HATS Field Measurement Design

The purpose of the HATS (Horizontal Array Turbulence Study, formerly SGS2000) field program was to measure spatially-filtered and subfilter-scale (SFS) turbulence, in order to provide data for studying the interaction between these two scales of turbulence, with the ultimate goal being improvement of LES SFS models. However this unique data set may prove valuable to other investigators for studying other spatial aspects of surface layer turbulence.

The HATS field measurement design is based on the transverse array technique proposed by Tong et al. (1998) for 2-D, horizontal filtering of turbulence variables. The sonic configuration consists of a primary horizontal line of 9 equally-spaced sonic anemometers mounted at one height and a parallel line of 5 sonic anemometers at a second height. The two lines of sonics are oriented perpendicular to the prevailing wind direction so that crosswind-filtered data can be estimated by calculating a weighted sum of the data from 5 adjacent sonic anemometers at each height. Streamwise filtering is approximated by invoking Taylor's hypothesis and calculating a similar weighted sum of the time series data at each measurement location. Finally, the subfilter-scale velocities are determined from the difference between the unfiltered u and 2-D filtered, resolved--scale u^r velocities.

$$u^s = u - u^r$$

The primary line of 9 sonics enables determination of resolved-scale variables at 5 adjacent locations and thus computation of finite-difference estimates of the crosswind gradients of those quantities. Similarly, Taylor's hypothesis can be used to estimate streamwise gradients from the time series data. Finally a separate line of 5 sonics is used to calculate resolved-scale quantities at a second height, which permits estimation of vertical gradients of resolved-scale quantities. The second line of sonics is parallel to and either above or below the primary line of sonics, so that the central sonics of both lines have the same horizontal coordinates.

The goal of the HATS field project was to investigate the turbulent interaction between resolved and subfilter scales over a wide range of atmospheric stability and filter sizes. The nature of the interaction is expected to differ depending on whether the filter cut-off wavelength is in the energy-containing range or in the inertial subrange of the turbulence spectrum. That is, the physics of the interaction will depend on the ratio of the filter cut-off wavelength to the turbulence integral scale. The cut-off wavelength is directly related to the filter width $4S$, while the integral scale is a function of both height z and stability. Since the integral scale depends most strongly on height, the ratio of height to filter width was used as a design parameter for the geometry of the sonic configurations.

Based on current LES capabilities and practice, practical logistical considerations, and the recent results of Porte-Agel et al. (2001), we chose to investigate 4 values of $z/4S$: 0.25, 0.5, 1, and 2. The actual values of sonic spacings and heights used in the field are listed in Table 1, along with the start and end times of data collection for each of the four configurations. Here the primary line of 9 sonics is denoted by the subscript d (referring to the double filter) and the secondary line of 5 sonics is denoted by the subscript s (single filter). In order to investigate a wide range of thermal stability, data were collected continuously from each of the four configurations for 6-9 days.

Table 1. Transverse Array Dimensions

Start	**End**	$z_d/4S$	z_d	S_d	z_s	S_s
(PDT)	**(PDT)**		**(m agl)**	**(m)**	**(m agl)**	**(m)**

8/31 17:00	9/8 08:00	0.26	3.45	3.35	6.90	6.70
9/9 11:00	9/15 12:25	0.50	4.33	2.17	8.66	4.33
9/15 17:25	9/24 13:00	1.00	8.66	2.17	4.33	1.08
9/25 17:30	10/1 07:00	2.08	4.15	0.50	5.15	0.63

In order to increase the measured differences used to estimate the vertical gradients of resolved-scale wind and temperature, the ratio of the heights of the two lines of sonics was chosen to be a factor of 2 for all configurations except the last. For the first three configurations, the sonics were mounted on 9 adjacent towers aligned transverse to the prevailing wind direction, while for the closely--packed fourth configuration the sonics were mounted on two horizontal tower sections supported between two upright tower sections. Finally, the spacing of the sonics in the single-filter array of sonics, s_s, was chosen to achieve the same value of z/s at both heights.

