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A NEW METHOD OF ON-SITE DATA ANALYSIS OF TURBULENT TRANSPORTS NEAR THE GROUND

By

Tatsuo HANAFUSA

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Abstract

A new method of on-site data analysis of turbulent transports near the ground, using the hybrid analog system, HYSAT, is presented. A method of field application, using the sonic anemometer and the fine thermocouple psychrometer as the sensors is shown and the field performance was tested in comparison with the traditional digital method and was confirmed to be satisfactory.

1. Introduction

The vertical transport of such quantities as momentum, heat and water vapor within the planetary boundary layer must be incorporated in the numerical models for large scale motions when one hopes to predict the atmospheric behavior for periods of a week or more. However, present knowledge of the mean vertical transport over the vast area compatible to the mesh size of the numerical models is quite unsatisfactory. Extensive studies on the vertical transport processes in the planetary boundary layer are now required for the purpose of increasing the accuracy of weather prediction as well as for the purpose of better understanding of atmospheric turbulence.

The greatest difficulty in the study of turbulent fluxes has been shortage of accurate observational data under the various conditions. Recent development of the sonic anemometer-thermometer and other sensors for turbulence measurement (Mitsuta, [1966]) has made it possible to adopt the eddy correlation method of turbulent flux measurement in the field experiment, by which highly accurate results can be obtained. Even though accuracy in measurements can be improved, the eddy correlation method requires a great amount of computation to obtain the results. This is the greatest disadvantage of the eddy correlation method in field application.

The present author is convinced that practical application of the traditional procedure of the eddy correlation method is a time-consuming and costly undertaking and a new method of data processing will be necessary, since the completion of the sonic anemometer-thermometer (Mitsuta, Hanafusa & Sahashi [1967]). In this paper, the new method of on-site data processing of turbulent fluxes developed by the present author is presented.

2. The basic principle

The necessary and minimum informations in the study of turbulent transport processes to be obtained on-site, are means, standard deviations of the physical entities and the cross-correlations between them. The data processing time should be as short as possible to decrease the turn around time of the experiment, therefore, real time or semi-real time data acquisition system is ideal for on-site processing. Of course, detailed analysis of the data in the laboratory is also important, but for the present purpose of increasing the observational knowledge of turbulent flux, the on-site processing of the necessary information, if possible, is more desirable.

For the purpose of on-site processing of the turbulent flux, the data should be sampled at the rate of about 10 samples per second or so for an observational period of about at least half an hour or so. This means that the data of about 10^4 per channel should be processed. It is possible, of course, to make the on-site processing of turbulent fluxes entirely in digital form by the use of a high speed A–D converter and an electronic computer with a tape memory installed in a trailer cabin as reported by Kaimal, et al. [1966]. By this method, the data are sampled and processed with enough accuracy at all stages of the data processing, but the instrumentation becomes too large in physical dimensions and requires large initial and running costs, which can not be afforded by a small study group.

While the analog technique of the data processing is also applicable in on-site processing of atmospheric turbulence. The Evapotron and the Fluxatron (Dyer et al. [1965] and Dyer [1970]) are typical examples of the analog data processing method in the measurement of atmospheric turbulence. The instrumentation is much simpler than the digital form and on-site real time processing is also possible. However, the computing procedure is limited and the integration in analog form is not so easy and overall accuracy is a little less than the digital method.

The digital method has enough accuracy and flexibility in procedure, but is too expensive and complicated to be used in the on-site processing of field data, while the analog method is simpler but is difficult to attain high accuracy in the overall results. Thus the one which is something between them seems to be practically the best. Therefore, the author has tried to establish the new method of on-site data processing in hybrid analog method, which will be explained in this paper.

3. The new hybrid analog data acquisition system for atmospheric turbulence (HYSAT)

The hybrid analog method is a combination of analog and digital methods. The procedure employed in the present system (henceforce abbreviated as HYSAT) is that the pre-processing of data is made in analog form and the outputs of the unit analog computing circuits are sampled and converted into digital form and then integration is made in digital form to obtain the final results. The analog computing circuit has a fast enough computing speed and accuracy compatible with those of the sensors, so smoothing, multiplying and root-mean processing can be done without losing accuracy in real time. The output of the analog part can be sampled at the slow sampling rate of once or twice in one minute and the digital part of the system can be a very simple slow speed instrument.

