4. DATA ACQUISITION

4.1. Image acquisition

The images of the pivots were acquired by means of airborne remote sensing. The flights were conducted with a Jabiru micro-light aeroplane operating from the Witbank airport. For the imaging itself, the STS-DMSV sensor was utilized. A brief description of the platform and the sensor is provided below.

4.1.1. The airborne platform

The Australian-built, fixed-wing, Jabiru aircraft (See Fig. 2.) was used as the airborne platform. The Jabiru, because of its reduced size and 235 kg total mass, is classed as a micro-light aeroplane but looks and performs like a proper aircraft. It is manufactured using Fibre Reinforced Plastic (FRP) technologies and is powered by a Jabiru 4 cylinder, 4-stroke, 2200 cc, air-cooled engine.

Table 1: Characteristics of the Jabiru Engine

Displacement	2210 cc
Bore	97.5 mm
Stroke	74 mm
Compression Ratio	8.3:1
DC Output	10 Amps - single phase
Power Rating	60 kW (80 hp) @ 3300 rpm
Fuel Consumption	Cruise power 0.46 lbs per horsepower hour (274 grams/kW-hour at cruise power.)

Unlike a conventional micro-light, the Jabiru is a practical commuter and can carry up to 215 kg. It needs about 100 metres of runway to get off the ground and 160 metres to land, depending upon the load. The plane's ceiling is 4500 metres above sea level (a.s.l.) and its rate of climb 300 metres per minute (at sea level). Stall speed is a low 33-38 knots (about 60 km h^{-1}).

Fig. 2: The Jabiru micro-light aircraft

4.1.2. The Digital Multi-Spectral Video System (STS-DMSV)

The SpecTerra Systems, Digital Multi-Spectral Video system (STS-DMSV) is a four CCD[4], compact and lightweight, video imaging system, designed primarily for the acquisition of high-resolution digital multi-spectral[5] imagery of terrain, vegetation, water bodies and coastal environments.

Its spectral resolution enables four selectable bands to be acquired simultaneously in the visible to near-infrared region (0.4 - 1.0 μm). Spatial resolution is in the range of 0.5 to 4.0 metres per pixel, depending upon the height above mean terrain level at which the airplane is flying. For most applications, the recommended pixel size is in the range of 1.5 to 3 metres.

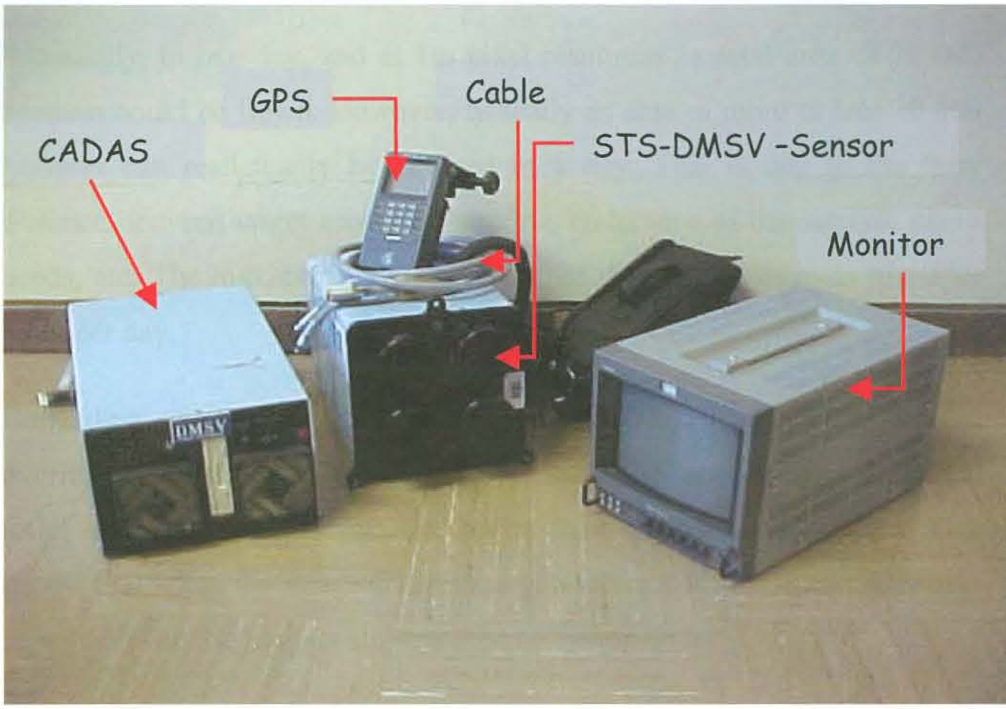
The system uses band-pass filters, typically with bandwidths from 0.1 – 0.8 μm. These may be selected based on individual application specifications.

