Soil moisture and surface roughness measurements during HAPEX-Sahel 1992

Ground data collection report

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Soil moisture and surface roughness measurements during HAPEX-Sahel 1992 campaign

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1 Introduction

During 1992 a large land surface-atmosphere experiment took place in the Sahelian region of West-Africa in Niger under the name HAPEX-Sahel, which is an acronym for Hydrologic-Atmospheric Pilot EXperiment in the Sahel. The objectives of this experiment are to improve the parameterisation of surface hydrology processes in semi-arid areas within the framework of global climate models and to develop and apply methods for monitoring the surface hydrology at a large scale using remote sensing for climate prediction models.

Similar experiments have been conducted in the past in areas with a different climatological and meteorological circumstances like HAPEX-MOBILHY in France (1986), FIFE in Kansas in the United States (1987 and 1989), Monsoon in Arizona in the United States (1990) and EFEDA in Spain (1991). All these studies permitted the development and verification of various experimental strategies and the construction of comprehensive data bases.

The Sahelian region is chosen as an experimental site for its dynamic energy and water balance which are very sensitive to changes in the environment. The semi-arid climate in this region is characterised by a well marked rainy season in dry year with corresponding differences or better fluctuations in soil moisture and vegetation. In these vulnerable areas global changes like a change in climatic or local changes like a increase in population can be disastrous. Desertification is one of the actual problems in the region and forms a serious threat. The Niamey area in Niger is chosen because it has a good infrastructure, the country is fairly stable in a political sense and the area is representative for the whole region.

The program is a combined effort of scientists of different kind of disciplines like hydrology, meteorology, soil science, vegetation and ecology and remote sensing. In this way it deals in a very general and interdisciplinary way with the (geophysical) problems in this area and in long term may be answer to or an explanation of other problems on a different level related to more sociological sciences. A good example is the shortage of food which is due to the marginal agriculture.

The strategy involved is based on a combination of low intensity long term monitoring of a large surface and intensive short term monitoring during the most dynamic period of the year, rain season and dry down, over a few selected locations. Furthermore a distinction can be made between time and space sampling. The first one consist of certain hydrological and meteorological data collected during 1991 and 1992, for a more detail description see Goutorbe et al., 1992. The latter, space sampling, is related to the different kind of measurements and their spatial coverage. Three spatial scales can be distinguished: 1) measurements in the large domain (100×100 km), e.g. satellite remote sensing, towards cgm models grid level; 2) measurements on a intermediate scale (10x10 km), e.g. aircraft remote sensing and boundary layer measurements, so called supersite level; 3) the "traditional" scale of measurement (200×200 m), e.g. measurements of and around a flux station, this is the so called sub site level. These three types of measurement scales have to be linked, this is called up scaling. With this up scaling we try to give an answer to the question how do processes on the smalle(st)r scale relate to processes on a larger scale and vice versa.

2 Description of the experimental site

2.1 The experimental sites

The up scaling requires different levels of measurement scales (Fig. 2.1). This experiment is set up in such a way that for "each scale" a certain area size is defined and selected. Three major area sizes are defined:

-1) Grid: The grid chosen is the one around Niamey in Niger, the size is a 1 degree box, i.e. about 100×100 km. This is the size on which GCM's and climate prediction models are validated using primarily satellite remote sensing. To verify and to be able to use the remote sensing data measurements have to be done on other scales as well.

-2) Supersite: There are within this grid three supersites of about 15×15 km. At this scale aircraft remote sensing, weather balloons etc. are used to perform the measurements. The three supersites are; Southern Supersite (S) under supervision of mainly English scientist, East-Central Supersite (EC) under supervision of mainly French scientists and the West-Central Supersite (WC) under supervision of scientist of different nationalities among them Dutch, German, Danish and American scientists. A separate site is the Satellite site (SSS) around Danguey Gorou, this site was "abandoned" for safety reasons and replaced by the West-Central Supersite. Eventually there was decided to equip one mast supervised by the Danish team. The function of this site became than an extra 'check' for the up scaling.

-3) Sub sites: within each supersite several (three or four) flux stations are placed at different but representative areas called a sub site. The fetch of the stations is in the order of a few hundred meters. On this scale besides the flux measurements most of the other ground measurements are performed as well.

The measurements discussed in this report are done at the West-Central Supersite and therefore this supersite is described more thoroughly in the next paragraph. For a description of the other supersites is referred to the experimental plan (Goutorbe et al., 1992).

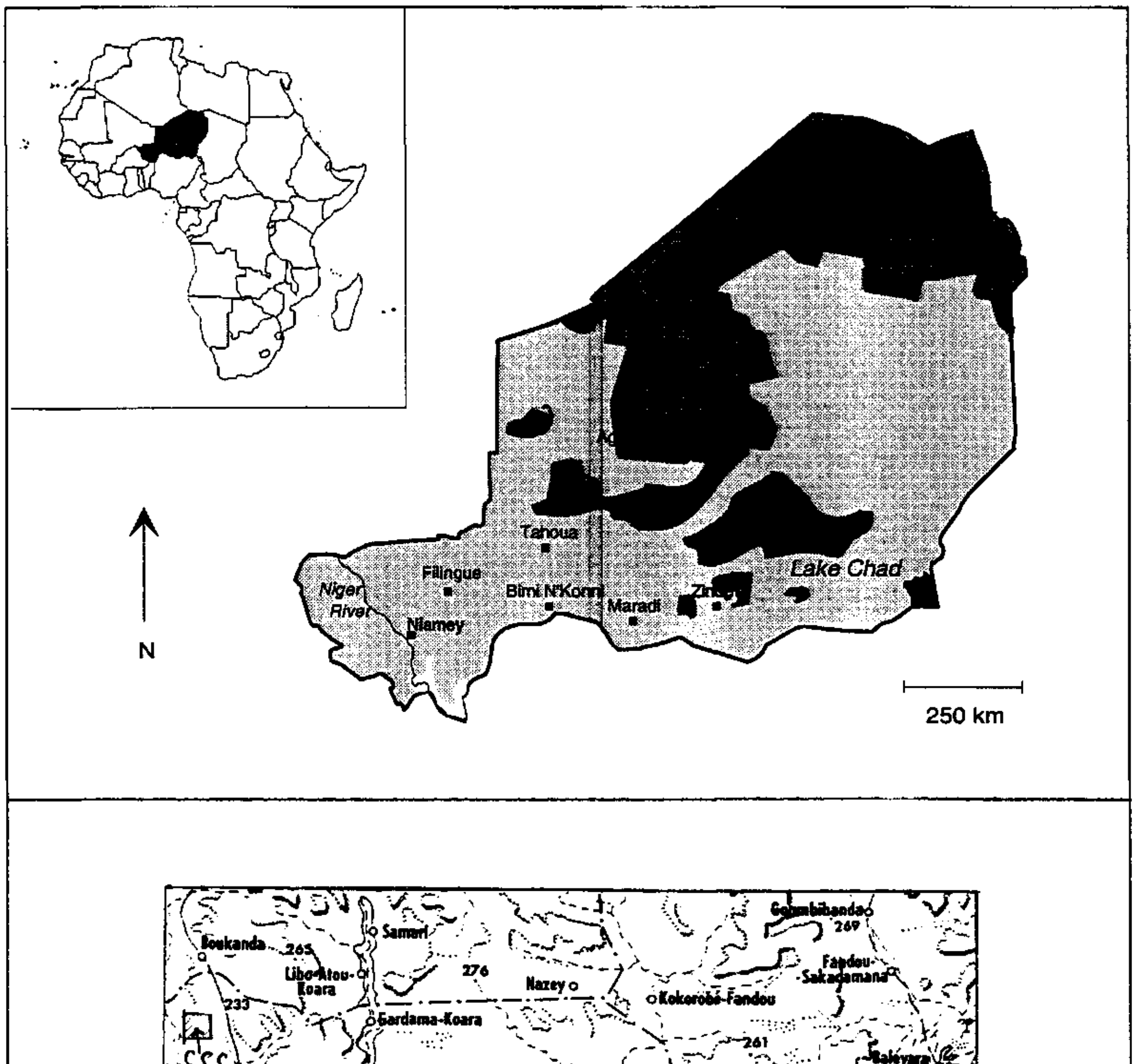

Fig. 2.1: The location of the experiment Niger in Africa, and the locations of the different sites

2.2 Central West Supersite

The Central West Supersite is located about 50 km east from Niamey capital in the western Sahelian zone. The area which is about 15 by 15 km large is centred around a small village called Fandou Beri (13°31' N; 0°33' E). The geomorphology of the area is rather simple and consists of plateaux separated by valleys with dunes over glacis. The higher lying plateaux with a steep escarpment surrounding them and the dune covered glacis are the dominant land forms. The plateaux are covered with tiger bush, so called because seen from above they show a tiger like striped pattern (see Fig 2.2), and the valleys are covered with cultivated fields and bush/grassland fallow (Frederiksen, 1992). The dominant crop grown in the area is millet although other crops like groundnuts for example can also be found. Wind and water erosion are important land degrading processes. Water erosion has locally a very strong impact, wind erosion on the other hand is considered much more severe because it removes or diminishes the (already thin) A-horizon over large areas. The villages in this area are mostly located in the valley bottoms and have in contrast with their surroundings quite some trees around them. The villages are usually connected by unconsolidated roads or tracks. Tarmac (tar) and laterite roads are rare, the road from Niamey to the Supersite is a tarmac road and the road towards Fandou Beri and Dantiandou is a laterite road.

