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Experience with the EURECA Packet Telemetry and Packet Telecommand System

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ABSTRACT

The European Retrieval Carrier (EURECA) was launched on its first flight on the 31st July 1992 and retrieved on the 29th of June 1993. EURECA is characterised by several new on-board features, most notably Packet telemetry, and a partial implementation of packet telecommanding, the first ESA packetised spacecraft. Today more than one year after the retrieval the data from the EURECA mission has to a large extent been analysed and we can present some of the interesting results.

This paper concentrates on the implementation and operational experience with the EURECA Packet Telemetry and Packet Telecommanding. We already discovered during the design of the ground system that the use of packet telemetry has major impact on the overall design and that processing of packet telemetry may have significant effect on the computer loading and sizing. During the mission a number of problems were identified with the on-board implementation resulting in very strange anomalous behaviours. Many of these problems directly violated basic assumptions for the design of the ground segment adding to the strange behaviour. The paper shows that the design of a telemetry packet system should be flexible enough to allow a rapid configuration of the telemetry processing in order to adapt it to the new situation in case of an on-board failure. The experience gained with the EURECA mission control should be used to improve ground systems for future missions.

Key Words: Packet Telemetry, Packet Telecommanding.

1. INTRODUCTION

The European Retrievable Carrier (Eureca) is a reusable platform supplying power, cooling, ground communications and data processing services to a variety of independently operated payloads (ref 1). Fifteen experimental facilities are carried to support more than fifty individual experiments. The operational altitude was 500 Km. The Operations Control Centre (OCC) was at ESA's European Space Operations Centre (ESOC) in Darmstadt, West Germany. The primary groundstations were at Maspalomas in the Canary Islands and Kourou at French Guinea. During the deployment and retrieval phases contact was maintained via the NASA Communications Network and the STS.

At ESOC, operational data processing was carried out on the Eureca Dedicated Computer System (EDCS) that hosts the mission-configured Spacecraft Control and Operations System (SCOS) (ref 2) and the Eureca-Specific Software (ESS) applications.

The Eureca-A1 mission has characteristics differing quite considerably from those of missions hitherto supported at ESOC. One of these is the use of Packet Telemetry and Packet Commanding. EURECA was the first ESA application of Packet Telemetry and Commanding.

2. WHY PACKET TELEMETRY AND COMMANDING FOR EURECA

Spacecraft previously and currently controlled from ESOC all use a time-division multiplexed (TDM) telemetry, in which fixed-size subframes are generated and downlinked at constant rate. In the simplest case a given parameter appears at a fixed address in the subframe and this parameter reports the value of some on-board physical quantity, sampled in principle at the subframe rate. Many spacecraft make rather more sophisticated use of TDM telemetry, essentially because their operations and on-board applications cannot live with the restrictions of fixed sampling/fixed telemetry address. Thus innovations have appeared such as switchable formats, programmable formats and floating formats (this last named being an ad hoc packetisation). These sophistications illustrate a weakness of TDM telemetry, namely its inflexibility of handling a variety of on-board data sources, generating data at temporally varying rates, possibly as determined by an elaborate plan of instrument operations. The traditional TDM approach of allocating fixed proportions of the available bandwidth to each source then becomes both restrictive and wasteful.

Eureca is a re-usable spacecraft supporting a different payload complement on each flight (15 instruments on the first flight). It also has to be assumed that most instruments are controlled with "unknown design" and that each instrument would require on-board flexibility to cover different mission phases and instrument modes. Packet Telemetry provides powerful capabilities to satisfy variable data rates and configurations, also providing abilities for late definition and changes. With Packet Telemetry the source can generate observational data when needed, hence the occurrence pattern or rate may be selected according to the phenomenon being observed. Packet telemetry provides variable partitioning of downlink avoiding unnecessary loading of resources. Another important considerations was that the packet telemetry is a standard where other options would have required special development with no or little reuse leading inevitable to higher cost in the long turn.

