Paper ID: 5a008

NEW HIGH PERFORMANCE INTEGRATED RECEIVER/ RANGING/DEMODULATOR SYSTEM FOR ESTRACK

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ABSTRACT

The new high performance integrated receiver/ranging/demodulator system, also called Intermediate Frequency and Modem System or IFMS for short, is presently being developed under ESA contract. The system is going to replace various older, separately developed, functional blocks at the ESA Tracking Stations (ESTRACK).

The IFMS integrates into a single unit the functionality of a common receiver for the incoming left- and right-hand circular polarised signals with an integral pre-detection diversity combiner usable for arbitrary modulation formats, a high precision ranging demodulator for ESA's hybrid tone/code ranging format including high precision Doppler (range rate) measurement capability, a remnant carrier data demodulator and a suppressed carrier data demodulator. In addition to the receiver capabilities the IFMS integrates a corresponding uplink modulator. Although all functions are capable of multipurpose usage, the design is primarily driven by the requirements for deep-space satellite communication and deep-space ranging/Doppler measurements.

The physical hardware is highly integrated and relies on only three special developed modules. Other functions are implemented with commercial off-the-shelf components. The control software is to a large extent based on already existing packages.

After a short introduction and background this paper gives a general description of the IFMS system design along with some further details on selected topics which are deemed to be of novel or interesting character. The operational aspects are briefly described and the main technical specifications are presented.

INTRODUCTION

At present all modulator and demodulator functions within an ESTRACK station are implemented in various dedicated units. Since these units were developed over a time frame of 20 years, some units, like the telemetry receivers, are implemented in pure analogue technology. The ranging function is implemented in a hybrid fashion where most processing is analogue, while the narrow band filtering (down to 1 mHz) is performed digitally. The remnant carrier demodulator is fundamentally digital in nature but has been designed to work together with the presently existing 10 MHz IF interface of the analogue telemetry receiver. The DSP-based suppressed carrier demodulator, which is modern and self-contained, interfaces directly to the 70 MHz IF.

It is clear that the maintenance and further development of such a mixed system is expensive and imposes many unnecessary constraints. To prepare for future activities, ESA initiated two parallel studies aiming to find the most economical structure for the next decade. Technically, the new system should have a multi-purpose character, though the design drivers were the requirements for deep-space operation. Briefly stated, “deep-space” requirements indicate long turn around delay times (hours) and very low signal-to-noise ratios. Other foreseen operational scenarios that the IFMS could support include data relay satellites at Ka-band frequencies and low orbiting satellites at 100 to 200 km altitude, which implies high Doppler rates. Such a multi-purpose system called for the following, very often conflicting, requirements:

- High Doppler shift covering ±1.5 MHz
- High Doppler rate of ±52 kHz/s
- Remnant carrier signal-to-noise density ratio down to 12 dBHz with a target of 6 dBHz
- Ranging tone-to-noise density ratio down to -10 dBHz
- Remnant carrier symbol-to-noise ratio of Es/No = -9 dB
- Suppressed carrier symbol-to-noise ratio of Es/No = -1.5 dB with a target of Es/No = -9 dB
- In-band spurious suppression of more than 83 dBc
- Timing stability better than 1 ns over 20 hours and full temperature range

Both study groups concluded independently at a very early stage that the system had to be fully digital, apart from the input analogue to digital conversion, in order to fulfil the main technical specifications. Secondly, an economically viable solution had to avoid any functional duplication.

The last conclusion created some hard decisions for ESA because it implied the exchange of the full chain in one step. This inevitably would require high capital costs over a short period for both development and recurrent units.

SYSTEMS DESIGN

The various trade-offs led finally to a highly integrated approach. Basically, the system will be based on three new developed hardware VME (physical but not electrical) compatible modules, viz.

