THE FREJA WAVE AND PLASMA DENSITY EXPERIMENT

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Abstract. The Wave Experiment, F4, on the Swedish/German satellite *Freja*, is designed to measure the electric wave fields up to 4 MHz, the magnetic wave fields up to 16 kHz and the plasma density and its relative variations up to 2 kHz. Six wave signals and four density probe signals can be measured simultaneously. The wave forms of all signals are transmitted to ground without any analysis onboard. The limited TM allocation does not allow continuous sampling of the wave signals, so normally the measurements are made in snapshots of various lengths dependent on sampling frequency, etc. Continuous sampling can be made for shorter time periods by using a 6 Mbyte memory as a buffer.

1. Introduction

This report describes the design, principles of measurements and the different modes of operation of the Freja Wave Experiment F4. It also gives some examples of data obtained in flight as illustrations to the description of the operation of the instrument.

The experiment is designed to measure the wave forms of the electric field signals up to 4 MHz, of the magnetic field signals up to 16 kHz and of the density variations up to 2 kHz. It also measures the total plasma density and electron temperature by means of up to four Langmuir probes. The plasma density can also be deduced from the characteristic electron frequencies in the plasma. The available telemetry capacity is far from enough for continuous measurements of the wave forms of all signals. Therefore, the measurements are made in snapshots of various lengths and at various intervals dependent on sampling rate, TM allocation, etc. However, for short time periods it is possible to make continuous sampling of the Low and Medium frequency signals by using the onboard 6 Mbyte memory as a buffer.

The experiment is built in close cooperation between several institutions which have contributed both hardware and software as listed in Table I.

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TABLE I
Contributors to the wave instrument

Institute	Contribution
Swedish Institute of Space Physics, Uppsala Division (IRF-U) (PI)	Main electronics, Langmuir probes, flight software
Centre Reserch en Physique l'Environnement (CRPE) Paris	Search Coil assembly
Cornell University (CU) Ithaca	High-frequency assembly
University of Oslo (UiO)	Burst memory

Novel features of the *Freja* F4 experiment compared to earlier satellite experiments include:

– Actual wave form measurements up to 4 MHz.

Possibilities to measure density wave fields with four different sensors, facilitating interferometric measurements with four different baselines.

Possibilities to measure electric wave fields with eight different antenna lengths, thus providing some sampling in wave vector space and making electric field interferometry possible.

Possibilities to separate density and temperature fluctuations by operating pairs of probes at different bias voltages.

An improved absolute electron temperature measurement by utilising two different types of probes (spherical and cylindrical) simultaneously.

Very good determination of ambient plasma density from plasma frequency.

2. Booms and Sensors

The F4 instrument utilises a number of sensors mounted on booms in the satellite x/y (spin) plane. The locations and orientations of these sensors are schematically shown in Figure 1 where the lengths and angles to the satellite X-direction of the wire booms are indicated.

There are three pairs of spherical probes, P1–P2, P3–P4, and P5–P6 mounted on three wire boom pairs, two of which are extended to 10.5 m and the third pair to 5.5 m giving separation distances between opposite probes of 21 and 11 m, respectively (see Figure 1). The probes are 6 cm in diameter and coated with graphite of type Dag 213. Four of the probes, (P3, P4, P5, P6) have switchable preamplifiers inside and can be used for either electric field measurements (potential mode) or plasma density measurements (current mode). The P1 and P2 probes are dedicated electric potential measurements only and the preamplifiers of these probes have extended frequency bandwidth (1 MHz). All six probes, P1–P6, are located in the spin plane and are also used by the F1 experiment for the DC electric

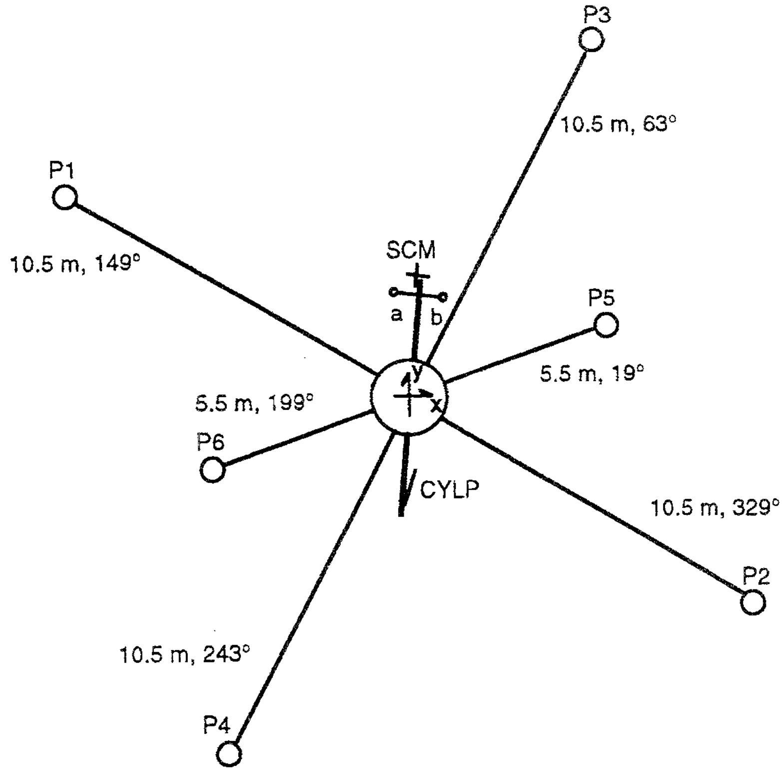

Fig. 1. The F4 sensors and booms.

