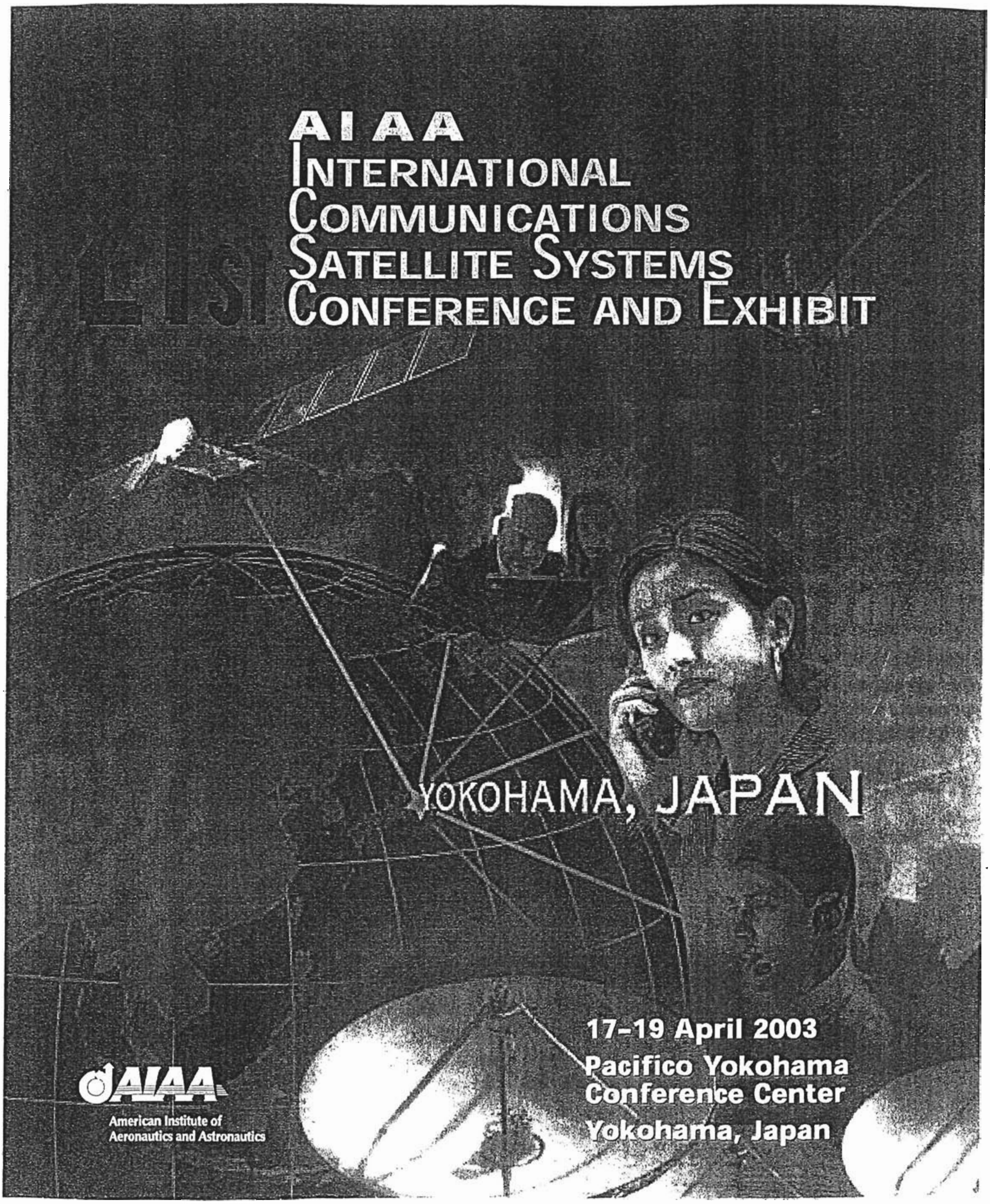
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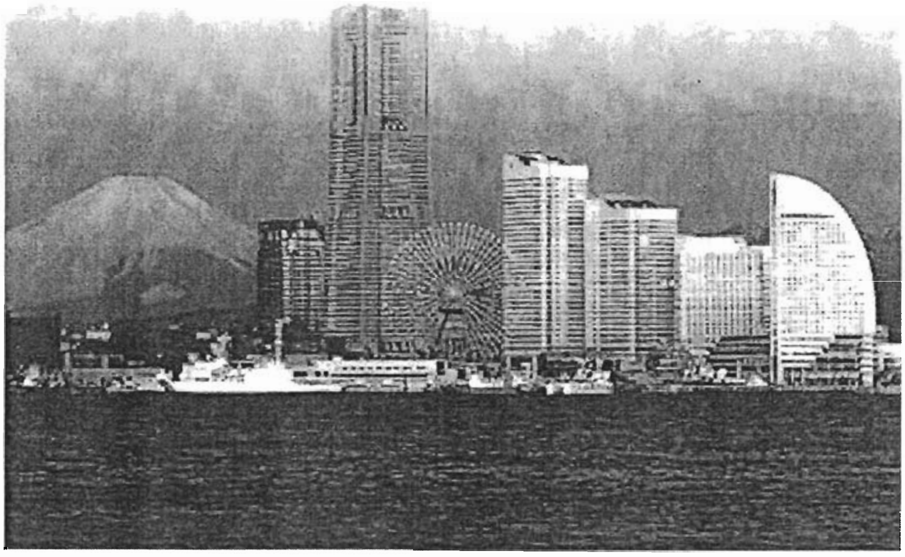

Date: April 15-19, 2003

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THE MOBILITY PROJECT – PROVIDING DVB-S SERVICES ON THE MOVE

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ABSTRACT

The MOBILITY project (Mobile real time TV via satellite systems) aims at the provision of DVB-S services for mobile receivers. In the framework of this project, a novel antenna design was developed allowing a hybrid (mechanical and electronic) pointing, acquisition and tracking (PAT) approach. Trials in a maritime scenario have been carried out onboard a passenger ferry to prove the viability of the MOBILITY concept. This contribution presents the peculiarities regarding the antenna and PAT system design. Further, the trials results and the collected data will be discussed.

