Development of a telemetry node for Mnmemosine, a Flight Test Instrumentation System for Sport Aviation Aircraft

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Abstract

Among the reasons for the remarkable success of the class of flying machines referred to as Ultra Light Machine (ULM), Very Light Aircraft (VLA) or Sport Aviation (SA), the unique combination of enjoyable, *real aircraft like* performances and a low total cost of ownership can be considered preeminent. One of the main contributions in keeping costs calm is the very relaxed - or in some cases (like Italy) totally absent - Authority requirements for the certification of the machine. For this reason no systematic Flight Test activity is normally planned by the manufacturing companies as a part of the design, development and production process of ULM, and therefore no suitable Commercial Off The Shelf (COTS) Flight Test Instrumentation (FTI) system is available on the market.

The Department of Aerospace Engineering of the Politecnico di Milano acquired in 1999 one of such machines, a P92 ECHO-80. As soon as research activity started on the P92 some degree of frustration has derived from the use of a general purpose data acquisition system adapted to the Flight Test activity.

A project to develop a tailored FTI system has therefore been launched, and the *Mnemosine* system is the result of such efforts. It consists in a federated architecture data acquisition system, composed of a number of independent nodes sharing information on a dual 1 MBit/s Controller Area Network (CAN) based digital data bus.

This paper presents how a telemetry subsystem has recently been added to the Mnemosine system. It is built around a Digital Enhanced Cordless Telephone (DECT) based Radio Frequency (RF) system, providing a bidirectional data link up to a planned distance in excess of 10 km at a net data rate in excess of 100 Kbs. The system is complemented by a Ground Station (G/S) that features a servo controlled Pan & Tilt Positioner that takes care of pointing the high gain antenna in the aircraft direction.

1 Introduction

In the last years a new class of aircraft has attained a tremendous commercial success. The definition of these machines is different around the world - Ultra Light Machine (ULM), Very Light Aircraft (VLA), etc - but will eventually converge to some kind of generally accepted Sport Aviation (SA) category.

Among the reasons for the mentioned success, the unique combination of enjoyable performances and a low total cost of ownership can be considered preeminent.

One of the main contributions in keeping costs calm is the very relaxed - or in some cases (like Italy) totally absent - Authority requirements for the certification of the machine. For this reason no systematic Flight Test activity is normally planned by the manufacturing companies as a part of the design, development and production process of ULM. Even when it is performed, Flight Test activity is generally carried out adapting to the task some kind of general-purpose, Personal Computer based data acquisition system, since no Commercial Off The Shelf (COTS) Flight Test Instrumentation (FTI) system exists on the market. Such systems tend to be bulky, highly intrusive - especially considering the lack of room available in a 450 Kg Maximum Take Off Weight (MTOW) aircraft - and very little flexible.

In 1999 the decision has been taken by the the Department of Aerospace Engineering of the Politecnico di Milano to acquire one of such machines, a P92 ECHO-80 manufactured by Capua-based Costruzioni Aeronautiche Tecnam S.r.l. [1].

It has soon be realized, that the P92 could be exploited as a unique opportunity to perform research activities. In fact it offers an unbeatable combination of

- *real* aircraft behavior, including controls and performance
- minor aerodrome operation capability
- very low cost per flight hour
- extremely relaxed (practically non existent) airworthiness requirements

However, performing any serious research activity that included Flight Test inevitably turned out to be a fairly frustrating experience. Costing orders of magnitude more than the aircraft under test itself *real world* FTI systems available on the market are out of reach for economic reasons. Even neglecting costs, many problems would arise when trying to fit an FTI system designed for an inevitably larger aircraft into an ULM: it suddenly appears to be too bulky, heavy, power hungry, intrusive and definitely over specified.

The decision has been therefore made to tackle the P92 FTI issue investigating whether it was possible to conceive a low cost, dependable, dedicated FTI system for the aircraft of the Department, and what performance could be expected from such a system, within the stringent budget constraints dictated by the application. The *Mnemosine* system in the result of such an effort.

2 The Mnemosine system

Mnemosine is a low-cost FTI system designed at the department of Aerospace engineering of the Politecnico di Milano keeping in mind the particular preconditions of ULM aircraft with the aim to realize a Flying Laboratory capable of fulfilling the necessities and requirements of both research and didactic activities.

In order to achieve sufficient performance from low cost, low grade sensors, particular attention has been given to the design of a sensor fusion algorithm capable of obtaining a final data quality better than that given by the sum of the single parts taken separately.