field measurements. For the high frequency measurements of the electric field, in addition to the P1 and P2 probes, there are two dedicated HF probes, HFa and HFb, that are 2.5 cm in diameter. Pre-amplifiers are placed inside the probes giving a frequency bandwidth of 4 MHz. They are mounted on short stiff booms, deployed in the spin plane giving a probe separation distance of 1.2 m. The probe-boom assembly is mounted at the outer end of the Search Coil Magnetometer (SCM) stiff boom about 2 m from the satellite body.

A CYlindrical Langmuir Probe (CYLP), 57 cm long and 1 cm in diameter, is mounted at the outer end of the DC magnetometer (F2 exp.) stiff boom. The probe, which is made of carbon fibre, is oriented parallel to the spin axis. As the spin axis is 'sun-pointing' within about 30 degrees, this will minimise the projected surface area being sunlit and thus the photo emission.

The Search Coil Magnetometer (SCM) assembly consists of three identical coils which are mounted at the outer end of a stiff boom of about 2 m length. The coils are mounted orthogonally with one parallel to the spin axis (z) and the other two in the spin plane (x and y). The signals are directed to pre-amplifiers, one for each coil, that are mounted in a box placed close to the boom hinge.

TABLE II
Measurement ranges

Signal	Dynamic range		Frequency range		
e (HF)	0.10–600	mV m^{-1}	0.1–4	MHz	
	0.002–2.5	mV m^{-1}	0.02–1	MHz	
$e_{i,k}$	0.004–1000	mV m^{-1}	0.001–16	kHz	MF
			0.001–2	kHz	LF
$b_{x,y,z}$	10^{-5}–10^{-1}	$nT/\sqrt{Hz}$	0.03–16	kHz	MF
			0.03–2	kHz	LF
$\Delta n/n$	0.05–50	%	0.002–2	kHz	LF
n	5–6 $\times$ 10^4	cm^{-3}	DC-60	Hz	

3. Measured Quantities

The wave forms of the following quantities are being measured by the F4 instrument:

– Electric wave fields up to 4 MHz (sample rate 8 MHz).

– Magnetic wave fields up to 16 kHz (sample rate 32 kHz).

– Plasma density variations up to 2 kHz (sample rate 4 kHz).

– Cold plasma density and electron temperature (sample rate 128 Hz continuous).

The measurement ranges are summarised in Table II.

The electric field components are derived from the potential differences between any two of the spherical probes (P1–P6) operated in potential mode or between any probe and the satellite body. For waves having wavelengths shorter than the probe to probe or probe to satellite distance, the measurements give the potential difference rather than the electric field strength. Using various combinations of probes with different separation distances, information on wavelength or spatial scales of structures can be inferred.

The plasma density fluctuations are measured at up to four points by means of the probes P3, P4, P5, and P6 while operated in Langmuir mode. From the AC component of the resulting probe current the relative variation in the density ($\Delta n/n$) is deduced. The measuring range is of the order of 0.05 to 50% and the frequency bandwidth is 2 kHz. The multipoint measurements give input to calculations of phase velocities and wavelengths of short wavelength waves.

The Langmuir probes are biased with a voltage and, dependent on the sign and magnitude, electrons and/or ions are attracted. The relation between the bias voltage and the resulting current is fairly well known from conventional probe theories and the probe current is mainly a function of the electron and ion temperatures and the number density of the particles although we have to consider effects introduced by the magnetic field. By keeping the bias fixed at a level well above the electron temperature expressed in volts, and assuming a constant electron temperature, the probe current is directly proportional to the plasma density. By sweeping the bias between negative and high positive values, it is possible to determine the temperatures and also get a calibration of the probe performance. The Langmuir probes belong to two different biasing systems, Bias1 and Bias2, different bias voltages. This makes it possible to derive the electron temperature without making sweeps of the biases and thus achieve a far better time resolution in the determination of the temperatures. Also, the electric field induced in the booms by the geomagnetic field provides a natural spin modulation of the bias voltage, thus providing a continuous sweeping. The bias sweeps are made normally about 2 min apart.

The CYlindrical Langmuir Probe (CYLP) concept is similar to the spherical Langmuir probes except for the shape of the probes and the lack of pre-amplifier in the probe (placed in the main electronics box). As the electron collection to a cylindrical probe is different that of a spherical probe, the differences can be used to determine the electron temperature and, hopefully, also to reduce the interference caused by the photoelectrons. CYLP and P4 share one channel in the TM format so that CYLP is automatically operated at times when P4 is used for e-field measurements (which is the status most of time).

