NEW AIRBORNE SENSOR FOR SOIL MOISTURE MAPPING

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ABSTRACT:

MIRAMAP has developed a fully operational digital airborne sensor to produce detailed soil moisture maps. The airborne soil moisture sensor is based on Passive Microwave Radiometry (PMR), a space technology for monitoring changes in soil moisture and ocean salinity of the earth from for example Space Station Mir and the International Space Station. This technology measures the naturally emitted radiation of the earth in the millimeter to decimeter range of wavelengths, where the land surface radiation is primarily a function of the free water content in soil. MIRAMAP has altered the space sensors for airborne operations to increase the spatial resolution from tens of kilometers to a few meters. This increase of detail combined with simultaneous data collection in X-, C- and L-band and GNSS positioning makes it possible to track regional changes in soil moisture and to detect water seepage. A first flight campaign with the new digital soil moisture sensor is to be performed in the fall of 2006 in collaboration with the Dutch government. The objectives are to produce reliable brightness temperature and soil moisture maps, and to validate the overall map quality using ground truth data. The results of this first airborne PMR flight campaign are to be presented at the workshop.

1. INTRODUCTION

Flooding events in New Orleans and Wilnis in the Netherlands are fresh in our memory. The climate change, rising water levels and heavier rainfall enforce decision makers who are responsible to protect their country for the human and economic consequences of flooding and drought to change their policies. The addition of soil moisture products to other geo-referenced data such as lidar elevation data seems critical for safety, emergency response operations, and the prediction of damage in case of flooding or drought.

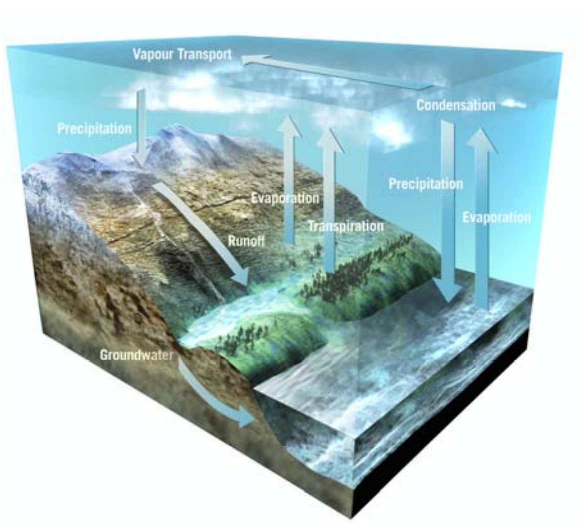

Figure 1. Water Cycle (image courtesy ESA)

Over the last few year, scientists have used soil moisture products to study environmental effects such as vegetation dynamics (Wen and Su, 2004; Krapivin et al, 2006; Chukhlantsev, 2006), heat fluxes between the atmosphere and the land surface (Su et al, 2001; Su, 2002; Su, 2006), pollutant flows, and climate change (Kondratyev et al, 2003). Quantitative soil moisture remote sensing plays an important role in the evaluation of water cycle exchanges in hydrosphere, biosphere, atmosphere and land surfaces (Figure 1).

Several space programs have been developed to map near-surface soil moisture, land surface salinity and temperature, and ocean surface salinity and temperature, using Passive Microwave Radiometry (PMR). This technology at the millimeter to decimeter range of wavelengths is the most sensitive remote sensing technology to soil moisture and ocean salinity, while maintaining the least sensitivity to interfering signals like from vegetation cover. The first radiometer launched to space for earth remote sensing to monitor global changes in soil moisture and ocean salinity was the Russian/Bulgarian Interkosmos-21 satellite in 1981. The Priroda (Nature) module with several scanning and non-scanning radiometers on board was attached to the Russian Space Station Mir in 1996.

Additional future space programs are currently under development. Planning for launch in 2007 is the Soil Moisture and Ocean Salinity (SMOS) program developed by ESA (Figure 2). This system is based on first-ever 2D interferometric radiometer system to capture images of emitted microwave radiation around the radio astronomy frequency of 1.4 GHz (L-band). Planning for launch in 2009 is Aquarius of NASA. Aquarius includes a set of three L-band passive and active radiometers that are sensitive to salinity. Realization the Hydrosphere State Mission (Hydros) was cancelled last year by NASA due to funding.

