Tracking the Correlation at Sacramento Peak

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Image motion stabilization for ground based solar telescopes in the 1980s

- Real-time image stabilization as a tool to remove instrument and seeing jitter from solar observations with ground and space telescopes.
  - Solar Area Correlation Tracker proposal by Goodyear Aerospace in 1972
  - Study of correlation algorithms for a solar space telescope by Robert Smithson and Theodore Tarbell in 1977
- Adaptive Optics development was in full swing in the military sector, but an exotic topic for astronomy.
- General purpose computers had way too little power, requiring development of custom real-time hardware.

The NSO – KIS collaboration for a solar feature correlation tracker

- R. B. Dunn and G. Spence developed a fast camera in the early 1980, based on a 32x32 Reticon diode array
- This device was used by me to collect several high cadence sequences of images, which were analyzed during my term as a Sac Peak summer student in 1981 (*von der Lühe, O. A&A 119, 85-94 (1983)*)
- J. B. Zirker, director of SPO, invites KIS to collaborate in the development of the hardware for a correlation tracker for DST and VTT in Feb. 1983. This triggered a successful application for DFG funding.
- Hardware development started in 1984, based on a concept by A. L. Widener. It involved two custom computer boards for real-time AD conversion and preprocessing, and for implementing the actual cross correlation (CORAD and CORPR).

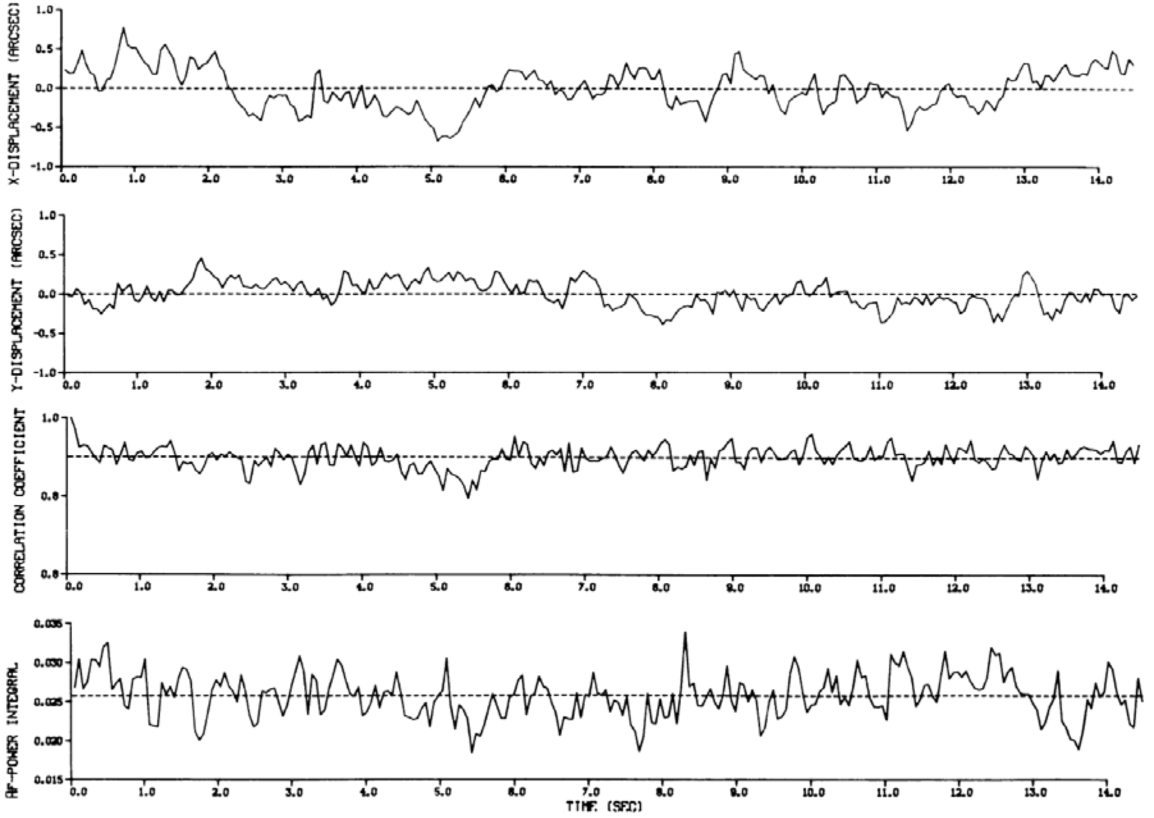


Fig. 4. The four properties of the two-dimensional cross correlation functions for a period of 14.5 s of time. These results are based on 32 × 32 points. The dashed lines represent average values

