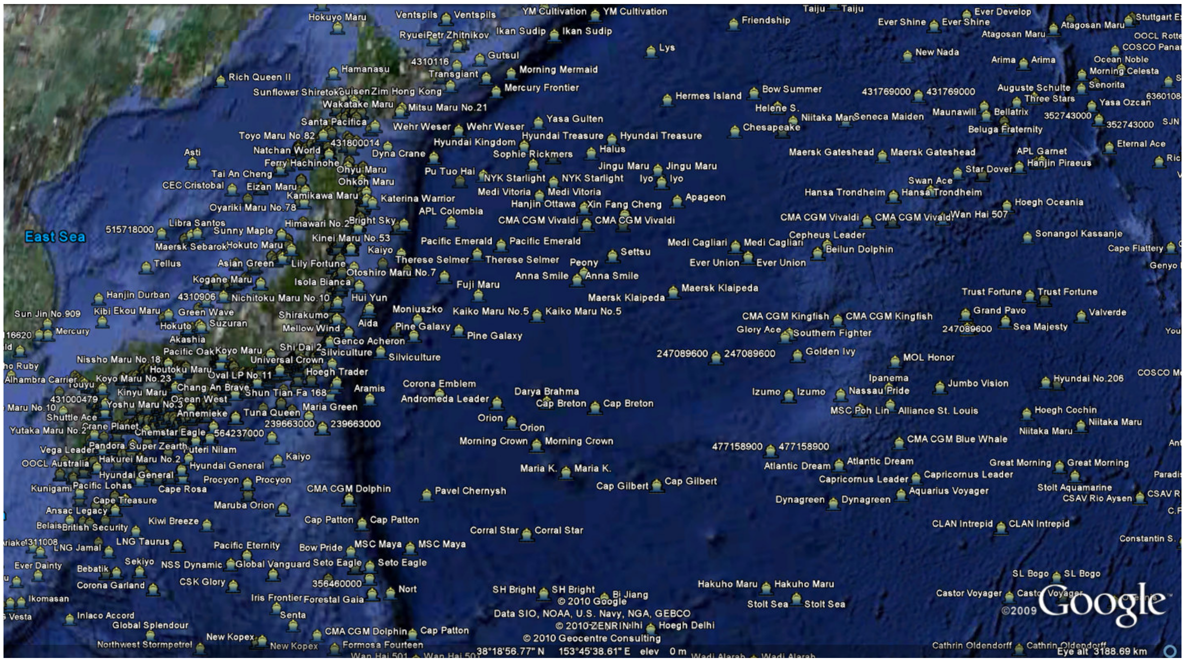
for large values of N (number of ships in FOV).

4. NTS MEASURED DATA RESULTS

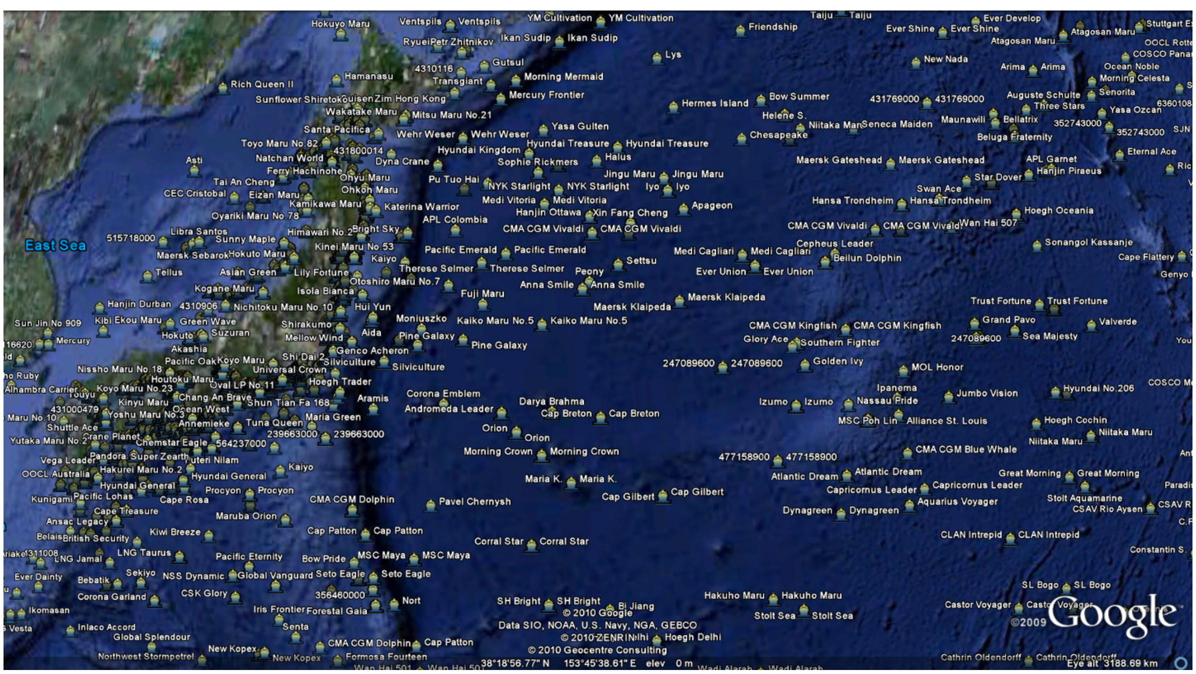
The following data shows detections, in 90 seconds of observation, of ships in various areas of the world. The NTS demonstrator has detected up to 1056 unique ships and over 3400 (verified) AIS messages in a single 90 second data capture. This far exceeds reported results from other space AIS systems.

