

Scintillometry for Evapotranspiration estimation over irrigated alfalfa and dry grassland

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Abstract. In recent years scintillometry technology has become a recognized tool for the estimation of spatially-averaged vegetative ET rates. In particular, a Large Aperture Scintillometer (LAS) can provide estimates of the surface sensible heat flux (H) and, in combination with measurements of surface net radiation (Rn) and ground heat flux (G), can be used to solve for evaporative heat flux (λE) using the surface energy balance method. The LAS can operate over path lengths between 250 and 4500 m approximately and reports a path-averaged signal whose largest weight is at the path center. Two separate deployments of a Kipp and Zonen model LAS were considered; the first case (alfalfa deployment, site 1) during the 2010 summer over a fully irrigated alfalfa field and the second case (grassland deployment, site 2) at a dry grassland site during the 2011 summer. In each case, ancillary instrumentation was deployed for capturing necessary meteorological inputs and measurements of Rn and G. For the alfalfa deployment, a two-week subset of near-reference condition (50 cm crop height) data was processed and analyzed to derive hourly estimates of energy-balance ET from the LAS signal. The resulting H for this condition was generally less than 50 W m^{-2} during the morning/early afternoon periods, and negative H between $50\text{-}150 \text{ W m}^{-2}$ was observed during the afternoon/evening periods, which suggests advective conditions. ET rates for the same data subset had a generally consistent daytime peak near 0.8 mm h^{-1} . For the grassland deployment, hourly ET rates were derived from the LAS signal for a two-week subset of data following two significant precipitation events. Daytime peak hourly ET varied from approximately $0.6\text{-}0.7 \text{ mm h}^{-1}$ following the precipitation events to approximately 0.3 mm h^{-1} at the end of the subset. Daytime peak H for the same period ranged from $150\text{-}300 \text{ W m}^{-2}$.

1. Introduction

In the earth's water cycle, the evaporation component becomes particularly important when considering agricultural crop water needs. Transpiration from crop leaves is a bi-product of the crop's active growth and as crop roots extract soil water to replenish the water lost from the leaves, the reservoir of available soil water is depleted. For this reason, in regions where natural precipitation does not meet the crop water demand (i.e., the evaporation and transpiration rates from the crops and soil surface exceeds the water recharge), supplemental irrigation is a requirement for sustaining healthy crop yields. In order to intelligently apply irrigation water, it is necessary to track inputs and outputs from the soil crop root zone, including precipitation and irrigation gains, and runoff, deep percolation, and evaporative losses. Hereafter evaporation and transpiration losses will be referred to as evapotranspiration (ET). Much research in the last century has been done to develop methods for quantifying ET, which vary in regards to required inputs, theoretical basis, temporal scale of output, spatial scale of output, accuracy, and cost. In the latter half of the past century, more methods have been developed for the direct and indirect

