SPECTRODIRECTIONAL REMOTE SENSING
From Pixels to Processes

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Spectrodirectional Remote Sensing: From Pixels to Processes

Inaugural address

reprinted in modified form of the original address given by the author on the 7th October 2004 on the occasion of his accession to the post of professor of geo-information science with special emphasis on remote sensing at Wageningen University.

President, ladies and gentlemen, highly valued audience,

In summer 2004, the Centre for Geo-Information of Wageningen University organized a national workshop here in Wageningen on the value-added chain management in Earth observation[1]. It was basically a review of the past 35 years of remote sensing activities in favour for a long standing member of the Dutch delegation to ESA, Dr. ir. N.J.J. (Nico) Bunnik from NIVR. In total 14 speakers discussed the progress of remote sensing made in that period with special focus on the Netherlands. As usual, such an event will not close before a reasonable reception has taken place. During that particular reception, a member of the search committee responsible for my appointment here in Wageningen, approached one of our senior staff and remarked, that the topic I am discussing today – imaging spectroscopy and directional remote sensing - is not that new like assumed by him and has been researched already in depth in the Netherlands over the past 35 years!

In particular the early spectroradiometric measurements performed by Verhoef (Verhoef & Bunnik, 1976) and Bunnik (Bunnik, 1978) in the proximity of Wageningen prompted him to this reaction. The work was continued and expanded in this domain (Clevers, 1989), and still today, the topic is of growing relevance and scientific interest as can be seen on the recent acquisition over Wageningen (cf., Fig. 1).

Figure 1: Early spectroradiometric measurements in Wageningen ((Verhoef & Bunnik, 1976), left) and an airborne imaging spectrometer data take over Wageningen[2] during summer 2004 (right).

The Netherlands has been a forerunner in this particular topic and has significantly contributed to its scientific advancement, but 35 years of past history are by far not sufficient to acknowledge the origin of spectrodirectional remote sensing. Therefore I will start with a short review and put the evolution of spectrodirectional remote sensing into a historical perspective.

Brief History of Spectroscopy

About 300 years ago, in 1704, Sir Isaac Newton published in his 'Treatise of Light' (Newton, 1704) the concept of dispersion of light (cf., Fig. 2). He demonstrated that white light could be split up into component colours by means of a prism, and found that each pure colour is characterized by a specific refrangibility. The corpuscular theory by Newton was gradually successed over time by the wave theory. Consequently, the substantial summary of past experiences performed by Maxwell (1873), resulted in his equations of electromagnetic waves. But it was not before the 19^{th} century, until the *quantitative* measurement of dispersed light was recognized and standardized. A major contribution was Fraunhofer's discovery of the dark lines in the solar spectrum (Fraunhofer, 1817); and their interpretation as absorption lines on the basis of experiments by Bunsen and Kirchhoff (1863). The term spectroscopy was first used in the late 19^{th} century and provides the empirical foundations for atomic and molecular physics (Born & Wolf, 1999). Nevertheless, it was not before 1999 until the first launch of an imaging spectrometer in space[3].

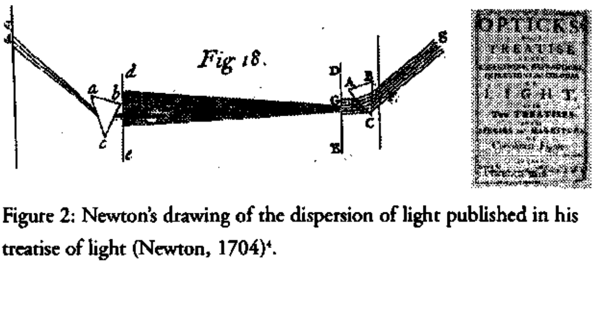

Figure 2: Newton's drawing of the dispersion of light published in his treatise of light (Newton, 1704)[4].

Brief History of Directionality

Historically, directionality developed apart from spectroscopy and it was only after Galilei (1632) had developed his mechanics, that optics was put on a firm foundation by Leonardo Da Vinci (cf., Fig. 3). Hooke (1664) discovered in 1664 the presence of light in the geometrical shadow, but an earlier qualitative description exists from Leonardo Da Vinci in his notebooks, where he demonstrates using experimental methods, that 'The position of the Eye above or below [trees] varies the shadows and lights in trees' (following Richter (1970) as cited in Lucht (2004). Even though this was an early start for directional observations, the quantification of directionality was also only achieved in the late 19th century. Early works combining observational methods with physical definitions appear in the mid of the 20th century, lead by Minnaert (1940) and more remote sensing related by Middleton (Middleton & Mungall, 1952). Finally the standardisation of the geometrical nomenclature was due in the early 1970ies as coined by Nicodemus (Nicodemus, 1970; Nicodemus *et al.*, 1977). The term Bidirectional Reflectance Distribution Function – or short BRDF – originates also from that time and the directionality found subsequently its way into computer science and particular photorealistic rendering, which gave this science a large boost in the 1970ies. But alike spectroscopy, it was not before 1991, until the first directional instrument on a satellite – having 2 view angles – was launched in space[5].

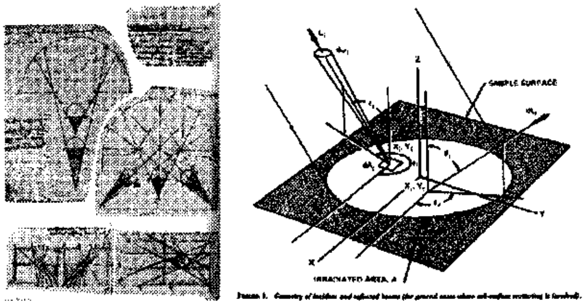

Figure 3: Excerpt from Leonardo Da Vinci's notebook on shadows and light ((Richter, 1970), left), and a conceptual drawing of Fred Nicodemus on geometrical optics in reflectance (Nicodemus *et al.*, 1977, right).

Brief History of Spectrodirectional Remote Sensing

Early concepts of acquiring directional information from natural targets where discussed already in 1958 in the former Soviet Union (Arcybashev & Belov, 1958). The idea was to acquire a scene – a forest in this case – under various view angles by using a complex flight pattern (cf., Fig. 4). In addition, the camera – a spectrophotometer at this time – was tilted to different view directions to increase the amount of observation angles. Several satellites were launched in the 1990ies to measure multiple spectral bands and view angles in various combinations[6]. But it was not before 2001 until a 'true' imaging spectrometer with directional capabilities was launched. The British CHRIS (Compact High Resolution Imaging Spectrometer) on board of the Belgian PROBA platform, operated by ESA (European Space Agency), can be considered as the first true spectrodirectional spaceborne instrument. The expression spectrodirectional is a typical finding of the 21st century. Mainly the efforts of the NASA MISR team around John Martonchik (NASA, JPL) and Michel Verstraete (JRC, It) coined this expression. Regularly the terms 'multiple view angles' or 'multiangle radiometer' – amongst others – were used before. Currently the subject of spectrodirectional as being a combination of high spectral resolution and multiple view angles can be found regularly in literature (Baret, 2001; Strub *et al.*, 2003), as well as sound discussions on having a combined benefit of both acquisition methods (Diner *et al.*, 2005; Verstraete *et al.*, 1996).