The system has been tailored around the Department's P92 ECHO ULM aircraft, but has been designed to be flexible enough to match the needs of a wider variety of applications.

2.1 System Architecture

Mnemosine is conceived in a *federated architecture* [2], characterized by the system as a whole being split into a number of autonomous units, or *nodes*. Every single unit can operate independently from the others, and is specialized for a particular task: it has processing power, memory, power supply and all the signal conditioning/interface resources required to manage the particular sensor and or device it controls.

2.2 Data Bus

Data generated by the various nodes is shared by means of a common communications line: a *digital data bus*. The particular data bus chosen for Mnemosine is the Controller Area Network (CAN), initially developed by Robert Bosch GmbH in the mid-1980s for automotive applications as a method for enabling robust serial communication [3].

Over the CAN bus a custom designed variant of the CANAerospace interface (originally created in 1997 by Stock Flight Systems GmbH [4]), particularly aimed at FTI applications is used: CAn For Flight test Equipment (CAFFE).

Mnemosine features a dual 1 MBit/sCAN bus architecture: one bus is dedicated to distribute across the network exclusively timing information, and is defined Timing BUS (T-BUS). The other carries all parameter data traffic, and is referred to as Data BUS (D-BUS).

2.3 System nodes

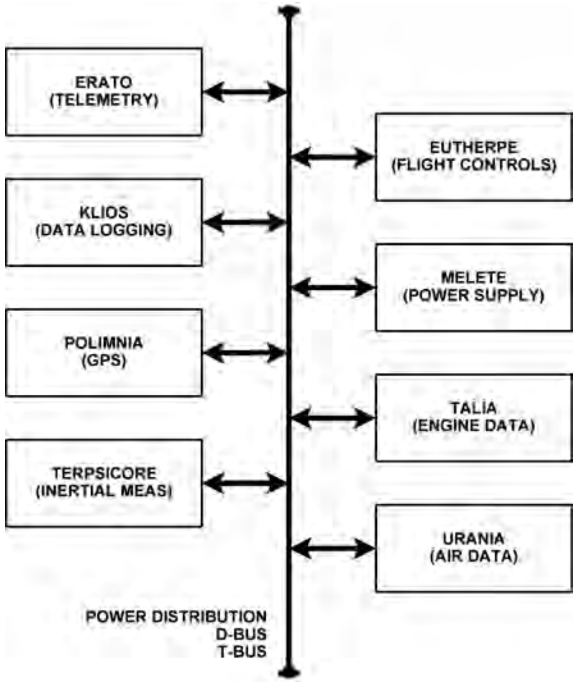

Figure 1: System block diagram

The block diagram representing the system architecture can be seen in figure 1.

It consists, so far, in eight units, named after the Ancient Greek mythology Muses, each performing its dedicated subset of data acquisition:

1. *Erato* Telemetry
2. *Eutherpe* Flight Control (FC)
3. *Klios* Data logging
4. *Melete* System power supply management
5. *Polimnia* Global Positioning System (GPS)
6. *Talia* Engine data
7. *Terpsicore* Inertial Measurement Unit (IMU)
8. *Urania* Air Data

Table 1 shows the main parameters acquired by the Mnemosine system.

2.4 Data flow

All parameters and data undergo a twofold process before they finally become ready to be processed.

Parameter	Node	Rate
Flight controls position	Eutherpe	10 Hz
Battery voltage and current	Melete	10 Hz
GPS Time	Polimnia	4 Hz
GPS Position	Polimnia	4 Hz
GPS Velocity	Polimnia	4 Hz
GPS receiver status	Polimnia	4 Hz
Satellite Raw measurements	Polimnia	4 Hz
Propeller Revolution Per minute (RPM)	Talia	4 Hz
Attitude angles	Terpsicore	56 Hz
Attitude rates	Terpsicore	56 Hz
Body acceleration	Terpsicore	56 Hz
Body Magnetic field	Terpsicore	56 Hz
Static Pressure	Urania	10 Hz
Dynamic Pressure	Urania	10 Hz
Static temperature	Urania	10 Hz
Angle of Attack (AOA)	Urania	10 Hz
Side Slip Angle (SSA)	Urania	10 Hz

Table 1: Mnemosine Acquired parameters

The basic philosophy that has been followed in the data flow design is to perform on board the aircraft, in real time, all the operations necessary for acquiring every *basic* parameter from a suitable sensor, condition and filter it, transform it into engineering units and store it on non-volatile memory.