- a Common Front End (CFE) sampling at 280 M samples/s
- a (number of) Generic Digital Signal Processing (GDSP) modules for the implementation of the various demodulator functions
- a digital modulator module with an IF at 30 MHz and a digital to analogue conversion rate of 105 M samples/s followed by an analogue up-conversion to 70 and 230 MHz IF.

All other functions, like the UNIX-based control system, the time code readers, LAN distribution, etc., are commercial off-the-shelf products. The special modules use a VME standard bus structure even though the design calls for non-standard signal assignment. The basic hardware structure is shown in figure 1.

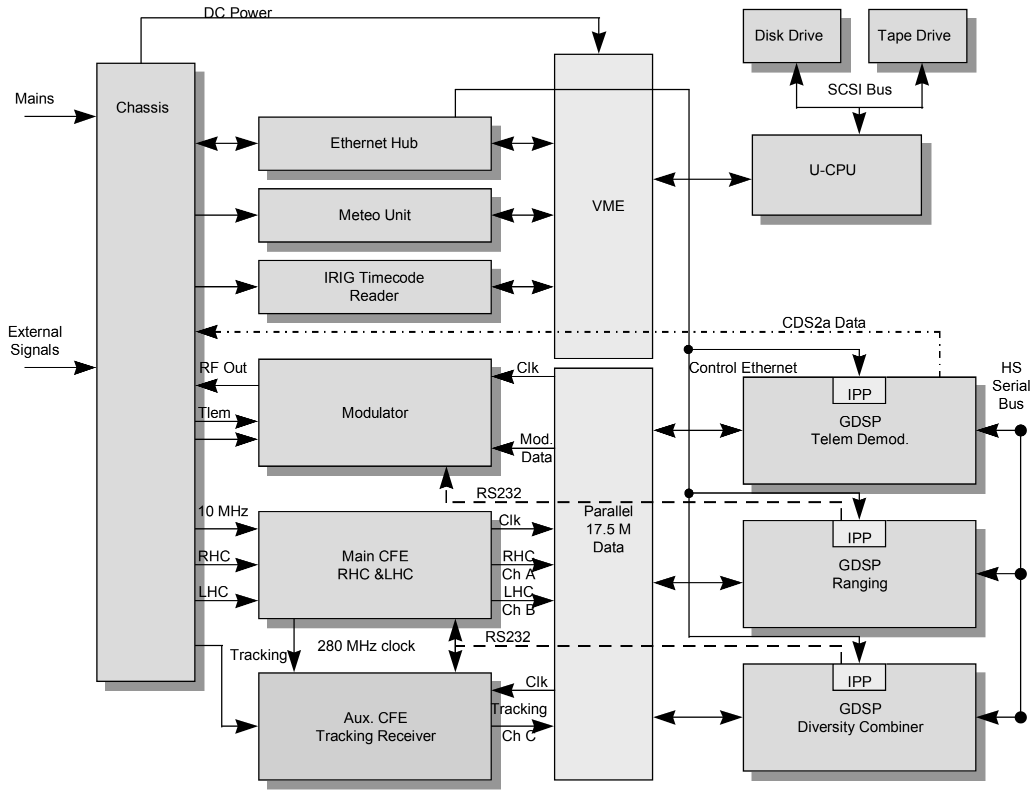

Figure 1: IFMS Block Diagram

An important feature of this systems design is the relatively low number of base modules required to be developed, coupled with a high degree of flexibility. The latter point is achieved through the possibility of re-programming the various modules. This is most applicable to the Generic Digital Signal Processing module. Presently, it is intended to implement each of the following functions using the same GDSP module structure:

- diversity combiner estimator
- diversity combiner followed by telemetry receiver, Doppler measurement and the ranging demodulator
- diversity combiner plus remnant carrier receiver
- diversity combiner plus suppressed carrier receiver
- monopulse tracking receiver (possible, but no implementation planned at present)

The remnant carrier and the suppressed carrier demodulator are from a frequency allocation point of view mutually exclusive; hence both functions can be covered by one hardware module.