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measurement of crop ET. Some of these are the Bowen Ratio (BR-EB) method, Eddy Covariance (EC) technology, Remote Sensing Energy Balance (RS-EB) and reflectance-based crop coefficient (Kcr) methods, and Scintillometry (for a description of these methods see Allen et al., 2011; and Neale et al. 1989). As a ground-based measurement method, large aperture scintillometry can be attractive for use in validating RS-EB ET estimates, as the spatial scale of measurement tends to be on the order of $100,000 \text{ m}^2$ (approximately, including the upwind flux source area). The development of the large aperture scintillometer (LAS, Wang et al., 1978) made provision for measurement of the structure parameter of the refractive index of air (boundary layer turbulence measure) over path lengths in excess of 4 km. In this regard, the subsequently derived sensible heat flux (H) is effectively a path-integrated average of H over the same transect. Incorporating the surface energy balance equation, given as " $R_n - G = H + \lambda E$," where R_n is net radiation, G is soil heat flux, H is sensible heat flux, and λE is latent (evaporative) heat flux, the LAS system can be used to provide estimates of ET over large areas. For this purpose the LAS has been used with some success in variable environmental conditions since the 1990s. De Bruin et al. (1995) show good results for LAS-derived H from a (dry) vineyard in Spain when comparing to EC-H. Hoedjes et al. (2002) tested a LAS over an irrigated field in Mexico affected by regional advection and compared fluxes again with EC instrumentation. In this case, the authors found good agreement between EC and LAS H and λE . Brunsell et al. (2011) show LAS results for undulating grassland with variable surface moisture in Kansas, U.S.A. The authors again find reasonable agreement between the H from a LAS and two EC towers. Kleissl et al. (2009) tested a Kipp and Zonen (Delft, the Netherlands) LAS against three Scintec boundary-layer scintillometers (BLS, Rottenburg, Germany) over a flood-irrigated crop field in Mexico. This study reveals very small inter-sensor deviation for the BLS, but significant deviation between the LAS and BLS instruments, which showed the LAS to overestimate H-BLS. The authors conclude that the BLS more accurately estimated H, thus demonstrating some Kipp and Zonen LAS deficiency.

The focus of this study is the use of the (Kipp and Zonen) LAS to derive H and to further estimate ET using ancillary measurement of net radiation and soil heat flux. Particular consideration will be given to the experimental methods and data processing, and the performance of the LAS will not be addressed here, except in regards to the above-mentioned and other literature recommendations.

2. Experimental and Data Methods

2.1 The Large Aperture Scintillometer

A scintillometer functions by transmitting an electromagnetic beam between a source unit (transmitter) and a receiver. The propagation of the beam through the lower atmosphere is affected by turbulence resulting from gradients of temperature, humidity, and, to a lesser degree, pressure. Because of the relationship derived between the variance of the beam intensity reaching the receiving unit and the change in the refractive index of air (C_n^2 , $\text{m}^{-2/3}$), the scintillometer can be used to describe fluxes of heat (or humidity) in the atmospheric surface layer (e.g., Moene et al., 2005; Meijninger, 2002). It is important to note that the derived C_n^2 signal is spatially integrated over the optical path length according to a specific weighting function where the most significant contribution comes at the path center. The Kipp and Zonen Large Aperture Scintillometer (LAS) operates at a

near-infrared wavelength (880 nm) and is considered in this regime to be primarily affected by turbulence from temperature fluctuations (Moene et al., 2005). This permits a relatively straightforward approximation of the temperature structure parameter (C_T^2) from C_n^2 , with additional input of the Bowen Ratio (β). Further, incorporating Monin-Obukhov similarity functions derived for the C_T^2 parameter (Andreas, 1988), the sensible heat flux (H , $W m^{-2}$) can be derived iteratively (Moene et al., 2005; Meijninger, 2002). This involves estimation of the friction velocity (u^* , $m s^{-1}$), and computation of the Monin-Obukhov atmospheric stability length (L_{mo} , m),

$$C_T^2(z_{LAS} - d)^{(2/3)} / T_*^2 = f_T[(z_{LAS} - d) / L_{mo}] \quad (1)$$

$$L_{mo} = u_*^2 T_a / g k_v T_* \quad (2)$$

$$T_* = -H / \rho_{air} C_p u_* \quad (3)$$

where z_{LAS} is LAS effective beam height (m), d is the surface displacement height (m), T_* is the temperature scale ($^{\circ}C$) as described in Eq. 3, ρ_{air} is air density ($kg m^{-3}$), C_p is air specific heat ($J kg^{-1} ^{\circ}C^{-1}$), T_a is air temperature ($^{\circ}C$), g gravitational acceleration ($9.81 m s^{-2}$), and k_v is the von Karman constant (0.41, dimensionless). These equations are solved iteratively to derive H , since L_{mo} is unknown. The similarity function (f_T) is a function of the stability parameter z/L (ζ , dimensionless) and is formulated differently for unstable and stable atmospheric conditions. Since the LAS instrument does not sense the direction of H , up or down (i.e., unstable or stable atmospheric conditions, respectively), post-processing requires independent estimation of the atmospheric stability condition to derive a unique H solution (i.e., value and flux direction).

