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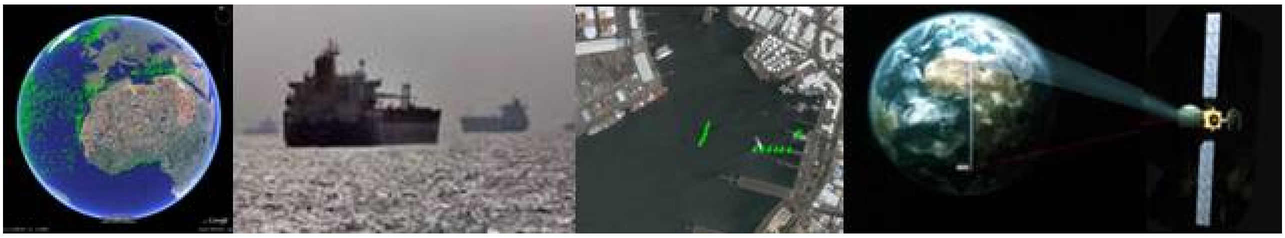

Technical Note TN5: Performance test procedures, methodology, data sources, quality of acquired AIS spaceborne data

Issue 2 August 2010

Preparatory Action for Assessment of the Capacity of Spaceborne Automatic Identification System Receivers to Support EU Maritime Policy

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1B	02.07.2009	LXS	First draft reviewed by MJ, JB and forwarded for review
1C	06.07.2009	LXS	Comments by ComDev included
1D	20.01.2010	LXS	Chapter 5 “Performance indicators” reviewed New Chapter 7 included
1E	19.04.2010	LXS	Correction of Chapter 5.2 formula
2	29.09.2010	LXS	Addition of ComDev method linked to receiver performance

TABLE OF CONTENT

1. SCOPE OF THE DOCUMENT

The Technical Document TN5 aims at describing the procedures and methodology to be applied for assessing the performance of the space-based AIS data as well as those collected during the air borne test campaign of ESA's AIS receiver.

2. APPLICABLE AND REFERENCE DOCUMENTS

RD1	TN 1: PASTA MARE Vessel location data sources: terrestrial and spaceborne AIS data, LRIT
RD2	TN2: PASTA MARE Description of AIS project database
RD3	TN3: PASTA MARE Ship Movement Prediction Simulator description and test results

3. DEFINITIONS AND ACRONYMS

AIS	Automatic Identification System
EMSA	European Maritime Safety Agency
FoV	Field of View
LRIT	Long Range Identification and Tracking
VMS	Vessel Monitoring System

4. INTRODUCTION

One of the key tasks of the PASTA MARE project is the assessment of the performance of space borne AIS receivers in terms of vessel detection probability or detection rate.

The main reason and concern of acting parties regarding the potential of space borne AIS are receiver saturation and message collision, causing that only a fraction of the vessels within the satellites Field of View (FoV) can be detected.

Current technology developments in the AIS receiver design try to overcome this problem. The assessments will show to what extent the new receiver designs have increased performance.

The following chapters provide an overview of the test procedures, test areas and data sources used for the assessment as well as the methodology applied for the analysis.

4.1 SPACE-BORNE AIS SENSORS

The following space based AIS receivers will be used:

- COM DEV NTS 1 (operational)
- Orbcomm - 2 out of 6 satellites are still operational (FM 37 and FM39)
- LuxSpace - Pathfinder 2: attached payload (launched September 2009)
- ISS AIS (COLAIS) switch on scheduled July 2010
- COM DEV exactEarth AOS payload on Resourcesat2 – launching April 2010

A detailed description of the space borne AIS sensors and systems can be found in RD1.

The assessment will first focus on the number of messages detected by each sensor. The greater the number of messages/unit time the greater the detection capability of a sensor. In addition vessels detected can also be used as a performance indicator, though this can be deceiving in areas where the ship traffic is not very dense. This is because in low density areas one can expect that all sensors should perform quite well. The distinction will be the number of messages per individual vessel.

4.2 SHIP REPORTING SYSTEMS USED AS REFERENCES

The availability of validation data is certainly a very critical element of the performance tests. Close to coastlines, ground based AIS data can be used as they provide a comprehensive picture of the vessel traffic on a 24 hours per day basis due to the fact that all messages are captured by a station. Outside the range of the costal AIS stations, LRIT and VMS data will be used as reference information. However, due to the LRIT update frequency of several hours, it might be possible that a ship was crossing the test area but without sending any position report. To fill this gap, it might be necessary to estimate the LRIT tracks form individual ships, in order to obtain a real coverage map.

Superimposing the space borne AIS data with the terrestrial AIS data and the other ship reporting data shall allow a clear statement on the detection rate. As such, it is of major importance to make available as many ground based AIS data as possible for the project.

