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An historical empirical line method for the retrieval of surface reflectance factor from multi-temporal SPOT HRV, HRVIR and HRG multispectral satellite imagery

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ABSTRACT

SPOT satellites have been imaging Earth's surface since SPOT 1 was launched in 1986. It is argued that absolute atmospheric correction is a prerequisite for quantitative remote sensing. Areas where land cover changes are occurring rapidly are also often areas most lacking *in situ* data which would allow full use of radiative transfer models for reflectance factor retrieval (RFR). Consequently, this study details the proposed *historical empirical line method* (HELM) for RFR from multi-temporal SPOT imagery. HELM is designed for use in landscape level studies in circumstances where no detailed overpass concurrent atmospheric or meteorological data are available, but where there is field access to the research site(s) and a goniometer or spectrometer is available. SPOT data are complicated by the ±27° off-nadir cross track viewing. Calibration to nadir only surface reflectance factor (ρ_s) is denoted as HELM-1, whilst calibration to ρ_s modelling imagery illumination and view geometries is termed HELM-2. Comparisons of field measured ρ_s with those derived from HELM corrected SPOT imagery, covering Helsinki, Finland, and Taita Hills, Kenya, indicated HELM-1 RFR absolute accuracy was $\pm 0.02\rho_s$ in the visible and near infrared (VIS/NIR) bands and $\pm 0.03\rho_s$ in the shortwave infrared (SWIR), whilst HELM-2 performance was $\pm 0.03\rho_s$ in the VIS/NIR and $\pm 0.04\rho_s$ in the SWIR. This represented band specific relative errors of 10–15%. HELM-1 and HELM-2 RFR were significantly better than at-satellite reflectance (ρ_{SAT}), indicating HELM was effective in reducing atmospheric effects. However, neither HELM approach reduced variability in mean ρ_s between multi-temporal images, compared to ρ_{SAT}. HELM-1 calibration error is dependent on surface characteristics and scene illumination and view geometry. Based on multiangular ρ_s measurements of vegetation-free ground targets, calibration error was negligible in the forward scattering direction, even at maximum off-nadir view. However, error exceeds $0.02\rho_s$ where off-nadir viewing was ≥20° in the backscattering direction within ±55° azimuth of the principal plane. Overall, HELM-1 results were commensurate with an identified VIS/NIR $0.02\rho_s$ accuracy benchmark. HELM thus increases applicability of SPOT data to quantitative remote sensing studies.

1. Introduction

SPOT (Satellite Pour l'Observation de la Terre) satellites have been providing consistent optical imaging of Earth's surface since SPOT 1 was launched in 1986. Currently SPOT 4 and 5 are still in orbit and operational. The High Resolution Visible (HRV) sensors on SPOT 1, 2 and 3 collected data at 20 m spatial resolution in the green, red, and near-infrared (NIR) wavelengths, whereas the SPOT 4 High Resolution Visible Infrared (HRVIR) and the 10 m resolution SPOT 5 High Resolution Geometric (HRG) sensors additionally image in the shortwave infrared (SWIR). To increase revisit time, all SPOT sensors can view off-nadir cross track through ±27° which, due to the Earth's curvature, relates to a sensor view incidence angle (θ_V) range of ± 31°.

Optical satellite imagery is most commonly used for mapping land use and land cover (LULC) and LULC change over time (Song et al., 2001). However, raw digital numbers (DN) recorded in SPOT imagery are not an accurate measure of change over time because they are a function not only of surface conditions but also of diurnally variable atmospheric conditions, the seasonally variable Earth–Sun distance, solar zenith angle (θ_Z), θ_V, and sensor calibration (Moran et al., 2001). Sensor calibration can be achieved utilizing supplied gain and offset coefficients to convert DN into at-satellite radiance (L_{SAT}, W m^{-2} sr^{-1} μm^{-1}). It is then possible to convert these radiances into at-satellite reflectance (ρ_{SAT}), which normalizes for variations due to the Earth–Sun distance and θ_Z. This then leaves the contribution of the atmosphere and the effect of an off-nadir θ_V to be accounted for.

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Arguably, absolute atmospheric correction is a prerequisite for quantitative remote sensing studies utilizing optical satellite imagery. As Moran et al. (2001) note, surface reflectance factor (ρ_S) has become the basic measurement required for most remote sensing applications and models. The ρ_S is defined as the ratio of radiant flux reflected by a surface to that reflected into the same reflected-beam geometry and wavelength interval by an ideal Lambertian standard surface under identical conditions of illumination (Schaepman-Strub et al., 2006). This standard surface is commonly approximated in field measurement circumstances by a Spectralon® panel. Under typical field conditions viewed by spaceborne or ground based sensors, with a ground instantaneous field-of-view (GIFOV) formed from a conical solid angle of observation, the ambient sky irradiance is formed of both direct solar illumination and a hemispherical anisotropic diffuse irradiance (Martonchik et al., 2000; Schaepman-Strub et al., 2006). The ratio of direct to diffuse irradiance is a function of wavelength, with decreasing Rayleigh and aerosol scattering with increasing wavelength, which strongly influences the spectral dependence of ρ_S (Martonchik et al., 2000).

