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DEVELOPMENT, TEST AND FLIGHT RESULTS OF THE RF SYSTEMS FOR THE YES2 TETHER EXPERIMENT

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ABSTRACT

This paper highlights design, realization, testing and flight results of the Radio Frequency developments (RF) for ESA's second Young Engineers' Satellite (YES2), that included GPS systems, an inter-satellite UHF link and a re-entry capsule telemetry and recovery system. The YES2 piggybacked on the Russian-built Foton microgravity platform in September 2007 with as objective the controlled deployment of a 32 km tether, in order to release a small re-entry capsule. That mission was successfully performed, although the capsule could not yet be retrieved. This complex project was performed by hundreds of students from all over Europe. One of the student teams was concerned with the development of RF systems. Most significant is the inter-satellite link between the tethered sub satellite and the tether deployed, through which tether science data from the sub satellite (e.g. tensiometer and dynamic sensors) can be recovered. Furthermore, a GPS/GLONASS receiver was placed on both ends of the tether to monitor the tether deployment. Next, the re-entry capsule has its own transmitter which sends data to an especially developed mobile ground station. Finally, recovery of the landed capsule was planned using an ARGOS beacon, for which two DDRR (loop antennas) were designed that transmit the beacon signal to the ARGOS constellation for positioning. This paper provides a brief overview of these systems and tests performed, and concludes with a discussion of flight results and applicability of the systems to other low-cost satellites, balloon experiments or sounding rockets.

1 INTRODUCTION

On 25 September 2007, the 2nd Young Engineers' Satellite (YES2) broke a Guinness World Record by deploying the longest man-made structure in space, a 32 km tether[1]. The YES2 was designed, built and qualified by hundreds of students from Europe and beyond, managed by Dutch company Delta-Utec, for the Education Office of the European Space Agency[2]. YES2 is ESA's most ambitious student project so far[3]. The objective of YES2 was to return a small re-entry capsule (Fotino) from an orbit of about 300 km altitude using the swing-effect of the 32 km tether and demonstrate in this way a sustainable, propellantless method of space transportation[4].

The YES2 consists of 3 parts (Figure 1):

- Fotino, a 6 kg re-entry capsule, with science and recovery package and parachute system
- MASS, a 8 kg tether sub satellite, containing science package and a release system for Fotino
- FLOYD, a 22 kg tether deployed, containing the main mission hardware and control, as well as a spring system that initiates the deployment of the tether by ejecting the MASS/Fotino. FLOYD is mounted on a large Russian platform (Foton), which also provided unregulated power and telemetry of YES2 mission data.

Figure 1. YES2, from top to bottom: Fotino re-entry capsule, tethered MASS sub satellite, FLOYD tether deployed.

The tether deployment takes about 2.5 hours and is controlled by FLOYD to follow a predefined trajectory through space relative to Foton/FLOYD (Figure 2). The trajectory ends in a swing of the fully deployed tether towards the vertical, where the capsule is released and is hurled towards the atmosphere. Next the tether is cut at FLOYD, so MASS will follow Fotino, dragging the tether out of orbit. Fotino is designed to survive the re-entry[5] and land in Kazakhstan, whereas MASS and tether will burn, Figure 3.

The main mission data needed to reconstruct the tether deployment is recorded on Foton/FLOYD. The primary data point to be obtained from the Fotino capsule was its landing location, which is to be achieved through an ARGOS beacon.

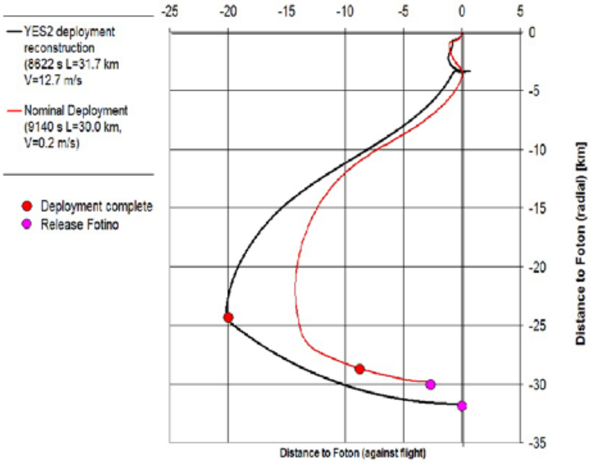

Figure 2. Trajectory of MASS/Fotino during deployment on the YES2 tether. Red = nominal, Black = YES2 flight result. View in local horizontal, local vertical, with respect to Foton/FLOYD, orbital direction is left, Earth is below.

As a late addition to the project a number of science instruments were placed in both MASS and Fotino (by the YES2 team in Europe), and a GPS/GLONASS unit was added to the Foton in order to track the tether deployment, by the YES2 SSAU team from Samara, Russia. GPS units were also developed for MASS and Fotino, but out of these two only the one for MASS was built into the YES2 flight equipment (Figure 4). A UHF transmitter was placed on MASS, transmitting its science data to FLOYD (which would then forward it to Foton for telemetry to the ground).

Fotino was not intended to be recovered, due to import/export and other political issues. Nor was there an official intention by ESA to transmit any science data to the ground. Nevertheless, a transmitter was built-in and a mobile ground station/recovery team was deployed on location in Kazakhstan as a student-only initiative.

The Fotino heat shield is radio-transparent, so the antenna's could be contained beneath the outer shell of the capsule[6].

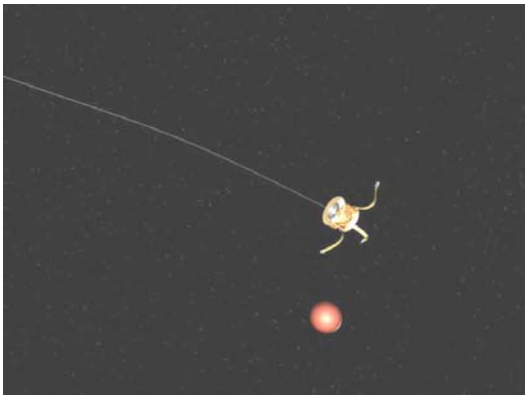

Figure 3. Fotino and MASS with tether are both on their way to the atmosphere. Only Fotino should survive that ordeal.

A highly international team of students developed themselves the YES2 transmitters, receivers, splitters, combiners and antenna's. Although not the same rigid engineering standards were followed as for the critical subsystems of YES2, as much as possible the same system engineering methodology was applied[7].

These many last-minute RF developments and innovations (Figure 5) are the topic of this paper. In the next sections, design, performance and test results of each of the units is described. The paper concludes with flight results and an outlook.