The paper is organised in three parts: an introduction to the MOBILITY project, a detailed description of the antenna development and design and the PAT system.

INTRODUCTION

Following the action line "Integrated Satellite Services and Systems" of the European 5th IST Framework Programme, the MOBILITY project aims at the provision of live DVB-S services to people on the move for cases in which a satellite will be the adequate solution (in particular the maritime scenario). The expected impact of the project is the availability of DVB-S services (video, audio, data) in maritime vehicles with similar quality as known from a static environment and the establishment of a road map for the practical implementation of a fully operational European system for digital satellite TV provision for maritime mobiles.

The key technology point is based on the receiving user terminal. It is fundamental to provide an innovative solution for the mobile scenario, irrespective of the vehicle's trajectory and movement.

The main difference between fixed and mobile reception is that the outdoor unit must be based on an antenna with dynamic pointing towards the satellite providing the signal.

There are two main technological challenges that must be given deep consideration:

One is the antenna system for the reception in Ku band and vertical polarisation and the other one is the pointing acquisition and tracking system, which allows to find the satellite position and track it independent of the motion and changing geographical position of the vehicle.

The project was focused on the development of these systems during a total duration of 24 months under the European Commission (EC) figure of "Specific Target Research & Development Project". That supposed the starting point for a line of works addressed to the design of a DVB-S/DVB-RCS bi-directional system. Once closed the project, the return channel technology could be developed under any other EC tool.

DVB-S implies not only video broadcasting, but also multimedia broadcasting and multicasting, allowing in this way the provision of unidirectional and quasi-interactive IP services (based on caching technologies, for instance). The MOBILITY system implies just the downlink from the satellite and, hence, the satellite EIRP and the mobile antenna G/T are the determinant parameters of the link, and as a consequence, they have been the reference of our system.

MOBILITY project has defined two different scenarios for the particular case of ships taking into account the range of angles covered by the ship's motions. For specific sea conditions, small vessels are more affected in motion range than bigger ones. So, yachts and ferries scenarios were defined by different ranges for pitch, roll and yaw motions.

Antenna and PAT were developed in parallel and after their conclusion the integration phase covered exhaustive tests in laboratory.

The viability of the technical approach developed and realised in the MOBILITY project was proven during trials and demonstrations in the maritime scenario. For this, the equipment was mounted on a passenger ferry serving a route in the eastern Atlantic (between Cádiz and the Canary Islands).

ANTENNA SYSTEM

The antenna system has been designed and developed at T.T.I. laboratories. The main challenges and requirements of the antenna system were the following:

- Wide band: 10.7 – 12.7GHz.
- High G/T >14dB/°K.
- Agile and dynamic beam pointing and polarisation matching by means of a hybrid electronic-mechanical system according to the ships motion. Pointing and polarisation losses lower than 1dB.
- Narrow main beam and low secondary lobes to avoid interference from other satellites.
- Wide electronic scanning range >40°.

In some points the final performance of the antenna has been significantly better than the initial requirements (e.g. electronic scanning range).

The antenna system comprises three main parts:

- the planar array,
- the antenna platform,
- the control system.

They are described in the following sections.

PHASED ARRAY ANTENNA

The planar phased array is formed by 32 active linear sub-arrays. Each sub-array comprises 32 linear-vertical polarised printed antennas. They are wide-band aperture-coupled microstrip patches. The phase of each sub-array is controlled electronically by a phase shifter at radio-frequency (RF). This arrangement provides antenna beam scanning capability in the elevation plane. After the phase shifters the signals from the sub-arrays are combined and down-converted to intermediate frequency (IF), ready to connect to a conventional receiver. Fig. 1 depicts the functional architecture of the phased array.

Before the first amplification stage the 32 elements of each sub-array are grouped in 4 elementary passive sub-arrays (ESA's) of 8 patches each (see Fig. 1). In each ESA a wide-band corporate network combine the signals from the 8 patch antennas. The measured gain of the ESA ranges between 14.1 and 14.6dBi in the required frequency band. These values lead to overall efficiency higher than 50%.

The signal from each ESA is low-noise amplified. The amplifiers are transistor-based and designed to minimise the noise figure. The amplifiers provide more than 9dB of gain with a noise figure of less than 1.1dB in the entire frequency band. The variations of gain and phase shift between different amplifiers are limited to 1dB and 15°, respectively. These values guarantee a low side-lobe level in the H-plane radiation pattern and main beams perpendicular to the sub-arrays axis.