Because of the close spacing of the sonic anemometers, there was the possibility that distortion of the flow by one anemometer might contaminate the measurements of adjacent anemometers, particularly for a sonic spacing of 0.5 m. In order to monitor this possibility, a `reference' tower was erected in alignment with the other towers, that is transverse to the prevailing wind direction, but displaced 10 m from the end of each of the d arrays. Two sonic anemometers were mounted on this tower at the heights of the two sonic spatial filter arrays, with the assumption that flow distortion would be minimal at the locations of these anemometers.

Investigations of Taylor's hypothesis have found that the eddy advection speed generally exceeds the mean wind speed by factors as large as 1.2 (e.g. Powell and Elderkin, 1974). In order to directly measure the eddy advection speed, two additional towers were erected which were displaced parallel to the prevailing wind direction and normal to the spatial filter arrays. The separation of these two towers was 26.8 m for the first configuration and 17.3 m for the other three. Except for the fourth configuration, this corresponds to the span of the 9-sonic d array. The corresponding separation for the fourth configuration would have placed one tower about 3 m upwind of the sonic on the other tower, which would have directly interfered with the measurements at the downwind sonic.

Supplementary observations were made to document the meteorological environment of the detailed turbulence measurements, including the basic state variables of mean temperature, humidity, and pressure. In addition, temperature, humidity, and wind speed and direction profiles were measured at 5 levels between 1 m and 10 m. The temperature and humidity profiles are needed in order to perform an in-situ calibration of sonic virtual temperature for determining the spatially-resolved vertical potential temperature gradient, and the wind profile is needed to determine the vertical location of the sonic filter arrays within the surface layer. In order to measure the water vapor flux, an open-path fast-response UV hygrometer was co-located with the lower sonic on the downwind tower used for the measurement of the eddy advection speed. The two eddy--advection towers and the two micrometeorological profile towers were located approximately 60 m crosswind from the sonic filter arrays.

HATS Measurement Site

The field site for the HATS field study was selected to satisfy several criteria. In order to simplify interpretation of the observations, this study required a reasonably homogeneous site, particularly one with a spatially-uniform surface roughness. For the same reason, it was desired that the turbulence measurements be made above the roughness sublayer (conservatively 100 times the roughness height), requiring a reasonably smooth site with a roughness height on the order of 3 cm or less. Since one of the goals of the field study was to make measurements with a wide range of thermal stratification, including quite stable conditions at night, a site was sought with weather conditions that featured predominantly clear skies. Most importantly, aligning the sonic filter arrays transverse to the wind direction required that the wind direction be highly predictable and not vary significantly between day and night. These conditions were found to be satisfied in the San Joaquin Valley of southern California. During the summer months, the valley has mostly clear skies and the wind direction is very persistent, both day and night, from the north to northwest. Large expanses of the valley feature naturally flat topography and, in addition, agricultural fields have been accurately leveled to enable flood irrigation of the crops.

The HATS measurement site was located about 3.5 miles ENE of Kettleman City, CA, at the southeast corner of a 3-mile-square area of unplanted farmland (Section 10, Range 19E, Transect 22S). In addition, square-mile sections to the east and south of the measurement site were also unplanted. These fields were covered with various mixtures of crop stubble and weeds. Large irrigation ditches, on the order of 2 m deep, were located at one mile intervals on the N/S boundaries of each section, and the fields were crossed at roughly 60 m intervals by E/W irrigation check dams that rose about 20-25 cm above the level of the field. An aerodynamic displacement height of 32 cm and a roughness height of 2 cm were calculated from HATS near-neutral wind profiles.

Data collection

The HATS field measurements were obtained from the Integrated Surface Flux Facility (ISFF) which is maintained and operated by the Atmospheric Technology Division of the National Center for Atmospheric Research. Power at the measurement site was supplied by a gasoline generator, and the raw data were transmitted by wireless ethernet transceivers to the ISFF field base, a semi-trailer located adjacent to ac line power about 7 km to the northwest. As indicated in Table 1, data collection extended from August 31 to October 1, 2000.