LAS raw data were retrieved at 1 Hz frequency (one record per second) from the data logger and resolved to a 60 minute output interval. These data were combined with time series of air temperature (T_a , $^{\circ}C$), horizontal wind speed (U , $m s^{-1}$), relative humidity (RH, %), and atmospheric pressure (BP, hPa). Friction velocity (u^*) was estimated using a logarithmic wind profile model requiring input of horizontal wind speed at one height and estimates of surface roughness length for momentum transfer (z_{om} , m) and zero displacement height (d , m). The latter two parameters were approximated as a fraction of the crop height (h_c , m), appropriate for homogeneous canopies, where $z_{om} \approx 0.123 \times h_c$ and $d \approx 0.67 \times h_c$ (Brutsaert, 1992). Subsequently, information on the atmospheric stability was gathered to determine the appropriate solution (unstable or stable) at each time step for H , u^* and L_{mo} . Since measurement of air temperature at two heights was available in-situ, these data were used to assign the atmospheric stability using the sign of the air temperature gradient (i.e., for air temperature decreasing with height, the stability condition is unstable). The Bowen Ratio (β) was determined iteratively according to the method proposed by Green and Hayashi (1998) and the C_n^2 LAS output signal was corrected iteratively using a correction suggested by Hartogensis (2006).

2.2 ET-LAS

Once the LAS-H solution was acquired, the R_n and G measurements for the representative area covered by the LAS system were used with H to solve for λE as a

residual according to the energy balance equation described in the introduction. The ET was resolved with additional input of air temperature and a time constant as follows:

$$ET = \lambda E \times t / \lambda_v \quad (4)$$

$$\lambda_v = [597.3 - (0.564 \times T_a)] \times 4184 \quad (5)$$

In the above equations, λ_v is latent heat of vaporization, t is a time constant (seconds / averaging interval), and T_a is air temperature ($^{\circ}\text{C}$). For hourly ET, the time constant is 3,600 sec / hr. In order to estimate area effective R_n and G , the averages from the two measurement locations were used for both sites 1 and 2. The measurement of surface G was determined by measurement of G using HFT3 soil heat flux plates (Campbell Scientific, Logan, UT) at a measured soil depth (~ 8 cm) and subsequent calculation of the heat stored in the soil surface layer using measurement of soil temperature and soil moisture (Campbell Scientific, Inc., 2003). This required additional measurement of soil volumetric water content and soil temperature in the layer between the heat flux plates and the surface.

2.3 Quality Control

Some automatic quality control (QC) checks were performed on the LAS data during processing, including filtering data where the signal strength absolute value, $|\text{Demod}|$, was less than 50 mV and checking for signal saturation conditions. During post-processing / analysis, other filters were imposed – Data during precipitation events were excluded. Any data points where the Bowen Ratio was between -0.05 and 0 were removed, due to instability of the solution for this extreme value range (This mainly occurred with site 1 data). Due to relatively coarse resolution (0.2°C) of the air temperature sensors, periods where the difference in temperature between the 1 and 3 m sensors was less than 0.1°C were excluded from analysis. In addition periods of u^* less than 0.1 m s^{-1} were filtered out to avoid conditions of poorly developed turbulence, since the LAS theory requires turbulent conditions. For the well-irrigated location, a source area model (Kormann and Meixner, 2001; Neftel et al., 2008) was considered in order to filter LAS data whose source area extended significantly beyond the field boundary. This was considered by assuming the H-LAS to be a point measurement at the path center for simplification purposes.

