DOT Speckle Processor (DSP)

Introduction

The Dutch Open Telescope, DOT, (Figure 1) is located at the Observatorio del Roque de los Muchachos on La Palma at an elevation of 2350m. It has been designed and built by R.H.Hammerschlag, F.C.M.Bettonvil and a small team of coworkers of the Astronomical Institute (SIU) and of the Physics Faculty Instrumentation Group (IGF) at the Utrecht University and of the University Workshop (DTO) at the Delft University of Technology (TUD). The open concept is revolutionary. So far, all high-resolution solar telescopes use evacuation to avoid internal turbulence caused by focus heating. The open DOT instead relies on telescope flushing by the strong laminar trade winds. These winds make La Palma a world-class solar site, they are necessary for all daytime telescopes, also for the evacuated solar telescopes, for keeping the temperature homogeneous in the neighbourhood around the telescope.

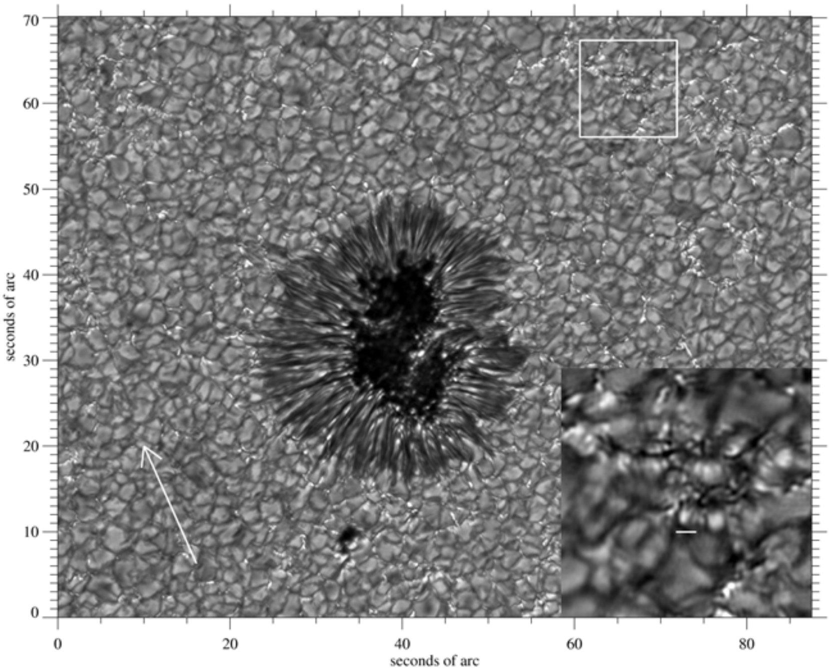

Fig. 1 (left): The Dutch Open Telescope (DOT) in operation on the Canary Island La Palma, Observatorio del Roque de los Muchachos 2350m on July 6, 2003. On top of the open frame work tower of 15m height the telescope with primary beam completely open for the strong trade wind resulting in the images and movies of the solar photosphere and chromosphere of outstanding resolution.
Fig. 2 (right): Example of a sunspot, taken in the Fraunhofer G-band (430.5 nm): AR 9407 taken on April 1, 2001 by Peter Sütterlin. The arrow marks the direction towards the disk center of the sun. The inset in the lower right shows an enlargement of the area in the white frame. This active granular area contains filigree. The white dash measures 1 arc second. The image is a single frame from a 1-hour movie, available on http://dot.astro.uu.nl

Fig. 3: Multi-wavelength system on the top of the telescope structure. The left image shows the water cooled diaphragm in the center of the picture. The front surface of the diaphragm is a mirror which reflects already most of the light. Only a field of 1.6mm diameter is used through a hole in the diaphragm. The primary solar image of 18.5mm diameter on the mirror is visible in the picture. After the diaphragm the light is guided to the multi-wavelength system visible at the right. Also visible at the right the hose for additional air suction around the diaphragm. Inside the hose are the invisible 2 small hoses for the water circulation through the diaphragm. The right image shows a top view of the upper part of the telescope structure. Visible are: to the left the multi-wavelength system, the primary mirror in the bottom center, the focus camera at the right and at the very right the box with control electronics. Below the primary mirror the entrance of the guider telescope is just visible.