Figure 4: Directional acquisition pattern for forest stand monitoring in 1958 (Arcybashev & Belov, 1958) (left), and a 2004 NASA Terra/MISR[7] observation in three view angles of the Canary Islands (E) ['+' denotes a forward looking, '-' a backward looking instrument] (right).

Increasing Relevance of Spectrodirectional and Hyperspectral Remote Sensing

Even though the terms 'imaging spectroscopy', 'hyperspectral', and 'spectrodirectional' and resulting products have only partially found their ways into operational remote sensing services, the referencing of them as well as associated citations are exponentially increasing over the past few years (cf., Fig. 5) – a good indication of the increasing relevance of this emerging topic.

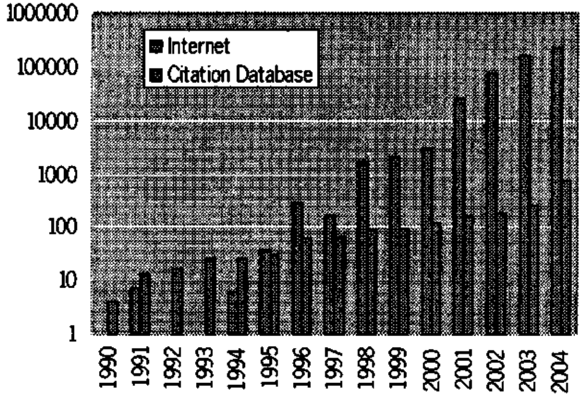

Figure 5: Exponential growth per year of Internet and citation database based terminology related to the terms 'imaging spectroscopy' and 'directionality' [8].

A thematic separation of these search terms in the above overview will be increasingly difficult in the future, since methodologies used in Earth observation related *imaging* spectroscopy are now also widely used in deep space research (Clark *et al.*, 2005), neurosciences (Devonshire *et al.*, 2004), chemometrics (Fernández Pierna *et al.*, 2004), amongst others.

The Art of Spectrodirectional Science

By reassessing Leonardo Da Vinci's (Richter, 1970) and Hooke's (1664) early transition between natural science and artistic views, these can be translated into today's analogies.

Sol LeWitt (USA, *1928) is attributed to be a Minimal artist, but states himself that his work is conceptual art.

Working along his idea 'the concept is the most important aspect of the work', he became a synonym of a sculptor of connected open cubes in his artistic career. When he created 'Cubes in Color on Color' in 2003, he gave a perfect example of a conceptual definition of imaging spectroscopy (cf., Fig. 6). Spectroscopists are using these cubes with different colours to depict the two-dimensional room of the space and the third dimension indicating wavelength. When imaging spectroscopists visualize their data, usually cubes are used to express the spatial and spectral domain. Finally an image cube can be plotted and the spectral component is coloured according to its surface reflectivity.

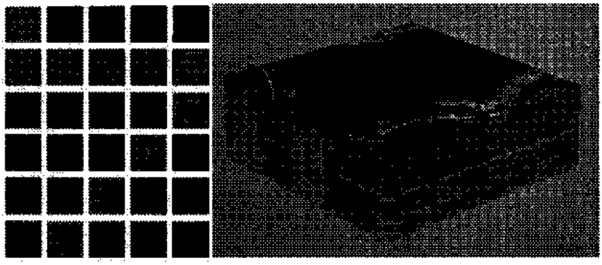

Figure 6: 'Cubes in Color on Color' (by Sol LeWitt[9], left) and imaging spectrometer data cube[10] (right).

Paul Klee (CH, *1879, †1940) frequently used a personal sign system in his works that is abstract and figurative at the same time. His painting named 'Ueberschach' is therefore a perfect example to visualize the directional component of a directional data acquisition (c.f. Fig. 7). The chess-board like pattern in the directional image acquisition seems to be an abstract feature of the landscape, but has its origin in different view- and illumination geometries. While flying an aircraft North-South, the scene is illuminated homogeneously. A few minutes later the same scene was recorded East-West and differences in ground reflectance are due to variation in sun-target-observer geometries.

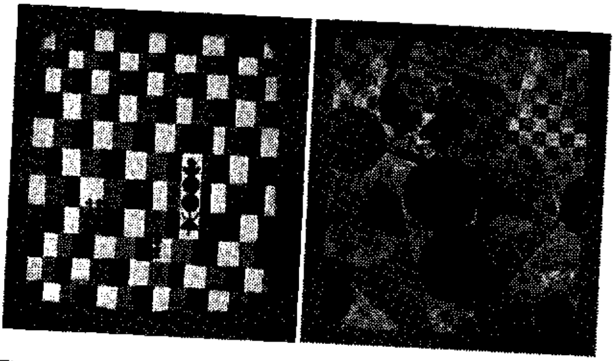

Figure 7: 'Ueberschach' (by Paul Klee[11], left) and directional chessboard pattern (Beisl, 2001).

Spectroscopy can be seen as detailing out *colours*, and when Johannes Itten (CH, *1888, †1967) – like Paul Klee a member of the Bauhaus - wrote his book 'The Art of Color' (Itten, 1991) it was a logical follow up that spectrodirectional models could make the best use out of these colour definitions. The similarity of Itten's painting 'Offenbarung' and the visualization of a directional model are not only analogous due to similar colour theories, but also due to a potential expression in directional illumination differences – so to say, colours have remained in the family.

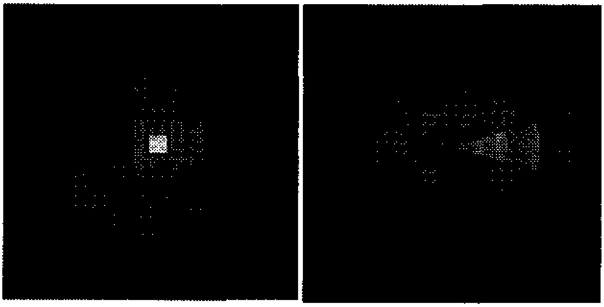

Figure 8: 'Offenbarung' (by Johannes Itten[12], left) and results of a directional model (Dangel *et al.*, in print).

Spectrodirectional Remote Sensing – A Definition

The overview of spectrodirectional imaging shall be completed by coining a definition and illustrating this definition with two different spectrodirectional acquisition concepts (cf., Fig. 9):

Spectrodirectional remote sensing is defined as being the *simultaneous* acquisition of spatially *coregistered images*, in many, *spectrally contiguous bands*, at *various observation and illumination angles*, in an internationally recognized *system of units* from a remotely operated platform.

Consequently, by applying this definition, the result will finally end in the quantitative and qualitative characterization of both, the surface and the atmosphere, using geometrically coherent spectrodirectional radiometric measurements. This result can then be used for:

- Unambiguous direct and indirect identification of surface materials and atmospheric trace gases,
- Measurement of their relative concentrations,
- Assignment of the proportional contribution of mixed pixel signals (spectral un-mixing problem),
- Derivation of their spatial distribution (mapping problem), and their
- Study over time (multi-temporal analysis).

