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A Transputer-based Multi-station Multi-technique Geophysical Data Acquisition System - S.P.A.M. Mk III

S.P.A.M. systems are SHORT-PERIOD AUTOMATIC MAGNETOTELLURIC instruments developed since 1980 by Graham Dawes at the University of Edinburgh, with updates as shown below:

revision:	year	note:
Mk I	1980-81	prototype
MK II	1983-84	main design phase
Mk IIa	1986	CPU upgrade
Mk IIb	1988	Data storage and printer upgrade

These instruments have been used in many studies worldwide not only by the University of Edinburgh but through the acquisition of two systems by N.E.R.C (the Natural Environment Research Council) for its general equipment pool by all other U.K. EM Induction researchers. S.P.A.M. systems are also in use in India by the Indian Institute of Geomagnetism (Bombay) and in Canada by the University of Alberta.

Since the last upgrade in the mid eighties many electronic devices have been greatly improved in terms of noise, power consumption and size and also completely new concepts for computational applications have become available. As a result, in 1990 Graham Dawes with support from N.E.R.C. undertook a feasibility study of a Transputer-based upgrade of S.P.A.M. This study (Dawes 1990) has led to a further major development phase with work in progress on a prototype of S.P.A.M. Mk III, a system for the acquisition of time-varying geophysical (not only magnetotelluric) data. This will be completed by October 1993.

Many aspects of the Mk III design are completely novel for geophysical instrumentation as indicated by this article which overviews the concepts and main design goals. Because of the historical association of S.P.A.M. with magnetotellurics the main ideas will be presented with respect to that technique.

Existing MT instrumentation and its deficiences

Historically MT studies were concerned with determination of the electrical resistivity of the Earth's crust or upper mantle on a regional scale. Signals in a period range between 100s and 10000+s were recorded with a typical site spacing of a few kilometres to some 10 kilometres. To collect enough data, recording was undertaken for 2 weeks to one month or even longer at each site. The recording systems for this frequency range were initially paper chart recorders, then data loggers with as little power consumption as possible to maximise battery life. Robustness, small size and weight were also desirable features for these systems. Loggers were primarily or only used to store data - they normally did not perform any data processing. In the Protokoll Elektromagnetische Tiefenforschung there are several papers illustrating how data loggers have been (and still are being) improved (Beblo, Donner, Steveling, this issue, Beblo&Hofer 1986, Beblo&Liebig 1986, Knödel et al. 1982, Steveling 1982)

Almost from their introduction, audiomagnetotelluric instruments (1000Hz - 10+s) have had very different characteristics, with real time processing being undertaken in the field. In some systems this involved cumbersome additional equipment such as bulky computers, large batteries and probably an additional vehicle or trailer. AMT magnetic sensors are typically induction coils rather than fluxgate magnetometers. Special hardware filters (notches) are incorporated to eliminate mains power frequencies and recording in narrow frequency bands is necessary to cover the whole dynamic range of the signals. (Liebig&Schreier 1984, Micheel 1980, Schnegg&Fischer 1980) Most AMT instruments record short, non continuous time intervals to enable the real time data processing. Typically it only takes between a few hours to one day to gather enough data at a site. Site spacing for an AMT survey is normally much less than for the traditional MT survey, being some hundreds of meters to a few kilometres (Brasse 1988, Drewes 1988) .

Today both instrument types merge as they benefit from improvements in memory and CPU technology. It is possible to achieve higher sampling rates with data loggers while real time systems have become increasingly more portable and continue to require less power. On the other hand, since it may be necessary to leave an instrument at the same place for a few days or some weeks - for the longer period soundings - the two different kinds of instruments have a complementary role to play with ideally both being deployed in many studies.

Flexibility of instruments and main design goals for S.P.A.M.III

The flexibility of instrumentation seems likely to become increasingly important for (A)MT projects in the future. Situations exist where acquisition other than that of standard 5-component-MT and data from very dense profiles or grids are advisable. New experiments with remote magnetic(s) or E- and B-mapping configurations could help to improve our understanding of some geological features. The acquisition of additional parameters, such as the vertical electric field which could be monitored with antennas or in certain active areas, the common registration of seismic and magnetotelluric signals might be interesting. In general, the instrumentation should be highly upgradable to adapt best to the problems posed by the physical, geological, logistical and the local noise conditions. Thus, the main design goals for the new S.P.A.M. have been defined as:

- Flexibility in quantity, type and distribution of sensors: Many kinds or numbers of sensors can be connected to one instrument, remote sensors can be connected by the concept of a distributed, networked instrument with digital data transmission.
- Portability: Low power consumption to allow for battery operation and small size and weight so that operation is not restricted to use from a vehicle.
- Continuous wide band recording with digital sub-banding: Because of a greatly improved dynamic range, data covering the whole frequency range can be recorded in one hardware band. The data are then digitally decimated and filtered into sub-bands.