The DOT is at the forefront of high-resolution observations in which diffraction-limited solar observing is achieved. The DOT became the first solar telescope to regularly achieve 0.2” resolution continuously over multiple hours and large fields (80”x60”) at high cadence (30 s) thanks to its successful open principle, superb optical performance, exceptional mechanical stability, and consistent speckle reconstruction. Figure 2 shows an example. The resulting DOT movies are of unique quality. They are available at http://dot.astro.uu.nl together with DOT publications, reports, and further details.

The DOT is being equipped with a multi-wavelength imaging system (Figure 3). Several synchronous channels together constitute tomographic sampling of the solar atmosphere from the deep photosphere (continua and G-band) through the low chromosphere (CaII), to the high chromosphere (H-alpha). Complementary EUV and X-ray observation from space adds coronal topology and dynamics. Five channels are operational, G-band (430.5/1.0nm), Blue Continuum (431.9/0.6nm), Red Continuum (655.9/0.5nm), CaII-H (396.8/0.1nm) and a tunable Lyot filter for H-alpha (656.3nm) with selectable bandpass of 0.025 or 0.050nm. By tuning the light wavelength the image plane moves from the high chromosphere for the line center to the lower regions of the chromosphere for the line wings. Figure 4 shows an example of a 4-wavelength mosaic image.