When the exactEarth versions of a fully operational spacecraft (able to capture full orbit data, not just 90 seconds) are launched in 2010, it is expected that a capability exceeding even NTS will be shown.

<u>Caribbean Sea (90 second observation)</u>

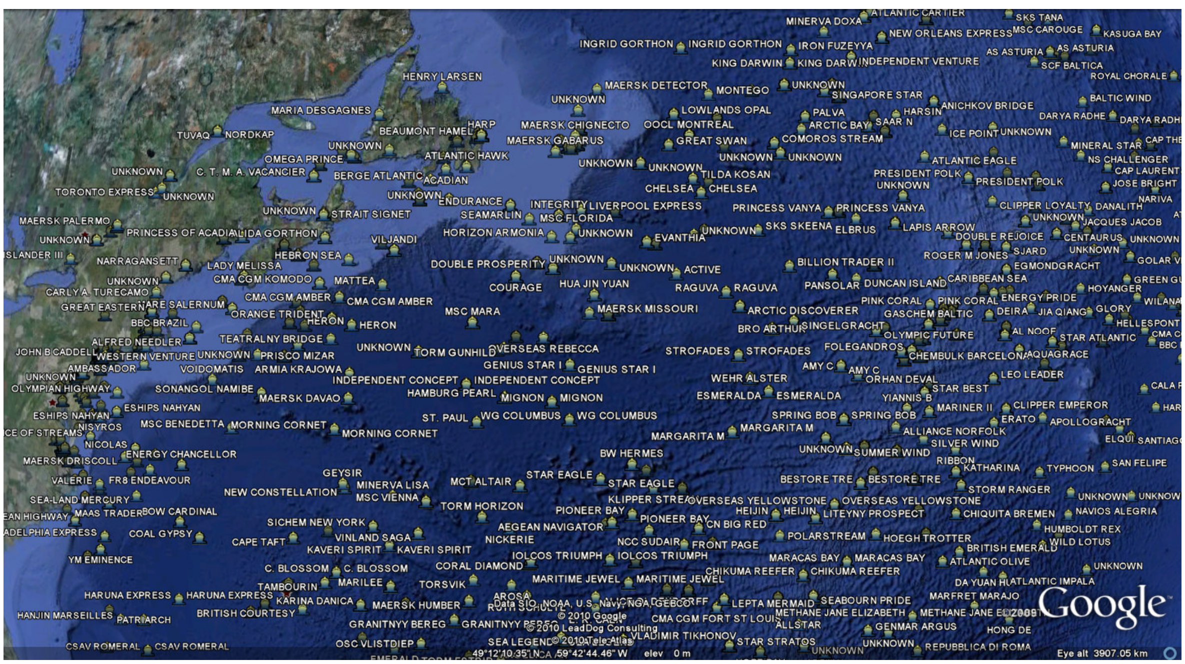


<u>Eastern Japan (90 second observation)</u>



<u>Northern Australia (90 second observation)</u>

Northern Atlantic (90 second observation)



5. REFERENCES

[1] The International Telecommunications Union's, "*Technical Characteristics for a Universal Shipborne Automatic Identification System Using Time Division Multiple Access in the Maritime Mobile Band*", ITU-R Recommendation M.1371-3.