THE TEAMSAT DATA HANDLING SYSTEM

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BACKGROUND

To better understand some of the factors affecting the design of the TEAMSAT data handling system, it is first necessary to perform a short review of this unusual project and the severe constraints under which we all had to work.

The TEAMSAT project came into existence in mid November 1996 when a budget of 750 KAU was provided to enable young engineers and students to exploit the opportunity offered by the Ariane 502 test flight to install some experiments in a module aboard the MAQSAT instrumented test platform. Thanks to the enthusiasm of the team and the generous in- house support, facilities and expertise provided at ESTEC, the TEAM/YES dual spacecraft was ready for shipment to Kourou by the end of June 1997. However, the data handling system had to be ready even earlier by about 6 weeks to support integration and testing via the TM and TC links. That is, only about 26 weeks after the go ahead was given. At the start what little was known could be summed up as follows.

1   EXPERIMENTS TO BE FLOWN

TETHER   Only the concept and a few parts existed. It was known that the in-flight deployment of a free- flying spacecraft was required (Young Engineers Satellite - YES). This was to be attached by a 35 km tether to a 12 kg mass. The YES satellite and its support systems plus the details of the tether deployment were still being discussed.

AVS   Autonomous Vision System. Provides an astronomical reference vector by recognising star constellations. An existing development model was available including a PC based ground support system.

FIPEX   Flux Probe Experiment. Measured atomic oxygen. Also existed as a flightworthy system already flown on sounding rockets. Included PC based ground support system.

VTS   Visual telemetry System. Existing engineering model of a programmable digital camera system intended to monitor mechanical status, array deployment etc. Included PC based ground support system

ODD   Orbiting Debris Device. The MAQUSAT exterior was painted to create black and white sectors of known reflectivity to act as a passive calibration target for ground based observation equipment. No TM or TC required.

2   PLATFORM - INITIAL OUTLINE

Size   Established by the space available on MAQSAT, i.e. room for a cylinder about 94 cm in diameter and 75 cm long.WeightGenerous allowance available, but fixed at 300kg.

Power   Battery only - no possibility to deploy solar panels. Spare batteries left from ECS II (1982!) were available.

Structure   Unknown except that (a) it had to be mounted in MAQSAT as a self-contained box to fit into the space given above and (b) during flight, the separation of YES was required as part of the TETHER experiment deployment. TM & TC Unknown, but transponders left over from OLYMPUS (an approx. 16 year old engineering model) and EURECA were available and appeared to be working normally. No suitable, already existing on board data handling system was available. However, we had an adequate number of sample VLSI devices recently developed by ESTEC from which the core of a suitable system could be implemented with comparatively little effort.

AOCS   There was to be no active Attitude and Orbit Control System. It was intended to inject MAQSAT into orbit with a spin rate of around 0.5 RPM to provide the required stability.

Thermal   There was to be no active thermal control system. Given the short mission, it was expected that temperatures could be kept within reasonable bounds by means of appropriate thermal coverings.

3   LAUNCH IMPOSED CONSTRAINTS

Launch Window   TEAMSAT was a "freeloader" on Ariane 502 test flight and therefore had no possible influence on launch dates or times.

Non interference   TEAMSAT must not present any kind of hazard or interference source, electrical or mechanical, up to the time of MAQSAT separation. Mechanically, this meant enclosing the whole TEAMSAT structure in a containment box of proven mechanical integrity (no bits falling off). Electrically it meant no RF transmissions and no live connections outside the TEAMSAT box until after MAQSAT separation.

4　INITIAL DESIGN DECISIONS AND TRADEOFFS

The most serious omission from the list of essential, available equipment was an on board data handling system to format the experiment data for transmission and decode and distribute commands and data received from the ground. Also still to be addressed were the issues of providing platform housekeeping data, plus power distribution, switching and conditioning. However, the availability of the ESA data handling chip set reduced to manageable proportions the effort involved in designing a data handling system from scratch. This chip set consists of Application Specific Integrated Circuits (ASIC) that form the core of an ESA/CCSDS compliant system for generating TM transfer frames and decoding TC transfer frames. The TM chip set accepts up to 8 independent data streams and formats them into a transfer frame stream without the involvement of a processor. It also automatically inserts filler to maintain the transfer frame stream when users are unable to exploit the bandwidth offered. The inherent flexibility of the asynchronous TM channels meant that details of channel bandwidth allocation amongst users could be left until later and even adjusted in flight.