4. Principles of Measurements

There are two categories of signals: (i) the AC or Wave signals and (ii) the DC or Langmuir Probe signals. All are transmitted to ground as Wave Forms and there is no on board treatment but filtering, analogue to digital (A/D) conversion and intermediate storage. However, due to the high sampling rate compared to the TM capacity, it is not possible to transmit the wave signals continuously for longer time periods. Therefore, the measurements are made in snapshots and the data is intermediately stored in a buffer memory (part of the Burst Memory) before it is transmitted to ground in a slower tempo. This technique is called Time Lapse and it is the basis for operating the experiment. The length, or time duration, of the snapshots varies dependent on frequency range, telemetry allocation and rate, use of memory etc. The time needed to transmit one snapshot to ground is called a Cycle and each branch of signal handling has its own sets of cycle times. The Duty Cycle, defined as the snapshot length divided by the cycle length, varies between 0.01% (for the HF signals) and 19% (for the LF), all counted for low, or normal, TM rate (in high rate, the F4 TM allocation is twice as high and thus the duty cycle figures are twice as good). A true frequency analysis of the sampled wave signals require effective low pass filtering of the signals prior to the digitisation. Frequency components higher than half the sampling frequency (Nyqvist frequency) must be cut away or they will show up as lower frequency components in the result. As the filters are not perfectly sharp, the break point should be well below the Nyqvist

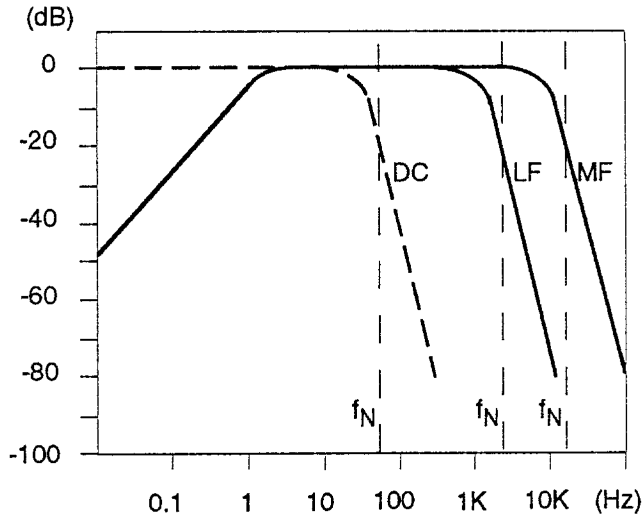

Fig. 2. Anti-aliasing filter characteristics for DC, LF, and MF branches. The vertical dashed lines indicate the Nyqvist frequency, respectively.

frequency. For the DC, LF and MF, the 3 dB damping point is adjusted to a frequency corresponding to the sampling frequency divided by 2.5. Figures 2 and 3 show the filter characteristics for the DC, LF and MF branches and the HF branch, respectively.

5. The Different Branches of Signal Handling

The measured signals are handled in three AC branches of different frequency bandwidths and one DC branch. The AC branches are called the Low Frequency (LF), having four channels in parallel, the Medium Frequency (MF) and the High Frequency (HF) with one channel each. The DC branch has four channels in parallel for handling the Langmuir probe signals.

5.1. The High Frequency (HF) Branch

The HF branch contains one channel of 8 Msamples per second and of 8 bit resolution. The HF signal can be either of two which have slightly different frequency bandwidth and originating from probes with highly different base lengths. The P1–P2 signal has a bandwidth from a few tens of kHz up to 1 MHz and the probe separation is 21 m. The HFa–HFb signal has a bandwidth of about 100 kHz to 4 MHz and the probe separation is 1.2 m only. The gain of the signals can be set manually in two steps with a factor of 50 in difference. In order to increase the probability to catch short lived events like solitary structures etc., which are supposed to have higher power, many snapshots are taken within each cycle but only one is selected for transmission to ground. An automatic process compares each

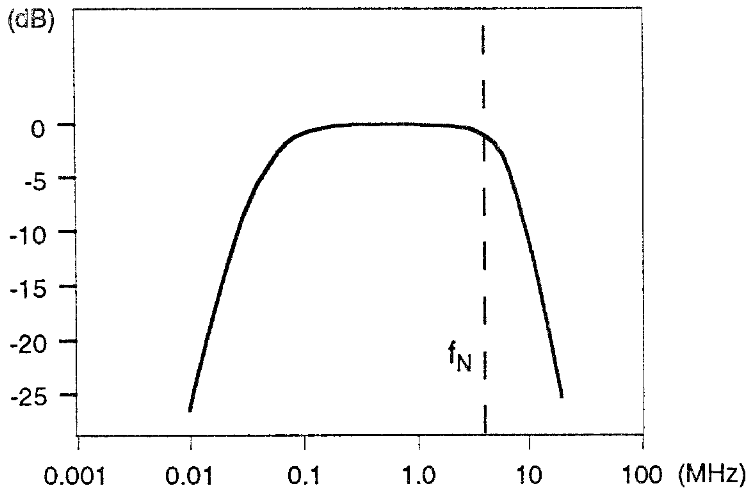

Fig. 3. Anti-aliasing filter characteristics for the HF branch showing the input voltage to the A/D converter as a function of frequency.

new snapshot with the one that is stored in the memory. If the new snapshot is better (having higher power), it overwrites the old and the new one is used as reference for the next. At the end of the cycle the snapshot that is stored in the memory is the one having the highest power and thus the best and will be telemetered to ground. The power is measured by a Root Mean Square (r.m.s.) detector that monitors the signal within the frequency band 0.1 to 4 MHz. The HF snapshots are always 1.024 ms long (8192 samples), but the number of samples that are transmitted to ground is selected by command to be 8192, 4096, 2048, or 1024 giving cycle lengths of 8, 4, 2, or 1 s, respectively, for Normal TM mode. An example of HF data received by the HFa–HFb probes on the short booms and for high gain is found in Figure 4, showing the Wave Form of a Langmuir wave with strong amplitude modulation.

