Space Operations Communicator
Vol. 5, No. 1, January—March 2008

COST EFFICIENT EVOLUTION OF THE ESA NETWORK IN THE SPACE ERA

P. Maldari
ESA Directorate of Operations and Infrastructure[1]

N. Bobrinsky
ESA Directorate of Operations and Infrastructure[2]

This paper addresses the evolution of ESA's Tracking Stations Network (ESTRACK) subsystem families within the overall architecture of the Network since the early 70's. The upgrading was guided by the following main principles: enforcement of high homogeneity within the Network, avoidance of proliferation of mission-specific equipment, optimisation of station operations and maintenance by allowing centralised, remote Control Centre access for station monitoring and control, software maintenance and upgrade purposes. The Network evolution employed automated operations concepts and also respected standards and international recommendations (e.g. CCSDS) related to the interoperability aspects of facilities belonging to cooperating space agencies. Finally, the planned enhancement of the ESA Tracking Stations Network and its perspectives in the foreseeable future is presented.

I. THE ESA TRACKING STATIONS NETWORK AND ITS EVOLUTION

A satellite mission includes three main elements: the Space Segment (one or more satellites), the Launcher and the Ground Segment.

A generic Ground Segment is composed of:

1) The Control Centre, responsible for the operation of the satellite from its separation from the launcher until the end of the mission. The Control Centre responsibility extends to the maintenance of the satellite in its orbit and to the operation of the payload for optimal exploitation of the mission and reception and distribution of the mission products to the User Centres.
2) The User Centres, where the mission products are received, usually from the Control Centre of the mission, processed as required and distributed to the final users. The User Centres are normally also responsible for the planning of the utilisation of the satellite payload, and provide the Control Centre with planning schedules for payload operations throughout the mission.
3) The Ground Network composed of one or more ground stations, provides the TT&C interface between the Control Centre and the Space Segment. Additional station's functions include tracking of a satellite in its orbit, determination of its position and movement in the orbit as seen from the ground station (range and range-rate); coding of the telecommands received from the Control Centre and timing of their transmission to the satellite; pre-processing and time tagging of the telemetry (housekeeping and payload) received from the satellite and transmission to the Control Centre, etc. The geographical locations of the stations are selected as a function of the characteristics of the orbit of the satellite and its required visibility from ground, stemming from the mission requirements.

[1] Robert-Bosch Strasse 5, 64293 Darmstadt, Germany, paolo.maldari@esa.int
[2] Robert-Bosch Strasse 5, 64293 Darmstadt, Germany, nicholas.bobrinski@esa.int

The initial ESRO[*]* missions were all in high-inclination orbits and the Ground Network was composed of the Redu, Fairbanks and Spitzbergen stations, i.e. by stations with good visibility for the support of polar orbit missions. Launch services were provided by NASA, and the Network was augmented as required by external NASA stations. The space link interface between satellite and ground network was operating in VHF (136 MHz downlink and 148 MHz uplink).

NASA ground station technology was widely used in the ESRO stations at the beginning; however, quite substantial technology development was initiated in parallel in Europe. One of the major developments of those days was the Redu VHF receiving antenna produced by an Italian company (Vitroselenia) and based on a planar design with distributed dipoles providing ca. 22 dB gain.

Figure 1. ESA VHF antenna in Redu

The breakthrough of European independence on ground station design came with the design and implementation, in the first half of the 70's, of the ground station for the support of the GEOS and METEOSAT missions (GEOS-1 launch 20 April 1977; the launch failed and GEOS 2 was launched successfully on 14 July 1978 – METEOSAT-1 launch 23 November 1977).

Both missions were geostationary. GEOS was a scientific mission operating at VHF on the uplink and in S-band on the downlink (the first ESA mission with an S-band link), METEOSAT, a meteorology mission, had TT&C in VHF and payload operations in S and L band. The S-band dedicated station for the support of the two missions was built in the Odenwald, at some 40 km from ESOC in Darmstadt where the Operation Control Centre (OCC) of both missions was located. The newly designed telecommand chain for GEOS uplink support was located in Redu (Belgium). The GEOS and METEOSAT ground segment design, although mission-dedicated, has been the precursor of the future design of the ESA Network in the sense that some basic architecture design concepts of the Network were first established and validated at the Odenwald Station. These included a uniform design of subsystems' interfaces within the station; the conception of a centralised computer-based Monitor and Control system, allowing the control of the station configuration from a central position and hence minimising station operation manning; and the adoption of a newly developed ISO standard (HDLC) for communications between the station and the OCC. The GEOS and Meteosat ground segment also provided ESOC with precious experience in subsystem's design (RF, IF and digital baseband) and station integration which were used later on in the building of the ESA Launch and Early Orbit Phase (LEOP) Network.