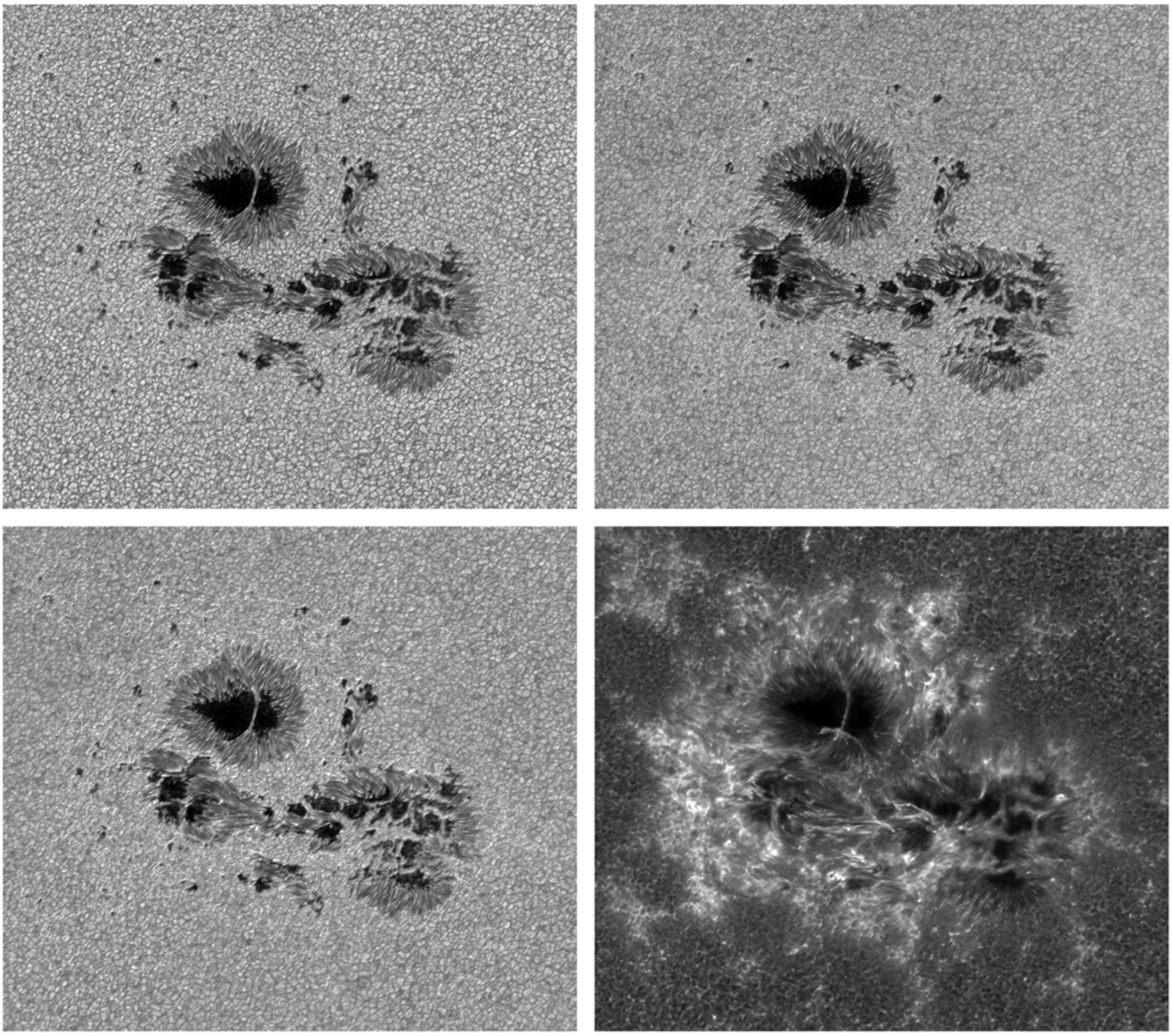

Fig. 4: 4-wavelength mosaic image of AR10375, June 6, 2003.
Left top: Blue continuum 431.9nm, deep photosphere. Best contrast of the convection cells of a 1000-2000km size, the so called granulation.
Right top: G-band (CH absorption lines) 430.5nm, slightly higher in the photosphere. Bright points caused by magnetic tubes between the granules are arranged in a kind of chains. These magnetic tubes stick out of the solar surface.
Left bottom: Red continuum 655.9nm. Higher in the photosphere than the blue continuum. Less contrast in the granulation. Bright points are visible like in G-band.
Right bottom: Ca II-H line 396.8nm. Low chromosphere above the photosphere. The bright structures are caused by magnetic fields. Note the light bridge in the dark core of the largest spot visible in all 4 wavelengths with a light bow perpendicular to the bridge only visible in the Ca II-H line. Outside the magnetic active region the granulation is partly visible in negative.

DOT speckle processing

Correction of the wavefront perturbations caused by the Earth's atmosphere is now an absolute must in optical solar physics. There are three methods: speckle reconstruction, phase-diverse imaging plus speckle reconstruction, and adaptive optics (AO). Speckle reconstruction was chosen for the DOT because it delivers relatively good restoration over the whole field of view defined by the camera chips, presently one thousand isoplanatic patches. The disadvantage is the laborious post-detection processing.

Figure 5 illustrates the three-phase procedure. The DOT speckle code uses the speckle masking formulated by Weigelt (1977) and Hofmann (1986), as implemented at Göttingen by de Boer (1993) and improved and ported to Utrecht by Sütterlin. Because speckle exposures of 10ms have insufficient S/N in Hα 656.3 nm and Ba II 455.4 nm narrow-band images, Sütterlin has adapted the two-channel restoration technique of Keller and von der Lühe (1992) for these. It employs a wider passband in the neighbouring continuum to derive and correct for the atmospheric modulation transfer function.