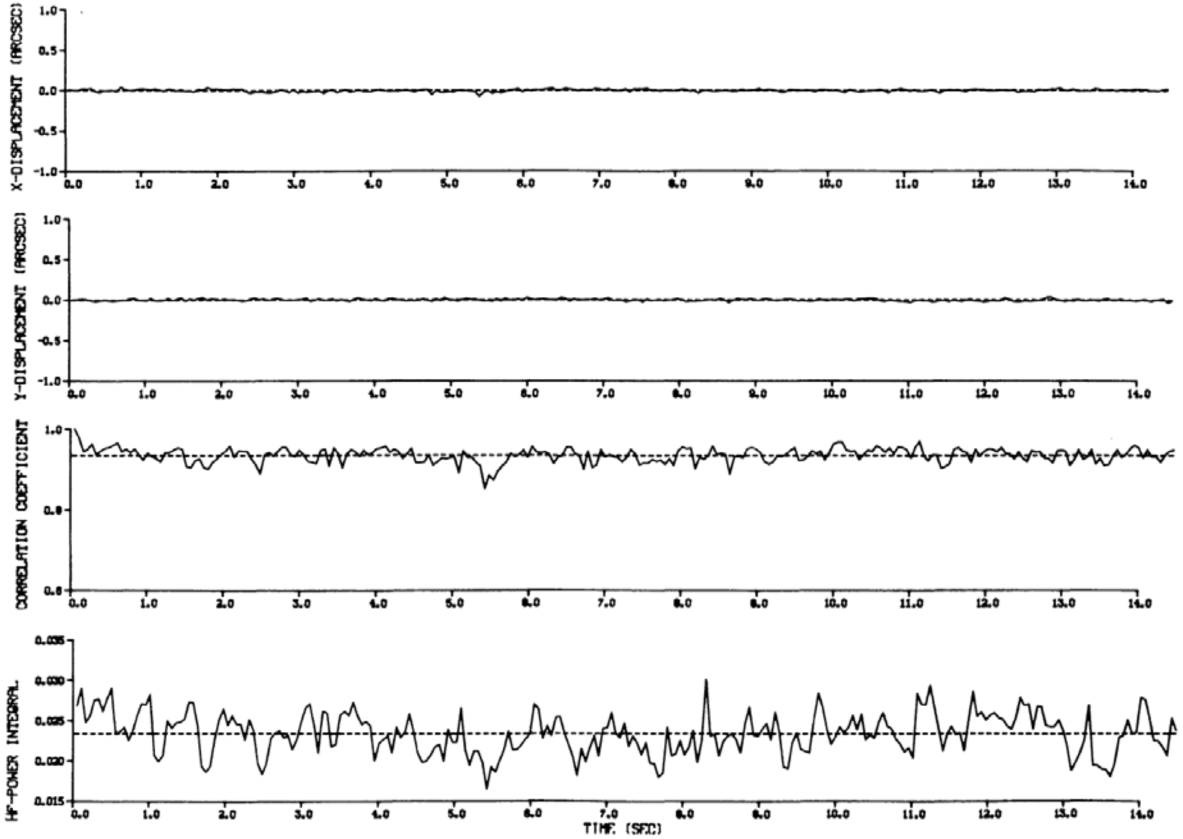
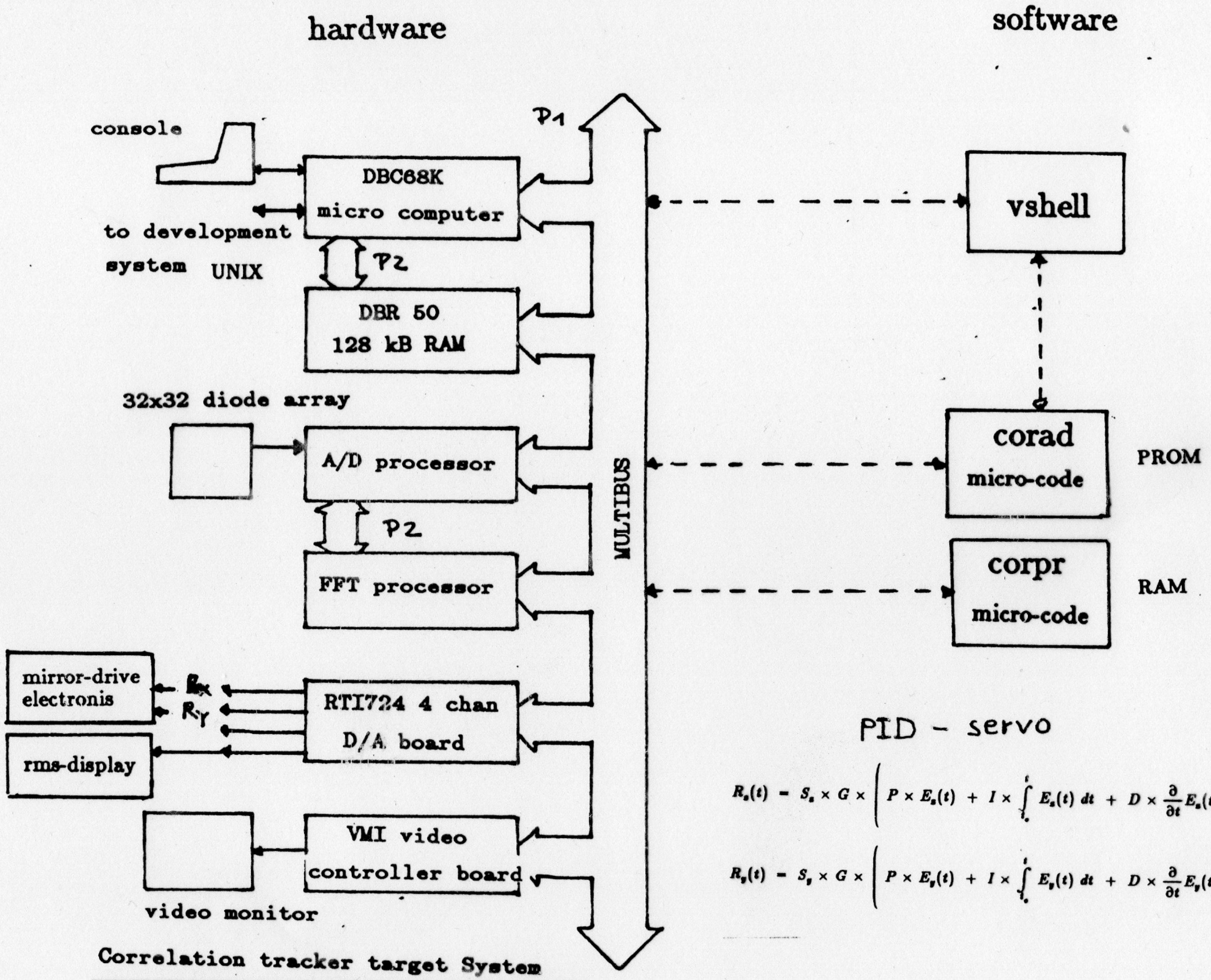