Sonic Anemometer Data Quality and Data Processing

Sixteen identical Campbell Scientific three-component sonic anemometer-thermometers (CSAT3) were used for the two horizontal lines of sonics which composed the spatial-filter arrays, as well as for the two sonic anemometers on the nearby reference tower. The sonic anemometers were programmed to output data in the single-measurement mode (not oversample mode) at a rate of 20 Hz.

Wind tunnel test

Prior to and following the field campaign, each of the sonic anemometers was operated in the 89-cm-diameter wind tunnel of the NCAR Sensor Calibration Laboratory. The working section of this wind tunnel is too small to accurately calibrate the sonics, but the wind tunnel is sufficiently repeatable to examine the consistency of the sonics. This was done by operating the wind tunnel over the range from 0 to 15 m/sec and calculating the linear regression of the total wind speed $(u^2+v^2+w^2)^{1/2}$ measured by each sonic with respect to the wind tunnel speed measured by a pitot-static tube. The slopes of the regressions were on the order of 0.97. Prior to the field measurements, the slopes of the regressions for the 16 sonics had a standard deviation of less than 0.5% and a range of less than 1%. The intercepts of the regressions were generally less than 4 cm/sec, commensurate with the manufacturer's specifications for wind measurement offset. Anemometers with an intercept exceeding the offset specification were recalibrated by the manufacturer prior to the field measurements. Similar tests were made following the field program. The slopes of the regressions again had a standard deviation of less than 0.5% and a range on the order of 2%. Two anemometers with intercepts exceeding 4 cm/sec were sent to the manufacturer for recalibration. The manufacturer confirmed that one of the anemometers had an offset exceeding their specifications, ~6 cm/sec, but the other appeared to meet their specifications.

Coordinate transformation

The sonic anemometers were mounted on 1.5 m horizontal booms that precluded leveling the sonics using their bulls-eye bubbles. However, for measurements close to the surface in gently sloping terrain, it can be assumed that the mean streamlines are parallel to the local surface. In order to orient the measured wind field relative to a coordinate system aligned with the mean streamlines, the data from each sonic was rotated during post-processing using the planar fit technique described by Wilczak et al. (2001). The calculated sonic tilt angles were generally quite small, ranging from a few tenths of a degree up to 1-2°.

The horizontal orientations of the sonics were measured in the field using a precision theodolite to sight along one of the the measurement paths of each sonic from a distance on the order of 100 m. The theodolite was referenced to true north, using known sun elevation and azimuth angles tabulated for that location as a function of date and time of day. After using the theodolite-measured azimuths to rotate the data to a common coordinate system, it was found necessary to further correct the data for inferred offsets in the measurements of the horizontal wind components by each of the sonic anemometers, which ranged up to 6 cm/sec, as well as for residual systematic wind direction biases of up to 2°. The offsets in the horizontal wind components were generally commensurate with the previously-noted manufacturer's specifications for sonic anemometer performance. However, the range of the residual wind direction biases was larger than expected, considering that the theodolite procedure used to measure the sonic orientations was repeatable to better than 0.3°.

Flow distortion

The data from the sonics in the spatial-filter arrays was compared to the data from the reference tower to determine whether there was any evidence of flow distortion between adjacent sonics. The investigation was done by computing a linear regression between each of the sonics in the spatial-filter arrays and the sonic at the same height on the reference tower. The linear regressions were done on 30-minute-averaged samples of wind speed and turbulence kinetic energy, $\langle u'^2+v'^2+w'^2 \rangle/2$, selected for those times when the wind direction was within 45° of normal to the transverse array. Assuming that there would be minimal flow distortion for the largest sonic spacing and maximum flow distortion for the smallest sonic spacing, the slopes, intercepts, and the residuals from the linear regression were examined to determine what, if any, trends were observed with sonic spacing. No trends were detected, suggesting that there was no significant change in flow distortion as the sonic spacing decreased.

References

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