Some amount of inherent redundancy can also be achieved by re-configuration and re-programming of modules. For example, if a hardware module fails then it is possible to disable the diversity combiner estimator and redefine that module as a demodulator.

The following chapters will highlight some of the design features of each function and give a brief description of the control software.

DESIGN FEATURES

<u>The Common Front End</u>

The CFE takes profit of the frequency limiting bandpass filter in the down conversion to the 70 MHz IF. The bandwidth is approximately ± 35 MHz with a -60 dB roll-off at 140 MHz. The broad bandwidth ensures very good group delay stability and phase stability versus frequency and temperature. The critical, and hence expensive, anti-aliasing filter has therefore been omitted in the IFMS CFE module at the cost of a high sampling frequency of 280 M samples/s. Although such an implementation has a relatively high initial development cost, it brings immense advantages in the ensuing digital down conversion and bandwidth limitation to ± 7 MHz.

The analogue to digital converter has eight bit resolution with seven effective bits at the 70 MHz frequency. In the following decimation stage, the signal-to-noise ratio is improved, thereby increasing the effective number of bits with 1.5 at 17.5 M samples/s. A truncation is avoided and both I and Q signals are distributed on 12 bits each for both left- and right-hand circular polarised signals. These signals are routed to all the Generic DSP modules on a parallel bus.

A digital down conversion is elegantly achieved by a judicious change of sign of each second sample at 280 M samples/s. However, like in a conventional down conversion, the aliased, complex image at 140 MHz must be filtered away. For the IFMS this requirement is extremely hard and specified at -83 dBc. This is due to the possible corruption of the very weak ranging tone in the following decimation by a factor 16 to 17.5 M samples/s. The problem is solved by a Finite Impulse Response (FIR) filter as seen in figure 2.

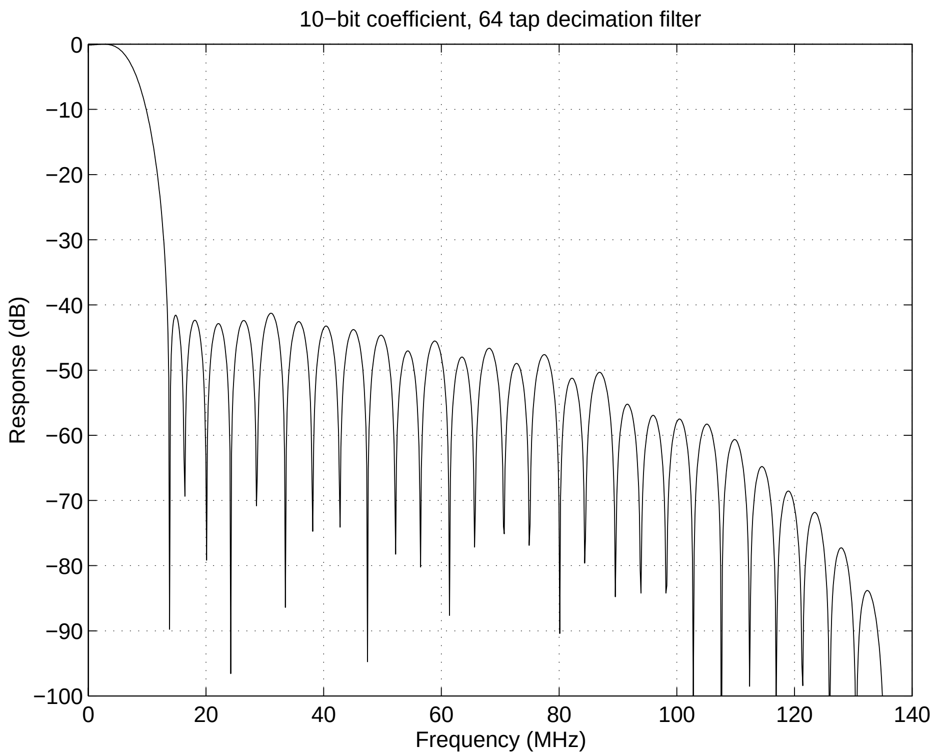

Figure 2: Frequency response of the 64-tap [1 2 1] modified FIR filter.