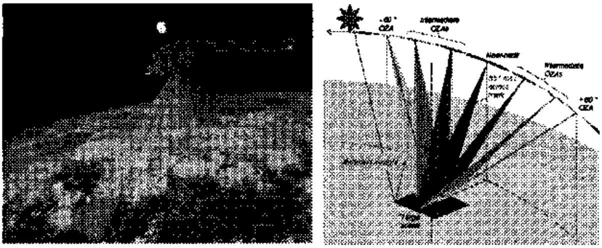

Figure 9: Two different acquisition methods of directional information using either 9 cameras pointing at different locations (left) (NASA MISR[13]), or by using an agile platform (right) (ESA SPECTRA[14]).

Research Directions using Spectrodirectional Remote Sensing

The understanding of the relevance to measure biogeophysical parameters using novel techniques such as spectrodirectional remote sensing arises from various efforts in environmental policy on a global level. The often referred to Kyoto Protocol to the UN Framework convention on Climate Change (UNFCC) proposes a global policy to be applied at international level, based on assessments of carbon emission and sequestration rates. The aim of the protocol is therefore to stabilize the CO_2 concentration in the atmosphere in the long run. In particular, the consideration of carbon sinks in the protocol has given a large momentum to implement a scientifically sound accounting and verification system. The key issues to be resolved there are the ***variability, uncertainty, attribution, non–permanence, leakage,*** and future ***evolvement*** of the carbon sequestration in the terrestrial biosphere (Valentini *et al.*, 2000). The estimated carbon up–take of the biosphere must be consistent with all other evidence at three levels of integration of the carbon budget: ***global, national, and local.***

One particular component of the Earth system, the terrestrial environment has been identified as being a critical component of the variability of the global carbon cycle. But given the natural diversity of landscapes, the (instrumented) measurement and validation approach remains challenging. Earth observation from airborne or spaceborne platforms is the only observational approach capable of providing data at the relevant scales and resolution needed to extrapolate findings of in situ (field) studies to larger areas, to document the heterogeneity of the landscape at regional scale and to connect these findings into a global view. Extrapolation can either be done by statistical and/or GIS techniques (Guisan & Zimmermann, 2000), as well as by process modelling of ecosystems. The latter is a very promising approach for testing ecological hypotheses and for assessing and forecasting the state of large landscapes up to the global scale.

Such approaches usually require the spatial input of the state of the ecosystems at simulation start and of relevant biophysical, biochemical and/or structural information of the terrestrial ecosystems (Schaepman *et al.*, 2003). Ecosystem models – often referred to as biogeochemistry models because they simulate pools and fluxes of relevant ecosystem elements such as carbon, nitrogen or water – ideally combine remote sensing information on the structure of the vegetation with monthly (e.g. CENTURY, see (Wilson *et al.*, 2003)) to daily (e.g. BIOME-BGC, see (Thornton *et al.*, 2002)) meteorological data and a set of ecophysiological parameters, which drive the processes of ecosystems. When applied to a gridded landscape, the combination of spatially explicit air- or spaceborne information on the vegetations structure with ecosystem models allow for an accurate assessment of ecosystem processes, for testing novel ecological theories and for predicting possible future states of the land surface (e.g. (Kimball *et al.*, 2000; Turner *et al.*, 2003)).

Such large scale to global quantifications are clearly beyond the realm of experimental analysis. The close coordination of Earth observation satellites and airborne instruments is thus essential for the successful validation of the contribution of the terrestrial component to the global carbon cycle (Schaepman *et al.*, 2005). Space agencies and international organizations have recently established a coordination mechanism (e.g., the Integrated Global Observing Strategy Partnership (IGOS–P) that facilitates progress in space-based measurements (Rast *et al.*, 2001)).

Rast (2004) outlines that the interannual variability of CO_2 fluxes is much higher for the terrestrial biosphere than for the oceans. Recent estimates suggest even that during the 1980ies, 23% of the total anthropogenic carbon emissions were taken up by the oceans, and as much as 32% by the terrestrial biosphere. For the 1990ies the figures are 28%

for the oceans and 34% for the land. The land-atmosphere flux represents the balance of a positive term due to land-use change and a residual terrestrial sink. The two terms cannot be separated on the basis of current atmospheric measurements. Using independent analyses to estimate the land-use change component for the 1980s based on Houghton & Hackler (2000) and Houghton *et al.* (1999), and the CCMLP (McGuire et al., 2001) the residual terrestrial sink can be inferred for the 1980ies. Comparable global data on land-use changes through the 1990ies are not yet available.

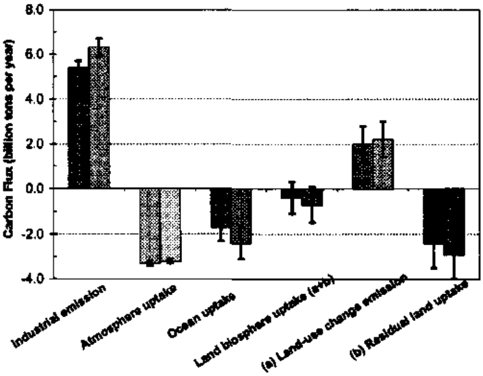

Figure 10: Global CO_2 budgets (in PgC/yr) based on intra-decadal trends in atmospheric CO_2 and O_2. Positive values are fluxes to the atmosphere; negative values represent uptake from the atmosphere. Error bars denote uncertainty (± 1s), not interannual variability, which is substantially greater[15].

When estimating future terrestrial carbon fluxes, the contribution of the terrestrial biosphere remains unclear, and in addition inter-model differences are still large. Simulations using Dynamic Global Vegetation Models (DGVM), consistently indicate that rising CO_2 levels are causing a persistent, later saturating carbon sink, while the effect of climate change may lead to a reduction in sink strength or even in a source (c.f. Fig. 11) (Rast *et al.*, 2004).

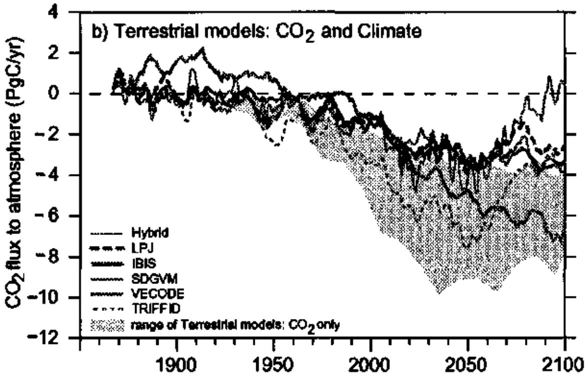

Figure 11: Projections of the uptake of anthropogenic CO_2 by six dynamic global vegetation models driven by changes in CO_2 concentrations (IPCC, 2001).

In summary, the land biosphere CO_2 uptake and its associated uncertainty must be understood and reduced further by performing the following actions:

- Better determination of relevant biosphere parameters by representing the biosphere at their relevant scale in appropriate spatial and temporal scales,
- Enhanced (and standardized) parameterisation of the carbon exchange between vegetation, soil and atmosphere, and
- Attributing the anthropogenic disturbance a higher importance by establishing 'vegetation scenarios' analogous to the IPCC defined 'atmospheric scenarios'.

