ADVANCES IN MOBILE USER TERMINALS USING OPEN LOOP PREDICTIVE POINTING AND BEAM-SWITCHED ANTENNAS

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ABSTRACT

This paper focuses on ongoing activities by Spacesys for defining and developing an innovative S_band terminal for two-way communications between helicopter and Ground via geostationary satellite. With respect to airplanes, helicopters represent a major challenge for satellite communications, due to their shape, presence of rotating blades, maneuvering flexibility, lower flying altitude. All factors deeply impacting the characterization of the relevant aeronautical channel, which is highly dependent from the specific helicopter type and its operational requirements. After initial considerations on the prospective market of helicopter communications via satellite, the paper briefly discusses the key technical aspects of the design, realization, installation and operation, looking at reasonable compromises between performance and costs. Results of an in-house funded activity aimed at realizing an S_band helicopter terminal for experimental flights by the end of 2012 are then presented.

1. HELICOPTER COMMUNICATIONS VIA GEOSTATIONARY SATELLITES: APPLICATIONS AND MARKET

Helicopters operational characteristics, making them unique, are considerably enhanced by implementing, via geostationary satellites, two way links with remote data stations. At present, very few helicopters are equipped to meet this requirement.

Most existing installations concern military helicopters, while civil helicopters, that would considerably benefit from that additional communication capability, are not aware of the new possibilities and, moreover, cannot afford the relevant terminals for cost reasons.

Although the bandwidth cost at S_band is not expected to decrease substantially in the future, nevertheless the injection of innovations on the helicopter terminal is expected to reduce the communication costs thus reaching a fair compromise between performance and price.

Representative application cases where medium and long-distance, real-time, satellite communications with helicopters may provide operational improvement are the following:

- Defence: both piloted and unmanned helicopters need efficient two-way communications between the mobile and ground posts. Military helicopters are used, besides transportation of goods and personnel, also for surveillance purposes and for taking and relaying in near-real time, pictures and videos of the scene below during military operations. This implies a communication capability in the helicopter to ground direction of several hundred kbps. An equivalent capability may be required to transmit updated operation maps from ground to helicopter. A quasi-broadcast mode might be used to convey, to a fleet of helicopters, operational instructions, weather forecasts or warnings;

- Civil Protection: this governmental Body is continuously involved in inspection activities in occasion of disasters. The Civil Protection supports post-disaster activities that involve people, urban and cultivated areas monitoring using helicopters equipped with cameras and auxiliary instrumentation. Due to the morphology of Italy the helicopters in charge of this task would benefit from the availability of efficient and low-cost terminals for remotely relaying in near real-time videos and other data to the Operation Center located in Rome. Other European Countries might have similar operational requirements;

- Coast Guard: they are involved in rescue operations that frequently involve helicopters needing good communications, especially when the rescue operations happen in the open sea and far from national coasts;

- Industrial operations and civil works: there are several entrepreneurs operating abroad managing and
operating quite complex civil works and infrastructures. The liaison between the local supervisors and the home base is typically based on conventional deferred-time communications. Real time video relay, as might be required for remote monitoring or inspection of the work progress, is unfrequent because of the high cost of wideband satellite channels and helicopter terminals;

- News and live events: the owners and operators of TV news organizations are expected to increasingly become real time witnesses of both peacetime and wartime events. The use of helicopter for live events video taking is expected to grow specially if the mobiles can be rather inexpensively equipped with terminals capable of transmitting and receiving data at useful data rates compatibly with good quality. Indeed the value of information provided in real time will increasingly become the divider between an old and new mode of information delivery.

In the world of entertainment business, helicopters are sometimes used to monitor the progress of a competition. However the lack of real time relay capabilities results in significant delay between the event and its delivery to the general public. Also in this case it is expected that the availability of low cost helicopter-borne terminals for links with the home-base via a geostationary satellite will increase the event attractiveness. One point is however clear: signal transmission between helicopters and home bases does not aim at a mass market. The most appealing, thus sellable applications fall, instead, in the domain of governmental, scientific and selected industrial interests. As such the production of helicopter-borne terminals will imply modest quantities with an expected high content of non-recurring work.