Within this supersite four sub sites are located, each on a typical land cover class:

1) sub site 'a': Fallow bush/grassland on a sandy skirt with a slope of 0.5-2.0 %, for a number of years uncultivated agricultural land to recuperate;
2) sub site 'b': millet on a sandy skirt with a slope of 0.5-2.0 %, an annually grown traditional crop;
3) sub site 'c': tiger bush on the laterite plateau, a flat crusted bare surface interspersed by series of bushes of varying sizes, mainly used for fire and construction wood and grazing;
4) sub site 'd': degraded fallow bush land on shallow sandy soil over shallow laterite.

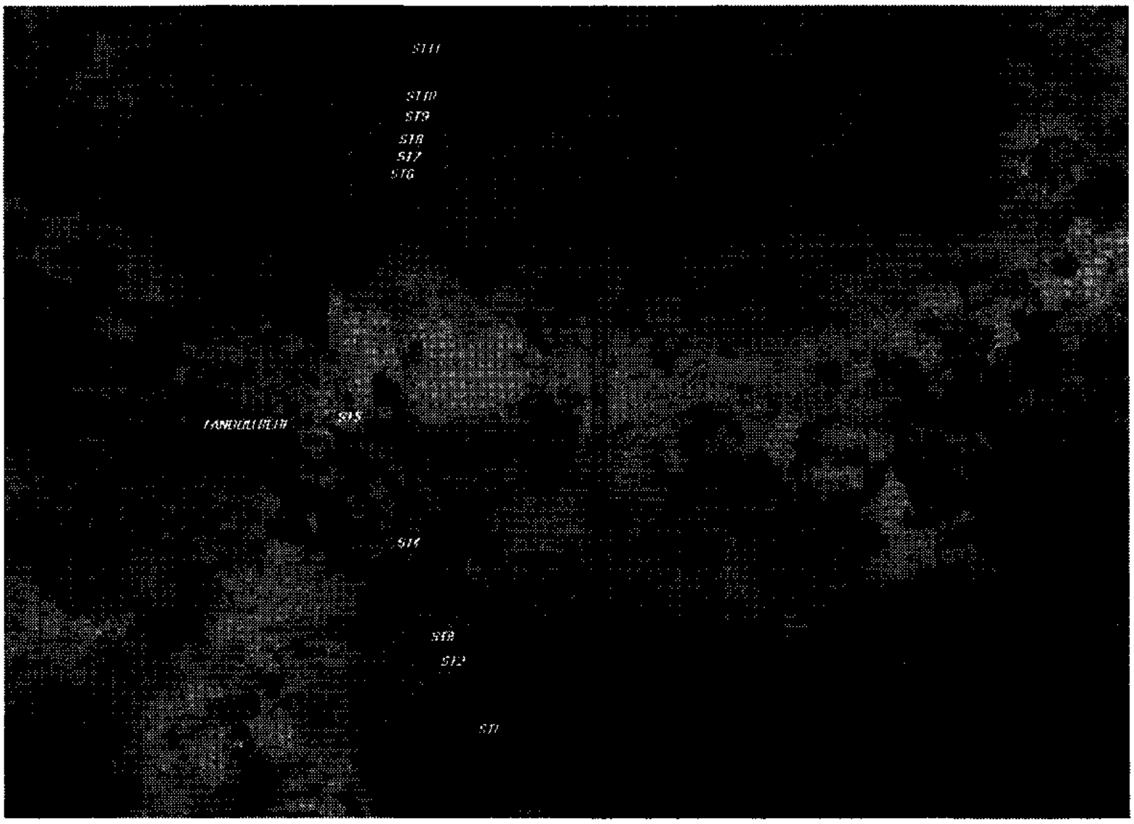

Fig. 2.2: SPOT image[1] *with the location of Fandou Beri, the transect and subtransects within the West Central Supersite.*

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[1] Made available to us by Dr. G.F. Epema, Department of Soil Science and Geology, Wageningen Agricultural University.

The soil moisture measurements were performed along a transect chosen for its diversity and easy access. The transect is about 5 km long and is divided into 11 different measurement areas or subtransects (see also Fig. 2.3) and are referred to as ST1 for subtransect 1 etc.. A description of the subtransects with their total length and number of measurement locations (locs.) per TDR is given below:

ST1 (length ±100 m; 6 locs.): The southern laterite plateau on which also the sub site 'c' is located with the flux station (mast) of the Staring Centre. The tiger bush is the dominant vegetation type on the plateau. The bare laterite (brownish red coloured) soil mixed with laterite nodules ("gravel")becomes very hard, like brick, under the heating of the sun. Only under the bush the soil is softer and stays much longer wet. The soil contains a lot of clay compared to the most other soils found in this area and is mixed with gravel. The plateau is nearly level with a slope of 0-1%.

ST2 (length ±125 m; 6 locs.): Piedmont and escarpment of the southern laterite plateau is characterised by a very hard and rocky soil with scattered shrubs upon it. The surface under influence of intense showers becomes easily eroded resulting in more (laterite or Continental Terminal) rocks than on the plateau. Water erosion produces also the gullies. The escarpment is very steep and sometimes almost vertical. The piedmont is less steep with a slope of 5-8%.

ST3 (length ±250 m; 11 locs.): A millet field just below the piedmont of the southern plateau on glacis. The soil is fine textured, light brownish red to yellow sand. The condition of the crop on this field is very poor, partly due to overland flow gully forming in this field during heavy showers. The field has a 2-5% slope.

ST4 (length ±100 m; 5 locs.): Fallow land on glacis with a yellow sandy soil and covered with a fast growing herbaceous vegetation. Hardly any bushes are present and only some scattered trees are found. This subtransect is probably left fallow for the first year. The site is almost level with a 0-2% slope.

ST5 (length ±200 m; 9 locs.): A millet field near the village of Fandou Beri in an alluvial valley bottom with white fine textured sands . The soil is almost purely quartz and due to the manure coming from the village the millet is growing fairly well.(0-2% slope)

ST6 (length ±250 m; 11 locs.): The degraded bush land situated near sub site 'd' with a mast of the German group of the Free University of Berlin. The soil is yellow and fine textured. The vegetation is nearly exclusively dominated by Guiera Senegalensis. Normally under Guiera Senegalensis there is also a herbaceous layer present but at this site hardly any can be found. Only in the rain season a fast growing very thin layer of one type of herb (not known to the authors) is present. This site is located on partly lowerlying glacis and partly on the lowerlying plateau (subplateau) with a 0-2% slope. Heavy showers have produced numerous gullies that are not very deep.

ST7 (length ±100 m; 5 locs.): Sub plateau with laterite (gravel) surfacing and a 0-2% slope. This lowerlying plateau separates the higher laying glacis from the lower laying glacis and is at this point very small but at other locations can be much larger.

ST8 (length ±250 m; 11 locs.): Degraded bush land is found on the higher lying plateau with a 0-2% slope. This site is comparable to ST6.

ST9 (length ±250 m; 11 locs.): Millet on the higher lying glacis with a 2-5% slope. The soil is yellow fine textured sand. The millet is doing poorly on this site, although there are spots in the field where it grows very well. In general such spots can often be found around trees where cattle, like goats, donkeys, cows etc., is tied down regularly and thus a higher deposition of manure takes place.

ST10 (length ±75 m; 4 locs.): Piedmont of the northern laterite plateau with a 5-8% slope. This site is comparable to the ST2

ST11 (length ±75 m; 6 locs.): Northern laterite plateau looks much like the southern plateau (ST1) is covered with tiger bush and is nearly level with a 0-1% slope.

In Fig. 2.3 a schematic drawing of a crossection of the whole transect is given (Epema and van Oevelen, 1993). The (sub)plateaux as seen in the figure are those we observed in the field. After a more thorough geomorphological study of the area it could turn out that there are more plateaux. These plateaux are probably remnants of old river terraces covered with eolic deposition. This deposition layer is at some places very thin or absent, e.g. subtransect ST7, and thus the laterite surfaces. In the valley bottom a very thick layer of white sands with a high permeability, which act as a drainage canal for the valley (Legger, 1993).