4.3 SPACEBORNE AIS TEST AREAS

The performance of space borne AIS is largely determined by the number of ships within the satellites footprint. Therefore, the capabilities of the space borne sensors are assessed over several areas with high and low-density vessel traffic. The following test areas are selected for the space borne trials (see Figure 1):

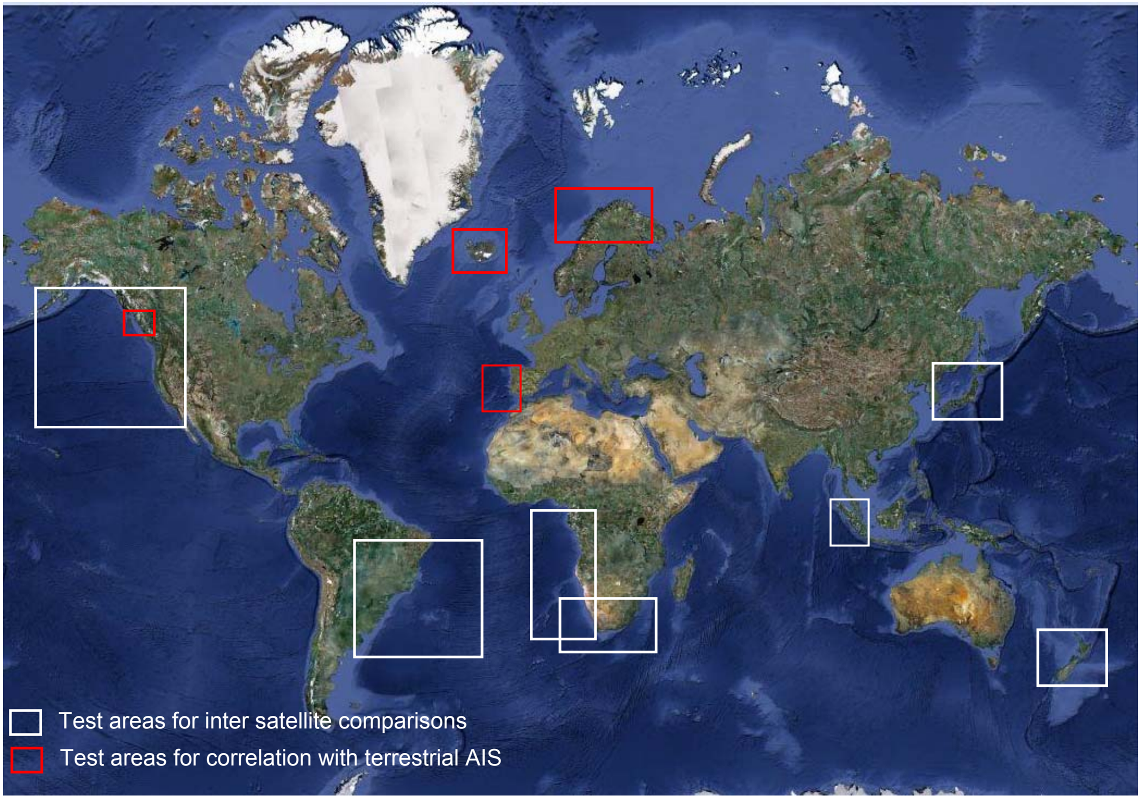


Figure 1: Test areas considered

4.4 DEFINITION OF THE TIME WINDOWS FOR DATA GATHERING

Key requirements for an in depth assessment of the space borne AIS data is to ensure that the AIS receivers capture the AIS messages within the test area at the same point in time. Thus synchronisation of the data capture is essential to enable a sound comparison of the receiver's capabilities. Synchronisation refers to the fact that for a specified geographical region (test area) and time window. AIS data from the various sources needs to be gathered.

Since reference data (LRIT, VMS terrestrial AIS data) will be available for the test regions almost without any time restriction or geographical limitation, the challenge is to synchronise the Field of Views of the various space borne AIS systems and the test areas.

Using the two line elements, the AIS satellite orbits and path will be simulated and the common FoV for a given target region can be determined. The simulation also enables to determine the time interval in which both satellites “see” the target area, i.e. the satellites FoV enters and leaves the test areas.

For this time interval, corresponding to a few minutes, the space borne AIS and the reference data will be collected.

The following maps show some examples of a common FoV of ComDev NTS1 (CANX6), Orbcomm AIS constellation and the ISS on which the LuxSpace COLAIS will be flying.