The FIR filter has a constant group delay versus frequency. This is an indispensable feature for the following high precision ranging demodulator module. A similar performance over the same frequency range would virtually be impossible to reach with an analogue design.

The Diversity Combiner Estimator

The diversity combination is done in a quite unusual way in the IFMS. Firstly, the implementation is a true pre-detection combination; that is there is only one receiver. This topology ensures the lowest implementation losses and the signal is utilised to a maximum extent. The block diagram of the diversity combiner estimator is shown in figure 3.

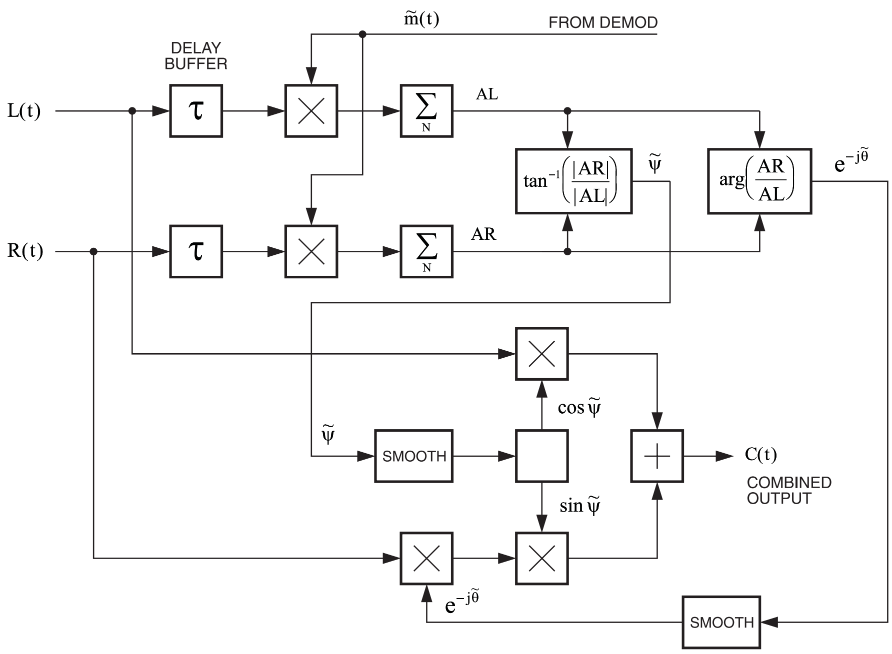

Figure 3: Block diagram of the diversity combiner structure.
ψ = depolarisation angle.
θ = electrical phase angle.

Figure 3 reveals some interesting features compared to the usual type of combiner used for space applications. First of all, the combiner can work with all types of modulation formats, including suppressed carrier modulation. Secondly, the estimator works with only one feedback loop from the selected demodulator. This inherently prevents the instabilities seen in applications where the depolarisation angle and the phase angle are controlled separately. The structure in figure 3 shows that these two parameters are estimated in a feed-forward manner.

The combiner works in a type of bootstrap manner. If the available signal-to-noise ratio in each channel is too low for demodulation the combiner cannot resolve the problem immediately; it has to wait until the signal strength is transferred either to the left- or to the right-hand channel. In deep space this is often a valid assumption due to the rotation of the satellite. When the receiver is locked, it can then follow the change of power from one channel to the other at considerable rotating velocities, e.g. at 50 rpm. For non-rotation satellites or satellites sending in linear polarisation, the power is normally enough to ensure a demodulator starts to work, even though the bit error rate might be extremely high. The feedback loop in the combiner is satisfied with an error rate of 0.2. After locking, the feedback to the diversity combiner estimator ensures a higher signal-to-noise ratio and hereby the process is boot strapped to maximum performance.