The Packet telemetry recommendation (ref 3) uses two principal data structures, the source packet and the Transfer Frame, source packets being multiplexed within transfer frames. Each on-board source must label its data packets using CCSDS defined headers, although no requirements on the contained data are imposed. The transfer frames are of fixed length, optimised for high-performance transfer to the ground. The concept of Virtual Channels (VCs) also exists, to allow separation between data of different priorities, for example real-time data needed for operations and non time-critical dump of science data stored on board. VCs are identified at the transfer frame level. In the case of Eureca there are two VCs, VC0 and VC1, to handle real time and playback data respectively. Playback data is downlinked from on-board bubble memory and will contain bulky payload data as well as housekeeping data from the out-contact periods.

The Eureca telecommanding system is an hybrid between the older command standards (Ref 4) and the new Packet command standard (Ref 5). The reason for this lies in the way it has been implemented on board. Command decoders using the old standard have been used as a basis, but the extra services of the packet commanding have been built into the on-board computer. Thus when the on-board computer is nominally activated, the commanding system acts like a packet command system, using a subset of COP 1 of the standard (ref 5) . If the OBC is off, the old standard has to be used. This paper will only concentrate on the experience in using the COP-1 Procotol.

NOTE: In this section, although the word COP-1 is used, EURECA has only implemented a subset of the COP-1. The EURECA terminology and services are not completely compatible with the latest issue of the CCSDS recommendation.

COP-1 is a closed-loop Telecommand Protocol that utilises sequential ("go-back-n") retransmission techniques to correct Telecommand Blocks that were rejected by the spacecraft because of error. COP-1 allows Telecommand Blocks to be accepted by the spacecraft only if they are received in strict sequential order. This is controlled by the necessary presence of a standard return data report in the telemetry downlink, the Command Link Control Word (CLCW). A timer is used to cause retransmission of a Telecommand Block if the expected response is not received, with a limit on the number of automatic retransmissions allowed before the higher layer is notified that there are problems in sending Telecommand Blocks. The retransmission mechanism ensures that:

- No Telecommand Block is lost
- No Telecommand Block is duplicated
- No Telecommand Block is delivered out of sequence

The COP-1 protocol has also an expedited service. This service is used for exceptional spacecraft communications. Typically, this service is required for recovery in absence of telemetry downlink (i.e no CLCW), or during unexpected situations requiring unimpaired access to the spacecraft data management system.

3. THE GROUND CONTROL SYSTEM

The introduction of Packet Telemetry makes it possible to define Packet Types, and for each of these packet types to define a standard for the format and presentation of data in the Packet Data Field. The following packet types are defined for Eureca: Housekeeping 1, Housekeeping 2, Time, Acknowledge, Exception, Report, Acknowledge and Private Packets. Housekeeping 1 (HK1) packets are similar to the subframes of TDM systems, containing snapshots of on-board parameters which can be subjected to limit and other checks and displayed on alphanumeric and graphic displays. The other packet types are different and require specific processing, thus making the processing system more complex.

One of the major changes going from a TDM to Packet Telemetry system is the change to an event driven system (packets arrive asynchronously, rather than at fixed format rates). This impacts both design and computer loading.

The Architectural Design of the Eureca Dedicated Computer System (EDCS) is based on a Telemetry Processing Chain and a Telecommnding Chain. The Telemetry Processing Chain consists of a Telemetry Receiver, Telemetry Processing Task, Command Verifier, Filing and Display Tasks (alphanumeric, graphical displays, report/exception displays). The Telecommand Chain consists of the Manual Commanding Stacks, Automatic Commanding Queues, Command Verifier, Command Uplinker, Command Filing Task, Display and Configuration Tasks. The Communication between these individual tasks is based on the Buffer Manager, a tasks responsible for passing Telemetry and Command buffers around the system. Telemetry and Command buffers are given to the Buffer Manager and asked tasks are informed that a data buffer is available for processing. The Buffer Manager does not pass around the actual data buffers, only small mailbox messages are send to the relevant tasks with a reference to the data buffer. This architecture is very convenient for Packet Telemetry, the Packets are distributed according to the packet type. If for a mission other packet types are required, such architecture makes it possible to setup a new task to process these new packet types without disturbing the functionality of already existing tasks.

