Advances in Regional Evapotranspiration Estimation Using the Scintillation Method: Postprint

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Abstract

Evapotranspiration constitutes a crucial component of water and heat transfer in the Soil-Plant-Atmosphere Continuum (SPAC) and represents an important element of global water balance, having consistently served as a significant research theme across meteorology, hydrology, geography, ecology, and related disciplines. The spatiotemporal variation of regional-scale land surface evapotranspiration is exceedingly complex. To date, conducting representative observations of land surface evapotranspiration at the pixel scale, particularly under conditions of heterogeneous underlying surfaces and undulating terrain, remains exceedingly challenging. Although remote sensing methods can acquire regional-scale evapotranspiration data, they primarily rely on empirical or semi-empirical models for estimation. The parameters employed in these models and their resultant outputs necessitate improvement and optimization through ground-based measurements. Consequently, obtaining ground-measured evapotranspiration data that corresponds to remote sensing scales has emerged as a critical focus and formidable challenge in model validation. The advent of the optical scintillation method offers promising solutions to these issues. Capable of accommodating complex underlying surfaces while delivering accurate measurements with the advantage of spatial and temporal averaging, the optical scintillation method has become an effective approach for measuring regional evapotranspiration and an optimal tool for validating remote sensing model results. This paper summarizes research progress in regional evapotranspiration observation via the optical scintillation method, covering theoretical principles, calculation methodologies, and primary applications, identifies uncertainty factors influencing measurement accuracy, and proposes future research directions, with the aim of further promoting the application of this method in regional evapotranspiration observation studies and advancing the development of related disciplines.

Advances in the Study of Regional-Averaged Evapotranspiration Using the Scintillation Method

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Abstract

Evapotranspiration is a key component of water and heat transfer in the soil-plant-atmosphere continuum (SPAC) and an important part of global water balance, representing a significant research topic in meteorology, hydrology, ecology, and related disciplines. The spatiotemporal variation of surface evapotranspiration at the regional scale is highly complex, making representative observations at the pixel scale particularly challenging under conditions of heterogeneous underlying surfaces and undulating terrain. While remote sensing methods can provide regional-scale evapotranspiration estimates, these rely primarily on empirical or semi-empirical models whose parameters and outputs require validation and optimization using ground-based measurements. Obtaining ground-based evapotranspiration data at scales corresponding to remote sensing pixels has thus become a critical focus and technical bottleneck for model validation. The development of scintillation methods offers a promising solution to these challenges. The scintillation method can adapt to complex underlying surfaces and produces accurate results when both temporal and spatial averaging are applied, making it an effective approach for measuring regional evapotranspiration and potentially the best method for validating remote sensing model outputs. This study discusses the theoretical background of scintillometry, summarizes its primary applications in regional evapotranspiration measurement, analyzes uncertainties related to hardware equipment, environmental factors, and key calculation parameters, and proposes future research prospects. Our synthesis aims to promote broader application of the scintillation method in regional evapotranspiration observation and advance related disciplines.

Keywords: regional-averaged evapotranspiration; large aperture scintillometer; microwave scintillometer; remote sensing; flux

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1. Principle of the Scintillation Method for Measuring Sensible and Latent Heat

When light propagates through turbulent atmosphere, fluctuations in air temperature, humidity, and pressure cause variations in atmospheric refractive index, resulting in irregular changes in beam intensity and frequency—a phenomenon known as scintillation. The scintillation method determines the refractive index structure parameter (C_n^2) from measured fluctuations in received light intensity using the formula:

$$C_n^2 = f(\text{path length } L, \text{aperture size } D, \text{variance of log-intensity } \sigma^2_{\ln I})$$

The refractive index structure parameter C_n^2 is influenced by temperature fluctuations, humidity fluctuations, and their covariance. For near-infrared wavelengths, temperature fluctuations dominate C_n^2, allowing simplification by introducing a Bowen ratio coefficient. To calculate C_n^2 for the near-infrared band (LAS), the variance of the natural logarithm of received light intensity is measured. Calculating C_T^2, C_q^2, and the temperature-humidity covariance term C_{Tq} requires additional assumptions. The dual-wavelength method employs both infrared and microwave systems, enabling simultaneous determination of C_T^2, C_q^2, and C_{Tq} through combined measurements.