To commence with the purely physical aspects, the mandatory TEAMSAT containment box was a robust, aluminium construction in the form of an octagonal box shown in Fig. 1. Two of the 8 faces could be removed individually for testing and inspection. The free-flying YES spacecraft was built on the external end-face or "lid" of the box. It would be released by a ground command to pyro-cutters and ejected from the box, leaving the TEAM satellite behind, as shown in Fig. 2. Four springs were to provide the necessary impetus for tether deployment. The tether would then unwind from a bobbin aboard YES and once fully deployed, the solid, 12 kg mass, "TORI" would be released from TEAM, leaving it to form a free-flying tethered pair with YES.

Various tether control and monitoring capabilities were required on YES (tether deployment brake, accelerometer, visual monitor etc). These were to be co-ordinated via a small on board computer. Also attitude and position measuring capabilities were required to monitor deployment conditions and subsequent tethered pair behaviour. To meet these requirements, a commercially available GPS system and a simple but effective in house designed and constructed Solar Aspect System (SAS) were added.

Other devices were to appear and sometimes disappear from the manifest in the early design stages, but the above list represents the main, mission defining instruments actually flown. In the absence of a MAQSAT model, the eventual in flight antenna pattern was a relatively unknown factor. However, it was clear that things would be at best marginal around apogee with the 2 watts RF power available. Fortunately, our TM chip set included a Reed-Solomon and Convolutional Encoder chip that provided about 7 dB of gain on the link. Even then, concerns about antenna pattern holes led us to provide cross coupling between the two spacecraft that enabled essential TM and TC traffic of one to be routed via the RF link of the other. However, the YES ejection system required that any such coupling be "zero extraction force". We could not find a suitable connector in time

and so had to design an optically coupled system. This was to be the source of some problems later. To gain yet more link margin if necessary, provision was made to reduce TM bit rates by factors of 2 or 4 by telecommand. TEAM was provided with two low gain helical antennas mounted on the MAQSAT structure. It was hoped these would provide reasonably uniform coverage in the aft direction in which the earth would lie at apogee. YES was provided with 2 low gain antennas, positioned to provide the best omnidirectional capability in free flight, i.e. on opposite ends of the spacecraft. One of these was mounted on the exposed "lid" which meant that before deployment, the other was inside the composite TEAM/YES octagonal box and so had to be switched off to avoid RF interference during that phase. All together, the uncertainties of the RF links imposed some sophisticated spacecraft design features and special requirements on the data handling system.

The spacecraft structure design team had to be given individual equipment box dimensions as soon as possible. Consequently, circuit board dimensions were fixed before the circuits they were to carry had been fully designed. One victim of this situation was the analogue section of the housekeeping system. Due to lack of space, we could not provide differential inputs. This resulted in noisy but still usable analogue results.

In our position as data handling system design team we were the only group with the professional expertise to assess and deal with many broader, spacecraft system level design issues that fell into the cracks between the main structural, experimental and other disciplines. The power system design is one such case. Structural constraints and battery dimensions obliged us to adopt an "unusual" arrangement with part of the TEAM power source located in YES before separation.

We decided to incorporate all the power switching relays, voltage converters, housekeeping and signal filtering functions in the same box as the TC and TM circuit boards. This provided a self-contained, data handling and power service module (known as the `OBDH Box') to which the experiments could be connected using their already existing and unmodified PC type asynchronous serial interfaces (see Fig. 3). The OBDH boxes for both spacecraft were mechanically identical. Each contained one identical TM board and one identical TC board populated with components according to the requirements of the individual spacecraft. The number and types of relays, power converters and filters used was specific to each spacecraft.

