COMPONENTS FOR BUILDING TELECOMMAND AND TELEMETRY ON-BOARD SYSTEMS

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ABSTRACT

The new ESA (CCSDS) telecommand (TC) and telemetry (TM) standards will be used by many future spacecraft. This paper introduces the standards, summarising their main characteristics. A typical spacecraft configuration based on these standards is then presented.

Radiation hard components for building a Packet Telecommand Decoder and a Packet Telemetry Encoder are introduced. The components fully support the standards, and are suitable for several types of spacecraft configurations. They are available as standard components from European foundries, supported by complete data sheets and VHDL models.

1 INTRODUCTION

1.1 CCSDS Recommendations for Standards

The Consultative Committee for Space Data Systems, CCSDS, is an international organisation with CNES, DLR, ESA, NASA and NASDA as members, among others. CCSDS establishes recommendations for communication protocol standards ensuring world-wide interoperability. The communication protocols intrinsically support requirements of modern communication systems, such as error control, automated services and data format flexibility. By taking advantage of the capabilities of modern technology, high communication reliability can be provided.

1.2 ESA Space Data Communication Standards

The Packet Telecommand Standard (ESA PSS-04-107), the Packet Telemetry Standard (ESA PSS-04-106) and the Telemetry Channel Coding Standard (ESA PSS-04-103) are directly derived from the corresponding CCSDS recommendations. The Telecommand Decoder Specification (ESA PSS-04-151) further specifies the interfaces and data formats for a Packet Telecommand Decoder. A similar document is planned to be established for Packet Telemetry Encoders.

1.3 Packet Telecommand Standard

The Packet Telecommand Frame has a variable length, each Frame containing exactly one TC Segment. A TC Segment consists of a 1-byte Segment Header and a TC Packet, if shorter than 249 bytes. Longer packets need to be transferred using several Frames. The 5-byte Frame Header contains Spacecraft Identifier, sequence count etc. The complete Frame is error-protected using a 16-bit Cyclic Redundancy Check (CRC) word.

To improve the Frame rejection ratio, the Frame is split into 7-byte pieces each with an added 1-byte error correcting BCH code, together forming a number of 8-byte Code Blocks. The last Code Block will normally be completed with a fill pattern, in order to obtain exactly 8 bytes. All the Code Blocks making up one TC Frame preceded with a 16-bit Start Sequence and ended with a Tail Sequence in the form of a special Code Block is called a Command Link Transfer Unit (CLTU), shown in figure 1.

There are three types of TC Frames:

- AD Frames utilize a protocol for sequence verification and automatic transmission called COP-1, ensuring that the TC Segments are received in the correct order;
- BC Frames are used to control the onboard part of the COP-1 protocol machine;
- BD Frames are always accepted if correct, without sequence control.

In order for the COP-1 protocol to work properly, the status of the onboard protocol machine, the Command Link Control Word (CLCW), must be provided to the ground. The CLCW is normally placed in the Telemetry Frame trailer. In the case of failure on the down-link, BD Frames can be used, by-passing the automatic sequence control.

1.4 Packet Telemetry Standard

The Packet Telemetry Frame has a fixed, mission-dependent length. The original CCSDS standard Frame length for cross support was 1115 bytes, but in principle

Characteristic	Packet Telecommand	Packet Telemetry
Frame generation	When needed (spurious)	Continuous
Frame length	Variable 8 to 256 bytes	Fixed Typically 1115 bytes. Other lengths possible, e.g. 223, 446 or 892 bytes
Frame error detection	Mandatory 16-bit CRC	Mandatory 16-bit CRC (optional when Reed-Solomon encoding is used)
Frame error correction	Mandatory 7-bit BCH for each 8-byte code block	Optional E.g. Reed-Solomon and/or convolutional encoding
Data unit transported by Frame	TC segment with (part of) one TC packet (or non-packet data)	TM packet or non-packet data
Organisation of data units within the Frame	Exactly one data unit per Frame	Variable; from one data unit in many Frames, to many data units in one Frame

Table 1: *Packet Telecommand and Packet Telemetry Transfer Frame characteristics*

any Frame length is now possible. When using Reed-Solomon encoding, the Frame length need to be a multiple of 223 bytes. Since the Frame length is fixed and the data packets can be of variable length, the Frame Header contains a pointer to where in the Frame the first packet is located. Subsequent packet positions within the Frame can be found by adding the packet lengths. Since the packet can be much smaller or larger than the Frame, a TM frame can contain many small packets, or only a part of one large packet. The 6-byte Primary Header contains Spacecraft Identifier, sequence counts etc., and the optional 4-byte Secondary Header can contain an extension to the sequence count.