According to Monin-Obukhov Similarity Theory (MOST), the structure parameters relate to stability functions:

$$C_T^2 = \frac{T_*^2}{\kappa^{2/3}} f_T\left(\frac{z-d}{L_{MO}}\right)$$

$$C_q^2 = \frac{q_*^2}{\kappa^{2/3}} f_q\left(\frac{z-d}{L_{MO}}\right)$$

where z is measurement height, d is zero-plane displacement, L_{MO} is Obukhov length, κ is the von Kármán constant (0.4), T_* is temperature scale, and q_* is humidity scale. These equations typically lack analytical solutions for sensible heat flux (H) or latent heat flux (L_vE). For near-infrared scintillometry, H is solved iteratively, then L_vE is obtained as a residual from the energy balance equation: $L_vE = R_n - G_s - H$, where R_n is net radiation and G_s is soil heat flux.

1. Single-Wavelength Method

Single-wavelength scintillometry using near-infrared wavelengths (880-940 nm) has been widely validated against eddy covariance measurements. Studies over flat grasslands, barley fields, and irrigated areas demonstrate strong agreement, with standard errors typically within 25 W/m². The method' s statistical uncertainty is smaller than eddy covariance due to shorter averaging times required.

Applications in China's Yellow River Basin, Tibetan Plateau, and various ecosystems (farmland, semi-arid, and arid regions) show high consistency with eddy covariance results.

For heterogeneous surfaces, the method' s applicability has been extensively investigated. Research in mixed vegetation areas of Sri Lanka, forest-farmland mosaics in northeastern Germany, and hilly terrain in northern China demonstrates that with proper consideration of path weighting functions and source area contributions, scintillometry yields reliable regional flux estimates. Correlation coefficients between weighted eddy covariance measurements and scintillometer results can exceed 0.93. The method effectively validates satellite remote sensing retrievals, showing good agreement with AVHRR and LANDSAT data across various ecosystems.

Commercial instruments from Kipp & Zonen (Netherlands) and Scintec (Germany) have matured, making single-wavelength scintillometry operational for kilometer-scale flux measurements. However, the method requires additional energy balance sensors (net radiometer, soil heat flux plates) and relies on the energy balance residual approach, introducing uncertainties from spatial heterogeneity in radiation and soil heat flux components.

2. Dual-Wavelength Method

Dual-wavelength scintillometry, combining near-infrared and microwave systems, directly measures both temperature and humidity fluctuations, eliminating spatial representativeness issues inherent in the energy balance method. Early theoretical work in the 1980s–1990s established the foundation, with Kohsiek (1983) first deriving latent heat flux from optical and radio-wave scintillation. Systematic analyses identified optimal wavelength pairs (e.g., 1.86 mm/160 GHz and 11 mm/27 GHz) that balance sensitivity to water vapor and cost-effectiveness.

Field applications over suburban areas, grasslands, and heterogeneous landscapes validate the method' s feasibility. Studies in Swindon (UK) and Chinese grasslands report correlation coefficients of 0.96 for sensible heat and 0.76 for latent heat compared to eddy covariance. The method simplifies evapotranspiration calculation by directly measuring both flux components without requiring energy balance closure.

However, most dual-wavelength instruments remain research-grade, with limited commercial availability and higher costs compared to single-wavelength systems. The method also faces challenges from instrument separation, which creates different path weighting functions and source areas for the two wavelengths, adding uncertainty to flux calculations.

1. Uncertainties from Instrument Limitations

Signal saturation represents the most significant limitation, occurring under strong turbulence when scintillation intensity exceeds the instrument' s dynamic range. Saturation thresholds are typically expressed as $L^{-8/3}\lambda^{1/3}D^{5/3}$, with values around 0.193 or 0.074 depending on experimental conditions. Correction methods include saturation factor adjustments and geometric path length modifications, though these remain imperfect. Water vapor absorption also affects optical signals, potentially causing errors up to 5-10% that can be reduced through appropriate filtering.