Thus, short and long period data are recorded simultaneously, reducing the overall recording times.

- Real time processing and stand alone operation: Real time operation enables the evaluation of data quality, noise conditions and best system settings. All inputs, even for distributed systems with remote sensors can be made centrally. 'Stand alone' operation to gather more data (long periods, 'dead band') can be undertaken without further user interaction.
- Up- and down-gradable computational power: As the more powerful computers also have higher power consumption, 16 and 32 bit processors of the same compatible transputer family are used to optimise the overall performance.
- Accurate time synchronisation: This enables applications using the remote reference or difference field techniques (or Seismics).
- Integral calibration facility: This facility is used to test for functioning and accuracy of all or selected devices of the instrument (excluding the sensors).
- Support for mixed methodologies: By common registration , e.g. MT + seismic, on hardware and software level mixed methodologies can be supported.

Instrument overview and principal components

S.P.A.M. is constructed in a highly modular fashion. Since a module is an option, replacing one module by another is equivalent to invoking another option (compare Wehmeier 1988). The principal instrumental components, consisting of many smaller modules, are shown in figure 1 and comprise:

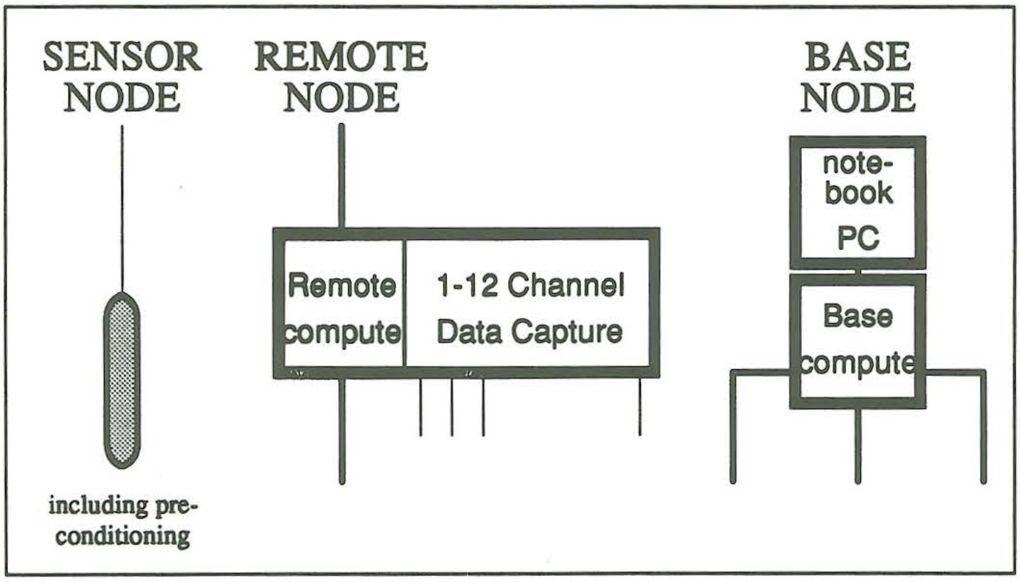

Figure 1: The principal instrument components

- the sensor node: - sensors (e.g. magnetometers, electrodes or seismometers) including signal preconditioning (e.g. preamplifiers, filters)
- the remote node: - data capture, all analogue signal conditioning, like band -pass and notch filtering, signal amplification and finally, analogue to digital conversion. Furthermore the digital data are decimated, digitally filtered, subjected to FFT and distributed to the base node.
- the base node: - collection of data in the time and/or frequency domain from all remote nodes. Performance of real time processing of all time synchronous channels and calculation of all (inter-site) transfer functions. 1D & 2D inversion, contouring and execution of user supplied software dependent on the actual configuration of the sensors. Data transfer to the PC, the integrated hard disk or an optional printer.
- notebook PC: - the user interface to the base node and the whole instrument. Software for instrument set-up, control and testing, graphical data visualisation and data storage. This can be disconnected during stand alone operation.
- the branch node: - a device to increase the number of communication branches by two (not shown in the figure).