The block diagram of the HYSAT is shown in Fig. 1. The digital computing part has been planned to be a modified desk top electronic calculator but is not completed at the present stage, and the digital integrations have been made by hand from the printed outputs of the A–D converter in the earlier experiments. However the computations are only the total of about 60 figures at each channel (e. g. output at every one minute in about an hour) and are not so laborious and analysis in quasi-real-time is possible.

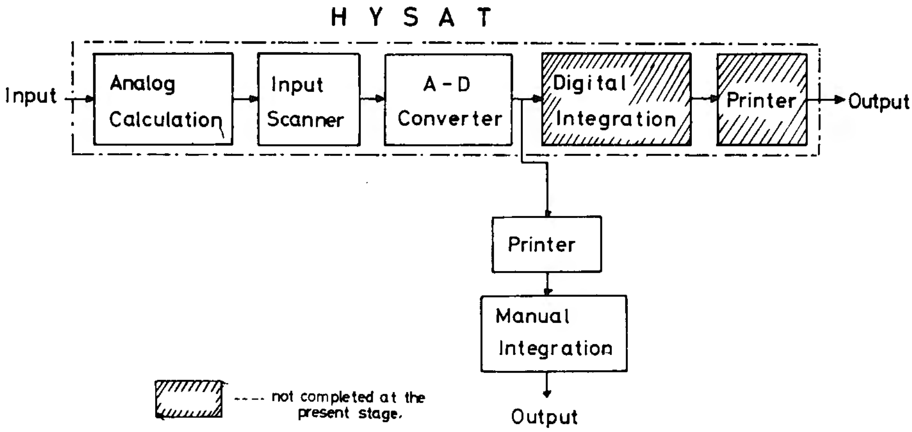

Fig. 1. The block diagram of the new hybrid analog data acquisition system for atmospheric turbulence (HYSAT).

The details of the instrumentation of the HYSAT are described in the separate paper (Hanafusa [1971]). By this system, we can obtain the turbulent character of arbitrary intervals without interrupting the observation. Therefore, we can make observations continuously over a long period which is a great improvement in the study of the turbulent transports in relation to larger scale phenomena.

4. Application of HYSAT to the study of turbulent transport processes

The mean value, standard deviation and covariance of about six meteorological parameters can be processed by the system, HYSAT, designed by the present author (Hanafusa [1971]). The parameters to be determined in the field observations for the studies of vertical transport of momentum, heat and water vapor near the ground are the means and variances of horizontal and vertical components of wind velocity, air temperature and specific humidity.

For the sensor of the three dimensional components of wind velocity sensor, the sonic anemometer (Mitsuta et al. [1967]) is the most suitable. While for the sensor of measuring humidity, the ideal instrument might be infra-red or ultra-violet absorption hygrometer (Chen & Mitsuta [1967] or Randal, Hanley & Larison [1965]), but, the instrument of this kind is still unreliable for the field experiment in various conditions. Therefore, the fine thermocouple psychrometric hygrometer (Sano & Mitsuta [1968]) is the most reliable one for the author at present. As the dry bulb temperature is measured in this method, the air temperature information can be obtained. This is better than the use of the sonic thermometer output because the response time is compatible with the humidity sensor and the sonic temperature is a virtual temperature to be corrected in the process of the sensible heat flux computation (Mitsuta [1968]). From the outputs of these sensors, the necessary parameters can be computed as following;

Mean value- The output of the mean-meter is compatible with the moving averaged values over 45 sec of the input signals (Hanafusa [1971]). Therefore, the mean values within the sampling duration under consideration can be computed digitally by averaging the sampled value for the period as follows,

$$\bar{X} = \bar{\hat{X}}, \tag{1}$$

where the figure with a bar denotes the mean value over the sampling duration of D in length and the figure with a hat denotes the output of the mean-meter or the 45 sec moving averaged value.