Fig. 5. The same as in Fig. 3, this time for the artificially stabilized time series

Main result from the 1983 CT paper. Graphs from top to bottom: X and Y positions of cross correlation peaks of 256 images (17.7 frames/s), correlation coefficient, high frequency power as image sharpness proxy. Left: original data set; right: the same data set after artificially removing image motion from the original set by bilinear interpolation. The conclusion was that real-time correlation tracking should result in a residual jitter of better than 0.02 arcsec. The referee, Ted Tarbell, called the approach “a little iffy”, and he was dead right.

The NSO – KIS collaboration for a solar feature correlation tracker

- SPO was combined with the KPNO solar group to form the National Solar Observatory as part of NOAO in August 1984. Bob Howard was appointed NSO director and Ray Smarrt became Sac Peak deputy. CORAD declared „almost ready“ and CORPR development began.
- KIS duplicated the real-time computing evironment which was based on AT&T Unix System III as development environment and VRTX for the RTOS. Software simulators for CORPR were developed to verify the FFT coefficients.
- NOAO director John Jefferies announced in March 1985 the closure of Sac Peak as of Oct. 1985, creating panic at the peak. Through intense lobbying, the closure was averted, resulting in the resignation of Jefferies and Howard in the following year.

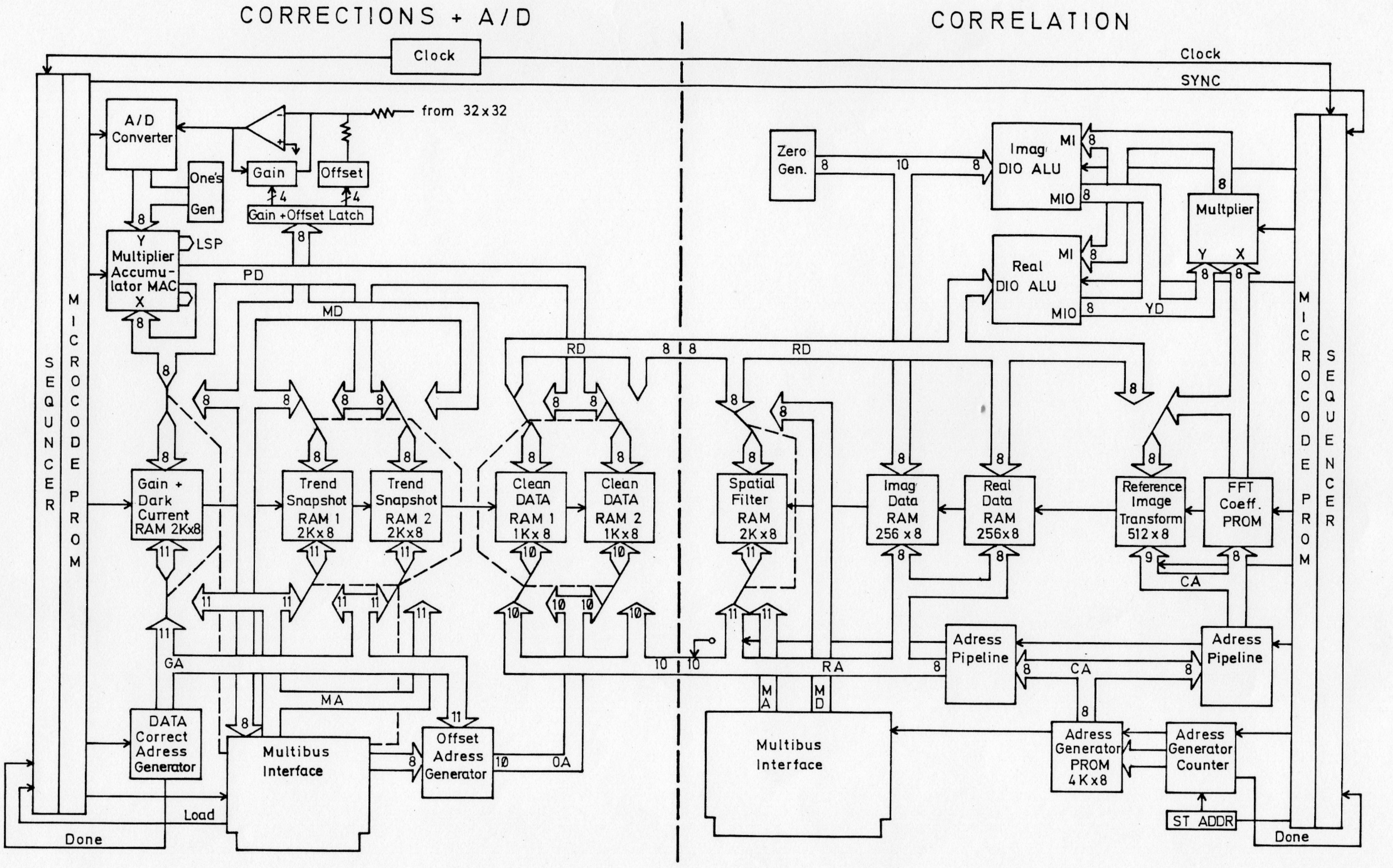


Correlation tracker target System

PID - servo

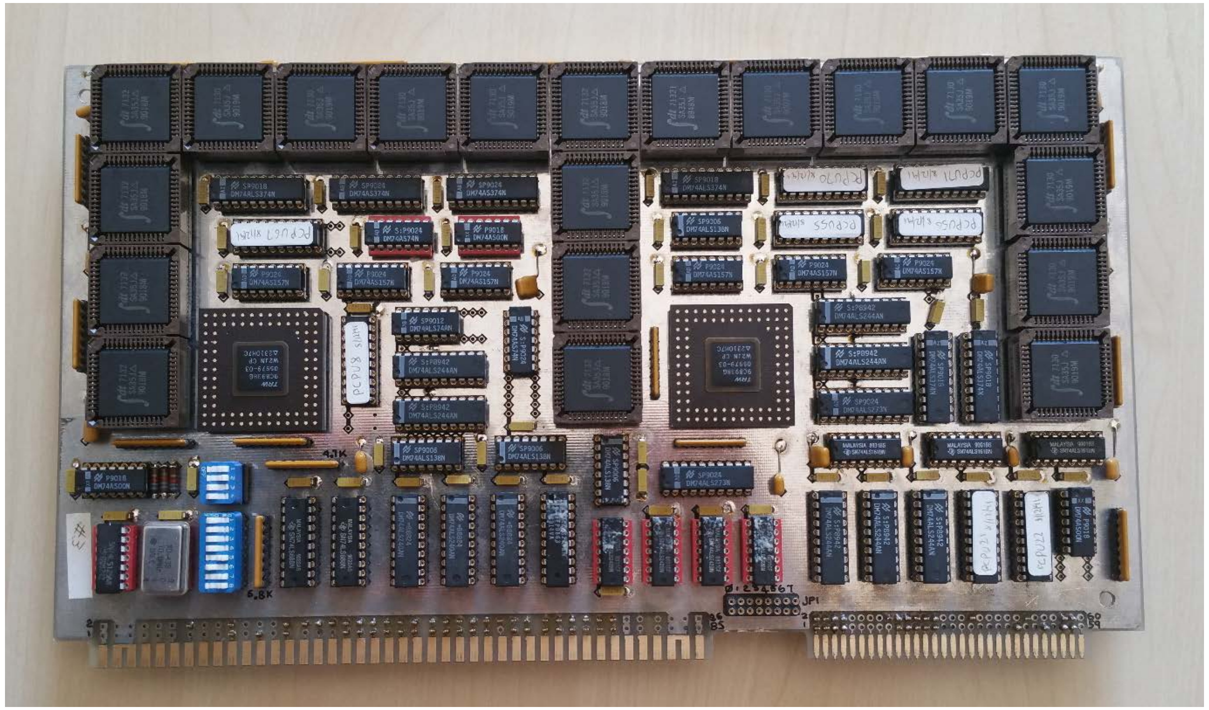
$$R_x(t) = S_x \times G \times \left(P \times E_x(t) + I \times \int_{t_0}^{t} E_x(t)\, dt + D \times \frac{\partial}{\partial t} E_x(t) \right)$$

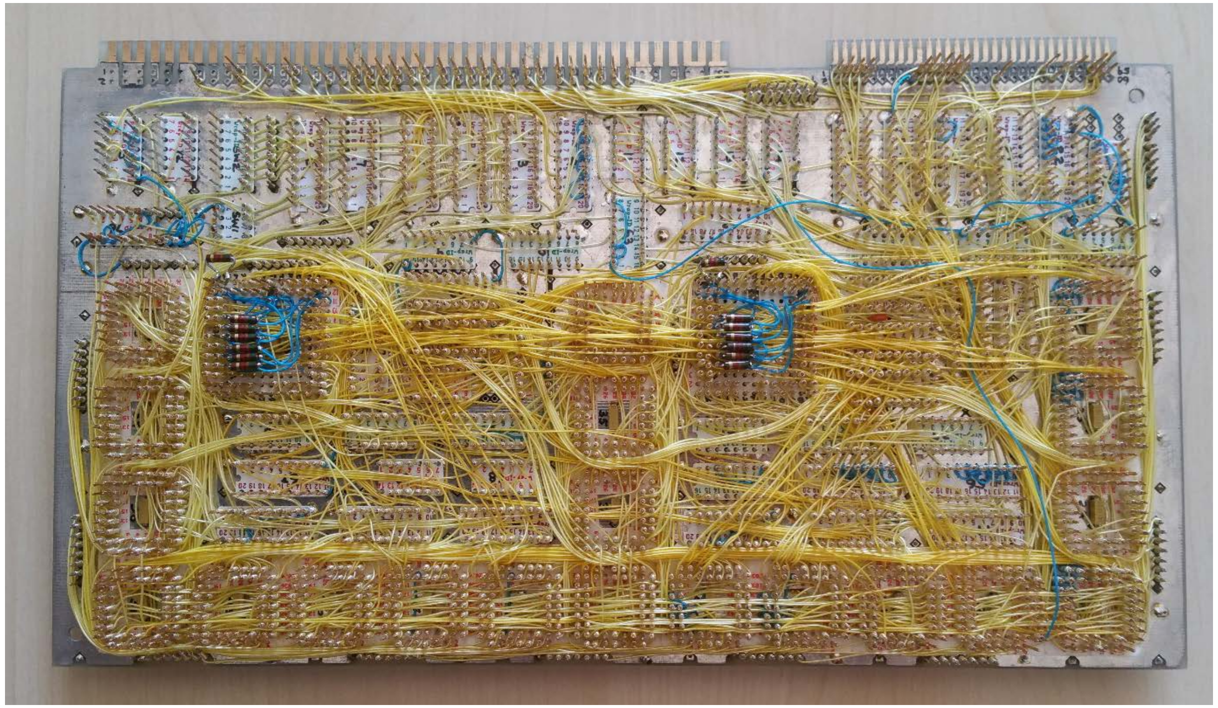
$$R_y(t) = S_y \times G \times \left(P \times E_y(t) + I \times \int_{t_0}^{t} E_y(t)\, dt + D \times \frac{\partial}{\partial t} E_y(t) \right)$$