Demodulator Functions

These functions shall only be treated briefly in this paper because they are all implemented in a similar fashion in the IFMS. The ranging and Doppler measurements play the central role in the IFMS and we shall therefore take a closer look at these functions. The block diagram is shown in the following figure.

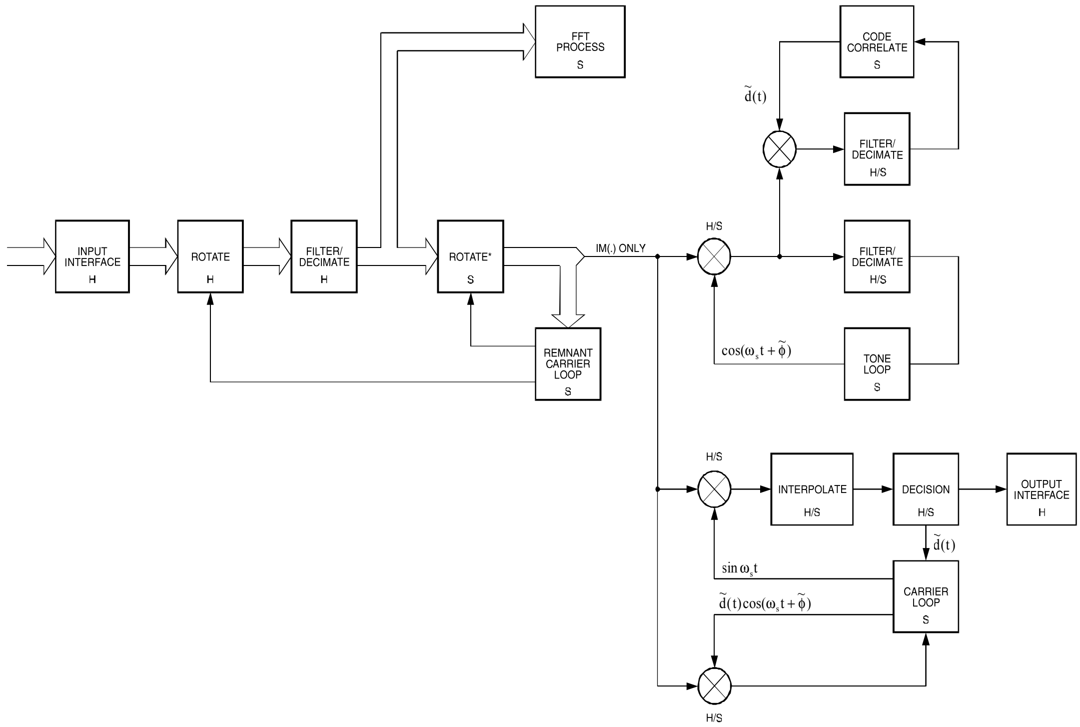

Figure 4: Functional block diagram of the Ranging and Remnant Carrier Demodulator

This diagram reveals a lot of common features for the other demodulators, especially the remnant carrier demodulator that is included in the figure. First the carrier frequency is determined by Fast Fourier Transform (FFT) analysis. Hereafter, the carrier loop is closed in hardware (marked H in figure 4) apart from the loop filtering, which is performed in a DSP. The ensuing tone processing is done in a mixed hardware and software fashion as shown in the upper right-hand part of figure 4. The remnant carrier demodulator, which is depicted in the lower right-hand part of figure 4, is having a very similar physical layout. In the actual implementation, the two parts are only different in the configuration of the Field Programmable Gate Arrays (FPGAs) and the DSP software. This illustrates the aforementioned implementation of all the demodulator functions in a common Generic DSP module.

The design of the FFT-based acquisition and tracking capabilities was driven by the requirement to support a wide range of operational environments — from deep-space to low-Earth. The resulting FFT parameters were set by the common cell error probability requirement of less than 1%, which equates to a cell signal-to-noise ratio requirement of about 14dB.