All subsequent operations, such as *derivate* parameters computation or sensor information fusion are left to an off line, post-processing sequence.

Among the advantages of such approach, reduced on board embedded number crunching capability can be considered preeminent. The greatest part of the math work is carried out on a multi Floating Point Operations Per Second (FLOPS) Personal Computer, without the stringent requirements of real time processing.

In addition, since data is saved in the most raw format, should different or more efficient post-processing routines be developed in the future it will always be possible to run them on all the previous Test Flights data.

3 Telemetry subsystem design

After the first Flight test missions with the Mnemosine system it has been decided to add some form of telemetry capability to the system for two main reasons.

The first necessity is to be able to control how good the test flight pilot complies to the flight card schedule. On board the airplane, in fact, only very coarse pilot's instrumentation is installed, and in the past it happened that some non compliance of the actual Flight test points with respect to the planned ones was discovered only at post-processing time, generally some *days* later than the date of the flight.

Moreover, during didactic Flight Test missions it is interesting for the students remaining on the ground at the time their colleague if airborne conducting his or her experience as a flight test engineer to be able to follow the test flight in real time.

3.1 Telemetry system architecture

The requirements for the telemetry subsystems were defined as:

1. **Low cost**: the system should rely on a very tiny budget
2. **Free usability**: every Radio Frequency (RF) device is subject to pay a license from the National Telecommunications Authority in order to be used. Some particular classes of devices, however, are exempted from such regulation, and therefore are often referred to as *free usage* RF devices
3. **Several kilometers range**: from an analysis of the typical mission of the P92 it has been found that the requested maximum range of the telemetry system is somehow in the 8/10 km area.
4. **Reasonable net bandwidth**: data sent over the telemetry link will be interpolated and reduced from the 1 MBit/s stream flowing on the on board D-BUS to some 100 kBit/s rate
5. **Dependability**: in the sense of being immune to interference from similar or different systems operating in the same frequency range, and providing intrinsic data integrity control.

Starting from these requirements it has been finally designed a solution founded on a RF data link based on the Digital Enhanced Cordless Telephone (DECT) system, which is briefly presented in the next subsection.

3.1.1 Overview of the Digital Enhanced Cordless Telephone (DECT) system

The Digital Enhanced Cordless Telephone (DECT) standard provides a general radio access technology for wireless telecommunications, operating in the preferred 1880 to 1900 MHz band using Gaussian Frequency Shift Keying (GFSK) (BT = 0.5) modulation.

DECT has been designed to provide access to any type of telecommunication network thus supporting numerous different applications and services.

The DECT radio interface is based on the Multi Carrier (MC), Time Division Multiple Access (TDMA), Time Division Duplex (TDD) radio access methodology.

Basic DECT frequency allocation uses 10 carrier frequencies (MC) in the 1880 to 1900 MHz range (figure 2). The time spectrum for DECT is subdivided into time frames repeating every 10 ms. Each frame consists of 24 time slots each individually accessible (TDMA) that may be used for either transmission or reception. For the basic DECT speech service two time slots - with 5 ms separation - are paired to provide bearer capacity for typically 32 kBit/s (ADPCM G.726 coded speech) full duplex connections.

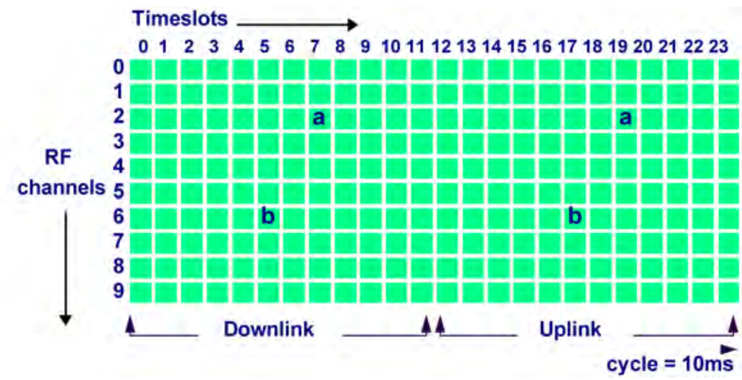

Figure 2: DECT framing

To simplify implementations for basic DECT the 10 ms time frame has been split in two halves (TDD) where the first 12 time slots are used for Fixed Part (FP) transmissions (down link) and the other 12 are used for Portable Part (PP) transmissions (up link).