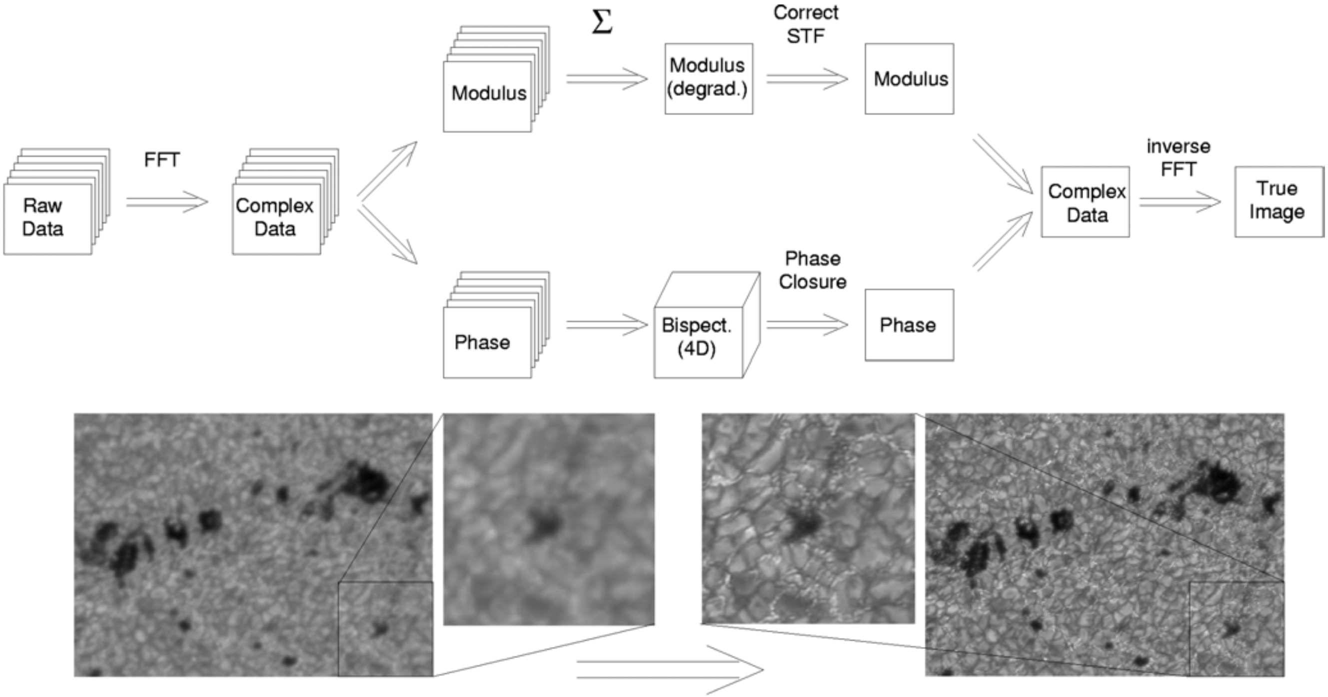

Fig. 5: Schematic illustration of speckle reconstruction. The Fourier amplitudes and phases are treated independently, employing the spectral ratio technique to restore amplitude spectra and phase closure to restore phase spectra. The technique requires a speckle burst of 100 frames taken at 10 frames/s with exposures below the seeing-freezing time of 10ms, representing independent samples of the wavefront distortions. A burst must be completed within the time in which the solar scene does not change, 20-30 s when set by the gasdynamical sound speed. In the initial pre-processing, all frames of a burst are co-aligned (“tip/tilt correction") and the full field of view is tessellated into about a thousand subfields, each smaller than the isoplanatic patch over which the atmospheric wavefront perturbations do not vary with angle. The speckle reconstruction is done independently for each subfield, using all burst frames. The post-processing merges all restored subfields to a single sharp image. Local correlation tracking is applied to the full image sequence to correct small subfield mismatches. The resulting sequence is usually also space-time Fourier-filtered to remove “solar seeing" consisting of the global solar five-minute oscillations.

DOT speckle bottleneck

Our present computers on La Palma cannot store or handle the data stream when all six cameras will be operational. One single frame of 1296x1030 pixels represents 2.7 Mbyte; at 30 s burst cadence, one camera deposits 33 Gbyte/hour; a “run" of all 6 cameras during 8 hours amounts to 1.6 Tbyte.

The DOT presently has 72Gbyte storage per camera, permitting runs of only two hours. The data are now archived overnight on an Exabyte Mammoth-2 7-tape library. The subsequent tape processing on the present DOT cluster (14 pieces 600-MHz CPU's) is done remotely from Utrecht and takes, per burst, about 15 min for pre-processing, 15 min for the speckle reconstruction part (with subfields divided between computers), and 5 min for the post-processing. With all six cameras, a two-hour run will need at least one month of wall-clock time on our present system - a ratio of 350 between observing duration and processing duration.

Consequently, the speckle processing becomes a terrible bottleneck. It does not fully kill our own DOT science utilisation because just one good tomographic run on an active region, plage, or even a quiet solar area is likely to contain enough material for very interesting science. However, the bottleneck obviously inhibits offering DOT observing time to others on anything more than a very modest scale. It inhibits exploiting the full potential science niche that DOT tomography offers. In addition, two-hour sequence duration per day is really too short for many evolutionary processes such as flux emergence and sunspot breakup, and for hunting to catch relatively rare and briefly-lasting dynamical phenomena such as pore formation, lightbridge collapses, filament eruptions, and above all flares. When opting for speckle reconstruction, we anticipated that large-throughput speckle reconstruction should eventually become affordable by the steadfast decline in CPU price/performance ratio (Moore's law). At the same time, this decline motivated us to wait until the last possible moment in order to get more speed for money. With the imminent completion of the 6-camera DOT tomography system, that moment has arrived.