5.2. The Frequency (LF) Branch

The MF branch can handle one signal at a time which is sampled at 32 768 per second to 16 bit resolution, giving a frequency bandwidth of 16 kHz. Up to four different signals can be cycled between, one for each MF cycle. The snapshot lengths can be selected between 15.6 and 125 ms in steps of a factor of 2. A special option is the possibility to sample two different signals within the same snapshot. This can be made only in the 125 ms mode where the first signal is sampled for 62.5 ms and then the MF Multiplexer, where the signals are selected, is switched to the other signal for 62.5 ms. Thus, the two signals are sampled as close in time as possible giving a possibility to make comparisons.

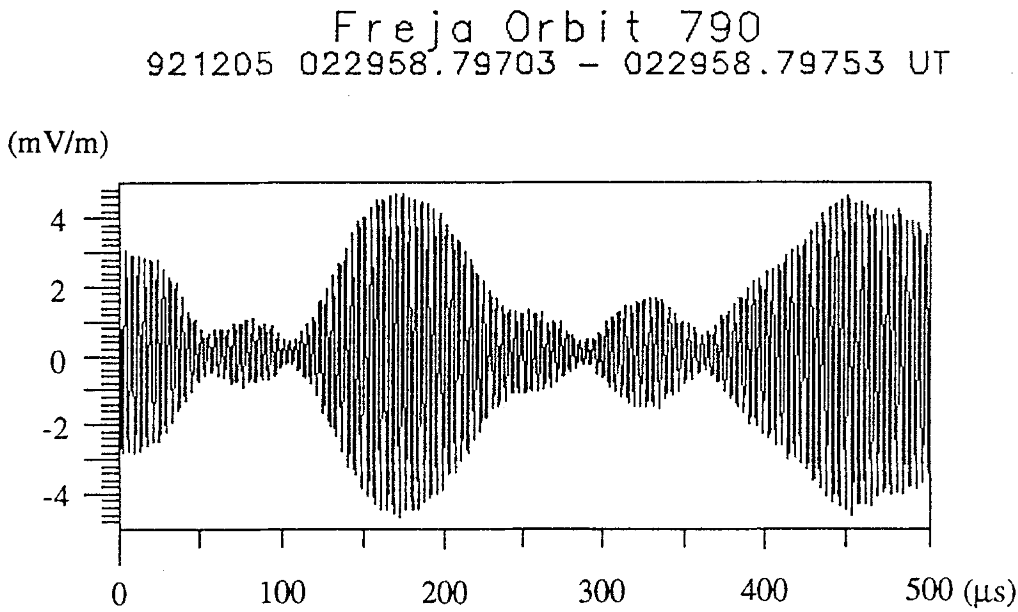

Fig. 4. The Wave Form of a strongly modulated Langmuir wave as measured by the HF branch.

5.3. The Low-Frequency (LF) Branch

The LF branch handles four channels in parallel at a sample rate of 4096 per second and to 16 bit resolution. The four channels are sampled simultaneously and the snapshot length can be selected in seven steps between 0.375 and 24 s. Each channel has its own Multiplexer for selection of signals with 8 inputs on each. The great number of combinations of electric field probes are handled by the Multiplexers $\pm a$ and $\pm b$ where two different differential signals are made called dea and deb. These signals are routed both to the MF Mux and to the LF Muxes. Figure 5 shows the Wave Form of a Lower Hybrid Solitary Structure as measured by two LF channels an the MF channel (E-field and $(\Delta n/n)$ signals).

In the Burst Mode, the frequency bandwidth of the LF branch is switched to Medium frequency range with a sample rate of 32 ksamples per second and the Nyqvist filters are switched accordingly. The four channels are in this mode directly comparable to the MF branch giving a total of five MF channels for the Burst Mode.

5.4. The DC Langmuir Probe Branch

The DC branch contains four channels dedicated to the Langmuir probe DC signals (sometimes denoted n). They are sampled at 128 per second and to 16 hit resolution and are transmitted continuously to ground. One of the channels is time shared between probe P4 and CYLP. Figure 6 shows an example of signals from two opposite Langmuir probes (P5 and P6). The strong spin modulation of the signals are due to $\mathbf{v} \times \mathbf{B}$ electric field effect on the probe bias, to the wake effects from the