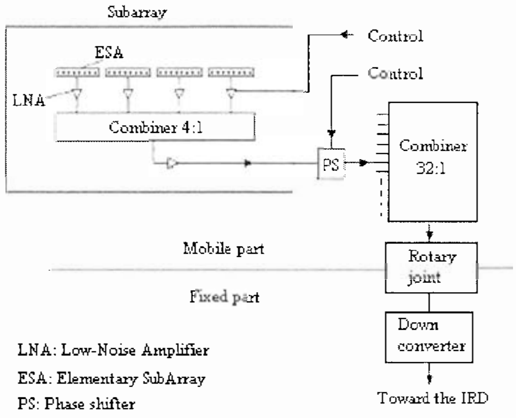

Fig. 1: Functional architecture of the phased array

After the first amplification stage, the signals from the ESA's are combined using an active wide-band corporate network. This network is printed on the bottom side of the sub-array being well isolated from the antenna elements by a ground plane. Apart from the RF lines, combiners and amplifiers, the active network also comprises the DC lines for amplifier feedings and a filter for the DC signals. The RF output is provided through a SMA connector. Fig. 2 shows the top and bottom views of one sub-array.

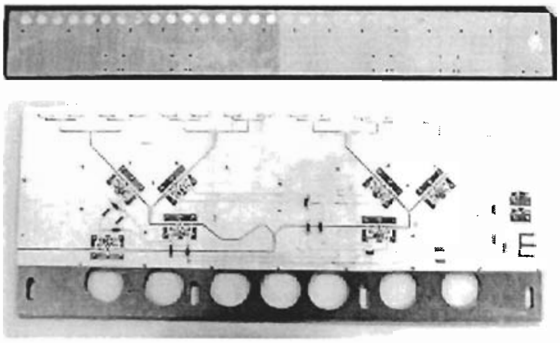

Fig. 2: Top and bottom view of a sub-array

The sub-arrays are inclined 25° with respect to the antenna aperture (see Fig. 3). This arrangement allows a reduced separation (18.75mm) between sub-arrays providing enough space to accommodate their active networks. This inclination leads to an asymmetric scanning range of the phased array in the E-plane. The resulting antenna aperture area is 570x570cm^2.

The phase shifters (see Fig. 4) have high insertion loss of about 18dB. On the other hand, the insertion loss is nearly constant in the phase-shift range and between different phase shifters. But, the main advantage of these phase shifters is an excellent phase resolution (better than 1°) which provides the required accuracy of the antenna beam pointing in the E-plane.

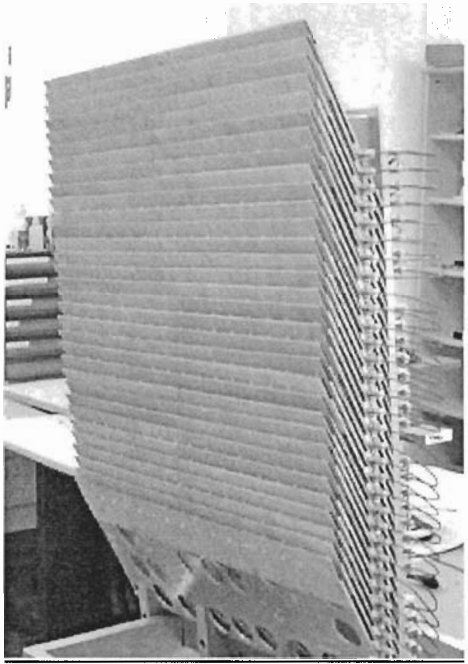

Fig. 3: View of the phased array

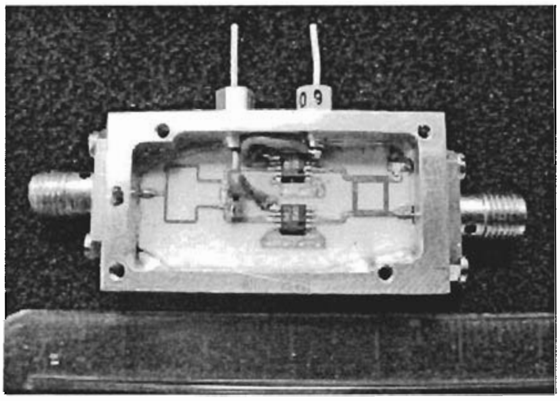

Fig. 4: View of one phase shifter

The phase shifters and the rest of the electronics (combiners, driver amplifiers, down-converter, control cards, etc.) are mounted on the bottom side of the antenna platform avoiding the possibility of coupling and interference with the antenna elements (Fig. 5).

After the phase shifting, the signals received by the sub-arrays are coherently combined by means of an active 32:1 wide-band combiner. This is done in two stages as Fig. 6 shows. The measured overall isolation between ports is better than 15dB and the phase shift between ports is less than 10° in the entire frequency band.

Two commercial rotary joints have been used. One is used for the RF signal and the other is a six-channel axes-hollow rotary joint intended for DC-power and control signals.

After the rotary joint, the RF signal is down-converted to IF. The output of the down converter is a F-female connector at 75Ω, ready to connect to a conventional IRD using a conventional satellite-TV coaxial cable.