In figure 2 the modular concept of S.P.A.M. is illustrated. Analogue signals are fed from the sensors or the calibration signal generator into the analogue signal conditioning modules of a REMOTE. The first transputer module (TRAM) performs data acquisition and oversampling filtering. As the output registers of the analogue to digital converters are directly mapped into the transputer memory, very high sampling rates can be achieved. From the acquisition module, the data are transferred to the REMOTE computer TRAM for digital band pass filtering, prewhitening and transformation of the data to the frequency domain. Corrections for sensor response functions are also performed at this level.

BASE and REMOTEs have three and two channels/branches respectively for long distance digital communication. The communication modules and the attainable data transfer rates may vary, depending on the physical media used (e.g. cable or telemetry). REMOTEs can be connected to each other and a REMOTE or branches of REMOTE(s) can be connected to a BASE. Thus, a networked instrument with virtually any number of channels can be created. This concept is limited by the accumulated bandwidth of the communication media and at the base the computational power of the TRAMs.

Time series and/or frequency domain data are stored on the internal hard disk and processed by the BASE computer module. Time series, frequency spectra and (intermediate) results can be visualised and archived on a standard notebook or laptop PC. Optionally, hard copies may be produced on a fast thermal printer.

As all REMOTEs are usually connected to one BASE, all channels are synchronised with a time signal generated by the BASE. An accuracy better than 5µs is anticipated. With external clocks (e.g. GPS or DCF), higher accuracy or synchronisation of unconnected S.P.A.M.s can be accomplished.