The STS-DMSV collects GPS[6] information in the image file header. This is navigational GPS information and is not intended for precise registration of imagery. Mostly it is used for instrument triggering data and for approximate locations during image registration.

---

[4] **CCD:** Charged Couple Device, a silicon chip at the heart of every digital camera that takes the place of photographic film.
[5] **Multi-spectral**: The capacity of an optical instrument of subdividing spectral ranges of radiation into bands (intervals of continuous wavelengths), allowing sensors in several bands to form multispectral images.
[6] **GPS**: Ground Positioning system

Fig. 3: The Digital Multi-Spectral Video System



The STS-DMSV has a CCD array of 578 by 740, which represents the size, in pixels, of the image that can be collected.

The basic pre-processing includes standard radiometric and geometric corrections, taking into account systematic distortions due to system effects, such as interlacing[7] and band alignment.

The system can be operated under a wide range of conditions of illumination as the aperture, and therefore the sensitivity of the video cameras, can be adjusted in parallel for the target area. This method of adjustment allows one to retain the inter-band radiometric sensitivity relationships. An operator will adjust the aperture setting for the line or for the whole area by taking a sample frame over the target area and analysing the histograms representing this distribution of the incoming radiation over a 1 to 255 range for the four bands. By changing the aperture and re-

---

[7] **Interlace:** In video system a picture is "written" on the display device in two halves. Interlace is the process of placing lines of the second half of the picture in-between lines of the first half.

analysing the histograms, he can find the best aperture setting for the target area.

Potentially, in one day, and at 1m pixel resolution, a total area of 20 000 hectares could be flown. However, typically an area of more or less 10 000 hectares can realistically be covered in a day. This is due to the ferry distance between target areas and airports, endurance of the aircraft, client needs, etc. The maximum number of frames that can be taken is just over 1000 per day.

Depending on the topography, the target area is covered by a forward overlap of 60% and a side overlap of 30-35%. The imaging of even limited relief areas will produce smaller pixels than the surrounding ones. This means that when the image frames are geo-referenced, the ones taken over areas with varying heights are stretched to the topography.

The STS-DMSV technical features are listed here:

- Four CCIR[8] format high sensitivity CCD video cameras, recording 578 lines of 740 pixels per line;
- Rigid mounting framework, enabling precise alignment and locking of the positions of the four video cameras;
- Narrow band-pass interference filters that may be interchanged for specific applications;
- Synchronised, digitally controlled irises, enabling reproducible adjustment of settings for varying illumination, atmospheric and albedo conditions, and
- Manually controlled camera integration periods to extend illumination range for imaging.

Filters with bandwidths as narrow as 0.1 μm, within the range 0.4 – 0.8 μm, are available and may be substituted for any or all of the standard set. The narrow band-pass filters are easily interchanged for specific applications;

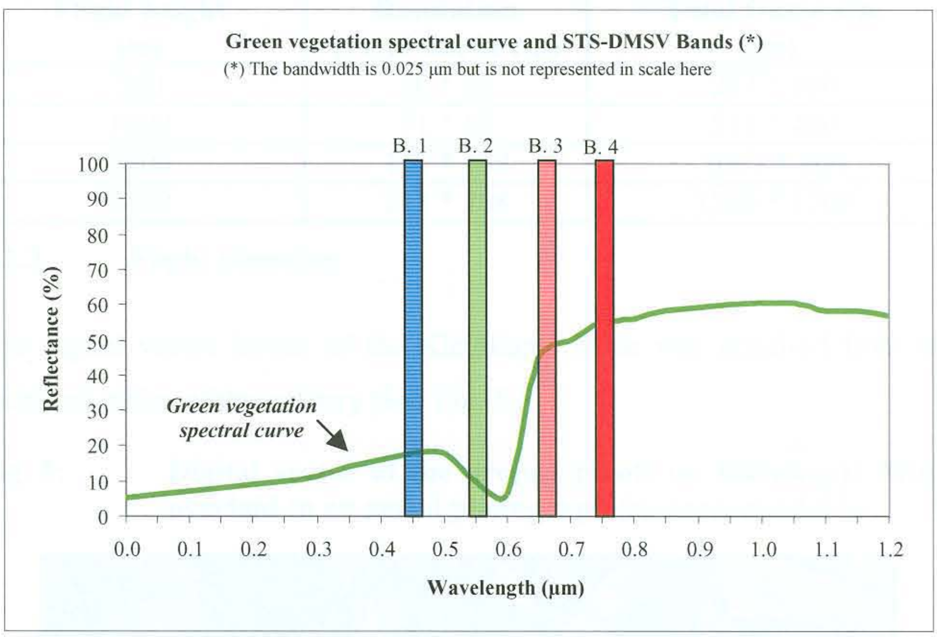
[8] **CCIR** International Radio Consultative Committee was a global organization responsible for establishing television standards.

