



Introduction to EISCAT hardware

Assar Westman

EISCAT HQ

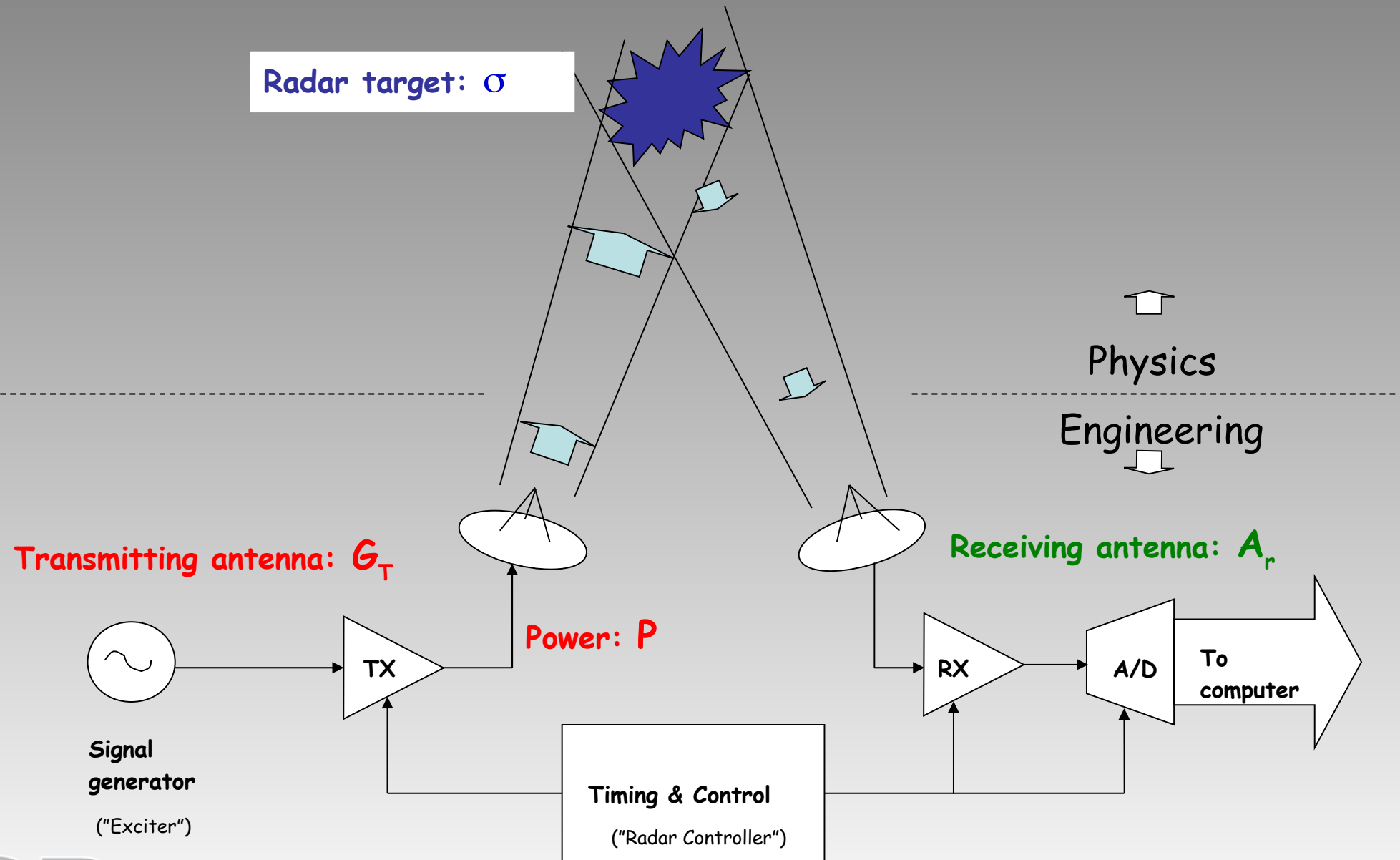


Review of the Radar Hardware

- A generic radar system
- Controlling the radar:
 - timing microscale: the Radar Controller (tlan)
 - timing macroscale: EROS (elan)
- RF spectrum issues and problems
- Generating the RF waveform: the Exciters
- Raising the power level: the Transmitter Power Amplifiers
- Radiating the high power signal and picking up the scattered energy: the Antennas
- Recovering the scattered signal: the Receivers
- Digitising and processing the signals: the Digital Back-Ends and the Process Computers (fil)
- Hardware restriction



A generic radar system





What parameters can we actually control ?

The basic notion of *designing* experiments implies that some aspects of how the incoherent scatter radar (ISR) works are actually under your control. In most ISRs there are essentially only two areas that you can really control –

- I: **Antenna**
 - pointing / scanning
 - dwell times
 - beam selection (when multiple beams available)

- II: **Transmitter modulation**
 - frequency
 - phase
 - coding
 - duration



EISCAT radars –system parameters

Location	Tromsø		Kiruna	Sodankylä	Longyearbyen	
Geograph. coordinates	69°35'N		67°52'N	67°22'N	78°09'N	
	19°14'E		20°26'E	26°38'E	16°02'E	
Geomag. inclination	77°30'N		76°48'N	76°43'N	82°06'N	
Invariant latitude	66°12'N		64°27'N	63°34'N	75°18'N	
Frequency band	VHF	UHF	UHF	UHF	UHF	
Frequency (MHz)	224	929	929	929	500	
Max. tx band (MHz)	3	4	-	-	10	
Transmitter	1 klystrons	2 klystrons	-	-	16 klystrons	
Tx channels	8	8	8	8	continuously tuneable	
Peak power (MW)	2x1.5	2X1.3	-	-	1.0	
Average power (MW)	2x0.19	0.3	-	-	0.25	
Pulse duration (us)	1-2000	1-10000	-	-	1-2000	
Phase coding	binary	binary	binary	binary	binary	
Min. interpulse (us)	1000	1000	-	-	100	
System temp. (K)	250-300	≅100	40-50	40-50	55-65	
Receiver	analog-digital	analog-digital	analog-digital	analog-digital	analog-digital	
Digital sampling	14-bit ADC				14-bit/12-bit ADC	
Data processing	lag profiles and raw data, 32-bit complex					
Antenna	cylinder	dish	dish	dish	Antenna 1 dish	Antenna 2 dish
	120mx40m	32m	32m	32m	32m	42m field-aligned
Feed system	line feed	cassegrain	cassegrain	cassegrain	cassegrain	cassegrain
	128 crossed dipoles					
Gain (dBi)	46	48	48	48	42.5	45
Polarization	circular	circular	any	any	circular	circular



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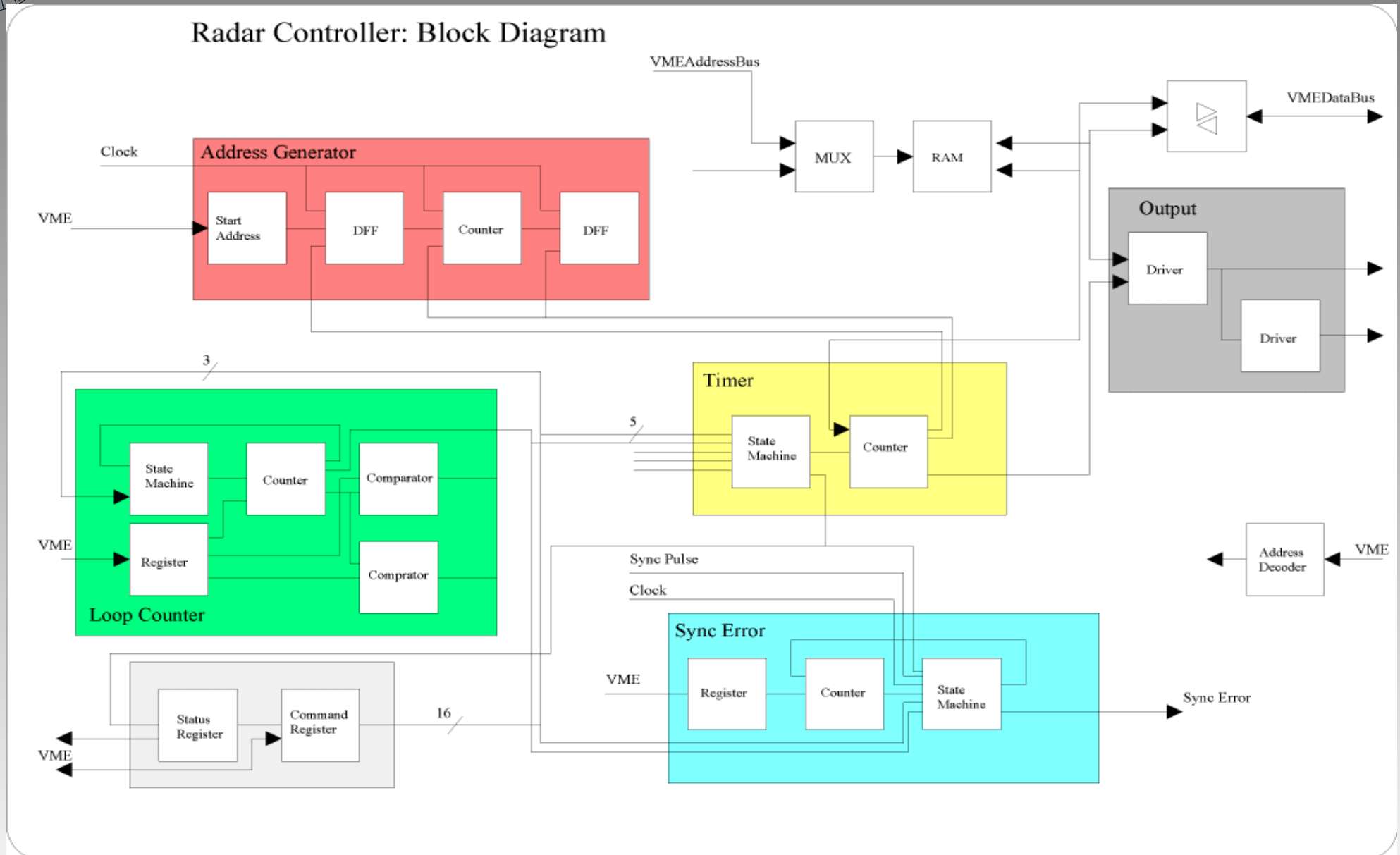


The Radar Controller

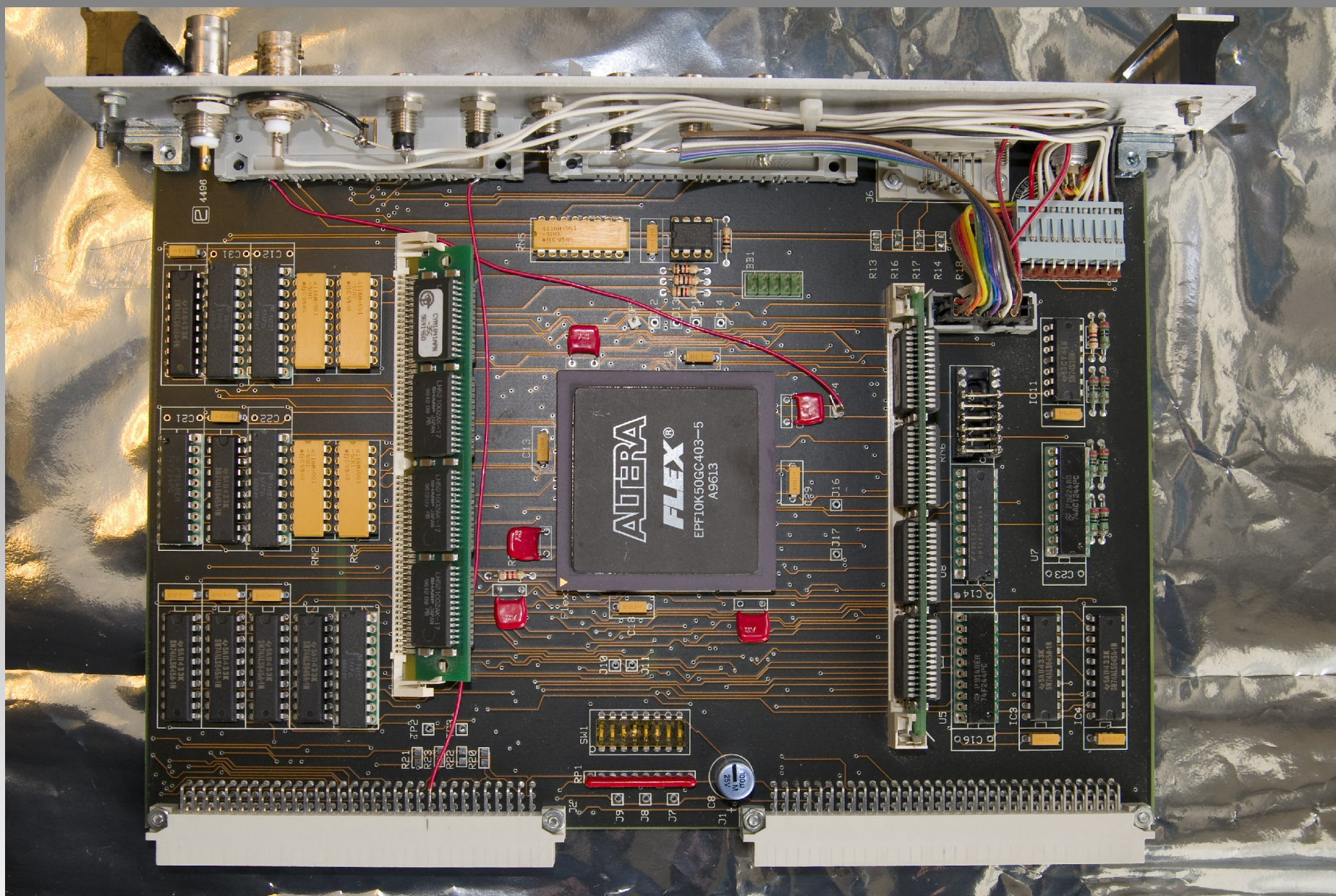
- The "heart" of the EISCAT radar systems
- Controls all functions that require microscale (sub-microsecond) timing precision:
 - TX waveform generation and amplification
 - Antenna selection (at ESR)
 - TX/RX switching
 - Noise injection (for calibration)
 - RX frequency hopping
 - RX sample stream gating
 - various RX housekeeping functions
 - data dumping to crate computer
- Basically a big, wide RAM bank, clocked at 10 GPS-MHz (100 ns)
- One or more RAM bits assigned to every critical function