In a system using both Packet Telecommand and Packet Telemetry, the CLCW from the TC Decoder will be transported to the ground in the TM Frame trailer. The TM Frame shall be error-protected since an error in the CLCW status will disturb the COP-1 protocol. The TM Frame preceded by a 32-bit Synchronisation Marker and optionally followed by the Reed-Solomon code is called a Channel Access Data Unit (CADU), shown in figure 2.

The Packet TC and Packet TM packets have the same data structure. However, since the protocols are layered, any type of data structure could be transported by the Frames, for example when adapting existing non-packet equipment to the Packet TC/TM standards.

Figure 1: *Packet Telecommand Transfer Frame*

Figure 2: *Packet Telemetry Transfer Frame*

2 SPACECRAFT CONFIGURATION

The parts of a spacecraft related to Packet TC and Packet TM are shown in a typical configuration in figure 3.

2.1 Up-link

Each receiver demodulates the Radio frequency signal and provides a bit-stream containing CLTUs to the TC Decoder.

The CLTUs are decoded by the TC Decoder, and if accepted the decoded TC Segments are provided to the Central Computing Unit (CCU), the onboard data handling main computer, possibly for further distribution to the onboard Users. In some configurations the TC Segments could be sent directly to particular Users, as selected by the address in the TC Segment Header. The TC Decoder generates various status reports, which can be requested by the TM Encoder (for the CLCW) or by the CCU.

2.2 Down-link

The data generated by the CCU is fed to the Telemetry Encoder, which generates CADUs. Data from onboard Users can be sent via the CCU, or in some configurations directly to the TM Encoder. The CLCW is retrieved from the TC Decoder, and inserted into the TM Frame trailer.

For missions where data cannot be sent to the ground at all times, data in the form of complete Frames is temporarily stored in a mass memory. If Reed-Solomon encoding is employed, it can also be used for error correction of the stored data. When communication with the ground is reestablished, the mass memory contents are dumped to the TM Encoder exactly as recorded, i.e. as non-packet data (*asynchronous data* in CCSDS terminology). For spacecraft with solid-state mass memories alternative data flows could be foreseen, e.g. storing packets instead of entire Frames.

The transmitter receives CADUs from the TM Encoder, to be modulated and sent to the ground.

2.3 Cross-coupling

To avoid loss of the spacecraft in the case of a failure in one subsystem, all critical units are normally duplicated. To further increase the reliability, the subsystems are often cross-coupled, allowing operation also with failures in more than one subsystem, provided that they do not occur in the same type of subsystem.

A cross-coupled version of the Packet TC and the Packet TM subsystems is shown in figure 4. Since cross-coupling implies a large number of connections, serial interfaces are normally the most efficient in a fully cross-coupled system.

However, the integration levels of today allow a TC Decoder or a TM Encoder each to be implemented using a few devices. One would therefore expect that the level of cross-coupling can be decreased. The decrease in reliability of such an approach would be compensated by the higher reliability of each subsystem compared to older subsystem implementations (high integration leads to few devices, yielding high reliability). One possibility could be to integrate the TC Decoder and the TM Encoder into the CCU, only cross-coupling the CLCWs and the spacecraft data bus. In this case parallel interfaces would be most efficient, except for the CLCW which should always be directly coupled to the TM Encoder.