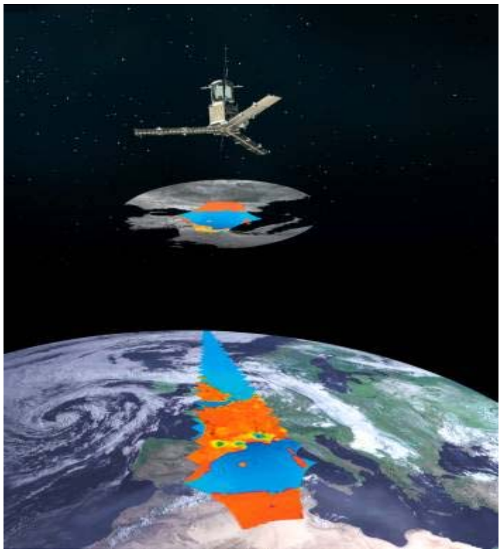

Figure 2. SMOS (image courtesy ESA)

Unfortunately, at the millimeter to decimeter range of wavelengths higher spatial resolution requires a large aperture. All of the above mentioned space programs deliver a spatial resolution of 50-60 kilometers. To date, there are no high-resolution soil moisture products available, and in fact there is not even an operational low resolution satellite product available.

2. SYSTEM SPECIFICATIONS

MIRAMAP has developed a fully operational digital airborne sensor to produce detailed soil moisture maps. Identical space sensors were altered for airborne operations to increase the spatial resolution of soil moisture products from 50-60 kilometers to a few meters. MIRAMAP is a private company at the European Space Incubator (ESI) initiative from the ESA Technology Transfer & Promotion (TTP) office. The TTP office is contributing to the capitalization of space-based technology and know-how for the benefit of Europe's economy in all industries. The innovation of MIRAMAP was nominated for the Holland Innovation Price in 2005 and was quoted in several newspapers and magazines such as the Dutch Financial Times.

The MIRAMAP instrument consists of three microwave sensors in X-band, C-band and L-band that are all GNSS integrated. The X-band and C-band sensor makes a conical scan at constant incidence angle over a wide swath, while the L-band sensor makes a twin-beam oscillating scan (Figure 3). The small instrument sizes and weights enable use of a low-cost light aircraft as the observing platform, providing decision makers with a new affordable tool. The instruments enable the measurement of top soil moisture content and salinity under low to moderate vegetation conditions and/or ocean salinity at 5-50 meters resolution.

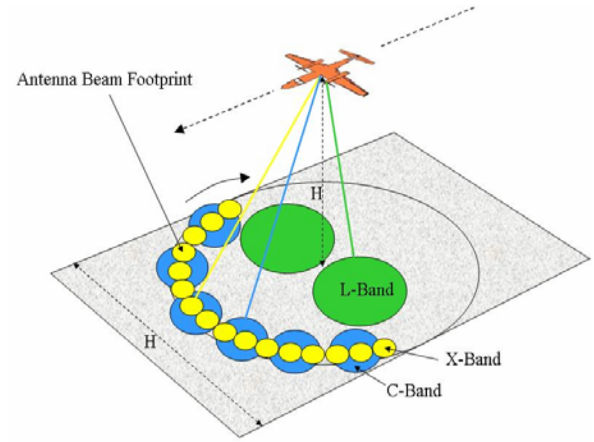

Figure 3. MIRAMAP Sensor Configuration

	X-band	C-band	L-band
Frequency (GHz)	15.2	5.5	1.4
Wavelength (cm)	2.0	5.5	21
Pixels/Scan	16	6	2
Incidence Angle (º)	30	30	15
Beam Width (º)	3.5	5	25
Polarization	H	H	H
Sensitivity (K/s)	0.15	0.2	1
Absolute Accuracy (K)	±5	±5	±5

Table 1. MIRAMAP Sensor Specifications

Each channel is calibrated by internal sources and by measuring the levels of radiation from a metal sheet or a water body and an artificial black body measured on the ground before take-off. The platform on which these instruments are flown is a reliable and safe twin Aero Commander (Figure 4). The aircraft is specially modified to simultaneously carry a range of other instruments available, such as (digital) photogrammetric cameras, lidar scanners and multispectral sensors. The capability to measure such a comprehensive range of remotely sensed parameters from a single low-cost airborne platform is unique worldwide.

Figure 4. MIRAMAP Sensor Aircraft

MIRAMAP is the first-ever company to develop and commercialize high-resolution airborne soil moisture products that are collected and combined simultaneously with supplementary data to be used for the most detailed surface information. The new soil moisture products have several benefits over traditional satellite- and ground-based soil moisture methods. First, detailed maps are produced with total area coverage showing regional variations. The system provides availability on a very short notice, collects large areas at a time, day or night, even over dangerous or inaccessible areas, and quality data are delivered within budget and schedule.