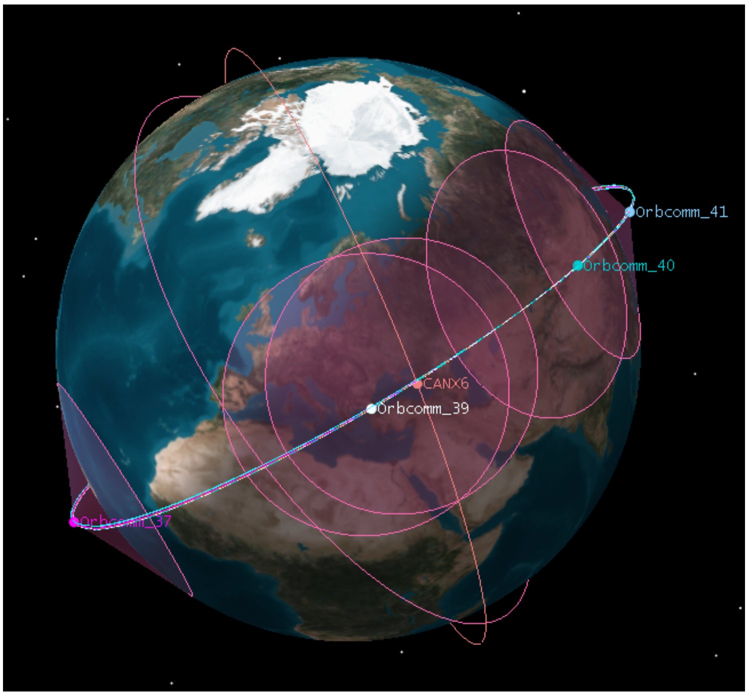


Figure 2: Common FoV Orbcomm 38 and CANX6 over the Mediterranean Sea

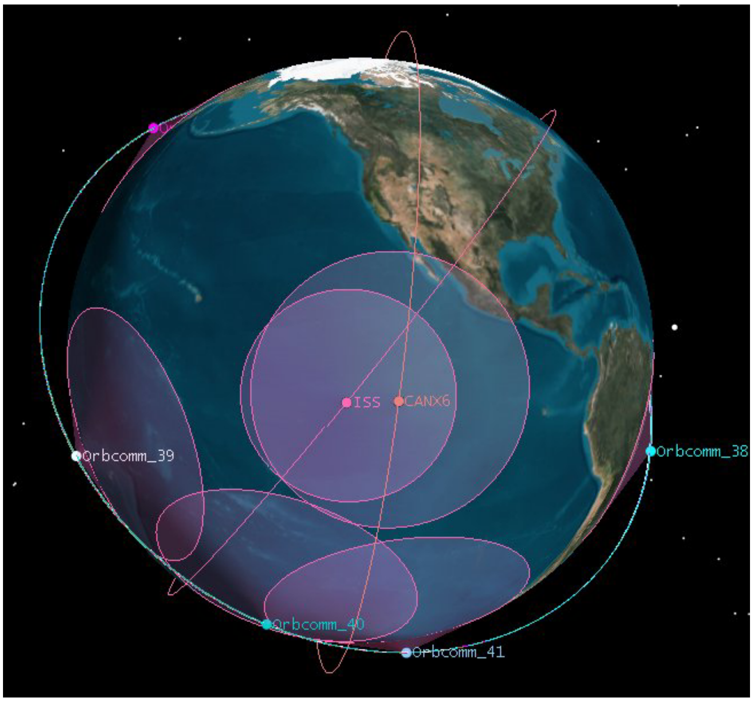


Figure 3: Common FoV ISS and CANX6 over the Pacific

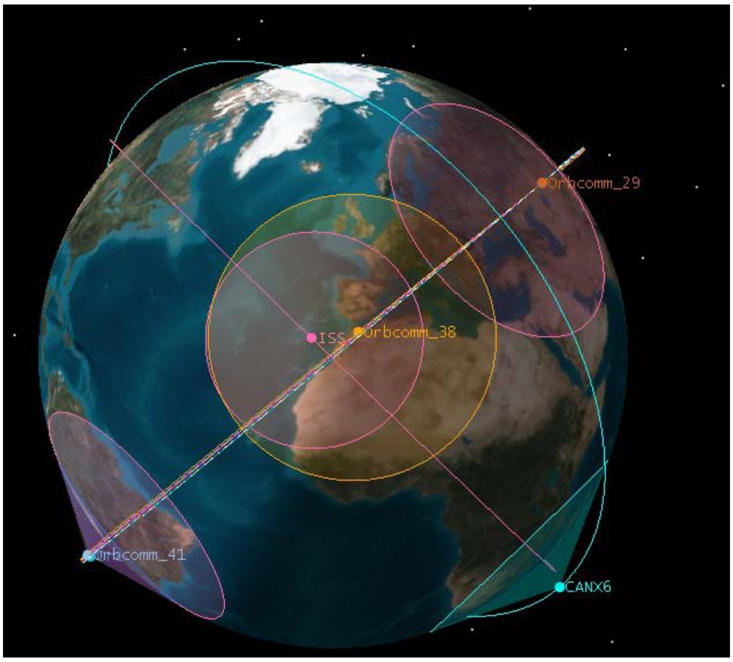


Figure 4: Common FoV ISS and Orbcomm 38 over the Atlantic

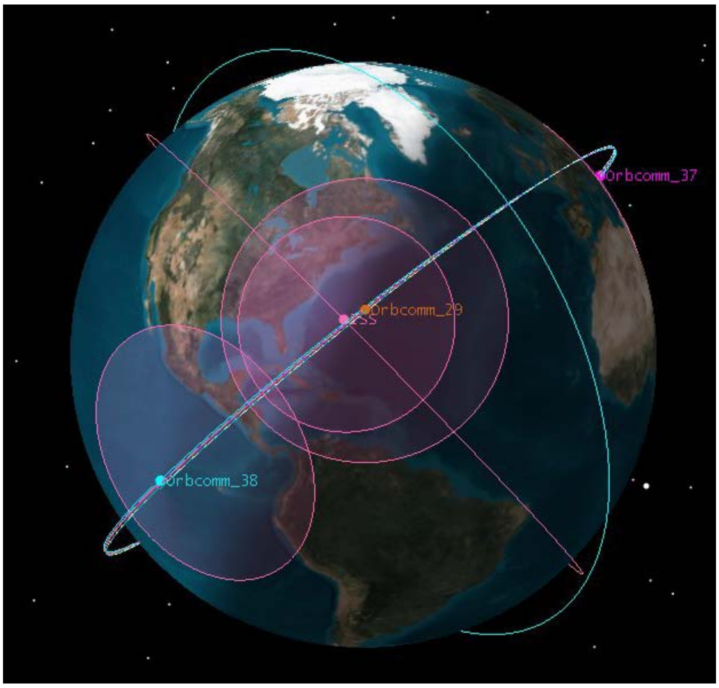


Figure 5: Common FoV ISS and Orbcomm 29 over the Atlantic

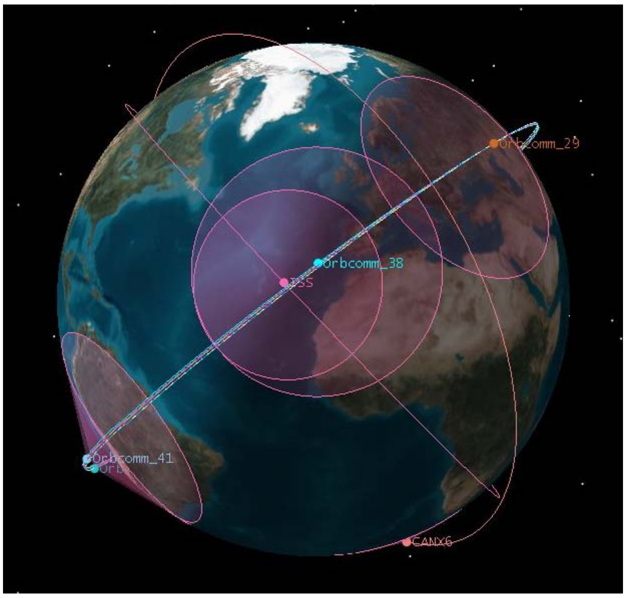


Figure 6: Common FoV Orbcomm 38 and ISS over the Atlantic

5. PERFORMANCE INDICATORS

The assessment of space based AIS requires a set of meaningful and robust performance indictors. In the following the basic metrics are given from which performance indicators can be derived:

5.1 BASIC INFORMATION DERIVED:

For each AIS data capture the following database queries are performed:

- Number of messages AIS [receiver 1] [receiver 2][receiver3]
- Total number of MMSIs identified by the receiver. This total number is composed of
  - unique MMSIs (ships), i.e. vessels identified only by the sensor concerned and not by one of the two others
  - MMSIs identified also by one of the other two receivers
  - MMSIs identified by the other three receivers.

S- AIS system	**Total N° of vessels identified by**		**PF2**	**FM39**	**NTS1**	**Vessels identified by all three sensors**
PF2	154	Out of which seen…	**30** only by PF2	**16** also by FM39	**58** also by NTS1	**50** also identified by FM39 and NTS1
FM39	225	Out of which seen…	**16** also by PF2	**77** only by FM39	**82** also by NTS1	**50** also identified by PF2 and NTS1
NTS1	284	Out of which seen…	**58** also by PF2	**82** also by FM39	**94** only by NTS1	**50** also identified by FM39 and PF2

Table 1: Example of a detection matrix for three AIS receivers

5.2 ESTIMATION OF NUMBER OF SHIPS IN THE COVERAGE AREA