This will allow to better estimate the evolution of the biospheric uptake, define if the biospheric sink is stable over time, and finally to resolve the question if unknown feedbacks are hidden somewhere.

The Contribution of Spectrodirectional Remote Sensing

There is little disagreement over the fact that remote sensing in general and spectrodirectional remote sensing in particular is well suited to (modified/added from (Cohen & Goward, 2004):

- Map spatially distributed phenomena at various scales, such as ecosystems, habitats, plant functional groups/types, and species,
- Measure continuous fields incorporating biophysical and biochemical variables,
- Map categorical variables in the form of discrete classification and land use/cover change (LUCC),
- Map temporal phenomena, in particular successional stages,
- Map spatio-temporally coupled processes such as the phenology, and
- Record disturbance induced by humans (also expressed as land use changes), fires, volcanoes, and other extreme events.

Even though this is an important achievement, remote sensing is still confined to mostly above ground and limited penetration depth measurements. This results in the fact that approximations must be made, when assessing relevant biogeophysical and biogeochemical cycles: NPP (Net Primary Productivity (cf., (Gower *et al.*, 1999)[16]) will always be confined to aNPP (aboveground Net Primary Productivity) when using reflective remote sensing data. Proper estimates of (global) plant growth or NPP will therefore always need significant amount of data to be assimilated or integrated to satisfy a more rigorous system (c.f. Fig. 12).

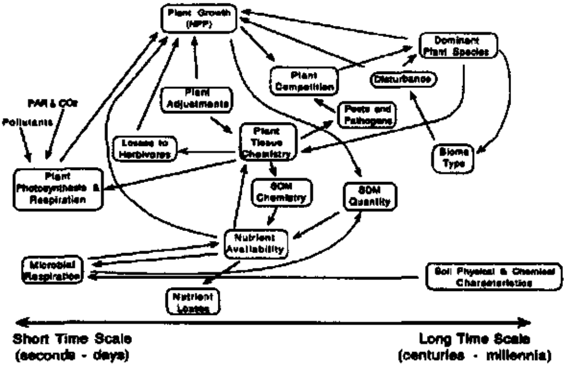

Figure 12: Net Primary Productivity (NPP) estimates or plant growth listed in various scales and interactions (Field *et al.*, 1995).

The particular benefit of using spectrodirectional measurements over single viewangle and limited spectral band measurements is the significant improvement of the quality and reliability of the retrievals. Spectro-directional imaging is increasingly seen as an acquisition technology that enables biogeophysical variables of the Earth's surface to be mapped with unprecedented accuracy (this progress is well documented in Rast (Rast *et al.*, 2001; Rast *et al.*, 2004)).

Additionally, the gained knowledge of directional effects – or surface and atmospheric anisotropy – is presently also being used to correct undesired effects of wide field of view angle sensors (Govaerts *et al.*, 2004).

Concluding it can be said that the (spectro-)directional remote sensing science community has two major research objectives:

- Minimizing the influence of the anisotropic behaviour to achieve high quality, standardized and therefore comparable and reproducible data sets, as well as
- Maximizing the information retrieval to enhance the quality and reliability of the derived products.

From Pixels to Processes

In-situ measurements, individual radiance measurements, as well as satellite observations in the solar reflected domain in remote sensing are always influenced by five dimensions (e.g., the spatial, spectral, directional, temporal, and polarisation dimensions), whereas the dimension 'space' is usually a two dimensional observation (x and y), and the direction a combination of four angles (illumination zenith and azimuth angles, as well as observation zenith and azimuth angles).

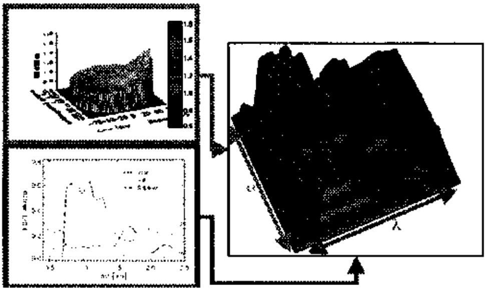

Figure 13: Combining the spectral (left, bottom) and directional (left, top) component of remotely sensed data to achieve spectrodirectional data sets (right) (Data: (Strub *et al.*, 2003) and (Rast *et al.*, 2004)).

Figure 13 identifies a monotemporal in-situ measurement, with neglected polarisation dependent information, reducing the dimensions to a spectral and a directional component.

Compiling literature references of documented spectral absorption features (cf., Fig. 14), one can easily estimate the potential of remote sensing to identify biochemical compounds in plants. Nevertheless, the documented features are in many cases measured using dried plant material, suggesting a potential shift of spectral features compared to fresh material, which may result in a variety of absorption lines located close to each other, and slightly offset of standard reported absorption features (Curran, 1989; Wessman *et al.*, 1988). A major challenge remains to separate plant water content (leaf water) and columnar water vapour contained in the atmosphere (Sims & Gamon, 2002, 2003).

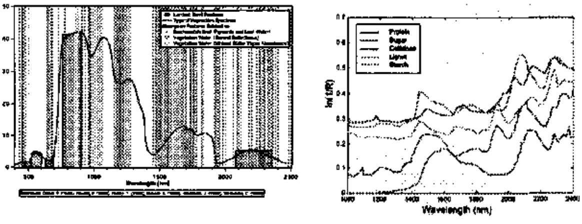

Figure 14: Spectral features of vegetation biochemicals in the solar reflected domain: literature identified biochemical feature extraction based on spectral band position (left, Schaepman (unpublished[17]), absorption of five biochemical compounds found in leaves (right) (Wessman, 1990)).

The measurement of the spatial extent using spectrometers can also vary significantly and is a crucial item when trying to integrate various spatial scales. In particular the sampling scheme for in-situ measurements plays an important role for the choice of the final application. Scaling from leaf to canopy level as well as choosing the right spatial sampling interval to characterize the landscape heterogeneity properly, is highly over-determined in remote sensing and requires trade-offs to be made to achieve the desired product accuracy. Figure 15 illustrates the measurement of leaf optical properties at spatial scales from less than a few cm^2 up to the canopy level where usually half a m^2 is a proper measurement unit. These spectral scales ranging from leaf to canopy level, can be successfully modelled using radiative transfer based approaches (Jacquemoud *et al.*, 2000; Pinty *et al.*, 2001; Pinty *et al.*, 2004; Verhoef & Bach, 2003).

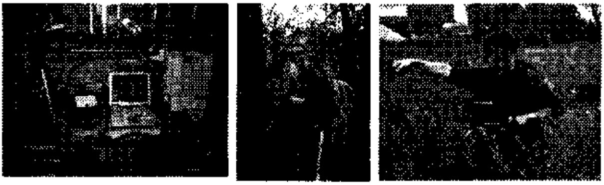

Figure 15: Spectral measurements from leaf (needle transmission in the laboratory) (left), and *in vivo* (middle) to canopy level (right)[18].