CORRECTIONS + A/D
CORRELATION
Clock
SYNC
SEQUENCER
MICROCODE PROM
A/D Converter
from 32x32
Gain
Offset
Gain + Offset Latch
One's Gen
Y Multiplier Accumulator MAC X
LSP
PD
MD
RD
Gain + Dark Current RAM 2Kx8
Trend Snapshot RAM 1 2Kx8
Trend Snapshot RAM 2 2Kx8
Clean DATA RAM 1 1Kx8
Clean DATA RAM 2 1Kx8
Spatial Filter RAM 2Kx8
Imag Data RAM 256 x 8
Real Data RAM 256x8
Reference Image Transform 512 x 8
FFT Coeff. PROM
Zero Gen.
Imag DIO ALU
Real DIO ALU
MI
MIO
Multiplier
YD
GA
MA
RA
CA
OA
DATA Correct Adress Generator
Multibus Interface
Offset Adress Generator
Adress Pipeline
Adress Generator PROM 4Kx8
Adress Generator Counter
ST ADDR
Load
Done

Customized Hardware - CORAD





The NSO – KIS collaboration for a solar feature correlation tracker

- CORPR was completed and tested in Summer 1985, while CORAD was still „almost ready“ because of a noise problem. The development for the Reticon 32x32 camera to be used with the system has not yet begun.
- Lee Widener left Sac Peak in August 1985, not having been able to complete the CT hardware. Steve Colley took over.
- I submitted my dissertation on solar speckle interferometry in the fall of 1985. After ist defense, I joined NSO in Feb. 1986 as a postdoc.

The NSO – KIS collaboration for a solar feature correlation tracker

- Thomas Rimmele joined the CT development in Nov 1985. He took over most of the development work in the following years and worked both at KIS and Sac Peak.
- The hardware was completed in 1988. A verification run at the DST took place in June and August 1988. The results were published in 1989 (*von der Lühe, Widener, Rimmele, Spence, Dunn, Wiborg, A&A 224, 351-360 (1989)*)
- A second system was built for the Vacuum Tower Telescope of KIS in Tenerife. Both systems were operational until the mid-1990s when they were replaced by modern, faster hardware.