One basic question is: which could be the market size for this terminals? The total helicopter number was estimated 1 by the middle of last decade- around 56300, of which slightly more than 50 % were for military use. North America accounted for 39.5 % while Europe accounted for 19.5%. The Italian share is quite modest 1 few percent of military helicopters and probably a similar percentage for civil helicopters. The above implies that a business hypothesis should absolutely consider at least a European prospective. To give an idea of the target we could set on this business, we may say that considering an helicopter population of 12000 units at European level, a 10 % capturable military market and a 20% capturable civil market, and selling prices of, respectively, 150 keuro/15 keuro for military/civil equipment, one could project, over a 10 years period, an income of 108 Meuro, and assuming a 10 % profit for the Producers, a net profit of 10.8 Meuro, which tough not attractive to large aerospace industries might be appealing for a few medium size SMEs sharing that market.

2. HELICOPTER TERMINAL

2.1 Requirements

Looking at the growth of mobile communications and at the unfulfilled needs of operators, concerning the availability and affordability of helicopter terminals for real time exchanging medium-high speed data with remote Stations, Spacesys decided to invest on the definition and initial development of an helicopter terminal emphasizing cost reduction and reliability, while trading performance with complexity. Although both maritime and aeronautical mobiles currently use the L_band for satellite communications, the S_band was preferred in view of the expected growth of the total bandwidth allocated to the MSS [1]. This implied the possibility of performing demonstration test with the Eutelsat W2A spacecraft and was in line with the prospective availability of geostationary satellites designed to carry a plurality of S-band transponders from the year 2014 onwards. Anyway, the terminal architecture and main features can be easily scaled for operation at L_band, if needed. The key technical requirements, stemming from experience and field returns from Users of subsystems, were:

- no electromechanical components and no use of phasing devices: to reduce costs and wearout impacting reliability and maintenance costs;
- no closed loop tracking: acquisition and pointing were assumed to be based on open loop real-time predictions;
- coverage: by latitude and longitude intervals depending from the prevalent service zones;
- low mass, compatibly with the helicopter environmental conditions and construction features: this was more important for commercial, light helicopters more than for military ones;
- performance intermediate between those of an INMARSAT terminal type 7 and 6;
- circular polarization, preferably one hand only;
- simultaneous transmit and receive capability: non mandatory but desirable;
2.2 Terminal design

The helicopter terminal under development consists of:

- a transmitter chain with 40 W output power, that can accept 4PSK modulated signal;
- a receiver chain provided with a demodulator. Uplink and downlink can carry different types of signals, therefore modulator and demodulator may be different too.
- a switched beam antenna consisting of body-fixed multiple radiating elements each covering a sector of the sky hemisphere. The radiating elements boresights orientation results from computation of minimum gain within a prescribed area defined in terms of operational longitude and latitude limits, by varying the beam size and orientation in azimuth and elevation.