The mean horizontal component of wind velocity can be obtained from the mean value of the two 120° components of wind measured by the sonic anemometer by the following coordinate transformation formula (Mitsuta, Miyake & Kobori [1967])

$$\bar{U} = \frac{2}{\sqrt{3}} (\bar{\hat{u}}_1{}^2 + \bar{\hat{u}}_1 \bar{\hat{u}}_2 + \bar{\hat{u}}_2{}^2)^{1/2},$$

$$\bar{\alpha} = \tan^{-1} \frac{1}{\sqrt{3}} \frac{\bar{\hat{u}}_2 - \bar{\hat{u}}_1}{\bar{\hat{u}}_1 + \bar{\hat{u}}_2}, \tag{2}$$

where U is mean wind speed, α, the mean wind direction from the axis of the wind antenna of the sonic anemometer and u_1 and u_2 being the two horizontal component of the sonic anemometer in 120° coordinate (Mitsuta, Miyake & Kobori [1967]). While the mean specific humidity, $\bar{q}$ can be approximately obtained from the mean dry and wet-bulb temperature, (T_d and T_w) by the aid of psychrometric formula as follows

$$\bar{q} = q_s(\bar{\hat{T}}_w) - \frac{c_p}{L}(\bar{\hat{T}}_d - \bar{\hat{T}}_w), \tag{3}$$

where $q_s(\bar{\hat{T}}_w)$ is saturated specific humidity at $\bar{\hat{T}}_w$, L, the latent heat of evaporation, c_p, specific heat of air at constant pressure.

Standard deviation- The output of the sigma-meter of the analog part of HYSAT is the effective value of the fluctuating energy in the frequency range between 10 and 0.01 cps (Hanafusa [1971]). The high cutoff for the purpose of noise suppression in the frequency range is not so important in the turbulent flux studies and the low cutoff is determined from the limitation of the technical point of view. The output is compatible with the standard deviation of the input averaged over 0.045 sec and sampled for 45 sec (Hanafusa [1971]). Therefore, to obtain the standard deviation sampled over the long sampling duration of D, the following procedure is necessary. The variance of data sampled over D can be written as follows (Pasquill [1962]),

$$\sigma_D{}^2{}_{,0}(X) = \sigma_D{}^2{}_{,\tau}(X) + \overline{\sigma_\tau{}^2{}_{,0}(X)}, \tag{4}$$

where $\sigma_{a,b}$ denotes the standard deviation of the parameter X averaged over "b" and sampled over "a" of time, here 0 means the input of the sigma-meter in which high frequency part is cut off, and a bar denotes the mean value over D. As the output of HYSAT are the 45 sec averaged value of mean-meter and the standard deviation sampled over 45 sec of sigma-meter, the variance of X over the sampling duration of D is given as

$$\sigma_D{}^2(X) = \sigma_D{}^2(\hat{X}) + \overline{S(\hat{X})^2}, \tag{5}$$

where $\sigma_D(X)$ means the standard deviation of X sampled over D period, $\bar{\hat{X}}$ being the output of the mean-meter, $\overline{S(\hat{X})^2}$ is the mean value over D of the square of the output of signa-meter ($S(\hat{X})$). These computations are easily done in digital form with high accuracy because the data to be handled are very small numbers such as 60 for one hour observation with digitizing rate of once a minute. The variance of the horizontal wind component measured by the sonic anemometer with a 120° crossing wind antenna can be approximated as follows, neglecting the correlation between two horizontal components, in which the standard deviation of each component should be computed by the procedure shown as Eq. (5) from the outputs of the mean-meter and the sigma-meter.

$$\sigma^2(u) = \frac{4}{9\,\bar{U}^2}\left[(2\,\bar{u}_1 + \bar{u}_2)^2\,\sigma^2(u_1) + (\bar{u}_1 + 2\,\bar{u}_2)^2\,\sigma^2(u_2)\right] \tag{6}$$

while the variance of the specific humidity can be approximated, using the equation derived by the present author (Hanafusa [1970]) as follows, neglecting the correlation between dry-and wet-bulb temperatures,

$$\sigma^2(q) = A^2\sigma^2(T_w) + B^2\sigma^2(T_d), \tag{7}$$

where A and B are constant parameters determined by the mean temperature, as defined in his paper. And this is also computed from the dry-and wet-bulb temperatures outputs of A–D converter using Eq. (4).