5　UNUSUAL PROJECT FEATURES

The ridiculously short time scale and budget obliged us to resort to some unusual and frankly dubious practises on occasions. In general, no corner was left uncut and no stone turned over if it could be avoided. However to maintain a sporting chance of success, this approach required the experience to divine which corners could be cut with impunity and which stones had the nasty things lurking underneath. Fortunately ESTEC is still well provided with such expertise. Any not already held by the design team was freely and enthusiastically given by the appropriate specialists in ESTEC.

The design process for the whole spacecraft could be described as "fluid". That is, the imposed deadlines often forced us to start construction based on provisional assumptions before some important parameters were frozen or even identified. In effect phase A/B lasted only a week or two and merged rather than switched into phase C/D. This meant we required designs with reconfigurable, generic capabilities rather than inflexible, case specific solutions. Typical examples are the antenna pattern situation, the visibility of the spacecraft and composition of the TM and TC traffic during different mission phases.

When integration and testing of TEAMSAT was already well advanced, a decision of the Space Debris Committee lead to the abandonment of the major experiment, TETHER. However, by that time the whole deployment system was fully developed and installed. Consequently it was decided to treat this mission as a system qualification flight from which valuable information could be extracted for a future mission in better circumstances. YES would be ejected, but the deployment of the tether itself and the TORI counter-mass would be excluded.

6   THE ELECTRICAL DESIGN PROCESS AND FEATURES OF THE DH SYSTEM

Overview The main TEAMSAT experiments were effectively "off the shelf" and came with fully developed ground support hardware and software. To be able to use these during integration and test and also in flight required a suitably transparent space link. This in turn meant that there was no possibility of imposing on users the decidedly non transparent, traditional ESA TM system that collects fixed quantities of data at fixed intervals. The requirement to accept user data structures and timing "as is" meant we had to provide them with an asynchronous "byte stream" service rather than a packet service in both up and down links. However, ESA/CCSDS packet structures were used to send the main power switching and configuration telecommands and also carry the platform housekeeping data on the TM link.

Multiple users may share a common channel by using standard packet structures to delimit the different data units. Since we could not impose such structures on users, delimiting was done by allocating them different Virtual channels (VCs) and Multiplexer Access Points (MAPs) on the TM and TC links respectively. This is not necessarily a strategy we would advocate in other circumstances since VCs and MAPs are intended primarily to delimit different levels of service and/or address redundant paths in the transport layer. Then a given VC or MAP may carry packets with compatible requirements for bandwidth and latency but with different sources and destinations, as identified by the packet Application IDs. The ESA TM chip set was designed to support simultaneous byte stream and packet modes on different VCs.

The TC decoder chip and supporting ground segment software provided us with self contained, easy to use module which eliminated any significant development work in that area. It was just a matter correctly designing the circuit board to accept the chip, programming the correct mission dependent parameters in its associated ROM and providing it with suitable interfaces to the individual users. ESA/CCSDS compliance was assured,

including the COP-1 "guaranteed in sequence, error free delivery". The receivers did not demodulate the sub- carrier, so this was performed by a single, digital ASIC, of which we had a few samples.

Given the availability of the ESA TM/TC chip set, the greater part of the electrical design effort could be focused on application interfaces and related matters. These included providing the cross coupling paths between the two spacecraft, power switching etc. Other facilities necessary were (a) a simple platform housekeeping system to monitor battery voltages, temperature, relay states etc and (b) programmed time delays for command execution. The housekeeping system monitored up to 32 single bit state inputs and 16 analogue inputs with 8 bit resolution. Additional analogue circuits were required for the TC zero- crossing detectors and a low pass filter on the TM data input to the YES transmitter.