At all spatial scales, vegetation canopies and leaves are undergoing substantial dynamic behaviour, and the dynamic change of vegetation is still encapsulated with a significant uncertainty in their quantification (Cao & Woodward, 1998). By coupled analysis of spectral and temporal features, it can be demonstrated that full spectral coverage is a predominant requirement to monitor all relevant processes occurring at leaf and canopy level (Lichtenthaler *et al.*, 1998). This is demonstrated and visualized in Fig. 16, which suggests that depending on the stress exposure time of a single leaf, different portions of the reflective part of the electromagnetic spectrum undergo more changes than others (early stress is dominating the shortwave infrared region at the beginning, whereas leaf decomposition is affecting the visible part more significantly in a later stage).

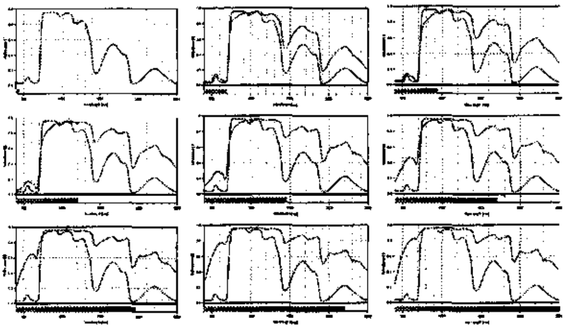

Figure 16: Measured decay of a '*Ficus benjamina* L.' leaf under laboratory conditions with accelerated (water) stress, induced by illuminating the leaf with a leaf clip using a built-in illumination source (Schaepman & Bartholomeus, 2004[19]).

Another aspect of multitemporal analysis is the inherent measurement stability of remote sensing instruments. Significant advances have been made in measuring the radiance field with higher accuracy (Fox *et al.*, 2003), and long-time calibration experiments demonstrate measurement stability of better than 2% uncertainty on the long run (Kneubühler *et al.*, 2003). Fig. 17 demonstrates this using MERIS on ENVISAT as an example, and puts additional emphasis on the proper characterization of the atmosphere, including the proper choice of radiative transfer models and the solar spectrum.

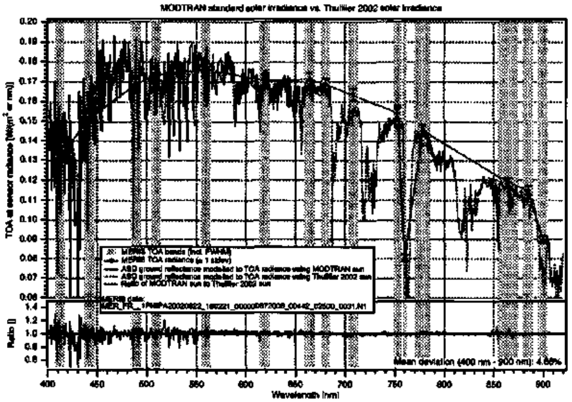

Figure 17: Top-of-atmosphere (TOA) radiances of MERIS on ENVISAT as modeled using vicarious calibration methods in comparison with two different solar irradiance standards (Kneubühler *et al.*, 2003).

The directional (anisotropic) component is increasingly covered with ground measurement instrumentation (Bruegge *et al.*, 2004; Schoenermark & Roeser, 2004), which are in generally referred to as goniometers (Sandmeier, 2000). They are existing in various designs, which are represented in Fig. 18.

Figure 18: Various directional ground acquisition instruments – or so called goniometers (Bruegge *et al.*, 2004)[20].

The general understanding of surface anisotropy and its importance to include in an overall uncertainty evaluation of spectro-directional based products has found its general way into the common understanding of processing remotely sensed data. Existing uncertainties can further be minimized by introducing a standardisation of terminology (Schaepman-Strub *et al.*, 2005 (submitted), as well as carefully evaluating the limitations of spectroradiometric measurements (cf., Fig. 19). But due to the fact that a spectroradiometric measurement is a multidimensional problem – as mentioned already earlier – as well as the inherent instability of the measuring instruments, and the techniques used for eliminating measurement errors, spectroradiometric measurements will remain one of the least reliable of all physical measurements (Kostkowski, 1997)!

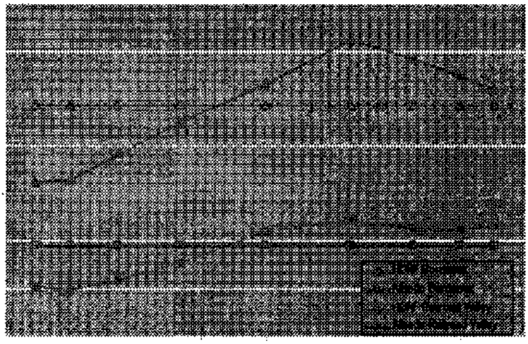

Figure 19: View angle dependent error of Albedo product retrieval accuracies when ignoring directionality (Schaepman-Strub *et al.*, 2005 (submitted)).

The importance of directional research is expressed in two user communities, one of them trying to stress the uniqueness of spectrodirectional images (Gobron *et al.*, 2002; Pinty *et al.*, 2002) whilst retrieving related parameters with increased accuracy, whereas others try to minimize the impact of directionality (Csiszar *et al.*, 2001; Hu *et al.*, 2000; Richter, 1998). Figure 20 depicts the retrieval difference of directional corrected and non-corrected results expressed in a difference image (Schaepman-Strub *et al.*, 2003). The resulting difference LAI product shows clearly vegetation structure aspects as well as the position of the hot-spot (Li & Strahler, 1992; Liang & Strahler, 1993) as a strong backscattering effect in the irrigated canopies.

Figure 20: Vegetation index difference images of directional corrected versus uncorrected images. Left: Directional differences visible in two differently acquired flights. Right: Ambrals (Hu *et al.*, 1997) BRDF corrected images, minimizing the directional differences. Middle: Difference image of left and right with applied GRVI (Green Vegetation Index, (Broge & Leblanc, 2001)). Obviously the difference image in the middle reveals information about the vegetation structure as can be clearly seen (Data from Moreno (2001)).

Finally, spectrodirectional remote sensing will allow the generation of products that support the estimation of critical vegetation parameters (Rast *et al.*, 2004), but neither is this approach limited to vegetation nor can all relevant parameters be estimated using these sensors alone.

The following table gives an indication of relevant input parameters for land-biosphere modelling as well as the technical implementation concept needed to successfully retrieve them with acceptable uncertainties.

Vegetation Variables (Parameters)	Spectrodirectional (reflected)	Spectrodirectional (emitted)	Radar (SAR)	Laser (LIDAR)
Vegetation spatial distribution and phenology Fractional vegetation cover (fCover) Leaf Area Index (LAI) Fraction living / dead biomass Canopy structure Vegetation height	✓		✓	✓
Vegetation interaction with radiation Albedo Fraction of Absorbed Photosynthetically Active Radiation (fAPAR)	✓	✓		
Foliage chemistry and water status Leaf chlorophyll Leaf water content Leaf dry matter Leaf nitrogen / foliage nitrogen	✓			
Vegetation and soil energy balance Foliage temperature (related to stomatal evaporation rate) Soil temperature (related to water stress)		✓		

Table 1: Four relevant vegetation parameter blocks needed to successfully run a land-biosphere model and associated remote sensing acquisition concepts.