2.4 Study Areas

The current study reflects a part of a project involving the testing of LAS systems over varying terrain in order to assess the performance of the Kipp and Zonen LAS and to use the LAS systems as a validation tool for RS-EB satellite imagery-based methods. During the 2010 growing season, a LAS was set up over a fully-irrigated alfalfa field at the Colorado State University (CSU) Arkansas Valley Research Center (AVRC) near Rocky Ford in Colorado (site 1). A surface aerodynamic profile tower (SAT) was installed by the north edge of the same field (Figure 1). This tower was equipped with air temperature and relative humidity sensors (Vaisala, Inc. HMP45C, CSI, Logan, UT) and wind speed cup anemometers (R.M. Young Wind Sentry 03101, CSI, Logan, UT) at six levels (1m-6m, approx.). The LAS was set up over a path length of 250 m with an effective beam height of 2 m. Note that the field west boundary is marked approximately by the LAS receiver

(Figure 1, 'LAS 1R'), since the image from 2004 is out of date. The setup included Rn and G instrumentation at two field locations. During the study period subset from August 5th to August 19th (2010), the crop was at reference conditions and some lodging was observed on August 16th. Significant precipitation (approx. 55 mm) fell during the July 31st to August 4th window, and the alfalfa was cut on August 20th. The alfalfa field was immediately surrounded in 2010 by mostly corn fields, with exception for the northeast triangular field and the field / area to the north / northwest. For this reason, a fair portion of the adjacent area was irrigated and therefore of generally similar evaporative conditions.

During the 2011 growing season, the same LAS unit was set up over dry grassland approximately 17 miles southwest of the AVRC, near Timpas, CO (site 2). This location featured short and tall grasses with some exposure of bare ground and occasional shrubs. Effective vegetation height for this location was estimated to be approximately 11 cm, although the tall grasses could reach up to approximately 50 cm. The location was generally flat, similar to site 1, and the LAS was set up on a north / south transect of approximately 600 m. The effective height of the beam was approximately 2.25 m, and a SAT tower nearly identical to the tower described at site 1 was set up at the path center, offset several meters to the west of the transect (Figure 2). It is apparent from Fig. 2 that the area (as of 2004) was largely homogeneous, which was the case during the 2011 period of record as well. Some hilly terrain exists beyond the study area to the south. As for site 1, measurements of Rn and G were made at two locations in order to derive the energy balance ET for the site. The study data subset was selected between July 29th and August 13th (2011) in order to depict results for a range of conditions, since two significant precipitation events occurred on July 28th (23+ mm) and August 2nd (12+ mm).