Block Diagram of EISCAT Radar Controller



Radar Controller





EISCAT Radar Controller

1.1 Specifications

RAM	2 MB (64 bit X 256 K).
Clock	10 MHz.
Internal Address Bus	18 bit (addresses 256K word).
External VME Address Bus	32-bit (32D32) for RAM (Extended). 16-bit (32D16) for ID PROM and Registers (Short)
Programmable Base-address	8-bit DIP Switch (SW1)
Four most significant bits	Bit 1 – 4 for extended Bit 5 – 8 for short
Dwell time	100 ns – 1.6777216 s/Instruction. (24 bit word)
Output bits	32 (+ 6 Optional).
Limitations	>100 ns in first instruction (Dwell time value = 0).
Sync Error Counter	16 bit.
Loop Counter	16 bit.
Loop Counter Comparators	Two (CMPA and CMPB)
Command Register	16 bit.
Status Register	16 bit.
Number of Programmes	Limited by Memory size.
ID-PROM	256 bytes.
Power Supply	5 volt



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EROS and macroscale timing

- EROS is a tcl/tk software application running on the main process computer at each site.
- In addition to providing the run-time user interface, EROS handles all "slow" (> seconds) timing in the system:
 - loads and configures microscale-timing HW,
 - schedules, starts, stops and changes experiments,
 - controls antenna pointing,
 - controls the polarisers and delays the R/C master clocks as required (only at the remote UHF sites)

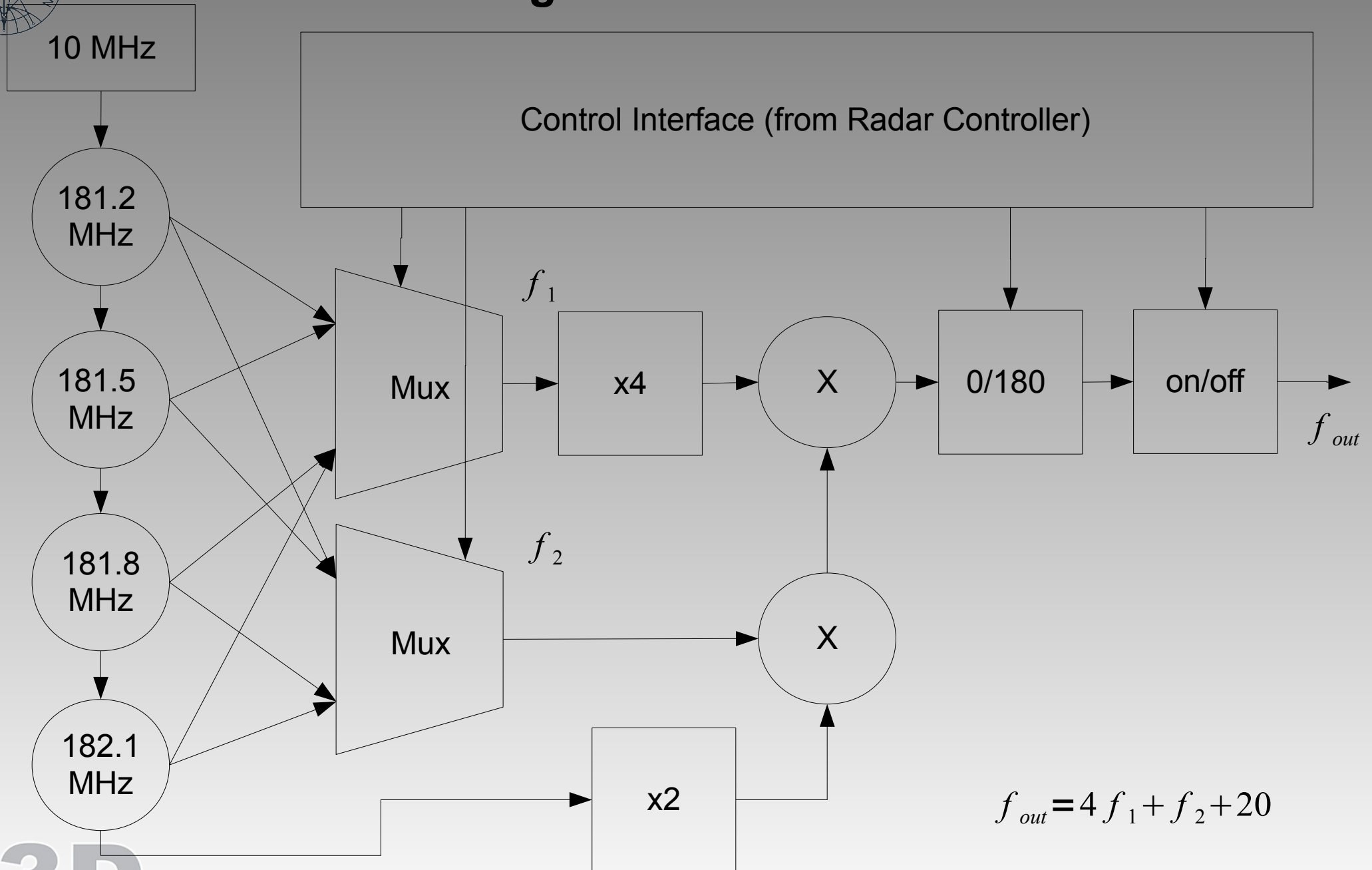


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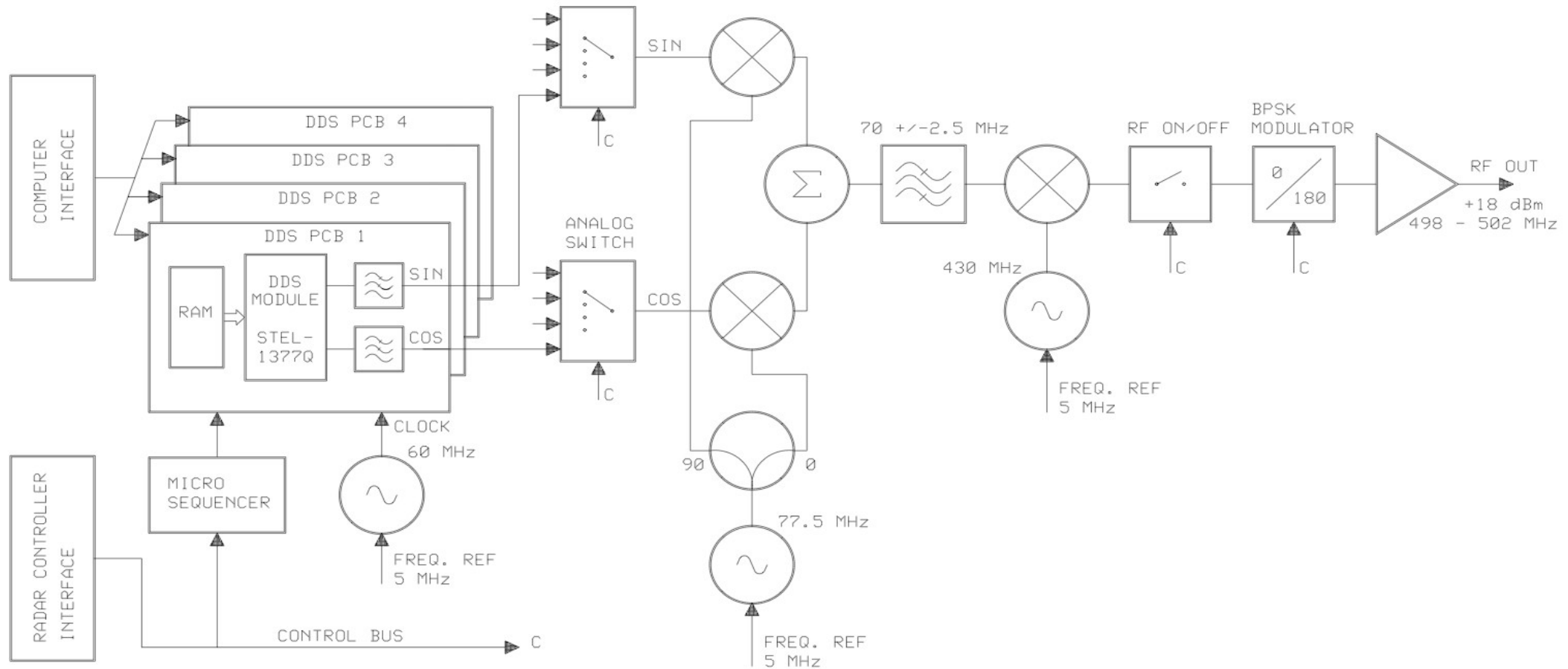
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Block diagram of EISCAT UHF exciter



Block diagram of ESR Exciter

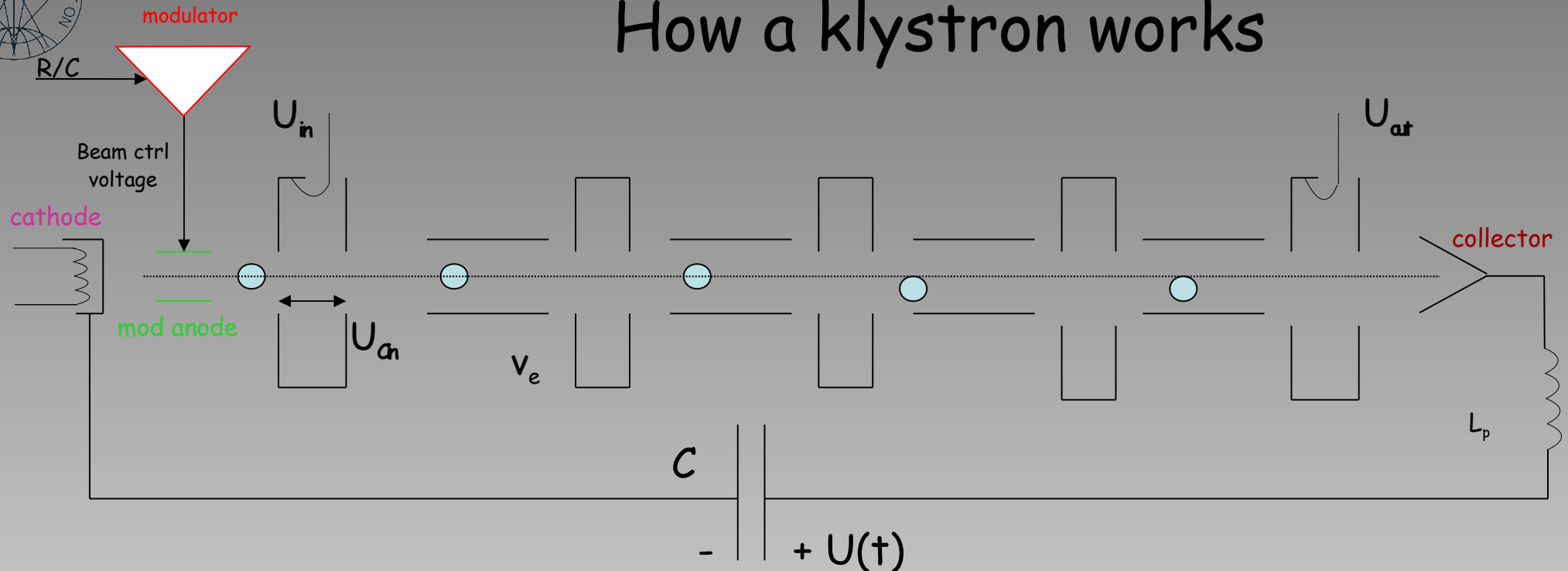




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How a klystron works

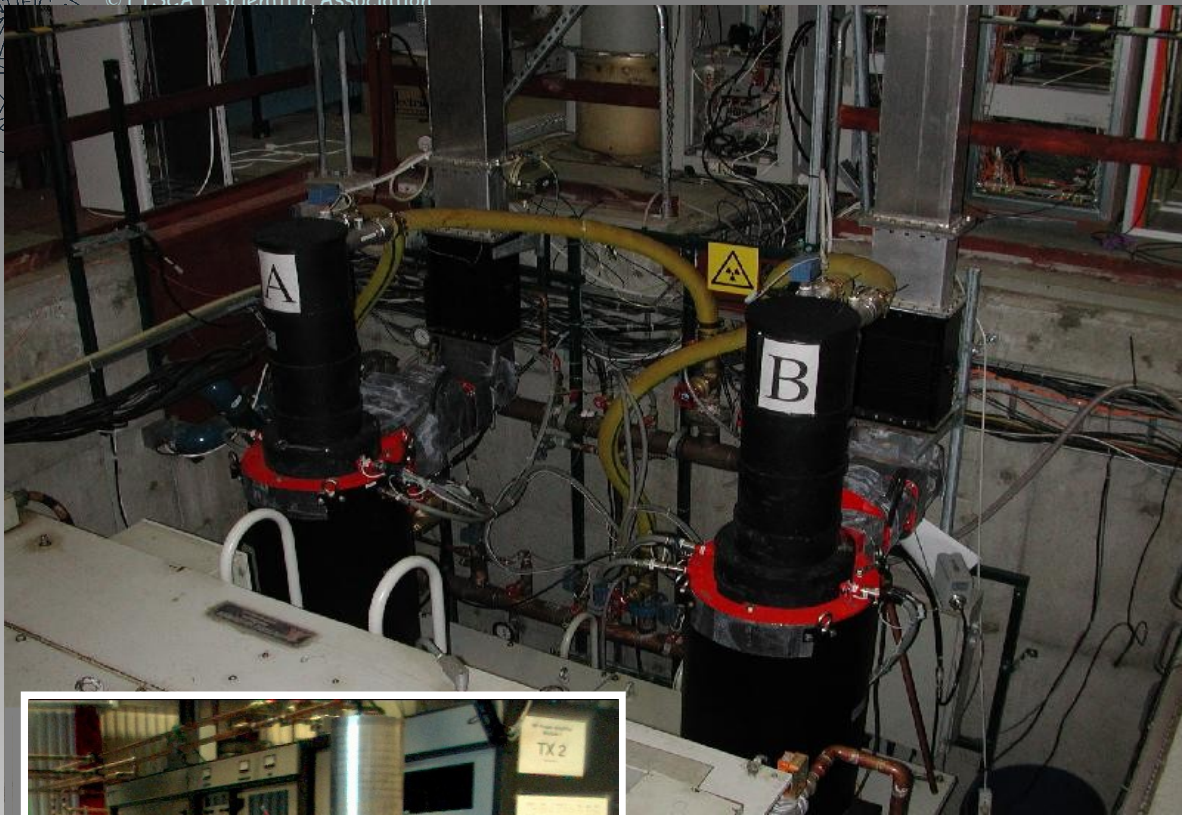


Electrons are emitted from the **cathode** and form a space-charge cloud around it. When the **beam control electrode** ("mod-anode") is raised to a high positive DC voltage U_m , the electrons are accelerated. They pass through the mod-anode and are focussed into a beam, which is further accelerated by a voltage U . The beam goes through a series of resonant RF cavities to a **collector**. The beam current does not reach its full value instantaneously; the parasitic inductance of the the supply leads L_p introduces a time constant, which in the UHF is $\approx 10 \mu s$.

