ELBARA, the ETH L-Band Radiometer for Soil-Moisture Research

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***Abstract*— A 1.4 GHz radiometer, ELBARA, was constructed in 2001 at the Institute of Applied Physics, University of Bern, in collaboration with and for studies at ETH in soil-moisture research, especially to infer soil-hydraulic properties from the dynamics of the water content in the top soil. ELBARA is used together with MORA, an older, but equivalent system at 11.4 GHz and with a set of time-domain reflectometer (TDR) sensors. In the normal setup, the radiometers are operated from a tower at incidence angles between nadir and zenith. Here we report on the realization and on features of ELBARA. Results from first measurements in 2002 were presented elsewhere [1].**

Keywords: L-Band Dicke radiometer, calibration, soil, water

I. Radiometer Concept

A. General

ELBARA is a Dicke Radiometer with internal two-point calibration. Photos of the front end are shown in Figure 1, and Figure 6 shows the whole system in the field. The block diagram and the communication between front end and back end are presented in Figures 2 and 3, respectively. Components between antenna and isolator require low loss and low reflection. A large dual-mode horn, originally designed for submm wavelengths [2], with vertical and horizontal polarization (diameter 1.4 m, length 2.7 m, 12° full width at -3dB) was the best solution for the antenna; the beams are axially symmetric (gain 23.5 dB), have high return loss (23 and 28 dB, respectively) and 38 dB isolation between ports. The front end is mounted on the horn feed to minimize losses.

A low-loss GaAs SPDT Dicke Switch and Dicke Load are combined with a high-performance mechanical SP4T Switch for selecting the polarization and for calibration, all stabilized at T=315 K. Measures were taken for protection against man-made interference: Band-pass filters suppress out-of band radiation. Furthermore, two simultaneous channels (1400-1418 MHz, 1409-1427 MHz) are used to identify in-band interference, i.e. to distinguish between white noise and narrow-band disturbances within the protected frequency range. Direct amplification between the filters, square-law detection, DC amplification and AD conversion are done before the signals are registered together with house-keeping information.

B. Analog signals

ELBARA provides 7 analog voltages in the range ±10V for measuring antenna angle, ambient temperature, front-end plate temperature, hot- and cold-load temperature, and the radiometer signals of Channel 1 (1400 to 1418 MHz) and Channel 2 (1409 to 1427 MHz).

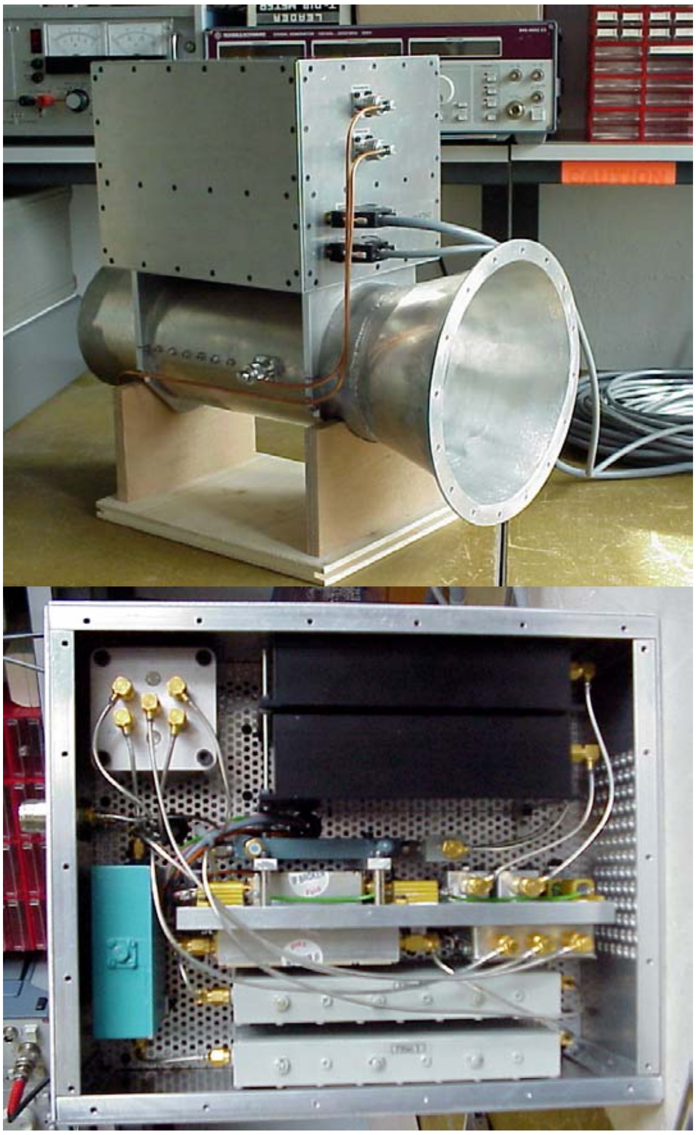

Figure 1. ELBARA front end: top, front end mounted on dual-polarized horn feed; bottom, with cover removed, calibration switch at upper left, isolator lower left, Dicke switch, amplifiers and detectors on temperature-stabilized plate in center, full-band filters below and split-band filters above.