however, the four spectral bands typically utilised for vegetation mapping and monitoring are 0.025 μm wide and centred about the principal reflectance spectral features of vegetation:

- Band 1 (blue): pigment absorption band, around 0.45 μm.
- Band 2 (green): relatively higher reflectance band, near 0.55 μm.
- Band 3 (red): chlorophyll absorption band, in the 0.65 – 0. 67 μm waveband interval
- Band 4 (NIR): near-infrared reflectance, 'plateau' band, beyond 0.75 μm.

These band positions relative to the reflectance spectra of a standard green vegetation cover can be seen in the graph below.

Fig. 4: Spectral set up of the STS-DMSV sensor



The CADAS (Control And Data Acquisition System) supports the STS-DMSV sensor. This incorporates a ruggedised 486 industrial PC and a single board digital frame grabber that acquires the four spectral channels simultaneously, with 8 bit digital resolution data. Parts of the system are also an on-line hard disk storage device for 300 plus frames of data, a display device and image enhancement and analysis software packages. The digital frame grabber occupies one slot in the frame of the instrument.

A 3-m cable, comprising four coaxial video lines, a coaxial sync line, stepper-motor control line and a 12V power supply from the PC to the sensor head, is supplied with the system. Also provided with the system are:

- Optional reading of navigation and time data from GPS with recording of data in file header records;
- User friendly interactive, menu driven operating software for aircraft and ground based operation.
- Real-time colour display and immediate, post acquisition image processing, enhancement and display capability, enabling review of coverage and data quality control while flying.

Table 2: Spatial resolution and coverage of the STS-DMSV Sensor with 12 mm focal length lens

Flight height (m)	Resolution (Pixel size in cm)	Total frame size (m)
500	36 * 35	257 * 200
1000	71 * 69	533 * 400
2000	142 * 138	1067 * 800
3000	213 * 208	1596 * 1200

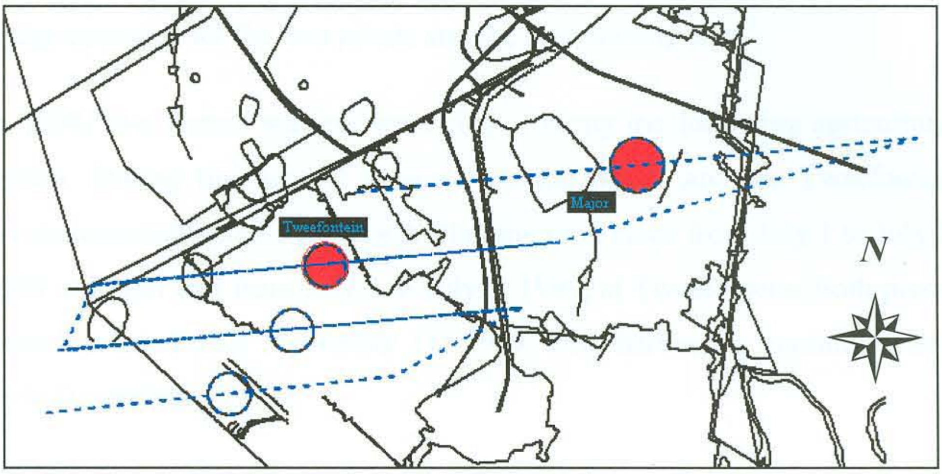
4.1.3. Flight planning

The digital vector layout of the Kleinkopjé Mine was acquired from the technical office of the colliery (See Fig. 5.).

Fig. 5: Digital vector of the project pivots on Kleinkopjé Mine, overlaid to an aerial photograph *(no scale available)*

The flight lines and flight height were planned in order to guarantee a 1 m resolution of the raster data, with a 60 % on-line and 30% across-line overlap of the images. Flight direction was planned in order to minimise 'hot spots[9]' (See Fig. 6.).

Fig. 6: Flight plan for the February 1999 aerial survey



4.1.4. Remote imaging of the pivots

The FLY HIGH Company based in Cato Ridge, Durban, in Kwa-Zulu Natal, operated the JABIRU plane. The platform supplier was contracted by the ARC-ISCW to operate the instrument without the use of an on-board operator. The plane was flown from Cato Ridge to Witbank on the same day of the surveys and ARC-ISCW personnel provided the ground base support.