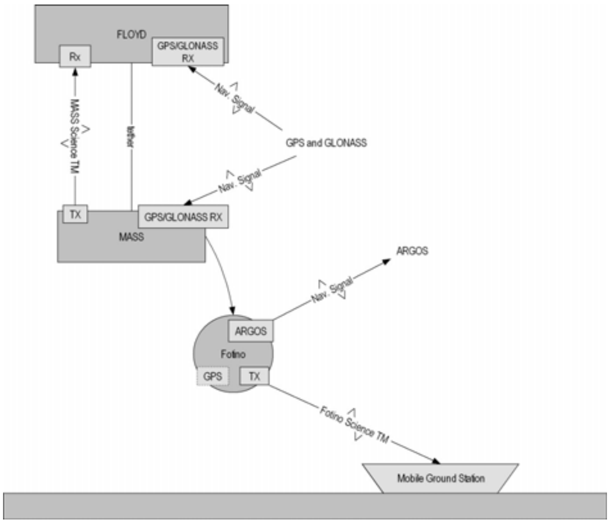

Figure 4. Schematic overview of the YES2 RF project.

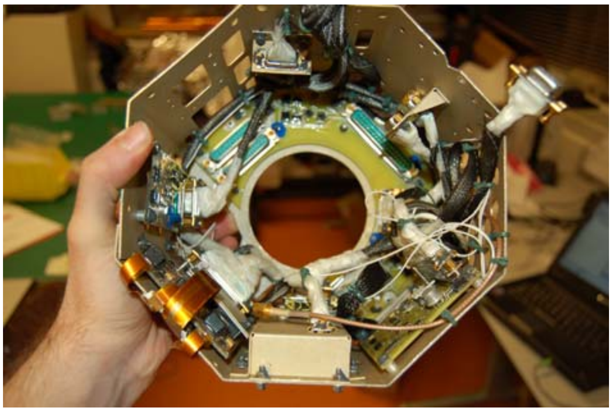

Figure 5. Some of the electronics inside the 6 kg capsule. Not integrated here yet are the beacon system, the GPS (not flown) and the 27 external sensors (pressure sensors and thermocouples).

2 INTER-SATELLITE LINK

As it has been said before, MASS and FLOYD will be spatially separated but physically connected through the tether. The inter-satellite link allows the communication between these two parts of the satellite, and allows the transmission of all necessary information from MASS to FLOYD in a constant manner after the MASS deployment. Data such as GPS and sensors signals – magnetometer, tensiometer, gyroscope, accelerometers – is transmitted to FLOYD through this radio link, this way allowing for the correct characterization of the mission. Then, once the data reaches FLOYD, all the information of the sensors is safely stored in Foton through a serial link to the TSU inside it and will be recovered after its controlled landing.

The inter-satellite link is implemented at a frequency of 437 MHz, using part of the spectrum allocated for amateur satellite services in the UHF band. The subsystems which comprise the link are a transmitter placed on MASS and a receiver placed on FLOYD, each one with its own custom made antenna. With regards to its functionality, the system was able to provide with a transparent link between the two satellite units.

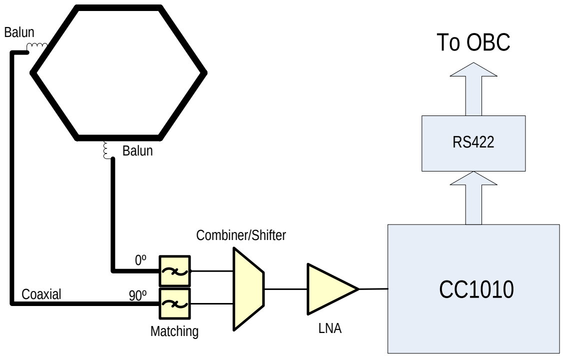

Figure 6 FLOYD UHF Receiver block diagram

The main constraints when designing the system were size and power consumption, but also special attention was put in the shape of the antennas so that they were as much integrated as possible with the spacecraft.

The MASS transmitter relies on a custom PCB design using the low-cost COTS (Commercial Off The Shelf) integrated transceiver Chipcon CC1070 from Texas Instruments as the main processor and signal generator. The design included an digital input stage and a RF output stage, and all the electronic SMD parts were chosen with at least a MIL standard (when possible) that ensured the correct operation under a hostile environment. The most critical aspect when choosing the components was the operating temperature range, although other constraints, as for example the base material, were also taken into consideration. The digital side consisted of a RS-232 driver as well as an 8-bit parallel data interface plus the CC1070, while in the output a high power amplifier RF2155 from RF MicroDevices was needed to boost the signal from the transceiver output to an appropriate power level. The transmitter board has a 50Ω output, providing approx +27 dBm of RF power.

During continuous transmission, the board will approximately dissipate 1 W of heat because of the Power Amplifiers' efficiency being about 50%.

The final PCB layout was fitted in a 45x84 mm board, therefore compliant with the small size requirement. The board was implemented in microstrip technology in a commercial 1.6mm FR-4 PCB.

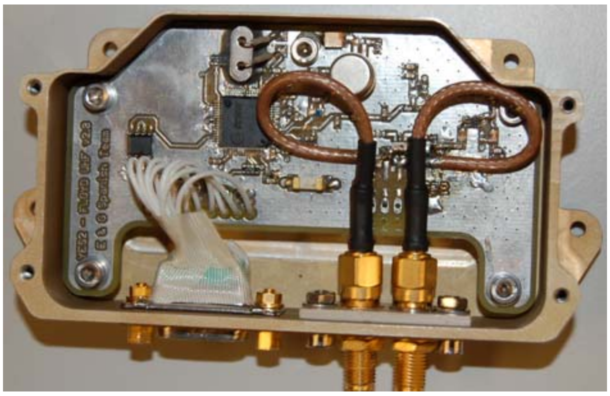

Figure 7. Receiver unit

Similarly to the transmitter, the design of the receiver in FLOYD (Figure 7) is implemented using the Chipcon COTS transceiver CC1010. The design had an analog input comprising a matching network, a 90 degrees phase shifter and combiner, Low Noise Amplifier (LNA part MAALSS0025 from M/A-COM), and the CC1010 (see Figure 6). The digital output of the chip was interfaced to a RS-422 driver (ST3485E). The sensitivity of the transceiver was -99 dBm, therefore due to the mission requirements an additional LNA stage was used in order to increase the range of the link up to 30Km., according to the detailed link budget. When the signal is received and demodulated, the data are transmitted onto the OBC in FLOYD. The final layout had a size of 49x90 mm, with low power consumption and a low mass.

The antennas represented an innovation. The driving requirement was to have no protruding elements (to avoid tether catching) and little effect on satellite dimensions. The transmitting antenna is a modified version of a commercial folded monopole-like layout implemented with copper tracks in a pcb (Figure 8). A common patch antenna design was discarded for dimensional issues due to the low operating frequency, as well as other options such as PIFA implementation due to the necessary reduced dimensions.

By testing in anechoic chamber in ESTEC facilities using the VNA HP8510C, the antenna dimensions were tuned in order to get the desired performance when mounted on the satellite plate in MASS, with a final size of 90x90 mm. Matching was achieved by means of varying the distance between the MASS plate and the antenna, leading to a final protuberance of only 7.5 mm. The antenna S11 performance was measured to be -14 dB at desired frequency of 437 MHz (Figure 9) therefore having a VSWR of 1:1,50.