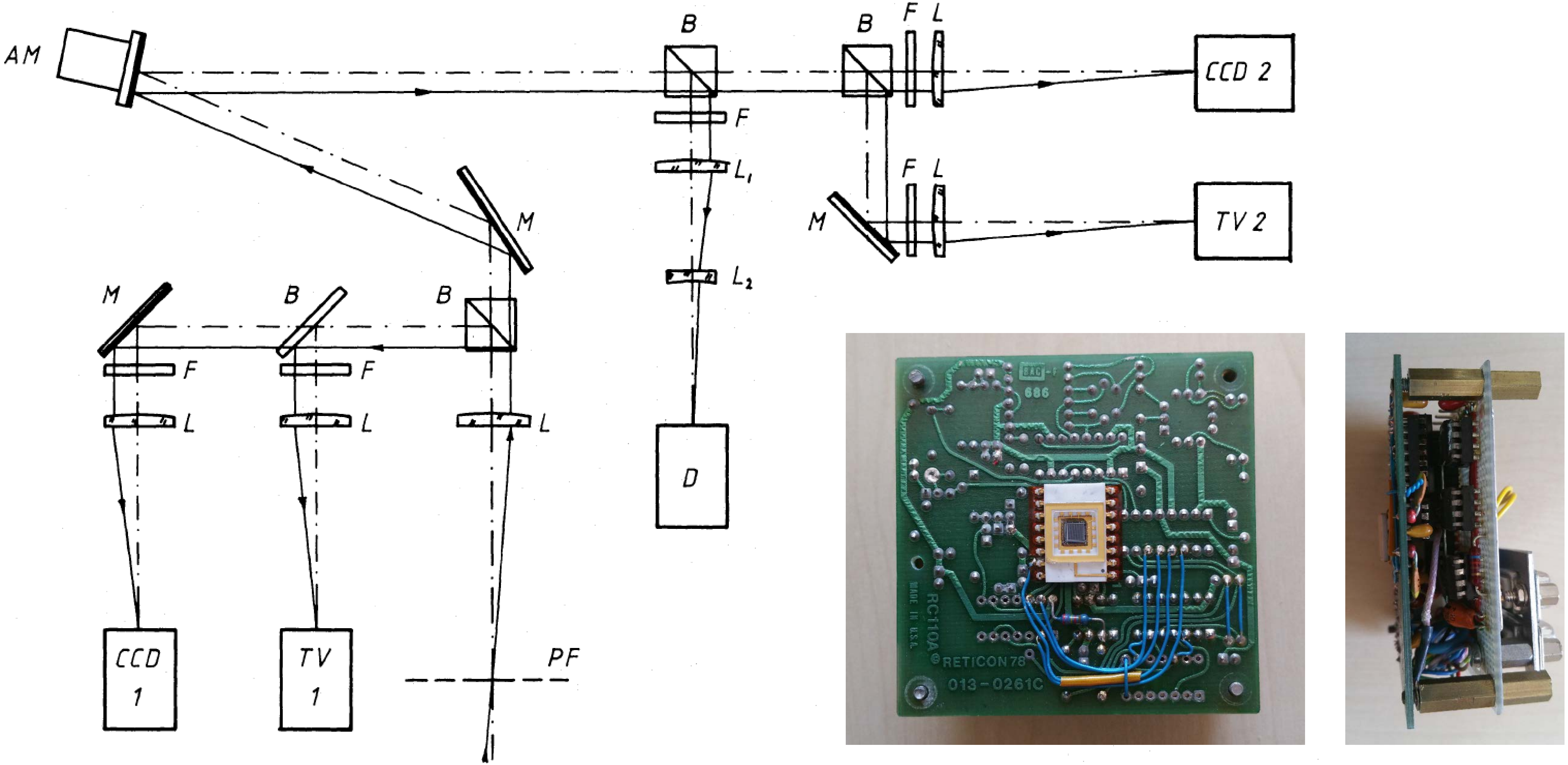
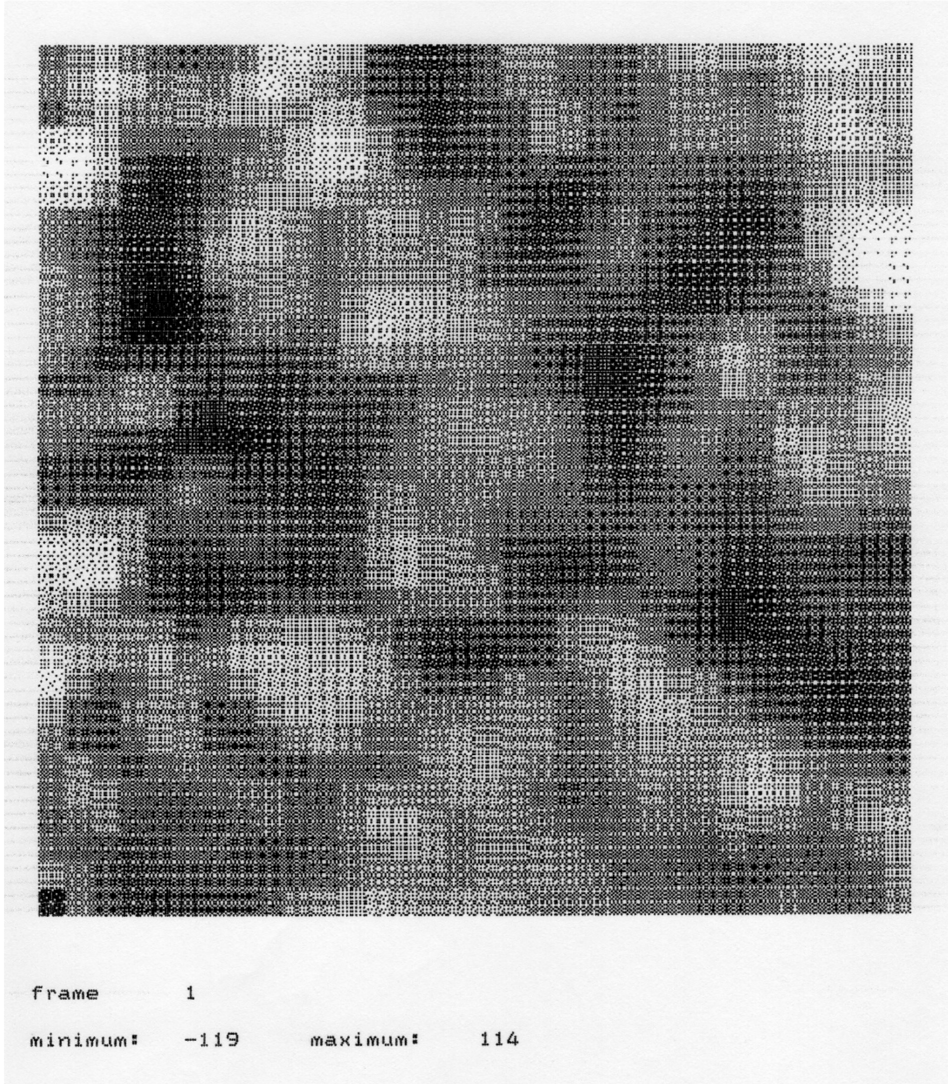