At Kleinkopjé Mine, pictures of the two pivots were taken over two growing seasons (1998 and 1999). This was motivated by the requirement to monitor the evolution of the crop and map the spatial variability over time for the same crop and for the different fields. The flights were all conducted taking off from the Witbank airport.

During the 1998 season Pivot Major was cultivated with maize while Tweefontein was cropped to dry beans. The first survey was flown on November 11, 1998. This survey provided a full coverage of Pivot

[9] **Hot spots**: In remote sensing, an area where the temperature appears to be much higher than the surroundings, due to the convergence of reflected light on the lenses

Tweefontein but only partial coverage of Major.

A second survey was conducted on February 25, 1999. The more accurate flight planning of this mission was such that the survey was flown at a higher altitude compared to the previous one, allowing the pivots to be included completely in a single frame and providing the acquisition of a full image coverage for the two pivots and the surrounding area.

In 1999, two further surveys were flown during the following agricultural season. During this second season both the Major and the Tweefontein pivots were cultivated with wheat. Planting took place from July 1 to July 2, 1999 at Major and from July 3 to July 5, 1999, at Tweefontein. Both pivots were harvested after November 11, 1999, with harvesting continuing into early December.

In order to catch the crop in two different phases of development, a first flight was carried out on September 14, 1999, during the vegetative stage and the second one on October 7, 1999, at flowering.

The images of the pivots acquired in the course of the four flights are shown in Figures 7 to 10.

Fig. 7: Images acquired for the Major (left) and Tweefontein (right) pivots in December 1998

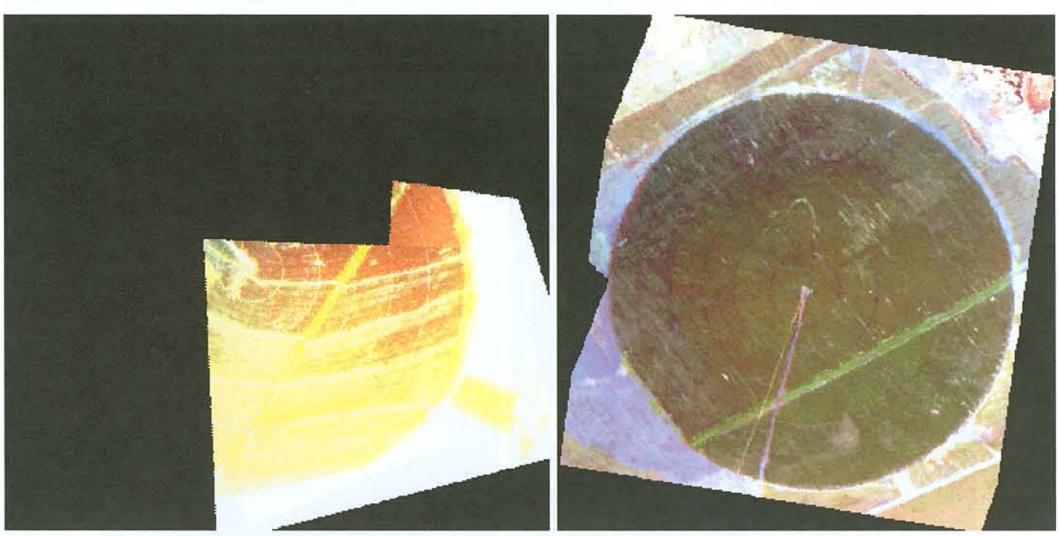


Fig. 8: Images acquired for the Major (left) and Tweefontein (right) pivots in April 1999