Based on these fundamental specifications, the following tables illustrate the range of carrier-to-noise ratios and Doppler rates that can be supported, along with the corresponding FFT parameters such as processing times and storage requirements.

FFT Size [samples]	Normal Processing [ms]	Interleaved Processing [ms]	Storage Requirements [kB]
2^{8}	0.26	0.52	2.5
2^{10}	1.3	2.6	10
2^{12}	6.1	12.2	40
2^{14}	28.7	57.4	160
2^{16}	131	262	640
2^{18}	590	1180	2560

Table 1a: IFMS estimated FFT processing times and storage requirements

C/No [dBHz]	Max Doppler Rate [Hz/s]	FFT Cell BW [Hz]	Block Length [samples]	Block Length [seconds]
41.3	$1.43\cdot10^{+5}$	534	2^{15}	$1.87\cdot10^{-3}$
30.0	555	33	2^{19}	$3.00\cdot10^{-2}$
20.0	8.7	4.2	2^{22}	$2.40\cdot10^{-1}$
10.0	$3.4\cdot10^{-2}$	0.26	2^{26}	3.83
6.0	$8.5\cdot10^{-3}$	0.13	2^{27}	7.67

Table 1b: FFT acquisition performance for a target cell SNR of 14dB at a 17.5 M samples/s data rate to the GDSP module

In the high Doppler rate case (e.g. support via a Data-Relay Satellite) the maximum Doppler rate requirement sets the minimum carrier-to-noise density ratio, as indicated in the first row of Table 1b.

In very noisy deep-space environments, the driver is the low carrier-to-noise density ratio, which in turn sets the maximum allowable Doppler rate, as indicated in the last row of Table 1b. The table also demonstrates that even under these conditions, acceptable acquisition times of less than 10 seconds (sample collection and interleaved processing time) are attainable. Such times are very short compared to the acquisition times characteristic of the presently used sweeping method.

Comparing the required samples in the deep-space conditions (2^{27}) in Table 1b, to the largest listed FFT size (2^{18}) in Table 1a, one recognises the need for a pre-decimation. In this case, a pre-decimation of at least 2^{9} would be necessary. Since the pre-decimation factor determines the analysis bandwidth, a larger decimation factor could be employed in the case where a good a-priori knowledge of the carrier frequency is available.

COMMUNICATION AND SOFTWARE

Although the IFMS has been designed with the ESA Tracking Stations (ESTRACK) in mind, the system is relatively easy to configure to other environments by omission of specific communication packages. For example, the Generic Subsystem Controller is a typical special ESA interface method to the Station Computer (STC) and the Man-Machine Interface (MMI) which easily can be removed. An overall communication and functional overview is given in figure 5.