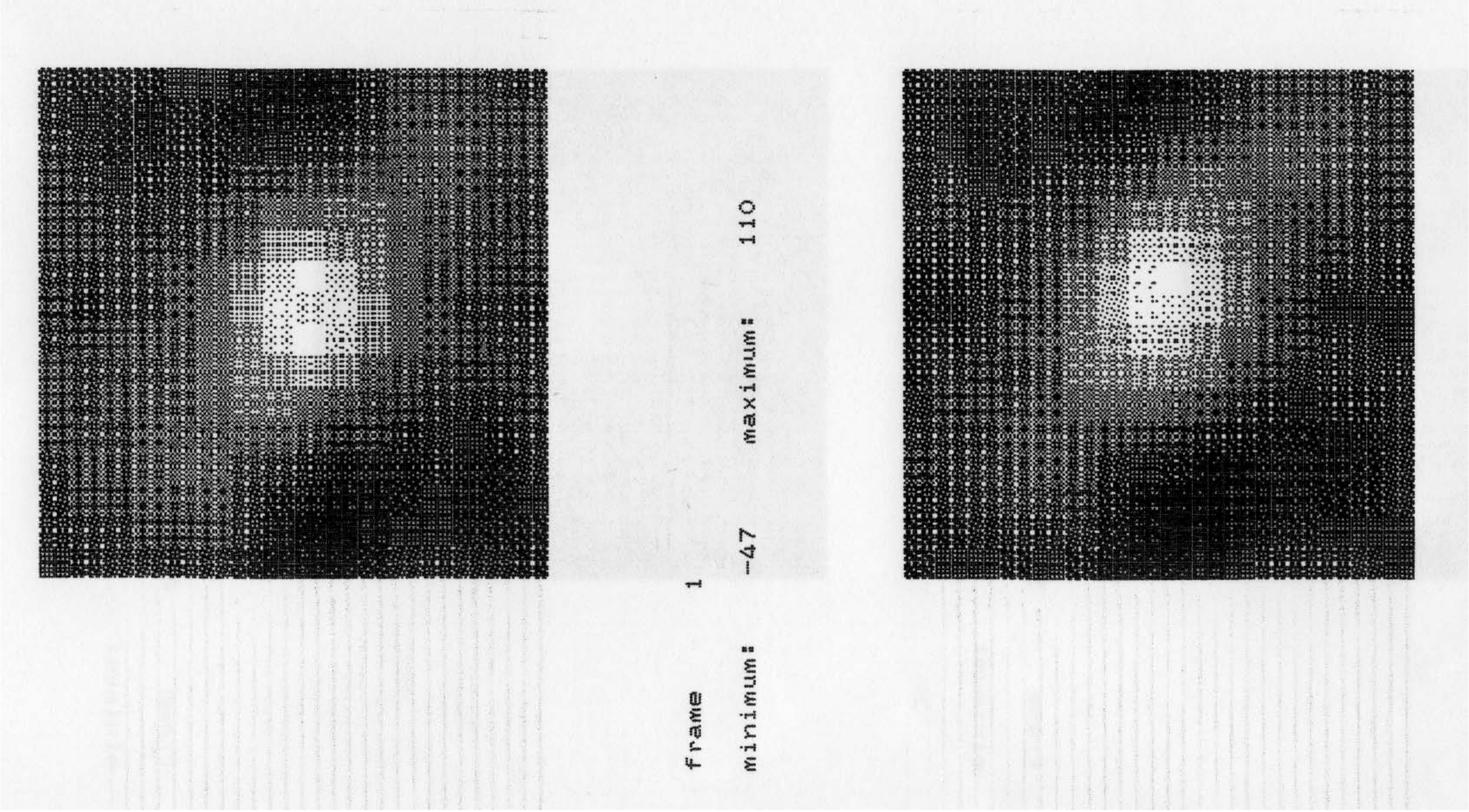
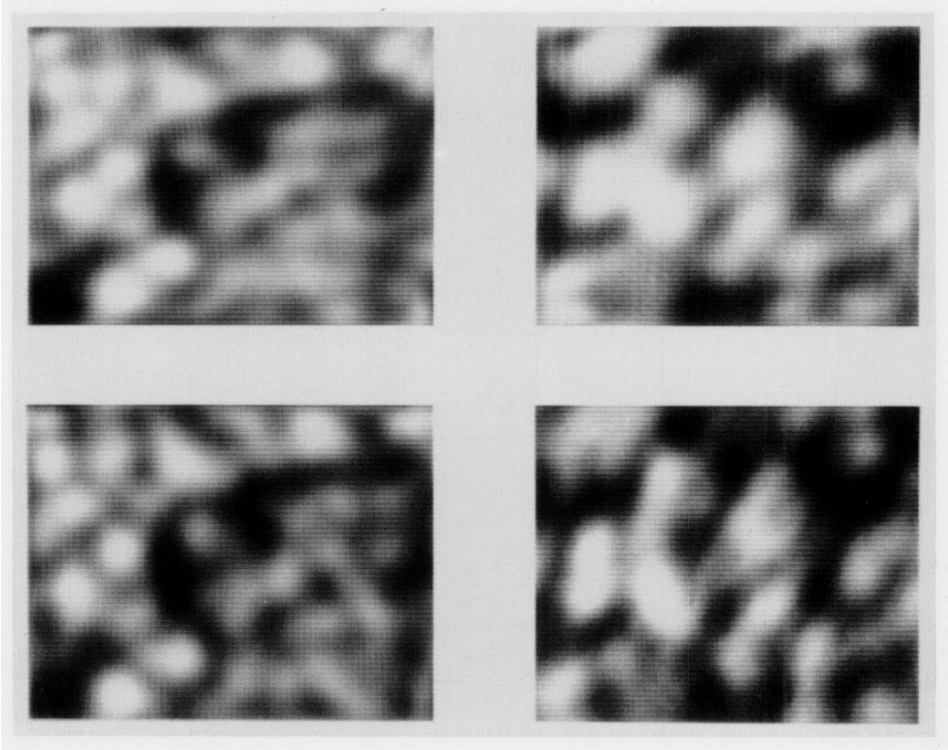