A RF signal applied to the first cavity density sets up a RF voltage U_{an} across the first cavity aperture, which modulates the electron beam, creating "bunches" of charge at the RF rate; i.e. the electron beam current is RF modulated. Propagating down the drift tube, the beam excites each cavity in turn and the induced fields amplify the density modulation. At the output cavity, the beam is almost fully bunched. This cavity is connected to a load (the antenna) and the beam now gives up that part of its kinetic energy stored in the RF structure (over half of the total) in the form of a strong RF current that drives the load. The power gain (input-output) can be over **50 dB**. Leaving the output cavity, a little less than half the initial kinetic energy is left in the beam and this is dumped into the collector as waste heat, which must be removed by water cooling.

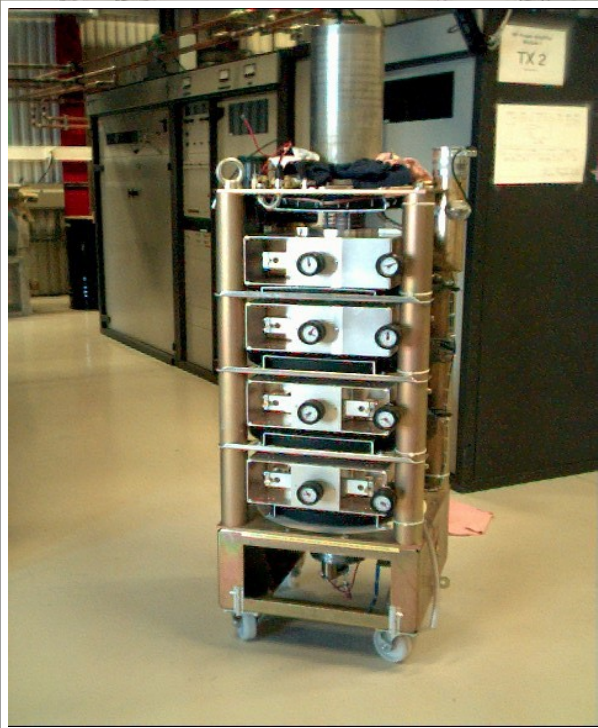
When not transmitting, the electron beam is shut down by applying a negative (ie repulsive) voltage (a few kV) to the mod-anode.

The mod-anode voltage is generated by a modulator; we can control the modulator by the BEAMON and BEAMOFF commands. Because of the time delay between the mod-anode voltage and the beam current, we cannot start to transmit RF immediately after a BEAMON but must first wait 3-4 time constants (**30-40 μs**) for the beam current to stabilise.



Two 1-MW UHF klystrons (930 MHz) at Tromsø.

A 1.5-MW VHF klystron (224 MHz) at Tromsø.



A 60-kW VHF klystron (500 MHz) at ESR.



High voltages for the UHF and VHF radars

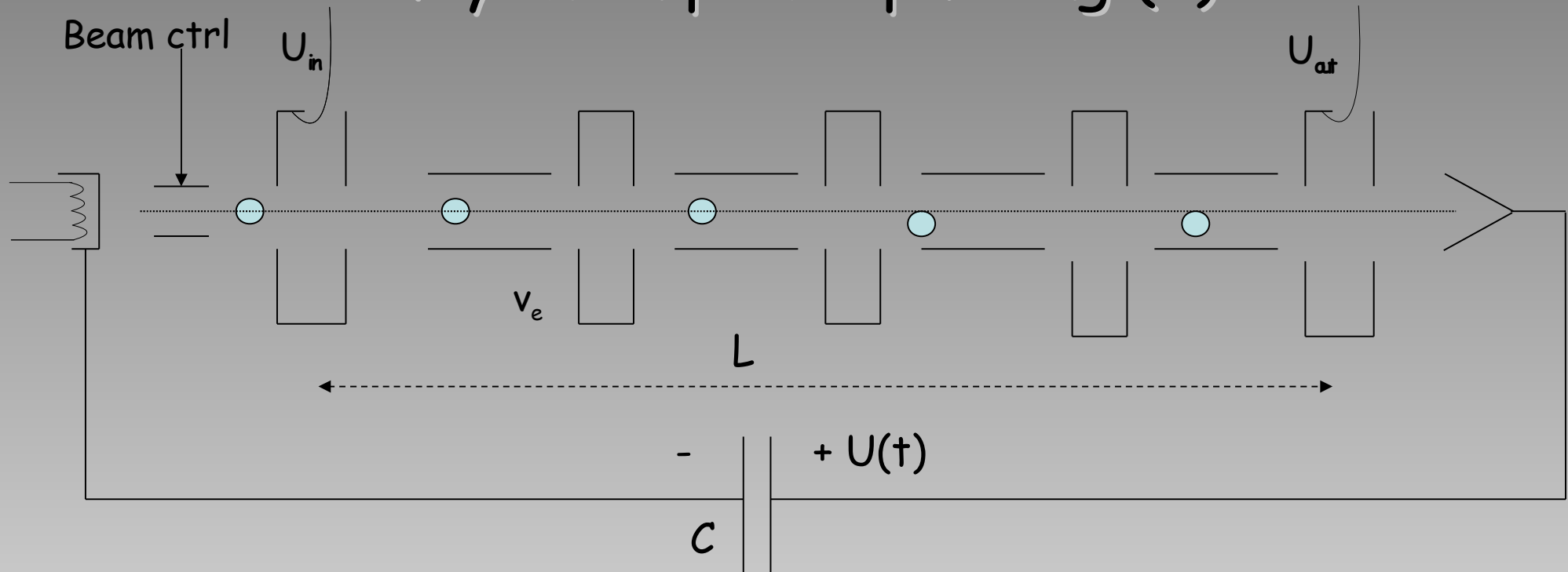


Stored on a 60 μF
capacitor bank



"Crowbar": a fast switch to
discharge the ca. 90 kV to
ground safely

Klystron phase pushing (I)

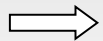


The phase length λ_ϕ of the klystron is a function of electron speed v_e :

$$\lambda_\phi = 2\pi (Lf_o) / v_e \text{ where } L, \text{ the drift tube length, is } \sim 1.4 \text{ m (UHF)}$$

But v_e is a time-varying function of the accelerating voltage $U(t)$:

$$v_e(U(t)) = c \{1 - 1/[1 + eU(t)/(m_e c^2)]^2\}^{\frac{1}{2}}, \text{ where } m_e c^2 = 511 \text{ keV}$$



$$\lambda_\phi = 2\pi (Lf_o/c) \{1 - 1/[1 + eU(t)/(m_e c^2)]^2\}^{-\frac{1}{2}} \text{ (in radians)}$$

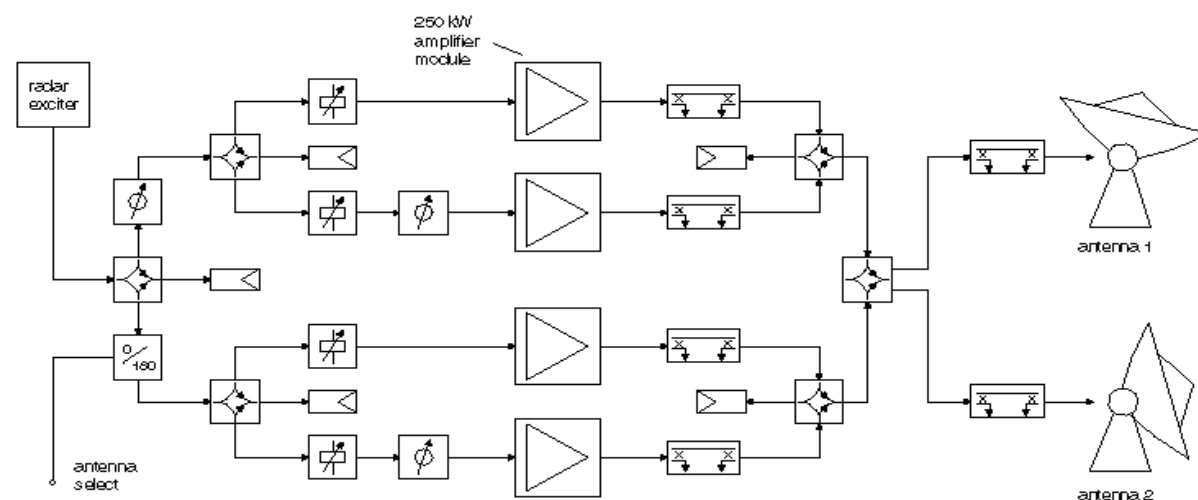
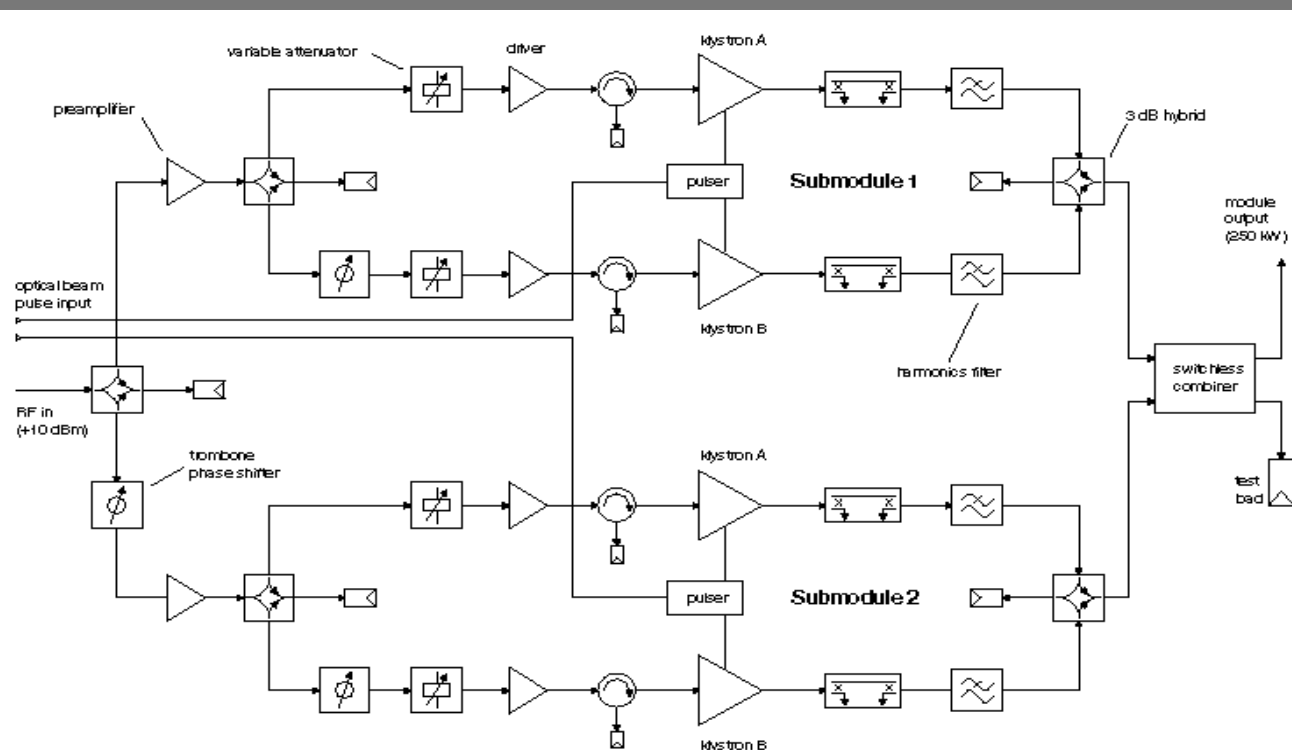


Notes on Phase Pushing / Spurious Doppler

- Present to some degree in all pulsed klystron amplifiers,
- Always causes the output signal to shift downwards in frequency,
- EISCAT UHF / VHF transmitters fitted with feed-forward correction to reduce the effect (but not totally remove it...),
- ESR transmitter has no feed-forward, but the envelope of the transmitted signal is measured through the receiver and recorded,
- **USE THE ENVELOPE DATA TO CORRECT FOR SPURIOUS DOPPLER IN THE ANALYSIS PHASE !**
- If the envelope data shows a positive spurious Doppler shift, or a frequency shift greater than some tens of Hz (+ or -), suspect a receiver and/or exciter malfunction (for instance a local oscillator running out of phase lock) - if you cannot make the Doppler look reasonable by restarting your experiment, call for help !!!