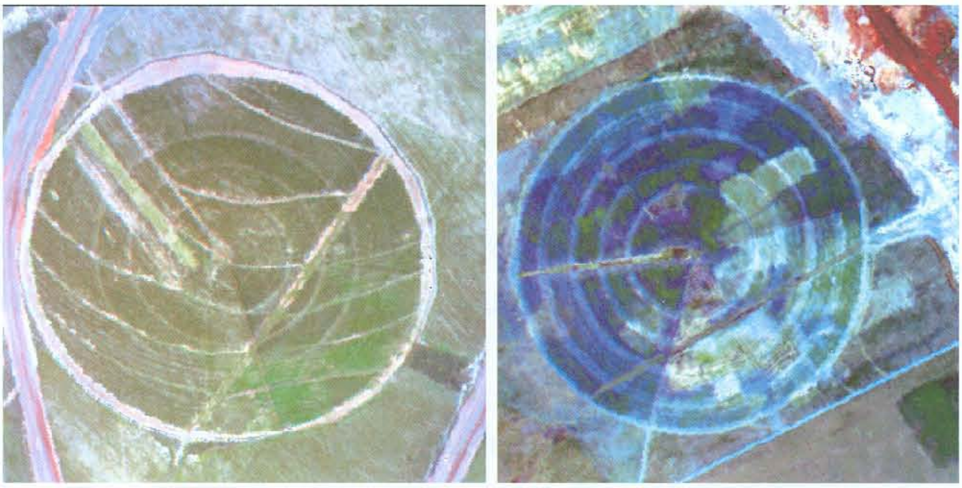


Fig. 9: Images acquired for the Major (left) and Tweefontein (right) pivots in August 1999

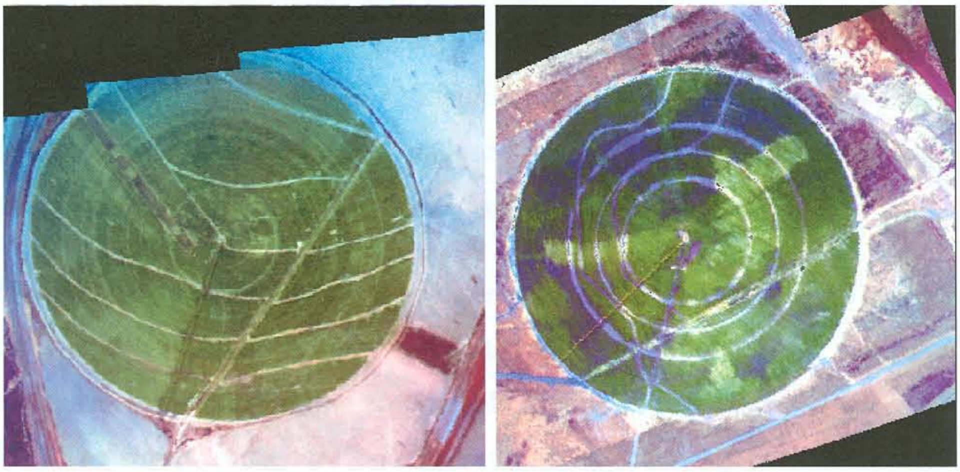
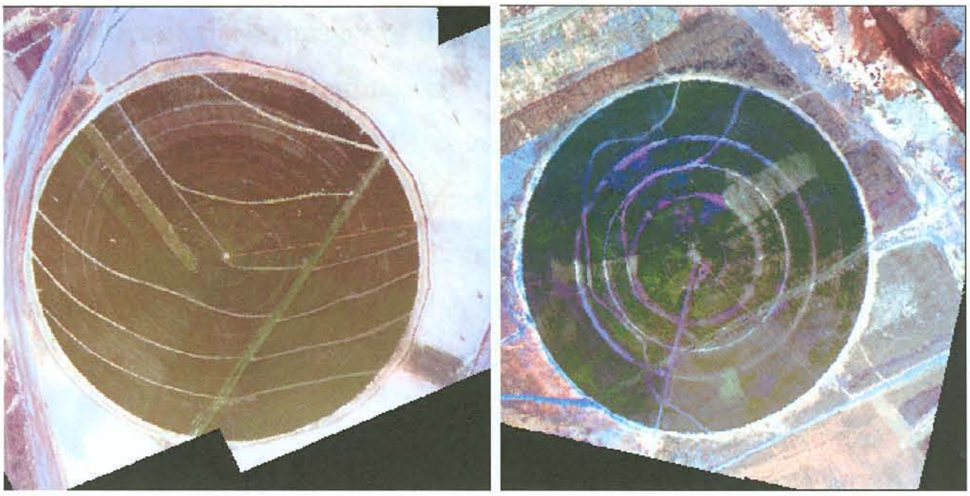


Fig. 10: Images acquired for the Major (left) and Tweefontein (right) pivots in October 1999



4.2. Data collection

4.2.1. Stratification[10] and sampling plan

A ground truth collection campaign was conducted so as to coincide with the third survey flight in September 1999. The survey had the multiple scope of providing ground truth data for the classification of the acquired images and collect data on the crop condition at the time of flight.