Fig. 4. Schematic of the optical setup used for evaluation of the correlation tracker system. PF: primary telescope focus. L: lenses, B: beamsplitters, M: mirrors, F: filters, D: correlation tracker detector, AM: agile mirror, TV: television cameras, CCD: CCD cameras. More details are described in Sect. 3.1





A 32x32 pixel sample frame covering 10“ by 10“ (0.3 arcsec/pixel). The cross correlation was computed using the center 16x16 pixels. Sample correlation functions on the right. Five values centered on the maximum were used for computing sub-pixel shifts.



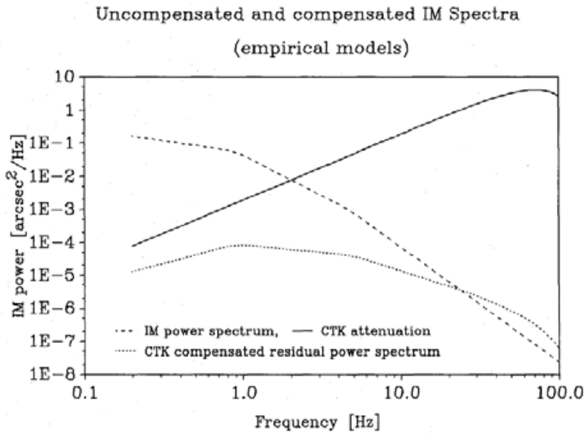
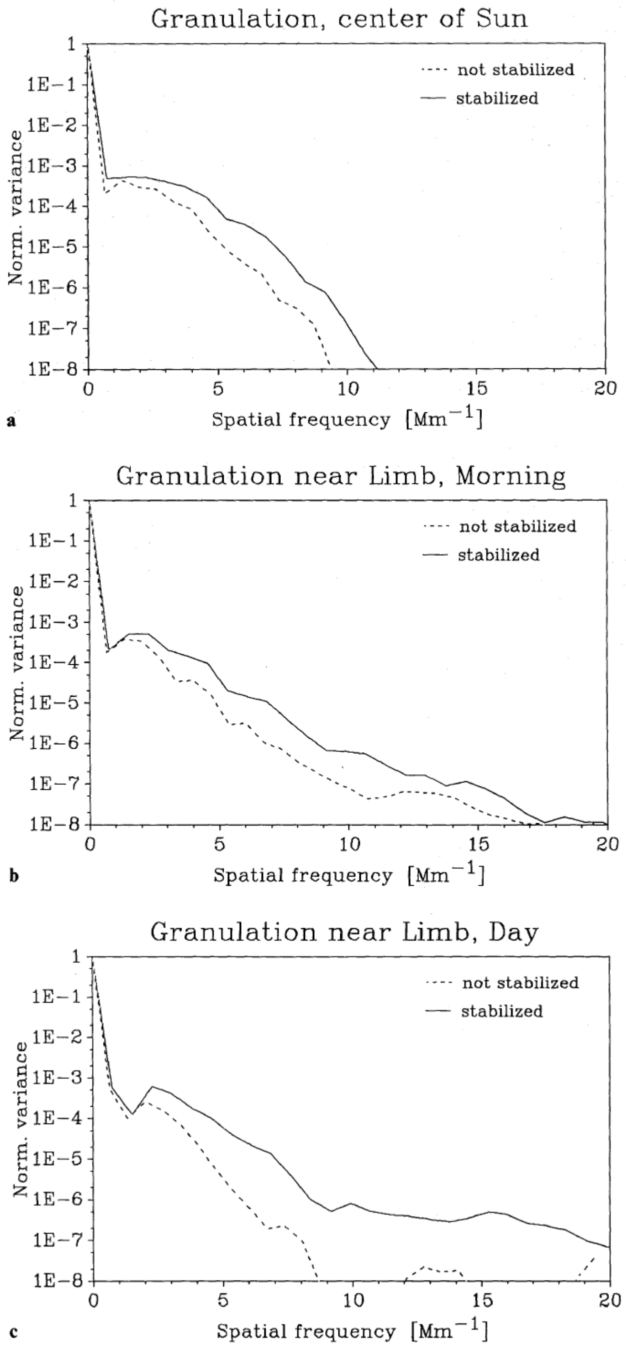


Fig. 8. Empirical models of uncompensated and compensated image motion power spectra. *Solid line:* temporal power transfer function of the tracker system, according to Eq. (9). *Dashed line:* empirical image motion spectrum adopted from von der Lühe (1988). *Dotted line:* resulting residual motion spectrum of the stabilized image



Teamwork

For a few years in the Eighties, Sunspot had a rock band. Standing members were Charlie Miller (gt, voc), Debra Haber (perc, voc), Leonard Sitongia (gt), Domenico Bonaccini (dr), Thomas Rimmele (gt, dr) and myself (bs, voc). We rehearsed in the community center and performed at a few local events.

Competitors

- A solar areal tracker, based on an image difference algorithm (L. Mertz), was developed by Lockheed for a solar space telescope at the same time. The algorithm effectively uses only four points in the correlation function, which was considered unsafe for the ground.
- The mean-square residual function (MSRF) can be shown to be equicalent to the CCR function. Even if limited to a few values covering the minimum, the computing cost is comparable to an FFT based CCR algorithm.
- A solar areal sensor cased on tracking the phase of two Fourier components was proposed for THEMIS, but has to my knowledge never been realized.

Lessons learned and conclusions

- The solar feature correlation tracker was one of many successful joint projects of NSO and KIS. The sensing principle forms the basis of today‘s solar adaptive optics.
- The system which was developed in this collaboration was quickly superseded by newer technology which was easier implemented. A source of delay were the many pitfalls when developing edge-of-the-technology realtime hardware. It is sometimes easier to wait until the general purpose technology is there.
- It needs a rock band to get these kind of things done.