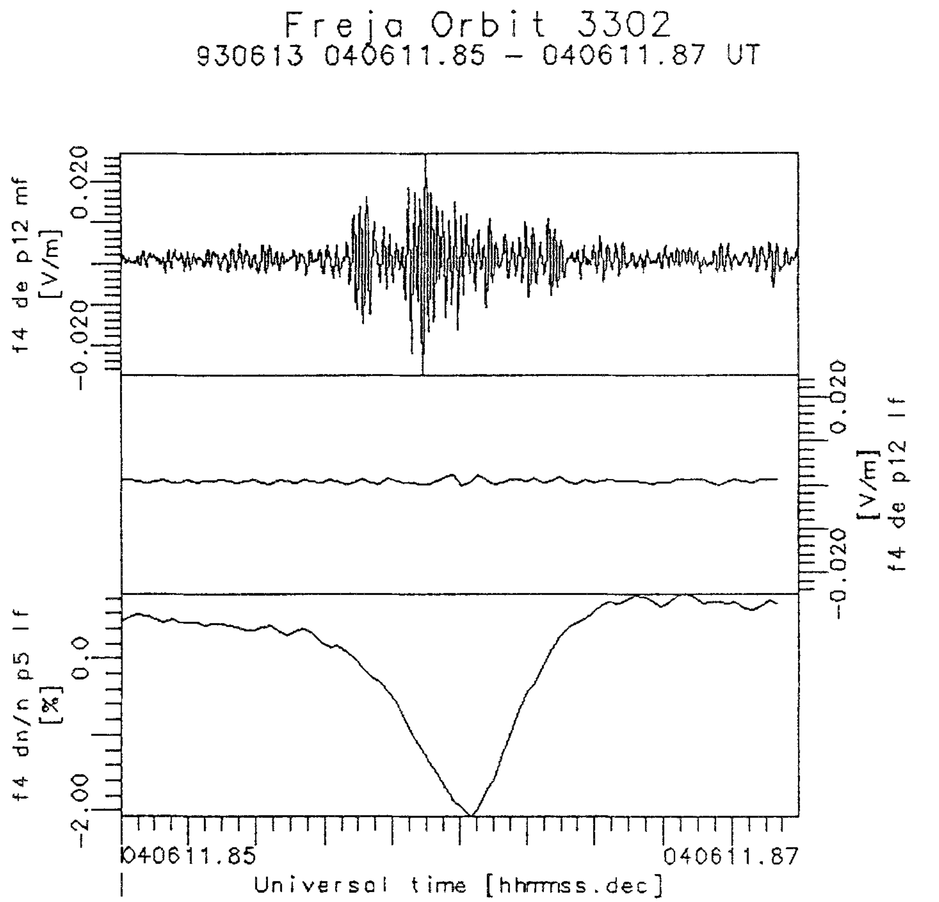

Fig. 5. Example of the electric field and denstiy signatures of a Solitary Strccture as seen in the MF and LF branches. Top panel shows the de12 electric field signal in the MF channel middle panel shows the same signal in the LF branch and bottom panel the ($\Delta n/n$) signal also from a LF channel.

satellite body, from photo electron contamination, etc. (The boom length is 5.5 m from centre).

In the following table the characteristics of the different branches and channels are summarized.

6. Modes of Operation

The Wave experiment can be operated in a great variety of different modes which can be grouped into four categories. Three of those are measurement modes and one is for dumping of data that has been stored in the Burst memory. The four categories are: time lapse, continuous, survey, and the dump modes. A time lapse mode (or normal mode) is defined as a mode where data, taken during one snapshot, is transmitted to ground during one cycle and no data is accumulated in the Burst

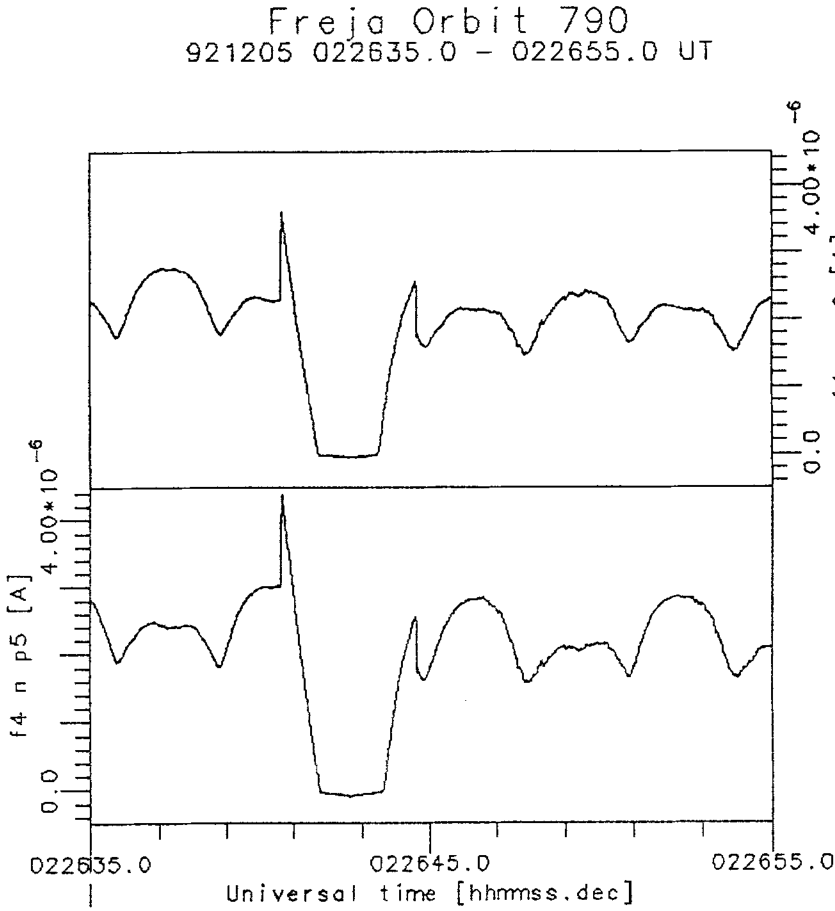

Fig. 6. Spin modulation of the Langmuir probe current from two opposite probes (P5 and P6).