The TDMA structure allows up to 12 simultaneous basic DECT (full duplex) voice connections per transceiver providing a significant cost benefit when compared with technologies that can have only one link per transceiver. Due to the advanced radio protocol, DECT is able to offer widely varying bandwidths by combining multiple channels into a single bearer. For data transmission purposes error protected net throughput rates of n x 24 kBit/s can be achieved, up to a maximum of 552 kBit/s with full security as applied by the basic DECT standard.

3.2 On board telemetry node

Erato (the Muse of lyric poetry) is the node in charge of controlling telemetry. The chore of this note is basically to manage the operation of the RF module on one side, and to listen for all the data traffic passing on the D-BUS, extract a number of predefined parameters, process them and send them to the ground station.

Radio link for telemetry is base on an Embedded DECT Module, model HW 86012 manufactured by German Hoeft & Wessel GmbH [5]; the main characteristics of the module are presented in table 2

Parameter	**Unit**	**Value**
Operating frequency	MHz	1880 - 1900
Channel spacing	MHz	1.728
Output power	dBm	21.0
Air data rate	Mbps	1.152
User data rate	kbps	26
Max active bearers		6

Table 2: Hoeft and Wessel DECT module characteristics

The module integrates the complete radio with latest low-IF technology for enhanced performance along with a low-power high performance 16 bit RISC Micro Controller Unit (MCU) for both DECT baseband and application processing.

In the current application the module is used in simple point-to-point data transmission mode, with all the 6 permitted bearers used in parallel for a net throughput of 156 Kbps.

As on board antenna for telemetry model K 70 55 64 by Kathrein Werke KG [6] has been chosen.

3.2.1 Installation aboard the aircraft

Erato node is tied into the aircraft in the area right behind the seats backrests, and connected in daisy-chain tho the twisted pairs cabling that carries power distribution, D-BUS, and T-BUS signals.

The RF antenna is installed on the lower panel of the fuselage, in the rear carriage attachment zone (figure 3).

This permits to have a good-sized and flat a metallic ground plane that provides an homogeneous, hemispheric, down-looking antenna radiation pattern.

3.2.2 Node acquired parameters

Even if Erato is not strictly part of the Mnemosine data acquisition system, in the sense that it doesn't manage any flight data acquisition sensor, indeed it does acquire a couple of parameters and sends them on the D-BUS.

- The first is RF *signal intensity*. It is a measure of the intensity of the telemetry RF signal received from the ground Station, and is expressed in

Figure 3: Telemetry antenna installed

dB where $0dB$ represents the intensity of the signal received by a couple of modules connected to two omni directional antennas.

- *Signal quality* gives and indication of the quality of the received signal, in terms of percentage of error-less data packet received with respect of the total number of data packets received. It must be noticed that signal quality can somehow be independent from signal intensity, since even in case of strong signal power data packets may be corrupted by propagation related issues, mainly multipath.

3.3 Ground Station

Figure 4 shows the block diagram of the Ground Station (G/S). It is composed of an antenna, with its Pan & Tilt Positioner and Controller, a Radio Modem, and a Personal Computer.

In the following sections each component is briefly presented.

3.3.1 Antenna

In order to reach longer distances with the modest (250 mW) maximum transmitting power of DECT systems, a high gain, directional antenna has been chosen for the G/S (Figure 5).

It must be noted, however, that the high gain of the antenna is obtained at the expense of radiation pattern isotropy, as it is shown in figure 6.

It is necessary, therefore, to provide a system to aim the antenna to the aircraft in order to establish a telemetry link.