---

[*] ESRO (European Space Research Organisation) was founded in June 1962 on the initiative of 10 European countries (Belgium, Denmark, France, Italy, Holland, Spain, Sweden, Switzerland, United Kingdom, and Federal Republic of Germany), the co-signatories of the Agreement for the conception and realization of space missions for exclusively civil and peaceful purposes.

ESRO together with ELDO (European Launcher Development Organisation) were joined together in May 1975 into ESA, the European Space Agency.

Based on the ESA mission model of the late 70's and 80's, the need for establishing a VHF Station Network for the support of launches into GTO (Geostationary Transfer Orbit) became evident, and a VHF Network comprising stations in Kourou (French Guiana), Malindi (Kenya) and Carnarvon (West Australia) was built in the second half of the 70's. The network design was based on the VHF antenna design used for the GEOS telecommanding from Redu and extended to cover the full VHF transmission and reception band allocated for space operations. For the other station subsystems, new development was minimised by utilising already existing designs.

In the middle of the 70's, projecting far into the future, it was realised that the VHF band allocated to space operations would be 'fading out' within the next 20 years, in view of the high pressure by commercial operators to take over the band for ground communications usage. ESA had therefore to prepare for an upgrade of the Network to the S frequency band, newly allocated for space operations (uplink: 2025 to 2120 MHz – downlink: 2200 to 2300 MHz). The occasion came with EXOSAT (launched on 26 May 1983), a science satellite operating in S-band only in all its mission phases. The design of the EXOSAT station in Villafranca (near Madrid) in the second half of the 70's constituted the prototype of the design used for the upgrade of the ESA VHF-band Network to S-band. The main characteristics of the newly designed 15m Villafranca antenna were: EL over AZ mount (-1° to 91° El; -5° to 720° AZ), light weight and fast moving (to cope with the tracking of satellites in low orbits during perigee passes in early orbits, and to minimise recovery time of antenna key-hole for overhead passes), equipped with Autotrack and Programtrack modes, covering the full transmission and reception allocated to S-band and providing automatic adaptation to the received RF signal polarisation (to cope with signal reception from tumbling satellites). The antenna was also equipped with a subreflector defocusing mechanism allowing widening of the antenna beam for increased probability of initial acquisition of the satellite and with a calibration transponder within the subreflector allowing the establishment of a long-loop at radio frequency for ranging and station calibration purposes.

Other major developments for the Villafranca station, adopted for the ESA S-band network design were:

1) The RF subsystems: frequency converters and 1 KW Klystron S-band transmitter covering the overall allocated band.
2) The High Performance Demodulator; a digital design optimised for the reception of very low signals with low Signal to Noise Ratio and minimally contributing to the station losses.
3) The Tone Ranging System: a development adopted later by other European institutions for satellite ranging.

Figure 2. ESA 15m antenna in Maspalomas (set for EURECA)

4) Convolutional Decoders: EXOSAT was the first ESA mission with convolutional coding on board.
5) Introduction of the X25 ISO standard in the communications between the station and the OCC.

Further major upgrades of the ESA Network were driven by requirements stemming from the mission support of GIOTTO (the first ESA Deep Space Mission, launched on 2 July 1985 and operated during the cruise to the Halley Comet from the 15m Carnarvon Station in West Australia) and EURECA (launched on 31 July 1992), the first European microgravity mission released in space and recovered at the end of the mission (6 months later) by the Shuttle.

The three major developments for the GIOTTO support ground station, later adopted in the ESA Network, were the S/X band antenna feed and RF front-end covering the full TX and RX band at S-band and allowing contemporary reception in X-band (8000-8500 MHz); the Deep Space Tracking System (DSTS) upgraded in 1986 for inclusion of tracking of Low Earth Orbiting satellites and known under the name of MPTS (Multi Purpose Tracking System); and, finally, the development of the Concatenated Decoding System.