The final products generated using spectrodirectional remote sensing approaches do not differ from any 'conventional' retrieval in their final appearance, but significantly differ in the resulting uncertainty. Fig. 21. illustrates three classical products, such as LAI (Leaf Area Index), fAPAR (fraction of Absorbed Photosynthetically Active Radiation), and fCover (fraction of vegetation cover) as described in the DAISEX experiments in Spain (Berger *et al.*, 2001).

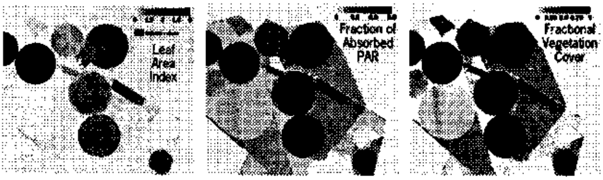

Figure 21: Three Level 3 products (from left: LAI, fAPAR, and fCover) derived from imaging spectrometers using atmospheric correction, geometric correction, and including a compensation for directional effects induced by the atmosphere and the ground.

From Pixels to Processes: The Land-Biosphere Model Approach

Typical land-biosphere models are composed out of 'building blocks' with associated functions that treat the interaction of photons with vegetation as follows:

- Carbon engine
    - o *f*(CO_2, light, water availability, temperature, nutrients)
- Carbon allocation
    - o *f* (geometry, physiology, plant functional type, species)
- "Remineralisation"
    - o *f* (plant functional type, physiology, microbiology, molecular structure (e.g. lignin vs. waxes or cellulose)
- Soil hydrology
    - o *f* (root depth)
- Population dynamics
    - o Succession
        - *f* (stand height, stand age, physiology)
    - o Disturbance
        - *f* (climate, fire, humans)

The *Carbon engine* usually defines how much carbon is fixed per unit time by photosynthesis. In general the amount of carbon fixed per unit time is a function of ambient (atmospheric) CO_2, light, water availability, temperature and nutrients. The second part deals with a recipe for ***carbon allocation*** of carbon fixed by photosynthesis to different living tissue like stems or roots. Carbon allocation is a function of plant geometry and physiology. This is followed by a description of the fate of dead plant material (*Remineralisation*), i.e. the carbon flow from living to non-living forms and its subsequent decomposition. The decay processes are a function of plant species, physiology, microbiology and molecular structure of plant tissue (e.g. lignin vs. waxes or cellulose). Next, a predictive equation of soil moisture (*Soil hydrology*) is given. Soil moisture is a function of soil hydraulic properties, evapotranspiration and precipitation. And finally a representation of the dominant stochastic *Population dynamics* processes like early versus late successional species through competition for resources (light, nutrients, water) which is a function of stand height, stand age, and physiology, and - disturbance by humans (land use), fire, windfall, insects which is a function of climate and human activity (Gloor, 2005).

Land-biosphere models can be grouped into two broad classes. The ones that use satellite data to locate the "photosyntetically active" land vegetation. In these models, the "Carbon engine" is then driven by absorbed light estimated from satellite and a prescribed light use efficiency. Typical representatives are the CASA model (Potter, 1993) and the TURC model (Ruimy *et al.*, 1996). Population dynamics is in a sense implicit in this formulation as explained later on. The second class of models predicts the spatial vegetation distribution and the organic soil pools on its own, while hydraulic properties of the soils are prescribed. Typical examples are the Lund-Potsdam-Jena (LPJ) model (Sitch *et al.*, 2003), and the Ecosystem Demography (ED) model (Moorcroft *et al.*, 2001). Several models include population dynamic processes like fire disturbance (e.g. LPJ). Nonetheless only a model that includes the description of demographics (age distribution of species classes as a function of time) and competition for light by including a description of height distribution can properly describe disturbance processes and their effect on land vegetation. The only model that currently propagates both height and age distributions is ED.

The following table compares five different land-biosphere models indicating their implementation of the building blocks (modified following (Gloor, 2005; Schaepman, 2005). A more detailed discussion can be found in the literature (Cramer *et al.*, 1999; Ruimy *et al.*, 1999)).

Model / Building Block	CASA	BETHY	PnET	LM3	SMART/SUMO
Carbon Engine	Light use efficiency, PAR, fPAR	(Farquhar *et al.*, 1982) or LUE	Pmax=a+b*N, where N is foliar nitrogen	(Farquhar *et al.*, 1982)	C-ass = f(light, N,P,water availability, temp)
Phenology	fPAR	?	Predicted	fPAR	Not relevant (timestep = 1y)
Allocation	Globally fixed ratios; leaf, litter, roots	?	Simple allocation rules for tissue types	Allometries	Ratios (root, shoot, leaf) fixed per vegetation type
Remineralisation	5 litter, 2 organic pools, first order decay	?	No soil carbon component	Fast and slow pools of C and N	Litter + 2 organic pools, fixed ratio + 1st order decay
(Soil-) Hydrology	Bucket type	Bucket type	One soil layer	Bucket type	Supplied by external hydrological model (WATBAL, SWAP)
Discretization	PFT's	PFT's	Biomass produced only by tissue type (foliage)	Defined by mortality and fecundity functions (species build a continuum)	5 FT's that compete for light, N, P, water
Demography	None	None	None	Core of model	None (but tree mortality included)
Reference	(Potter, 1993)	(Knorr, 2000)	(Aber & Federer, 1992)	(Anderson *et al.*, 2004)	(Wamelink *et al.*, 2000)

Table 2: Comparison of five land-biosphere models describing individual functionality of their core parts ((P)FT – (Plant) Functional Type; C-ass – Carbon assimilation; N – Nitrogen; P – Phosphorus) (Schaepman, 2005).

Observations by Data Acquisition Systems

In remote sensing, there are several mission categories described, that contribute to the systematic measurement of the Earth's reflected radiance.

Exploratory missions,

- ESA: SPECTRA (Rast *et al.*, 2004); NASA: ESSP (Earth System Science Pathfinder Missions, cf., (Crisp & Johnson, 2005) and AVIRIS (Green *et al.*, 1998)

Technology demonstrators / operational precursor missions,

- ESA: CHRIS/PROBA (Cutter *et al.*, 2004) and APEX

(Schaepman *et al.*, 2004); NASA: Hyperion/EO-1 (Ungar *et al.*, 2003)

Systematic measurement missions, and

- ESA: MERIS/ENVISAT (Bezy *et al.*, 1999); NASA: MODIS (Myneni *et al.*, 2002)

Operational missions.

ESA: MSG-1 (Borde *et al.*, 2004); NASA: NOAA AVHRR (Rao & Chen, 1999)

Figure 22: Current and future remote sensing missions can be subdivided into the following categories: exploratory missions, technology demonstrators (or operational precursor missions), systematic measurement missions, and operational missions (from left: SPECTRA, APEX, CHRIS, ENVISAT, and MSG).

Several international programmes and national space agencies and various national initiatives worldwide are developing missions in the above framework. With a particular European focus, the most important to be mentioned is the Living Planet Programme of ESA (Readings, 1998), composed out of two major elements

- a science and research element in the form of the Earth Explorer missions[21], and
- an element designed to facilitate the delivery of Earth observation data for the eventual use in operational services. This includes the well-established meteorological missions with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and also new missions focusing on the environ-

ment and civil security. This latter element, which is a joint initiative between the European Commission and ESA, is called GMES[22]. The space component of GMES includes the development and operations of all satellite and ground segment infrastructure providing the required data streams for the Sentinel 1-4/5[23].