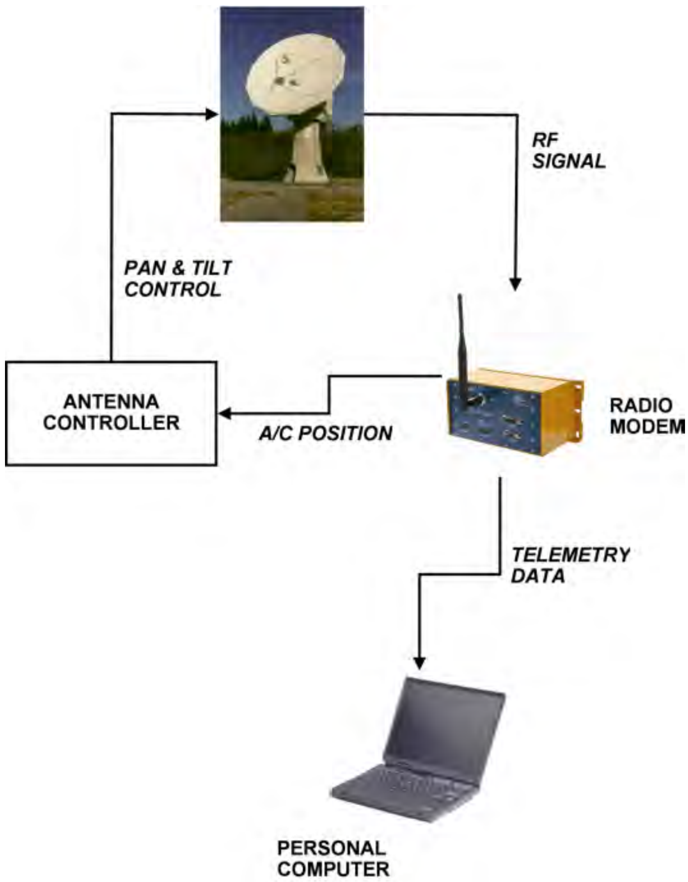

Figure 4: Ground Station block diagram

Figure 5: G/S Directional Antenna

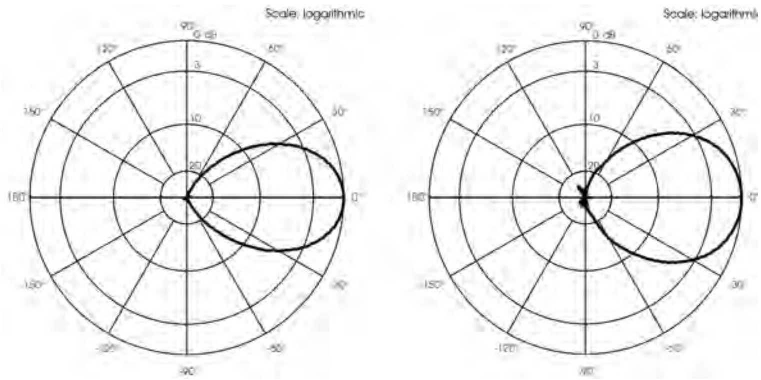

Figure 6: Vertical (left) and Horizontal (right) antenna radiation patterns

3.3.2 Pan & Tilt Positioner and controller

Antenna aiming to the aircraft is done by means of a Pan & Tilt Positioner, model QPT 20XD by Quickset International, Inc [7] (figure 7) and a custom developed controller.

Since many parameters have been made available by the Pan & Tilt Positioner manufacturer, it has been possible to model, design and simulate the performance of the controller in MATLAB/SIMULINK before actually building it.

Aircraft coordinates (coming from on-board Mnemosine Through telemetry) are fed to the formula that, knowing G/S coordinates, outputs reference azimuth angle (θ), elevation (α) angle and distance (ρ).

Reference values are then compared with actual values read from the Positioner's potentiometers and generate the error that is fed to the controller, together with distance information. The controller has been designed using a fuzzy logic [8] [9] approach.

Figure 7: Pan & Tilt Head

Finally, the controller outputs a Pulse Width Modulation (PWM) signal that is fed to the Motor power controllers of Pan motor and Tilt motor.

3.3.3 Radio modem

The radio modem chosen for the the G/S is modem MXX-dDECT by GPSAeroborne S.r.l. [10] (figure 8)

Figure 8: MXX-dDECT Radiomodem

The radio modem is based on the same DECT module used for the on board Erato node, so it can take advantage of the 6 simultaneous active bearers mode, for a a net usable throughput of 156 Kbps.

Parameter	Unit	Value
Operating frequency	MHz	1880 - 1900
Output power	dBm	21.0
Receiver sensitivity	dBm	-87
Max active bearers		6
User port		RS 232/RS 422

Table 3: MXX-dDECT radio modem characteristics

Data is output from the radio modem through an RS232 serial line, suitable to be fed to the Pan & Tilt Antenna Controller and to the PC.

3.4 Visualization software

A data visualization program for Personal Computer has been developed, using Delphi language tools, to display telemetry data in real time.