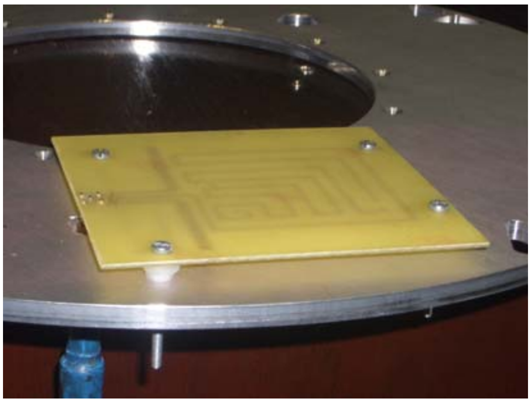

Figure 8. MASS TM UHF patch antenna mounted on MASS dummy plate. Note the 7.5 mm spacers.

Due to the incompatibility of the low operating frequency with the available anechoic chamber equipment, free range measurements using the spectrum analyzer Tektronix 2792 were carried out in order to characterize the antenna. The antenna maximum gain was achieved at 0 degrees with a value of -0.5 dBi . The antenna beam width was around 60 degrees and it was linearly polarized with a cardioid pattern, however the test set up didn't allow for the best grade of accuracy due to the reflections with the ground.

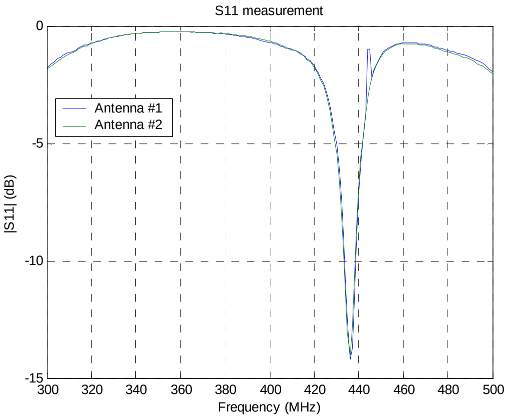

Figure 9. MASS antenna measured S_{11} parameter

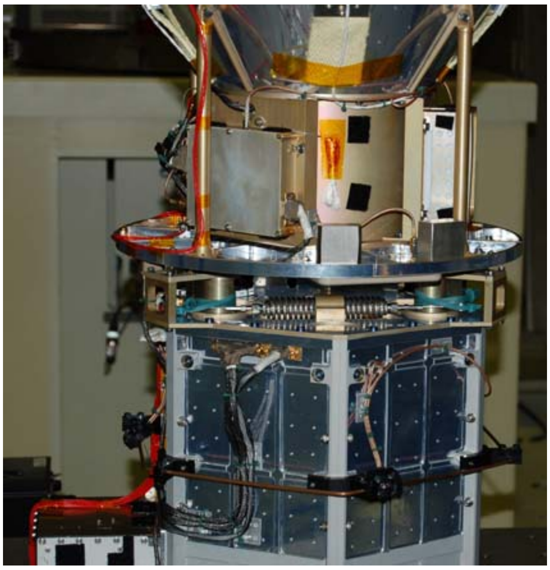

Figure 10. Visible is the MASS RF box (left of middle), MASS TM antenna (mid, flat white at bottom of MASS) and the FLOYD hexagonal receiving antenna (bottom, copper)

The receiving antenna is a hexagon-shaped dual feed circularly-polarized loop (Figure 10). This innovative shape has been chosen to obtain an antenna element that is conformal with the satellite body (to avoid risk of tether catching)[8].

It is fed through two ports with signals shifted 90 degrees so that an omnidirectional gain pattern is obtained (Figure 11). The fact that this antenna was a balanced radiator, presented some additional complexity when matching it to the receiver output. Several options were carefully considered and in the final implementation the matching was done by means of coaxial 4:1 baluns placed at the antenna output ports. The phase shift was achieved through an integrated SMD phase shifter placed in the receiver PCB. The antenna body was manufactured using semi rigid coaxial cable with PTFE dielectric and proper stress treatment was performed in order to avoid any harmful thermal expansion.

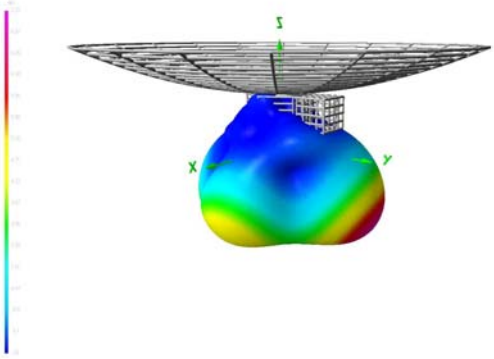

Figure 11. 3D view of total gain, vertical plane.

It was tested in an anechoic chamber as a 1:5 scale model (Figure 12) and in open air as a 1:1 model. Tests were carried out to determine the best feeding technique and they included a mock up of the Foton Battery Pack which acted as the main reflector for the structure.

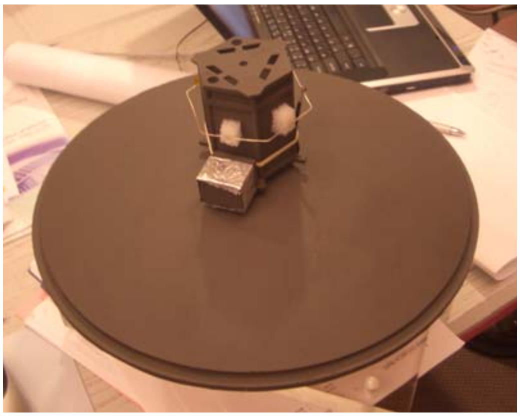

Figure 12 FLOYD UHF antenna 1:5 scaled model

After the flight model construction, several tests were performed in order to demonstrate the feasibility of the UHF subsystem, including range and EMC ones (Figure 13). Successful results proved that designing and building the UHF link subsystem with COTS components is an option to take into account in spacecrafts where weight, size or consumption represent critical constraints.

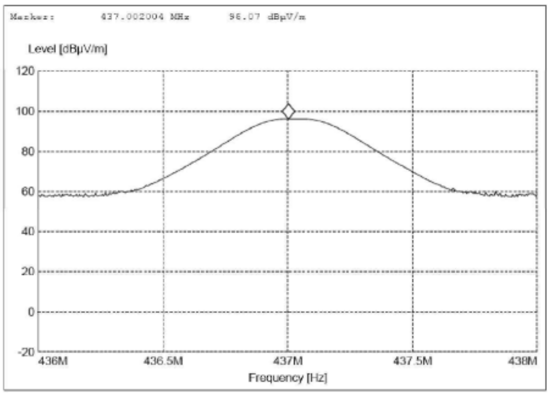

Figure 13. Transmission strength of MASS TM as determined in the Maxwell facility at ESTEC

3 GPS SYSTEMS

In 2003, the YES2 team successfully tested a Russian-built GPS receiver in the Spirent GPS test facility at ESTEC. Prepared by Samara State Aerospace University it then flew successfully on Foton-M2. Based on the YES2 specifications, IRZ in Izhevsk developed a much more compact and low-power next generation unit, which was installed on Foton and on MASS (Figure 14, Figure 15, Figure 25, Figure 26). Another, even more compact unit, was designed and tested for installation on Fotino (Figure 16, Figure 17), but due to interference issues and time constraints, it was eventually not included in the flight model.