Trends – Integrated Systems Solutions and *In Situ* Sensing

Historically, remote sensing and GIS needed to be integrated, because they pursued different and separate tracks. Integration of GIS and Remote Sensing was a keyword in Geo-Information Science in the 80ies and 90ies. At this time it sounded like people dealing with vector and raster representation of data needed further integration. But today we are looking at much more elaborated systems, namely integrated systems solutions supporting data assimilation. These solutions will provide scalable approaches, allowing the integration of multiple data sources. They also represent collaborative environments, supporting quantitative data analysis at several scales. Data assimilation will further allow the solid coupling of physical models, linking soil-vegetation-atmosphere-transfer (SVAT) models to state space estimation algorithms (e.g., Kalman filters) (Choudhury, 2001; Crow & Wood, 2003; Houser *et al.*, 1998; Olioso *et al.*, 1999; Weiss *et al.*, 2001).

Remote sensing will be increasingly part of a multidisciplinary research environment, complemented by *in situ* sensing. The latter will be a technology that is used to acquire information about an object, where the distance between the object and the sensor is comparable small to any linear dimension of the sensor (sensing in place). Networks of *in situ* sensors are existing already for a while (e.g., meteorological stations), and its becoming increasingly feasible to provide telecommunication technologies with these networks to achieve (near) real time integration of heterogeneous sensor webs into the information infrastructure (Bacharach, 2005; Chien *et al.*, 2005).

Current Achievements and Outlook

Spectrodirectional remote sensing enables biophysical and biochemical variables of the Earth's surface to be mapped with unprecedented accuracy. In addition to this, our quantitative understanding of the photon-vegetation interaction has been significantly deepened, by looking at many, contiguous spectral bands, as well as various view-angles to the Earth' surface.

Practically, this particular success is based on improved data quality and wider availability of consistent remote sensing observations to the user community. And secondly due to the broader availability of computing resources, that are needed to run quantitative, physical based models.

In the near future, new emerging applications in spectrodirectional remote sensing of vegetation will focus on monitoring

- Transitional zones
    - in particular ecotones, e.g., ecosystem-, communities-, or habitat boundaries (e.g., tundra – boreal forest, forest – heathland, etc.), where most of the pressure and changes in terms of disturbance are being identified,

- Managed ecosystems
    - o where precision appliance is a key economical factor, contributing to better yield estimates, and
- (Un-)managed ecosystems
    - o where plant succession, plant functional types, and invasive species are important focus areas

The above will be complemented by the consistent measurements of calibrated and validated surface reflectance to derive Albedo products, retrieval of columnar atmospheric absorption, such as water vapour and aerosol particle size distribution, the fraction of vegetation contributing to the photosynthetic processes, separation of canopy water and atmospheric water content, the canopy light use efficiency (LUE) for estimation of the carbon fixation rates, fire fuel and fuel moisture, as well as anthropogenic and non-anthropogenic induced disturbance (Asner *et al.*, 2005; Stuffler *et al.*, 2004).

Major challenges to be resolved with spectrodirectional remote sensing is still a continuous potential mismatch of spatio-temporal scales of field, airborne and spaceborne measurements, and model requirements. These must be addressed by pursuing a rigorous scientific agenda that is not limited to the scientific use of spectrodirectional data usage, but also includes a more thorough view on

- Spatio-temporal discontinuities in measurements that may result in variable data and product quality,
- Disturbance processes that are difficult to capture, due to limited mission duration times and missing backward compatibility,

- Data assimilation schemes becoming more important due to the steadily increasing availability of geo-data at large, and finally there will be a
- Convergence to Earth System Sciences observed, truly linking various disciplines into multidisciplinary approaches.

The combination of coupled soil-vegetation-atmosphere transfer in view of ecological and CO_2 related research questions will be – as demonstrated in this short overview – a primary focus for the upcoming years.

The multidisciplinary expertise of WUR, as well the international setting of it, provide an excellent framework to realize this.

Spectrodirectional remote sensing has made significant advances over the past years, and it has been shown before, that a good design is simple and survives a long time (Fig. 23).

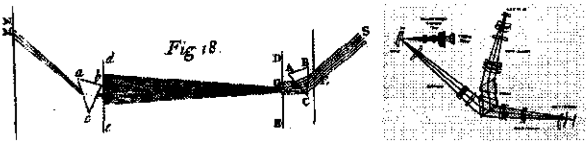

Figure 23: Comparison of two optical designs dated 1704 (left) and 2004 (right). Similarities in design are striking (Newton, 1704; Nieke *et al.*, 2004).

Acknowledgements

Following a good Wageningen tradition, I would like to review in brief my scientific career that finally results in this speech today.

I pursued and finalized my MSc in Geography (with minors in computer science and experimental physics) and my PhD in remote sensing at the University of Zurich (Fig. 24) in Switzerland. I am personally honoured, that both Klaus Itten and Harold Haefner from the University Zurich have given me excellent guidance during these steps in science, and I am particularly thankful to Klaus Itten for his patience and generosity. My co-workers at the Remote Sensing Laboratories[24] were always helpful in further deepening my knowledge in imaging spectroscopy.

Figure 24: Arial photograph from the University of Zurich (CH), Irchel campus in 1998[25].

The commercial market was tempting in times of the upcoming Internet in the early 90ies, and on January 1st 1996, a handful of students from the University of Zurich jointly with a few professionals founded a computer company named Netcetera AG, which today is a commercial endeavour of 85 employees. I endow my co-founders and colleagues[26] a lot of respect for being patient with me on getting to know the commercial side of business more in depth.

By slightly moving towards instrument design and optical performance estimation, I was involved in the development of an airborne imaging spectrometer named APEX. Within this project I had the chance to spend some time in 1999 in the 'optics valley' of the USA at the Optical Science Centre (Fig. 25) of the University of Arizona in Tucson (AZ). Calibration, specifications and instrument design of imaging spectrometers were the primary topics of interest and I received great support[27] from the Optical Science Centre!

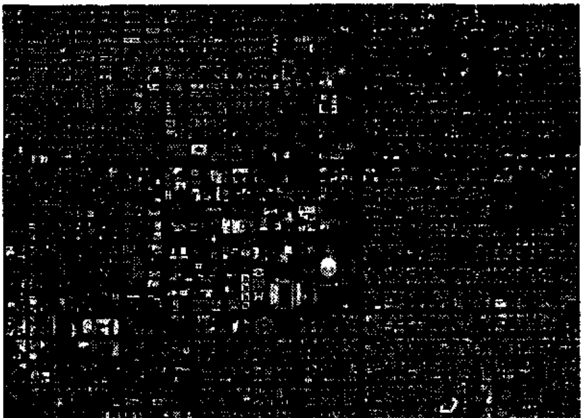

Figure 25: High resolution satellite image from the Univ. of Arizona, Tucson (USA), acquired on April 4, 2004[28].