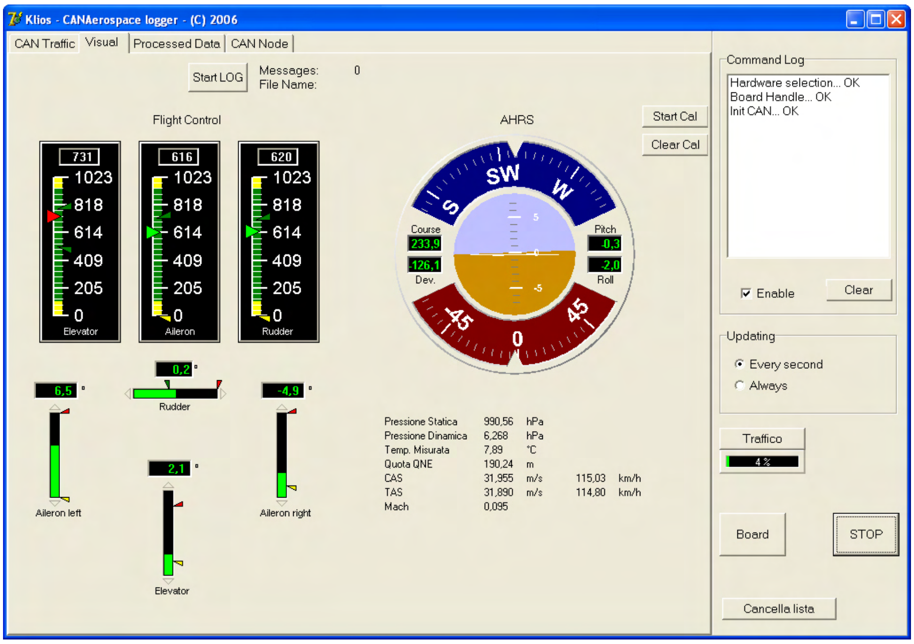

Figure 9: Telemetry data visualization program

All data read from the telemetry stream received on the serial line is displayed in its raw engineered format.

4 Telemetry in action

A number of dedicated Flight Tests have been performed with telemetry, in order to assess the system effectiveness.

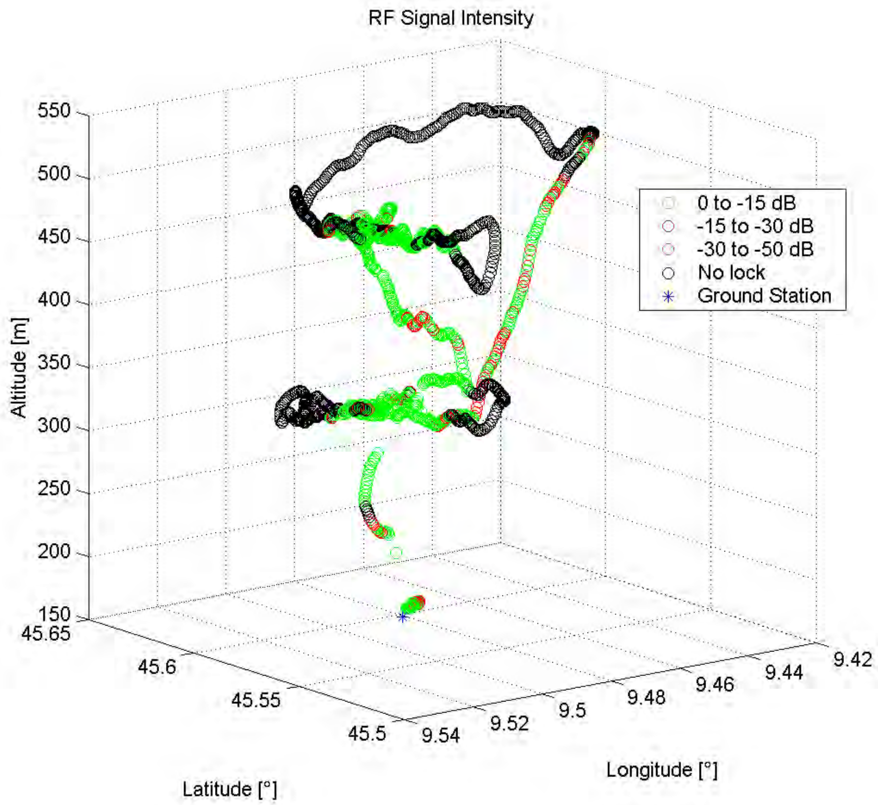

Figure 10: RF Signal Intensity 3D plot

Figure 10 shows the 3D plot of the aircraft trajectory of one of such Flight Tests. Colored marks show the RF signal intensity received from the on-board Erato node.

As it can be noted, there are two areas, with black marks, where the telemetry link does not operate correctly: a *near* area and a *far* area.