3. FROM SENSOR TO PRODUCT

Through both laboratory and field experiments it has been documented that the passive microwave radiometers, and the processing/retrieval algorithms from the Institute of Radioengineering and Electronics (IRE), Russian Academy of Sciences (RAS) are feasible to determine several soil, water and vegetation related environmental parameters and conditions. These are soil moisture content, depth to shallow water table, buried metal objects under shallow dry ground, contours of water seepage through hydro technical constructions (levees and dams), plant biomass above wet soil or water surfaces, salt and pollutant concentration in water areas, on-ground snow melting and ice on roads and runways.

	Operating Range	Max Abs Error
Soil Moisture (g/cc)	0.02 - 0.5	0.07
Depth to Water Table (m)	0.05 - 5	0.3 - 0.6
Plant Biomass (kg/m²)	0 - 3	0.2
Pollutant Concentrations (ppt)	1 - 30	1 - 5

Table 2. MIRAMAP Product Specifications

The operating range and errors of the main parameters that can be established with the MIRAMAP system are listed in Table 2. Spectral models were developed for bare soil and vegetation covered soil, for soil with a flat and rough surface with uniform and stratified moistening, and for dynamic moisture profiles and temperature changes. The following simplified but effectively working adaptive models and assumptions are a part of the current MIRAMAP workflow to obtain soil moisture retrievals from measurements simultaneously conducted in X-band, C-band and L-band.

Dielectric Permittivity

Formula (1) derived by (Krotikov, 1962) is used to describe the relationship between the dielectric constant of dry soil ε_d and soil density ρ_d in g/cc:

$$\sqrt{\varepsilon_d} = 1 + 0.5\,\rho_d \tag{1}$$

The "refractive" formula (2) derived by (Birchak et al, 1974) is used in the model to provide a satisfactory description of the real and imaginary parts of dielectric permittivity versus soil moisture as compared with experimental data (Shutko, 1982; Shutko and Reutov, 1982; Shutko, 1986):

$$\sqrt{\varepsilon} = \rho_w \sqrt{\varepsilon_w} + (1-\rho_w)\sqrt{\varepsilon_d} \tag{2}$$

where $\varepsilon = \varepsilon' + i\varepsilon''$ and $\varepsilon_w = \varepsilon'_w + i\varepsilon''_w$ are complex dielectric permittivity of wet soil and water in soil respectively

ρ_w = relative volumetric water content in soil

Emissivity

Formulas (3) and (4) derived by (Shutko, 1982; Shutko, 1986) are used in the model to provide satisfactory assessments of land surface emissivity $\kappa = T_s^b / T_s^{eff}$ for bare soil assuming small changes in soil moisture profile and for ± 20 degrees off nadir viewing observation:

$$\kappa = \frac{4\sqrt{/\varepsilon/}\cos\delta/2}{/\varepsilon/ + 2\sqrt{/\varepsilon/}\cos\delta/2 + 1} \tag{3}$$

and

$$\kappa = \frac{a\rho_w + b\rho_d + c}{d\rho^2{}_w + e\rho_w + f\rho_w\rho_d + g\rho^2{}_d + h\rho_d + q} \tag{4}$$

where $/\varepsilon/ = \sqrt{(\varepsilon')^2 + (\varepsilon'')^2}$

$\delta = arctg\, \varepsilon'' / \varepsilon'$

$a - q$ = coefficients depending on wavelength λ, temperature T and soil mineralization S

The effective thickness of the emitting layer, that is the characteristic sensing depth (skin-depth) at wavelength λ, is connected with the absorption coefficient γ as

$$l = \frac{1}{\gamma} = \frac{\lambda}{2\sqrt{2\pi}\sqrt{/\varepsilon/ - \varepsilon'}} \tag{5}$$

Impact of Vegetation

Formulas (6) to (9) derived in (Kirdiashev et al, 1979; Shutko, 1982; Shutko and Chukhlantsev, 1982; Chukhlantsev and Shutko, 1990; Shutko, 1992) are used in the model to provide satisfactory assessments of soil-vegetation system emissivity in the assumption of a negligible effect of reflectivity from running vegetative canopy and for $T_s \cong T_v$, where T_s and T_v are effective physical temperature of soil surface and vegetation respectively:

$$T_{sv}^b \cong T_s^b \beta + (1-\beta) T_v \tag{6}$$

$$\beta \cong e^{-2\tau} \tag{7}$$

$$\tau = \gamma_v h_v \approx \eta_v Q_v \tag{8}$$

$$\beta \cong \frac{\Delta T_{sv}^{b} / \Delta \rho_w}{\Delta T_s^{b} / \Delta \rho_w} = \frac{\Delta T_{sv}^{b}}{\Delta T_s^{b}} \qquad (9)$$

where T_{sv}^{b} = brightness temperature data for soil-vegetation system

T_s^{b} = brightness temperature data for bare soil

ΔT_{sv}^{b} = changes in brightness temperature data for soil-vegetation system due to changes in soil moisture