Turbulent flux- The vertical turbulent flux of a physical entity is defined as follows

$$F = \overline{(\rho w)' X'}, \tag{8}$$

where (ρw) is the vertical component of mass flow measured by the sonic anemometer, X, the intensity of the physical entity and the figure with bar means the time mean value over sampling duration of D and that with a prime, the deviation of instantaneous value from the time mean. This equation can be rewritten in the following form

$$F = \overline{(\rho w)\hat{} X} - \overline{(\hat{\rho w})}\,\overline{X}, \tag{9}$$

where $(\rho w)\hat{}X$ means the output of the flux-meter whose inputs are (ρw) and X. Thus, the turbulent flux can be obtained from the mean values of the outputs of the flux-meter and the product of mean values. By this method the results are not subjected to the errors even if there are some errors in the zero point adjustment of the sensors.

The momentum flux measurement by the three dimensional sonic anemometer with the 120° wind antenna is defined as follows (Mitsuta [1967]),

$$M = -(\cos\alpha - \frac{1}{\sqrt{3}}\sin\alpha)\,\overline{(\rho w)' u'_1} + (\cos\alpha + \frac{1}{\sqrt{3}}\sin\alpha)\,\overline{(\rho w)' u'_2}, \tag{10}$$

and this is computed from the product of the vertical component and two horizontal components by the following formula,

$$M = -\frac{3}{2U}[(2\bar{\hat{u}}_1 + \bar{\hat{u}}_2)(\overline{(\rho w)\hat{} u_1} - \overline{(\hat{\rho w})}\,\bar{\hat{u}}_1) + (\bar{\hat{u}}_1 + 2\bar{\hat{u}}_2)(\overline{(\rho w)\hat{} u_2} - \overline{(\hat{\rho w})}\,\bar{\hat{u}}_2)]. \tag{11}$$

The turbulent flux of heat is defined by the following equation.,

$$H = c_p\overline{(\rho w)' T_d'}$$
$$= c_p[\overline{(\rho w)\hat{} T_d'} - \overline{(\hat{\rho w})}\,\overline{\hat{T}_d}]. \tag{12}$$

The turbulent flux of water vapor is defined by the following equation

$$E = \overline{(\rho w)' q'}\,. \tag{13}$$

And this is obtained from the fluctuations of dry- and wet-bulb temperatures by the following simplified relation derived by the present author (Hanafusa [1970])

$$E = A\,\overline{(\rho w)' T_w'} - B\,\overline{(\rho w)' T_d'}\,, \tag{14}$$

where A and B are the same as the ones used in Eq. (7). To obtain the value of water vapor flux from dry- and wet-bulb temperatures, the following equation can be used

$$E = A\,[\overline{(\rho w)\hat{T}_w} - \overline{(\hat{\rho w})}\,\overline{\hat{T}_w}] - B\,[\overline{(\rho w)\hat{T}_d} - \overline{(\hat{\rho w})}\,\overline{\hat{T}_d}]\,. \tag{15}$$

Thus the required informations of turbulent fluxes of momentum, heat and water vapor, and means and standard deviations of wind speed, air temperature and specific humidity can be obtained by HYSAT with input informations of the vertical and two horizontal components of wind measured by the sonic anemometer and dry- and wet-bulb temperatures measured by the fine thermocouple psychrometer by the aid of the formulae shown above.

5. Field performance of the system and comparison with digital method

The new hybrid data processing system, HYSAT was partly completed in 1968 and tested in parts as shown in another paper (Hanafusa [1971]). As the component computers had shown satisfactory performance, they were used in the experiment in the summer of 1969 and the results were satisfactory. After that, this system was used with the sensors shown before in the series of field experiments of the research group of atmospheric turbulence in Kyoto University as a part of GARP. Owing to the problem of the support of instrumentations, the first comparative experiment with digital method was made on the experimental field of the Tateno Aerological Observatory in December of 1970. As the digital computing part had not been completed as mentioned above, the output of the analog part of HYSAT was sampled at every 33 seconds and printed out. The digital computations were made by hand with desk top electronic calculator. All signals from the sensors were recorded on a magnetic recorder (TEAC R-200) with a 15 channel FM multiplexer (TEAC AU-1000) and were processed in the laboratory by a high speed data processor (TEAC DP-300) and the electronic computer of Kyoto University (KDC-2). The sampling rate of the A–D converter was chosen as one sample per 1.65 seconds per input channel. This rather lower sampling rate was chosen because the high frequency part of the fluctuations does not contribute to the total flux which is the main purpose of the comparison.