Basic ESR power module raises the power level from 10 mW to 250 kW

Combining four modules yields 1 MW, allows pulse-by-pulse switching between antennas





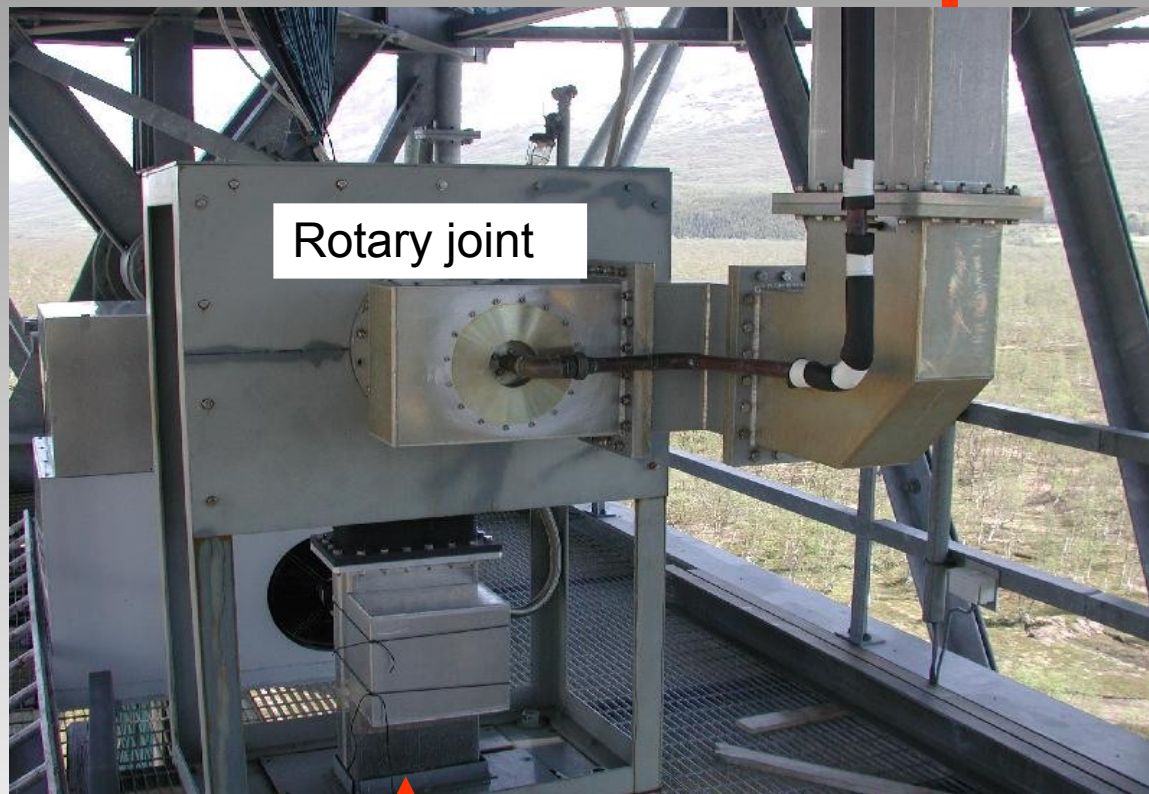
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Transmitting the power to the antenna

To the horn of the
UHF antenna



Rotary joint

Waveguide from transmitter (930 MHz)



EISCAT Antennas: Aperture Area and Gain

From antenna theory:

$$G = 4\pi A/\lambda^2$$

If the antenna aperture is circular with diameter = D , the maximum gain is

$$G_{\max} = \pi^2 D^2 / \lambda^2$$

The diameter of an EISCAT UHF antenna is 32 m. Operating at 930 MHz, the maximum gain becomes

$$G_{\max} (\text{UHF}) = 97260 \text{ or } 49.88 \text{ dBi}$$

So when transmitting through this antenna, the power density in the far field is almost 10^5 times the isotropic power density-

but at the same time we illuminate only 10^{-5} as many electrons, so the total scattered power doesn't increase !

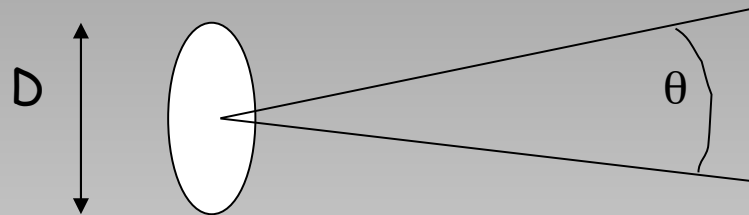
But:

- 1) A large aperture area picks up more scattered signal on receive
- 2) Gain translates into angular resolution

EISCAT Antennas: Transverse Resolution

The transverse resolution of a radar is set by the antenna beamwidth. The half-power beamwidth θ of an aperture antenna of size D , operating at wavelength λ , is approximately (in radians)

$$\theta = \lambda / D$$



Example: For $D = 32$ m and $\lambda = 0.33$ m (EISCAT UHF), $\theta = 0.59^\circ$

At a distance of R , this corresponds to a transverse resolution of

$$r_{\perp} = R \theta$$

Example: For $R = 100$ km $r_{\perp} = 10^5 \cdot 0.33/32 = 1.03$ km



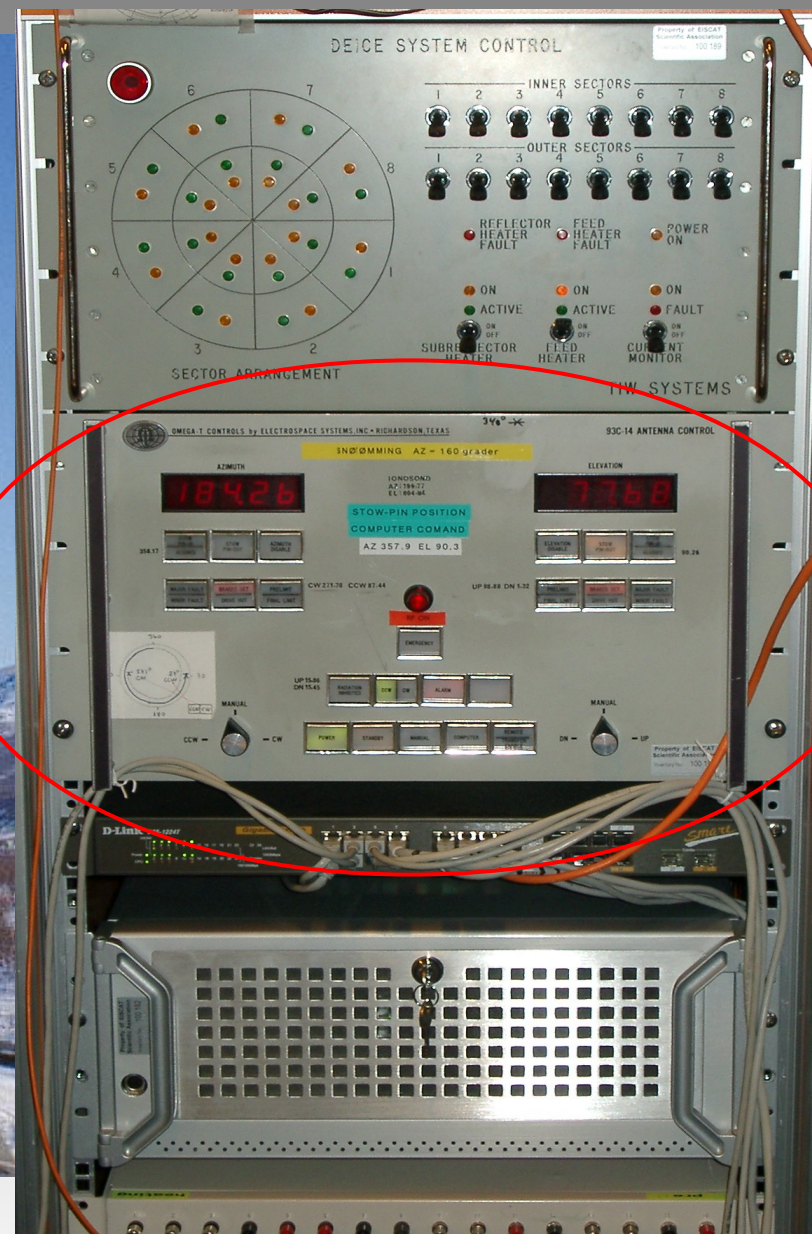
EISCAT Antennas

- UHF antennas
 - 32-meter fully steerable Cassegrain dishes
 - Wheel-on-track az drive, rack-and-pinion elevation drive
 - Max. rotation 1.5 turns in azimuth, 0-96° in elevation
 - Max. angular speed 1.2°/second both axes
- ESR 32-meter antenna
 - Fully steerable Cassegrain dish
 - Rack-and-pinion drive in az and el, angular speed up to 3°/second
 - Max. rotation 1.5 turns in azimuth, 0-180° in elevation
- ESR 42-meter antenna
 - Fixed Cassegrain
 - Pointing along tangent to local field line @ 300 km
 - Feed adjustable to follow the secular variation in field until > 2007
- VHF antenna
 - 40 x 120 m parabolic trough
 - Can be run as two independent, electrically steerable arrays
 - Elevation range (30° - 90° for transmission, 30°-120° for passive measurements)
 - Computer control presently disabled. Ask an operator.
Max. speed 5°/minute in elevation



UHF antenna, Tromsø

Antenna controller Unit (ACU) in control room





VHF antenna,
Tromsø

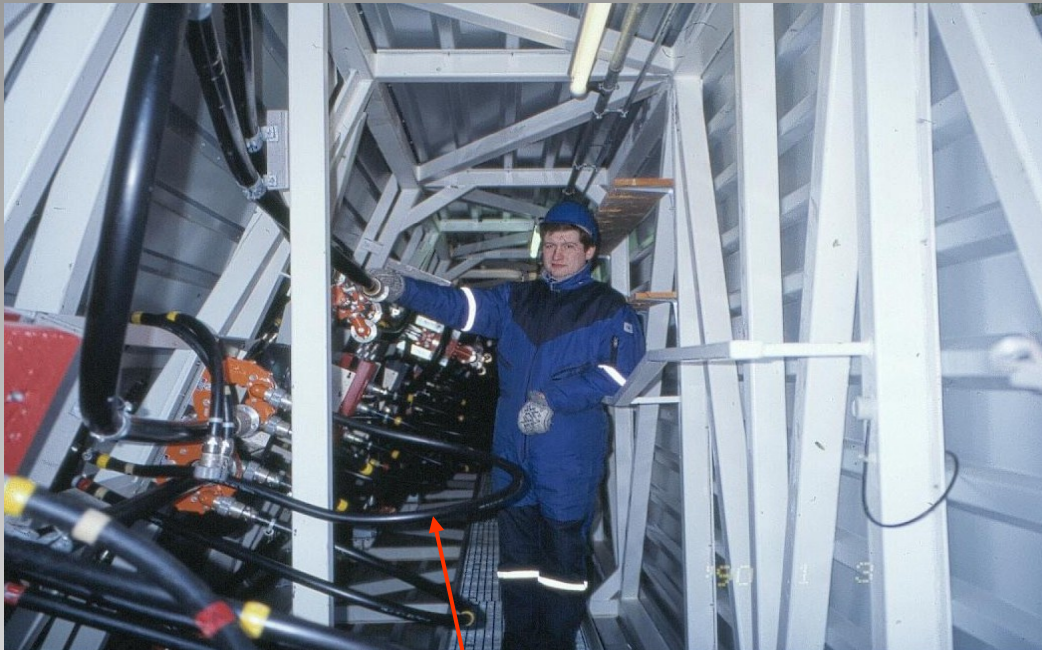
30° elevation

about 120°
elevation





VHF antenna, feeder bridge, Tromsø

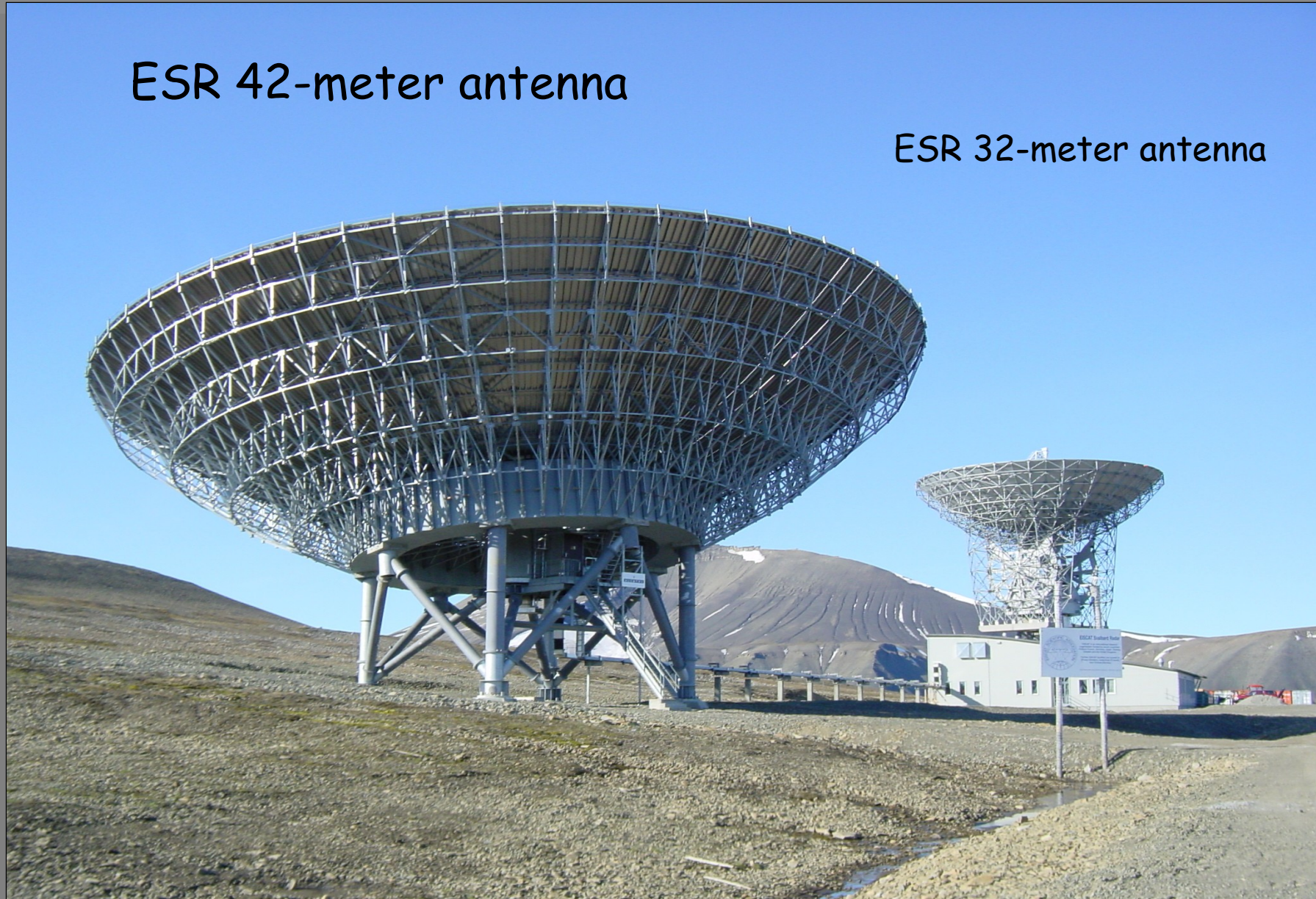


Swapping 64 of these cables with those of a different length
makes half the antenna point to a different east-west direction



ESR 42-meter antenna

ESR 32-meter antenna





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Antenna Feed and Receiver Front End:

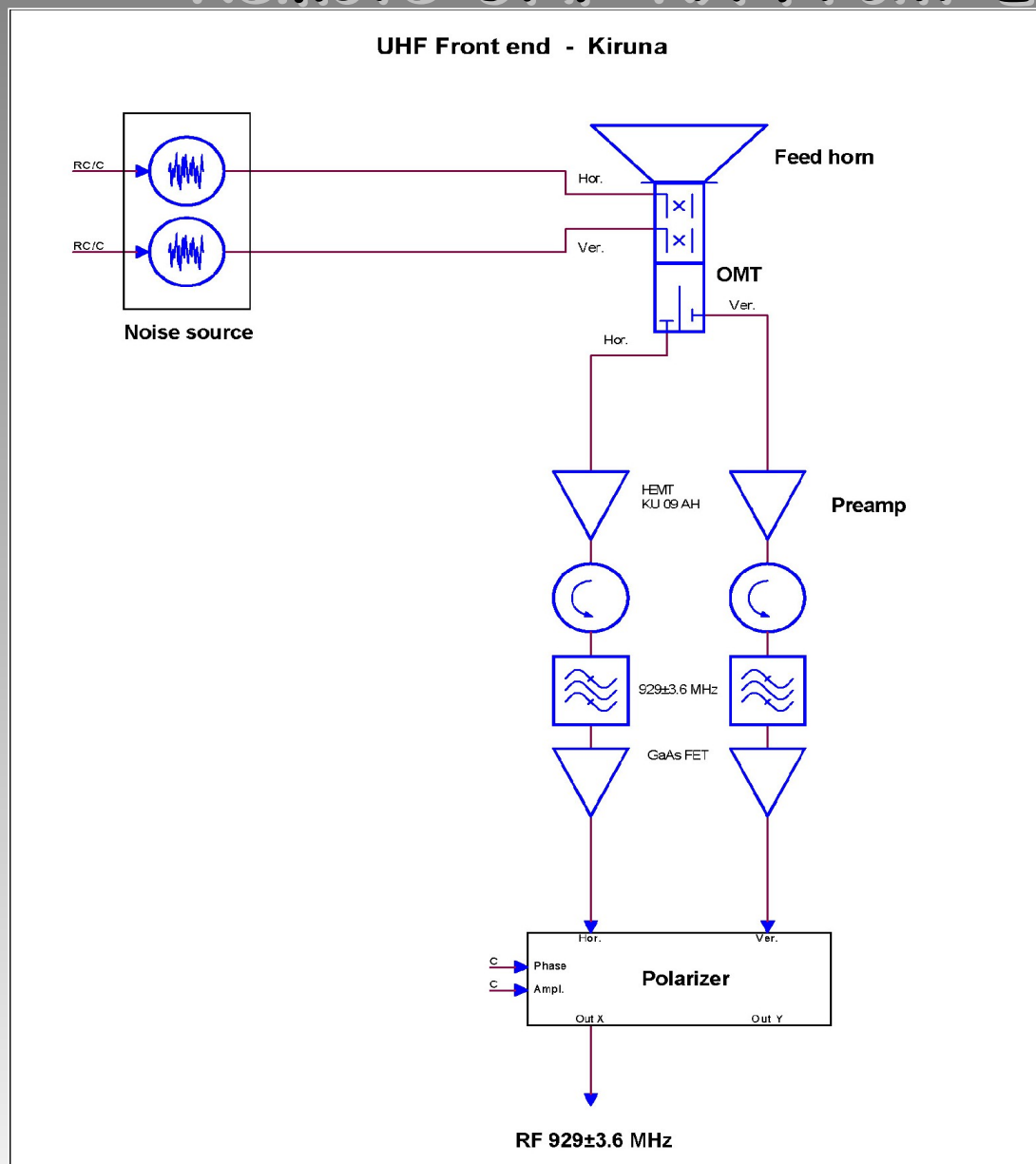
Polariser, Receiver Protector, Noise Injection and Preamplifier

- The **POLARISER** converts the high power TE_{10} WG mode into a RHC mode that is radiated by the antenna. On receive, the LHC polarised scatter signal is converted into a TE_{10} mode that leaves the polariser through its other port.

At Tromsø the signal then enters the

- **RECEIVER PROTECTOR (RXP)**, which is a R/C controlled switch that isolates the receiver from the transmitter by more than -90 dB when the transmitter pulses. In the receive state it is almost transparent (loss \approx -0.2 dB).

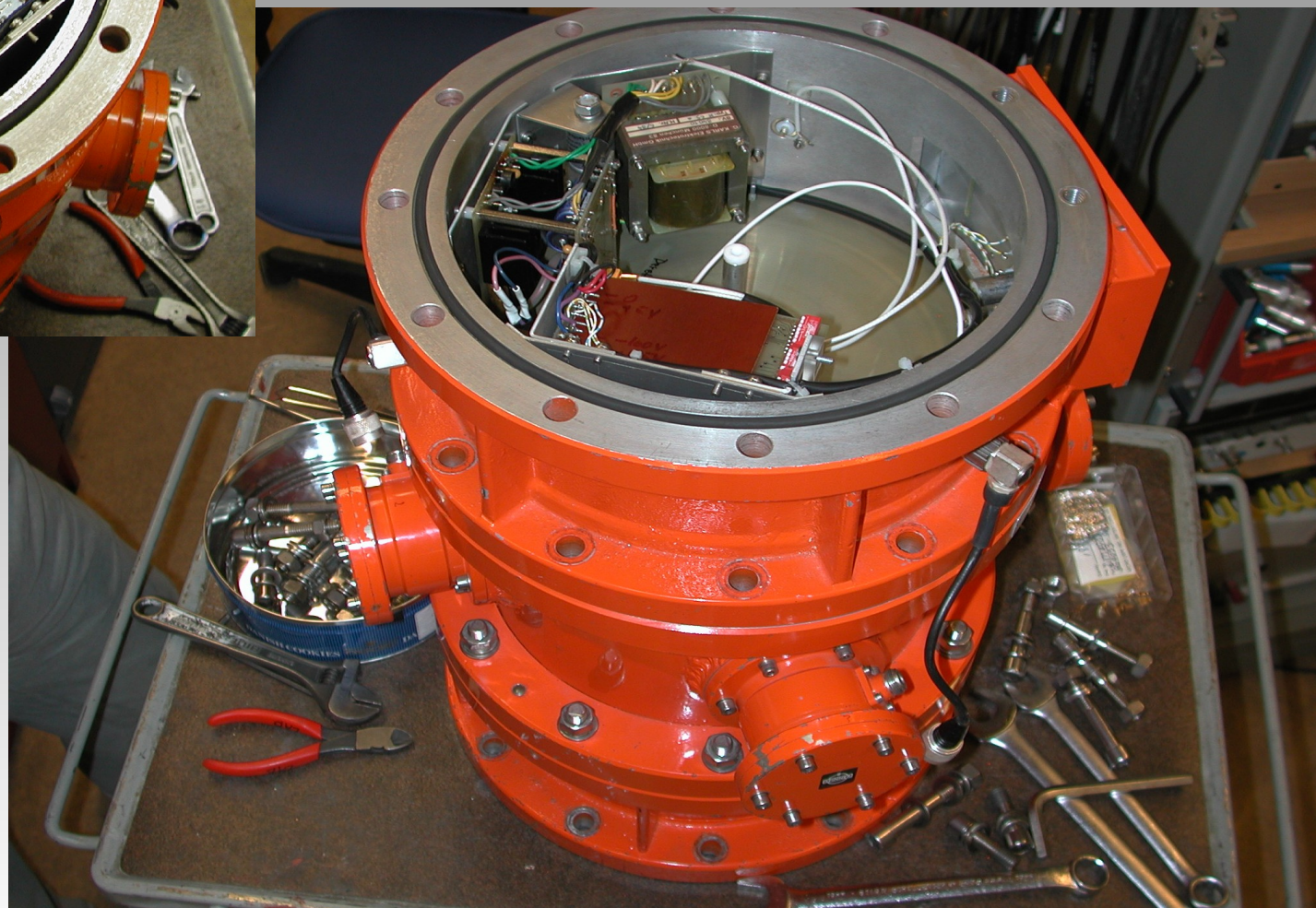
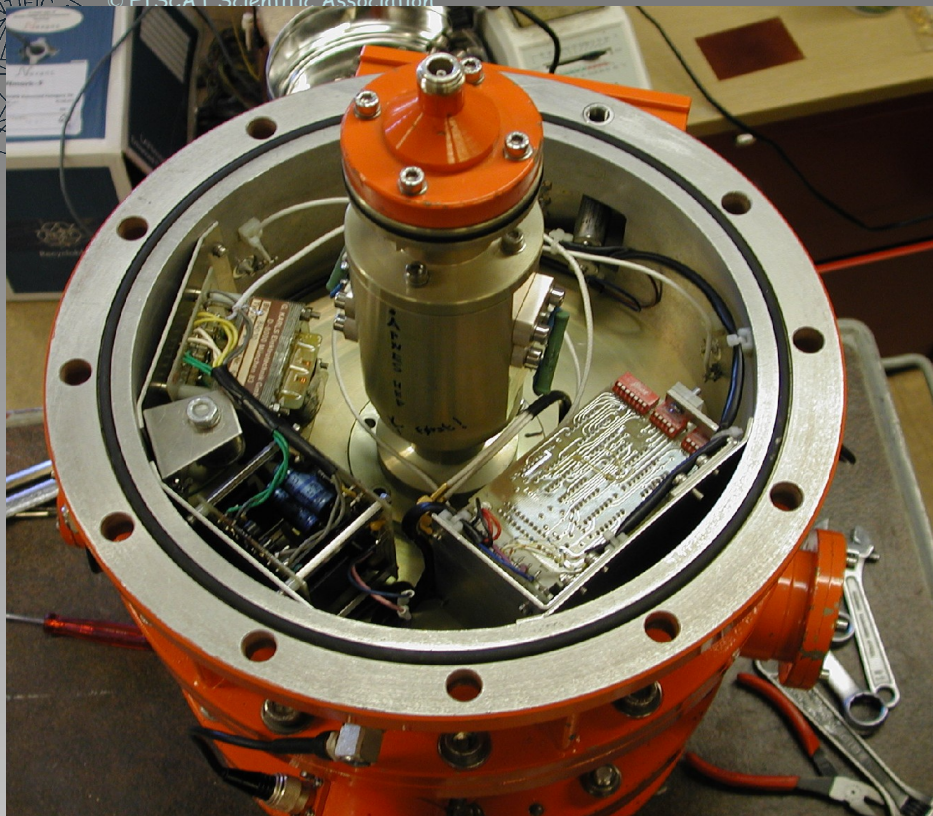
Remote UHF RX Front End



Note: To obtain optimum SNR, the polariser must be set to match the polarisation state of the received wave. As this is a function of the pointing geometry (which changes only when the antenna is moved - timing macroscale), the polariser control is included in the EROS antenna control software package.

Polariser phase and amplitude offsets are site-specific and can vary over time - beware !

VHF receiver protector





Antenna Feed and Receiver Front End:

Polariser, Receiver Protector, Noise Injection and Preamplifier

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- **RECEIVER PROTECTOR (RXP)**, which is a R/C controlled switch that isolates the receiver from the transmitter by more than -90 dB when the transmitter pulses. In the receive state it is almost transparent (loss \approx -0.2 dB). The received signal next passes through a
- **NOISE INJECTION** coupler. Noise can be injected on command from the R/C for calibration purposes. Finally, the scatter signal enters the
- **PREAMPLIFIER**, a low-noise GaAsFET or HEMT amplifier that raises the signal level by \approx 35 dB before sending it on to the first mixer unit.

How the receiver processes the signal (ESR example)