Use of FPGAs and VHDL Tools. Most of the glue logic required to convert the ESA chip set I/O protocols and timing to the PC type serial port protocols of individual users was implemented in Field Programmable Gate arrays (FPGA). There was one for the TM board and one for the TC board of each DH system. The TM FPGA also supported the digital part of the housekeeping system including the controller for the analogue section. The TC FPGA provided similar protocol and timing matching between the TC decoder chip MAP outputs and individual users. It also supported the delay generator for time tagged commands. The FPGA design process produced VHDL models of the chips. We also had an already existing VHDL library of the ESA chip set and some other key components, including the ground segment. This enabled us to model and verify the greater part of the data handling system end to end in considerable detail at an early development stage. This was certainly a vital factor in achieving a successful circuit board design very quickly and at the first attempt. The FPGAs were socket mounted so that circuit adjustments could have been incorporated at a relatively late stage. The design and modelling processes were so successful that this was not required.

Telemetry ASICs

Virtual Channel Assembler (VCA)

Assembles packets or bytes of data into one of up to 8 VCs on the TM link (one VCA per VC). Applies flow control (optionally) to match the data source production rate to the bandwidth available to that VC. Accepts data as ESA/CCSDS packets or byte stream. TEAM used 5 VCAs and YES used 4.

Virtual Channel Multiplexer (VCM)

Multiplexes outputs of up to 8 VCAs on to one TM link. An in flight programmable Bandwidth Allocation Table guarantees minimum portions to each VC. The VCM completes the transfer frame header (spacecraft ID etc.). Also provides interfaces for the Command Link Control Word (CLCW) from the TC decoder chip and the Reed-Solomon / Convolutional encoder chip. Each spacecraft used one VCM.

Reed-Solomon / Convolutional Encoder

The on board segment of a forward error detection and correction system. Although its use is optional, it is almost certainly the most cost effective way if improving the link budget by about 7 dB, i.e. a reduction transmitter power by about a factor of 6.

A complete TM frame generator core comprises one VCM, one VCA for each VC and the optional R-S /Conv. Encoder Chip. Power is typically about 10 mW per chip at 5V, but depends mostly on clock rate and output loading. The tight link and power budgets made the use of the R-S/Conv. chip mandatory.

All ASICs use latch up free, SOS technology, have a footprint of about 8cm2 and weigh about 15 grams.

Telecommand ASICs

PSK Demodulator

Demodulates the noisy PSK subcarrier from the TC receiver and recovers the NRZ data, bit clock and a `signal present' indicator when the S/N ratio exceeds a predetermined value. One chip was used on each of the two spacecraft. Belongs to the physical layer and is not strictly part of the data handling chip set.

Packet Telecommand Decoder

Protocol machine supporting the on board end of an ESA/CCSDS compliant up link providing error-free delivery of packets or arbitrary data structures via up to 62 addressable MAPs. Also hosts an Authentication check (not used for TEAMSAT) and a Command Pulse Distribution Unit (CPDU) which decodes multiple pulse commands of individually specified length delivered in a packet.

Power requirement for all the above chips is about 10 mW each at 5V, but depends mostly on clock rate.

7   SELF-ADAPTING, ASYNCHRONOUS TM SERVICE

This capability requires particular mention since without it useful data retrieval would have been severely restricted and the design of user interfaces made much more complex - possibly impossible to achieve in the time available. The TM systems of earlier designs obliged users to adapt their data production to a lock-step regime imposed by the fixed format TM transfer frame. Although the frame generated by the VCM/VCA chip set has a fixed size also, its internal format adapts itself dynamically to user activity. This met the requirement to accept user data as randomly occurring squirts of various sizes or as fully asynchronous individual bytes. A simplified format diagram comparing the two approaches is shown in Fig. 4.) The useful bandwidth available on the TM link was 28 259 Bits/Sec (overheads removed). The system shared this among individual users such that each got a guaranteed share, but any not taken up by one user would be offered to other users in proportion to their guaranteed share. If users failed to exploit all the bandwidth

offered, the generator itself completed frames with filler. The baseline guaranteed shares could be adjusted in flight via the TC link.

The AVS star finder experiment on TEAM is a good example of a sporadic data producer. In quiescent mode, it produced a small squirt of housekeeping data from time to time, but when an image was taken, a more prolonged squirt would be produced. The experiment had no flow control, so the TM system had to accept the data as it was produced at 19.2 kBaud from the PC type asynchronous serial interface. It was guaranteed a share of the TM bandwidth matching this peak requirement but this was only taken up occasionally due to the nature of experiment operations. The FIPEX experiment also on board TEAM was somewhat similar in its data production characteristics.