Figure 14. MASSTM unit and GPS/GLONASS receiver

The GPS in MASS provides information for accurate tracking of the trajectory of the MASS-Fotino structure during the tether deployment and for the tracking of the MASS structure until its burn out. The information is transferred to FLOYD through the UHF link and it is stored in Foton for further processing.

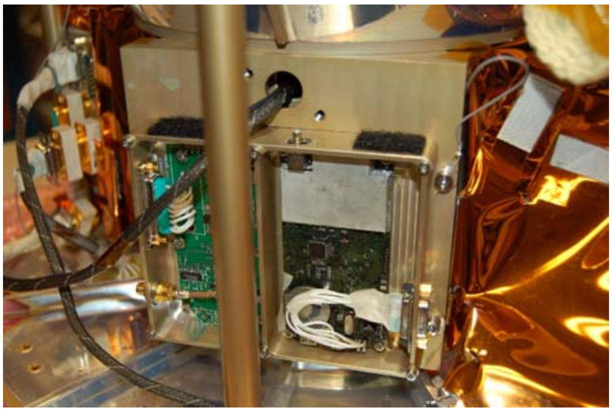

Figure 15. TM unit and GPS/GLONASS receiver installed on MASS (lid removed for picture)

The GPS unit was designed and manufactured by Izhevsk Radioplant in Russia. It had reduced dimensions (45x90mm), small weight (25g) and low power consumption (1.7W); and was also added the capability of GLONASS signal reception. In the YES2 mission, though, only the GPS signals were used to acquire position. The receiver provided the position and speed vectors, time and date UTC, changes on clock and carrying frequencies as well as the number of satellites under view in a custom format through the RS-232 protocol.

Several tests were carried out to ensure the proper performance of the units under a typical mission scenario. For this purpose, the GPS simulator at ESTEC facilities was used. The units showed good accuracy and tracking over the whole set of simulations.

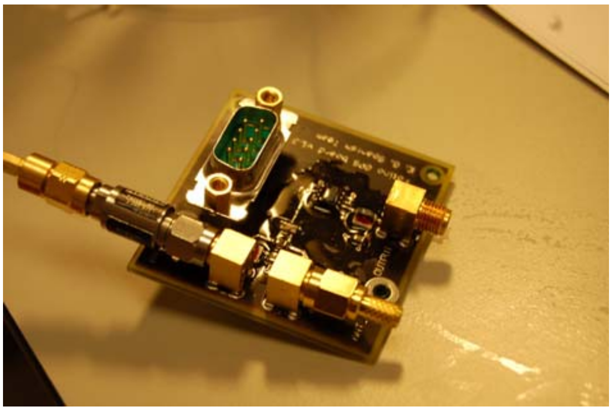

Figure 16. Fotino GCA (GPS Combiner and second Amplifier stage)

The GPS subsystem in Fotino initially comprised the receiver and two patch antennas (model AR-05 from SYNERGY SYSTEMS) with built-in LNA. A custom made pcb (GCA, GPS Combiner and Amplifier) which combined the two signals and gave an additional stage of amplification was used as an intermediate stage between the antennas and the receiver unit, S parameters showed in Figure 18. Since the antennas were not space qualified, they had to follow a process for space preparation which included the removal of all plastic parts and unnecessary complements, performed at the clean room in ESTEC.

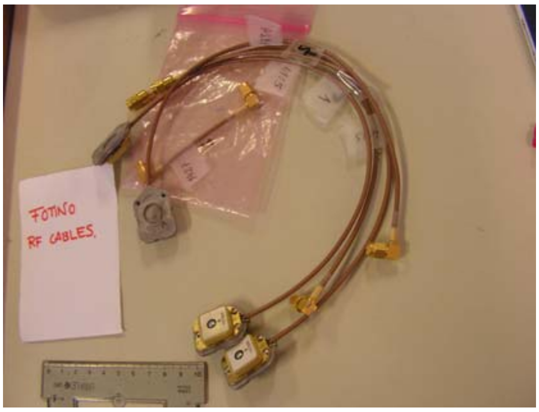

Figure 17. GPS antenna's prepared for installation on Fotino

The GCA also ensured the correct DC-feeding of both active antennas. By means of two SMD bias tees (JEBT-4R2G from Mini-Circuits) the DC current was injected into the coaxial RF line, this way allowing them to provide +28dB of gain each. When the RF signals reached the GCA, they were combined in-phase and then amplified again to ensure enough power at the receiver input. The GCA together with the antennas provided an amplification of up to 55dB.

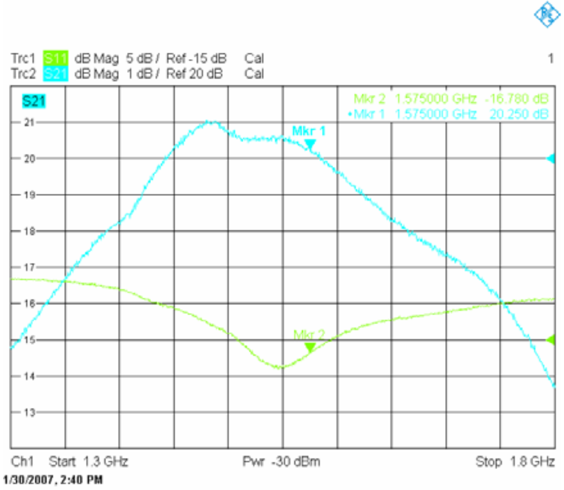

Figure 18. Fotino GCA *S*-parameters measurement (input F = port 1; output = port 2): more than 20 dB gain is achieved, with low reflections (-16 dB S_{11}).

The operation of the GPS system for Fotino has been checked by different test stages. First, the RF front-end operation has been verified by using a commercial GPS receiver with an external RF input connection. The GPS front-end consists of the two active patch antennas and the GCA. This configuration was tested outdoor and up to 8 satellites could be locked, with a SNR between 28 and 47 (over 50), allowing a few meters accuracy in the given position.

Test with a single antenna have also been carried on. The next step has been the interfacing of the front-end with the Russian flight model receiver. At this point issues started to arise. Further investigations on the front-end using a spectrum analyzer showed a severe EMI problem connected to the high gain of the system (Figure 19).

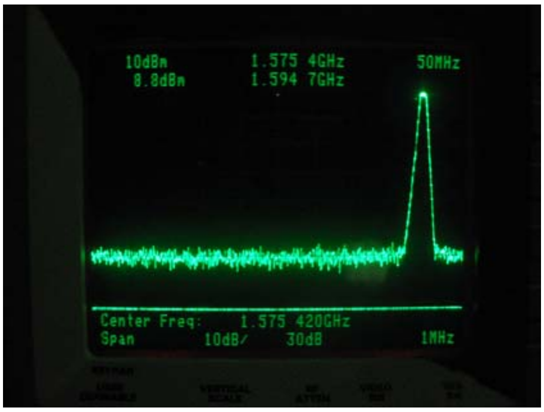

Figure 19. GPS front-end resonance shown in spectrum analyzer. GCA testing shows additional shielding was necessary to avoid EMI and feedback between LNA and antenna.