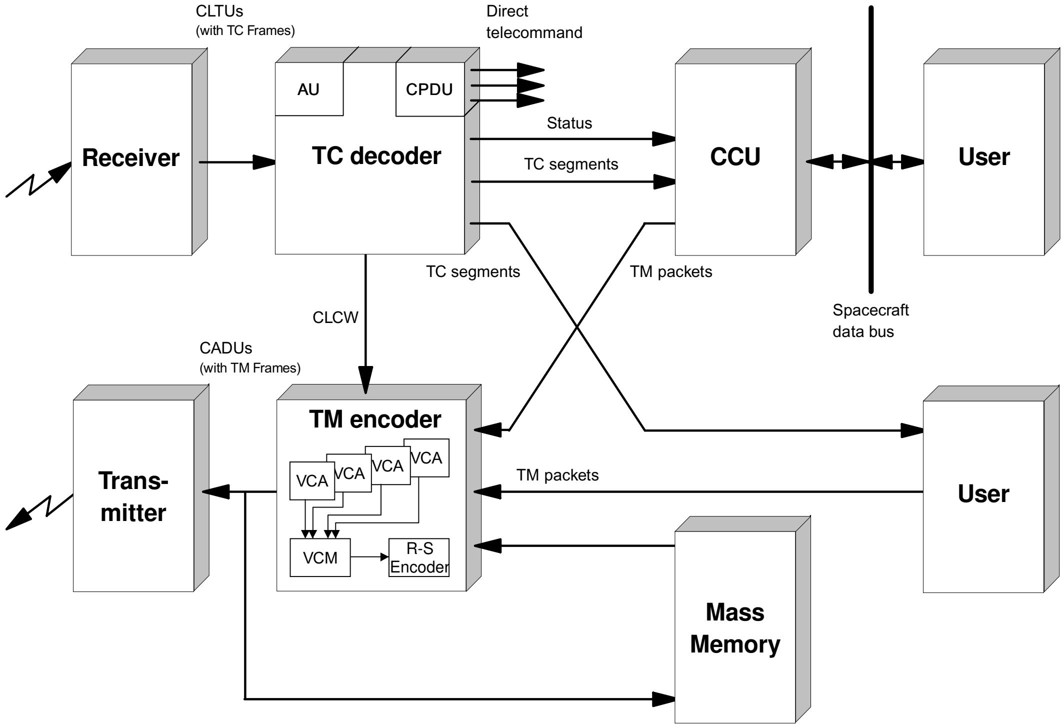

Figure 3: *Typical spacecraft configuration*

3 TELECOMMAND DECODER

The TC Decoder is searching for the Start Sequence on all inputs simultaneously, until detected at one of the inputs. The TC Decoder then accepts all Code Blocks of the CLTU from that input, correcting single-bit errors if detected, and removing the error correcting codes. When the Tail sequence is detected, the TC Decoder starts searching for a new Start Sequence on all inputs again.

The so received candidate Frame is verified w.r.t. to CRC, Frame length, spacecraft identifier etc. If it is an AD Frame, it will only be accepted if in correct order. If necessary retransmission of missing AD Frames is requested through the CLCW. Accepted TC Segments are output through a Multiplexed Access Point (MAP) interface. The MAP identifier contained in the TC Segment Header is an address for directing the TC Segment to one of 64 different destinations.

To prevent unauthorized commanding of the spacecraft, the TC Decoder may contain an optional Authentication Unit (AU). The AU verifies the 5-byte signature placed after each TC Segment to be authenticated. The signature is calculated using a complex, 'unbreakable' algorithm. Which MAP addresses require authentication is selectable.

The TC Decoder Command Pulse Distribution Unit (CPDU) is intended for critical reconfiguration of the spacecraft, sometimes called *Direct Telecommand*. After thoroughly verifying the Packet residing in the TC Segment, the CPDU executes its commands (from 1 up to 120); for each command one of 256 outputs is activated for a specified time. Since the CPDU function is critical, it is always protected by authentication when the AU option is enabled.

In addition to the TC Segment, the following four reports are available from the TC decoder:
- Part of the Command Link Control Word (CLCW);
- The Frame Analysis Report (FAR);
- The AU Status Report (AUSR), when authentication is used;
- The CPDU Status Report (CPDUSR).

The last three reports are useful to determine the TC Decoder status and to gather operational statistics. They are also valuable for compliance testing.

Since the TC Decoder is the only control connection from the ground, it must always be operational. It shall never be switched off or reset in flight, and consequently it must have very high reliability, also against Single Event Upsets (SEUs).