Since reference data (such as terrestrial data) do not exist for most of the open sea areas, the reference values need to be estimated.

The following statistical formula is applied, using the information from up to three sensors, which captured the AIS data from an identical geographical region at the same point in time.

The general formulae to estimate the number of ship in the region ***A*** is given with:

$$\left[\left(\sum_{i=1}^{M} N_i\right) - M\right] N^{M-1} - N^{M-2} \sum_{i,j=1;i<j}^{M} N_i N_j + N^{M-3} \sum_{i,j,k=1;i<j<k}^{M} N_i N_j N_k - ....+ (-1)^{M-1} \prod_{i=1}^{M} N_i = 0$$

N = estimated number of ships (MMSI's) within coverage area

N_i = N° of MMSI's detected by receiver i

M = N° of MMSI's detected by the M receivers (MMSI detected by the M receivers without counting them twice if detected by at least two receivers).

One could easily retrieve the equations given above in the case of two or three receivers from this general equation.

This linear equation must be solved to find the number of ships N in the observed region. Indeed, solving this equation could lead to N positive real values, but the solution shall be taken so that the estimated value of N being greater or equal to M. It has been observed that this criterion is sufficient to have just a unique solution to that problem.

Two sensors:

In the case where there are just two sensors, the following formulae giving the estimation of the number of ship in the coverage area is reduced to:

$$N = \frac{N_1 * N_2}{N_1 + N_2 - M}$$

N = estimated number of ships (MMS's) within coverage area

N_i = N° of MMSIs detected by receiver i

M = N° of MMS's detected by the M receivers (MMSI detected by the M receivers without counting them twice if detected by at least two receivers).