Being a re-design not possible for time constraints, a shielding approach was followed in order to mitigate the problem (Figure 20). The self-resonance of the system could in this way be reduced (Figure 21).

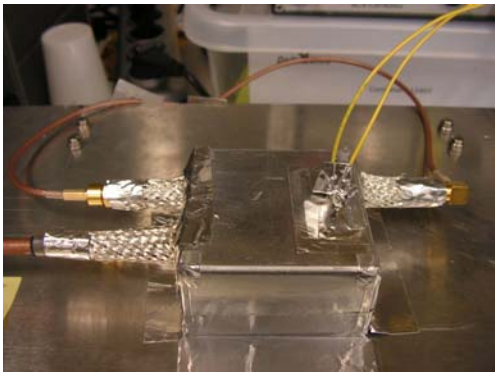

Figure 20. GCA shielded to avoid the spurious resonance.

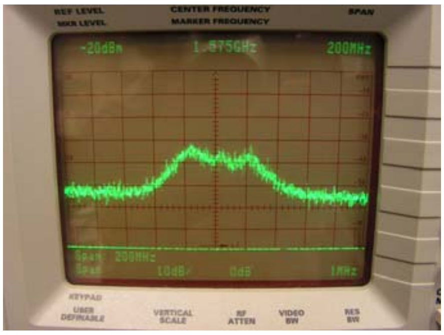

Figure 21. GPS front-end output after shielding: the resonant effect disappeared. The image shows the amplification provided in the GPS band.

Further GPS positioning tests showed the good effect of the interference reduction, but only when using a single active antenna. Mainly due to the low repeatability of these results it was decided not to integrate the GPS system into Fotino flight model. Unfortunately and as mentioned before, the GPS in Fotino was not eventually flown due to interferences and time constraints.

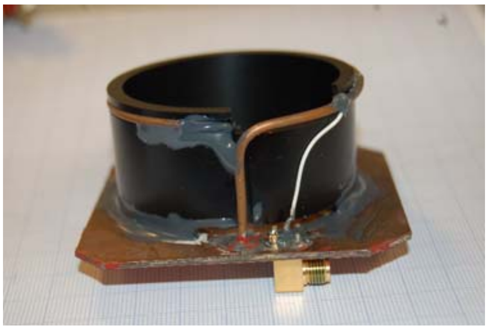

Figure 22. A DDRR antenna with mechanical support as used for Fotino TM and ARGOS beacon.

The Fotino capsule had various on board systems to be located after the landing, although the main one was the ARGOS beacon. The Argos system calculates the position of the beacon my means of 4 receiving satellites orbiting at 850 km altitude. After the beacon is switched on and transmits to the satellite constellation, its coordinates can be retrieved through the internet. In order to have an omnidirectional pattern for the ARGOS transmitting antennas, two loop antennas (DDRR) were used.

The antennas were tuned using the 85107 HP VNA at the Compact Antenna Test Range (CATR) facility in ESTEC. The adjustments for best match are limited to two: trimming the end of the loop with a tubing cutter and moving the feed tap (Figure 22, Figure 23), in order to obtain the minimum standing wave ratio SWR and the best reflection coefficient.

Figure 23. Installation of a DDRR antenna into the PU foam wall beneath the Fotino heatshield

The tuning was performed using the Fotino Capsule in order to consider all the materials that could affect the matching of the loop antennas. A S11 as good as -32 dB could be obtained at centre frequency (401 MHz), and better than -10 dB over a 20 MHz band.

In order to feed the antennas, a 3dB splitter was also designed, centered at 401 MHz (ARGOS carrier frequency) and using lumped elements in a Wilkinson configuration.

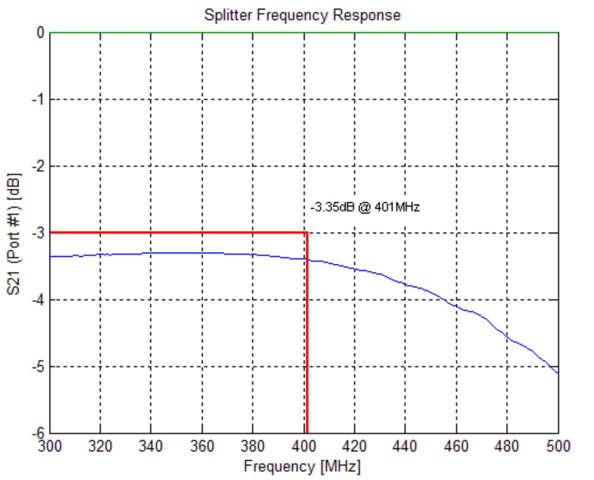

Figure 24. ARGOS splitter frequency response (transmission)

Special care was put to ensure that the components were able to withstand the output power of the beacon. The coupler showed good performance and very low losses (around 0.35 dB), as it can be appreciated in Figure 24.

Figure 25. The diametrally placed GPS/GLONASS antenna's and combiner of the YES2 SSAU experiment are visible on the Foton plate at the bottom of YES2. Also visible is the late addition of MLI for extra thermal insulation that blocks the FLOYD receiving hexagonal antenna and heavily reduces its performance.

Figure 26. Bottom view of YES2, MASS GPS/GLONASS antenna (large white, middle) and MASS UHF TX antenna (yellow, mid-left) are visible.

4 CAPSULE TELEMETRY SYSTEM AND GROUND STATION

The capsule telemetry system is a part of the Fotino Data Acquisition System (DAS). Its purpose is to continuously sample, store and transmit sensor data during re-entry flight to the receiving ground station (from now on, indicated as GS, Figure 27). Temperature, pressure, magnetic field, angular acceleration and position are the measured parameters. Moreover, after capsule landing the system shall transmit its position with regular intervals.

Figure 27. Portable ground station for Fotino telemetry reception and tracking (4 tracking yagi's and a central main receiving yagi).

The telemetry transmitter (Figure 28) uses the low-cost COTS transceiver Chipcon CC1070 from Texas Instruments in a custom PCB design. The digital input consisted of a RS-232 driver as well as an 8-bit parallel data interface to the CC1070, while in the RF output two high power amplifier RF2155 from RF MicroDevices boosted the signal from the CC1070 to the needed power level. The transmitter board has two 50Ω outputs, providing approx +27 dBm of power each.

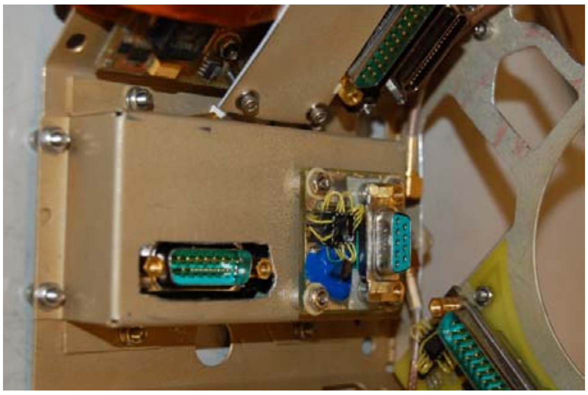

Figure 28. Fotino transmitter inside RF shield box (a sensor board is mounted on it).