Due to the helicopter motion in position and attitude, the angles between the l.o.s. (line of sight) joining the geostationary satellite and the radiating elements boresights change continuously. Open loop coarse tracking of the satellite is implemented by computing in real time these angles and selecting, as active element, the one for which the above angle is minimum. The realtime computation of the relative boresights to satellite helicopter l.o.s., is performed on board the mobile from the knowledge of the following data: geostationary satellite orbital data, helicopter position from GPS data, helicopter heading plus roll, pitch and yaw angles from measurements taken by dedicated, commercial sensors. A block diagram of the S band terminal presently under development as Technology Demonstrator, is given in Fig. 1. Moreover, as discussed later, the S band emissions must be synchronized to the blades rotation; therefore an additional proximity sensor must be used providing said sync pulses which, suitably processed, are passed to the the S band transceiver. The switching of the radiating elements, each handling up to 40 W, is performed by a coaxial 1PNT switch. Since the helicopter maneuvers are rather slow (turning rate of the order of 3°/s), and since the beamwidths of the radiating elements are of the order of 60° or more, it is not expected to switch beams more frequently than once every 2 or 3 seconds. The helicopter blades run, typically, at 3000 to 3500 rpm, that is one turn in 20 msec. The switching delay is also about 20 msec. This means that in occasion of radiator switching, the transmitter is muted for one turn of the blades, this causing a negligible loss (< 1 %) of data throughput. Much more worrisome is the periodic blocking by the helicopter rotor blades. The disruptive effects of the blades presence is well documented [3], [4], [5]. The effect of rotor-blades rotation on a communication link between the helicopter and a satellite, could be severe depending on the type of antenna and the frequency of operation. For a transmitting or receiving antenna in close proximity to the rotor blades, the rotation itself may create harmonics that are dependent on the angular frequency of the rotor as well as the number of blades. This Doppler effect may impose severe limitations on the communication channel. In addition, rotor-blade rotation may alter other antenna characteristics, including input impedance and polarization of the radiated field. In a few military cases, the
communication antenna is placed above the rotating blades, this helping in minimizing the interference, but for many commercial, smaller, helicopters this is not feasible owing to the implied costs. Accordingly only the helicopter body sides, top and skids are in principle available to antenna installation. Nevertheless, not all locations are equally good for interference reduction while maximizing the access to the wanted segment of the sky hemisphere.

2.3 Installation considerations

Usually an helicopter is operationally deployed in a rather delimited geographical area. We considered two latitude belts: a Mediterranean one (longitude 10 W to 40 E; latitude 30 N to 45 N), and a Nordic plus Baltic sea one (longitude 5 W to 30 E; latitude 45 N to 65 N). For an helicopter flying at the same geosat longitude and in the Mediterranean latitude belt the elevation angle with which the geosat is seen from the helicopter in level flight does vary between 55° and 38°. For the same conditions but for an helicopter flying in the Nordic plus Baltic sea zone, the elevation angle does vary between 38° and 16°. The radiating elements will initially have a boresight elevation angles of, respectively, about 45° (average of 55° and 38°) for the Mediterranean sea, and of 27° for the Baltic sea. Adjustments are possible to be assessed during development tests.

For a representative four-seats, three-blades, helicopter, typified by an ECUREIL AS355, Fig. 2 shows that, if the radiating elements would be put in the upper section of the body, thus very close to the blades, a complete signal blocking would occur for a considerable percentage of their revolution period. To partly counter this damaging behavior we moved down the radiating elements to the level of the landing skids. Now the blades do still interfere with the radiators patterns, but much less because of the greater energy dispersion due to the larger distance between the blades and radiators. This position is also better because of the reduced shadowing by the helicopter body nose and tail when the helicopter longitudinal axis is aligned with the satellite l.o.s..

Fig. 2 illustrates the geometrical relationships showing the impact of antenna installation and of the elevation angle with which the helicopter sees the geostationary satellite on the blocking effect of the helicopter rotating blades. Putting the antenna on top the pilot’s cabin implies a strong blocking effect for all signals arriving
angles. Lowering the antenna at the landing skids level reduces the blocking effect, specially for flights in the Nordic area. However the performance impairments due to the blocking are not completely eliminated. To illustrate the effect of the blades interference and of the distance between blades and radiators on the patterns, we show the azimuth and elevation cuts of an individual radiator (in this case a cupped quadrupole) in three cases:  
- simulated free space in Fig. 3(a);  
- radiator on the pilots' cabin top, as shown in Fig. 3(b);  
- radiator put at the landing skids level as shown in Fig. 3(c). 

For the simulations we used NECWIN complemented by WINSYNTH to generate the radiating and scattering/reflecting surfaces. The blade was simulated as a conductive sheet 30 cm wide by 5 m in length and was put on the symmetry plane with an inclination of 45° w.r.t. the radiator boresight axis, and at a relative distance computed from Fig. 2. We also assumed a good conductivity for the blade, which seemed realistic since blades are often made in carbon fibers.

In Fig. 3(a) we give as a reference the elevation and azimuth cuts of an isolated radiating element, in this case a cupped quadrupole.