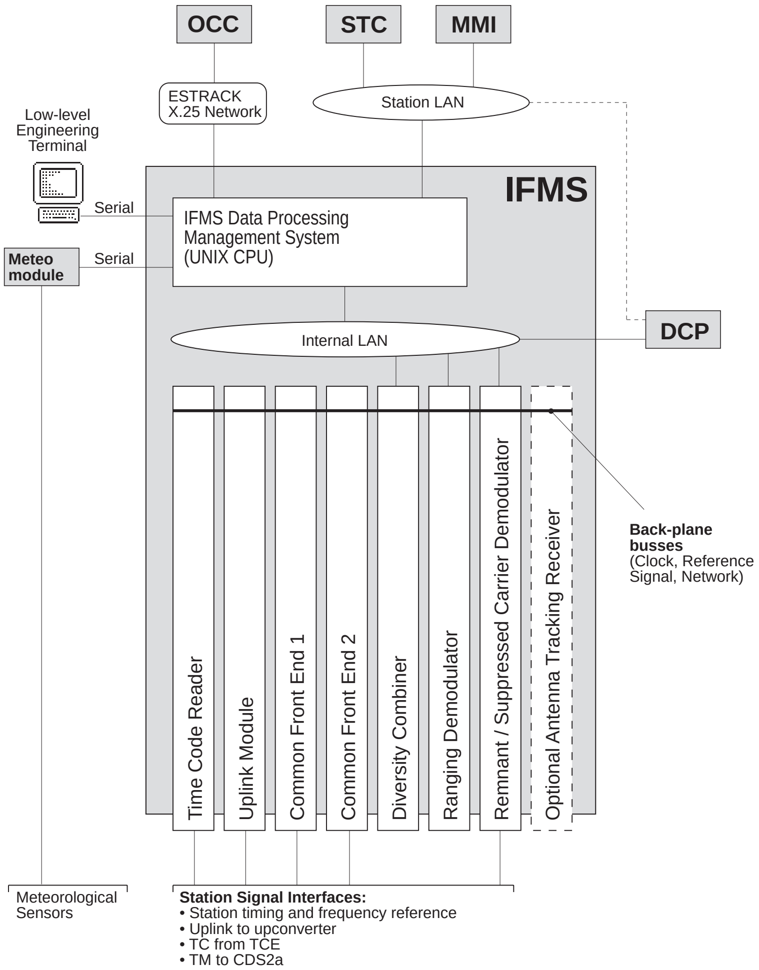

Figure 5. IFMS communication and functional overview.

Within ESTRACK the IFMS is controlled from the Station Computer (STC). Communication to both the STC and the Operational Control Centre (OCC) is supported via OSI protocols. Such a communication system can be considered special to ESA. Other interfaces can, however, be supported via more standardised means. For example, the Development Control Position (DCP) uses standard Internet protocols for its communication. Even though the DCP is only intended for development and maintenance, this “web browser” based interface could readily be used in another environment as the main operational console.

The internal architecture is innovative in the way that the Generic DSP modules exchange status/command information with the UNIX CPU. For this purpose, an internal Ethernet LAN is employed, avoiding M&C communication on the VME backplane. This feature conserves the VME backplane for high-speed signal data exchange between the Common Front End (CFE) and the processes within the Generic DSP modules. Hereby, it is possible to test the monitoring and control interfaces of the various GDSP modules in stand-alone using a simple PC with an Ethernet connection. This is of utmost importance for the IFMS project since the hardware modules and the UNIX-based application software are developed at physically different locations. Furthermore, the application software can be initially developed without the physical hardware by emulating the M&C functions of the GDSP modules.

A key aspect of the DCP design is its ability to use the Internet as communication medium. This implies that the IFMS is suited for both remote operation and also for remote engineering. This plays a significant role for ESTRACK due to the complexity of the system. Already at present it is difficult for local technicians to maintain and repair the station equipment. This will be even more pronounced in the future. Since the remote accessibility has been designed into the IFMS we expect a significant improvement in this respect.

The control computer is based on a SPARC VME module running a UNIX operating system. Since UNIX is not a real-time operating system in the “hard” sense, the IFMS is avoiding any real-time dependencies from its control computer by transferring these tasks to the local processors on the various hardware plug-in modules. The reliability and maintainability should hereby improve considerably.

CONCLUSION

This paper has very briefly described ESA’s new integrated modem and ranging system, also called IFMS. The aim of the project is not only to obtain a high performance baseband system for deep-space operation, but also to advance towards systems with much lower recurrent costs and maintenance costs over their lifetime. Built-in flexibility is a key development goal, since ground station equipment lifecycles are normally long, due to the limited number of customers and high development costs. In our case, we have achieved this by widespread use of DSP processors and other programmable logic, such as Field Programmable Gate Array components

The IFMS system is currently under development by GEC-Marconi Research Centre (UK) with ATNR (F) as a subcontractor. The first system is expected to become available by the end of 1999. Even though the design has been driven by deep-space requirements, we expect that the solution is sufficiently flexible and economical to be competitive in the commercial high-performance TT&C equipment market.