The third TEAM experiment, the Visual Telemetry System (VTS), produced small amounts of housekeeping as a background activity but it also had a very large picture buffer. Its output from this buffer was flow controlled by the VCA. This made it an ideal companion for AVS and FIPEX since it could soak up the substantial bandwidths allocated to them but not used most of the time. In effect, the flow control applied by the TM system emptied the VTS buffer as fast as the total link bandwidth and current activities of the other users would allow.

On top of this, we had platform housekeeping data being produced in ESA/CCSDS packets of fixed size and format every 4 seconds. The housekeeping system was similar to a classic ESA fixed format approach. It made very inefficient use of the bandwidth it occupied (constant values reported in successive packets etc.). In this case the bandwidth in question was a very small proportion of the total, so the inefficiency could be tolerated in the interests of simplicity.

8   THE GROUND SEGMENT

The ground segment had to be ready in time to support spacecraft integration and testing. Also, everything concerned with terrestrial and space link compatibility and procedures had to be resolved with ESOC during this period. Fig. 5 shows the general arrangements. The transparent TC and TM links ensured that existing PC based experiment development sets and software could be used for control and processing during testing and flight. A dedicated "front end" PC extracted each VC from the received TM frame using software written at ESTEC. It also provided data archiving so tests could be replayed. The TF synchronisation and convolutional decoding was done by hardware. Although the R/S decoding hardware was not available at ESTEC, it was fully supported by ESOC during the mission and preceding tests. All PCs were networked, so the data extracted by the front end processor was transferred directly to the dedicated experiment PCs. An additional PC provided graphical and digital housekeeping displays. In this way, a comprehensive spacecraft integration and test facility plus experiment mission control centre was created at very low cost.

The TC part of the ground integration and test system was also PC based and used software created during the PTD chip development. With the exception of those directed to the

CPDU, telecommands and data uploads were routed on board via different dedicated MAPs to individual users on board and did not use packet structures.

The experiment control centre was located at ESTEC with the main, TC command issuing control centre at ESOC. ESOC also provided the tracking station coverage from Kourou and Perth plus all the necessary terrestrial links. Commands and data to be up-linked were all entered in a database maintained at ESOC and executed on request from the experiment control centre.

9   EXPERIMENT RESULTS.

The ground segment provided a near real time view of experiment outputs at ESTEC. In Fig. 6 we see a sequence of the MAQSAT separation. It was stored in the VTS memory while the TM transmitter was still off and was dumped on command immediately after the Perth tracking station had acquired a TM link. Note the "filaments" visible at about 4 o'clock. This was unexpected and is being studied by the Ariane 5 authorities. The picture presented here may be viewed as a 10 step animated sequence on the TEAMSAT Website. It is immediately evident from the sweep of the field of view across the Earth that (a) there is a substantial nutation and (b) the expected axial rotation is much less than the 180 degrees per minute that it should have been. These pictures plus the accurately established behaviour of MAQSAT after separation by virtue of the TEAMSAT instruments have been of great value to Ariane Space in their diagnosis of 502 launch anomalies.

The AVS experiment behaved faultlessly throughout the mission and, once outputs like that shown in Fig. 7 were processed, provided very accurate attitude information. The FIPEX atomic oxygen sensor experiment fulfilled all expectations and measured atomic oxygen, which causes erosion problems to low orbiting spacecraft such as Spacelab. Measurements of great value to future missions were made through the range 525 to 1250 km altitude approximately.

The GPS experiment on YES scored what we believe is a world first by successfully tracking several GPS satellites when TEAMSAT was around apogee and up to 6000 km higher than the GPS constellation orbits of about 20 000 km. The indications are that future spacecraft can make use of GPS out to at least that distance

10   DATA HANDLING SYSTEM PERFORMANCE AND CONCLUSIONS.

TEAMSAT is the first ESA spacecraft to be flown with ESA/ CCSD compliant TM and TC systems and the first spacecraft anywhere to exploit the adaptive, asynchronous TM capabilities they support. The performance and ease of use delighted everybody. The short, relatively trouble free design and construction phases owed much to the use of the ESA TM/TC chip set which implemented all the tricky core functions and protocols. The availability of these well proven protocol machines provided a major shortcut by avoiding the use of a processor and software, thereby eliminating most of the system

behaviour verification tests which otherwise would have been required.