ANALOG

First mixer

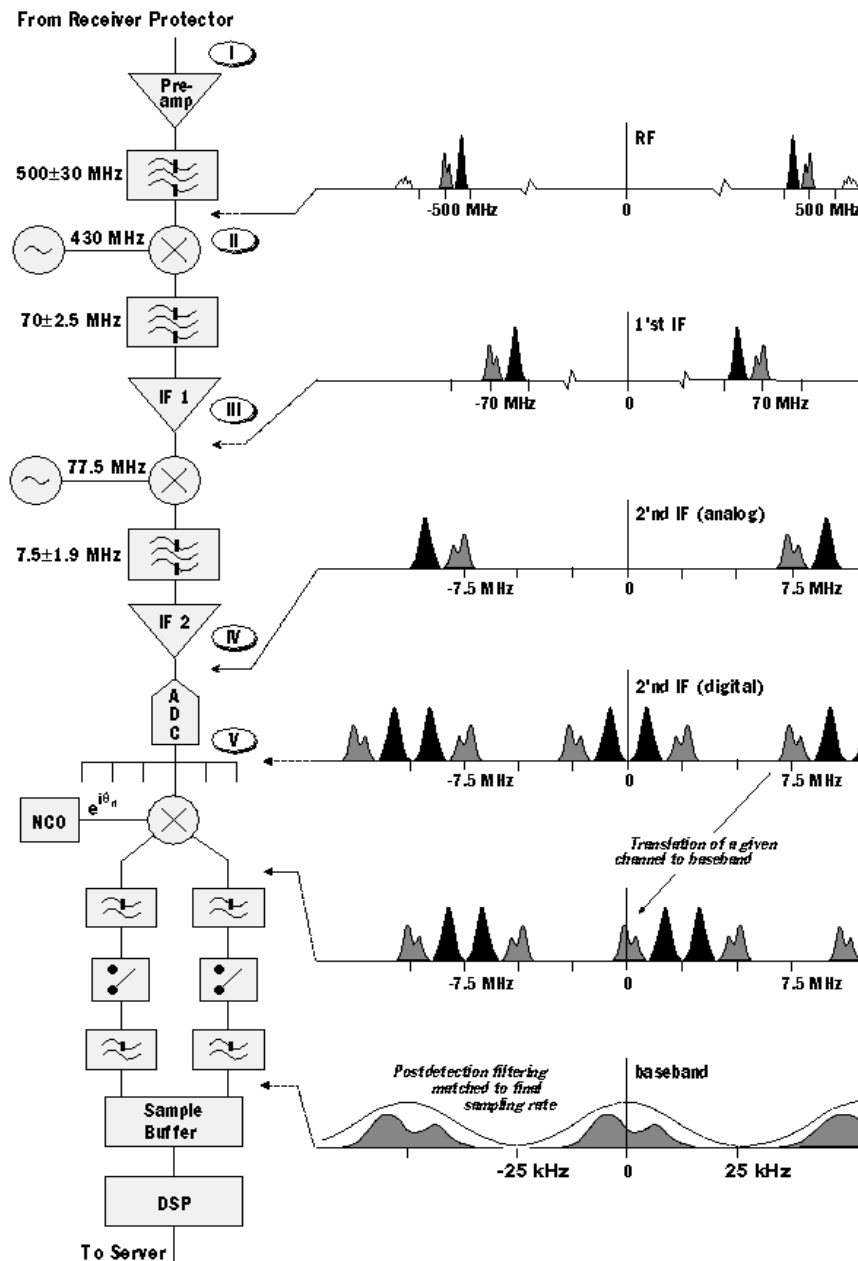
Second mixer

A/D conversion

Conversion to baseband

Low-pass filtering and decimation

DIGITAL



The ESR Antenna Feed and RX Front End

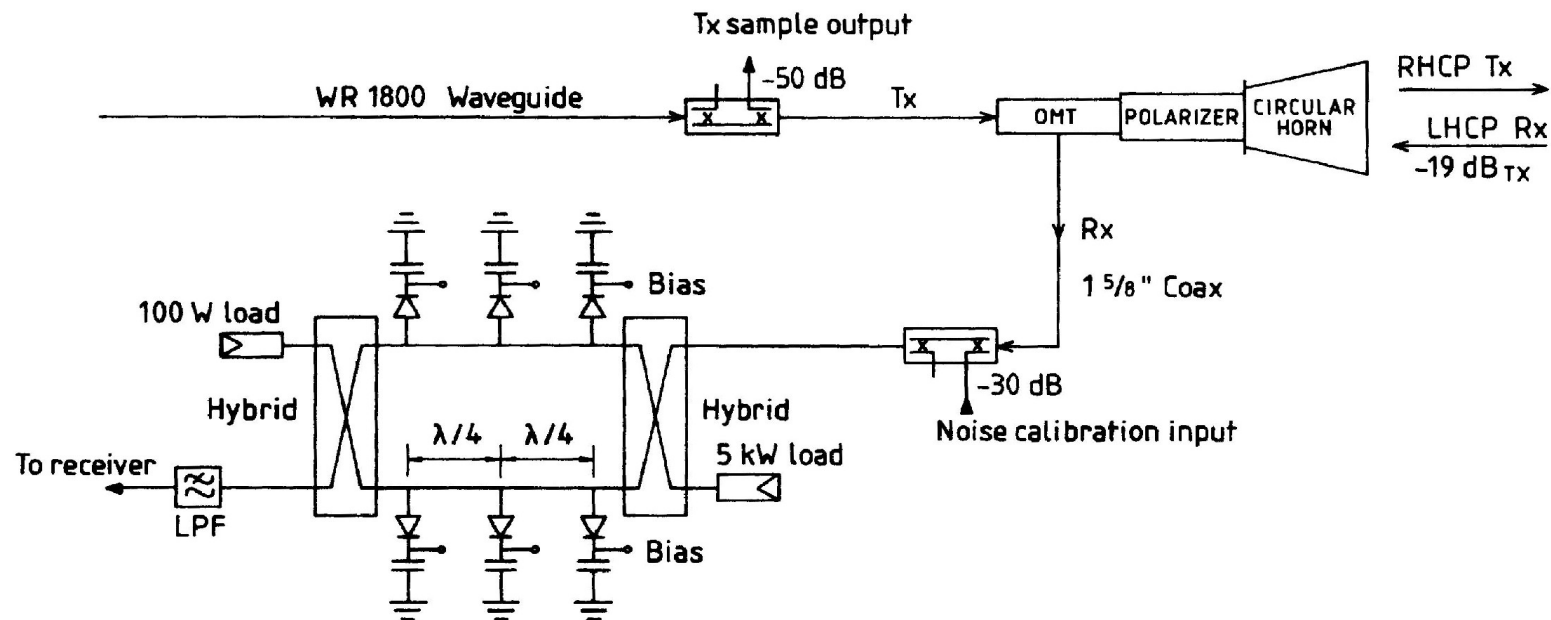
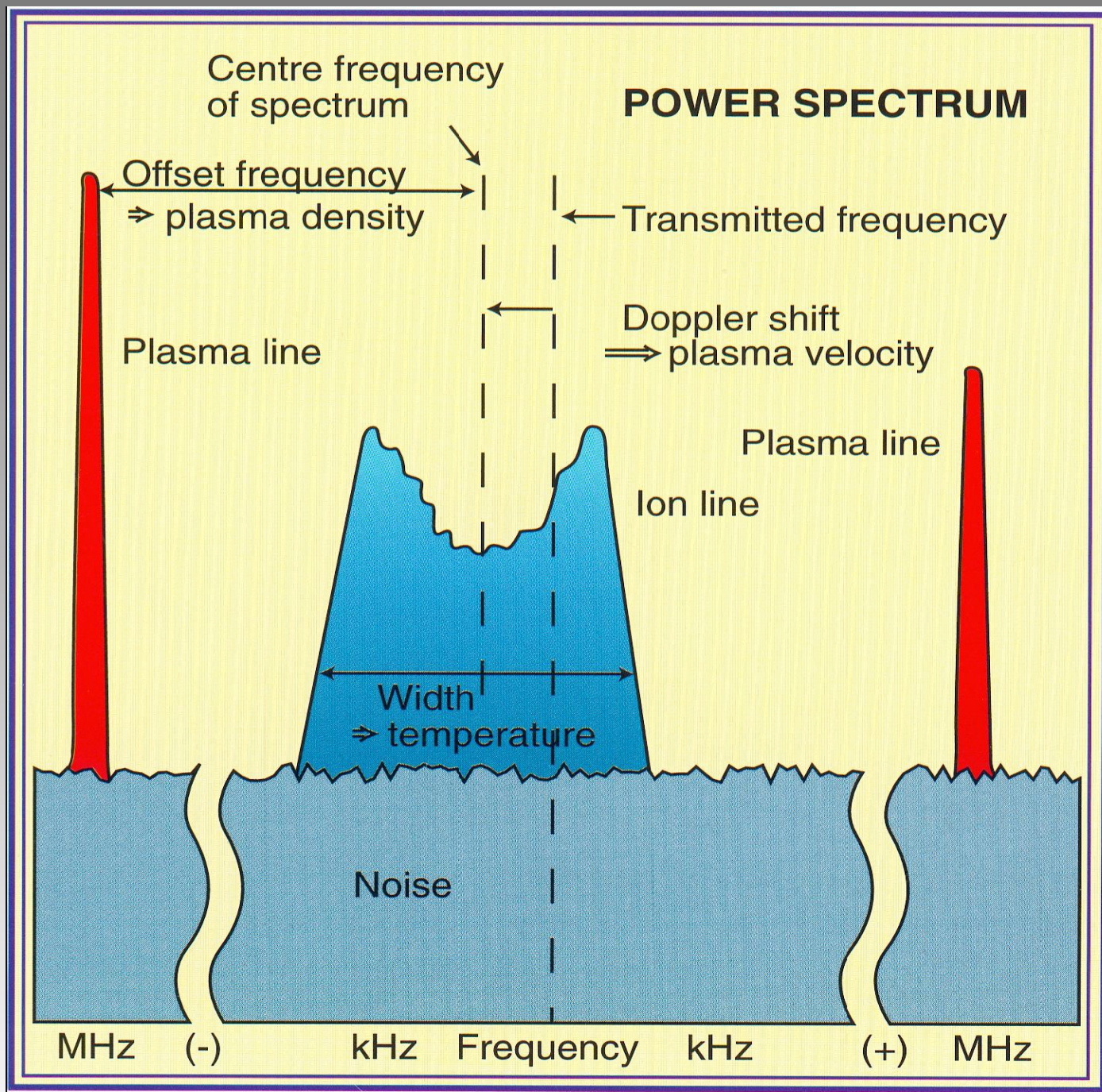
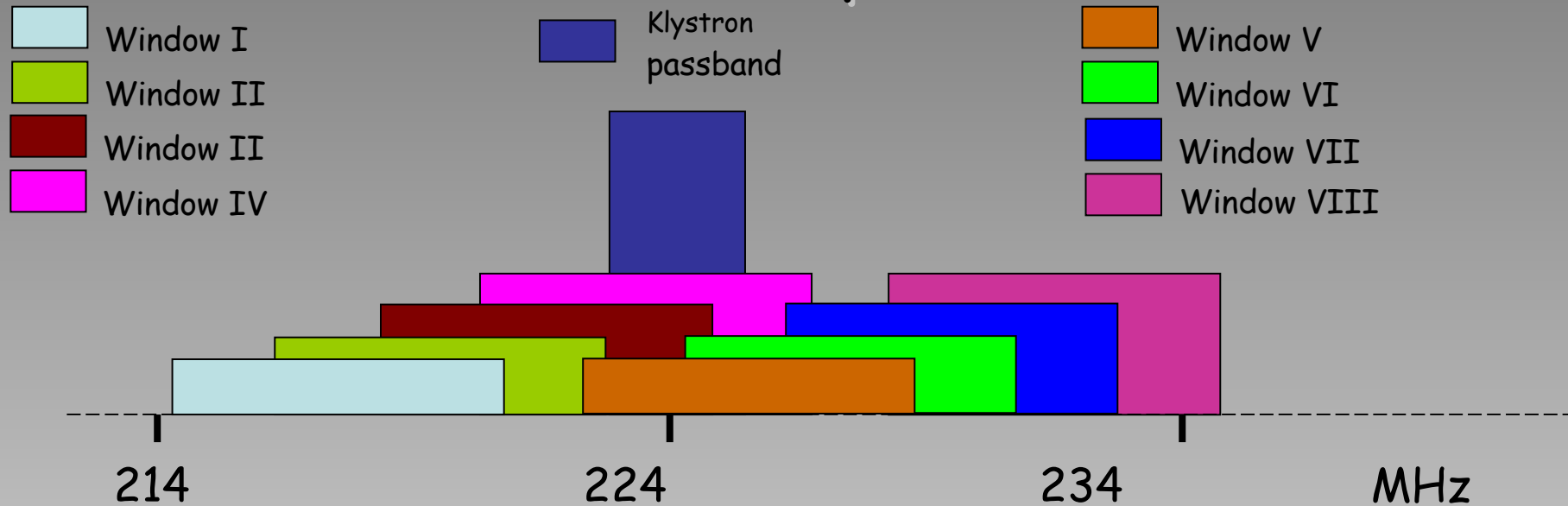


Figure 5. Diagram of the antenna feed and transmit/receive switching system. The balanced four-port receiver protector diverts all left-hand circular (LHC) polarized power intercepted by the feedhorn during transmission into a waste load. Calibration noise is injected through a -30 -dB directional coupler located between the orthomode transformer (OMT) and the receiver protector. Samples of the RF waveform extracted from a -50 -dB coupler in the transmitter waveguide are routed to a switching system located between the preamplifier and the first mixer.





EISCAT VHF RX Spectrum Windows



The eight possible combinations of 1st and 2nd LO frequencies correspond to the eight VHF spectrum windows as follows:

W #	f LO1 (MHz)	f LO2 (MHz)	Spectrum window (MHz)
I	290.000	84.000	214.3 - 220.7
II	290.000	82.000	216.3 - 222.7
III	290.000	80.000	218.3 - 224.7
IV	290.000	78.000	220.3 - 226.7
V	298.000	84.000	222.3 - 228.7
VI	298.000	82.000	224.3 - 230.7
VII	298.000	80.000	226.3 - 232.7
VIII	298.000	87.000	228.3 - 234.7
	290.000	External	
	298.000	External	

Either Window IV or Window V can be used to receive ion line signals. Windows I, II and VII, VIII are intended for plasma line work and can handle plasma frequencies up to about 10 MHz. If you don't deliberately select spectral windows in your experiment .tlan file, both channels will be set to **Window V** by default and the relationship between the signal frequency and the 2nd i.f. frequency becomes:

$$f_{if2} = f_{sig} - 214.000 \text{ [MHz]}$$



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EISCAT control room, ESR, Svalbard



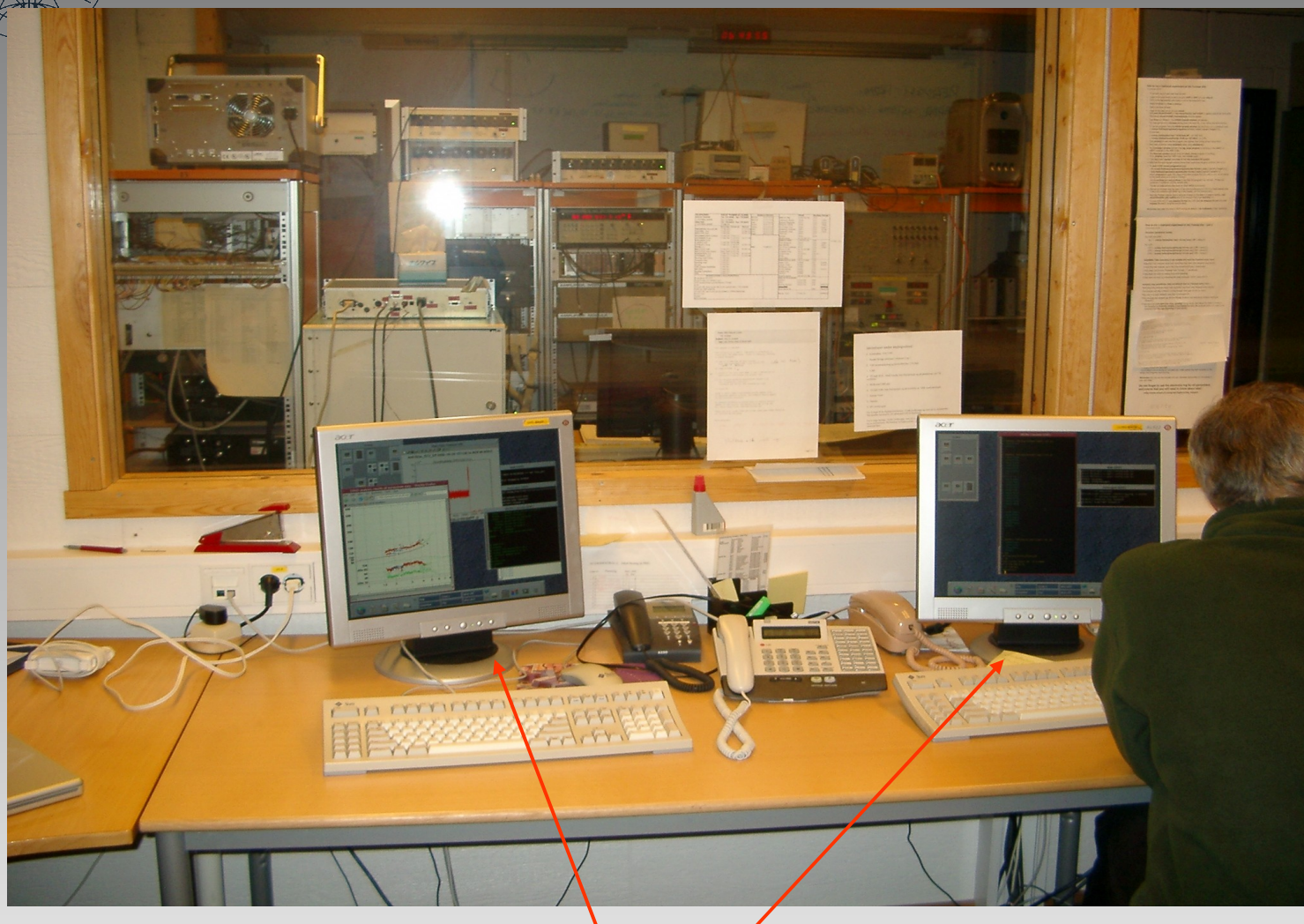


Inner part of the control room, ESR, Svalbard





EISCAT control room, Tromsø



You can also control and monitor the remote stations, Kiruna and Sodankylä and ESR from here