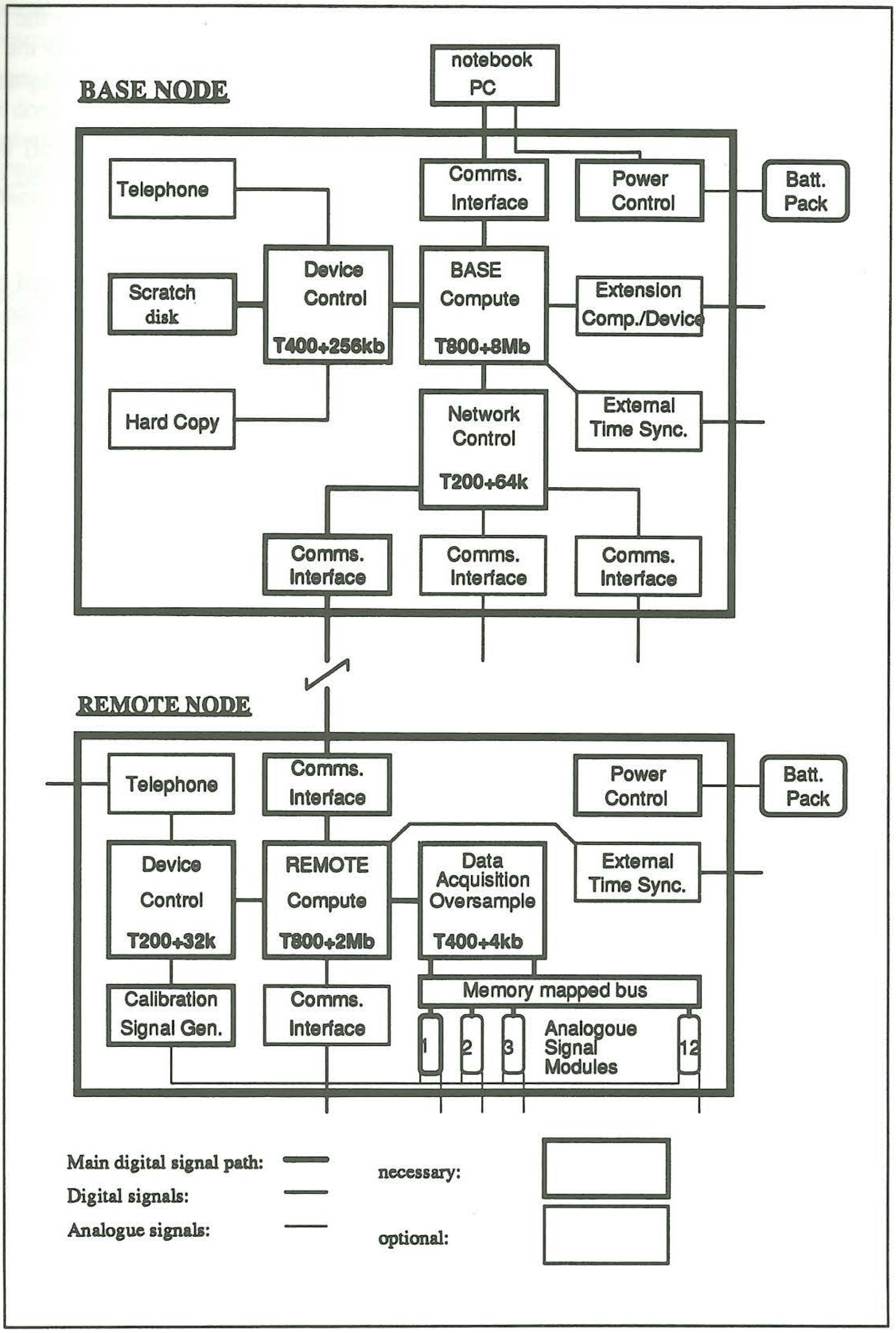

Figure 2: The modular concept of S.P.A.M. III

The need for a telephone may not be obvious, but one would be very helpful in the initial set-up phase, for calibration and maintainance of a working network. As all the high speed digital connections are already available, a telephone could very easily be incorporated into the system.

To save battery life, modules which are not used for some time are switched off by the power control module. If the device is needed at a later stage, it can be re-activated.

The modules

While some of the components shown in figure 2 are optional (e.g. telephone, hard copy or an external time base), others can be replaced by a different type or configuration (e.g. different analogue signal conditioning modules, size of the hard drive or the amount of RAM for a TRAM).

Data acquisition modules

The data acquisition modules operate in three frequency ranges:

- HF (high frequency) band: 8KHz - 1Hz
- SP (short period) band: 128Hz/2kHz (switchable) - 1000s[1]
- LP (long period) band: 1Hz - DC

All modules have fixed low pass filters (two, for the SP board), but the high pass filter corner frequencies are switchable over a wide range. Therefore, the values given above are only examples. The HF and SP boards will contain up to two notch filter modules for which the frequencies can be chosen (e.g. 16.6, 50, 60, 100Hz, etc.). For the HF band the maximum number of channels per REMOTE is 8, while for other bands it is 12. For the low frequency bands the signal are recorded continuously without the need to interrupt the data acquisition for processing the data. In the high frequency mode of the SP band (2kHz - 1Hz) and the HF bands, time windows of a fixed length are recorded and then processed by the same software as for real-time.

To improve signal to noise ratios all channels are oversampled, depending on the frequency band, by factors of 2, (2)4 or 16 respectively The CS5101, CS5102 and CS5505, 16-bit AD converters from CRYSTAL Semiconductor are used for the HF, SP and LP bands, respectively.

The signal amplification is divided into static and dynamic gain sections, which both provide amplification in steps of a power of 2 from 2^0 to 2^7. Initially the signal amplitudes are raised by the static gains, which are normally not changed during recording. After all the analogue filtering is done, the signals are again adjusted by an auto-gain circuit. Their amplification is changed continuously, while data are being recorded. This feature has been used successfully in the earlier S.P.A.M.s with the objective of further enhancing the dynamic range. The overall sample resolution is estimated to be 20-22bits (16Bits:ADC + 2Bits:auto-gain+ 2-4Bits:digital decimation) or 120db-132db. The

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[1] Only the SP board will be built in the initial design phase.

overall signal amplification is between 2^0 and 2^{14} plus any additional external preamplification (e.g. telluric).

Compared to the previous versions of S.P.A.M., more time domain signal processing can be done digitally, simplifying the design needs for the analogue filters. Very stable and cost efficient 5-pole low pass filters can be built with low noise specifications. An active 5-pole low-pass filter, in combination with a 4-times digital oversampling filter, results effectively in a 15-pole filter, with 90db signal reduction at the Nyquist frequency.

Computer modules

The computational heart of S.P.A.M. III is the transputer, a family of single chip, fast RISC microcomputers, each with its own internal memory, 2 timers and four high speed serial channels, the links. Transputers communicate through these bi-directional links at transfer rates selectable between 5/10/20 Mbaud. Three compatible transputer types coexist in the system:

- T200: 16-Bit-CPU for input/output operation, device control and network control
- T400: 32-Bit-CPU for data acquisition and oversampling filter
- T800: 32-Bit-CPU + 64-Bit-FPU for digital filtering (floating point), FFT and general data processing and interpretation.

The CPU, FPU, links and timers all work independently from each other. For example, while an operation is being executed by the FPU, data for the next operation is simultaneously being prepared by the CPU and the 4 links are transferring data to other transputers under DMA (direct memory access).