In Fig. 3(b) the pattern cuts of a radiator put on the pilots' cabin top (see Fig. 2) shows that the cleanliness and symmetry of the radiator pattern is adversely affected by the near-in presence of the blade. The elevation cuts shows a gain dip of about 5 dB close to the beam boresight that is in the direction where the signal is expected to go or arrive from. The pattern shape, highly lobed, indicates a predominant reflected multiray combination, most likely due to the energy scattered from different segments of the blade.

Fig.3(c) also shows a considerable presence of multirays interferences, but in much less proportion than in the previous case. This positive effect is probably due to the greater distance between the scattering/reflecting blade and the radiator. In other words, the scattered/reflect energy from the blade is distributed over a larger cone, decreasing the unwanted energy density collected by the radiator aperture. However, also in this case we get a gain loss around 5 dB in the beam boresight direction, which leads to consider the simultaneous presence of two effects: one is pure shadowing when the blade pass directly over the radiator, one is a compound of angularly distributed reflected and scattered rays impacting the general pattern shape.

The study of the antenna behavior in presence of the blades is just at the beginning considering the many variables tied to the geometry, helicopter attitude, beams orientation, and the materials used. Nevertheless, the problem due to pure energy blocking seems, at present, unsolvable relying on Electromagnetic tools and techniques, and requires the intervention of other electronic means.

2.4 Sending and receiving signals via an helicopter terminal

Since the blocking effect caused by the rotating blades cannot be solved recurring to expedients involving the antenna, then other means must be identified.
First, however, it will be necessary to define an antenna installation (see the previous paragraph) that minimizes the angular sector over which the antenna gain in the direction of the l.o.s. between the helicopter and the Geosatellite falls below limits defined by the link budget parameters. The time interval corresponding to the angular sectors during which the antenna gain is below the acceptable minimum, is unavailable for data transmission, which makes considerably more costly, system-wise, the data transmission tasks. To give an idea of the performance loss, a blocking angle of 10° would imply, independently from the antenna type, an 8.3% reduction in the time available for transmission or reception. If that angle increases to 20° the time loss goes to 16.6%, and for 30° increases to 24.2% which seems unacceptable: however the literature reports cases for which the loss was nearly 50%.

The loss in the available time results in an increase of the data rates to transmit the same information; alternatively one must accept a reduction of the transmitted data volume. In any case, the data relay to ground via a geostationary satellite, must be done by packets synchronized to the time intervals during which the antenna gain is not adversely affected by the presence of the rotor blades.

On reception the same approach is applicable, that is packetizing the data to be sent to helicopter via the geostationary satellite. However the sender does not know the timing of the slots where the available antenna gain is below a given threshold. A possible solution is to relay to ground the timing sync pulses normally used on transmit. The sender on ground will thus compute, taking into account the link geometry delays, the timing intervals useful for sending data to the helicopter. Since the sequence of non-blocked time slots is computed on board the helicopter, the approach herein described can be applied both when the helicopter performs simultaneously transmit and receive functions, and when only the receive function is activated, in which case the transmitter implements a ‘keep alive’ task.

At the time of this writing the matter is subject to further detailed analyses supported by software simulation under development.

2.5 The “helicopter version” of the aeronautical channel

The Company's funds available for the helicopter terminal R&D did not allow, so far, to develop a channel model beyond the appraisal of its structure related to the specific aspects of the helicopter-to-geostationary satellite links.

The version of the helicopter to-geostationary channel model that we intend to develop, is characterized by several differences w.r.t. a classical aeronautical model. First of all, it can be the model can only take into account the cruise phase in the 100 to 3000 m altitude range. This implies that the channel model may skip the landing, take off and taxiing phases that are often included in the generic aeronautical channel. Additional simplification seems possible. For example the main contribution on the scattered and reflected energy from the body comes primarily from the blades: the remaining of the structural parts of the body should not contribute much in particular for the antenna installation proposed in paragraph 2.3. Since the body structural parts contributions are deterministic they could be taken out from the statistic evaluation of the
fading channel. Since the scintillation effects are predominantly important in the equatorial belt, and since the operational latitude range of interest is above 30° latitude (see section 2.3) the atmospheric fading effects should be minor if not negligible. For military helicopters the situation could be different and must be investigated.