Tests were performed for both the transmitter and the receiver boards. The transmitter is powered by a double DC source: 3.3 V, 0.04 A for the digital section, and 3.8 V, 0.5 A for the RF section. The digital section was set up to transmit 12.5 kbps data with Manchester coding, while its RF outputs were then connected, in turn, to the Advantest R4131D Spectrum Analyzer and to a matched power load.

The measured power at each output, at the centre frequency of 434.6 MHz, was 25.9 ± 0.2 dBm, both for engineering model and for flight model (Figure 29). The actual frequency of the system was then changed to 437 MHz via software.

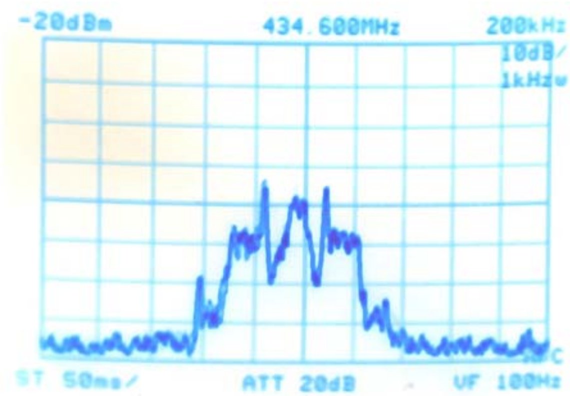

Figure 29. TM transmitter measured output spectrum

The receiver (Figure 30) was then tested in order to characterize its dynamic range and its immunity to noise. The receiver gives an indication of the received power through the use of five LED scales (one for each receiving channel), each scale using 10 LEDs. The interest is to know the correspondence between the received power and the number of LEDs in ON state. To obtain this characterization, the receiver was connected to a MARCONI 2024 signal generator. Minimum output power was set in the generator, and 1 – 2 lights were on due to the noise floor. The receiver sensitivity was measured to be -106.5 dBm.

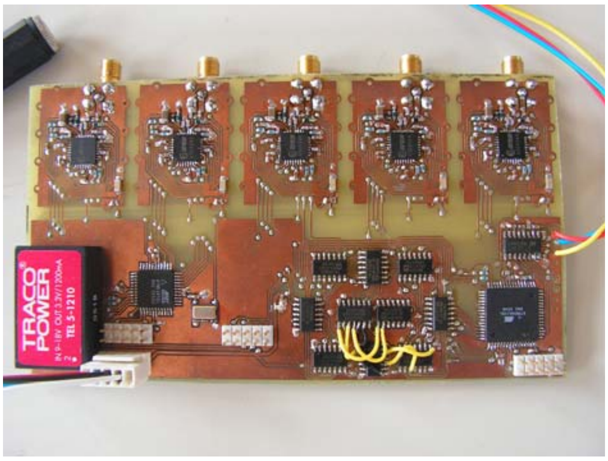

Figure 30. Fotino telemetry receiver board

Then the input power was increased in steps and the corresponding number of LEDs were observed. The results of this test are showed in Figure 31: one step on the LED scale indicates a 6 dB power change. According to the link budget computation, the power received from Fotino when entering the main telemetry zone would be around -90.8 dBm, corresponding to 4 LEDs on, and then increasing with Fotino getting closer to the GS.

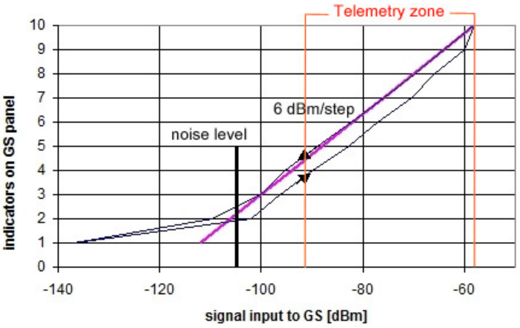

Figure 31. GS receiver test results

An interference test was also performed. For this purpose, a 12.5 KHz rectangular wave was injected in the receiver together with the transmitter signal. The signal and injected noise levels were measured using the spectrum analyzer. The power of the main peak of the noise was set to 40 dB over the desired signal level (see Figure 32). The modulating signal was tuned to move the interference closer and further to the centre frequency of the link. It was observed that the noise does not affect the correct reception until it keeps at least 50 KHz far from the central TM frequency. The reception is corrupted when smaller frequency spacing is set. The immunity was increased by setting the opportune receiver bandwidth in the RX transceiver.

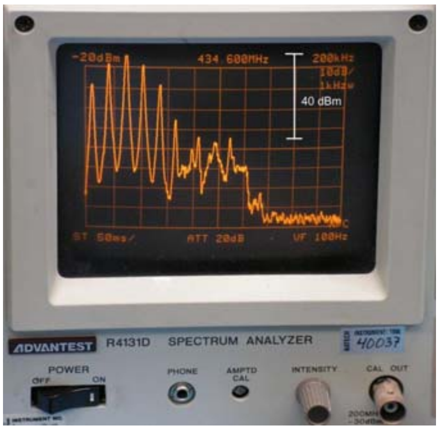

Figure 32. TM transmitter interference test result

5 CAPSULE RECOVERY SYSTEM

The most critical of all the YES2 RF developments is the capsule recovery beacon (Figure 33), as it is the primary system to provide the landing point of the capsule, and therewith evidence of a successful tether deorbit function and capsule survival. It is based on an ARGOS beacon, an animal tracking system transmitting at 401 MHz, and is switched on by the BAS/PAS system (Beacon and Parachute Activation System), triggered by altitude (< 5 km) or time since atmospheric re-entry (> 5 minutes)[8]. The beacon system is compact and self-powered. After landing, about 3 hours of transmission of a beacon signal is required until with sufficient certainty the ARGOS constellation has picked up the signal. The ARGOS satellites that pass over the Fotino calculate the capsule position by triangulation within about 350 m accuracy and forward the position to an ARGOS ground station, where it is made available to the user on the internet. To provide more or less omnispheric coverage, two DDRR antennas are connected to a splitter. The beacon transmits every 40 seconds a short signal (to save power) and has a supply that should suffice for 3 days.

As soon as it is switched on by BAS/PAS, the beacon will not switch off, even if the electrical connection with BAS/PAS is broken, e.g. by an inadvertent crash onto the ground.

Drop tests from as much as a kilometre altitude gave confidence that the beacon would survive a crash, Figure 34. It is however deemed likely that at least the longer one of the antenna cables would be severed. The other cable was kept very short. The system could not be made waterproof however, due to time and mass constraints, so a water landing would not be survived.

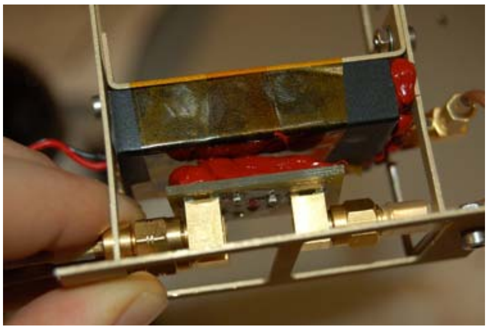

Figure 33. ARGOS beacon and splitter inside its compact crash frame.