Systematic errors between instruments of the same model (Kipp & Zonen or Scintec) are typically around 5-10%, with inter-model differences reaching 9.9%. Dual-wavelength systems face additional uncertainties from frequency selection and wavelength configuration, as optimal combinations vary by application. Table 1 summarizes microwave selections from various studies, showing wavelengths ranging from 1.8-11 mm and frequencies from 27-160 GHz.

2. Uncertainties from Environmental Factors

The Bowen ratio ($\beta = H/L_vE$), representing the ratio of sensible to latent heat flux, critically affects accuracy. Studies show that when β varies from 0.1 to 2, standard deviations in results can reach 20-50%. Using absolute humidity versus saturation vapor pressure to represent moisture conditions introduces additional uncertainty, as the temperature dependence of humidity variables affects C_n^2 calculations.

Surface heterogeneity challenges MOST applicability. Vegetation cover, land use patterns, and terrain undulation cause variations in effective measurement height along the path. While MOST functions derived from different experiments share similar forms, coefficients vary significantly (Table 2). In stable conditions where mechanical shear dominates over buoyancy, MOST performance degrades, leading to large discrepancies between different universal functions. Currently, no standardized approach exists for function selection, and most studies focus on daytime data while neglecting nighttime conditions where scintillometry faces greater challenges.

3. Uncertainties from Calculation Process

Single-wavelength methods using energy balance residuals can underestimate evapotranspiration because net radiation and soil heat flux measurements lack spatial representativeness along the scintillometer path. Even after Bowen ratio corrections, spatial heterogeneity in roughness length and displacement height introduces bias. For dual-wavelength methods, most studies assume $R_{Tq} = \pm 1$ (perfect temperature-humidity correlation), which fails under non-ideal conditions. Real-time R_{Tq} determination methods exist but require precise knowledge of instrument geometry and path configuration, with measurement errors in spacing and length affecting coefficients. The assumption that infrared and microwave paths intersect at mid-path is often violated in practice, introducing 20–50% uncertainty in evapotranspiration estimates.

4. Uncertainties from Flux Source Area Evaluation

Current source area models perform well over flat, homogeneous surfaces but have limited applicability over complex terrain. Factors including effective height variations, roughness changes, and atmospheric stability transitions can cause up to 20% bias in flux estimates. Studies over the Tibetan Plateau demonstrate that wind direction and source area mismatches between instruments significantly affect results. When scintillometer and eddy covariance source areas do not coincide, discrepancies become substantial. Proper application requires careful consideration of measurement height, surface roughness, and stability effects on source area distribution. For dual-wavelength systems, separate instrument locations create different source areas, increasing uncertainty when applying single-wavelength source area models.

4. Conclusions and Prospects

Scintillometry provides kilometer-scale averaged water and heat fluxes with high temporal resolution and strong spatial representativeness, making it ideal for validating satellite remote sensing retrievals. The method operates continuously under complex weather conditions with lower statistical uncertainty than eddy covariance due to shorter averaging times. Over homogeneous surfaces, results agree closely with eddy covariance; over heterogeneous surfaces, good agreement is achieved after accounting for wind direction and source area effects.

Single-wavelength methods are mature and commercially available but require additional energy balance sensors and suffer from spatial representativeness issues in radiation and soil heat flux measurements. Dual-wavelength methods, though less developed and more expensive, directly measure both flux components and show greater potential for high-precision regional flux research, particularly over non-uniform terrain.

Future research should address: 1. **Theoretical improvements**: Turbulence spectral corrections for frequency loss, development of appropriate similarity functions through combined turbulence spectral analysis and eddy covariance observations, and saturation/water vapor absorption corrections. 2. **Parameter determination**: Roughness length, displacement height, and source area analysis under complex terrain; real-time R_{Tq} estimation for dual-wavelength systems. 3. **Validation studies**: Aerosol absorption effects along optical paths, path weighting function discrepancies from instrument separation in dual-wavelength systems, and comprehensive uncertainty quantification.

Despite existing uncertainties in signal saturation, similarity function selection, and source area modeling, scintillometry has become an essential tool for regional evapotranspiration research. Continued development, particularly of dual-wavelength systems, will further enhance its capability for water resource management and climate change studies at regional scales.

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Note: Figure translations are in progress. See original paper for figures.