Subsequently, I had the chance to contribute to the Mission Advisory Group (MAG) of an ESA Earth Explorer Core Mission named SPECTRA. I owe Michael Rast from ESA and the MAG members[29] my thanks here, without their vision and tolerance, I would never have gotten an insight in a space program at such level. I need to add, that several members of the SPECTRA mission are present today as well, and that Wageningen UR has a significant instake in this instrument and science, which we want to keep up and continue!

In 2002 I have received almost countless e-mails from various places in the world reminding me of an open position in Wageningen (Fig. 26). It was as if the remote sensing world wanted me to make a move. In the process of getting there, I was very well assisted by various persons and my special appreciation goes to Steven De Jong, Jan Clevers, and Arnold Bregt, who supported me significantly in this process.

Finally I need to congratulate and thank the Centre for Geo-Information for bearing such a long time understaffed, while maintaining sufficient visibility and output. Your support and welcome made me further aware of a good decision!

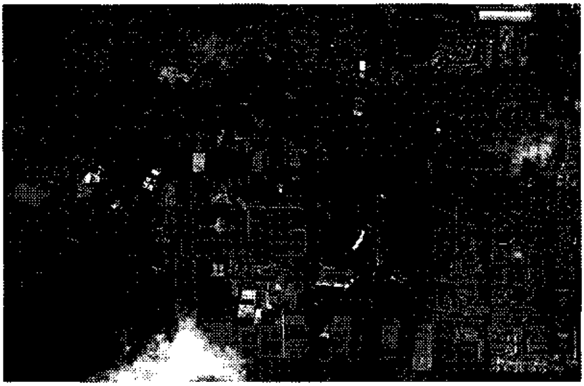

Figure 26: Digital aerial photograph from Wageningen University and Alterra, recorded on July 28, 2004[30].

Most important is the continuous support of my family, in particular my wife Gabriela and our son Linus, who supported me all this time with great patience – Thank you very much!

Finally I would like to thank the selection committee as well as the Trustees of the University for the honour they have bestowed upon me by asking me to speak at this very special occasion.

Meneer rector, dames en heren – Ik dank U allen voor Uw aandacht – Ik heb gezegd.

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[1] 'De Ketenbenadering in Aardobservatie – een overzicht van 35 jaar aardobservatie in Nederland'; June 23, 2004; Wageningen University; http://www.dow.wur.nl/NL/cgi/wks/wks_bunnik.

[2] HyMap data take over Wageningen, August 2, 2004, data courtesy Belspo, B.

[3] NASA Moderate Resolution Imaging Spectrometer (MODIS); http://modis.gsfc.nasa.gov/.

[4] Online access at http://dibinst.mit.edu/BURNDY/Collections/Babson/OnlineNewton/OnlineNewton.htm.

[5] ESA ATSR-1 on ERS-1, 1991.

[6] CNES POLDER on ADEOS, 1996; NASA MISR on TERRA, 1999.

[7] Online access at http://www-misr.jpl.nasa.gov/.

[8] Internet search based on *altavista.com*, citations on *scopus.com* using combinations of keywords (hyperspectral, imaging spectroscopy, imaging spectrometry, directional, multiangular, spectrodirectional, and variants thereof), as of September 2004.

[9] Barbara Krakow Gallery, http://www.barbarakrakowgallery.com/contentmgr/showdetails.php/id/339.

[10] HyMap image cube (Zurichsee (CH), 1999), rendering by the author.

[11] Paul Klee, Ueberschach (1937), Kunsthaus Zurich (CH).

[12] Johannes Itten, Offenbarung (1967), Container Corp., New York.

[13] NASA MISR - Multiangle Imaging SpectroRadiometer, http://www-misr.jpl.nasa.gov/.

[14] ESA SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis, http://www.esa.int/export/esaLP/spectra.html.

[15] Visualisation of Table 3.1, p. 190 from (Prentice *et al.*, 2001).

[16] NPP is widely accepted to be GPP (Gross Primary Production) minus the autotrophic respiration (*R*). However, neither NPP nor GPP can be measured directly and *R* is difficult to assess in particular in multi-species environments. Also NPP includes components such as roots which limit remote sensing based approaches to measure aNPP (aboveground NPP). Several definitions are documented in literature to assess aNPP, and generally it is composed of aNPP = B + D (where B is the biomass increment, and D detritus or litterfall production – and significant discussion arises whether or not to include tree mortality in aNPP). The belowground NPP (bNPP) deals with the components of fine and coarse roots, as well as Mycorrhizae. Usually bNPP is considered being a calibrated fraction of aNPP, but more modern approaches include the soil-carbon balance, amongst others.

[17] Data compiled from: (Curran, 1989; Fouche, 1995; Fourty *et al.*, 1996; Hurcom *et al.*, 1996; Sims & Gamon, 2003; Verdebout *et al.*, 1994; Wessman, 1990).

[18] Pictures by the author from the HyEco'04 campaign 2004 in the Millingerwaard (NL) and the EU MERCI project in Bily Kriz (CZ).

[19] Each image indicates a time step of 55 min. with the original, unstressed leaf as a reference (upper left). Total measurement time was 8.3 hrs. Data unpublished.

[20]From left to right: FIGOS (Univ. Zurich, CH), PARABOLA (JPL, USA), ASG (Univ. Colorado, USA), WAAC (DLR, D).

[21] Earth Explorer missions approved so far (2005): CryoSat (Determines variations in the thickness of the Earth's continental ice sheets and marine ice cover), GOCE (Gravity Field and Steady State Ocean Circulation Explorer), ADM-Aeolus (Athmospheric Dynamics Mission), SMOS (Soil Moisture and Ocean Salinity), Swarm (Dynamics of the magnetic field), and EarthCARE (Earth Clouds, Aerosols, and Radiation Mission).

[22] GMES (Global Monitoring for Environment and Security) – An initiative to secure Europe with an autonomous and operational information production system in support to environment and security policies.

[23] Sentinel 1 – C-band SAR, 2 – Superspectral, 3 – Operational Oceanography and Land Surface Mission (Altimeter plus spectrometer), 4/5 – Atmospheric Chemistry (Geostationary, low Earth orbit).

[24] At the time of my leave, these were Ulrich Beisl, Stephan Bojinski, Jason Brazile, Stefan Dangel, Johannes Kaiser, Mathias Kneubühler, Benjamin Kötz, Gabriela Schaepman-Strub, and Daniel Schlaepfer.

[25] Leica RC-40 aerial photograph, summer 1998, data courtesy Erich Meier, Univ. Zurich.

[26] Co-founders are Ronnie Brunner, Mike Franz, Joachim Hagger, Andrej Vckovski, Thomas Werschlein, and Peter Zurbruegg; board members Beat Stocker, Beat Barthold, and Hansruedi Vonder Muehll.

[27] Namely, Eustace Dereniak, Michael Descour, Derek Sabatke, and Kurtis Thome.

[28] OrbView, April 24, 2004, data by DigitalGlobe, USA.

[29] SPECTRA MAG members have been: Michael Rast, Frederic Baret, Bart van den Hurk, Wolfgang Knorr, Wolfram Mauser, Massimo Menenti, John Miller, Jose Moreno, Michel Verstraete. as well as the author.

[30] Vexcel UltraData, July 28, 2004, data courtesy Fred Hagman of Aerodata International Surveys, NL.