Three sensors:

$$N = \frac{\left(N_1 * N_2 + N_1 * N_3 + N_2 * N_3\right) + \sqrt{\Delta}}{\left[2 * \left(N_1 + N_2 + N_3 - M\right)\right]}$$

N = estimated number of ships (MMSI's) within coverage area

N1 = N° of MMSI's detected by receiver 1

N2 = N° of MMSI's detected by receiver 2

N3 = N° of MMSI's detected by receiver 3

$$\Delta = \left(N_1 * N_2 + N_1 * N_3 + N_2 * N_3\right)^2 - 4 N_1 * N_2 * N_3 \left(N_1 + N_2 + N_3 - M\right)$$

M = N° of MMSI's detected by the three receivers (MMSI detected by the three receivers without counting them twice if detected with at least two receivers)

The estimation is based on the following assumptions:

- The three (or two) receivers have the same area in their Field of View (FOV) within a narrow time window, so that a stable number of ships can be considered inside the region concerned.
- The three (or two) receivers should detect a valid number of MMSI with respect to the number of ships inside the area.
- The area shouldn't be so big in order to avoid not having an homogeneous estimation of the detection probability in the area.

The precision of the estimates largely depend on two factors:

- The number of AIS receivers (as independent sample). In general, the more data from different receivers are included, the better the estimates are.
- The number of individual vessels identified by each AIS receiver.

5.3 PROBABILITY OF DETECTION

In order to assess and to compare the performances of different AIS receivers, the term Probability of detection (PoD) will be used to define at a certain time t_0 (or range of time T_0) and for a given area A_0 in the FoV of the satellite, the ratio between the number of ships detected by the receiver in the region A_0 and the total number of ships that were in A_0 at t_0 (or T_0).

$$PoD_i = \frac{N_i}{N}$$

- *PoDi = Probability of Detection of Receiver i in %*

- *N = estimated number of ships within coverage area*
- *Ni = N° of MMSI's detected by receiver i*

Limitations, meaningfulness

Although the absolute number of ships can be estimated with certain reliability, the real number of ships remains unknown. Thus the might be derived PoD biased.

Moreover the estimated Number of ships and the derived PoD depends on the common share of vessels identified by the two (or) three sensors. The higher the share of commonly identified vessels, the higher the PoD.

Considering the above mentioned specific features the estimates and the of the calculation of the PoD, the derived probability of detection is just a "relative" measure. It just allows the performance comparison of two (or three) AIS receiver in relative terms and no "absolute" assessment.

Discussion

Strictly speaking, the probability of detection (PoD) of a satellite AIS receiver should be a constant value that is independent of the time and of the area in the field of view (FoV) of the satellite during a normal operational mode of the satellite.

The PoD should be given as a function of a certain time (or interval of time) and of the region (or part of the region) in the field of view of the satellite as $PoD(T_0,A_0)$ where $T_0 = [t_1\ t_2]$, $t_1 \leq t_2$.

Within this definition of the PoD, the problem is to estimate the total number of ships that were in A_0 at T_0. Since there is not some reference data that can provide this value, a method based on statistics assuming that at least two independent sensors are looking the same region at the same time have been developed in order to have an estimation of that value. Of course, in the real world, it may not or rarely happen that two receivers have the same region in their FoV at the same time; however since the ship are moving quite slowly with respect to the satellite, likely having two satellite crossing (having the region in their FoV) the same region in a range of time of few hours (less than 3 hours) could be considered as if they cross the region at the same time. Indeed, the number of ships in a given region could be taken as constant (quite realistic) in a range of time of few hours (less than 3 hours). So it is very realistic to apply that method for two receivers that have crossed the same region in a range of few hours.

This method of estimation of the total number of ships is working very well on low and medium density areas (density here in terms of the numbers of ships in the area) when the two (or more) sensors have detected in common a quite high number of ships. In the case of high density areas or when the different sensors don't have a high number of ships detected in common, this method of estimating the total number of ships in the area A_0 is not performing well anymore.

5.4 NUMBER OF MESSAGES

In general, the ability to detect ships is completely dependent on the ability of the sensor to correctly detect and decode messages. The number of messages decoded in a given time interval, or, plotted as a function of time is therefore another important indication of performance, particularly for the comparison of sensors with each other even if the number of ships detected is identical.

Depending on the type of data (derived vessel location data or AIS messages) made available by the space borne AIS operators, the analysis will be extended to the messages received, using the identical set of indicators. Using the AIS messages instead of the derived ship position would be an additional and robust measurement of the sensitivity of the receiver. Indeed, being able to assess the average number of messages received by a sensor in a given area is also a good indicator of the performance of the sensor. This is quite interesting if compare to the theoretical number of messages that should have been received by the sensor, assuming that the sensor is able to receive all the messages emitted by the ships he has detected. This theoretical value of the number of messages expected could be calculate taking into account the parameters of the ships inside the AIS messages received (the speed, the fact that the ship is changing course or not and the navigational status of the ship) .

Pathfinder 2 and NTS1 are the only receivers capturing all messages transmitted by a vessel during a path. The Orbcomm AIS receiver filter the received AIS messages and retain only one single message from a vessel.

6. OVERVIEW OF THE METHODOLOGY FOR ASSESSING SPACE BORNE AIS PERFORMANCE

The following section provides an overview of the methodological steps to be followed for each test area and space borne AIS sensor aiming at assessing space borne AIS receiver capacity.