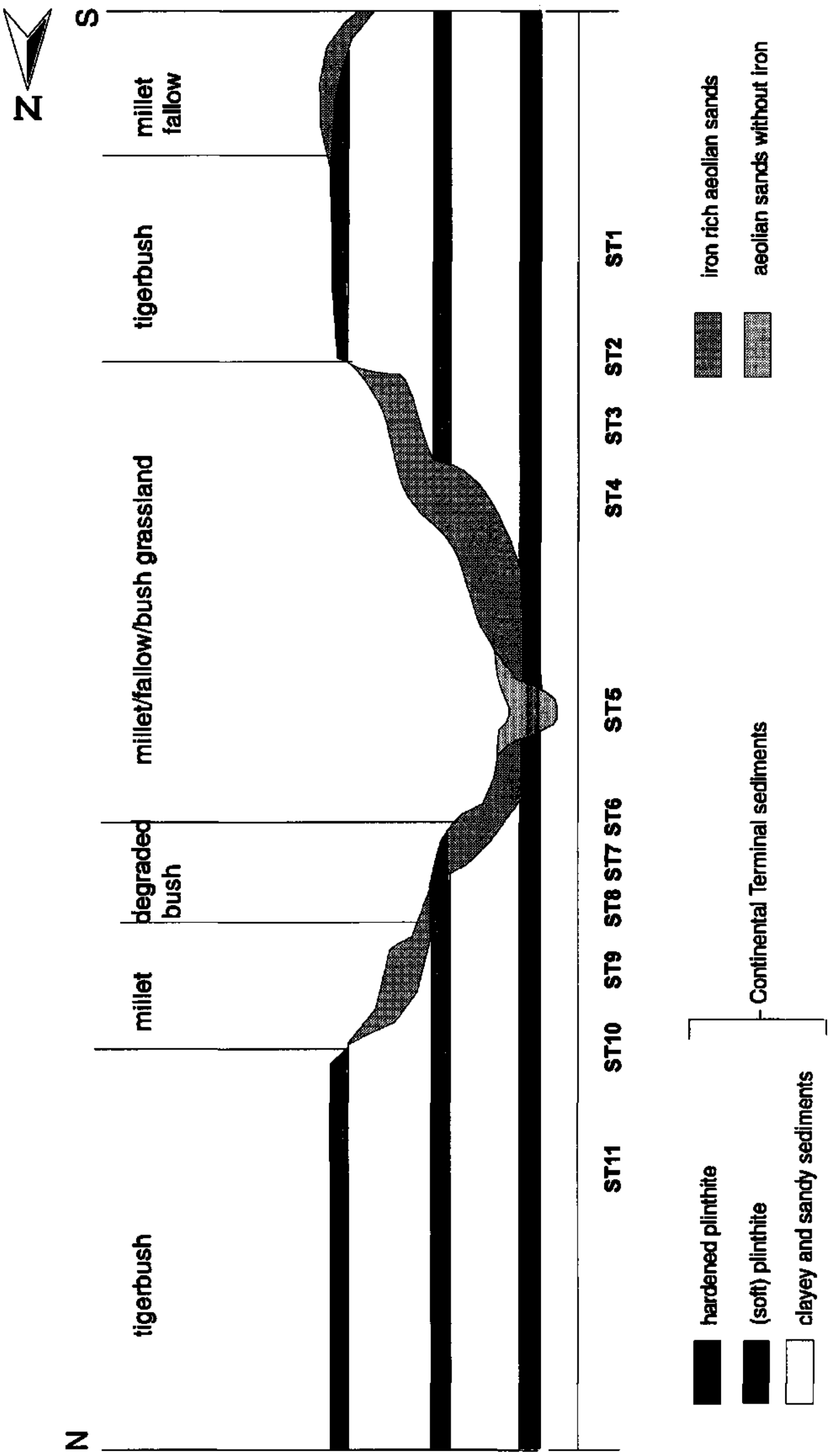


Fig. 2.3: Schematic drawing of a crossection of the area along the transect.

3 Data Analysis

3.1 Soil Surface Roughness

The soil surface roughness, an important quantity in microwave remote sensing modelling, is determined using a needle board (see Fig 3.1). The needle board consists of two aligned areas with different density of needles by which the measurements can be made. Macro roughness can be measured wit low density sampling (1 needle per cm) and micro roughness can be measured with high density sampling (3 needles per cm). Each measurement gives 151 samples in both high and low density, where the high density is measured over 50 cm and the low density over 150 cm (Vissers and Hoekman, 1991). The needle board has to be level placed over the surface, the needles can then be lowered such that the top of the needles just hit the surface and altogether give a profile of the soil surface. Of the whole board a photograph is taken and the profile can then be digitised. In this way two sets of x,y co-ordinates is given for each pair of needles, where 'x' stands for the distance between the needles and 'y' is the height of of the needles.

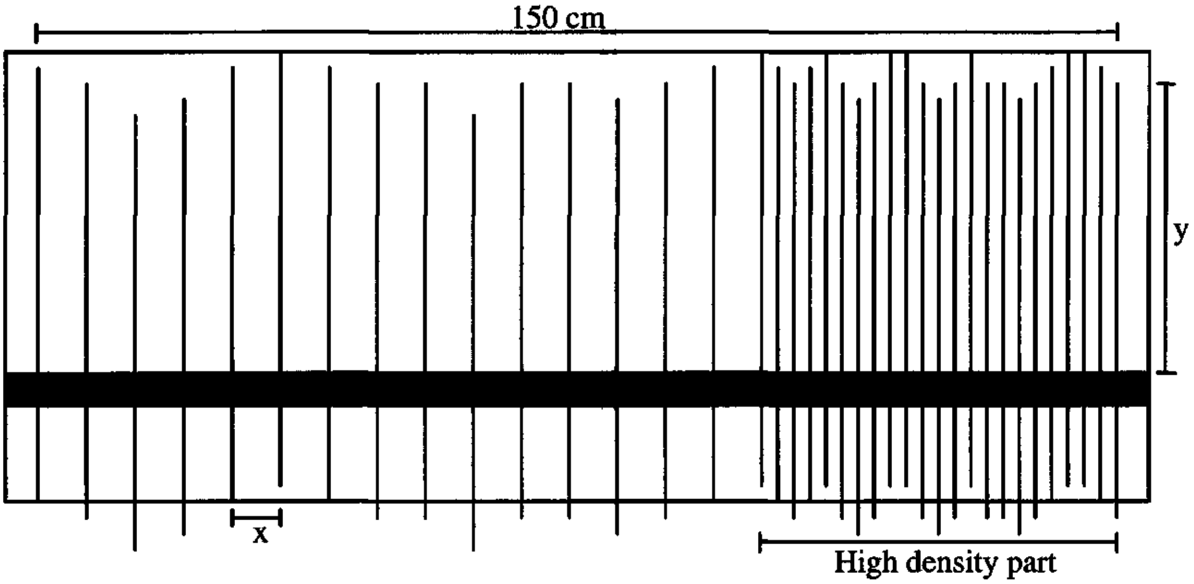


Fig. 3.1: Soil profile meter or "needle board"

Since it became in the field very clear that the surface was everywhere rather smooth and alike, the number of measurements made is limited to those surfaces that were distinct and representative for the area. For each site two pairs of measurements are made, resulting in two measurements directed towards the magnetic north pole (0°, the "y" direction) and two perpendicular to it (90°, the "x" direction). For site 10 only three of the normally four measurements were available, thus one measurement (102) in the 0° direction is missing (Table 3.1). Since we assume that the physical processes that cause surface roughness are uncorrelated for both directions. measurements restricted to these two directions are sufficient.

There are several ways to express the surface roughness. In this report we take the root mean square (RMS) (mm) of the height differences of the needles (Tables 3.1) and the autocorrelationlength (cm) as a measure of surface roughness. With these values he power density spectrum (Table 3.2) using the fast fourier Transform (FFT), and the Autocorrelation function (Table 3.3) using an inverse FFT were calculated using the algorithms from Numerical Recipes (1990).

Estimations of root mean square height or σ can be determined directly from samples of $h(x)$ and $h(y)$, yielding σ_y and σ_x. Likewise estimations of the autocorrelation functions $C(x)$ and $C(y)$, in x- and y-directions respectively, follow. Because of the assumed independence between the two directions $C(r)=C(x)\ C(y)$. The autocorrelation lengths l_x and l_y are defined as the distance at which the normalised autocorrelation functions (for which $C(0)=1$) fall off to a value of 1/e.

The power spectral density function is usually defined as the Fourier transform of the unnormalised autocorrelation function:

$$W(\bar{k})=\frac{\sigma^2}{(2\pi)^2}\int_{-\infty}^{\infty}C(\boldsymbol{r})e^{i\bar{k}\boldsymbol{r}}d\boldsymbol{r},$$

and is also called the surface roughness spectrum. Here $\bar{k}$ is the spatial wave number of the surface (k=2 π/λ), which in this case is related to the electromagnetic wave number k by the expression:

$$\bar{k}=2k\sin\theta_i$$

Also from the power spectral density (PSD) function the autocorrelation lengths l_x and l_y can be derived from the points where the normalised PSD function falls off to the value 1/e as $l_{x,y}=2\pi\ /k_{x,y}$. Using the theorems of Wiener-Khintchine and Parseval it can easily be shown that the total area under the power spectrum gives the variance, or 'power' of the surface:

$$\int_{-\infty}^{\infty}W(\bar{k})d\bar{k}=\sigma^2.$$

The theory of wave scattering from rough surfaces often assumes that surface autocorrelation functions are Gaussian and may be given as:

$$C(\boldsymbol{r})=\exp(-\boldsymbol{r}^2/l^2).$$

Then, the surface roughness spectrum $W(\bar{k})$ follows as:

$$W(\bar{k})=\frac{\sigma^2l^2}{4\pi}\exp(\frac{-\bar{k}^2l^2}{4}),$$

or in the direction of the wave:

$$W(2k\sin\theta_i,0)=\frac{\sigma^2l^2}{4\pi}\exp(-k^2l^2\sin^2\theta_i).$$

Site/	Root Mean Square (RMS)			Average RMS			Autocorrelation
Measurement.	High	Low	Direction	0°	90°	0°+90°	length
31	3.889	6.753	94	6.336	4.102	5.219	8.2197
32	7.093	10.852	4				19.2394
33	1.688	5.713	4				16.2671
34	2.466	3.301	102				20.6854
41	6.149	6.022	92	7.311	7.525	7.418	7.4309
42	4.401	5.343	12				4.2796
43	6.725	11.205	100				7.8461
44	8.726	16.116	10				15.3692
51	1.567	17.483	0	13.812	8.226	11.019	16.2118
52	4.824	14.075	90				6.9926
53	4.711	17.385	0				16.8043
54	0.058	8.206	-2				5.2246
71	2.197	0.247	88	3.463	2.941	3.202	1.6725
72	2.008	1.771	-4				0.7456
73	3.648	6.424	0				11.8685
74	2.954	4.141	92				1.4381
81	2.581	3.512	90	5.524	3.694	4.609	10.1851
82	2.517	7.53	2				5.4552
83	3.082	5.599	88				11.0305
84	3.215	8.834	0				14.8973
101	0.204	3.087	90	10.125	8.469	9.297	13.6802
102	-	-	0				-
103	10.513	18.234	90				10.7912
104	7.551	12.699	0				13.9093
111	4.146	5.424	90	5.626	5.577	5.602	0.8932
112	3.247	5.138	0				3.7229
113	6.171	6.566	90				4.0223
114	4.845	9.274	-4				8.2002

Table 3.1: Root mean square (mm) and autocorrelation length (cm) values of the different measurements

The raw data is stored in several files. The RMS values can be found in "ROUGH.DAT", the autocorrelation length values can be found in"NR.AUT", where NR is the site number e.g. "31.AUT". The original digitising files, the files used to generate all the other files, are named "NR.DIG", e.g. "31.DIG".