EURECA marks the introduction in the Network of the Telemetry and Telecommand Packet Standards.

Packet telemetry and telecommand, and concatenated coding are still widely implemented today in the majority of space missions.

The other 3 missions contributing with their developments to the upgrade of the ESA Network were XMM (launched on 10 December 1999) with the new M&C station computer design (STC-2), INTEGRAL (launched on 17 October 2002) with the development of the Space Link Extension (SLE) Services for interoperability between networks of different agencies and the design of the IFMS (Intermediate Frequency Modem System), a digital system integrating the station tracking (Range and Range Rate), receiver/demodulation and uplink modulation functions, and finally ROSETTA (launched on 2 March 2004) which, with the development of the 34m deep space antenna and the extension to X-band transmission (7145 to 7235 MHz) marks the start of the important ESA Deep Space Programme dominating the next decade.

A map of the distribution of the ESA stations around the world is shown in Fig. 4. The figure also contains the dedicated station for ESA Earth resources missions support (Kiruna, Sweden) and the station in Maspalomas (Canary Islands) built to support EURECA, and lately included in the ESA S/X band network.

In conclusion, ESA now owns an important asset of stations providing state-of-the-art functionality for space missions operations.

From 1968 until today, the ESA network has successfully supported in excess of 60 missions, including several 3rd party missions (mainly LEOP) and has recovered several missions from unexpected anomalies.