DSP description

Preparatory work in this direction started two years ago. The DOT speckle code was ported to C and rewritten into a parallel version by de Wijn, see appendix. He performed extensive tests on parallel clusters which demonstrated that the speckle reconstruction part parallelizes almost perfectly, but that the pre- and postprocessing are hard to parallelize. Detailed performance analysis of these tests and intensive discussions with external experts led to the architectural design proposed here, see Figure 6, a hybrid distributed/parallel 70-processor farm to be put on La Palma where it will enable overnight processing of the daily DOT harvest. It is not realistic to think of processing the DOT speckle stream elsewhere. Transfering 1.6 Tbyte data transfer per observing day via the Internet remains impossible in the foreseeable future; tape transfer is far too time consuming.

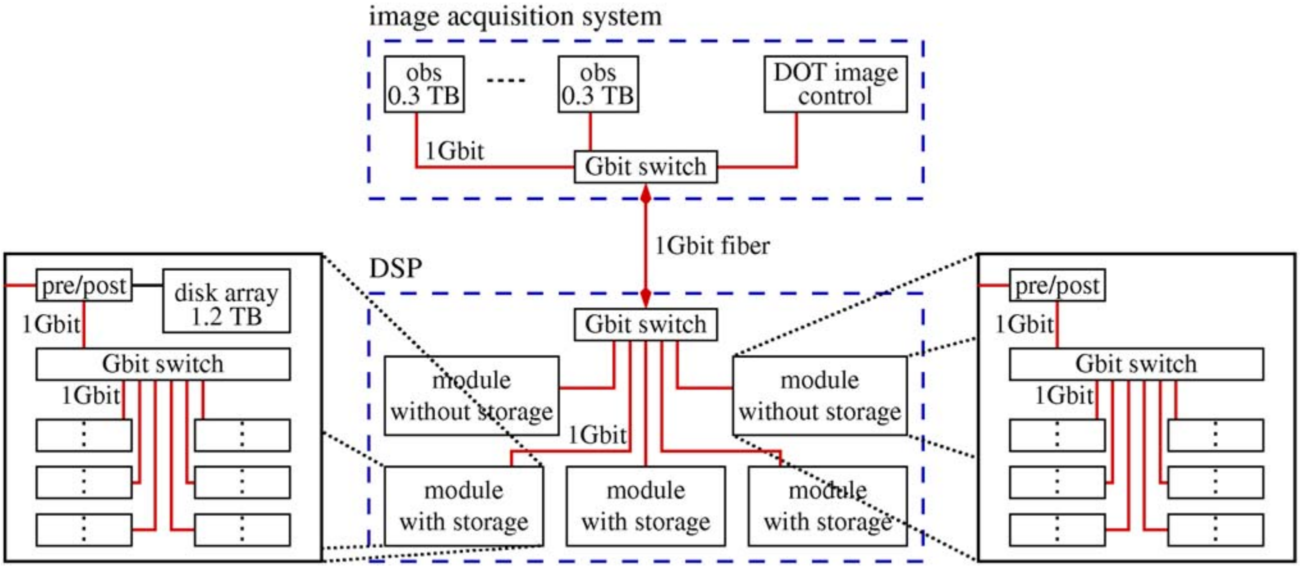

Figure 6: DSP architecture. The upper boxes (obs) denote the image-acquisition computers, one per camera, each to be upgraded with 0.3 Tbyte storage and a fast connection. They and the DOT control workstation are located in the DOT observing room in the basement of the Swedish SST building. A 1Gbit switch will pipe the data stream through optical fibers to the DSP. The master computer has storage for two full observing runs, and distributes the processing over five modules. The head node in each module has a large memory capacity to handle the pre- and postprocessing, and shares out the speckle reconstruction per subfield to 12 low-memory CPU's.
Three of the five modules have each 5 hard disks of each 300 GB, which gives a free storage space purely for data of 1.2 TB per module, all together 3.6 TB available for data storage.