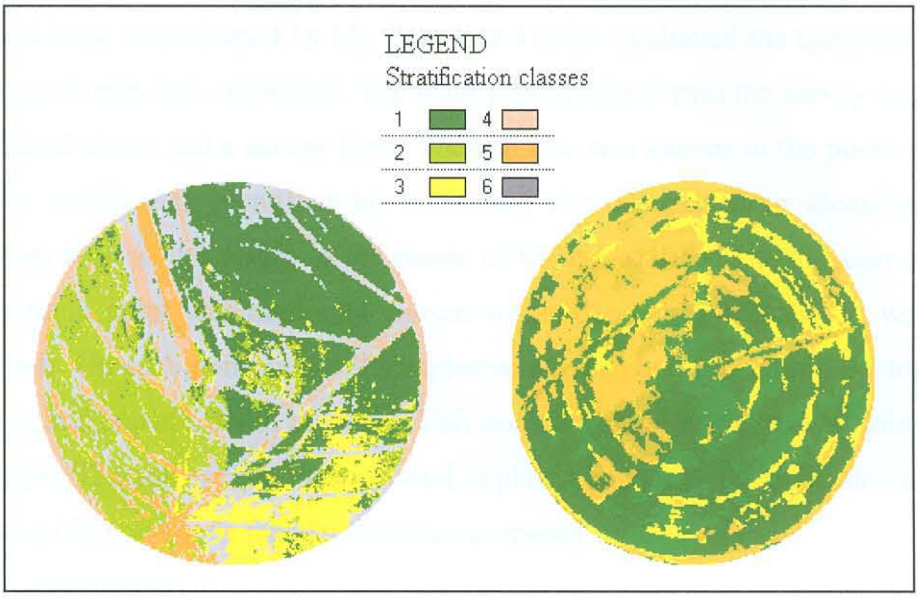
Soil samples were also gathered for analysis of their physical characteristics, as these could have an impact on the spectral features of the bare soil as well as on those of the vegetations itself. Since no previous knowledge was available of the meaning of the spectral features of the images it was decided to proceed with a preliminary unsupervised classification of the images as to identify a number of "classes", spectrally homogeneous within themselves and, at the same time, different from each other. These classes constituted strata for the sampling plan.

This stratification was adopted in order to save on the number of survey points that would have been generated in a traditional grid sampling procedure, while maintaining comparable descriptive accuracy. *(Arabia, G., 1993)* The survey procedure was then structured according to the following plan of action:

a) **Stratification**: The images of the two pivots, collected in February 1999 were classified to outline all those areas that showed marked commonalties in terms of 'colour' and 'texture' (Fig. 11). The identification of homogenous areas based on the external appearance of the canopy implies that the performance and appearance of the crop is an external reflection of the variability of the underlying soil.

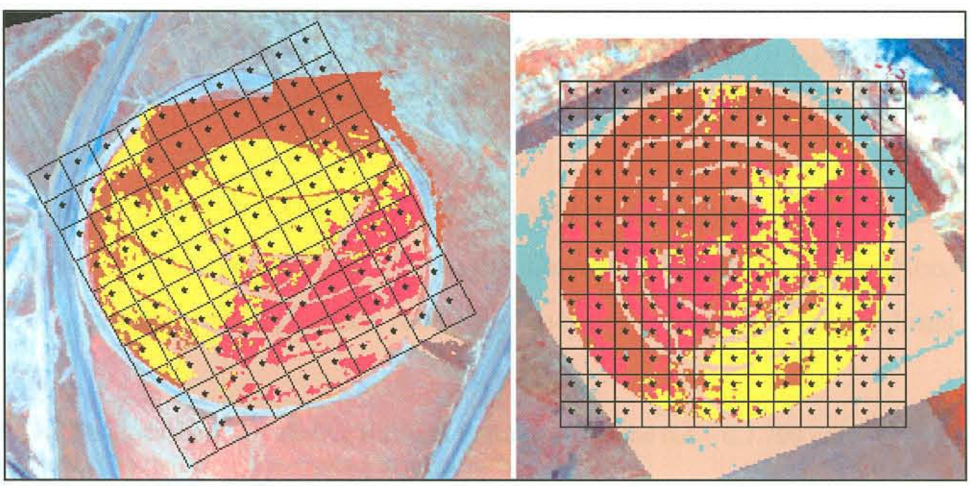
[10] **Stratification**: A sampling method in which the population is separated into groups (strata) usually based on some internal similarities, then selecting a random sample within each stratum.