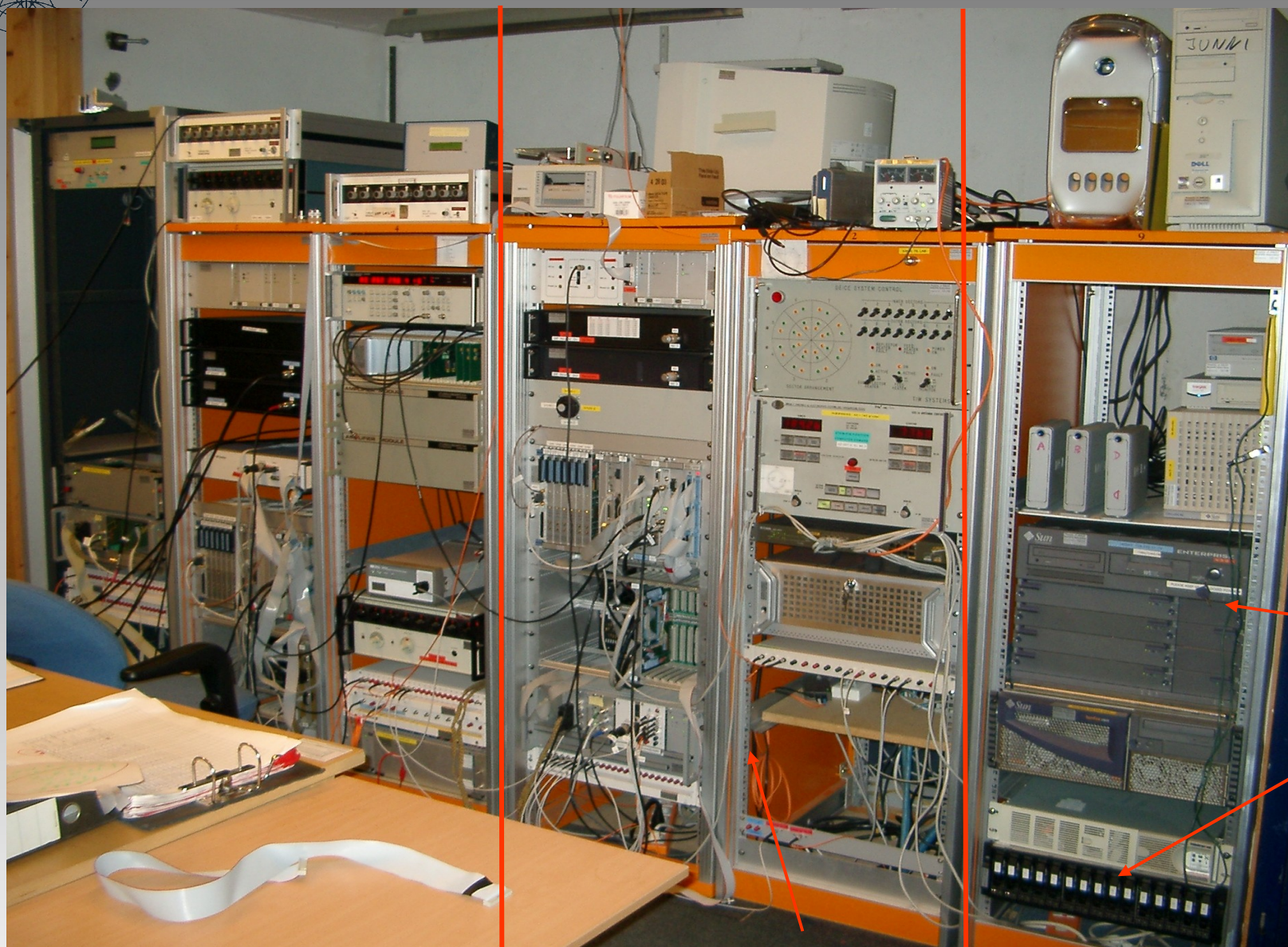
VHF

UHF

EROS consoles



Inner part of the control room, Tromsø



t45001 Server
computer
and RAID

← VHF receiver →

← UHF receiver →



UHF receiver system

Channel 1 receiver ion line
(analogue part)

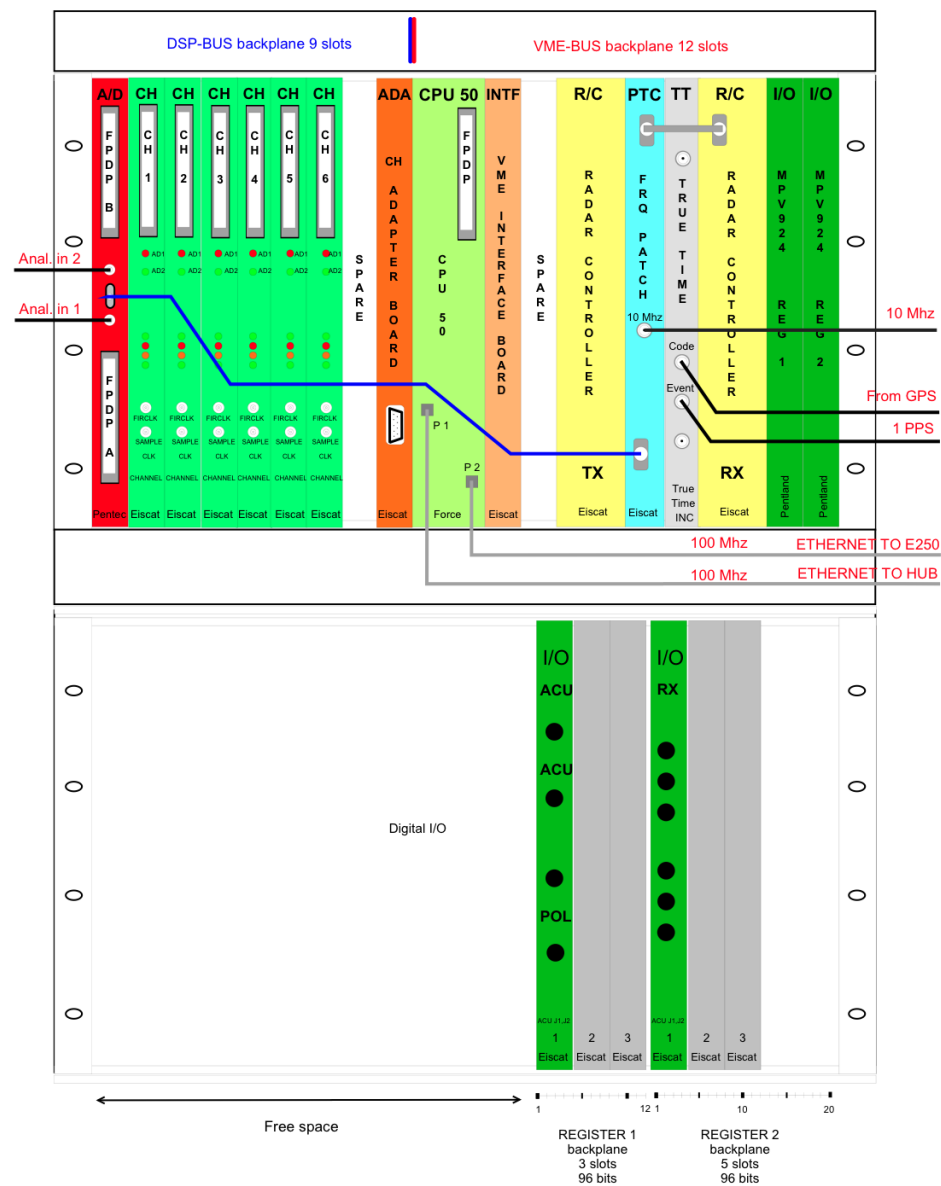
Channel 2 receiver down shifted
plasma line (analogue part)

VME crate with ADC,
Channel boards,
radar controller etc.





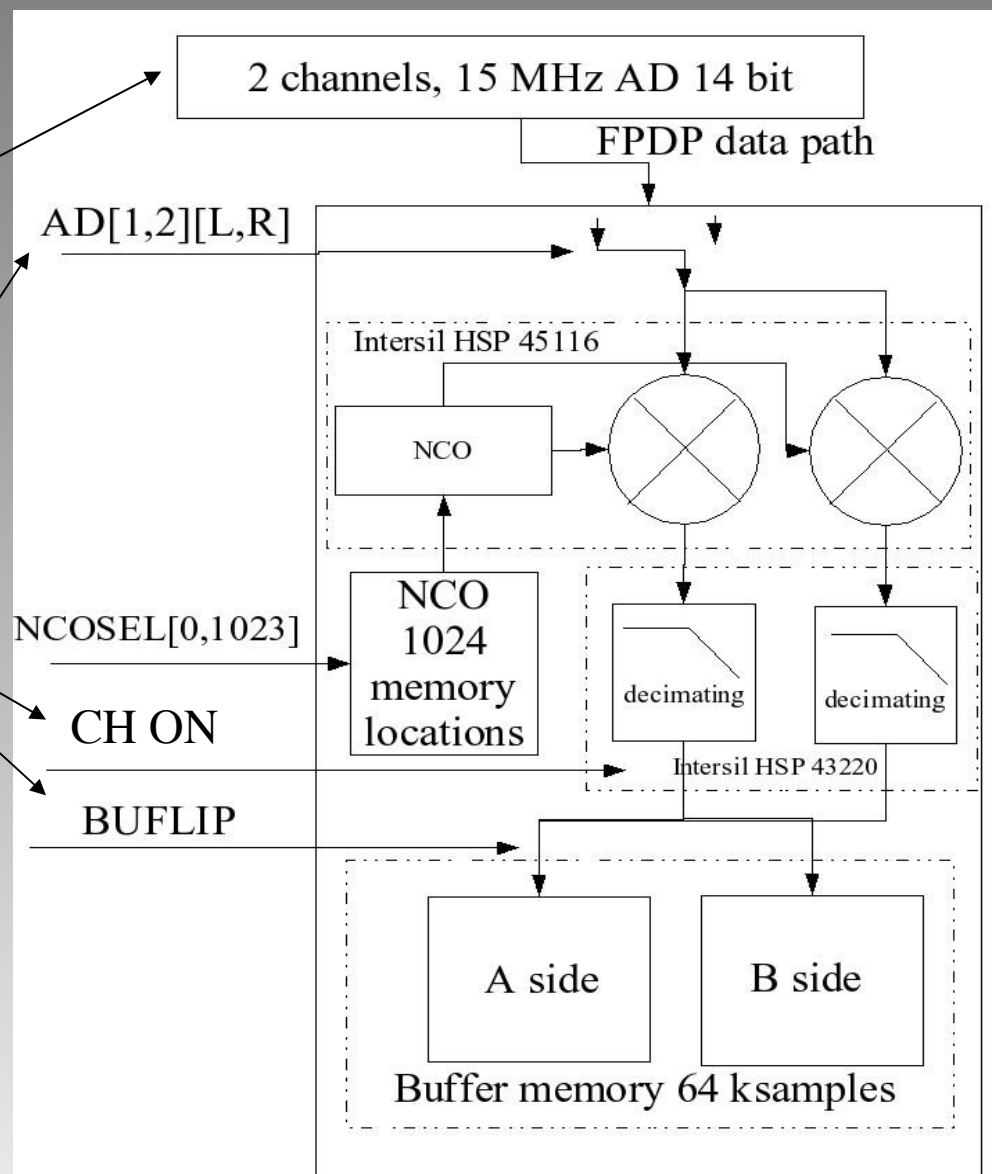
Tromsø UHF VME crate



Simplified block diagram of a channel board.

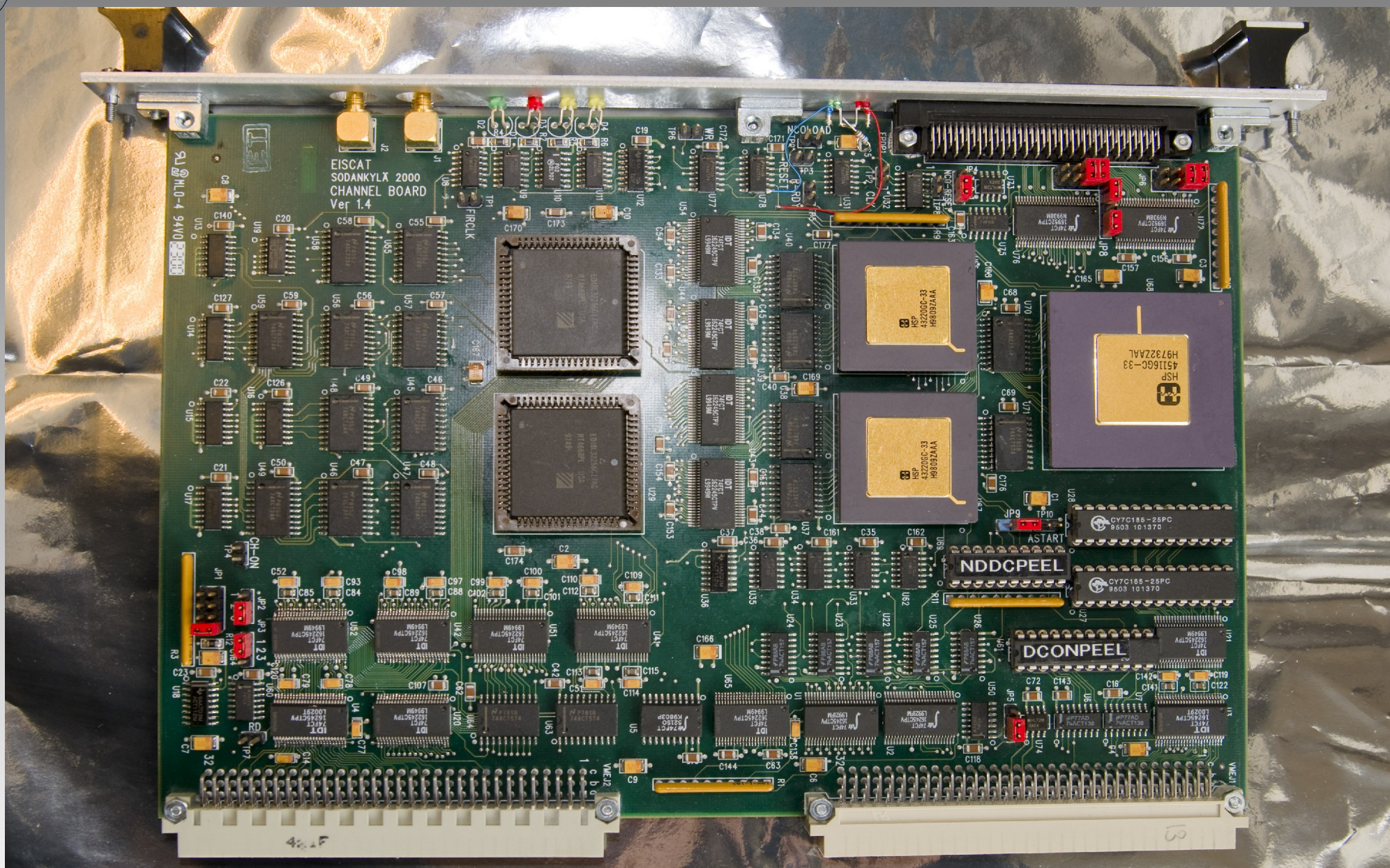
The AD converters are common to all available channel boards.