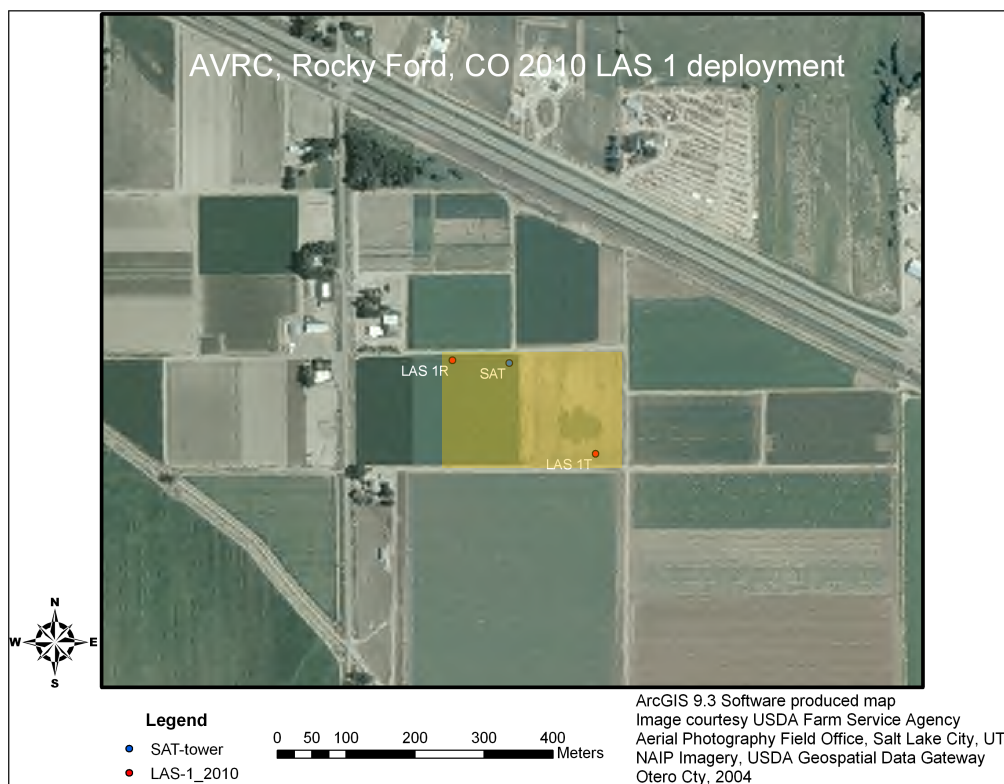


Figure 1. Aerial photograph of the site 1 well-irrigated location. The orange polygon represents the approximate boundaries of the 2010 alfalfa field where the LAS was located.

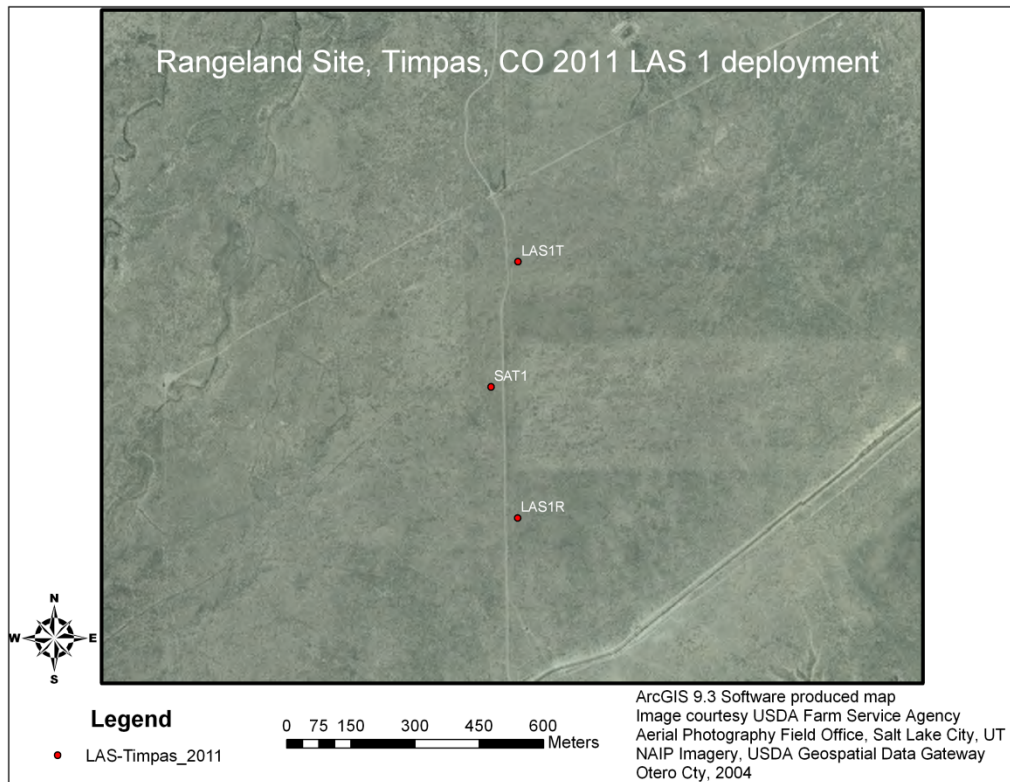


Figure 2. Aerial photograph of the site 2 dry grassland location. The property is occasionally-grazed rangeland.