Concerning the multipath from ground, the over-water flights represents a reference case. One can first order neglect the specular reflections due to the discriminating effect of circular polarization. For estimating the multipath power and delay, methods described in the literature are available at least for over water flights [6], [7]. Assessing multipath from land overflights is more critical: for flat land expanses one could consider the terrain scatter coefficients which are frequently used in the design of SAR instruments. For mountainous terrain one approach could be to make a piecewise approximation using worst case values for the slopes.

Concerning the multipath due to the rotor blades not much is available in the open literature, with few exceptions [8], but is rightly considered the most damaging cause of performance degradation in the helicopter variant of the aeronautical channel. Accordingly we plan, in following program phases, to focus our attention on this most challenging system aspect.

3. RESULTS OF THE HELICOPTER TERMINAL DEVELOPMENT BY SPACESYS

We show some pictures of the hardware developed so far according the operational requirements of section 2.1 and preliminary, self-defined, design specifications outlined in section 2.2.

Fig. 4 shows the 30W S-band power amplifier, the circuit for driving the 1P2T switch and the two coaxial switches type 1P3T that are put on opposite sides of the helicopter body. Each output port of the 1P3T switch is connected by rigid coaxial cable to one input port of a 90 degree hybrid whose outputs are connected to a pair of crossed dipoles who are in charge of generating patterns in circular polarization.

In Fig. 4 one can see the transmit branch, made from commercial components: an I/Q modulator; two stable oscillators for the frequency conversions, a frequency converter, a level amplifier, a passband filter and pads. All connections are made with rigid coaxial cable for both mechanical and electrical reasons. The receiver branch is missing in the picture and will be incorporated at a later stage. This platform carrying the

![Figure 4. Power amplifier, switch driver, pwr I/F](image)

![Figure 5. A single group of three radiators (a) and two groups of three radiators ready to be installed on the helicopter](image)

transmit and receive sections are positioned inside the cabin at least for the Demonstration tests.
Fig. 5(a) shows a group of three switchable radiators that constitute one-half of the antenna: in fact there are two identical radiator groups, one on the left and one on the right side of the helicopter. The radiators boresights are angularly displaced by 60 degrees; the angle formed by the boresights and a local tangent plane is about 45 degrees. The radiators are Short Backfire Elements having -3 dB beamwidths around 65 to 70 degrees in order to cover the full azimuth range. The radiators are held in place by a large diameter tube and, for the demonstration model only, means are provided for fine adjustments of the elevation angles. Inside the tube there are the three 90 degrees hybrids, the 1P3T coaxial switch, all rigid cables linking the various components, and a DC connector with wires connecting the mechanical switch to the associated driver which is up in the pilot’s cabin.

Concerning the radiator type, the project did initially consider a cupped quadripole; a very simple and low cost item to be produced. Subsequently we moved towards a SBA (Short Backfire Antenna) which achieves a better in-band matching. The choice of SBA instead of a patch antenna is due to the higher gain and better control of the pattern outside the main lobe. The measured mutual coupling between two SBA in contact was between -40 and -50 dB. A high independence of the radiator pattern from adjacent structures or radiators is of primary importance for a beam-switched antenna. Fig. 5(b) simply shows two groups of three radiators ready to be installed on board the helicopter.

Concerning the electronics controller, our approach was in the direction of using the least costly commercial devices compatibly with the minimum performance, in line with our effort to minimize costs for the civil market. To this end we are using low-cost sensors (GPS receiver module, a magnetic compass, tilt-compensated inclinometers) while the rest of the circuit is built around low cost ARDUINO platforms. For a military version a thorough upgrade will be probably required.

4. AREA FOR FURTHER IMPROVEMENTS AND DEVELOPMENT

We intend to derive, from a basic core architecture, two product families: one with fair performance and low cost for civil uses; and one, ruggedized, more performant and costly, for military applications. These products will require a comprehensive system capability to define the Terminal personalizations and adaptations to existing helicopters, needed to meet the Customer objectives and to drive their implementation up to final testing.

5. REFERENCES


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