As for a TDM spacecraft, the computer load on a packet TM system is dominated by telemetry processing and display support (neglecting any project specific peculiarities). Commanding tasks account for only a small fraction (3-5%) of the load. Two main considerations distinguish the load characteristics of the ground computer system supporting a packet telemetry Firstly, there will not be one format, but a set of packets, of different lengths each having different processing needs. Secondly, the packets are generated asynchronously, not at a constant rate, so it is essential to have a traffic model, which gives a fairly realistic representation of average and peak packet rates. In the case of Eureca, such models are needed for pass and post pass activities, which are quite different. During real-time processing (pass operations), the packet rate is (worst case) 12/s. This generates a much higher load than the rather low daily average data rate (2kbits/s) might lead one to suppose. By contrast , to give a TDM example Hipparcos (a geostationary spacecraft) has a continuous data rate of 23 kbits/s but produces one subframe each c. 10s. The loading of the Hipparcos Dedicated Computer System (HDCS) is comparable to that of the EDCS (possibly a little lower) despite the Hipparcos's much higher bit rate. Similar as for the ground system the on-board system must be carefully analysed and a software system budget should establish a clear reference case for on-board and space to ground traffic scenario, which can be used for system testing. Critical on-board areas are computer load, timing of cooperation or dependant applications, packet buffer sizes and number of packet buffers.

Data delivery to users is greatly facilitated by use of packet telemetry, which already results in decommutation according to application ID. This also simplifies the provision of security, i.e. protection of privacy of datasets. Eureca users require rapid access to their data, which rules out the traditional method science data delivery, dispatch on magnetic tapes.

The COP-1 protocol increases the complication of the command uplinker software, which has to handle for every telecommand with a number of messages coming from different units at the station in addition to the telemetry messages from the spacecraft. Testing this software in a realistic environment became absolutely necessary due to the importance of the timing aspects of the problem and this forced extension of precious testing time with the spacecraft flight model connected to a ground station interface.

4. THE ON-BOARD SYSTEM

The large number of independent processors on-board EURECA increases the likelihood of unexpected behaviours which result in corruption of the format or contents of the Telemetry Packet produced. During the mission a number of problems were identified with the on-board implementation resulting in very strange anomalous behaviours. Many of these problems directly violated basic assumptions for the design of the ground segment adding to the strange behaviour. Below is a table listing the problems experienced during the mission:

TRANSFER FRAMES

Problem	Consequence	On-Ground Detection	Prevention
Received a corrupted Transfer Frame (already corrupted before the FECW was calculated) The problem was with a spillover with Idle Frames between.	Ground system reported protocol an protocol error because the expected spillover data were not available. Packet Discarded	Always use the First Header Pointer in the Transfer Frame Header as the Master to locate the first Packet in a Frame. If inconsistent with the Packet Length from the last Packet in the previous Frame discard this Packet and report a protocol error.	Ground Testing
When the on-board Data Handling System changes mode from High Speed Link to Low Speed Link it cannot maintain the Transfer Frames proper (spillover etc.)	As above	As above	Spacecraft Design.
Received a Transfer Frame with two Idle Packets and with a non-idle packet between.	Allowed according to the standard.	Do not assume that an Idle-Packet always is at the end of a Transfer Frame.	

PRIMARY HEADERS

Problem	Consequence	On-Ground Detection	Prevention
Received Packets where the Secondary Header Flag was set to 1 but the Packet Length Field had the value 0 (SH is fixed to 6 octets for EURECA)	Ground system detected a corrupted packet reported a protocol error. Time calibration not possible.	Maintain a list of allowed length of each Application ID and check every received Packet. Check consistency between the information in the Primary Header and the Packet Length. Check the value of the P field in the Secondary Header if the P field is used.	Ground testing.
In one experiment the Source Sequence Counter is implemented as a 16 Bit Counter instead of the 14 Bit defined in the standard.	Ground system reported segmentation protocol errors because the SSC has been extended into the Segmentation Flags in the Primary Header. Packet discarded.	Normally build into the packet decommutation algorithm.	Ground testing shall check that all instruments handles correctly the wraparound of the SSC. This require normally a long test run. workaround: Restart experiment at regular interval.
In one experiment the Source Sequence Counter is shared between four different Application IDs.	Ground system reports jumps in Source Sequence Counter. Accounting for these Application IDs not possible.	Normally build into the packet decommutation algorithm.	Ground testing.