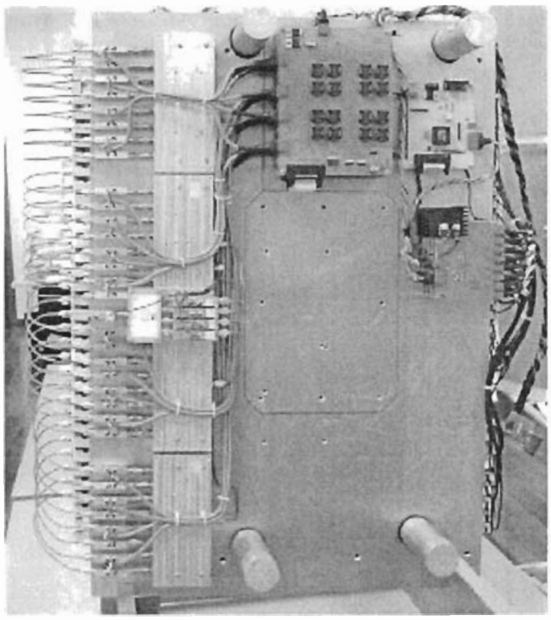

Fig. 5: Bottom view of the phased array

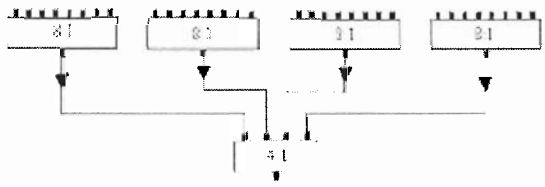

Fig. 6: Active 32:1 power combiner

PHASED ARRAY CALIBRATION AND MEASUREMENT

The calibration procedure consisted on the adjustment and determination of the control voltages (two control voltages for each phase shifter) of the phase shifters (32 phase shifters) to point the antenna beam to the desired discrete directions. The calibration procedure is very time-consuming in the anechoic chamber, so it was done only at a single frequency (12.4GHz). Considering the estimated squint losses, in order to operate in the whole band (10.7 – 12.7GHz), the antenna should actually be calibrated at two additional frequencies (e.g. 11.8 and 11.2GHz). Due to the wide-band characteristics of the antenna, similar performances were expected at these other frequencies.

Seventy discrete directions in the elevation plane (from –5° to 65° with respect the normal to the antenna support) were considered in the calibration, resulting in a 1° gap between two adjacent directions. Taking into account the antenna beam-width (about 3°), this angular gap guaranties pointing losses below 1dB. For each direction, the 64 control voltages were determined and stored in a memory of the control system. The radiation pattern in the principal planes was measured for each discrete direction. As an example, Fig. 7 shows the measured radiation patterns at 12.4GHz in the E-plane for some of the discrete directions (every 5°) in the range –5° to –55°.

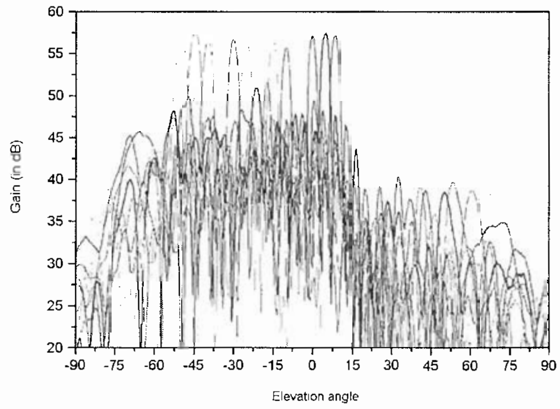

Fig. 7: E-plane radiation patterns

The measured performance parameters of the phased array in the entire scanning range are summarised in the following points:

- Beam pointing error in the E-plane <0.1°
- Beam pointing error in the H-plane <0.3°
- Beam-width in the E-plane between 3° and 5°
- Beam-width in the H-plane: 3°
- Secondary lobes level in the E-plane <-8dB
- Secondary lobes level in the H-plane <-9dB
- Gain variation over scanning range: 2.2dB
- Cross-polarisation discrimination: 30dB

A G/T higher than 15dB/°K was estimated during the field trials from the measured values of the signal-to-noise ratio at the receiver and the coverage of the satellite in the trials area.

ANTENNA PLATFORM

Fig. 8 depicts the functional scheme of the antenna platform. It comprises two mechanical axes for azimuth and polarisation and, further, one virtual electronic axis provided by the scanning capability of the phased array. All axes are perpendicular to each other. Therefore the system has three degrees of freedom ($\vartheta_1, \vartheta_2, \vartheta_3$) allowing to perform antenna beam pointing and polarisation matching at the same time.

During the design phase, the required specifications of the mechanical system were obtained from intensive kinematic and dynamic simulations of the model using a multi-body numerical simulator. Important inputs for these analyses were the satellite orbital position, the operational area of the ship and the kinematic characteristics of the ships motion (range, rate and acceleration) in the three main axis (pitch, roll and yaw/heading).

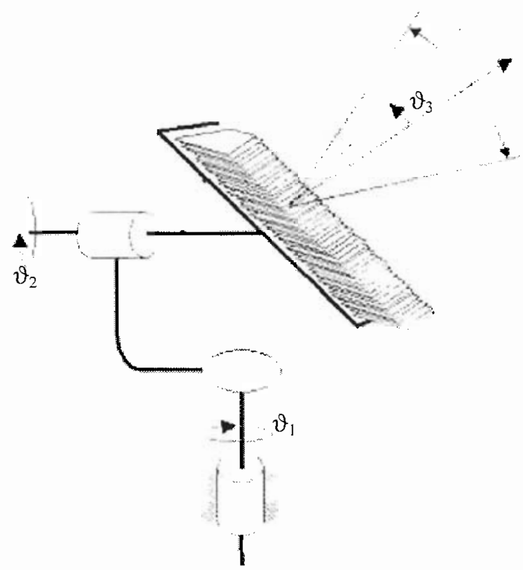

Fig. 8: Schematic structure of MOBILITY antenna (ϑ_1 is azimuth, ϑ_2 polarisation, ϑ_3 elevation angle)

The resulting system is shown in Fig. 9. One can observe the two gear units and the corresponding servo motors. The motors are AC brushless servo motors with incorporated resolver. All these devices are low-noise to avoid interference with the electronic elements of the antenna.