- **Test area and time window specification**

As outlined in chapter 4.3 and 4.4 the definition of the test areas as well as the specification of the required time window for data capturing is essential. The steps are the following:

1. Selection of the geographical extent of the test area
2. Simulation of the satellite paths and the common FoV

3. Derivation of the corresponding time window
4. Refinement of geographical test areas

- **Data Gathering**

5. Reference data: Gathering of corresponding terrestrial AIS, LRIT and VMS data through EMSA database
6. Test data: Collection of space borne AIS data directly put at disposal by AIS data owners

- **Data Storage and Pre-Processing**

7. Database query and selection of all ships within the specified test area and time interval
8. Data quality control of space borne AIS data, regarding completeness and content

- **Data Analysis**

After the data pre-processing, the computation of the performance indicators presents the final step:

9. Cross-correlation of reference data set with space borne AIS
10. Computation of performance indicators and creation of performance matrices.
11. Interpretation of the results

7. ALTERNATIVE APPROACH FOR THE ESTIMATION OF THE PROBABILITY OF DETECTION BASED ON THE OBSERVATION OF ONE SENSOR

7.1 INTRODUCTION

Considering the difficulties to obtain sufficient AIS data for estimating the real number of ships, related to the estimation or the lack of other reference sources, an alternative approach is currently under development.

The approach is based only on the number of messages received for each vessel during the satellites overpass. The idea is still under development and is not yet totally completed or validated in term of assumptions and limitations of that method. However, the main idea is presented.

Let’s assume that just the receiver1 is concerned.

- *N1 is the number of MMSI detected by receiver 1 over the covered area*
- *Lets define with k(i) the number of messages received from the ship i with (1 ≤ i ≤N1)*
- *Message(m) is giving the number of ships, on which m messages were received (1≤ m ≤ mMax, where mMax is the maximum number of messages received from one ship)*

Then by plotting the function Message(m) with respect to m, the distribution of the number of ships that emitted m messages is obtained. So if a good extrapolation is done to find the value of that distribution for m=0, then it will give an estimation of the number of ships, that were on the coverage area and that have not been detected since no message (m=0) from those ship has been detected by the receiver.

Let’s call Nnd the estimation of the number of ship non detected obtained by this way. So the total number of ship estimated in the area is N = N1 + Nnd and the probability of detection of that receiver is calculated as in the previous section:

P(D1) = 100*N1/N

7.2 APPLICATION AND COMPARISON OF THE TWO METHODS OVER THE SOUTH AFRICA REGION

The two methods of estimating the total number of ships in a coverage area have been applied on the same region: The South Africa (SA) region. The region taken for the study is delimited in term of Longitude and Latitude with the following border:

Longitude Max	40
Longitude Min	-15
Latitude Max	-4
Latitude Min	-60

For the first method, we had three AIS sensors:

- PathFinder2 (PF2)
- Obrcomm 39 (FM39) and Orbcomm 37 (FM37)

The three sensors cross the coverage region selected within two hours, so it is valuable to consider that this region were unchanged in terms of density or number of ship inside the region. The following table summarizes the number of ship and messages, received by each receiver and is giving the probability of detection of each one based on the method previously detailed with three sensors.

Sensors	MMSI Detected	Estimation of MMSI Non Detected	Probability of Detection (%)
PF2	613	337	64.5
FM39	410	540	43.1
FM37	369	581	38.8

The total number of ships estimated over the coverage area with this method is N=950 ships

The second method of estimating the probability of detection based on just one sensors and the number of messages received from each ship is used just for PF2. Indeed, the Orbcomm AIS data are received so that the user's can just know if a ship were detected or not, but don't have access to the different messages emitted by one ship.

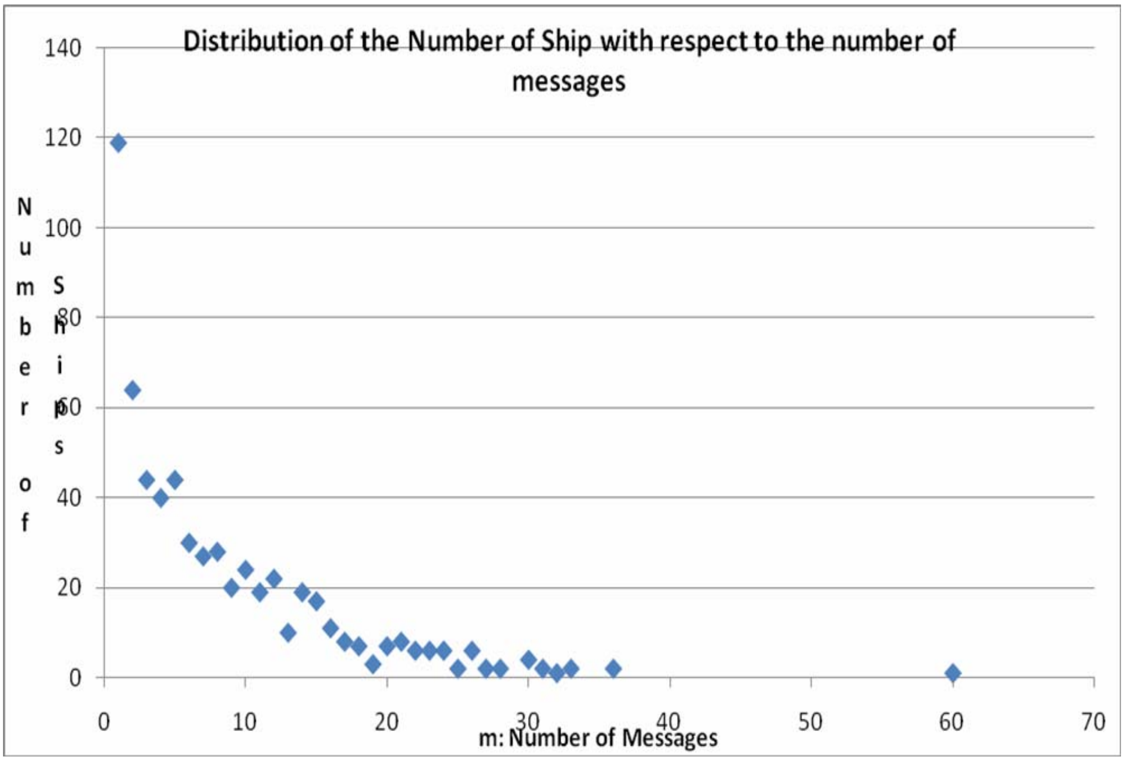
So with PF2, for the same acquisition pass, there were 613 ships detected from which we received 4847 AIS messages. The function Message(m) is summarized over the following table, giving the number of ship from which m messages were received.