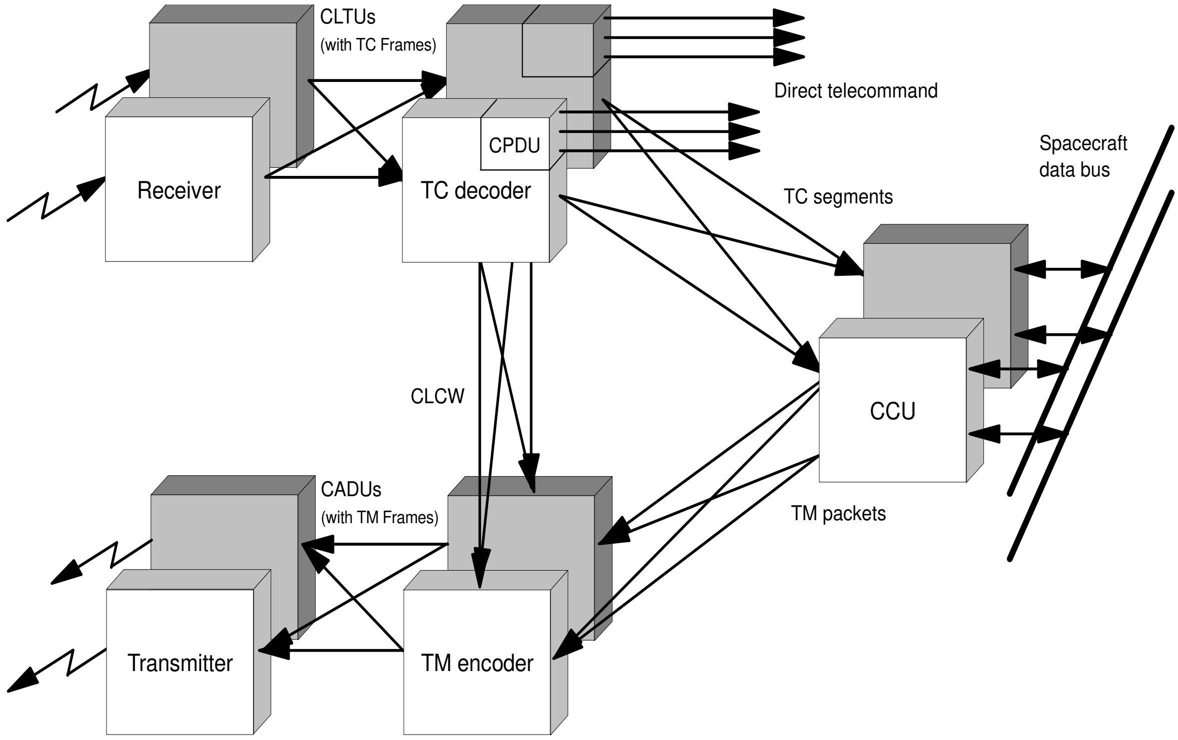

Figure 4: *Redundant configuration*

3.1 The PTD Component

The Packet Telecommand Decoder (PTD) is a radiation hard, single-chip implementation of a TC Decoder core. The PTD is a full implementation of, and fully compliant with, ESA PSS-04-107 and ESA PSS-04-151. It is manufactured in CMOS/SOS technology which has low power consumption and very low SEU sensitivity, but it has nevertheless been designed to always recover from an SEU. The PTD is a non-proprietary standard component available from GEC Plessey Semiconductors (GPS), under device number MA28140. It will be packaged in a 132-pin ceramic quad flat-pack. PTD samples are expected in 1994.

The PTD has 6 inputs supporting a maximum bit rate of 50 kbit/s. For higher bit rates, possibly up to 200 kbit/s, the TC Decoder would request retransmission for worst-case sequences of minimum and maximum length TC Segments, but would otherwise retain full functionality. Spacecraft up-link bit rates are currently in the range of 4 kbit/s, leaving ample margin for future requirements.

As an option, the PTD allows prioritized selection of the inputs; when a bit-stream is received on an input with higher priority the other inputs will be ignored.

The accepted TC Segments are output either through a serial MAP interface, or alternatively through a 16-bit CPU-type parallel interface. This allows the PTD to be used in fully cross-coupled configurations using a serial interface, as well as more integrated configurations where a parallel interface is more practical.

The PTD features on-chip full implementations of a CPDU and an AU. Alternatively, an external AU can be connected, in case another authentication algorithm is desired.

The PTD have separate and redundant interfaces for the CLCW, adapted for direct connection to the Telemetry Encoder described further on. This provides the highest possible reliability for the CLCW transfer, without any additional components being required. The three other reports can be retrieved by the CCU using a serial interface, alternatively the same parallel interface as for the TC Segments can be used.

It is not required to program the PTD in flight; it will automatically start operating after power-on. All mission specific parameters are stored in a PROM, together with the Authentication key, if used.

Figure 5: *Packet Telecommand Decoder implementation using the PTD*

3.2 Data Sheet and VHDL Model

Many existing European space-specific components have incomplete data sheets, and very few of them have VHDL models. This leads to high engineering costs when using a component for the first time, and sometimes to design errors. Developments of standard components will therefore require comprehensive data sheets and VHDL models to be produced.