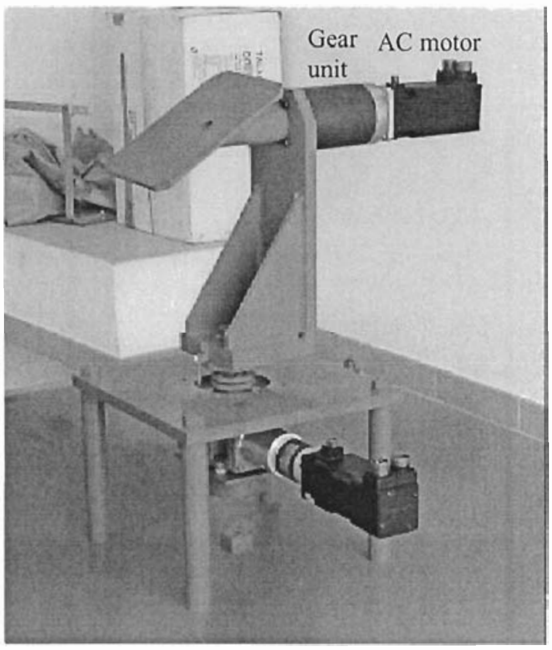

Fig. 9: ***Antenna platform***

Without the need of polarisation matching, the dimensions of the mechanical system can be substantially reduced, potentially leading to a light-weight, low-profile antenna platform[2]. This is what makes the hybrid approach particularly interesting.

CONTROL SYSTEM

Fig. 10 depicts the functional architecture of the control system. It consists of three micro-controllers that receive commands from the PAT unit (a detailed description will follow below) through a serial bus.

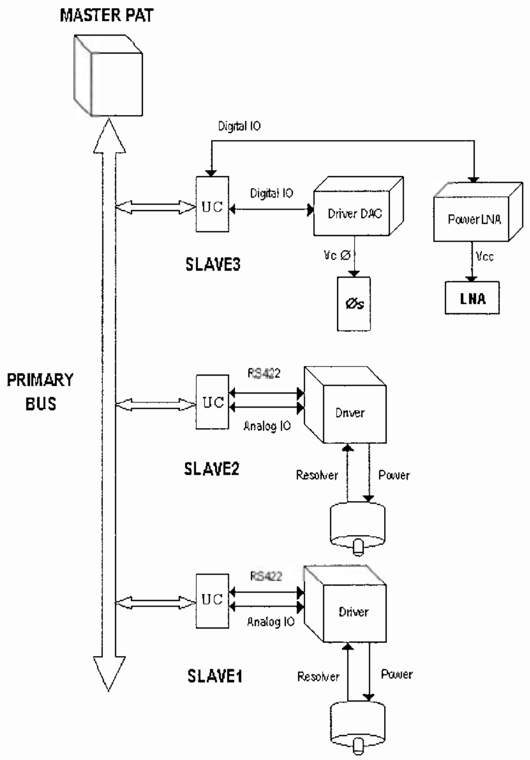

Fig. 10: Functional architecture of the overall control system

Micro-controllers 1 and 2 control the servo motors of the antenna platform. These process the information from the PAT system and provide the following information to the servo motors: relative angle, sense of rotation, acceleration ramps and PID (Proportional Integral Derivative). The system does not use any absolute encoder; all the operations for movement control are realised with the help of the relative resolver in each motor.

The micro-controller 3 is responsible for the electronic scanning of the phased array (by adjusting the control voltages of each phased shifter according to the values determined during the calibration) and of the DC supply (polarisation voltages) to the amplifiers. Finally, the phased array calibration required the ability to switch off and on any sub-array. This is done by the micro-controller by switching on/off the DC supply of the driver amplifiers.

PAT PLATFORM

GENERAL PROBLEM STATEMENT FOR PAT

The procedure of aiming an initially arbitrarily oriented antenna towards a wanted satellite is known as pointing, determining the direction of arrival of the signal at the receiver is termed spatial acquisition, and the subsequent operation of maintaining pointing and acquisition is called tracking.

While for a fixed receiver the high gain antenna has to be aligned with the satellite only once during installation, for a mobile receiver a PAT system must do this continuously to compensate the movements and attitude changes of the vehicle the antenna is mounted on.

Hence, the task of the PAT system is to provide the information that is required to control the antenna in such a way that, regardless of the motion and attitude changes of the ships, the antenna will point toward the satellite with a pointing error small enough to guarantee a sufficient signal quality.

Just as for the widely used fixed reception of DVB-S, a high gain and, hence, narrow beam antenna was needed for the MOBILITY demonstration as was shown in detail in the last section.

Further, in most mobile scenarios that involve a satellite component, the PAT system has to control an antenna with just two degrees of freedom (DOF), i.e. azimuth and elevation. This is sufficient, if the signal is circular polarised or, if in case of a linear polarised wave, the signal degradation due to a polarisation mismatch is negligible.

The satellite signal used for the trials in the eastern Atlantic (using HISPASAT 1C, positioned at 30.14° west longitude) has two orthogonal linear polarised components. Of particular importance for the antenna and PAT system design was that, to increase spectrum efficiency, *different* DVB-S signals are transmitted in both polarisations simultaneously. To ensure a sufficient level of cross-polarisation discrimination a linearly polarised antenna is employed at the DVB-S receiver and, in consequence, to compensate the ships movements it is required that besides continuous tracking of the satellite, also matching of the signal and antenna polarisation is maintained.

The required accuracy for pointing was defined to be 0.5°-0.8° (depending on the EIRP) and the maximum tolerable polarisation matching error to 2°.