N° of messages received	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

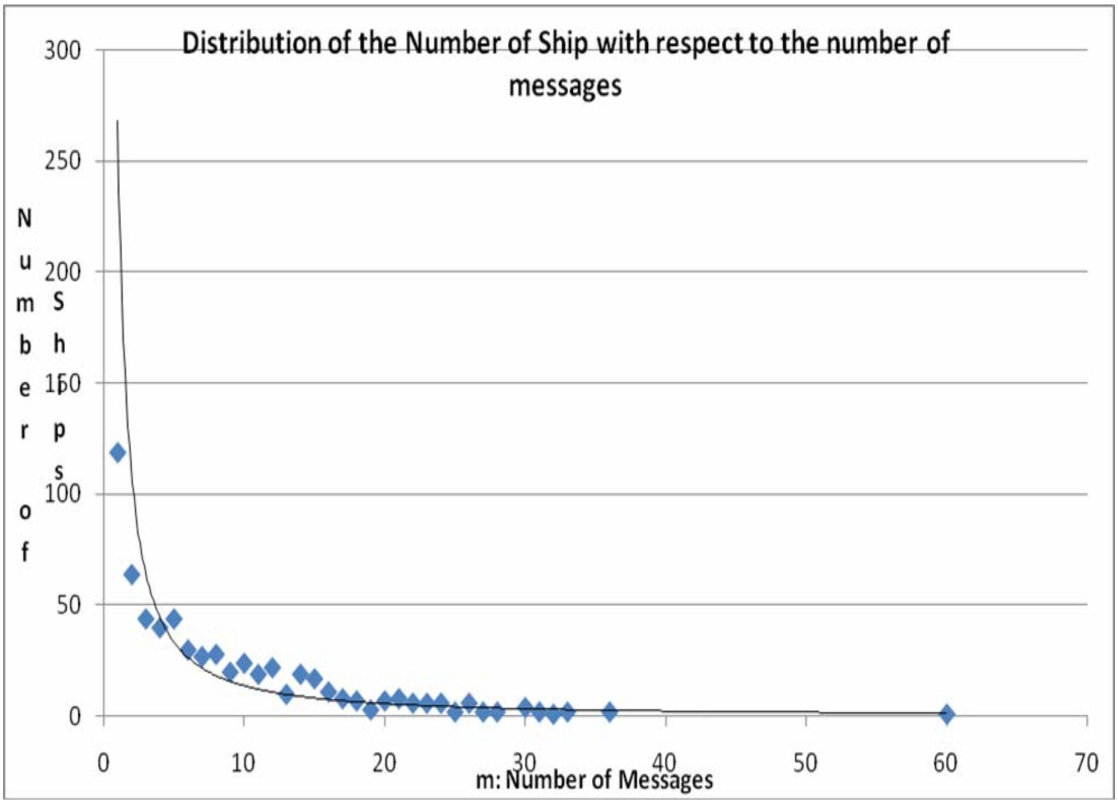
N° of ships	119	64	44	40	44	30	27	28	20	24	19	22	10	19	17	11	8

N° of messages received	18	19	20	21	22	23	24	25	26	27	28	30	31	32	33	36	60
N° of ships	7	3	7	8	6	6	6	2	6	2	2	4	2	1	2	2	1

From this table, we plot the representation of Message(m) with respect to m as shown below:



Later an extrapolation based on polynomial function is done and we obtained an approximation as the following one:



This polynomial approximation of the distribution is done up to the order 15 and we found that for that order we had over 293 ships that were not detected, meaning that with this method N = 906 and the probability of detection of PF2 is estimated to 67.7%.

The comparison of estimation of the number of ships with the two method over the coverage area is given below:

	Method1	Method2
MMSI Detected	613	613
Estimation of MMSI Non Detected	337	293
Estimation of the number of ship in the area	950	906
Detection Probability (%)	64.5	67.7

7.3 RESULTS

The second method seems to have results close of the first one that is more probabilistic based with clear assumptions. For the second methods, further tests over other regions showed unfortunately no significant correlation. Therefore the approach was not further developed.