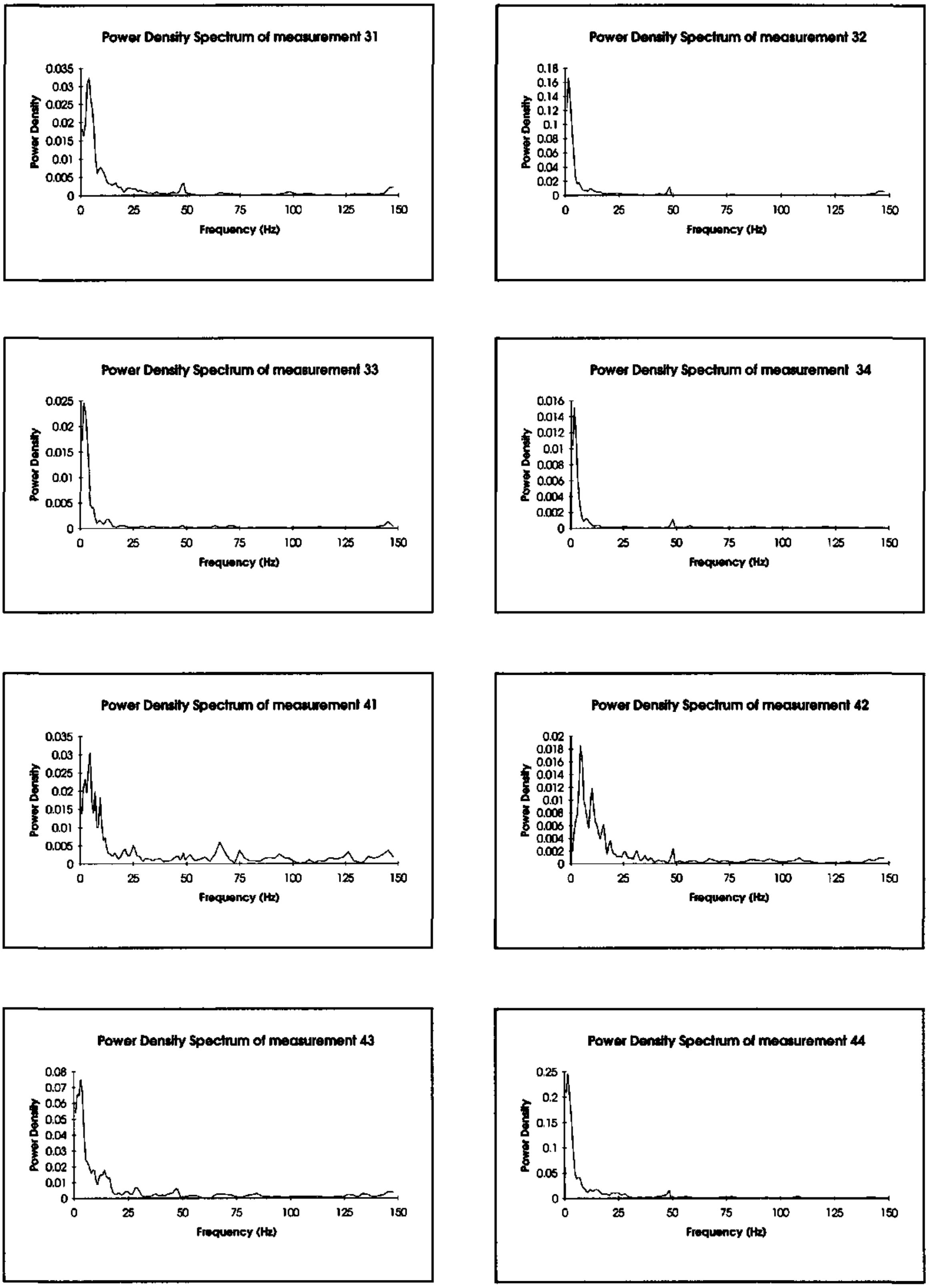


Table 3.2a: Power Density Spectrum of the various subtransects.

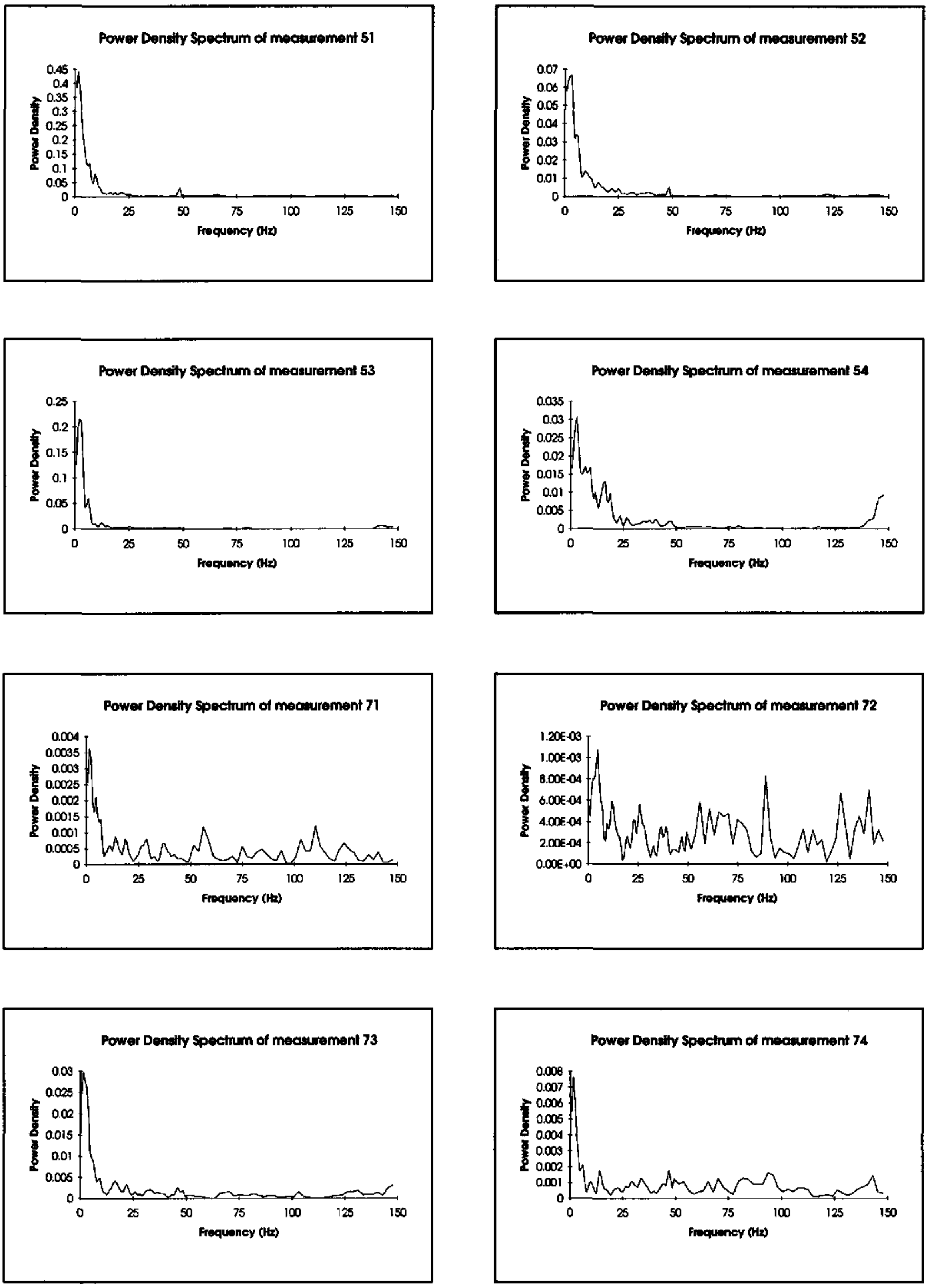
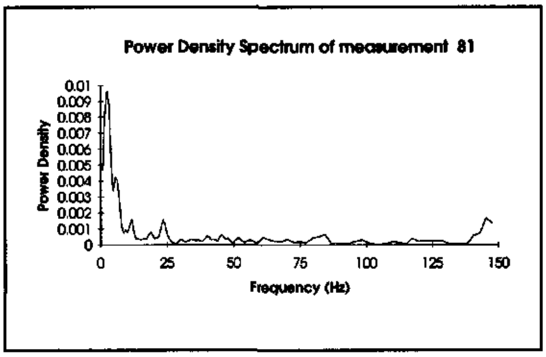
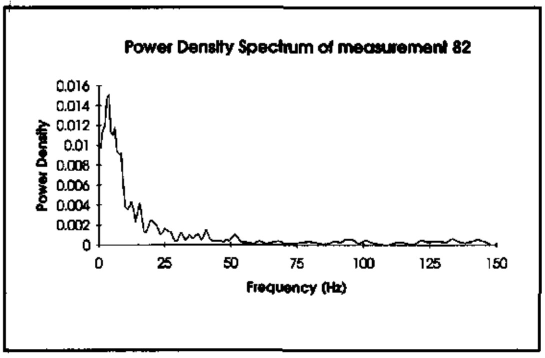
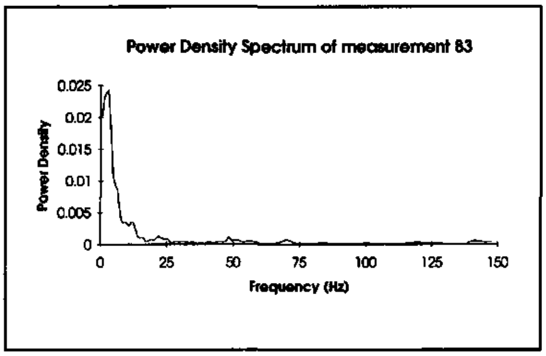
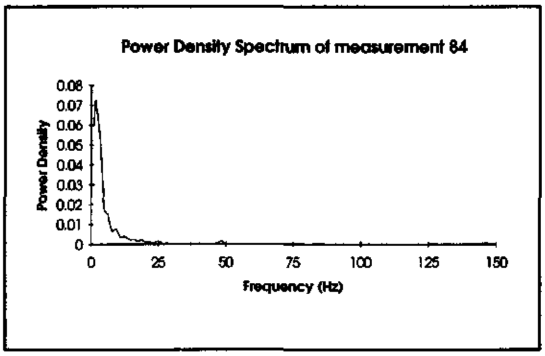