This fully applies to the PTD, as well as for the TM Encoder components presented further on. A comprehensive data sheet and a VHDL model allowing board-level simulation is available, as well as a VHDL model of a complete packet TC Decoder intended for system-level simulation.

3.3 Typical Application

A block diagram of a typical PTD application is shown in figure 5. In addition to the PTD device, the following is needed to create a complete TC Decoder:

- One 1k by 8 PROM containing the mission specific parameters such as spacecraft identifier, and the authentication key when the AU option is enabled;
- One 2k by 8 SRAM of standard type, to temporarily store received TC segments;
- Circuitry for de-multiplexing and amplifying the CPDU signals;
- Circuitry for distributing the TC Segments according to the MAP address;
- An external AU, if another algorithm than the built-in is required (not shown).

A small application note can be found in the PTD data sheet.

3.4 Second Sourcing

There are two European second sources for Packet TC decoder components:

- Alenia Spazio, a chip set with three devices exists since 1994, in a LSI Logic radiation hard process;
- Saab Space, a single-chip device is expected in 1995, in the ABB Hafo SOS5 CMOS/SOS process.

These components are company proprietary. The data sheets are believed to be less comprehensive than for the PTD, and it is not expected that VHDL models will be made available.

As a back-up solution, ESA has the right to use the PTD VHDL model for porting the design to another foundry in case it would not be available from GPS.

4 TELEMETRY ENCODER

A TM Encoder is a less complicated unit than a TC Decoder; its basic functions is to receive data to be formatted and output. The TM Encoder receives Telemetry packets from the Onboard Data Handling system, which are temporarily stored. In addition to packet data, non-packet data can be received.

Data can be received on eight Virtual Channels, where each Virtual Channel can be seen as an independent communication link. Since there is only one physical output from the TM Encoder, the data from the Virtual Channels are time multiplexed on a Frame basis, according to some algorithm. Since the TM encoder is continuously outputting CADUs without interruption, an idle Frame must be generated whenever there is not enough data to send a Frame containing data.

The TM Encoder generates the Synchronisation Marker, the Frame Header, including the First Header Pointer (allowing the position of the packets within the Frame to be located), and the optional Frame Trailer. If required, Reed-Solomon codes can be appended to each Frame.

The TM Encoder allows the onboard spacecraft time to be sampled at a defined place in the output bit-stream. The sampled time is then sent to ground, where it is compared with the ground time sampled at the same place in the bit-stream. By comparing the two samples, the spacecraft and ground time can be correlated.

4.1 The VCA and VCM Components

The Virtual Channel Assembler (VCA) and the Virtual Channel Multiplexer (VCM) are radiation-hard devices for implementing a Telemetry Encoder. Together they are fully compliant with ESA PSS-04-106. They are manufactured in CMOS/SOS technology which has low power consumption and very low SEU sensitivity. The VCA and the VCM are non-proprietary standard components available from ABB Hafo, under device numbers HAF_12399 and HAF_12396. Both are packaged in 84-pin ceramic quad flat-packs. VCM samples are available since 1993, and VCA samples since 1994. Both devices will be ESA/SCC qualified in 1994.

The VCA has an 8-bit parallel interface for receiving data, or alternatively a serial interface similar to the MAP interface of a TC Decoder can be used. The maximum burst input data rate is 25 MBit/s.

The VCA/VCM chip set supports 4 different Frame lengths: 223, 446, 892 and 1115 bytes. These lengths cover a useful span of Frame lengths which can be used both with and without Reed-Solomon encoding. The maximum output bit rate is 12.5 MBit/s.

The VCM has four Frame Trailer options: none, CLCW, CRC or both CLCW and CRC. The CLCW is retrieved from a TC decoder using a built-in interface, which can be directly connected to one of the PTD CLCW interfaces. It is possible to automatically toggle the retrieval between two TC decoders for redundant configurations. When Reed-Solomon encoding is not employed, the CRC option is mandatory.

The VCM features two built-in algorithms for selecting which Virtual Channel is to output a Frame; Bandwidth Allocation respectively Priority Selection. Bandwidth Allocation guarantees minimum bandwidth available for each Virtual Channel. Priority Selection always selects the Virtual Channel with the highest priority. The bandwidth, respectively the priority, can be reprogrammed in-flight. Alternatively, an arbitrary selection algorithm can be implemented externally.

The VCA generates a time strobe to be used for the spacecraft time correlation. The intervals are programmable in accordance with ESA PSS-04-106.