Transputers can be programmed by high level languages, such as FORTRAN, C and OCCAM. They provide very efficient, embedded multi-tasking without the need for an operating system. TRAM modules can consist of only internal on-chip-memory (4kb) or up to 4Gb external memory in a linear address space. Different kinds of memory (e.g. register, EPROM, SRAM and DRAM) can be attached at the same time. Typical power consumption is in the range 300mW to 700mW. Ready configured TRAM modules are commercially available and if necessary more powerful devices such as the TMS 320C40 or the new H9000 can be connected via the transputer links.

Digital communication modules

Although the constructors of these transputers probably never considered the requirements of a distributed MT instrument, our tests have shown that for distances of up to 300m, data transfer rates of 100kbyte/s can be achieved with normal cables (see fig. 3). Despite the long distances between single processors they still behave as a normal transputer cluster since they are connected by their standard link interfaces.

However, depending on the distance between BASE and REMOTEs different media and therefore communication modules for data transfer are necessary:

- ≤300m(-500m) - Dual twisted pair cables,are being used for the initial design.
- ≤4000m - Cable with repeater boxes or fibre optics: Longer distances can be achieved with normal dual twisted pair cables if the signals are refreshed every 200m by repeater boxes. Fibre optics weigh less than normal cable and provide very high transfer rates (in the order of Mbyte/s) but are very expensive and difficult to repair.
- ≥4000m - Radio telemetry: Telemetry could be used in applications where REMOTES are too far away to be connected by cable. Typical transfer rates for telemetry systems are in the range of 4kbaud and hence real time operation at higher frequencies would not be possible.

Transputers connected internally, inside a BASE or REMOTE communicate at full speed, e.g. 20 MBit/s. Depending on the peripherals to be attached, ports and software drivers for parallel (CENTRONICS), SCSI and serial (RS232 or RS422) connections can be included.

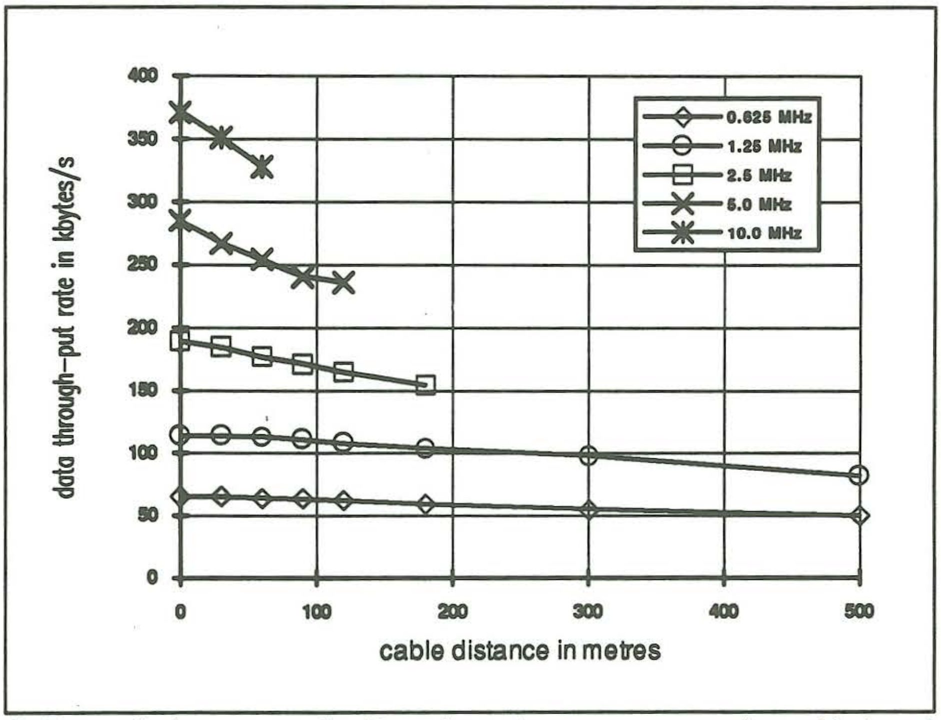


Figure 3: Transmission test results: Data through-put rates at varying cable lengths using RS422 receiver/transmitter devices. The transputer links are operated at frequencies between 0.625 MHz and 10 MHz. For distances of 300m transfer rates of more than 100kbytes/s are achievable.