Fig. 11: **Stratification of the Major (left) and Tweefontein (right) pivots, where each colour represents a different stratum.**



b) **Sample plan:** In order to facilitate the allocation of the sample points, a grid with cells of 20*20 m was drawn over the stratified images, each node of the grid being a candidate sample point. Within each homogeneous area, a set of random points was selected and a survey map was prepared showing the location of the sample points. The grid and the stratification were overlaid to the image of each pivot in order to facilitate the identification of each point that was characterised by an identification number (Fig. 12)

Fig. 12: **Sampling plan**



4.2.2. Soil and crop survey

A field team co-ordinated by Mr. Peet Van Torder conducted the operations of ground truth data collection. The team was equipped with the survey map described above and a survey form. The cell size was known so the position of the points was identified by measuring the distance from identified markers such as the centre of the pivots of the target cells. The location of the sample point was randomly chosen within the target cell once it was reached. On each point two soil samples were collected; one within the top 10 cm, and one at a depth of 30 cm. This second sample was extracted using an auger. The soil samples were placed in plastic bags with the indication of the specific point code for identification purposes.

The samples were analysed at the soil physics laboratory of the Department of Plant Production and Soil Sciences, at the University of Pretoria under the supervision of Prof. A. Claassens. The parameters that were measured were the gravimetric water retention capacity at wilting point (–1500 J kg^{-1}) and at field capacity (–10 J kg^{-1}). These values together with the known bulk densities (1.60 and 1.90 Mg m^{-3}) of the soils at Major and at Tweefontein and the reference depths of those spoils allowed the derivation of the available water capacity (AWC) for two soil layers on each pivot. (See Section 6.1.5). These two soil layers were conventionally set, one from 0 to 20 cm and the other from 21 cm to spoil. The following canopy measurements were taken:

- The Ground cover expressed as the fractional interception of PAR[11];
- The Leaf area index (or LAI)[12],

The canopy cover of PAR (0.4 – 0.7 μm) was measured on the grid with a Decagon sufleck ceptometer (Decagon Devices, Pullman, Washington, U.S.A.), making one reference reading above the canopy and 10 readings

---

[11] **PAR: Photosinthetically Active Radiation**: Radiation in the 0.4 – 0.7 700 μm waveband. The radiation is measured in μmol m^{-2} s^{-1}.
[12] **LAI**: A type of information worked out by calculating the volume of the surface of leaves in relation to the volume of ground that is directly below the plant. The index is measured in m^2 leaves m^{-2} soil

beneath the canopy. The LAI was calculated after measuring leaf area with a LI 3100 belt driven meter (LiCor, Lincoln, Nebraska, U.S.A.) by sampling plans covering 1 m^2 of ground surface.

In the course of this survey, a sample of plant material was also harvested from 1 m^2 of ground surface at each sample site. Fresh mass was measured directly after sampling. Once delivered to the laboratory, plant organs were dried in an oven at 60 °C for 4 to 5 days and weighed again. The above ground dry matter production is expressed in g * 0.25 m^{-2}.

The data were recorded on a survey form and then captured to a spreadsheet. The results of the survey are given in Tables 3 and 4.

The soil and crop data acquired during the ground survey were transformed into maps and subsequently introduced as information layers into a GIS.

Table 3: Soil and canopy measurements for the Major Pivot for wheat in September 1999

Sample	X (Lon)	Y (Lat)	Above ground dry matter production $g * m^{-2}$	Fractional intercept of PAR	LAI m^2*m^{-2}	AWC 0-20 cm mm	AWC 21 to spoil cm mm	AWC TOT mm
5	24049	-2874515.	108	0.84	1.10			
6	24133	-2874541	158	0.87	1.50			
9	24079	-2874570	83	0.75	0.77	8	65	73
10	23940	-2874574	135	0.91	1.49	11	88	99
11	24164	-2874597	104	0.68	0.79	8	26	34
15	24110	-2874626	137	0.87	1.16	1	51	53
17	23830	-2874632	150	0.92	1.66	12	39	51
20	23914	-2874657	98	0.85	1.04	11	21	32
23	24141	-2874682	88	0.69	1.00	11	51	63
24	24000	-2874684	89	0.61	0.93	10	38	48
27	24224	-2874706	102	0.83	1.36	11	33	44
30	23806	-2874715	96	0.88	1.07	11	23	34
35	23890	-2874742	95	0.86	0.94	11	44	55
37	24253	-2874759	129	0.72	1.11	11	46	57
38	24114	-2874764	193	0.92	2.39	13	47	60
39	23976	-2874769	135	0.79	1.58	19	24	43
48	24143	-2874817	128	0.81	1.24	10	60	71
52	24229	-2874843	140	0.62	1.44	10	27	37
56	23813	-2874856	119	0.90	1.30	10	24	33
59	24034	-2874875	121	0.83	1.43	13	25	38
64	24119	-2874901	97	0.55	0.81	13	39	51
70	23926	-2874932	161	0.86	1.41	12	78	89
73	24292	-2874955	140	0.62	1.19	10	42	52
75	24010	-2874959	95	0.86	0.97	13	74	87
79	24095	-2874987	83	0.58	0.65	9	79	88
83	24181	-2875014	109	0.59	1.45	13	102	116
84	23901	-2875016	80	0.64	0.58	11	42	53
87	24126	-2875043	72	0.46	0.62	11	115	126
91	23933	-2875073	102	0.65	0.74	11	34	45
92	24072	-2875072	81	0.44	0.66	11	81	93