4.1 Near area issues

The first critical area is in the lower left part of the graph in figure 10, in the 300 to 350 m altitude area. Distance from aircraft to G/S is always below 1 Km with no obstacles. Analysis on collected data have shown that link was lost every time the airplane changed its bank angle maneuvering, moving the antenna ground plane away from the ground station and thus having the aircraft structure itself shielding the view between the on board antenna and the G/S antenna. The observed phenomenon is quite reasonable, since at the DECT operating frequencies the propagation of RF waves can be considered to occur preeminently in a Line Of Sight (LOS) way.

A solution for this problem, that will be implemented in the near future, consists in exploiting the DECT *Antenna Diversity* capability. The on board RF module, in fact, can be connected to two different antennas at the same time, and has the ability to chose with a sophisticated algorithm, on a per-data-packed basis, which antenna to use for reception and transmission.

The second antenna will be installed on the upper part of the fuselage, opposite to the existing antenna position. Should high bank angles mask the latter from the LOS with the G/S, the same bank angle will guarantee that the new antenna gains a LOS line to G/S and will be seamlessly used by the module Antenna Diversity capability.

4.2 Far Area issues

Post processing Test Flights data it has also be noted that it exists a far Area Issue with telemetry.

Figure 11 shows a plot of the on board received Telemetry RF Signal Intensity with respect to distance from G/S. Intensity is expressed in dB, being the 0 dB point the signal intensity received by a module equipped with a perfectly isotropic antenna at a distance of 1m from a similar node.

Two radials have been flown from the G/S at a constant altitude of 1000 ft ground. One radial (top figure) is away from the station in westbound direction, and presents a number of obstacles, mainly a number of buildings, that eventually, in a zone between 2 and 2.5 km, completely obscure the LOS between aircraft and G/S antennas, causing the link to be suddenly lost. This behavior is easily explainable considering the above mentioned LOS propagation characteristics of DECT band signal.

On the eastbound radial away from the station, however, no obstacle whatsoever is present, so the practically usable range was expected to be somehow around the predicted 12 Km coming from overall link budged calculations, performed taking in account for antennas real characteristics, output power of transmitters, receivers sensitivity, and RF cabling and connectors loss. Surprisingly, as it can be seen in the bottom chart in figure, the signal intensity that was supposed to guarantee a reasonably good quality link up to the -45 / -50 dB zone, at the 3.5 km distance suddenly drops to minus infinite, preventing any possibility to establish a link.