C. Digital signals

Digital signals (+5V CMOS) are used to control the calibration switch, and status signals (SW-STAT-1, -2, -4) describe the switch position and define the operation state. The calibration switch is used to select the input signals of the two radiometer channels. These are: HOT-Load, COLD-Load, AH (Antenna h-pol) and AV (Antenna v-pol).

D. Measuring cycle and operation

A full cycle consists of radiometer measurements at all four switch positions and of the temperatures. At each switch position, measurements are averaged during 12 s. A full cycle lasts for 60 s. ELBARA can either be operated manually, using buttons and displays at the back end (mainly for testing), or with a computer, such as a data logger (data acquisitions). Further details are given in [3].

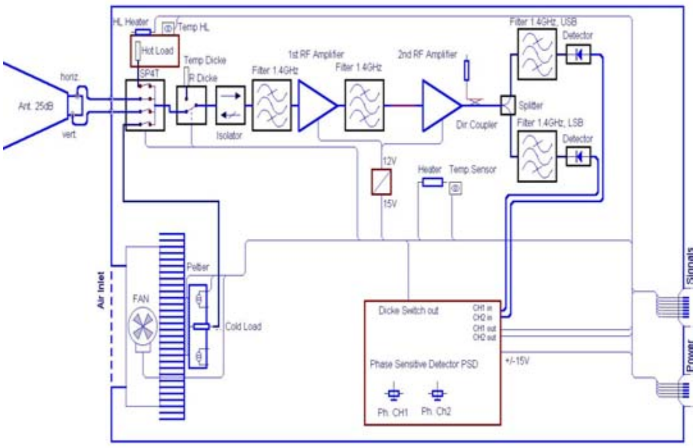

Figure 2. ELBARA, front-end block diagram

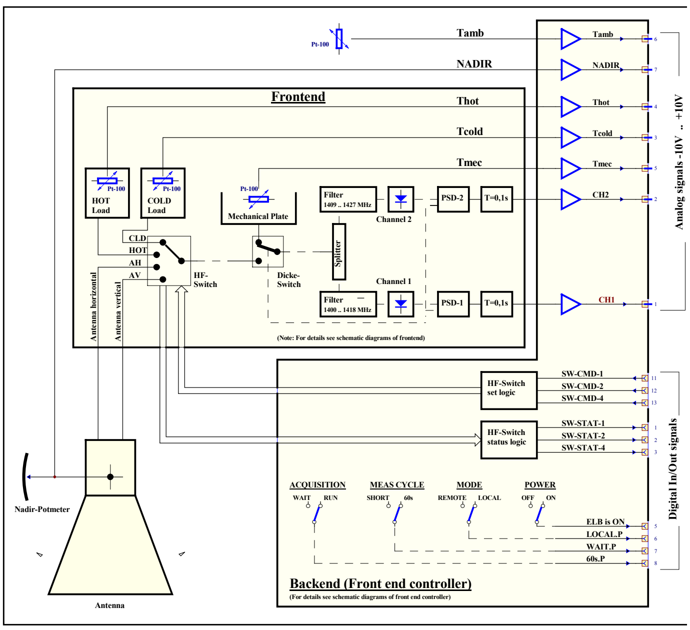

Figure 3. Links between front- and back end.

II. Calibration and Tests

A. The radiometer equation

The antenna temperature T_A of an ideal, internally calibrated Dicke radiometer (linear response, switches without loss, without reflection and without cross talk), is given by

$$T_A = \frac{U_A}{U_H - U_C}(T_H - T_C) + T_D \qquad (1)$$

where T_D=315K, T_C=278K and T_H=338K, are temperatures of the Dicke load, cold and hot load, respectively; U_H and U_C, are the radiometer voltages of the hot and cold load measurements, and U_A is the voltage of the antenna measurement. Each channel and polarisation has a separate equation. Losses, temperature errors of calibration loads, non-ideal switches, and voltage bias lead to modifications of the form

$$T_A = \alpha \frac{U_A - U_C}{U_H - U_C}(T_H - T_C) + T_C + \delta T \qquad (2)$$

where the parameters α and δT take into account the non-ideal properties.

B. Testing the internal calibration

For testing (1) and (2), and the linearity between U_A and T_A, radiators with known brightness T are to be measured. In the data of Figure 4, the antenna was replaced by coaxial loads whose temperature T was varied from –35 to +65C. The loads were connected to the front end by flexible cables of 2 m length. The results show the difference T_A-T for each channel, using (1): The values are small and the linearity is very good. The non-zero slopes are due to cable losses. Correction is achieved by (2) for α values from 1.06 to 1.08, and for $\delta T \cong$ 1K. By replacing the cables by 40 cm semi-rigid cables, α approaches 1, based on measurements at room temperature and at T=77K (liquid nitrogen). Such cables were used in the final setup to connect the horn with the front end (Figure 1).