Also shown are the control signals from the radar controller with the names used in the tarlan programs

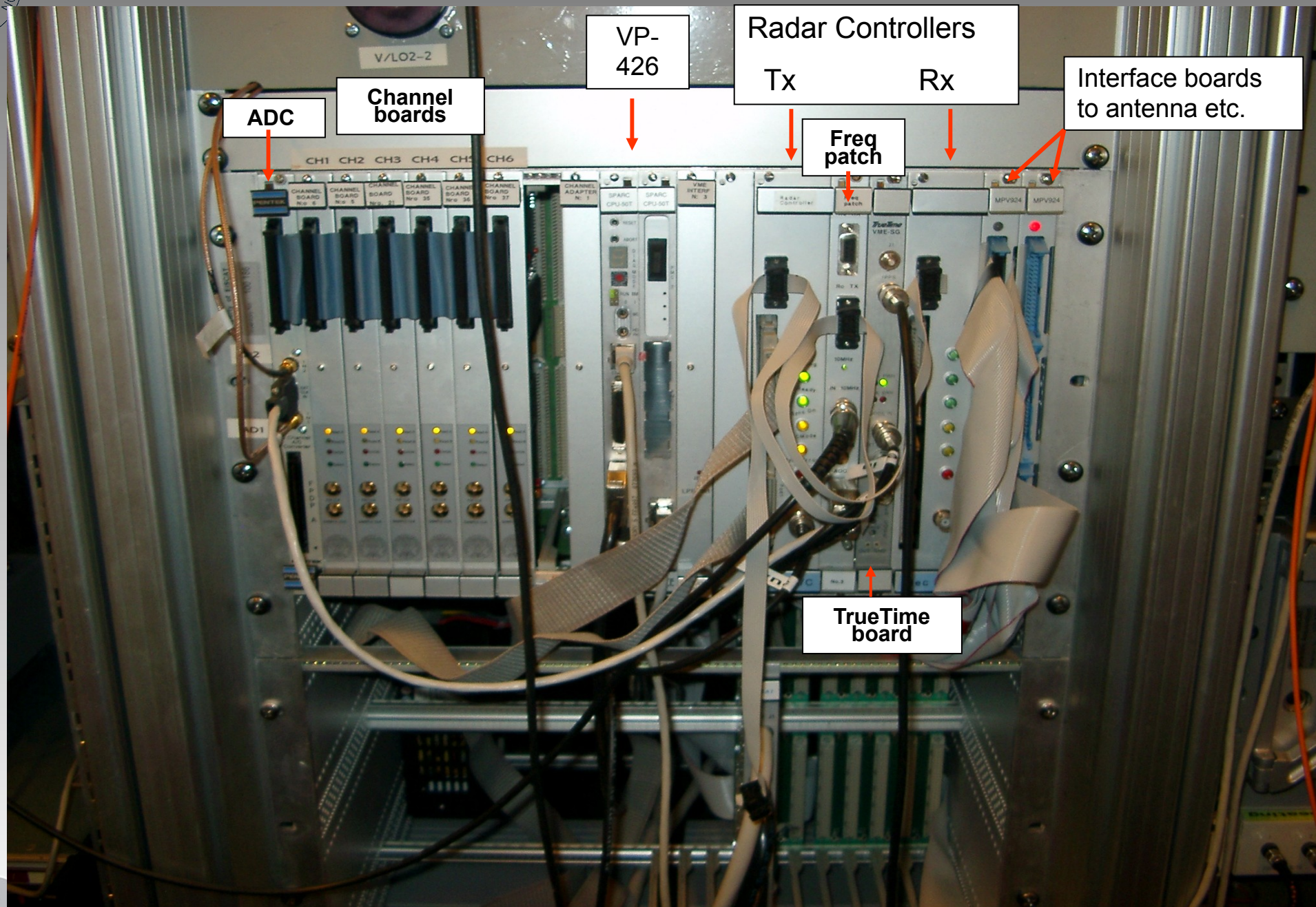




Channel board



Tromsø UHF VME crate



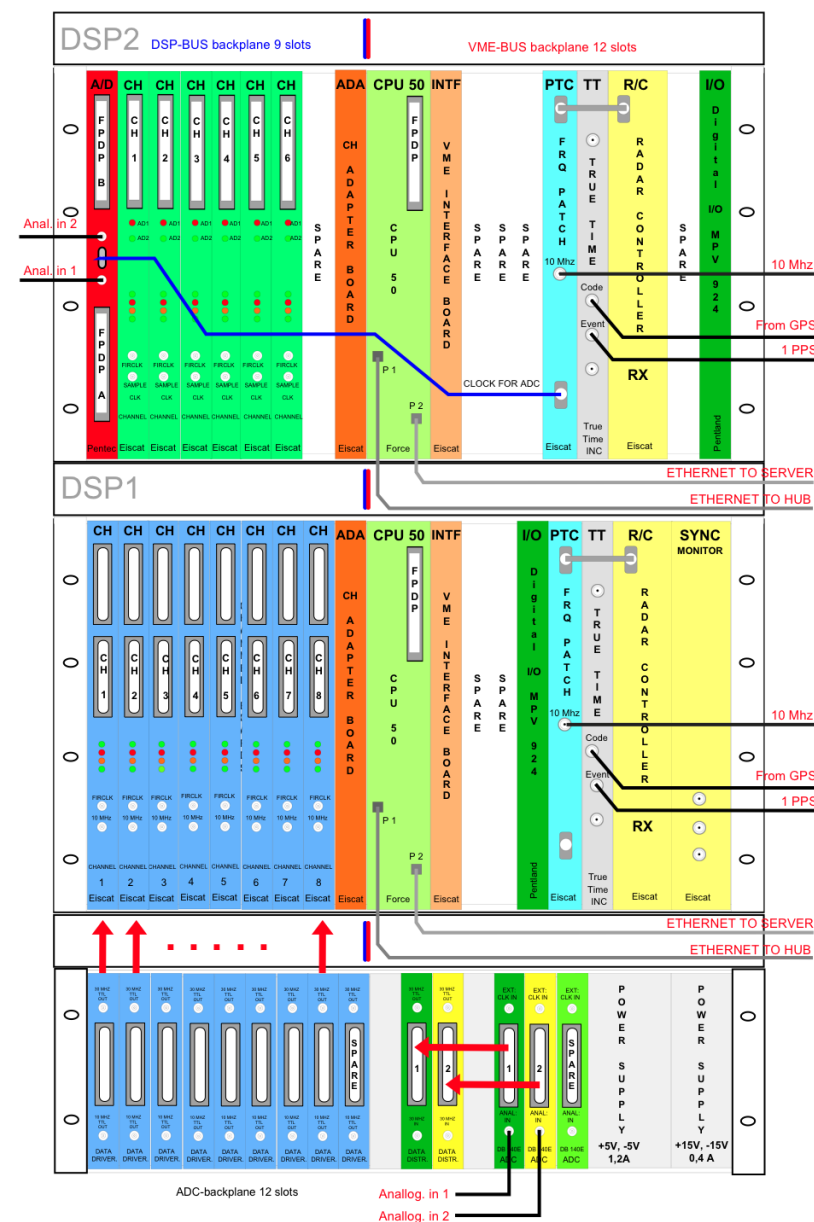
ESR RECEIVERS

(simplified block diagram)





DSP1 and DSP2 hardware for ESR



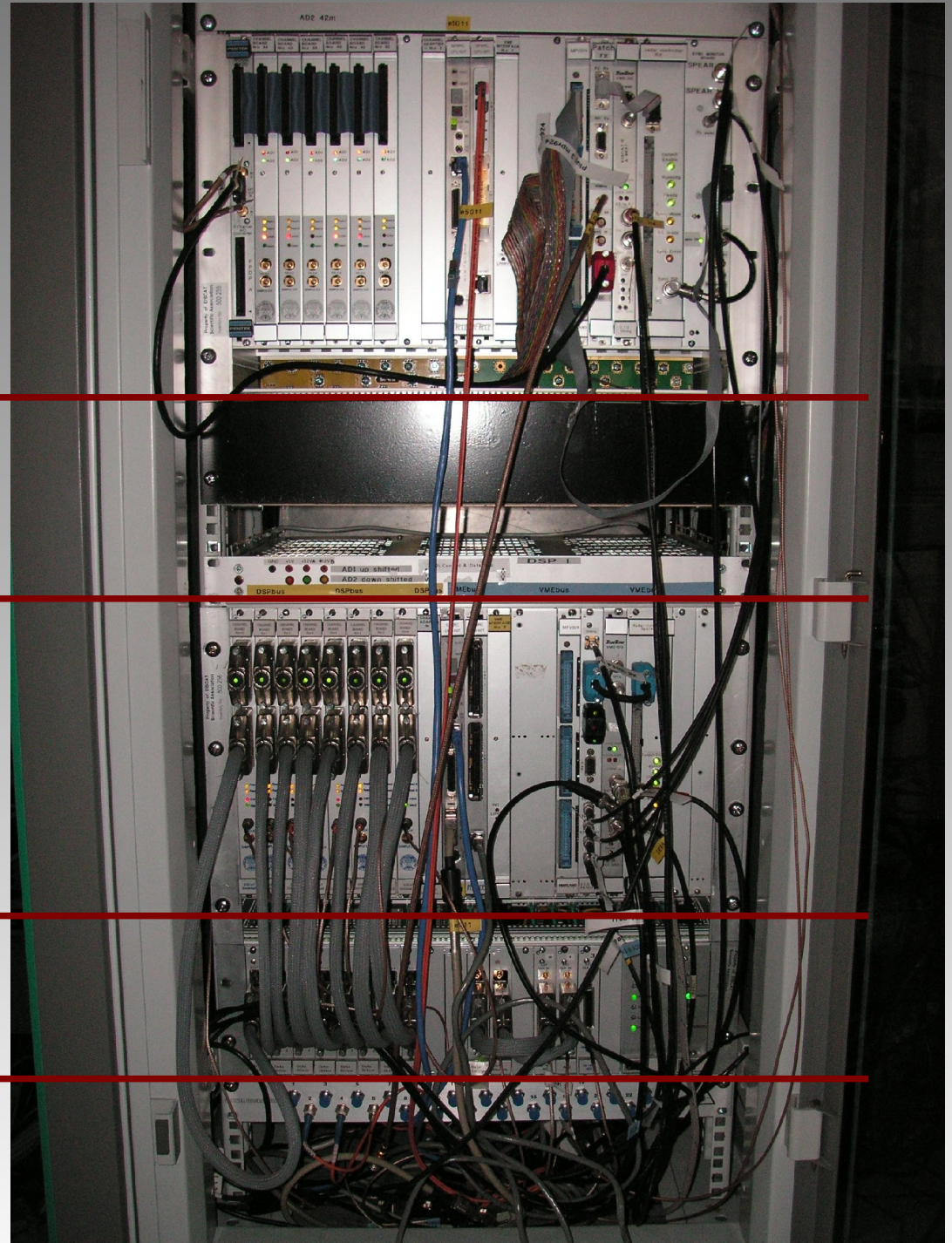


ESR DSP system

ION line DSP

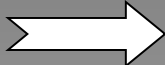

Plasma line DSP

AD converters and
data distribution for
plasma line





Process Computers and Data Transfer

- Channel boards  VP-426
 - via VME backplane (max. 50 MByte/s total)
- VP-426 always controls the reading out of data from the channel boards. Depending on the application, it may also process the data further before sending it on, thus the amount of data transferred out of the VP-426 may be different from that read off the channel boards:
- VP-426  Server (e10023 etc.)
 - via p-t-p Ethernet (max. 100 MByte/s)



Remote and ESR computers

Process computers running EROS and related software:

- t49851.eiscat.uit.no for Tromsø UHF and VHF
- e10023.esr.eiscat.no for ESR 32m, 42m and plasma lines
- k2501.eiscat.irf.se computer for Kiruna UHF
- s2501.eiscat.sgo.fi computer for Sodankylä UHF

Computers for analysis:

- tana.eiscat.uit.no for Tromsø
- kana.eiscat.irf.se for Kiruna
- sana.eiscat.sgo.fi for Sodankylä
- sandra.esr.eiscat.no for ESR



Hardware Restrictions on Experiment Design

- Radar Controller
 - program memory size limits the complexity of coded experiments
- Spectrum
 - not all sites can receive all UHF frequencies reliably
 - GSM base carriers above 935 MHz make UPL measurements difficult and limited at all UHF sites
 - in-band interference at VHF complicates full PL measurements
- TX
 - Klystron bandwidth limits altitude resolution
 - Max. modulator repetition rate limits resolution in P-to-P
- RX
 - RXP turnaround time/external clutter govern low altitude limit
 - limited number of channel boards restricts the number of simultaneous plasma line frequencies
 - buffer memory size limits the complexity of coded experiments



Noise-injection (calibration) sources:

Available in the parameter_block: d_parbl(21)

UHF Tromsø: 178 K

UHF Kiruna: 70K

UHF Sodankyla: 40K

VHF Tromsø: 280K

ESR 32m 228K

ESR 42m 163K



Some new and coming improvements

- UHF Tromsø: Gone back to old receiver protector and using switched HEMT amplifier. System temperature decreased 110-→80 K.
- ESR: Plasma line DSP (channel boards and ADC) will soon be upgraded to be the same type used in the ION line system.
- Kiruna and Sodankylä: For the 1.4 GHz system a 30 MHz wide band total power detector is available (Independent V and H polarisation)