Figure 3. ESA's first deep space antenna in New Norcia

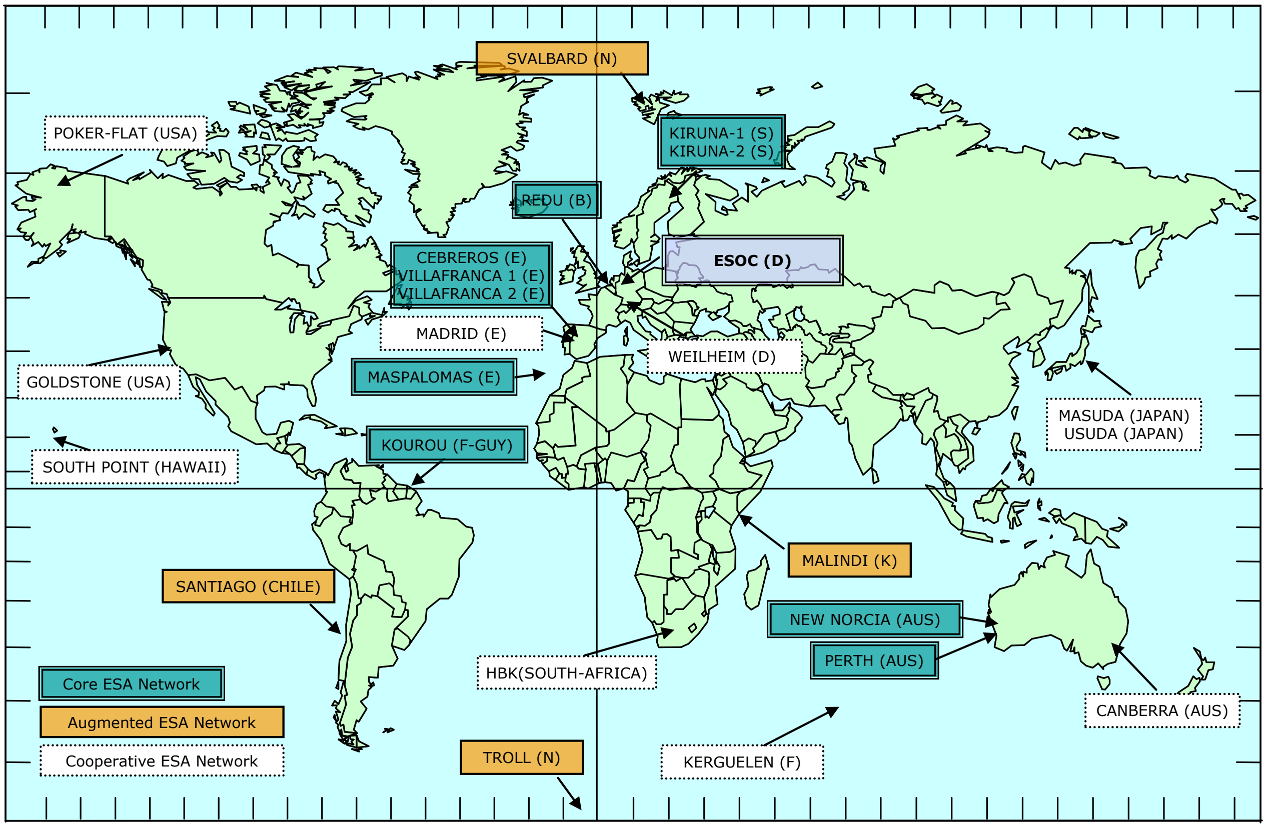

Figure 4. ESA Tracking Station Network (ESTRACK)

II. THE ESA NETWORK EVOLUTION PRINCIPLES

The several upgrades of the ESA Network mentioned above have been implemented following well-defined principles which have been technically and economically valid for the users of the ESA Network.

The first and technically most important principle has been the strict adherence of the Network stations design to the international standards adopted by ESA. This principle is essential to ensure full compatibility between the satellite and the Ground Segment for all missions designed in accordance with those standards. The compatibility with international standards is the basis of the concept of the infrastructure which accommodates the different mission-specific support requirements by simply 'tailoring' the infrastructure, i.e. avoiding changes in the infrastructure design. Clearly, this imposes additional specifications on the design of the infrastructure subsystems in the sense that they must be easily tailorable to cover the range of requirements specified in the standards. Nowadays tailoring is usually implemented by software, uploaded in the subsystem either manually from the subsystem man-machine interface or via the station M&C system, i.e. via the central station computer.

Deviations from standards in the satellite on-board design were accommodated in the past throughout the Network. However, such deviations became quite expensive since they cannot be accommodated within the subsystems tailoring range and, therefore, require a modification of the infrastructure. In these cases, the design of the modification calls for additional effort to maintain the integrity of the infrastructure for the other missions to be supported by the Network.

The second principle adopted in the ESA Network evolution has been to ensure, at any time, the Network 'uniformity' i.e. a similar (ideally equal) configuration of all stations belonging to the Network. This substantially simplifies the logistics connected with station engineering (tailoring, post design modifications, engineering consultancy, etc.) as well as the maintenance and it allows the central management of those aspects with minimal manpower dedicated to it. Network uniformity implies a careful planning in the upgrade of the Network so as to minimise dead times in the Network and to ensure continuity of the support to ongoing missions during the Network upgrade.

As shown in the previous section, upgrades in the Network are driven by missions adopting new functionalities on board (usually covered by new international standards). Consequently, the upgrade of the Network is driven by the mission model and comes in steps, i.e. is based on the concept of 'infrastructure generations'. As experienced in the past, new generations do not necessarily maintain compatibility with old standards, and this opens the question on how to operate legacy missions.

Contrary to the methodology adopted by other agencies of maintaining a specific infrastructure generation until the end of the user's missions, the ESA approach is to migrate legacy missions to the new infrastructure generation. Should this not prove possible, the approach is to implement in the new infrastructure generation minimal functionality as required for the support of legacy missions until the end of the mission. The advantages of such an approach are in the uniform and state-of-the-art configuration of the Network and, in particular, in the uniform maintainability and operability of the infrastructure generations, avoiding logistical overhead for spare parts and maintenance of the old infrastructure generation as well as additional personnel at the station for the support of legacy missions.

III. THE ESA NETWORK MONITOR & CONTROL EVOLUTION

The Monitor and Control of ESA stations has undergone a constant evolutionary upgrade in the past, from the initially distributed manual M&C performed by station operators from the station equipment front panels, to a central M&C position at the station and, finally, to today's system which allows automated station configuration and pass operation from the Ground Facilities Control Centre (GFCC) at ESOC.

As mentioned above, the concept of a station centrally driven M&C system was firstly developed in the early 70's in the implementation of the Odenwald Station for the support of the GEOS and METEOSAT 1 missions. The system was based on a central station computer communicating with the station subsystems via so-called MCM (Monitor and Control Modules). The functionality of the MCM was to provide interface adaptation to the different station subsystems M&C signals, to periodically scan the subsystems monitor parameters and format them in packets periodically transmitted to the station computer and, finally, to send to the station subsystems the control commands (configuration changes/redundancy switching etc.) from the station computer. The MCMs gradually disappeared from the stations with the evolution of the subsystem technology and, in particular, with the adoption of M&C interfaces based in the IEEE 488 standard. In today's station configuration the station computer communicates with the various station subsystems via a LAN.