Typical observation circumstances are, then, most accurately described by what can be termed the "in-field" hemispherical–conical reflectance factor (HCRF), acknowledging that the hemispherical diffuse irradiance component is not isotropic like a theoretical HCRF. If the instantaneous field-of-view (IFOV) solid angle of observation of a spaceborne sensor is very small, then the reflected radiance may be near constant over the full cone angle, approximating a directional reflectance; a *directional* reflectance meaning the conceptual scattering of a collimated beam of light into a specific direction within the hemisphere (Nicodemus et al., 1977). In such circumstances, in-field HCRF is equivalent to in-field hemispherical-directional reflectance factor (HDRF). However, SPOT satellites have an IFOV with a full conical angle of 4.18°, which consequently is only an approximation of a directional reflectance. Moreover, HDRF or HCRF depends on the angular distribution of the illumination and the proportion of the diffuse to direct irradiance, as well as the scattering properties of the surface itself. The amount and spectral distribution of diffuse irradiance is dependent on atmospheric conditions, local topography and the reflectance properties of the adjacent ground surface (Martonchik et al., 2000).

Consequently, as Lyapustin and Privette (1999) note, multiangular ρ_S field measurements made under ambient sky conditions show significant shape differences relative to the reflectance characteristics of the actual surface itself; this being described by the bidirectional reflectance factor (BRF) or the modelled theoretical bidirectional reflectance distribution function (BRDF) (Schaepman-Strub et al., 2006). BRF is *not*, however, retrievable in any meaningful way from single observation angle satellite imagery, such as SPOT data. Nonetheless, by accounting for the atmospheric effects in the imagery, it is possible to retrieve ρ_S described as the in-field HDRF, which is equivalent to ρ_S measurements made at the surface.

Many methods of reflectance factor retrieval (RFR) through absolute atmospheric correction have been developed. Where detailed overpass concurrent measurements of atmospheric properties are available, notably atmospheric optical depth, it is possible to make full use of radiative transfer models (RTMs), such as MODTRAN (Berk et al., 2000). However, it is logistically difficult to acquire such data, and may be impossible for archived imagery. Good quality historical meteorological records and generalized assumptions about atmospheric composition, based on modelled atmospheres, allows for a wider application of RTMs. Nevertheless, in many areas of the world there is a lack of meteorological data available that is detailed enough, and has appropriate spatial and temporal frequency, to allow for accurate application of RTMs. These areas are also often places where the most rapid and significant changes in LULC are occurring, and where the need for environmental monitoring is greatest.

In most local or regional scale remote sensing projects, the opportunity exists to visit the study area; for example, to collect LULC training and ground reference test data. Where a spectrometer or goniometer is available for use or can be borrowed, it is possible to make field measurements of ρ_S. Empirical line (EL) methods align L_{SAT} data to ρ_S field measurements of spectrally pseudo-invariant within-scene calibration sites (Smith and Milton, 1999). This is achieved utilizing standard linear regression. Previous researchers have successfully retrieved ρ_S from remotely sensed data utilizing EL approaches (e.g. Smith and Milton, 1999; Perry et al., 2000; Moran et al., 2001, 2003; Karpouzli and Malthus, 2003; Xu and Huang, 2006). The main assumptions are that the atmosphere is approximately homogenous throughout the image area and that there is a linear relationship between L_{SAT} and ρ_S. As Moran et al. (1990) note, although this relationship is quadratic for the full range of reflectance, it is sufficiently linear over 0–0.7ρ_S to allow linear interpolation with negligible error. Few surfaces have $\rho_S \geq 70\%$. Because of this, in outlining their refined empirical line (REL) method for Landsat data, Moran et al. (2001) showed that an accurate estimation of correction lines could be obtained using only two reflectance targets: firstly, ρ_S field measurements for one appropriate within-scene bright calibration target and, secondly, an estimate of L_{SAT} for $\rho_S = 0$ derived using an RTM and "reasonable" water and aerosol models, or measurements of atmospheric conditions on a "typical" cloud-free day.

The proposed *historical empirical line method* (HELM) is similar to REL. The atmospheric path radiance (L_P) estimate, however, is directly image derived from within-scene dark-objects, by making assumptions about their reflectance. Therefore HELM negates the requirement to utilize an RTM and estimate atmospheric parameters. Furthermore, as Smith and Milton (1999) note, if the calibration targets are spectrally pseudo-invariant over time then ρ_S measurement need not coincide with image acquisition.

SPOT data are, though, complicated by the off-nadir viewing capability. Consequently, ideally calibration site multiangular reflectance characteristics should be measured. However, it is acknowledged that in many circumstances it may only be possible to collect nadir ρ_S measurements reliably. For this study, the Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO; Suomalainen et al., 2009) was used to take multiangular ρ_S measurements and investigate the effect of HELM calibration to nadir ρ_S on RFR accuracy. Calibration to nadir ρ_S is denoted as the HELM-1 approach, whilst calibration to ρ_S data modelling the exact illumination and view geometry of the SPOT imagery is termed the HELM-2 approach.

Schroeder et al. (2006) stated that a benchmark for successful atmospheric correction of optical satellite imagery in the visible/NIR (VIS/NIR) bands is an absolute accuracy of $\pm 0.02\rho_S$. Liang et al. (2002) atmospherically corrected Landsat ETM+ data with an absolute RMSE of 0.009–0.015ρ_S in the visible bands and 0.027–0.041ρ_S in the NIR, based on a comparison with spectrometer field measurements. This represented a relative error of ~10% throughout the VIS/NIR bands. Hall et al. (1992) found that ±0.01–0.02 absolute ρ_S accuracy was achievable across the VIS/NIR bands of Landsat and SPOT data using RTMs and overpass concurrent radiosonde profiles. The Landsat SWIR bands, however, were found to be more problematic with ±0.06 absolute accuracy (Hall et al., 1991). HELM should, therefore, achieve VIS/NIR RFR within $\pm 0.02\rho_S$, derive SWIR absolute accuracy better than ρ_{SAT} estimates, and achieve ~10% overall relative accuracy in all spectral bands, in order to be considered as a usable effective atmospheric correction methodology.