The elderly OLYMPUS transponder on YES failed towards the end of the mission. However, by that time and given the fact that the deployment of the TETHER experiment had been blocked by the Space Debris Committee, this had little impact on the overall mission.

The efficient, adaptive behaviour of the TM system in accepting asynchronous, event driven inputs is of particular note. It is a mode of operation that, considering it too complex, project groups and industry have so far mostly avoided. In successfully flying such a system "straight off the drawing board" after ultra-short design and construction phases and without involving a processor, we have demonstrated that by using the ESA chip set, such misgivings are unfounded. Indeed, this mode is much easier to use than the traditional `fixed format' approach, not only for data handling system designers, but also for instrument suppliers who are provided with a much less rigid interface and data presentation environment. The system is inherently able to handle variable size, variable rate data units - ESA/CCSDS packets or otherwise. This means that on board data compression, event driven TM production and user defined, variable data sampling strategies can all be handled by the TM link without any special provisions other than a suitable minimum bandwidth allocation. The VCA Bandwidth Allocation Table (BAT) can be reloaded in flight if necessary.

There was no mission requirement for the authentication process supported on the TC chip so it was not used. The only other ESA/CCSDS capability not demonstrated in flight was the COP-1 protocol. TEAMSAT was the first ESA spacecraft to support it and there had been no time to verify ground station compatibility. However, its functionality on board had already been verified during integration and testing and its effectiveness in flight had already been demonstrated convincingly in 1994 by the low cost STRV-1 A and B satellites built by DERA, UK. These used an earlier prototype TC decoder chip.

The TEAMSAT project has proved that a spacecraft data handling system of high performance can be designed and built quickly and cheaply by using commercially available, space quality ASICs. These ASICs are fully ESA/CCSDS compliant, mutually compatible, and come with all the tricky protocol machines embedded in their silicon. This enables the radically new system capabilities and standards they support to be implemented with no risk. They are outputs of an on going TOS-ES development activity exploiting VLSI technology to reduce costs and improve performance in the framework of the new ESA/CCSDS standards. Currently, about 10 ESA projects and several commercial, non-ESA projects are already committed to using them.

11   REFERENCES

TEAMSAT Website http://www.estec.esa.nl/teamsat

Microelectronics Website http://www.estec.esa.nl/wsmwww

Comparison Between Synchronous and Asynchronous
Data Reporting in the TM Transfer Frame