With the Villafranca station implementation for EXOSAT support, additional functionality was implemented in the station computer to be able to decode selected satellite telemetry and uplink a limited set of telecommands to the satellite (usually via voice control from the OCC) in case of emergency or in case of malfunction of the communication lines between the station and the OCC. This functionality was abandoned in the following generation of station computers in view of the increased autonomy implemented on board modern satellites and in view of the increased availability of the station to OCC communications obtained with modern communication protocols and diversity routing.

GIOTTO saw the initial implementation of station calibration routines and station subsystems diagnostics in the central station computer and the first transmission of a selected set of station monitor parameters to the OCC, to provide the spacecraft controller at the OCC with a minimum of visibility of the station status. The Carnarvon station for GIOTTO support was also the first station with a routine installed in the station computer for the computation of the antenna pointing angles during a pass. The routine was based on Chebichev polynomials whose constants were regularly updated from the OCC.

A significant improvement of the station computer functionality came in the second half of the 90's with the Station Computer 2 (STC 2) which was first used in support of the XMM mission and which is still used throughout the ESA Network stations. Among others, the STC 2 implements functionality for a complete M&C of the station from the GFCC at ESOC, for remote diagnostic and recovery of several subsystems failures and, finally, for remote configuration of the station in support of a particular mission and automated station passes operations. This represents a significant step ahead for efficient network operation, limiting the need of in loco station operators and maintenance to a few people during normal working hours for preventive maintenance.

IV. OVERALL COST CONSIDERATIONS

The cost of a station's network is an important element of the overall cost of various space missions and is therefore the subject of permanent and consequent budgetary pressure. Over the operational lifetime of a space mission, a decrease in the stations costs allows substantial savings and a healthier economic model. On the other hand, outstanding performances are always expected from the ground stations, both in terms of technicality and reliability, for an optimum data return from the supported space missions.

ESA's approach to the resolution of this problem, i.e. offering highly efficient and reliable space communications at an affordable price, is based on the following principles:

a) Flexibility in the approach

A combination of deep space stations (35m diameter type) with stations for near-Earth missions (15m diameter type) has been put into place with frequency bands ranging from S-band to X- and Ka-bands. As a result, all types of missions can be autonomously supported by ESTRACK: deep space trajectories, Lagrange-type orbits, Moon missions as well as all near-Earth orbits (HEO, GEO, MEO, LEO).

In Fig. 5, the present status of ESA space communications is represented in a graphical form. In the figure, the Radio Frequency bands used in each mission for uplink (u/l)/downlink (d/l) communications between satellite and ground are indicated (e.g. for Rosetta SX/SX), together with the respective modulation schemes and bitrates.