Memory. A Continuous mode is one where wave signals in one or two branches are sampled continuously and data is accumulated in the Burst Memory for transmission to ground at a later occasion. There are three sub modes called ContinuousLF, ContinuousLFMF and Burst where the ContinuousLF and ContinuousLFMF are basically Normal modes, but where the LF and in the second case, both the LF and the MF branches are sampled continuously for 152, respectively, 50 s. The Burst mode is quite different to the others as nothing else is done by the experiment but sampling the Burst signals. Even the telemetry output from the experiment is blocked during the sample period. Up to five different wave signals are sampled continuously at 32 ksamples per second for times of 15 to 76 s, dependent on the number of signals. In addition to the wave signals, also the HF branch can be integrated into this mode. However, the HF signal is still sampled in snapshots, but the number is increased to about 8 per second instead of normally 1 per 8 s (for 8 ksample snapshot size). There are two different Survey Modes (called Timer mode in the Mode Scheme, Figure 7) that can be used at times when there is no ground station contact. In one of the modes, the experiment is run in a normal mode and the data is directed to the Burst Memory until the memory is filled, which takes approximately 10 min. In the other mode, the experiment is run in a Normal mode but the telemetry stream is directed to the Burst Memory only for a short time period equal to one LF cycle. After a rest time, the TM stream is directed to the Memory again for another LF cycle of data etc. The rest time is set by command and can be varied between 0 to 512 s. In this mode, data can, in principle, be taken for up to about 20 orbits before the Burst Memory is filled up. Within each of these categories of modes, there are a great number of sub-modes such as different combination of signals measured, different sampling times, etc. Most of these modes and submodes are described graphically in the Mode Scheme found in Figure 7. A default mode is stored in PROMs in the experiment and this mode is automatically loaded at each power up. Any changes to this must be commanded, either via timer controlled commands or directly from ground.

From the left in the Mode Scheme, the different sensors and their corresponding signals are shown. In the Signal Selection part, the multiplexers where the signals are selected to the different branches are found. Note that the multiplexers $\pm a$ and $\pm b$ are used only for creating differential e-field signals called dea and deb respectively. The Mode Select part shows the different alternatives of mode categories in terms of probes, signals, sampling periods (snapshot lengths) and cycle lengths, etc. Each branch has its individual cycle length, but at regular time intervals the start of the sampling periods of the LF and MF channels coincide. Only the alternatives for normal TM rate are indicated. For high TM rate, the cycle lengths are halved but all the frequency ranges remain the same. The default settings are indicated in which the experiment is automatically set at power up.

7. Commands

Commanding the F4 experiment is made either by the *Freja* operators at Esrange or directly from the F4 ground support equipment, which is also accessible from remote sites via Internet connection. At times when the satellite is out of reach from Esrange, stored commands are used that are loaded to the *Freja* System Unit (FSU) during periods of ground contact with Esrange. The stored commands, that are executed by an on board timer, make the operations very flexible and make data taking from any portion of the orbit possible. The Mode scheme in Figure 7 also serves as a guide for command possibilities.

8. Electronics

All electronics, except the probe pre-amplifiers and the SCM pre-amplifiers are contained in one box made of aluminium. Besides being a container for the electronics, it also serves as a radiation shield for the expected total radiation dose for