The test field is open flat grass land. The sensors were installed at the height of about 15 m. Each run was about an hour and the results were computed in both methods within the same sampling duration.

The examples of the traces are shown in Figs. 2 and 3. Fig. 2 shows the traces relating with the fluxes of heat and water vapor. The top trace shows the vertical component of wind and the second being its smoothed value obtained by the mean-meter, which is a little delayed in phase. The third and fourth show dry-bulb temperature, fifth and sixth, wet-bulb temperature. The seventh trace from the top

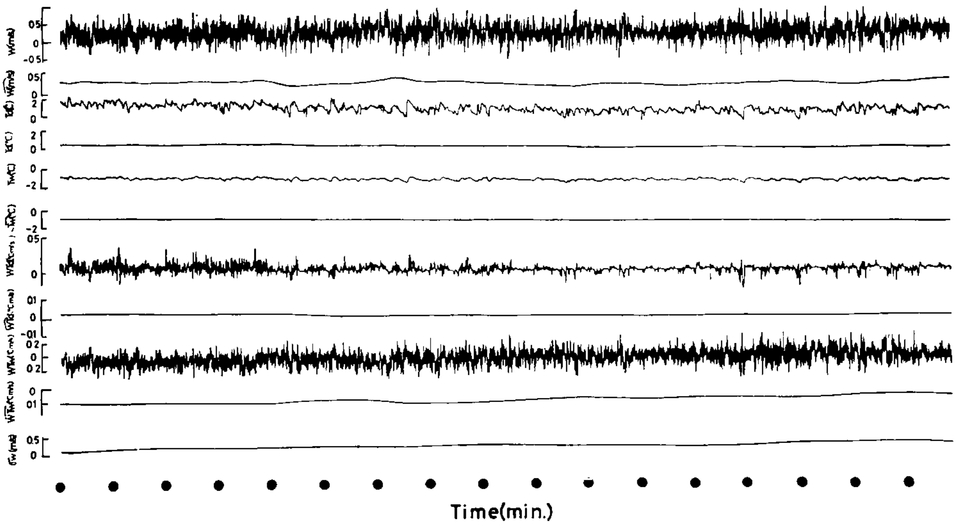

Fig. 2. An example of the monitor traces (heat and water vapor flux measurement).

shows the product of the vertical component of wind and the dry-bulb temperature and eighth is its smoothed signal which is the output of the flux-meter. The next two traces show the product of the vertical component of wind and the wet-bulb temperature. The bottom trace shows the standard deviation of the vertical component, while Fig. 3 shows an example of momentum flux measurement.

In the case (Run T-S-6) shown in Fig. 2 ,the mean wind speed computed by Eq.(2) is about 1.8 m/sec. The results are shown in Table 1. The sampling durations are the same for both and are 27.5 min. The mean specific humidity is 3.07×10^{-3} g/g by analog method and 3.09×10^{-3} g/g by digital one. The standard deviation of the

Table 1. The result of comparison with the traditional digital method (Run. T-S-6)

	Analog method	Digital method
Sampling duration	27.5 min.	
Averaging time	L.P.F. (f_c=10 cps)	1.65 sec
$\overline{q}$ ($\times 10^{-3}$ g/g)	3.07	3.09
σw (cm/s)	29 ($\sigma(\hat{w})$=17 cm/s, $\{S(\hat{w})^2\}^{1/2}$=24 cm/s)	31
σT_d (°C)	0.34 ($\sigma(\hat{T}_d)$=0.33 °C, $\{S(\hat{T}_d)^2\}^{1/2}$=0.08 °C)	0.41
$\overline{(\rho w)' T'}$ ($\times 10^{-3}$g cm^{-2}s^{-1})	6.07	5.81
$\overline{(\rho w)' T_w'}$ ($\times 10^{-6}$g cm^{-2}s^{-1})	4.81	5.54

Table 2. The result of comparison with the traditional digital method (Run. T-S-7)