Peripheral modules

The following peripherals can or must be connected to a S.P.A.M. system:

- internal hard disc drive as a scratch disk for temporary data storage, size e.g. 100Mb
- internal printer: a high speed thermal printer (e.g. 640 dots/line, 200 dotlines/s)

- time synchronisation: e.g. Omega clocks, GPS, DCF (optional)
- inter-node telephone (optional)
- calibration signal generator
- notebook PC (user interaction and data storage)
- external data storage: to dump data e.g. optical disk, exabyte, streamer (optional)

The data acquisition scheme

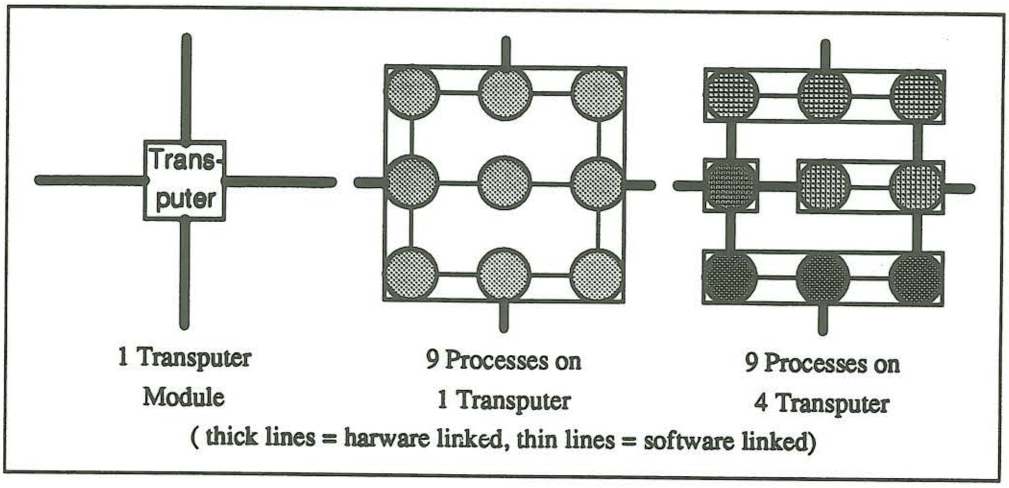


Figure 4: From the programmers viewpoint, hardware and software channels look the same. The actual number of transputers is specified at run time with a configuration file

On a Transputer a programme or better a *process* is defined as a piece of code that starts, performs a number of actions and may or may not stop. Many processes may run in parallel or concurrently. A process is the standard building block for both hardware and software. This is achieved at the programming level where no distinction is drawn between a number of concurrent processes on one transputer and the same processes on an arbitrary number of transputers. This is because all processes communicate with each other by channels and only at the final programme configuration stage these channels are defined as being either (see. figure 4)

- soft(ware) channels or
- hard(ware) channels, physical links between transputers.

Internally they are supported in the same way by the instruction set for concurrent processing within a transputer.

In the current system up to 12 channels can be digitised synchronously and in parallel. Each channel can now be *cascaded* (band pass filtered and decimated) independently from all others. The cascading however must be done sequentially (see figure 5), as the times series with fs/4 (fs=sampling rate) is derived from the fs/2 series which was itself generated from the original time series fs. The processing modules in this data acquisition scheme are low pass filter, high pass filter, prewhitening and fast Fourier transformation. After correct synchronisation of the cascaded signals however, all the processing code can be executed concurrently. Once again, the advantages of the transputer concept for this task should be obvious. Once the processing modules are written, the problem is reduced to connection of the correct data streams (links). The transputer itself ensures an optimised system performance.

Fig. 5 also shows that the data can be forwarded as the original time series, as decimated and low pass filtered time series, as band pass filtered time series or as time windows, transformed to the frequency domain. Any mixture is possible and all time series are the continuous, non-interrupted streams of data which can be stored and processed at a BASE.