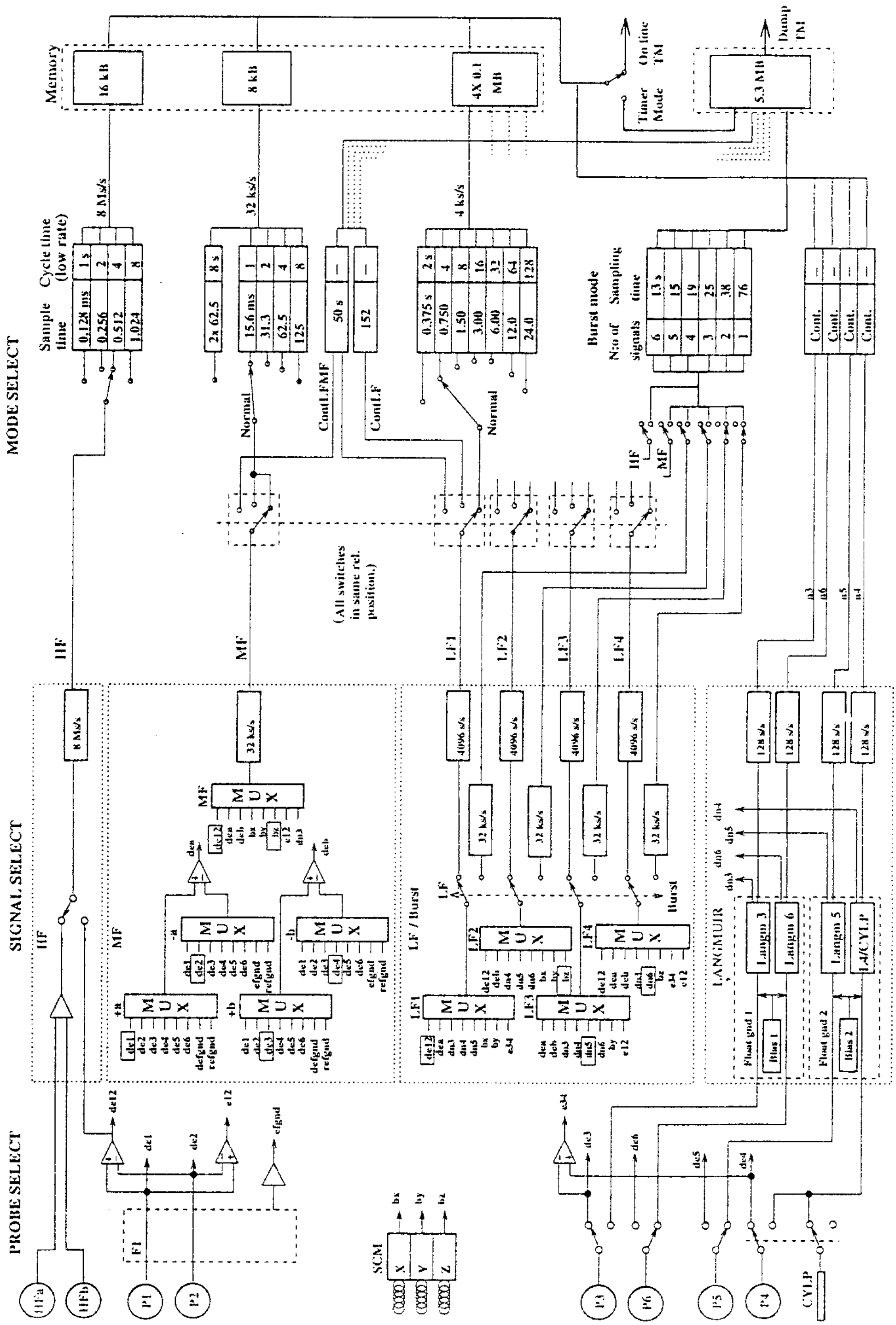

Fig. 7. Graphical representation of possible signals and modes. Default setup is shown.

TABLE III
Summary of the different signal handling branches

Branch	Signal	Sampl. rate ksample s^{-1}	Bits/word	Telemetry words s^{-1}	Dutcy cycle %
HF	$e_{a,b}$	8000	8	1024	0.01
1 ch	$e_{1,2}$				
MF	$e_{i,k}$	32	16	512	1.6
1 ch	$b_{x,y,z}$				
LF	$e_{i,k}$	4	16	768	18.8
4 ch	$b_{x,y,z}$				
	$\Delta n/n$				
n	$n_{3,4,5,6}$	1.128	16	128	100

a two year period in space, which requires a wall thickness equivalent to 4 mm of aluminium. This will keep the total dose inside the box below about 5 kRad. In order to save weight, the payload structure screening effect has been taken into account, which made it possible to make some walls thinner than 4 mm. The electronics components used are of Mil Standard quality, but not Radiation Hardened. The electronics are built on seven printed circuit boards of six-layer type and of size 190 × 170 mm. The inter-communication between the boards is made through a Mother board placed at right angles to the other boards and ordinary connectors are used. The different boards, except the mother board, and their labels can be seen in the Electronics Block Scheme shown in Figure 8. The electric field signals, except the signal from the short HF booms, are routed through the F1 Electric Field instrument. Probes P3 to P6 have switchable preamplifiers for E-field mode or Density mode and the switching between these modes is made from the individual experiments and is made via a Relay Box placed on the F1 main electronics box. The Burst Memory is of 6 Mbytes out of which about 0.7 Mbytes is used as a Buffer memory for the different modes of operation. The rest of the memory, 5.3 Mbytes, is used for storage of burst and continuous mode data. Two micro processors are used, one for control of the instrument and the other as an interface to the satellite FSU. The experiment is powered via a DC/DC converter made by Hollmings Ltd in Finland (part of Finland's contribution to the project). It is a specially designed converter containing two separate groups of floating voltages (Biasl and Bias2) which are needed for the operation of the Langmuir probes. A third group of voltages supplies the digital and the analogue electronics.

9. Summary of Physical Data

In Table IV a summary of the physical data of the Wave Experiment is shown.