ΔT_s^{b} = changes in brightness temperature data for bare soil due to changes in soil moisture

τ = integral absorption coefficient of electromagnetic radiation

γ_v = linear/running absorption coefficient of electromagnetic radiation

h_v = height of vegetative canopy

Q_v = unit biomass of vegetative canopy

Impact of underground irregularities

Radiation contrast, caused by some irregularity at z depth can be described by the following simplified expression:

$$\Delta \kappa \approx (1 - r_1)^2 r_2 e^{-2\tau} \qquad (10)$$

where $\tau = \gamma z$

r_1 = reflection coefficient from upper atmosphere-soil boundary

r_2 = reflection coefficient from lower soil layer-wet soil boundary

Figure 5 shows a Graphical User Interface (GUI) to produce one of the soil moisture products.

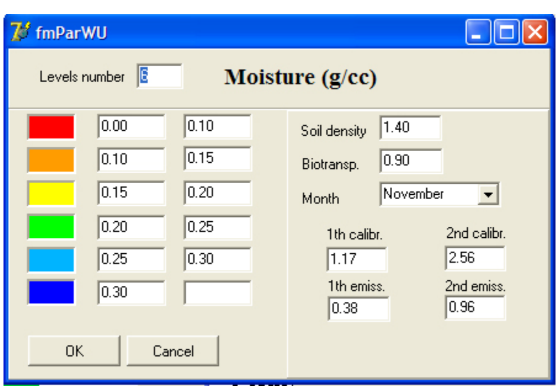

Figure 5. MIRAMAP Data Processor

4. FLIGHT CAMPAIGN

MIRAMAP is planning for its first data collection in October 2006. The project is supported by the Dutch Ministry of Transport, Public Works and Water Management and *Hoogheemraadschap De Stichtse Rijnlanden*, a Water Board, who are both responsible for protection against floods and falling water tables, and who are interested in the innovation for monitoring water barriers, and for improving their hydrological models.

Extensive gound-based data will be collected for validation and comparison studies. The MIRAMAP data will be compared against existing digital vector data, aerial photography, lidar elevation data, soil type information such as wilting point, field capacity and saturation, vegetation type and density, and overall topography. In-situ data are taken of soil moisture at three different depths, soil temperature, air temperature, depth to water table, and precipitation. The objectives are to produce reliable brightness temperature and soil moisture maps, and to validate the overall map quality using ground truth data.

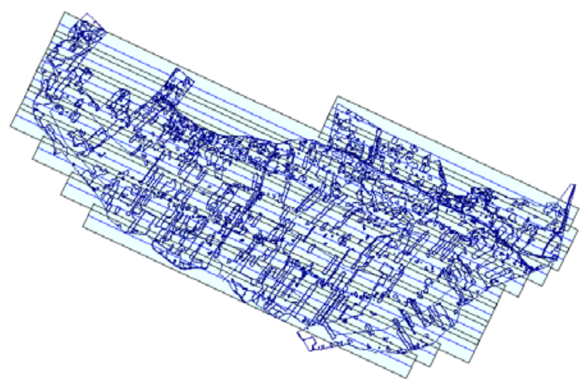

Figure 6. MIRAMAP Flight Plan

The MIRAMAP sensors will be flown at different altitudes over several sites with various characteristics, including primary and secondary water barriers. Figure 6 shows a flight plan of one of the interest areas. The first results of this campaign are to be presented at the workshop.

5. CONCLUSIONS

To date, there are no high-resolution soil moisture products available, and in fact there is not even an operational low resolution satellite product available. MIRAMAP has developed a unique, fully operational digital airborne sensor to produce detailed soil moisture products that can be used for several purposes such as environmental research, improving hydrological models, and for the protection against floods and falling water tables.

The capability to simultaneously measure three microwave bands in X-band, C-band and L-band and a range of other instruments such as (digital) photogrammetric cameras, lidar scanners and multispectral sensors from a single and reliable airborne platform is unique worldwide.

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7. ACKNOWLEDGEMENTS

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