PAT SYSTEM IMPLEMENTATION

At a first glance, a closed-loop approach (which makes use of signal power fluctuations caused by a pointing error) seems to be possible, because it is unlikely that any signal blocking/shadowing will occur during the trips. However, the need for polarisation tracking rules out a pure closed-loop approach, because a polarisation mismatch does not change the receive signal power. Hence, a closed-loop PAT can not detect a polarisation mismatch. In consequence, an attitude and heading reference system (AHRS) is necessary to provide the required information about the ship's attitude changes to maintain polarisation matching . This is termed open-loop PAT, as no receive signal power feed-back is used.

Using the information from the AHRS, the PAT system must provide the proper angles for the three orthogonal axes of the antenna structure. The angles are denoted as ϑ_1 (azimuth), ϑ_2 (polarisation) and ϑ_3 (elevation) as indicated in Fig. 8.

The open-loop PAT system is made up of the following devices

- Inertial measurement unit (IMU) to provide the ships attitude changes (yaw angle α, pitch β, roll γ),
- standard GPS receiver,
- dual antenna GPS (DAGPS) receiver to provide true-north vector,
- standard PC to collect data from the IMU and to control the antenna platform (in the further referred to as PAT-PC),
- standard PC for data logging (in the further referred to as LOG-PC).

The output from the GPS and DAGPS receivers is directly fed to the IMU, which uses the GPS position and true-north information for internal compensation of Earth rotation and to calculated the yaw angle with respect to true-north.

A block diagram of the PAT system is shown in Fig. 11.

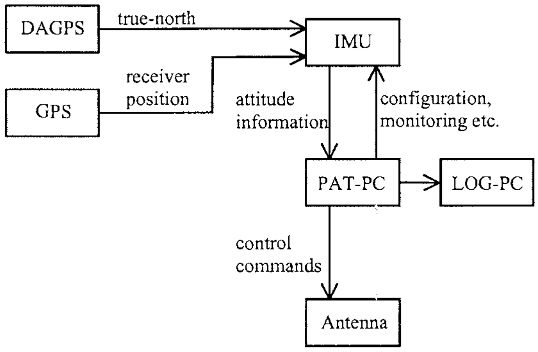

Fig. 11: Block diagram of the PAT system including the antenna control and feed-back data links

The achievable pointing accuracy mainly depends on the accuracy, rate and latency with which the AHRS provides yaw, pitch and roll. Further, it is important that the coordinate system of the antenna (defined via the joint axes) is aligned with that of the AHRS at an accuracy according to the required pointing accuracy.

The accuracy and other important parameters of the employed AHRS devices are given in the following:

- IMU: maximum dynamic angular error for roll, pitch and yaw is 0.1°; maximum sampling and output rate is 200Hz to 400Hz; maximum latency (varies with sampling rate) is 5ms to 2.5ms.
- DAGPS: accuracy is 0.4° for a baseline length of 1m (distance between the two GPS antennas); max. output rate is 5Hz.

The set-up of the antenna and PAT devices onboard the ship during the trials is shown schematically in Fig. 12 and 13.

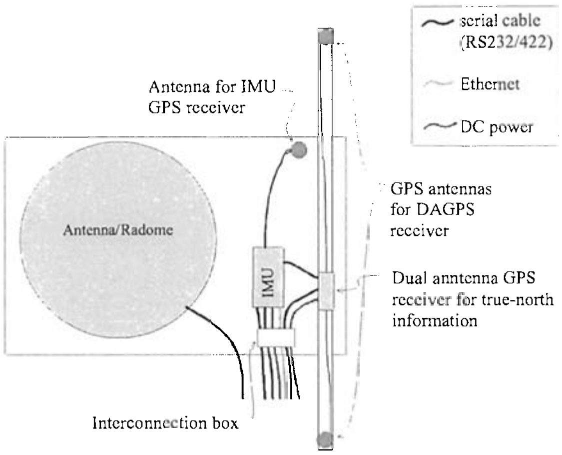

Fig. 12: Schematic set-up of outdoor platform mounted on ship's outdoor upper deck