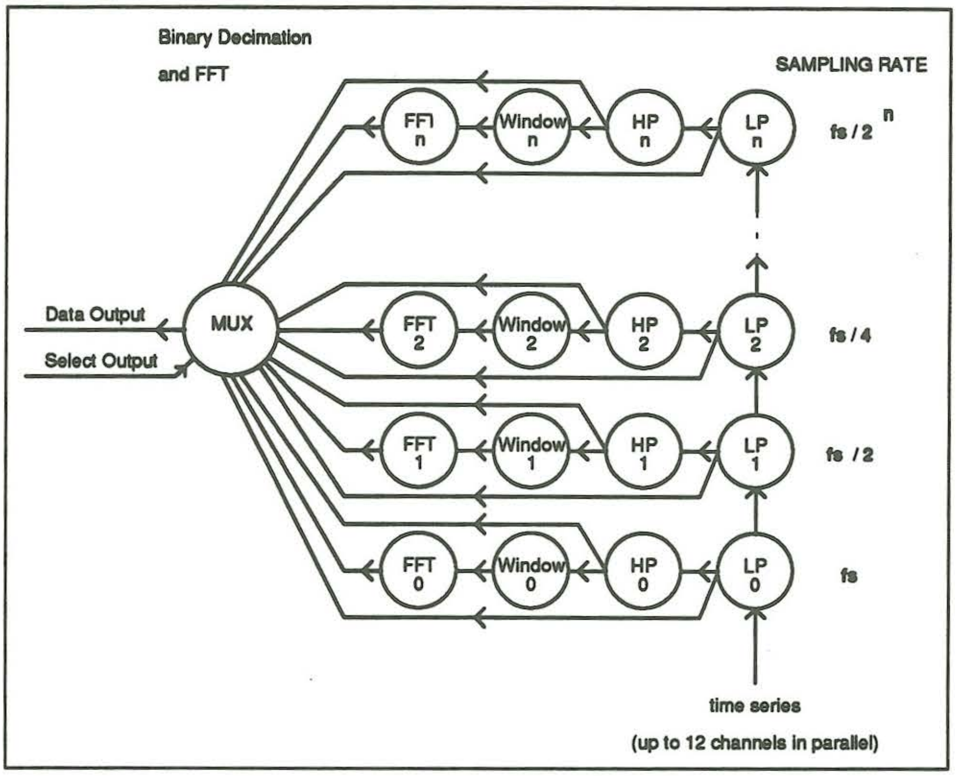


Figure 5: The data acquisition scheme

For this cascade scheme, the frequency bands in which the data are to be processed can be selected dynamically and modified in steps of a power of two.

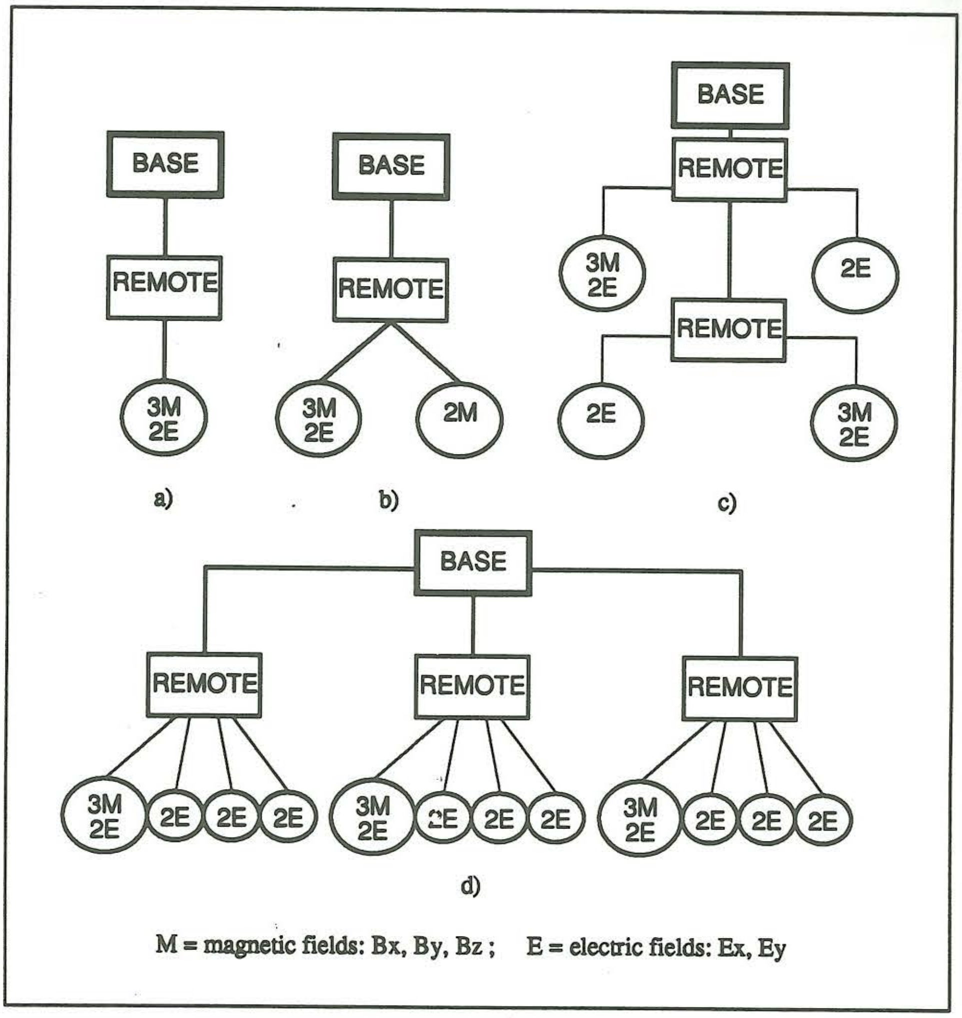
Decimation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Band-	[---------		frequency (Hz)				-----------	----]	[---	------------			period (secs)		------------			----]
corners	128	64	32	16	8	4	2	1	2	4	8	16	32	64	128	256	512	1024
Band 1	[------	------	------	------	------	------]												
Band 2					[------	------	------	------]										
Band 3							[------	------	------	------]								
Band 4									[------	------	------	------]						
Band 5											[------	------	------	------	------	------	------	------]