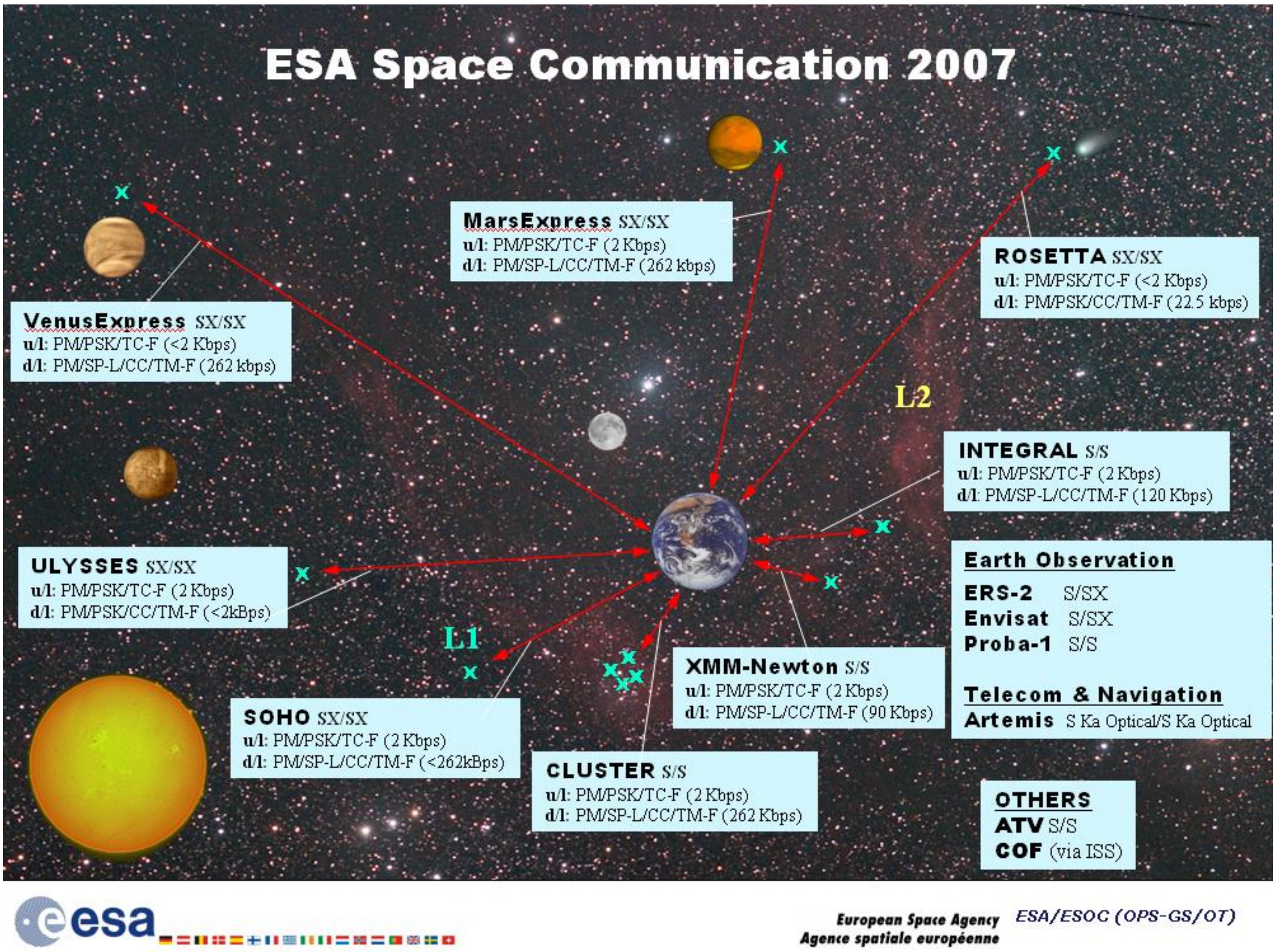

Figure 5. ESA Space Communication in 2007

b) International cooperation

While the core of ESTRACK (Fig. 4) is sufficient for the autonomous routine support of most of the ESA space missions, additional stations are procured on a cooperative basis (e.g. exchange of satellite data for the use of other agency resources) or through commercial contracts for LEOP support or for increased ground visibility of the orbit of a particular mission, in order to augment the data return from space, without investing considerable resources in the acquisition of new ground stations. As a result, only those stations that are absolutely required for the support of ESA's mission model are kept by ESA in an operational status with a substantial load, typically above 60% of the theoretically available time.

The additional stations are labelled as "Augmented ESA Network" and "Cooperative ESA Network" in Fig. 4.

The Operations of the additional station remains the responsibility of the station owner and is governed by a so-called "Service Level Agreement" which, among others, specifies the quality of service required.

Concerning the M&O functionality of the external stations, no specific implementation of remote interfaces has been put in place so far. This could, however, be implemented in the future, based on the SLE Management Services still under development.

The adaptation of external stations to the ESA Control Centre has been achieved through the years by the use of NDIU (Network Data Interface Unit) which were constituted by few racks of equipment interfacing the external station at IF (both on uplink and downlink) and were providing tracking, modulation, demodulation and baseband functionalities and finally protocol adaptation to the required ESA Control Centre interface.

In the last 5 years, thanks to the adoption of SLE by most International Agencies and by several commercial operators, the interface between the ESA Control Centre and the external station does not require special equipment (e.g. NDIU or protocol converters) and adaptation of the interface is obtained by simple tailoring of the SLE software.

c) Centralized maintenance and operations

The maintenance of an asset of such complexity as ESTRACK is managed centrally at ESOC while auxiliary tasks are allocated to local personnel at the stations. The operations, with the exception of mission critical phases, are also executed centrally from ESOC, putting into practice the concepts of remote and automated operations mentioned in Section 4 of this paper.