TABLE IV

Summary of physical data of the wave experiment

E-field and Langmuir probes	
Size	Spherical 60 mm diameter
Surface coating	Dag 213
Boom type	Weitzmann cable booms
Boom lengths	5.5 to 10.5 m from centre
Cylindrical Langmuir probe	
Size	Length=530 mm, diameter=10 mm
Material	Carbon fibre
Mass	40 g
HF probes[5pt] Size	Spherical 25 mm
Surface coating	Dag 213
Boom length	600 mm
Search coil magnetometer	
Number of coils	3
Size	20 × 20 × 270 mm
Mass of three coils	780 g
Pre-amplifier size	125 × 92 × 40 mm
Mass	320 g
Main electronics	
Main processor	National 32 C16
TM and command processor	National HPC 1600
Burst memory (RAM)	6 Mbytes
Power (In to DC/DC conv.)	28 V, 410 mA
Box size	200 × 204 × 140 mm
Box mass	4.8 kg
Surface coating	Dag 213
DC/DC converter	
Efficiency	Approx. 70 %
Box size	140 × 100 × 35 mm
Mass	460 g
Total weight excl. booms	8.27 kg
Telemetry	
Total bit rate payload	Low rate=262.144, High rate=524.288 kbits s^{-1}
Format size	16 frames × 128 words × 16 bits $word^{-1}$
F4 allocation	75.776 (Lo), 151.552 (Hi) kbits s^{-1}=37 words/frame

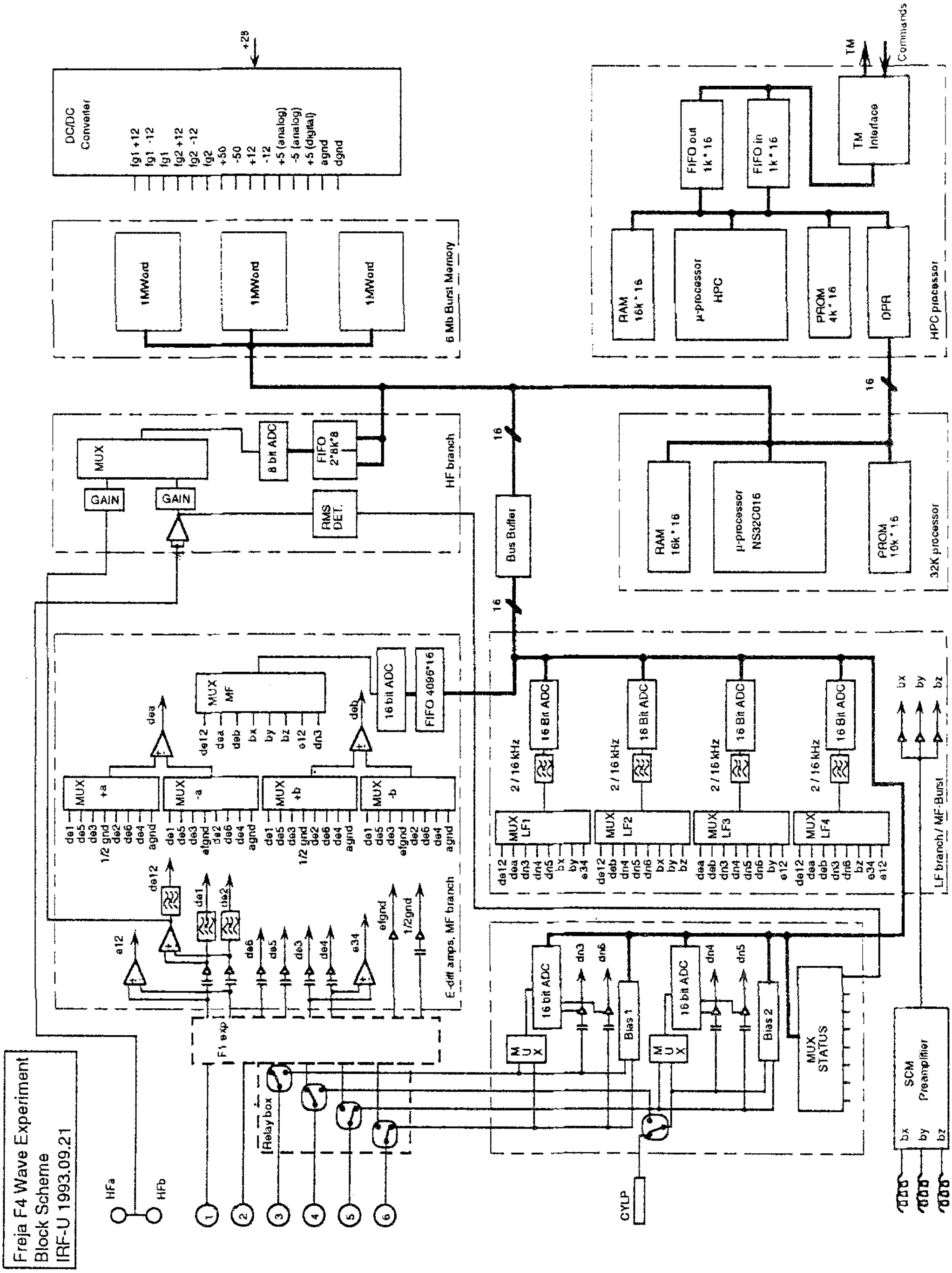

Fig. 8. Block scheme of the wave instrument.

Acknowledgements

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