The VCA can optionally generate and insert idle TM packets, in order to fill up an incomplete Frame. This feature can be used to ensure that the last packets in a Frame will be sent to the ground, even when there is no more data, e.g. after an instrument has been turned off.

The VCA and VCM devices are operational after power-on without needing any programming. Both devices feature optional Built-In Self Test (BIST), which can be used when designing more autonomous spacecraft than the currently existing ones.

4.2 Data Sheet and VHDL Model

As for the PTD component, the VCA and the VCM have complete data sheets and VHDL models for board-level simulation. It is intended to develop a VHDL model of a complete TM Encoder for system-level simulation when the need arises.

4.3 Typical Application

A block diagram of a typical Telemetry Encoder application is shown in figure 6, consisting of:

- One VCA per Virtual Channel;
- One 8k by 8 SRAM of standard type per Virtual Channel, to temporarily store the Frames (7 to 37 Frames depending on the Frame length);

Figure 6: *Packet Telemetry Encoder implementation using the VCA and the VCM*

- One VCM;
- One MA1916 Reed-Solomon encoder, in case Reed-Solomon and/or convolutional encoding is required (available from GPS, see Reference 5).

In this application four Virtual Channels have been used: VC0, VC1, VC2 and VC7. VC0 - normally used for house-keeping data sent from the CCU - and VC1 have parallel interfaces. VC2 and VC7 have serial interfaces, e.g. for a tape recorder. The MA1916 Reed-Solomon encoder can be directly interfaced to the VCM.

4.4 Second Sourcing

Alenia Spazio has a company proprietary device since 1994, implemented in a LSI Logic radiation hard process (though it cannot be used without Reed-Solomon encoding since no frame CRC can be generated).

Since ESA owns the VCA and VCM VHDL models, they can be used for porting the designs to another foundry in case they would not be available from ABB Hafo.

5 Demonstration System

In order to practically evaluate the components that have been developed, a demonstration system for the Packet TC and the Packet TM subsystems is under development at ESTEC. This system will allow compliance testing of the components versus the ground equipment at ESOC.

The Packet TC part consists of a PC-based ground station implementing the ground part of the COP-1 protocol, and providing a user interface. The CLTUs are fed to an interface box, which outputs a bit-stream and the corresponding clock signal. This part exists since 1990.

The Packet TM part consists of a PC-based ground station, which operates together with a Packet TM Encoder implemented using the VCA and the VCM devices in a flight-like design. The TM Encoder supports four Virtual Channels, and has an interface to Users (data sources) represented by PCs. The FAR, AUSR and CPDUSR reports can be fetched from the TC decoder to be inserted into a packet sent to the TM ground station. In addition, the TC segments received by the TC decoder can be looped back. The TM ground station extracts the CLCW from the TM Frames and sends it to the TC ground station, to be used by the COP-1 protocol. The TM Encoder exists, while the TM ground station is under development.

6 Conclusions

The Packet Telecommand and Packet Telemetry standards have been introduced. The operational concept has been outlined, and a suitable configuration has been presented.

Components for implementing a Telecommand Decoder and a Telemetry Encoder have been presented. These components allows the Packet Telecommand and Packet Telemetry standards to be introduced in spacecraft without major problems, since they:

- Are non-proprietary standard components;
- Are radiation-hard with very low SEU sensitivity;
- Have been designed for space applications;
- Are supported by complete data sheets and VHDL models for board-level simulation;
- Have low pow consumption, about one watt could be expected for two redundant TC and TM subsystems together;
- The chosen packaging allows dense implementation, a double Europe card should be sufficient for one TC Decoder plus a TM Encoder.

References

1. Packet Telecommand Standard, ESA PSS-04-107 Issue 2
2. Telecommand Decoder Specification, ESA PSS-04-151 Issue 1
3. Packet Telemetry Standard, ESA PSS-04-106 Issue 1
4. Telemetry Channel Coding Standard, ESA PSS-04-103 Issue 1
5. GPS SOS Radiation Hard Handbook, July 1994
6. ABB Hafo VCM HAF_12396 Data Sheet, January 1994
7. ABB Hafo VCA HAF_12399 Data Sheet, January 1994

Further Information

For data sheets and other information about the VCA and VCM devices, contact Phil Todd at ABB Hafo (Sweden);

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For the GPS Radiation Hard Handbook and other information about the PTD and the MA1916 Reed-Solomon encoder, contact Trefor Davies at GPS (United Kingdom);

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