The strict application of these principles allows keeping a maximum of 8 to 10 maintenance and operation staff in each ground station. They are tasked with preventive and corrective maintenance activities, support to critical operations and provision of emergency on-call support in case of systems failures that cannot be resolved remotely.

As a result, the typical average hourly cost of a tracking hour ranges between 300 and 450 Euros (15m or 35m station).

d) Pricing for space missions

As a matter of internal policy, ESA is widely open to international cooperation with other space agencies, and this is particularly visible in the stations domain. When possible, access to ESA's Network is made available to cooperating space agencies at a price covering both the utilisation of the stations and the manpower effort required for the preparation and validation of the stations for the supported missions.

This results in an hourly rate, which is typically degressive and takes into account such factors as, for example, the progressive decrease of human involvement in mission support and that the critical phase of a mission (e.g. LEOP) is in most cases at the beginning of the mission's lifetime.

For an ESTRACK user this charging principle results in the full control of the costs and in the possibility to fine tune the utilisation of the station as per individual requirements.

V. FUTURE TECHNICAL EVOLUTION OF THE ESTRACK

ESTRACK is currently fully rationalised (i.e. adapted to the needs of the missions presently in orbit). Future missions are, however, very demanding in terms of increased data rates and very precise navigation requirements and therefore call for a progressive migration of space communications to the next available band: the Ka-band.

These requirements, together with the recent adoption by the CCSDS of new standard coding schemes, result in the following main technical changes:

- Introduction of Ka-band reception and transmission components in the stations.
- Systematic utilisation of cryo-cooled technology for improved receive performances.
- Utilisation of turbo and punctured coding schemes.
- Deployment of ultra-stable maser-based frequency & timing systems.
- Adaptation of the Ground Communications Network and Control Centre systems to very high data rates (from 10 Mbps to 400 Mbps).

The implementation of these changes represents a considerable effort for the coming years, and will be accompanied by a decommissioning of those stations which are no longer required to support the quickly evolving ESA mission model.

CONCLUSIONS

After more than 30 years of existence the ESA Stations Tracking Network has reached maturity and a high degree of flexibility and technical performance, making it an essential tool for the execution of ESA space missions. Its role in the exchange of services between cooperating space agencies does not need to be demonstrated, and is always addressed at highest level in any discussion relevant to cross-support activities between various space organisations.

ESTRACK has evolved since its foundation from a rather limited network based on VHF communications and local operations, usable exclusively for the support of near-Earth missions to a highly sophisticated tool, operating at frequencies ranging from S-band to X- and Ka-bands, and supporting missions in deep space and near-Earth with excellent performances.

The systematic application of internationally agreed standards, especially within the CCSDS, to both space and ground parts of the communications (e.g. SLE, TCP/IP), have allowed ESTRACK to become a tool for inter-agency operations and cross support as regularly addressed in forums such as the IOAG (Interagency Operations Advisory Group).

Finally, a permanent scrutiny of the needs of space missions, and a centralised and consistent approach to maintenance and operations has resulted in the possibility to lower the costs of the stations to affordable levels.

REFERENCES

- Maldari, P. (1982) ESA's New Standard 15m S/X-band Antenna – First Installation at Villafranca. *ESA Bulletin*, No. 30, May.
- Maldari, P. (1983) ESA's New High Performance Tone Ranging System. *ESA Bulletin*, No. 34, May.
- Maldari, P. (1986) ESA's New Ground Station at Carnarvon, Australia. *ESA Bulletin*, No. 45, February.
- Maldari, P. (1999) Modern Design for Space Operations – the INTEGRAL Application. Proceedings of DASIA Conference, 1999, (1999) ESA Publications: Noordwijk.
- Maldari, P., Hell, W. and Boutonnet, A. (2006) Extending LEOP to X-band Operations; the LISA Pathfinder example. Presented at SpaceOps 2006, June 2006, Rome.
- Bobrinsky, N., Schulz, K.-J., Warhaut, M. and Winters, P.G. Evolution of the ESA Tracking Station Network, March 2007, ESA Council.
- ESTRACK Facilities Manual (EFM), Issue 1 Rev.0, 17 July 2006.