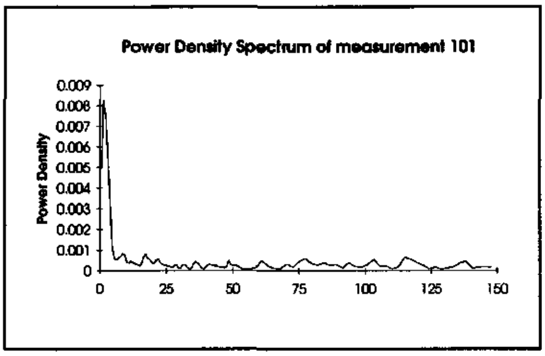
Table 3.2b: Power Density Spectrum of the various subtransects.

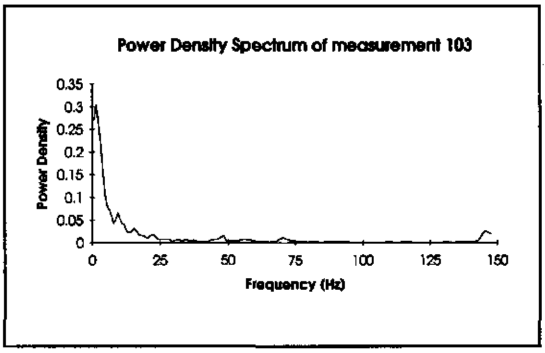

Power Density Spectrum of measurement 81


Power Density Spectrum of measurement 82


Power Density Spectrum of measurement 83


Power Density Spectrum of measurement 84


Power Density Spectrum of measurement 101


Power Density Spectrum of measurement 103

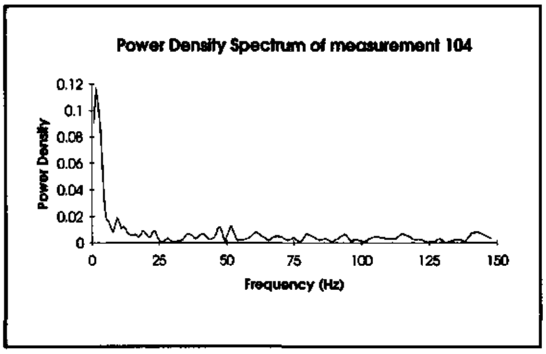

Power Density Spectrum of measurement 104

Table 3.2c: Power Density Spectrum of the various subtransects.

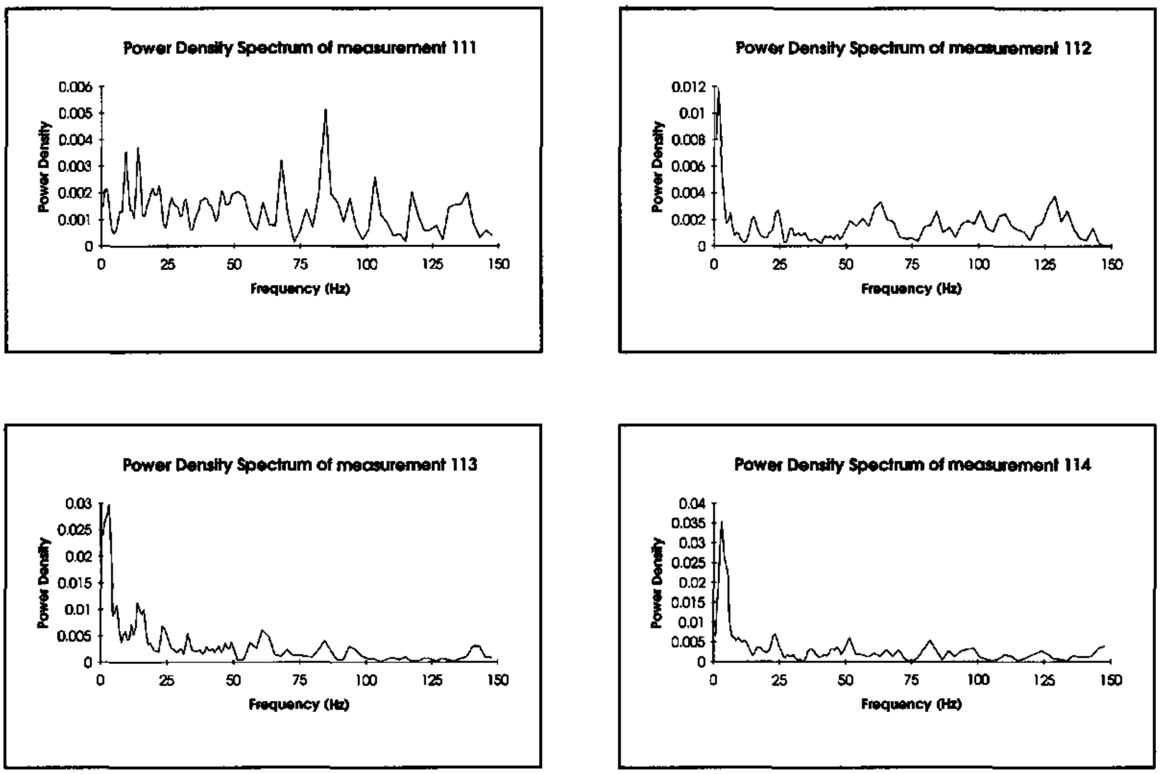


Table 3.2d: Power Density Spectrum of the various subtransects.