3. Results

3.1 Site 1

The period of August 5th to August 19th (2010) was marked by reference alfalfa conditions and assumedly no lack of water. For the approximate two week subset period, the LAS-predicted daytime H fluxes were very low, less than 50 W m^{-2} in almost every case, which would be expected in a well-irrigated field. Further, the measured temperature gradient showed an apparent afternoon stability inversion generally around 2-3 pm (MST). This means that the temperature gradient changed sign from negative to positive, where a positive temperature gradient is identified by temperature increasing with height and a flux of heat toward the surface. The subsequently predicted λE often exceeded the afternoon R_n , most notably on August 16th, where by 11 am the reported H-LAS was -78 W m^{-2} and λE was 417 W m^{-2} (61 W m^{-2} larger than R_n). During this period (11 am to 4 pm) the average observed wind speed at 2 m was approximately 4.5 m s^{-1} , which was relatively large for the site. Hourly R_n generally reached a peak of approximately 625 W m^{-2} and hourly G generally reached a peak of $50 - 70 \text{ W m}^{-2}$, typically about 1 hour following the R_n peak. The LAS-derived peak hourly ET was observed to be $0.8 - 0.9 \text{ mm h}^{-1}$ consistently during the subset period, with a maximum of 1.0 mm h^{-1} being observed on August 16th. The result of filtering for the scenarios discussed in the methods section was the reduction of the dataset (hourly time step) to approximately 50% of its original size. This result was obtained before the filtering imposed for source area “in-field” flux limitation. By adding a filter for a minimum of 80% in-field flux contribution, only about 20% of the hourly data points remained. Therefore, for analysis purposes, no source area filter was used. Some comments regarding the potential loss of data quality will be given

in the discussion section. From the results obtained for site 1, it is apparent that the ET consumed the majority of the available energy, and that very little energy was used to heat the surface (H).

3.2 Site 2

The period of July 29th to August 13th (2011) represented conditions ranging from very wet to dry. The precipitation events from July 28th and August 2nd provided approximately 36 mm of water to the site. Peak hourly ET on the days following the events was approximately 0.6 mm h⁻¹, which dropped quickly to approximately 0.45 mm h⁻¹ on the following days (i.e., July 30th and August 4th). Five days following the first precipitation event, the daily peak ET had dropped to 0.3 mm h⁻¹. However, after the second precipitation event, peak hourly ET dropped more slowly from approximately 0.45 mm h⁻¹ on August 4th to approximately 0.35 mm h⁻¹ on August 11th, finally dropping below 0.3 mm h⁻¹ on August 12th. Peak hourly Rn was generally near 600 W m⁻², although it was observed to be larger than 700 W m⁻² on the day after the second precipitation event. The G for site 2 was observed to be larger than for site 1, with a hourly peak generally between 100 – 150 W m⁻² and a maximum of 180 W m⁻² observed in association with the precipitation events. Note that for the site 2 (hourly time step) data subset, the imposed filtering resulted in 75% of the data subset remaining (i.e., 25% filtered out). Despite the missing time steps from the ET (time series) solution, the majority of the daytime data remained available, so that the total ET occurring over the subset period may be approximated by the sum of available hourly ET data. The sum of LAS-derived ET over the 16 day subset was approximately 43 mm (corresponding to an average of 2.7 mm d⁻¹ over the period considered), which exceeds the observed precipitation total (36 mm) by 7 mm. It is considered that some water may have already been present in the soil root zone. Assuming then that most of the available soil water had been consumed by the end of the period considered (i.e., August 13th), the data from the end of the subset would be considered to represent a (very) dry condition. Further, these conditions may be referred to here as ‘equilibrium’ conditions, since the location is un-irrigated and precipitation events were not very common. For the final two days of the subset, H was observed to peak near 300 W m⁻², which corresponds to an H / (Rn – G) ratio between 0.5 – 1.0. This ratio seems to increase as the day progressed from 0.5 in the morning to near 1.0 in the afternoon. Overall, this seems to show that for this environment, the H dominated but did not consume all of the available energy.