Table 4: Soil and canopy measurements for Tweefontein Pivot for wheat in September 1999

Sample	X	Y	Above ground dry matter Production	Fractional intercept of PAR	LAI	AWC		
						0-20 cm	21 to spoil cm	TOT
	(Lon)	(Lat)	$g * m^{-2}$		$m^2 * m^{-2}$	mm	mm	mm
10	19840	-2876609	118.7	0.61	0.68	16	28	44
15	20040	-2876569	105.9	0.11	0.64	14	32	46
16	19921	-2876609	113.2	0.39	0.73	15	43	58
20	19759	-2876690	92.1	0.64	0.61	12	25	37
21	19880	-2876649	63.6	0.38	0.46	12	27	39
28	19840	-2876690	106.3	0.69	0.68	19	34	53
32	20080	-2876609	101.1	0.80	0.67	14	51	64
34	20001	-2876649	100.8	0.42	0.77	10	49	59
37	19799	-2876730	71.9	0.34	0.52	13	42	55
38	19921	-2876690	122.8	0.63	0.99	16	15	32
57	19759	-2876810	78.4	0.04	0.52	14	50	64
61	20120	-2876690	101.9	0.57	0.52	12	30	42
65	20040	-2876730	193.1	0.58	0.94	9	43	52
67	19840	-2876810	148	0.78	1,28	13	58	71
68	19961	-2876770	81.8	0.52	0.54	7	14	21
84	20199	-2876730	384.6	0.94	2.29	16	34	50
87	20120	-2876770	183.3	0.77	1.00	16	39	54
88	19799	-2876890	113.4	0.43	0.51	13	39	52
90	19921	-2876850	150.1	0.91	1.36	12	55	67
99	20001	-2876850	129.9	0.68	0.77	21	43	64
100	20120	-2876810	105.2	0.73	0.78	11	37	49
103	19921	-2876890	95.8	0.97	1.37	14	34	48
109	20080	-2876850	57.8	0.63	0.44	15	24	40
110	20199	-2876810	175.1	0.57	1.40	15	51	65
114	19799	-2876970	119.6	0.77	1.04	13	25	38
131	20159	-2876890	107.3	0.39	0.73	13	31	44
135	20080	-2876930	68.4	0.24	0.40	6	36	41
138	20001	-2876970	92.9	0.56	0.74	14	27	40
150	20001	-2877009	94.3	0.37	0.66	14	40	54
151	20120	-2876970	99.1	0.34	0.75	12	51	64
157	20080	-2877009	76.6	0.37	0.43	14	41	55

4.2.3. Harvester data logging

The wheat crop over the two pivots was harvested in spring 1999 and the operation was conducted with a harvester specifically equipped for yield mapping. The equipment consisted of a GPS, a number of sensors to measure grain flow, the moisture content of the seed, the speed of the harvester and several other parameters.

The sensors[13] were situated downstream from the cutting head, and were placed in such a way to measure the grain flow in volume and with a sub-meter resolution.

Determining the sub-metre position was achieved using a Trimble real-time differential GPS receiver that associated each measurement with latitude, longitude and elevation. However, the elevation was only accurate to sub 1.5 metres. The distance covered by the harvester between each measurement was on average 2.6 m and the data is relative to the full width of the harvester table (17.5 m).

The data logger produced two files of 3.960 kB for Major and 2.499 kB for Tweefontein. These files stored the following information: longitude, latitude, grain flow (in kg per logging interval), time, logging interval (either 1, 2 or 3 seconds), distance (m), swath (m), yield (t ha^{-1}), moisture (%), marker data, pass, monitor serial number, field number and name, data type, grain type, GPS status, elevation (m a.s.l.).

The data collected using these sensors allowed the creation of maps showing the value of yield at specific points in the field. It was also possible to create an image of the moisture content of the grain harvested, as well as the variations in elevation across the fields. For Major some 39540 points were measured, whilst for Tweefontein the data logger recorded some 24390 points. (See Chapter 6.1.8).

[13] Model and make of such sensors are not available