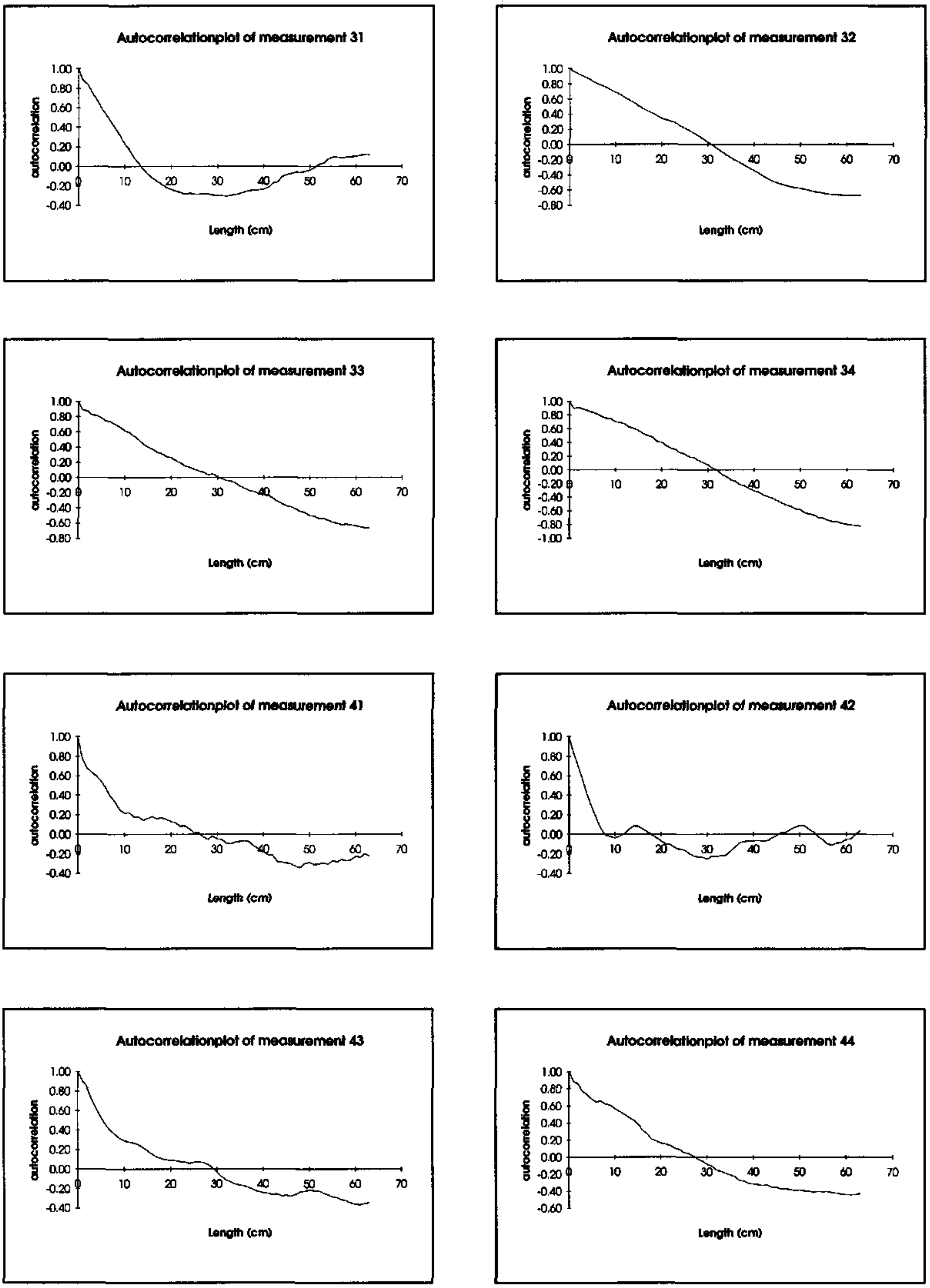


Table 3.3a: Autocorrelation function of the various subtransects.

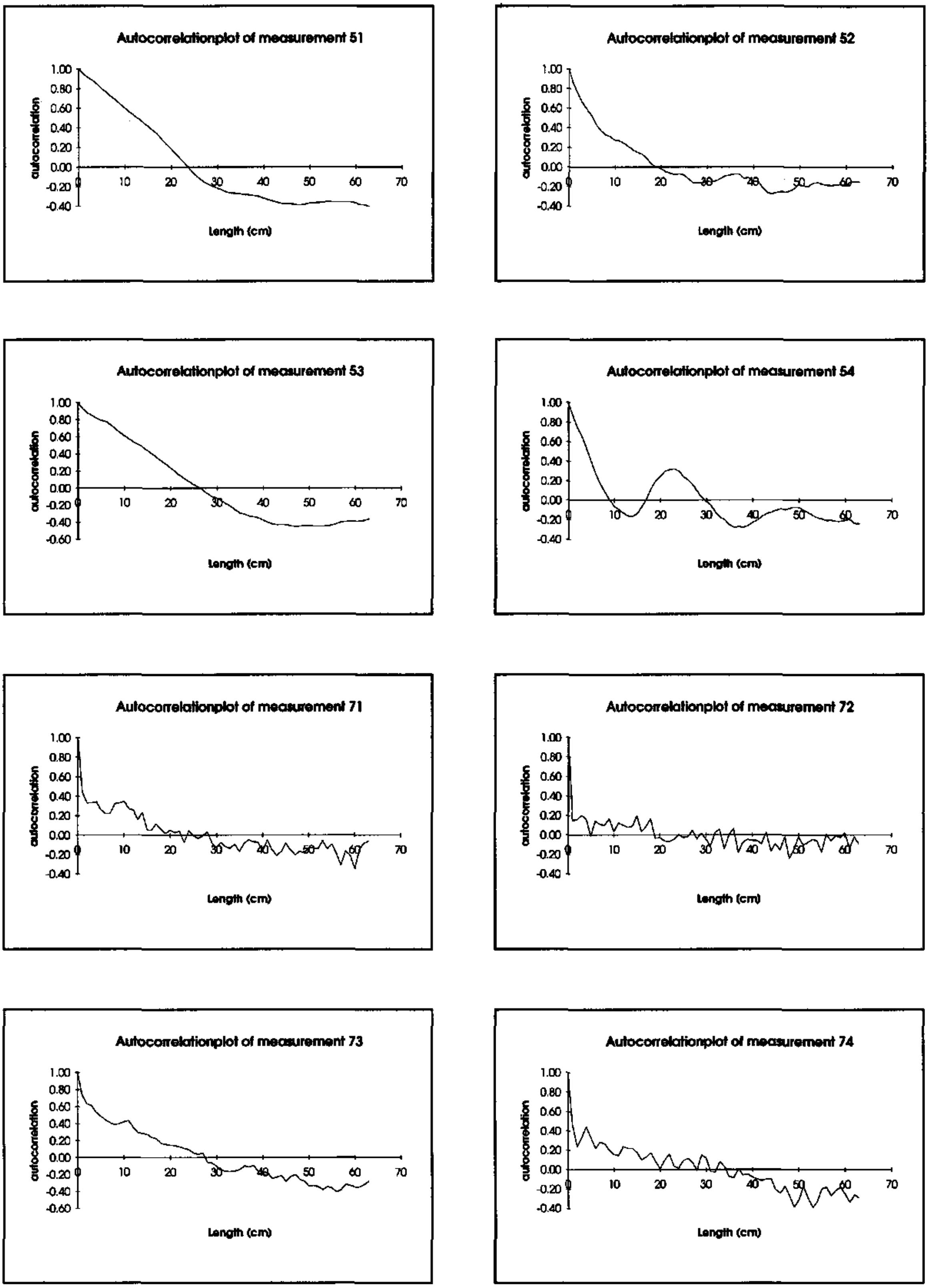


Table 3.3b: Autocorrelation function of the various subtransects.

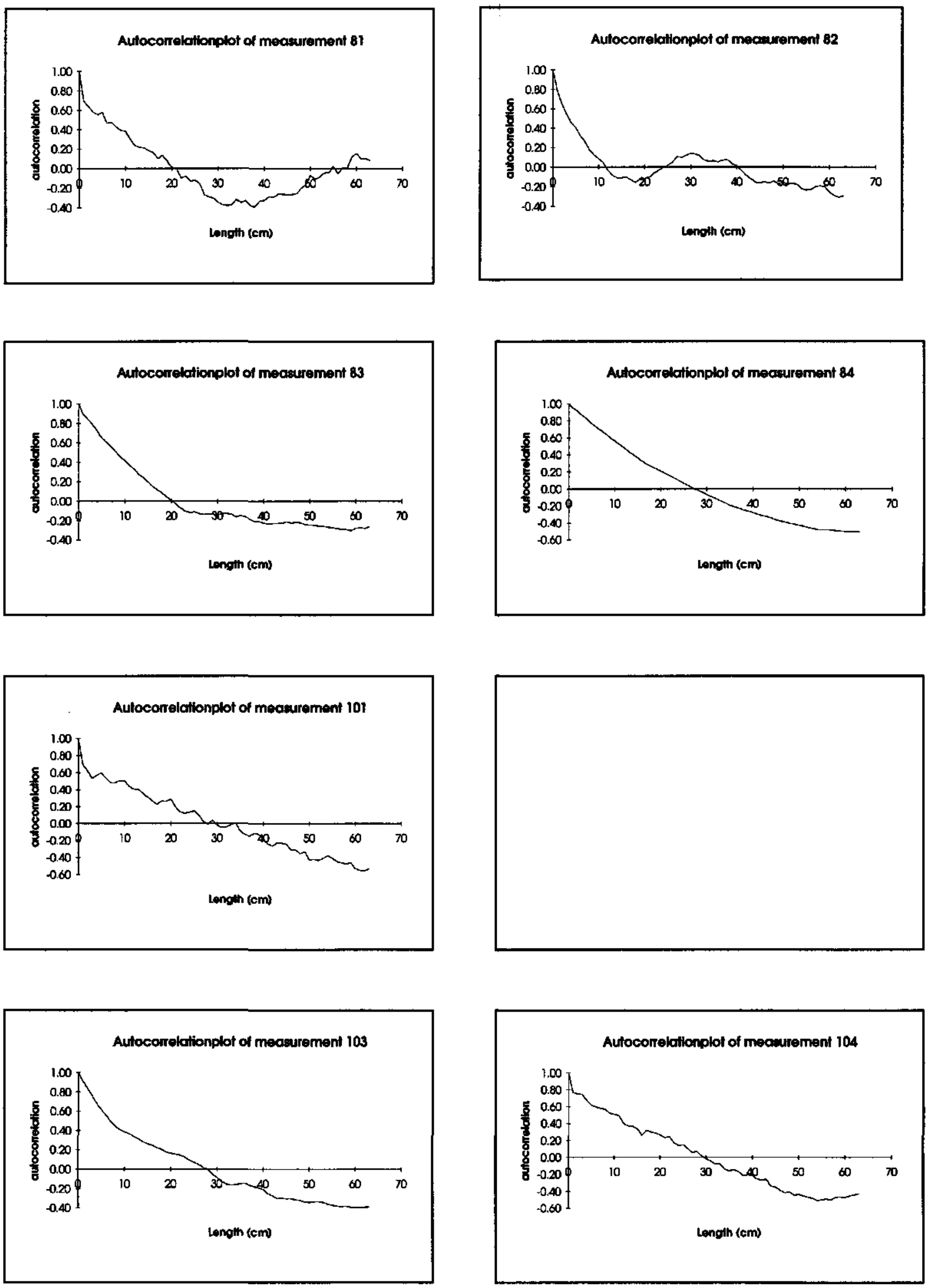


Table 3.3c: Autocorrelation function of the various measurements.