Problem	Consequence	On-Ground Detection	Prevention
General: Due to onboard power/cooling constraints it is necessary to activate/deactivate instruments frequently. In such cases the experiments resets the Source Sequence Counter to 0.	Allowed according to the standard	The Source Sequence Counter is not very useful in these cases. The ground design must take into account such type of operations	-

SECONDARY HEADERS AND TIME CALIBRATION

Problem	Consequence	On-Ground Detection	Prevention
Received Secondary Headers where the Time Field was shifted one octet.	Proper time calibration cannot be performed.	May be difficult. For real-time received telemetry it is possible to make a plausibility check against current time. However this does not work for playback of on-board stored Telemetry. In the playback case another plausibility checks must be implemented.	Ground testing
Many experiments have problems with the stability of their local clocks resulting in: Unacceptable drift Large jumps in time when they synchronize with the Master Clock. This can even cause the time to jump backwards.	Proper time calibration cannot always be performed. In case the time jumps backwards this may cause problems for the filing system. However this depends on the design of the filing system.	As above.	Design of the overall time concept including requirements on drifts of master and local clocks. During ground testing verify that the implementation is according to specification.

5. OPERATIONAL EXPERIENCE WITH PACKET TM/TC

One of the main advantages of packet Tm is that the TM sourcE can in principle decide what data to send when to the ground. This concept was extensively applied on EURECA, and the ground segment and operations concept used it as a basic assumption. While this proved to work well in the nominal cases, it became a problem in cases of on-board failures. In some cases the on-board unit which experienced that failure took the wrong decision on what TM to send, limiting the visibility to the ground of the causes of the failure. Some failures affected the functionality of the unit to the extent that the unit stopped generating TM or even started an endless loop in which event TM packets were generated continuously, overflowing the on-board data storage. Interaction between the subsystem TM generation and the system level decisions taken by DHS in case of specific failures were also very difficult to handle. In the case of AOCS special application software had to be written within DHS to guarantee extended TM generation in case of subsystem anomalies. This did not succeed in several cases during the flight, and the correct TM coverage of critical failures was lost as a consequence.

The implementation of the packet TM concept had a major positive effect on the on-board communications between "intelligent" instruments and subsystems and the central DHS over the DHS data bus. Low level protocol problems in the bus interface units were often cured at higher level by the packet transfer protocol. Those units which were not able to generate packets suffered from the low level problems, causing significant complications to the operations. One negative aspect of the EURECA implementation of packet TM was that the DHS application software was not able to read the contents of the TM packets generated by the other subsystems or instruments. This artificially limited enormously the system level fault management capabilities of the DHS. In particular the information contained in the Housekeeping packets and the Event packets (Report and Exception) was essential to detect and isolate problems with the subsystem or instrument which could be easily recovered at system level. This limitation of the DHS shifted the system level fault management to the ground control, which was in most of the cases only able to intervene after several hours, due to the limited visibility of the spacecraft from the ground stations (about 5% of the mission time).

The use of the different packet types by the different packet TM sources on -board (12 instruments and 2 subsystems) was not always correctly reflecting the definitions imposed by the design specifications. In particular an improper use of Report and Exception packets was causing some problems in flight operations. The ground segment was designed under the assumption that Exception packets would only report anomalous behaviours, and Report packets would indicate progress or completion of nominal activities; in several cases it was found out during final system testing or even during flight that this clear distinction was not always observed.

Another clear directive for the design of TM packets was that all TM parameters for which direct ground monitoring was required should have been included in Housekeeping packets. The ground segment was designed on this assumption and therefore was not supposed to open and process science packets. This rule was also in several cases not properly followed and the ground had to work around the problem by including some specific science packets in the list of TM packets to be processed. This was not trivial also due to the fact that no formal documentation was available to describe science packets, and the relevant information had to be extracted from various sources like meetings, private conversations and informal documents.

The packet TM implementation had a significant impact on the operational database preparation. Most of the TM parameters were contained in several different Housekeeping packets; this had an impact on the size of database tables and complicated the handling of derived parameters, which had to be defined and inserted in all TM packets containing a contributing parameters. A large amount of manpower had to be invested in the generation of the Event packets database. This was mainly caused by the large number of possible event packets (of the order of 2500 at the end) to be defined, but also to the lack of description of these packets in the AIT database. The contents description and meaning of each event packet had to be extracted in most of the cases directly from the on-board software code which was generating it. This manual ork had to be repeated every time a new version of the application software was generated and copied to ESOC, even after launch.