The ARGOS system test have been performed during January, 2007 (Figure 35, Figure 36), with the ARGOS transmitter connected to the power splitter and DDRR antennas, which were placed inside Fotino in flight configuration. The ARGOS transmitter was switched on and the test was performed with the capsule kept oriented, in turn, along the three x, y, z axes, in order to check the system functionality also with a random orientation of the capsule after landing. Good position data were received with the capsule kept in any of the different positions. Good precision was achieved, as shown in the satellite image comparison between the estimated and the actual position (Figure 37).

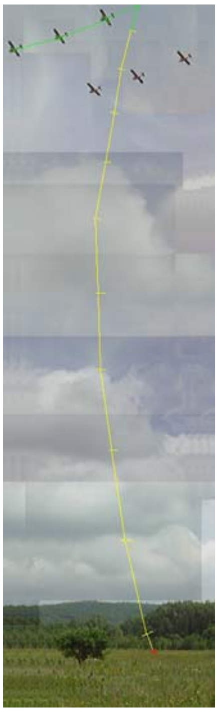

Figure 34. Capsule crash drop test with ARGOS beacon inside. The beacon survived the ground impact with 40 m/s.

Figure 35. Testing of the ARGOS system through the heat shield of the Fotino capsule

6 QUALIFICATION

Beyond such design and performance tests, all the RF flight model subsystems went through a system test campaign for full qualification, including electromagnetic compatibility (Figure 38), thermal vacuum and shaker testing. Although in the final stages of integration a number of compromises were made that reduced the flight performance, some high quality mission data was obtained and a number of systems can be recommended for future use.

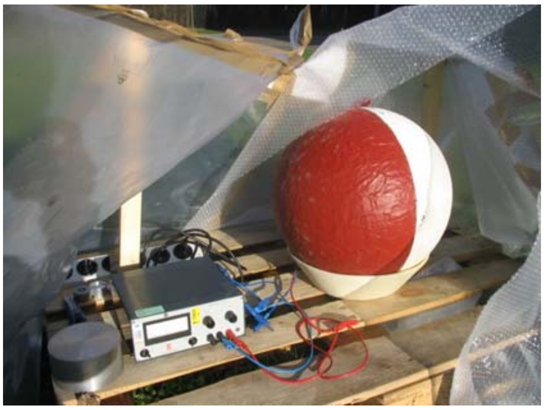

Figure 36. Testing of the ARGOS system through the heat shield of the Fotino capsule: test setup.

Figure 37. Comparison between the actual position of the capsule and the one estimated by ARGOS system (green arrow). Less than two hundred meters error was achieved.

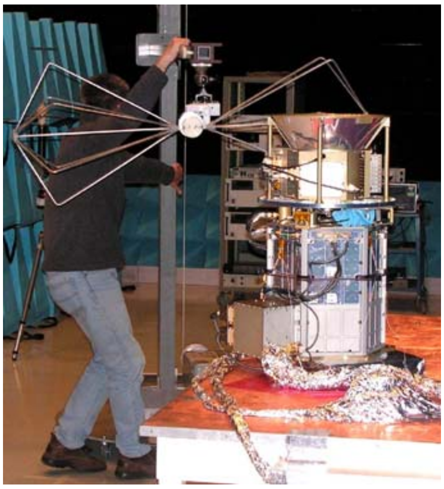

Figure 38. EMC testing of FLOYD/MASS (emitted radiation) in the Maxwell facility at ESTEC

7 YES2 MISSION AND RF

Excellent quality tether deployment science data was received from the tethered sub satellite MASS (Figure 39, Figure 40). Excellent quality data on the tether deployment was also received through the SSAU-built GPS unit on the tether deployed platform (Figure 41). Analysis of the MASS data has already led to confirmation of the ejection system performance, initial angular rate conditions of the MASS/Fotino, measurements of the minimum tether deployment tension, confirmation of deployment of several critical markers on the tether, confirmation of tether brake control, and even helped to estimate the stability and heat flux conditions during Fotino's re-entry[1].

The GPS data is the first data of its kind available for a tether mission and will be highly valuable to determine the tether deployment trajectory in high detail (as good as some tens of meters on 32 km) and resolve tether dynamics to a yet unseen level.

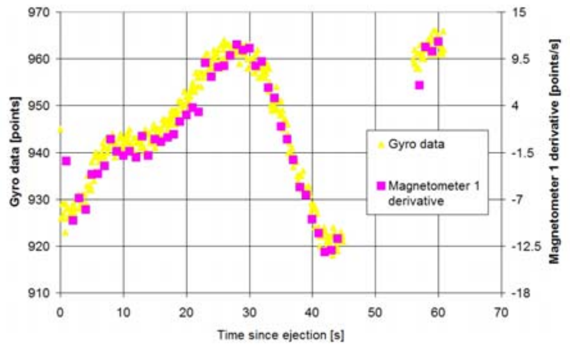

Figure 39. Data received from MASS on angular rate after ejection, confirming proper performance of the ejection system and supporting tether deployment reconstruction and even Fotino worst case entry conditions determination.

The performance of FLOYD's receiving antenna for MASS data was compromised by the late addition of MLI foil around the antenna (to counter an unforeseen thermal environment of the tether system) and data was only received over a 150 m range. As said, this data represented nevertheless much of the sub satellite science objectives, mostly related to initial conditions. Still, the design range of 30 km would have allowed analysis of the capsule initial conditions. An upgraded range of 300 km would have allowed tracking of tether dynamics upon entry into the atmosphere.

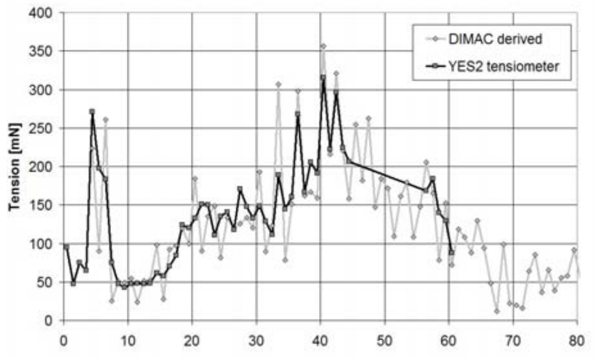

Figure 40. Data received from MASS on tether tension after ejection confirms correct deployment of a damping system integrated in the tether (First spike), correct functioning of the tether brake (broad spike), minimum deployment tension (lowest level around 10 s) and allows calibration of the DIMAC accelerometer data (grey).

The analysis of the data received from the UHF link, we see a continuous reception until almost 150 m, with a window of scrambled data between 92 m and 112 m (see Figure 42).

This can be explained considering that the capsule could have assumed, during the tether deployment, an orientation in which either the transmitting or the receiving antenna showed a null in their radiation patterns. In particular, in the RX antenna it could have been generated by the unforeseen late addiction of the MLI foil.

Figure 41. GPS altitude throughout the YES2 mission is of high quality and will allow a more detailed reconstruction of tether dynamics then ever achieved by any previous tether mission.