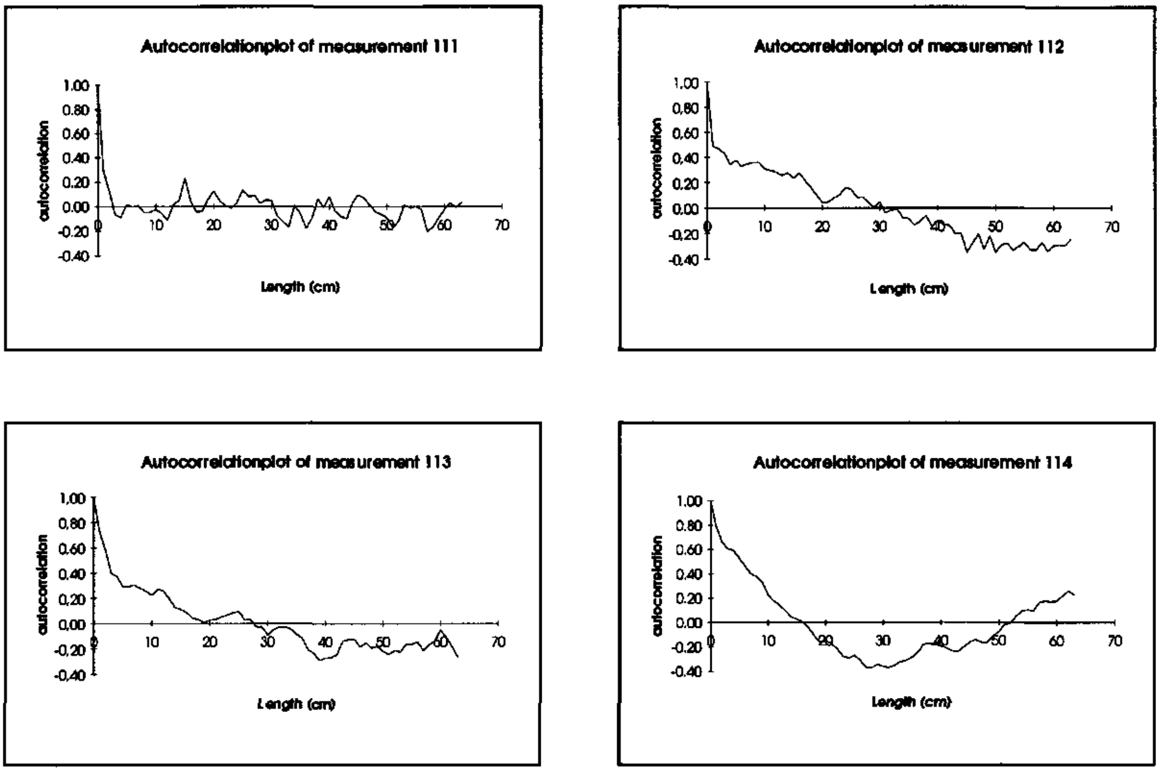


Table 3.3d: Autocorrelation function of the various measurements

3.2 Soil moisture data

The soil moisture data is collected over a depth of 5 cm using a Time Domain Reflectometry (TDR) system. The system used was the TRIME P2 system[1] consisting of a probe with two parallel rods of 10 cm length connected with a coax cable to the main module which has a digital display giving the volumetric soil moisture content. The rods of the probe are fully inserted into the ground under an angle of 45° with ground resulting in a measurement of the average volumetric soil moisture content over a depth of 5 cm. For a detailed discussion about TDR the reader is referred to Heimovaara and Bouten (1990) and Dasberg and Dalton (1985).

The soil moisture data is collected along the transect for 9 of the 11 subtransects during the 6 flights of the Push Broom Microwave Radiometer (PBMR). Two TDR's, referred to their serial numbers 1812 and 1696, were used to perform simultaneously the measurements with about 25 m distance between them. The shortest subtransect was about 50m long and the longest was about 250m long. Each TDR took every 25m a series of measurements within a square meter (called a measurement location) until the readings of the TDR gave two values that were less than 1.5% different from each other (see Fig 3.2). This is done to avoid outsprings due to the large variability of soil moisture; thus using both TDR's an average volumetric soil moisture content value could be obtained. In Tables 3.4, 3.5 the average volumetric soil moisture values for each TDR are given. In Table 3.6 some general statistics concerning these measurements are given.

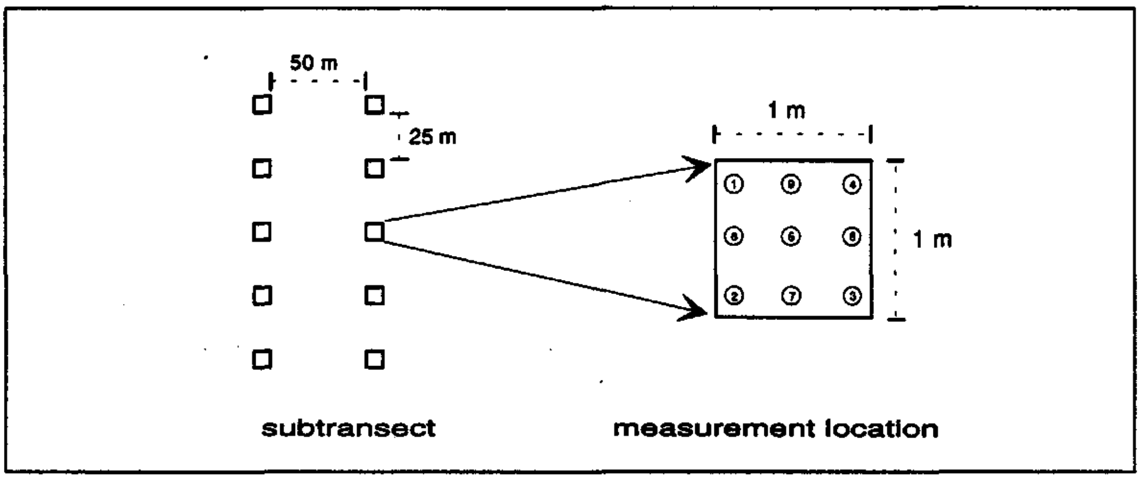


Fig. 3.2: A schematic representation of the measurement set up. The number inside the small circles indicates the measurement rank number.

From these statistics can be seen that there is sometimes a substantial difference between the given soil moisture values of the two TDR's. For the drier periods it became even more than 5% on average. Therefore both TDR's were tested and compared to another calibrated cable tester (Tektronix 1502) and volumetric soil moisture measurements in the soil physics laboratory of the department of Water Resources in Wageningen. From information of the supplier and from the tests performed two major conclusions can be drawn. First of all one of the TDR's is insensitive for low volumetric soil moisture values (< 3%) and secondly the way the probes are inserted into the ground is of major influence on the readings. One or both of these influences would explain the large differences observed in the measurements.

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[1] The name facturer is given for the benefit of the reader and does not imply any endorsement by the Wageningen Agricultural University.