4. Discussion and Conclusions

For the estimation of vegetative ET rates, the LAS is an indirect method that relies not only on its own measurement uncertainty but also on the uncertainty (accuracy) of net radiation and soil heat flux measurements. In order to obtain the sensible heat flux (H) from the LAS, some simplification assumptions were made. For example, the use of the Bowen Ratio (β) to determine C_T^2 from C_n^2 required (simply stated) that the temperature and humidity (fluctuations) be well correlated (cross-correlation function for temperature and humidity ~ 1.0) (Moene, 2003). For the site 1 case, where ET dominated and H was most often negative during the daytime afternoon periods, this assumption did not always hold. If β is small and negative this would result in an overestimation of |H|, where a small positive β would result in an underestimation of H. Further, the LAS requires an

independent determination of the atmospheric stability condition. For the case where independent air temperature profile measurements are used to determine the stability, these measurements must be representative of the LAS measurement area, and the measurements must also be precise (and accurate) to capture small temperature gradients. In addition, if horizontal wind speed measurements are made at only one level (height), an estimate of the roughness length (z_{om}) is necessary (for *all* cases an estimate of the zero displacement height (d) is required). For site 1, where the alfalfa canopy was largely homogeneous, the estimation of these parameters was not so questionable. However, for site 2, the accuracy of the effective crop height approximation was not as certain, which could have had some impact on the final output of H . Further, some attention has been given in the literature to the stability of the LAS support / mount in regards to (wind speed intensity) vibration of the instrument causing spurious changes to the output signal. This issue may play a role for sites 1 and 2, as high winds have been observed to result in misalignment of the LAS system at times. However, no intensive investigation for the relative impacts of high winds on the signal has been undertaken. Finally, the LAS method relies on the accurate and representative prediction of R_n and G in order to resolve ET . Since the R_n and G were measured at two locations for each site, this reduces uncertainty from the hypothetical case where only one measurement of the variables was made. In general, for both sites, fair to good agreement was noted between the R_n and G measured at both locations. For the differences observed between locations, some difference may be attributed to sensor bias, or to slightly variable surface conditions between locations. Therefore, the use of the average location R_n and G for each site may introduce some uncertainty in the ET solution.

Considering the above concerns, the overall performance of the LAS in both locations appears to be reasonable. For site 1, the range of the LAS-derived alfalfa ET maximum value of $0.8 - 1.0 \text{ mm h}^{-1}$ is in the range of expected values for a well-watered alfalfa field. Further, since the river valley region consists of a relatively thin area of well-irrigated plots surrounded by largely dry lands, the occurrence of regional advection is not unlikely. Further, on the local scale, neighboring fallow fields within the irrigated sub-region may result in cases of local advection. This advective atmospheric condition can be detected with the LAS instrument. The LAS captured the occurrence of $\lambda E > R_n$ and $H < 0$ during some afternoon periods in which wind speeds were relatively large. This fact suggests that the LAS can operate well under advective conditions. In regards to the issue of local advection, the reader is referred to Fig. 3, where a raster image of instantaneous ET values for August 10th (2010) at 10:22 am is shown. This map was produced by Mcebisi Mkhwanazi using Landsat 5 satellite imagery (USGS) and the surface energy balance for land (SEBAL) model (Bastiaanssen, 1998). It is apparent that the LAS alfalfa field, highlighted approximately in turquoise, is surrounded by some well-irrigated plots and some drier areas / fields. For this reason, neglecting the source area (in-field) flux filter may have negligible impact on the LAS- ET results, for the case where the upwind direction corresponds to a well-irrigated neighboring field. In regards to site 2, the LAS-derived ET values show well the increase in ET due to recent precipitation events. Further, expected trends can be observed of decreasing ET and increasing H during the periods following the precipitation events (dry-down). Nonetheless, the observation of maximum H at approximately 300 W m^{-2} suggests that H did not approach the magnitude of the available energy, and that some significant energy was consumed in the ET process, even

well after a precipitation event had occurred. This result raises the question whether the LAS may underestimate H for this case.