Fixed Sequence Data Point Sampling

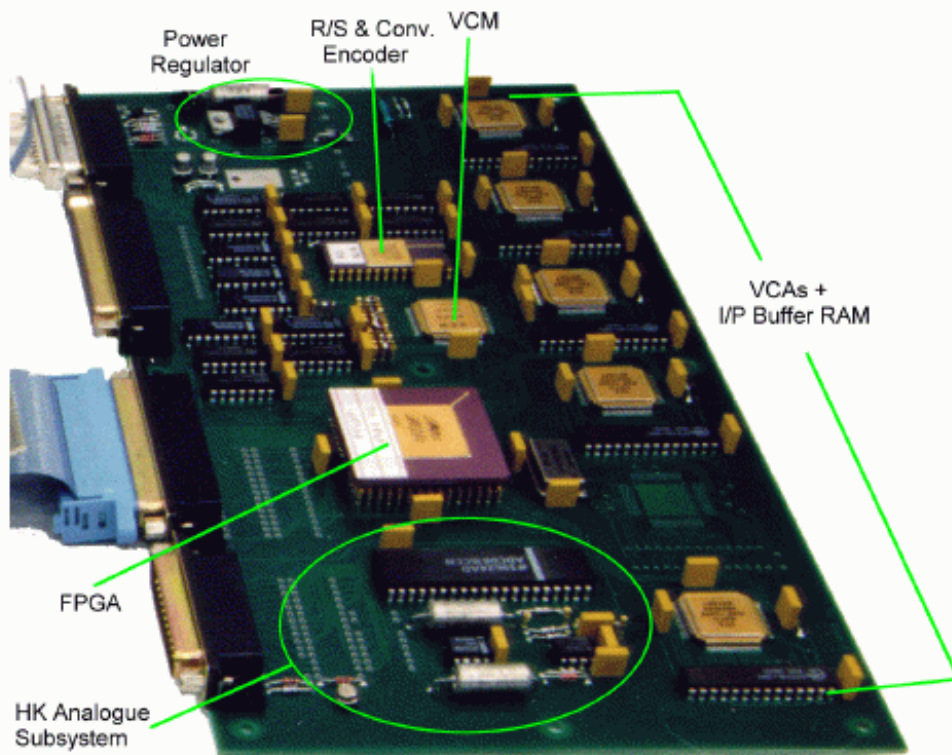| Header	A	B	C	D	A	E	F	G
	A	B	C	D	A	H	I	J
	A	B	C	D	A	K	L	M
	A	B	C	D	A	E	F	G
	A	B	C	D	A	H	I	J
	A	B	C	D	A	K	L	M

Data values are reported in fixed positions in the transfer frame whether they contain useful information or not.

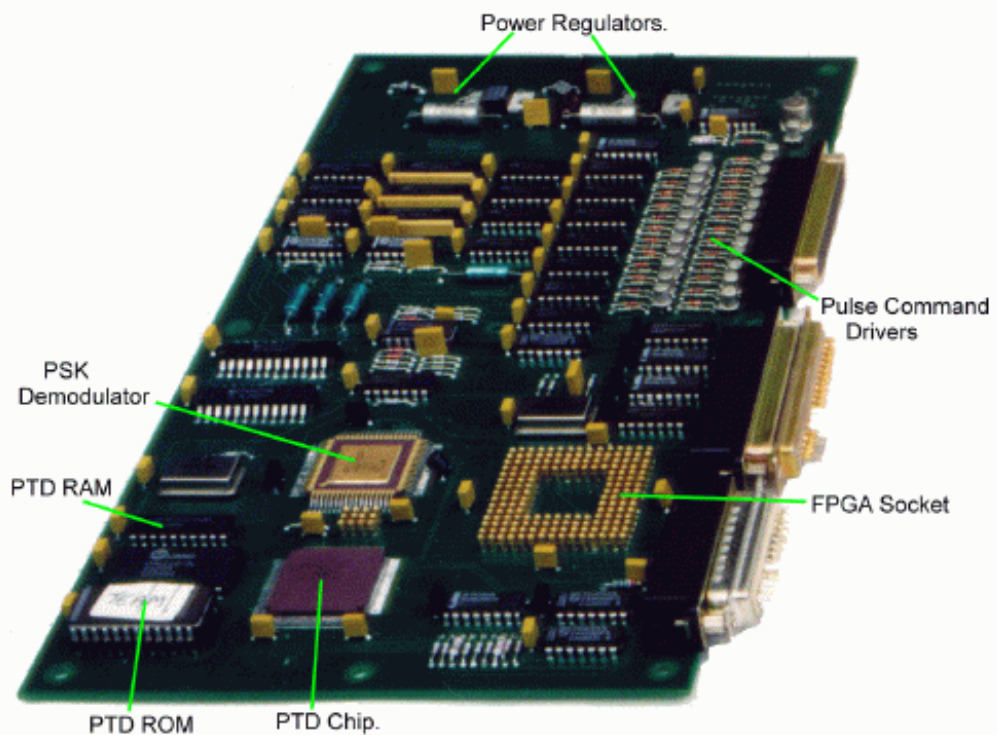## Asynchronous Packet and Byte Stream Service