8. SPECIFIC MEASUREMENT METHODS FOR DETERMINING RECEIVER PERFORMANCE DEVELOPED BY COMDEV

One of the fundamental issues in any assessment of receiver performance is the method used for the comparison. The ‘probability of detection’ methodology used in the analysis is one method but other methods are available and each has relative strengths. A method based on the number of messages received per second is the preferred method of COM DEV and is explained below.

8.1 PROBABILITY OF DETECTION OF SHIPS FROM AIS RECEIVERS

Definition: In general, the “probability of detection” depends on the total number of messages received from all the ships in the field of view in a given time interval. The greater the number of messages received, the higher the probability of detecting any particular ship. To understand “probability of detection” imagine the following: an imaginary ‘outside’ observer, having full ground truth knowledge of all the ships in the field of view (FOV), points to one particular ship at random and asks the following question: What is the probability of detecting this ship? This is the context of “probability of detection” being discussed below. If the answer to the question is 90%, this means that there is a 90% probability of detecting any particular ship in the field of view.

The following analysis makes use of the following concepts and definitions:

$N = \mathit{actual\ number\ of\ ships\ in\ FOV}$

$r = \mathit{average\ rate\ of\ ship\ AIS\ transmissions\ (typically\ 10\ per\ minute)}$

$T = \mathit{observation\ time\ interval\ length\ (typically\ 10\ minutes\ for\ a\ satellite)}$

$$\gamma = \text{probability of decoding a message arriving at satellite (fraction of messages extracted /decoded) this is a measure of a decoding systems performance}$$

Assume a scenario where there are *N* ships in the FOV of the satellite (or airborne receiver). When one message arrives at the aircraft or satellite, the probability that this message is from a *particular* ship is $\frac{1}{N}$ and the probability that it is *not* from that particular ship is $1-\frac{1}{N}$.

During the observation interval, T, the number of messages arriving at the satellite from all the ships is

$$NumberOfMessages_T = N\,r\,T$$

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

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

However, not all of the messages arriving at the aircraft or satellite are decipherable due to message collisions/overlaps or other transmission errors such as fading or noise. That is, only some fraction, γ, of the messages arriving at the aircraft or satellite can be decoded (by either some algorithm or special receiver). Thus effectively, we can consider that 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

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

Or, taking the log of both sides to bring out the exponent,

$$\ln(p) = \gamma NrT \ln(1-\frac{1}{N})$$

For large numbers of ships, *N* >> 100 say so that 1/*N* is much smaller than 1, this can be expanded, and to first order

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

Which is true for large values of N

Thus, inverting the last equation, the *probability of **not** detecting a particular ship* is

$$p \approx e^{-\gamma rT}$$

And the *probability of detecting* ***any*** *particular ship* is

$$P \approx 1 - e^{-\gamma r T}$$

WHAT THIS IMPLIES FOR COMPARING PERFORMANCE

If there are multiple receivers that can view the same geographic region (for example two different receivers onboard the same aircraft), each having observation time *T*, then the probability of detecting any particular ship becomes

$$P \approx 1 - e^{-\gamma r T}$$

The factor γ, which is the effective rate of deciphering (de-collision, or demodulating messages) is the only differentiator between the multiple AIS receiver systems, all other parameters being equal for any airborne experiment. *This is a critical result*. While systems may be compared by attempting to determine ***P*** by some other indirect means and comparing, in reality, a direct comparison is available by comparing γ for the different systems. This is the rate at which messages are extracted in any given time interval.

It should be noted that using γ as the comparison parameter automatically takes into account the performance changes of differing receivers as the number of ships in the FOV changes. As the number of ships in the FOV increase γ will decrease and as the number of ships in the FOV decreases, γ will increase towards the value of 1. But as long as both receivers are observing the same area, they can be compared. In fact they may be compared even if observation time intervals are different for each receiver since only the detection *rate* is being compared.

COM DEV proposes using γ normalized over an interval of *T* = 1 second to compare receiver performance. This is especially true for aircraft trials where a given ship will be in view for a much longer period of time than would be for a satellite. In the aircraft case, the probability of detection will be very high, simply because a ship will be in view for a long time (~ 1 hour). Thus using P as a comparison parameter will not give useful comparisons of receivers, since all receivers will produce similar results. To compare performance and be able to usefully project to performance in orbit, the comparison parameter should be γ.

8.2 COM DEV AIRCRAFT TRIAL EXPERIENCE

COM DEV has further evidence of the utility of this method. During a campaign of flight trials conducted by COM DEV, an aircraft (Falcon D20) was flown from Ottawa, Ontario to Halifax, Nova Scotia. AIS base-stations gathered data along the way through the St. Lawrence River system and along the east coast near Nova Scotia. On board the aircraft, COM DEV flew both a standard commercial AIS receiver and COM DEV's own AIS receiving system. At the end of the trial, the data from the commercial receiver, the COM DEV receiver and the ground station data was compared.

All three data sets showed the same number of ships detected. However, the COM DEV receiver detected a larger number of messages during the same time interval. That is, a comparison only of number of ships detected would have been a fruitless exercise; this is due to the large timescale involved in detecting the ships (~1 hour). It is obvious why all receivers detected all ships: this is because of the large time allowed for observation. The true distinction between receiver performance can only be seen by comparing the message detection rate (messages/second). This detection rate (messages/second) is a far superior indicator of performance in orbit, where the observation time would be only a few minutes, not hours.