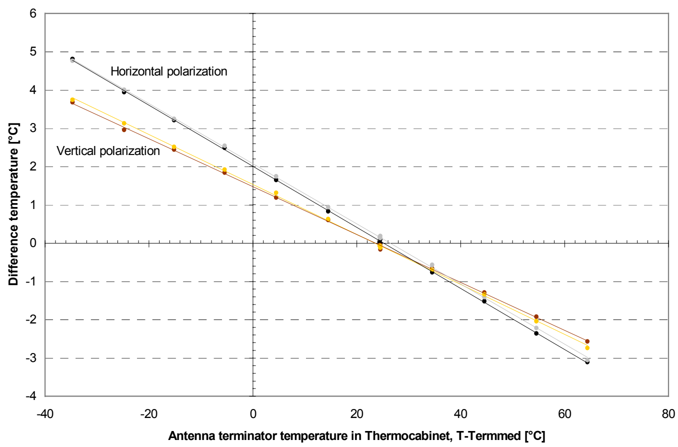

Figure 4. Linearity test: difference between internally calibrated radiation temperature T_A and physical temperature T of coaxial loads versus T from –35 to +65 C, assuming α=0, δT=0K; measurements (points), and linear fits (lines) for Channels 1 and 2, h and v polarization.

C. External calibration

External calibration - including the antenna - is required to test the overall behavior. Difficulties arise because the antenna aperture is large, making the use of artificial black bodies impractical. Natural calibration sources exist for low brightness temperature, such as sky radiation T_S and water surfaces. With α=0, measurements in zenith direction gave a reasonable mean value of $T_S \cong 9$K near the cosmic background of 3K. According to a recent study [4] made for ground-based radiometry at 1.4 GHz, the actual sky temperature is just in between, namely at T_S = 6.6K, especially in directions of the northern sky hemisphere. A further test was made by measurements of a calm water surface (Limmat, Zurich, Nov. 6, 2001) from a bridge. The reflectivity r_i (i=h, v) was computed from the i-polarized antenna temperature T_{Ai}, assuming an antenna with a pencil-beam and T_S = 6.6K

$$r_i = \frac{T - T_{Ai}}{T - T_S}; \quad i = h, v \tag{3}$$

where T is the water temperature. As shown in Figure 5, the comparison between model and measurements is reasonable up to nadir angles θ of 70°. For θ > 70°, the antenna was unable to resolve the strong angular variation of the brightness temperature near the horizon. External calibration of this kind will be repeated to monitor the state of the system.

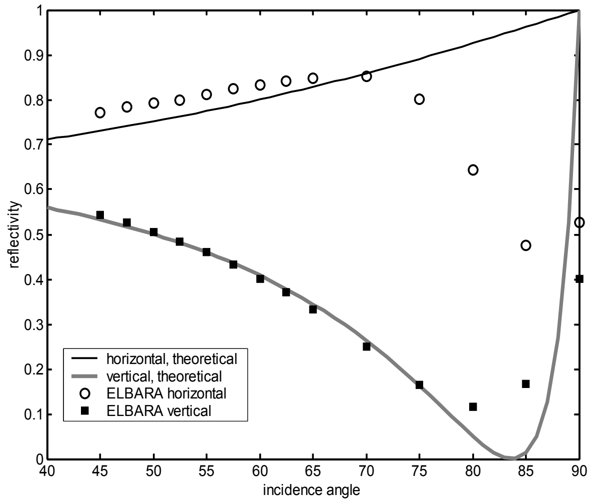

Figure 5. Reflectivity of a calm water surface at 1.4 GHz, h polarization (upper) and v polarization (lower values), versus incidence angle, computed Fresnel reflectivity for water permittivity ε= 81.9+7.8i (curves) and ELBARA measurements (points).

D. Testing the height dependence

Due to partial shadowing of the sky hemisphere by the radiometer setup, the measured radiation is increased. The effect decreases with increasing height and with increasing θ. On the other hand, the height should be small enough to limit the footprint. The dependence was tested with a extendable tower at the bare-soil site. In this way the optimal height was determined to be 4 to 5 m for θ ≥ 40°. The final setup during the field campaign in spring and summer 2002 is shown in Figure 6.

Figure 6. Test site in 2002 with ELBARA (1.4 GHz) on the tower, together with MORA (11.4 GHz) just left of the tower at the horizon level.

III. First Experience

ELBARA was designed as a robust, stable and accurate radiometer for long-time observations under all-weather conditions. After the first year, we got experience from a summer and a winter campaign, studying the emission of bare soil during changing water conditions and including freeze-thaw cycles. Consistent time variations in comparison with MORA and TDR data demonstrate the quality of ELBARA. Man-made interference has not been a problem so far; however, reflected radiation of the sun causes significant enhancements in specular direction due to the high solar brightness temperature at L Band.

Acknowledgment

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References

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