The 70 processors on 35 boards and the 15 hard disks of each 300GB are built into 2 racks of 24HE, see Figure 7. A very special and new development is the direct cooling of the main Central Processing Units (CPU's) with water. The overall heat production becomes much lower compared to air cooling. The racks have a secondary cooling system with air for the auxiliary electronics, but this heat production is only small compared to the CPU's. The heat in the air is moved to cold water from a active compressor cooling machine. The heat of the water through the CPU's is transported away in a passive system with only a water pump. Hence, the active cooler is much smaller than with air cooling of the whole system. More explanation in the caption of Figure 7.

The passive water system of the CPU's and the active water system of the auxiliary electronics give both their heat to a third watersystem with a plastic watertank of 5 cubic meter for storage of the heat. The stored heat is released with the help of a radiator and fan only during the two hours around sunrise and sunset, such that astronomical observations will absolutely not disturbed, both not of nighttime and not of solar observations. Also this is a new approach to the heat release of computersystems near astronomical installations. The heat release quantity of this pilot project is modest compared to other installations on the Observatorio del Roque de los Muchachos notwithstanding its huge computing power. The peak cooling capacity for the computer is 10 KW, the peak heat release capacity of the radiator plus fan is 60 KW. Normal operation values are substantial lower, because the processors are not continually running with full computing power. The increase of the water temperature in the tank between the release periods is maximum 15 degrees Celcius. This would only be the case after data reduction of a full 6-camera 8-hour run at 30s cadence, something what normally not happens because of seeing limitations.

The active cool machine for the auxiliary electronics and the heat exchangers with waterpumps are also built together in a rack, see Figure 8 left. A rack with an UPS is part of the system, see Figure 8 right. The watertank and radiator with fan are represented in Figure 9.

The DOT speckle Processor is a development of the Astronomical Institute and the Computational Physics Group both of the Faculty of Physics and Astronomy of the Utrecht University in cooperation with the Solar Physics group of the Institutt for Teoretisk Astrofysikk, Det Matematisk-Naturvitenskapelige Fakultet, Oslo University and the firms Icebear Systems, HTP Microsystems, Atotech and Rittal.

Financial support is received by a successful grant application with the Dutch science foundation NWO in the open competition for investments in medium sized scientific apparatus. The NWO rules require a substantial contribution from other sources. This is fortunately supplied by a small private fund, SOZOU, the Zwaan-fund.

Fig. 7: The 2 racks with the 70 processors on 35 boards and the 15 hard disks of each 300GB divided over 3 units with a board and 5 harddisks each in the upper part of the rack to he left. To each board are two cables and two waterhoses. From left to right are visible for each board the following connections:

Red cable with 1Gbit ethernet.

2 black waterhoses, for direct cooling of the CPU's, connected to the right with special fittings, which close immediately when disconnecting. Hot (dis)connection of the boards is possible without waterloss. Risk of waterdamage to the electronics is minimized. There is a lot of scepsis in this respect to direct watercooling of electronics. The manufacturers consider the speckle processor as a demonstration project, that safe direct water cooling is very well possible and an excellent solution for powerfull machines, where minimizing the heat production is important.

Black cable for remote switch off and on with reset by relays. The whole system is controlled and safeguarded by a special subsystem, that switches off units where a deviation of the normal function is detected, for instance with the cooling. If necessary a controlled shut down of the system will take place without loss of data.

The racks are completely closed. An air stream goes through each rack for cooling of the auxiliary electronics. On top of each rack is a box with the heat exchanger to the closed water circuit with an active cooling machine. The air circulation is completely closed, hence no heat leakage to ouside the racks. The heat of the auxiliary electronics is only a small fraction of the heat production of the CPU's, which is removed directly by the passive water circuit in a very efficient way, see further details in text.

Fig. 8 Left: rack with coolunit, heat exchangers and waterpumps with removed front cover. Right: rack with UPS system with removed front cover.

Fig. 9 Left: plastic watertank of 5 cubicm for heat storage. Right: radiator with fan for fast heat release only during sunrise and sunset.