Overall, the LAS appears to provide reasonable estimation of the sensible heat flux (H) for both well-irrigated and relatively dry (flat and homogeneous) terrain. Comparison to an appropriate reference measurement of H or ET would allow for evaluation of the LAS performance. Sensitivity analyses would address the relative impact of uncertainty in the input variables on the final ET output. It is notable that data filtering reduced the usable (hourly time step) LAS data by 25-50%, based on the case studies presented here.

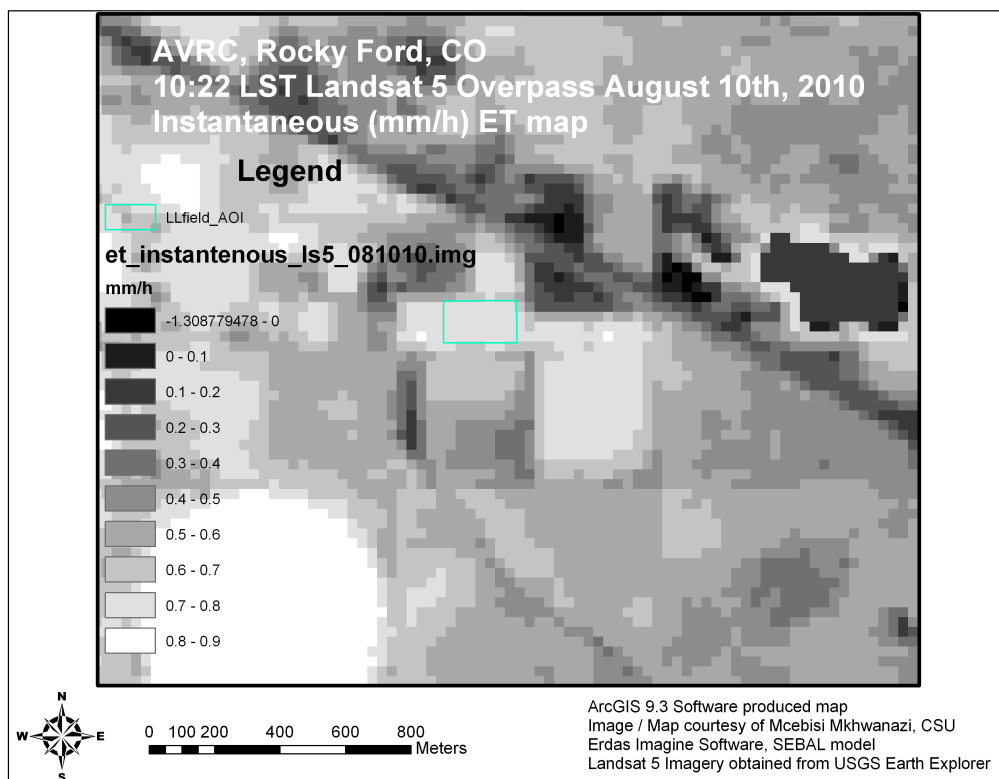


Figure 3. Aerial ET values image of the site 1 location, courtesy of Mcebisi Mkhwanazi (CSU). The turquoise polygon represents a restricted section of the LAS alfalfa field. Note the darker gray transect (U.S. Route 50) northeast of the field. The field area of interest (AOI) is offset by one pixel from the outer field edge, which was determined primarily based on the observation of the change in ET beyond the AOI.

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