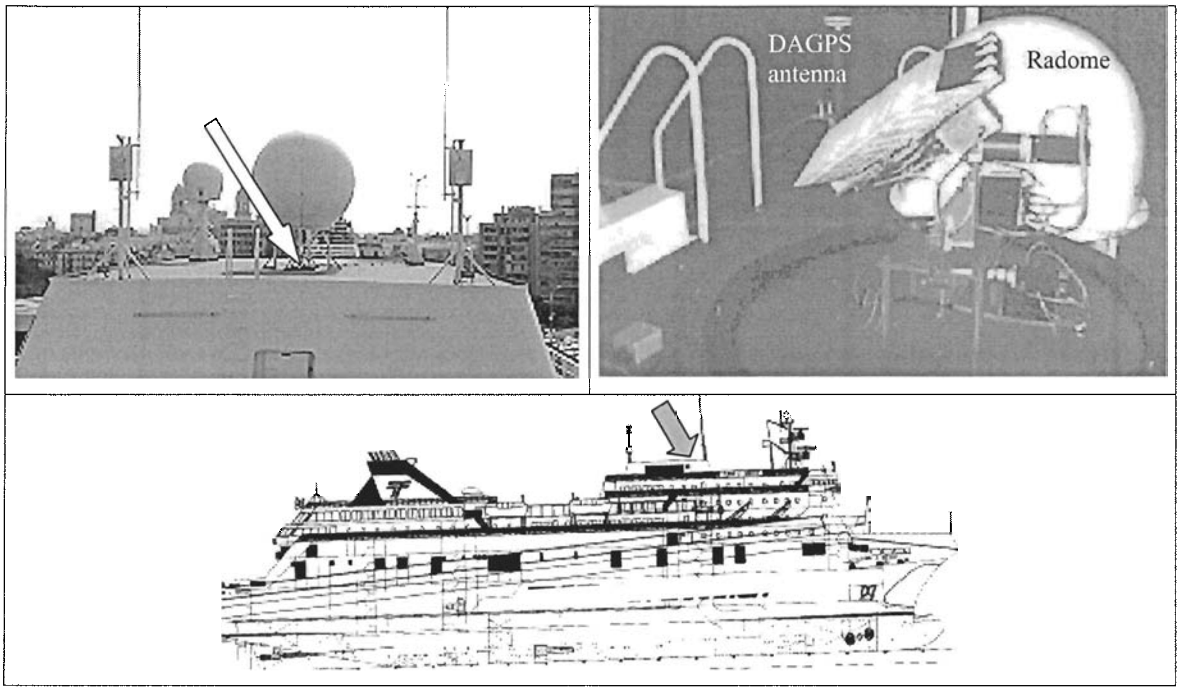

Fig. 13: View of platform location (upper left, bottom) and the antenna platform in-situ

The IMU provides the Euler angles yaw (w.r.t. to true-north), pitch and roll (w.r.t. local horizon) and the GPS position to the PAT-PC. The PAT algorithm implemented on the PAT-PC then calculates the angles ($\vartheta_1, \vartheta_2, \vartheta_3$) that have to be set at the antenna to track the satellite and, together with the feed-back information from the antenna, the control commands are generated and sent to the antenna platform.

CALCULATION OF ANTENNA CONTROL ANGLES ($\vartheta_1, \vartheta_2, \vartheta_3$)

Basically, calculation of ($\vartheta_1, \vartheta_2, \vartheta_3$) is achieved by a transformation of the pointing vector given in earth co-ordinates (calculated from the ship's and satellite's positions) to antenna coordinates. For this transformation three steps are required (s. Fig. 14 for an explanation of the unknowns and by what means to measure the unknowns; the basis $\mathbf{B}_A$ is defined by the three orthogonal rotary axes of the antenna introduced above). A possible pointing error caused by any misalignment between the antenna and the AHRS/IMU was eliminated by mounting on a common platform, allowing an exact mechanical alignment.

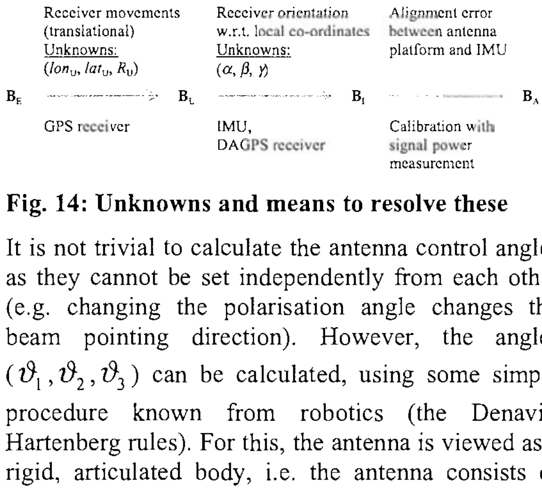

Fig. 14: Unknowns and means to resolve these

It is not trivial to calculate the antenna control angles as they cannot be set independently from each other (e.g. changing the polarisation angle changes the beam pointing direction). However, the angles ($\vartheta_1, \vartheta_2, \vartheta_3$) can be calculated, using some simple procedure known from robotics (the Denavit-Hartenberg rules). For this, the antenna is viewed as a rigid, articulated body, i.e. the antenna consists of rigid segments that are connected by joints, which pose constraints on the antenna movements. These constraints are the

1. degrees of freedom (DOF, defined by the type of joint) and
2. angular ranges of the joints.

The joints used in the MOBILITY antenna platform are revolute joints (1 DOF) and the angular ranges have to be chosen such that no restrictions are met during system operation. Each antenna segment is associated with a coordinate system and, hence, the antenna is described by concatenated coordinate systems (due to the limited space the full procedure of calculating the antenna control angles is not shown here).

Finally, the antenna control angles ($\vartheta_1, \vartheta_2, \vartheta_3$) are calculated using the line-of-sight (LOS) vector $\mathbf{p}_{US}=(p_x, p_y, p_z)$ and signals polar polarisation vector $\pi_P=(\pi_x, \pi_y, \pi_z)$ (both unit length) in antenna/AHRS coordinates (in contrast to Fig. 8, ϑ_3 in (3) is defined w.r.t. to horizontal):

$$\vartheta_1 = \arctan\left(\frac{\pi_z p_x - \pi_x p_z}{\pi_y p_z - \pi_z p_y}\right) \quad (1)$$

$$\vartheta_2 = \arccos(\pi_x p_y - \pi_y p_x) \quad (2)$$

$$\vartheta_3 = \begin{cases} a - \frac{\pi}{2} & \text{if } b < \frac{\pi}{2} \\ -a - \frac{\pi}{2} & \text{else} \end{cases}, \quad (3)$$

where

$$a = \arccos(p_y \cos\vartheta_1 - p_x \sin\vartheta_1) \quad (4)$$

$$b = \arccos(p_x \cos\vartheta_1 \cos\vartheta_2 + \ldots \\ \ldots + p_y \sin\vartheta_1 \cos\vartheta_2 - p_z \sin\vartheta_2) \quad (5)$$

In fact, one can easily imagine that there is no unique solution for the angles ($\vartheta_1, \vartheta_2, \vartheta_3$) to achieve pointing, if there is no restriction assumed for the angular ranges of ($\vartheta_1, \vartheta_2, \vartheta_3$). Because in our case we have to take care about the allowed angular ranges, the equations presented above provide the proper solutions only for the case that the satellite receiver location is north of the satellite.