Fig. 6: frequency bands can dynamically be selected and modified

In fig 6 for example, 5 overlapping frequency bands (more are possible) in the range 128Hz - 1024s have been selected. Wider bands have been used at both ends of the frequency range but small, narrow frequency bands at around 1Hz. This enables the identification and isolation of noise sources and derivation of sub-bands with similar signal amplitudes.

As the frequency range has to be divided into sub-bands for processing, this seems to be the most flexible way and it can be implemented painlessly with transputers. The data can be processed in a combination of cascade decimation and conventional methods with the length of the time segments depending on the band width (e.g. 1024 samples). As robust processing methods will also be incorporated good quality results are expected in real-time, and without the need for further main frame processing as is the current practice.

Typical field layouts



M = magnetic fields: Bx, By, Bz ; E = electric fields: Ex, Ey

Figure 7 a-d: Example field layouts with S.P.A.M.III

Some field layouts using the S.P.A.M concept are sketched in Fig 7. In 7a and 7b the normal 5 component MT and the Remote Reference cases respectively are shown. In 7c two 5 component MT sites plus two remote telluric sites are set-up on a grid and in 7d a combined MT and E-mapping project on a profile is illustrated.

In general, any tree structure of sensors can be assembled. To increase the number of communication channels for more complex networks, branch nodes can be linked between any two REMOTEs or BASEs, but only one BASE per tree is possible. Computationally, the BASE could be extremely powerful, as the BASE TRAM can consist of a whole cluster of transputers or other processors connected. It can also run as a stand alone compute engine for reprocessing and modelling data in the laboratory.

Software and operation

At the moment this is the most speculative part of the development, but S.P.A.M.III software consists of programs running on the PC and code executed on the transputer network with some communication between the two worlds. A decision has not yet been made as to the nature of the communication between the two, but a bi-directional printer port or a standard SCSI interface could be used. All programs, including the transputer code, will be located on the PC and down loaded to the BASE and REMOTEs:

- Initialisation: A small utility program is executed first, to reset and initialise a whole transputer network and to analyse all link connections to automatically determine the configuration beeing used and to check the processor states.
- Calibration: There are tools to test all devices and connections using the built in signal generator and to calibrate all channels, excluding the sensors.
- Processing and control software containing routines for:
  - Start/stop/programme recording
  - Instrument parameter: to set/reset gains, switches, high pass filters etc.
  - Program parameter: to set/modify frequency bands, stacking parameter, etc.
  - Data storage: Allocation map for internal hard disk, data dump.
  - Data visualisation: time series, frequency spectra, stacking results, transfer functions, etc.
- Database: Since very complex instruments can be created with many sensors and other hardware modules connected, it would be inefficient if the complete system had to be described from scratch in every detail on each deployment. Therefore, a PC based database is being implemented - this will contain the details of all available modules and where specific configurations can be put together, stored and be recalled. This database will also help organise the file handling, as existing file formats are normally unable to deal with instruments that can cover several sites with many sensors in non standard configurations. It is also possible to retrieve information from the data base for off-line data processing, e.g. site co-ordinates, sensor spacing, etc.
- Presentation of results: Programs are available for 1D and 2D inversion or modelling and a contouring package is included
- Optional Packages: Definition of an interface to allow external, user supplied software (PC or transputer based) to be included.

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