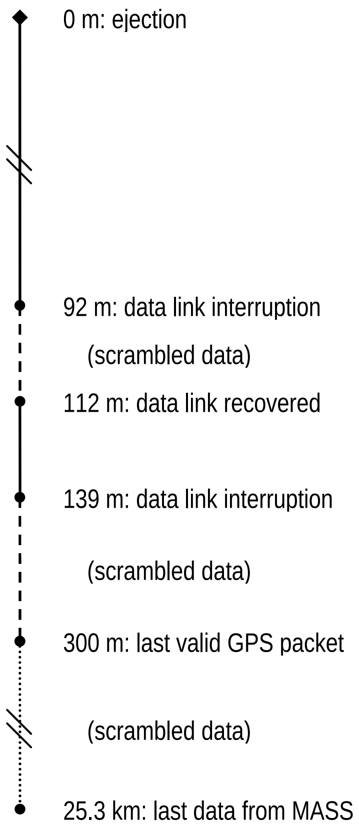

Figure 42. Mission UHF data received vs. distance

To receive data from the capsule a portable ground station was set-up at the initiative of the YES2 student team, about 130 km downstream of the nominal landing site near Tasty Taldy in Kazakhstan (Figure 43). A downstream location was chosen such that in a nominal situation, the main telemetry zone would be visible about 20 degrees over the horizon. The main telemetry zone (Figure 44) is defined as that after ionisation phase of re-entry, but before capsule destabilization in transonic regime. Having the main zone over the horizon allows for a simple set-up for the ground station without need for active tracking. If the capsule would land about 100 km upstream, this would still be acceptable. If the capsule would land downstream, it would still be observed first in the initial antenna orientation, then tracking would be required (for which the system was set-up), Figure 45.

Figure 43. Portable ground station deployed on the steppes of Kazakhstan during YES2 mission

Telemetry from Foton allowed to reconstruct the true trajectory of the deployment, compared to nominal (Figure 2). Acceleration measurements on Foton clearly indicated that the release of the tether was nominal (Figure 46). This evidence combined allowed to calculate the trajectory and targeted landing site of Fotino in the actual mission (Figure 47).

It turns out that the capsule trajectory was targeted for a site hundreds of kilometres upstream of the nominal landing point and was therefore outside the field of view of the mobile ground station, so no telemetry data from the capsule could be recorded.

Also the primary signal from the ARGOS beacon for yet unknown reason was never received by the ARGOS constellation. The capsule may have burnt, crashed (parachute failure) or have made a water landing (Aral Sea). Also charring of the capsule during entry may have blocked the transmission.

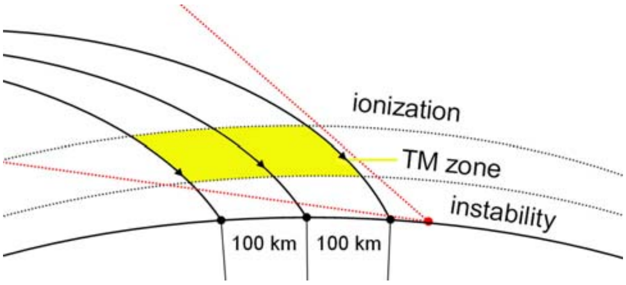

Figure 44. Definition of TM zone

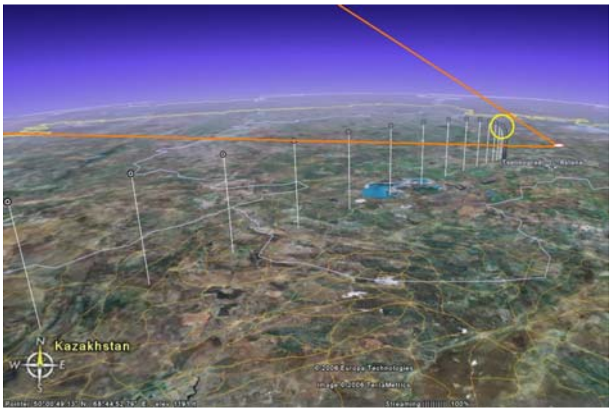

Figure 45. Ground station was set-up with respect to the nominal Fotino trajectory in order to view the main telemetry phase (yellow circle) within the field of view by orienting the ground station simply towards the south-western horizon (orange lines), without need for tracking.

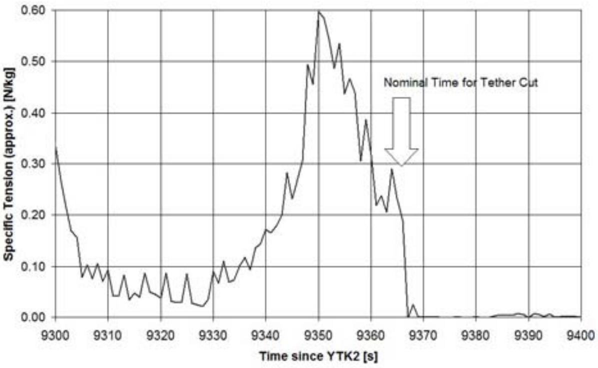

Figure 46. Evidence of proper release of tether and therefore, re-entry of Fotino

Figure 47. Estimated landing area of Fotino is considerably close to Aral Sea, so a wet landing may have been possible. The ground station was located too far upstream (over the horizon) to receive any telemetry

8 CONCLUSIONS

The YES2 tether-assisted re-entry experiment, an ambitious educational project performed successfully in September 2007, carried various RF systems for telemetry of tether and capsule re-entry data, GPS on both sides of the deploying tether and a recovery beacon for the re-entry capsule. The equipment was developed and added in a very late stage to the primary YES2 equipment that focused on observing the tether deployment. The primary YES2 equipment used third party telemetry systems (Foton) for download of the core mission data. In this context, the objective of the YES2 RF project was to provide additional scientific return and allow location and perhaps even recovery of the re-entry capsule after landing. Recovery of capsule data or the capsule itself was however not a YES2 mission goal and was not supported by the YES2 customer (ESA). Whereas the critical YES2 systems were developed under rather strict quality control, the YES2 RF project was performed under much more relaxed demands. Development of RF equipment for space applications is however no triviality. The performance of the equipment could be assessed before flight but unfortunately not all be optimised. A number of creative solutions and compromises were necessary to be ready in time for flight with a working system.

The YES2 RF project included innovative antenna designs, an inter-satellite communication using COTS electronics and a re-entry capsule to ground transmission through a radio-transparent capsule wall. Particular development successes of the YES2 RF project have also been the innovative GPS/GLONASS systems, a compact re-entry capsule recovery system and a mobile ground station developed in Poland and deployed on location in Kazakhstan within a few days notice. These systems can be applied for future small satellite navigation, satellite or aerial probe tracking and capsule or probe recovery. Both the inter-satellite link and GPS system proved to work in space and yielded valuable data, significantly contributing to YES2 science return. As far as the re-entry capsule is concerned, no signals from it were received, due to various circumstances. The capsule RF in-flight performance has therefore not become clear.The very short time-scale, size of the project, required innovations and the many creative solutions leading to successful qualification for a space-flight of virtually all the equipment make the development effort a success. The data from the GPS and tethered sub satellite are a real bonus to a successful YES2 mission, which is exactly what the YES2 RF project was all about.

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