TRIALS RESULTS

In the period of January 14th – 20th 2003 the MOBILITY trials were performed on a passenger ferry on a route in the eastern Atlantic between Cádiz and the Canary Islands (s. Fig. 15).

Fig. 15: Route for MOBILITY trials

The EIRP of the satellite signal in this region is shown in Fig. 16.

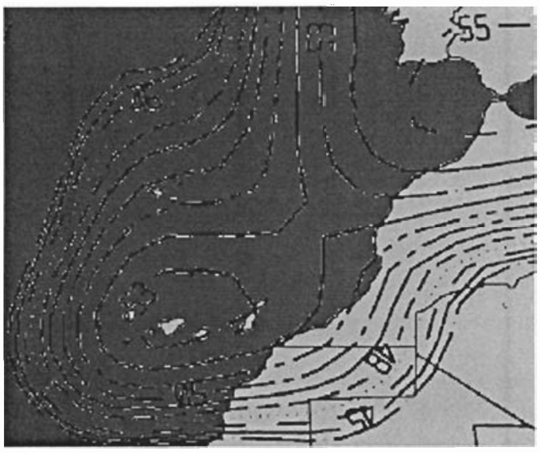

Fig. 16: Contour plot of EIRP for trials

The questions to be answered for the trials were:

- What is the quality of the DBV-S signal provide by the system?
- What is the performance of the PAT system?
- What are the dynamics of the ship's movements (to allow a cost-effective PAT solution tailored to this particular scenario)?

The ship has a total length of 151m, breadth 26m, speed 18knots. The capacity of the ferry is 556 passengers, 170 vehicles. The PAT platform was installed on the upper most deck, approx. 35m above sea level.

The most important technical installation onboard the ship with an impact on the PAT system was the hydraulic stabilisation system of the ship to dampen the roll movements caused by the sea. Similar stabilisers (either hydraulically operated wings or water tanks) are common on passenger ferries, while unusual on freight ships. Hence it can be assumed that the measured ship's movement data are also valid for other passenger ferries of similar size.

The stabilisation system kept the roll angle most of the time well below 2°. Of course, the maximum angular deflection depends on the weather situation. However, similar weather conditions, and hence ship movements, as experienced during the trials are encountered on approx. 360 days throughout the year on this particular route. On the other hand it is clear that other routes (e.g. transatlantic, in Pacific Ocean etc.) mean different changing weather conditions throughout the year, causing different movement behaviour of the ship, with or without stabilisation.

The maximum occurring roll and pitch angles were approx. +/-3°, while the angular rates and accelerations for yaw, pitch, roll were mostly less than 2°/s and 3°/s^2, respectively (yaw acceleration can reach peaks of up to 10°/s^2). Obviously, this kind of maritime application onboard a passenger ferry poses very little requirements on the pointing system[1].

For the received signal, DVB group suggests the measurements that should be taken of a digital television signal to make sure that its quality is satisfactory. They are often referred to collectively as the "DVB health check". The recommended measurements are many and diverse: the buffer errors, the clock phase errors, C/N etc.

Since DVB-S signal in the trials is the same as the one used for residential reception (commercial available) the purpose of trials in a mobile environment are aiming at verifying the receiving system's capability in such environments. In this case, the recommended measurements are targeting at reception performance and are the following:

- Digital channel power,
- Carrier-to-noise ratio (C/N),
- Bit error rate (BER).

A satellite signal analyser optimised for measurements of television signals was used for fundamental measurement set-up. This modular instrument enables the user to analyse both analog and digital TV transmissions.

Fig. 17 shows the final signal distribution scheme adopted for the trials. The IRD's output was connected to the existing system by taking advantage of the already installed analogue satellite TV distribution network. IRD output was RF modulated on a specific channel.

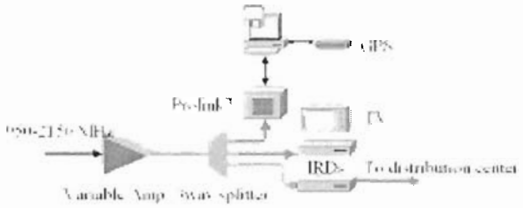

Fig. 17: Signal distribution scheme adopted for trials

The best way to check the quality of TV signal reception is to get the image on the screen of a TV set, since digital communications have the particularity to show a black screen when no signal is decoded. When some errors appear during the process of decoding they are showed as the "pixeling phenomenon". DVB defined an objective quality of "Quasi Error Free" (QEF) for a BER of $2 \cdot 10^{-4}$, measured after the Viterbi decoder.

During the trials this threshold was achieved, except in areas where the conjunction of low EIRP, raining weather conditions and radome attenuation produced a C/N budget under 6dB.

This indicates that the performance of the both the antenna and the PAT system are as expected.

CONCLUSIONS

This paper presented a detailed description of the system and its components developed in the frame of the European MOBILITY project.

Although not realisable in the MOBILITY trials due to the need of polarisation tracking, the hybrid approach using the electronic beam steering for elevation has the potential to allow light weight, low profile antenna designs for mobile satellite terminals.

In February 2003 the project has been reviewed by the European Commission and was considered successfully completed.

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