	Analog method	Digital method
Sampling Duration	27.5 min.	
Averaging time	L.P.F. (f_c=10 cps)	1.65 sec
Mean wind speed	160	168
σw (cm/s)	39	40
$-\overline{(\rho w)' u'}$ (dyne/cm^2)	0.55	0.57

vertical component is 29 cm/s by the analog method in which the contribution of low frequency component represented by the first term of Eq. (5) is 17 cm/sec and the contribution of high frequency part represented by the second term of Eq. (5), which is the averaged value of the square of the output of the sigma-meter, is 24 cm/sec. The standard deviation of the vertical component computed by the digital method is 31 cm/sec and the difference between the results of both methods is very small. The standard deviation of dry-bulb temperature is 0.34 °C by the analog method and 0.41 °C by the digital one. The vertical eddy transports of heat and water vapor show very good agreement between two methods within errors of about 15%.

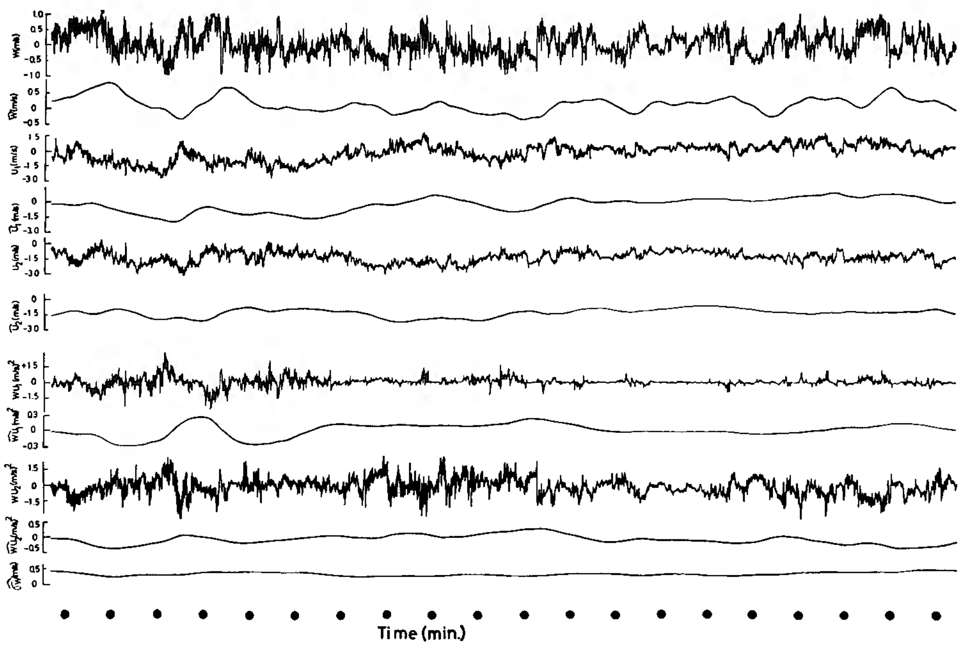

Fig. 3. An example of the monitor traces (momentum flux measurement).

The comparison of momentum flux measurement shown in Fig. 3 & Table 2 (T-S-7) also shows good agreement between two methods. Here it must be mentioned that there exists long period fluctuation in the vertical wind component in this case as seen in Fig. 3. The amplitude is as large as 1 m/sec in double amplitude and produces non zero mean value if the sampling duration is short. However, this long period fluctuation represented by the output of the mean-meter shown as the second trace in frequency lower than 0.01 cps does not contribute much to the total flux and its contribution is lower than 10%. This phenomenon has been pointed out in the separate paper (Mitsuta, Hanafusa & Fujitani [1970]) which suggests the existence of a helical circularion near the ground.

5. Conclusion

The new method of on-site data analysis of turbulent transports near the ground using the hybrid analog system, HYSAT, is presented. By this system with the sensor of a sonic anemometer and a fine-wire hygrometer, the means, and the standard deviations of horizontal wind speed, vertical component, air temperature and specific humidity and the turbulent fluxes of momentum, heat and water vapor can be obtained on-site in quasi-real time. The averaging time is short enough and the sampling duration can be chosen to be any length. Continuous observation is also possible by this method. The method of field application is shown and tested through field experiment in comparison with digital processing method. The performance was satisfactory and this method will be a standard method of turbulent flux measurement in future.

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