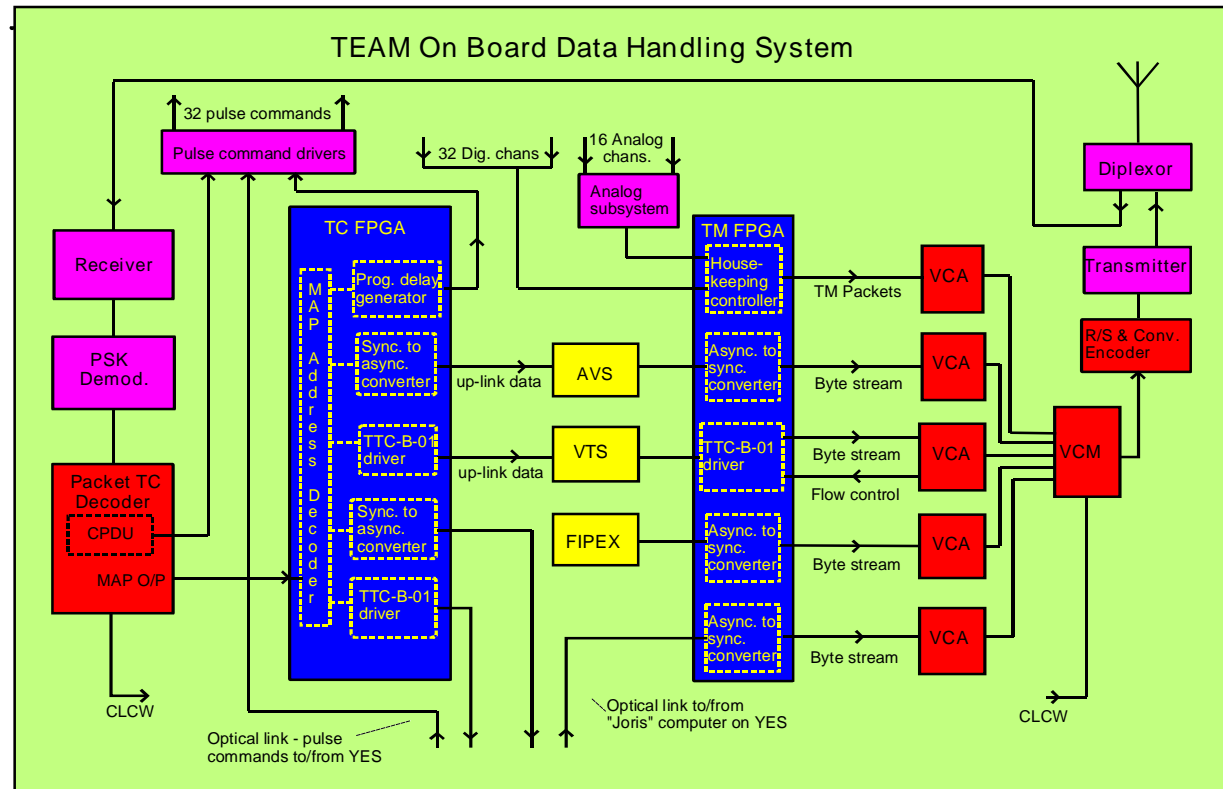| Header VC1	Byte Stream A				
VC2	Pkt 1	Pkt 2	Pkt1	Pkt 3	PKT4 →
VC3	Byte Stream B				
VC2	→ Pkt 4 (continued)		Pkt 5	Pkt 6	Pkt 2 →
VC3	Byte Stream B				
VC2	→ Pkt 2 (cont.)	Pkt 7	Pkt 1	Filler (no data avail.)	

VC reporting sequence and packet rate and size varies according to user activity. Filler is inserted to complete frames or create dummy frames when users are unable to fill the bandwidth offered.

TEAM Telemetry Board

Power Regulator

R/S & Conv. Encoder

VCM

VCAs + I/P Buffer RAM

FPGA

HK Analogue Subsystem

TEAM Telecommand Board

Power Regulators.

Pulse Command Drivers

PSK Demodulator

PTD RAM

FPGA Socket

PTD ROM

PTD Chip.

TEAM On Board Data Handling System

TEAM Structure.