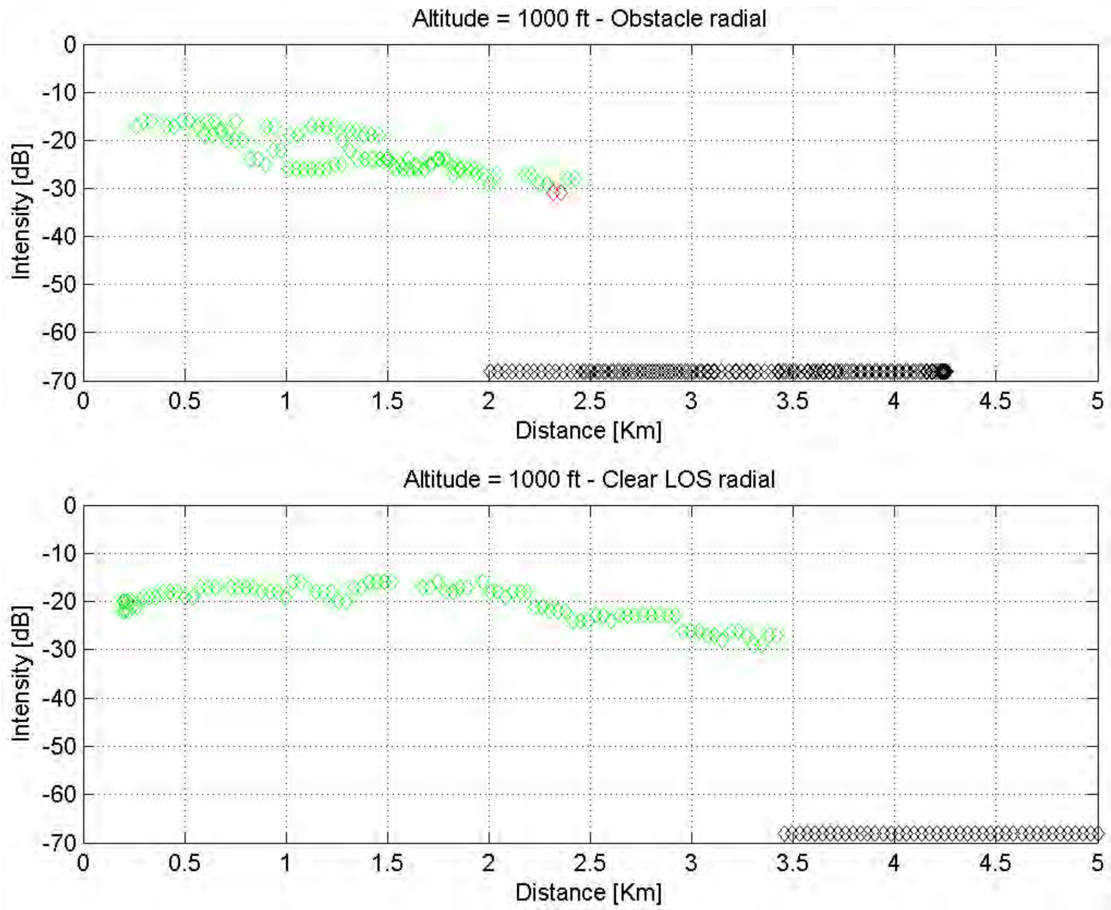

Figure 11: Signal Intensity as a function of distance

With the invaluable help of the DECT module manufacturer it has been possible to understand that the cause of such behavior was not related to RF signal intensity issues, but rather to *timing* issues. Recalling the DECT data framing introduced in figure 2 it can be observed that DECT uses TDD for permitting a duplex communications channel, and the 10 ms framing is divided in two 5 ms parts, one used for Fixed Part (FP) to Portable Part (PP) communication (down link) and the other for PP to FP communication (up link). The FP, managing the link and for the present application installed at the G/S side, therefore expects to receive packets back from the PP, installed aboard the aircraft, within the 5 ms delay specified by the standard plus a guard time. When the aircraft moves beyond the 3.5 km threshold distance from the base station, because of non null propagation delays such guard time is exceeded, and so the FP timeouts expires preventing any link to be established.

A solution for the above has been found. Since the terminal aboard the aircraft knows its exact position and the position of the G/S, it can continuously evaluate its distance from the G/S, and therefore it could be possible to inform the DECT module of this distance, and the related expected propagation delay, so that the transmission of the up link data packet from the aircraft to the G/S could be started with a calibrated advance in order to compensate for distance-induced delay and permit the FP DECT unit to receive such packet withins the standard framing specification time limits. Such solution requires a deep modification of the DECT module firmware, which is in progress at the time of this writing.

5 Conclusions

The telemetry subsystem developed for the Mnemosine FTI system has shown performance in accordance withe the design requirements.

For a start, cost has been kept well within the limits of such a tiny budgeted application.

Being based on the DECT system, besides, the implemented system use is free, in the sense that it doesn't require any special license.

Exploiting the multi-bearer feature guaranteed by the Hoeft and Wessel module, the available net bandwidth is even exuberant with respect to the initial requirements.

There exists a couple of presently unresolved issues, however, concerning the operations of the telemetry system. Telemetry link may be lost at high bank angles, should the fuselage mask the LOS between the on board antenna and the G/S antenna. This will be solved installing a second antenna on board and taking advantage of the antenna Diversity capability of the DECT module.

Timing issues, moreover, prevent the telemetry link to operate beyond a threshold distance, even if RF signal intensity is sufficiently strong. A firmware modification to the DECT module is in progress, and will permit to overcome this limitation and have telemetry link working over the full usable range.

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6 List of acronyms

AOA	Angle of Attack
CAFFE	CAn For Flight test Equipment
CAN	Controller Area Network
COTS	Commercial Off The Shelf
D-BUS	Data BUS
DECT	Digital Enhanced Cordless Telephone
FC	Flight Control
FLOPS	Floating Point Operations Per Second
FP	Fixed Part
FTI	Flight Test Instrumentation
G/S	Ground Station
GFSK	Gaussian Frequency Shift Keying
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LOS	Line Of Sight
MCU	Micro Controller Unit
MC	Multi Carrier
MTOW	Maximum Take Off Weight
PP	Portable Part
PWM	Pulse Width Modulation
RF	Radio Frequency
RPM	Revolution Per minute
SA	Sport Aviation

SSA	Side Slip Angle
T-BUS	Timing BUS
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
ULM	Ultra Light Machine
VLA	Very Light Aircraft