Event packets were the most powerful tool the flight controllers had to monitor the spacecraft and payload activities and to identify and diagnose anomalies. The lack of AIT database in this area reduced significantly the quality of the overall ground testing.

A final consideration should be made on the opportunity to involve flight operations personnel in the definition of the contents of Housekeeping packets. These packets were originally designed following engineering considerations and disregarding completely the utilisation during operations. This forced a complete redesign of the packets at a later stage in the development of the spacecraft, with impact on both the AIT/AIV programme and the operations preparation.

For commanding no real problems was encountered during flight with this concept. Its flexibility was properly exploited by the database editors specially designed for this mission in the mission control system. The block protocol and the related retry mechanism in case of failed uplink verification of a TC block worked very well, but were very difficult to test and tune before flight.

6. LESSONS LEARNED

The following lessons have been learned about packet telemetry and telecommand systems from development of the Eureca spacecraft control system and during the mission:

1. Sizing of ground and on-board computer systems needs to be carried out carefully, using a good traffic model for the generation of the various packets.

2. Very careful consideration has to be given to matching the design of the spacecraft and packet control system to the characteristics of packet telemetry. "Fudging "a TDM system work with packet telemetry is not advised and at the best is likely to be highly inefficient

3. On-Ground Testing must take into account the use of Packet Telemetry. This must include functional tests to verify 1) all implemented features of the Packet Telemetry (segmentation etc.), 2) proper wraparound of counters, 3) stability of on-board clocks (master and slave), 4) performance tests to verify on-bard loading of the system in

typical operational scenarios.

4. Ground system must be able to handle errors in the implementation of packet telemetry 1) check the consistency of all static fields in transfer frames and packets, 2) design the system to be robust against implementation errors, 3) design the system to minimise the impact on other users in case of implementation errors, 4) include knowledge of the on-board implementation (expected application id's, expected packet lengths etc.), 5) provide proper reporting for detected errors, 6) give operational staff proper visibility of detected errors, 6) provide tools to disable error reporting of "known errors"

5. The COP-1 protocol has proven to be very reliable and is able to recover transmission error with minimal operational impact. There have been a number of occasion where the COP-1 protocol has successfully recovered an error. These cases all concerns link degradation, and involved the following circumstances:

- During the deployment phase with a bad RF link between the Shuttle and EURECA
- During the deployment phase where the EDCS did not receive a Command Acceptance Pattern (CAP) from NASA.
- During ESA ground station passes where the spacecraft was configured with the wrong antennae.
- During ESA ground passes where commanding was executed down to 0° elevation (resulting in degradation of the telecommand and telemetry links).
- During on-board antenna switch over.
- When the OBC failed to allocate a telecommand buffer (due to an OBC overload condition).

Although not all of the above cases were foreseen in the design of the COP-1 protocol (in particular case 2 and 6) the COP-1 protocol has always successfully recovered the error with a maximum of two retries. It is also important that during EURECA routine operations with a normal link budget the COP-1 protocol has never been in retry (i.e no transmission errors).

6. The design of the commanding system in the control centre must consider end-to-end protocols (in particular needed for uplinking on-board software patches and master schedules) and provide elements that makes it possible to recover in case of ground failures.

7. Introduction of Packet Telemetry and Commands is a major step towards standardisation of on-board and ground systems. In order to fully archive this goal it will be necessary to define standards covering more of the format than that specified in present standards. At the very least local standards are needed for each packet type to avoid proliferation. Ref 7 describes some current ESA work on this topic.

7. CONCLUSION

The packet TM/TC concept proved very powerful in supporting complex operations of an autonomous low-Earth orbiter like EURECA. The system supported a heavy downlink and uplink traffic corresponding to a total of 10 million transfer frames containing 35 million packets and 240000 commands were send. Most of the above described problems do not relate to the overall concept but to the implementation, which suffered in the EURECA mission from the lack of previous experience. We have found a number of problems with the actual implementation of the Packet Telemetry Standard but we <u>have not found any problems with the standard itself.</u>

The lessons learned form this mission could be easily taken into consideration in the design of future missions applying the same approach to the space-ground interface.

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