TDR		1812	1696	1812	1696	1812	1696	1812	1696	1812	1696	1812	1696
Date		25/8/92		26/5/92		2/9/92		4/9/92		10/9/92		12/9/92	
Transect	Distance	average volumetric soil moisture content (%)											
ST3	0	15.7	13.1	14.6	14.1	10.7	7.4	9.8	6.3	9.2	6.0	16.1	14.4
	25	12.2	14.0	12.3	11.6	9.2	7.5	9.3	3.9	9.1	6.6	14.3	15.4
	50	14.4	16.1	11.3	12.8	6.4	6.8	9.2	7.1	9.8	8.8	14.7	23.6
	75	13.6	7.4	14.1	14.3	7.7	6.4	5.5	3.0	7.4	5.3	10.2	15.2
	100	14.4	9.7	13.2	7.9	6.3	7.8	5.9	3.4	5.3	4.1	11.5	7.8
	125	13.5	12.8	13.8	5.8	9.7	6.3	6.3	2.4	8.3	3.4	10.8	11.2
	150	12.7	6.4	13.2	7.2	7.2	5.9	7.8	2.0	6.2	5.6	12.8	15.0
	175	18.1	14.5	13.2	15.4	9.6	6.1	8.0	5.4	10.3	5.5	12.9	16.3
	200	15.3	15.7	13.9	9.1	9.1	6.8	5.9	6.0	9.7	4.2	13.7	14.1
	225	10.0	8.8	15.5	7.7	9.8	7.1	9.3	2.9	10.0	5.9	12.0	8.6
	250	13.1	7.7	15.1	8.3	9.9	6.7	8.7	0.3	9.5	4.8	15.2	7.8
st4	0	10.8	12.0	13.8	10.1	9.3	7.4	6.0	2.9	8.6	3.1	10.6	6.0
	25	16.5	14.1	14.4	13.6	10.9	7.0	9.4	3.5	7.3	3.1	11.6	6.5
	50	14.8	14.8	15.3	12.9	9.6	6.2	7.7	5.0	9.9	2.9	13.3	7.8
	75	14.2	14.7	15.4	8.1	9.7	5.7	8.5	5.6	9.6	4.7	13.4	7.8
	100	16.3	13.4	13.8	8.1	7.2	4.8	1.6	2.5	7.2	1.9	11.7	5.6
ST5	0	11.3	7.7	11.1	8.5	7.5	4.4	2.0	3.8	8.8	5.1	9.7	6.4
	25	11.6	10.7	10.7	10.1	8.8	4.8	5.7	5.2	9.7	6.1	10.8	6.7
	50	12.1	8.5	12.2	9.9	8.4	7.3	7.0	3.7	9.6	2.9	11.5	8.0
	75	12.4	14.6	13.4	10.2	9.6	6.5	6.8	1.9	9.8	4.1	10.0	7.7
	100	10.8	7.0	12.5	7.0	9.3	6.6	7.3	1.9	9.8	1.5	9.5	8.0
	125	14.2	9.4	12.1	7.9	9.3	6.5	7.8	1.4	9.7	5.6	11.7	7.1
	150	14.1	15.9	12.2	15.9	10.0	8.2	9.9	0.9	11.1	5.7	12.6	8.1
	175	13.8	13.4	14.0	15.3	9.8	5.7	6.6	5.7	12.6	5.7	11.5	7.9
	200	13.8	7.9	10.9	11.5	13.7	8.1	2.8	3.2	10.0	5.8	11.5	8.5
ST6	0	16.0	16.2	16.3	20.4	13.9	16.3	9.3	5.6	9.9	4.5	11.7	8.9
	25	16.7	22.2	18.9	24.1	14.6	20.6	15.3	7.3	6.5	7.8	16.1	15.9
	50	15.5	20.0	17.1	14.7	15.1	21.7	16.1	0.6	10.7	15.7	16.0	13.8
	75	15.7	15.9	17.3	16.5	10.8	7.9	10.6	5.7	9.6	4.4	12.1	14.7
	100	14.7	13.0	16.6	14.7	9.8	7.6	8.9	7.9	6.1	8.3	12.9	11.1
	125	13.3	19.3	15.2	17.0	12.2	7.0	8.8	6.7	9.7	6.4	14.4	12.7
	150	16.6	15.5	15.8	17.8	13.0	15.2	9.9	3.0	9.6	7.4	11.7	8.5
	175	15.3	14.8	15.7	16.9	9.7	7.3	9.3	5.6	8.4	8.0	14.6	9.0
	200	14.2	13.3	14.6	13.2	11.7	6.1	10.0	5.6	7.4	5.1	12.1	8.6
	225	11.7	12.3	13.2	14.9	11.7	7.9	10.1	5.6	6.6	2.7	11.4	6.4
	250	13.5	12.8	12.5	14.5	11.0	6.2	10.1	5.8	9.3	7.2	14.4	7.9
ST7	0	9.6	13.5	14.7	19.8		6.2						
	25	14.3	12.4	9.9	15.1		7.4						
	50	13.2	12.9	16.7	18.1		8.8						
	75	11.2	13.1	10.7	16.5		4.3						
	100	15.8	14.1	18.2	14.9		5.5						

Table 3.4: Volumetric soil moisture values for transects 2 until 7, the values in the column distance represent the distance in meters from the beginning of the subtransect.

Range		1812	1696	1812	1696	1812	1696	1812	1696	1812	1696	1812	1696
Date		25/8/92		26/5/92		2/9/92		4/9/92		10/9/92		12/9/92	
Transect	Distance	average volumetric moisture content (%)											
ST8	0	15.7	11.5	18.7	20.3	11.7	8.2	10.2	3.2	6.0	3.9	12.5	11.4
	25	15.6	14.2	17.1	15.9	13.3	14.7	5.7	7.1	9.9	3.1	13.4	4.9
	50	16.9	16.1	12.5	17.6	9.9	15.9	8.5	5.6	9.1	4.3	10.2	8.3
	75	15.6	19.8	17.9	16.0	11.0	14.6	11.8	7.4	9.1	9.2	13.0	13.7
	100	14.2	15.5	17.9	18.6	12.4	14.7	9.8	1.9	9.7	3.2	11.1	5.5
	125	13.5	13.6	17.3	17.5	12.7	9.4	14.1	3.9	9.1	0.9	12.9	7.3
	150	12.9	14.6	17.4	13.8	10.3	7.9	10.5	5.5	6.1	6.5	11.3	8.7
	175	16.7	15.2	16.7	17.0	9.3	15.7	10.0	6.0	9.9	5.6	12.1	13.0
	200	14.7	6.8	18.0	18.5	13.3	7.3	11.4	6.4	9.8	5.8	9.9	16.0
	225	16.0	13.8	15.4	16.1	12.1	9.0	12.2	6.1	6.9	7.3	12.3	7.7
	250	13.7	14.4	17.2	17.6	12.8	12.9	15.3	6.2	9.9	6.2	11.5	14.4
ST9	0	12.1	14.5	14.9	8.0	14.6	4.7	11.3	5.4	9.2	6.4	11.7	10.2
	25	12.1	14.5	11.7	8.3	11.7	6.1	9.7	8.0	9.3	5.9	10.5	8.0
	50	11.3	7.8	11.6	8.9	10.0	5.4	10.4	8.5	9.8	6.4	11.0	7.2
	75	11.0	8.0	14.1	11.1	9.5	5.5	10.2	7.8	9.5	7.9	11.5	7.8
	100	11.7	7.9	13.7	10.1	9.4	5.5	10.5	5.3	9.0	6.4	11.1	7.4
	125	11.7	7.1	10.8	12.2	9.7	2.6	10.0	7.7	10.2	5.6	13.3	6.8
	150	12.0	7.4	14.1	7.9	10.7	4.4	10.1	5.6	7.0	6.3	13.7	7.6
	175	12.1	12.8	14.1	15.2	10.5	5.8	8.5	7.0	10.3	7.1	10.1	8.6
	200	15.7	15.9	16.1	14.7	10.1	4.9	11.5	7.9	10.4	6.4	12.1	7.8
	225	15.1	14.7	15.1	14.2	14.0	7.4	11.2	6.4	9.5	6.9	12.9	9.8
	250	11.2	11.6	14.8	8.4	11.7	6.2	9.3	8.3	9.1	6.4	12.3	5.2
ST10	1	15.6	16.8	16.0	15.1	12.9	7.6	12.4	5.8			12.2	8.2
	2	16.0	9.6	16.6	16.3	12.4	8.0	12.8	6.9			12.9	9.7
	3	15.7	16.6	13.3	19.7	10.4	6.7	0.0	9.7			12.0	10.4
	4	15.0	11.7	9.7									7.8
ST11	Bush 1	24.0	24.9	20.9	28.8	19.9		21.7	18.9	13.6	22.7	17.2	6.9
	2	26.7	25.7	23.5	26.1	17.3		17.2	10.5	11.7	9.7	17.6	29.0
	3	25.5	25.9	21.4	26.5	22.5		17.9	16.8	15.9	19.7	18.2	6.2
	Bare 1	15.1	14.9										
	2	17.8	15.8										
	3	17.1	17.9										

Table 3.5: *Volumetric soil moisture values for transects 8 until 11 , the values in the column distance represent the distance in meters from the beginning of the subtransect.*[2]

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[2] For ST10 four measurements were done with varying distance (10-25m) instead of 25m. For ST11 bare soil and bush the three measurements were done in randomly selected locations in a area of roughly 50×50 meters.

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12
Mean	14.2993	13.5349	14.7507	14.092	11.0477	8.03333	9.47109	5.53594	9.19836	6.14508	12.507	9.89769
Standard Error	0.40323	0.49837	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Median	14.2	13.75	14.575	14.7	10.325	6.975	9.525	5.6	9.55	5.75	12.075	8.15
Mode	14.2	12.8	14.1	10.1	9.65	7.4	9.25	5.6	9.7	6.4	12.9	7.8
Standard Deviation	3.44523	4.2581	2.7292	4.92653	2.83181	3.82643	3.67762	3.16603	1.79796	3.6046	1.91941	4.29085
Variance	11.8696	18.1314	7.44851	24.2707	8.01916	14.6416	13.5249	10.0238	3.23266	12.9931	3.68412	18.4114
Kurtosis	6.75645	1.10534	0.71936	0.54386	4.28093	3.33766	2.01426	5.98337	2.8127	9.94051	0.95626	5.98395
Skewness	0.32868	0.64461	0.58661	0.62292	1.5721	1.89937	0.42644	1.71657	0.55889	2.71912	1.01538	2.08529
Range	26.6488	19.5	13.8	23	16.2	19.05	21.65	18.65	10.6	21.85	8.7	24.1
Minimum	9.6	6.4	9.7	5.8	6.25	2.6	0	0.25	5.3	0.85	9.5	4.9
Maximum	26.65	25.9	23.5	28.8	22.45	21.65	21.65	18.9	15.9	22.7	18.2	29
Sum	1043.85	988.05	1032.55	972.35	707.05	530.2	606.15	354.3	561.1	374.85	800.45	643.35
Count	73	73	70	69	64	66	64	64	61	61	64	65

Table 3.6: General statistics of the volumetric soil moisture data given in Tables 3.4 and 3.5, the columns in this table correspond to those in Tables 3.4 and 3.5.

Because the PBMR did not cover the whole area there is no data collected for subtransects ST1 and ST2. The other data that is missing in Tables 3.4 and 3.5 are due to the impossibility to insert the probes of the TDR's into the soil at that time. The subtransects where laterite surfaced, especially ST7 and ST11bare, became under exposure of the sun has hard as rock and could not be penetrated without the danger of breaking or damaging the rods.

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