ARM TR-037

Energy Balance Bowen Ratio
Handbook

January 2005

Atmospheric Radiation Measurement
Climate Research Facility
U.S. Department of Energy

Work supported by the U.S. Department of Energy
Office of Science, Office of Biological and Environmental Research

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1. General Overview

The Energy Balance Bowen Ratio (EBBR) system produces 30 minute estimates of the vertical fluxes of sensible and latent heat at the local surface. Flux estimates are calculated from observations of net radiation, soil surface heat flux, and the vertical gradients of temperature and relative humidity. Meteorological data collected by the EBBR are used to calculate bulk aerodynamic fluxes, which are used in the Bulk Aerodynamic Technique (BA) EBBR value-added product (VAP) to replace sunrise and sunset spikes in the flux data. A unique aspect of the system is the automatic exchange mechanism (AEM), which helps to reduce errors from instrument offset drift.

2. Contacts

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3. Deployment Locations and History

Table 1.

Extended Facility	Facility Location	Date Installed	Date Removed	Status
2	Hillsboro, KS	1997/05/23		operational
4	Plevna, KS	1993/04/03		operational
7	Elk Falls, KS	1993/08/29		operational
8	Coldwater, KS	1992/12/08		operational
9	Ashton, KS	1992/12/10		operational
12	Pawhuska, OK	1993/08/29		operational
13	Lamont, OK (at the Central Facility	1992/09/14		operational

Table 1. (cont'd)

Extended Facility	Facility Location	Date Installed	Date Removed	Status
15	Ringwood, OK	1992/09/16		operational
18	Morris, OK	1997/09/10		operational
19	El Reno, OK	1997/05/29		operational
20	Meeker, OK	1993/04/05		operational
22	Cordell, OK	1993/04/05		operational
25	Seminole, OK	1997/10/22	2002/04/08	facility vacated
26	Cement, OK	1992/06/10		Operational
27	Earlsboro, OK	2003/05/02		Operational

4. Near-Real-Time Data Plots

To view near real time plots of EBBR data, visit the NCV web site at http://dq.arm.gov/ncvweb/ncvweb.cgi. Choose "sgp" from the menu, and click the "Submit Site" button. Then choose sgp30ebbrE##.b1 from the next menu (## stands for extended facility number) and click the "Submit DataStream" button. Now highlight a date or range of dates for which you are interested in seeing EBBR data and click on the "Plot File" button. Choose a variable for the Y axis and click on the "Apply Changes" button to plot the data. Time series and multiple plots can also be created.

5. Data Description and Examples

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

30 minute:
Sensible Heat Flux (h): 10% uncertainty
Latent Heat Flux (e): 10% uncertainty
Net Radiation (q): 5% uncertainty
Average Soil Surface Heat Flux (ave_shf): 10% uncertainty

5.1.1.1 Definition of Uncertainty

We define uncertainty as the range of probable maximum deviation of a measured value from the true value within a 95% confidence interval. Given a bias (mean) error *B* and uncorrelated random errors characterized by a variance σ^2, the root-mean-square error (RMSE) is defined as the vector sum of these,

$$RMSE = \left(B^2 + \sigma^2\right)^{1/2}.$$

(*B* may be generalized to be the sum of the various contributors to the bias and σ^2 the sum of the variances of the contributors to the random errors). To determine the 95% confidence interval we use the Student's *t* distribution: $t_{n;0.025} \approx 2$, assuming the RMSE was computed for a reasonably large ensemble. Then the *uncertainty* is calculated as twice the RMSE.

5.1.2 Secondary/Underlying Variables

30 minute:
tair_top
tair_bot
thum_top
thum_bot
hum_top
hum_bot
vp_top
vp_bot
pres
sm1, sm2, sm3, sm4, sm5
ts1, ts2, ts3, ts4, ts5
shf1, shf2, shf3, shf4, shf5
c_shf1, c_shf2, c_shf3, c_shf4, c_shf5
cs1, cs2, cs3, cs4, cs5
ces1, ces2, ces3, ces4, ces5
g1, g2, g3, g4, g5
bowen
wind_s
res_ws
wind_d

15 minute:
rr_tref
rr_thum_r
rr_thum_l
rr_ts1, rr_ts2, rr_ts3, rr_ts4, rr_ts5
r_sm1, r_sm2, r_sm3, r_sm4, r_sm5
mv_hum_r
mv_hum_l
mv_pres
mv_q
mv_wind_d
mv_home
mv_hft1, mv_hft2, mv_hft3, mv_hft4, mv_hft5
tair_r
tair_l
wind_s

5 minute:
tref
tair_top
tair_bot
thum_top

thum_bot
hum_top
hum_bot
vp_top
vp_bot
q
pres
wind_s
res_ws
wind_d

5.1.3 Diagnostic Variables

30 minute:
tref
sigma_wd
hom_15
hom_30

15 minute:
bat
signature

5 minute:
sigma_wd
home

5.1.4 Data Quality Flags

30 minute:
qcmin1-24
qcmax1-24
qcdelta1-24
qcmin25-48
qcmax25-48
qcdelta25-48
qcmin49-72
qcmax49-72
qcdelta49-72

15 minute:
qcmin1-24
qcmax1-24
qcdelta1-24
qcmin25-48
qcmax25-48

qcdelta25-48

5.1.5 Dimension Variables

Note: lat, lon, and alt refer to the ground surface, not to the instrument system height

30, 15, and 5 minute:
lat
lon
alt
base_time
time_offset

5.2 Annotated Examples

The following plot of sensible (h) and latent (e) heat fluxes shows a normal diurnal variation in heat fluxes, with latent heat flux being mostly negative during nighttime hours, as evaporation continues, and sensible heat flux being positive. During daylight hours both h and e are negative, as energy is lost from the surface. The plot also shows the spikes in the data that can occur at sunrise and sunset when the Bowen ratio is near -1 (see the Bowen ratios annotated on the plot, near the data spikes).

Figure 1.

The BA EBBR VAP replaces the spiked data with fluxes calculated with the bulk aerodynamic technique. The resultant combined flux data is shown in the next plot.

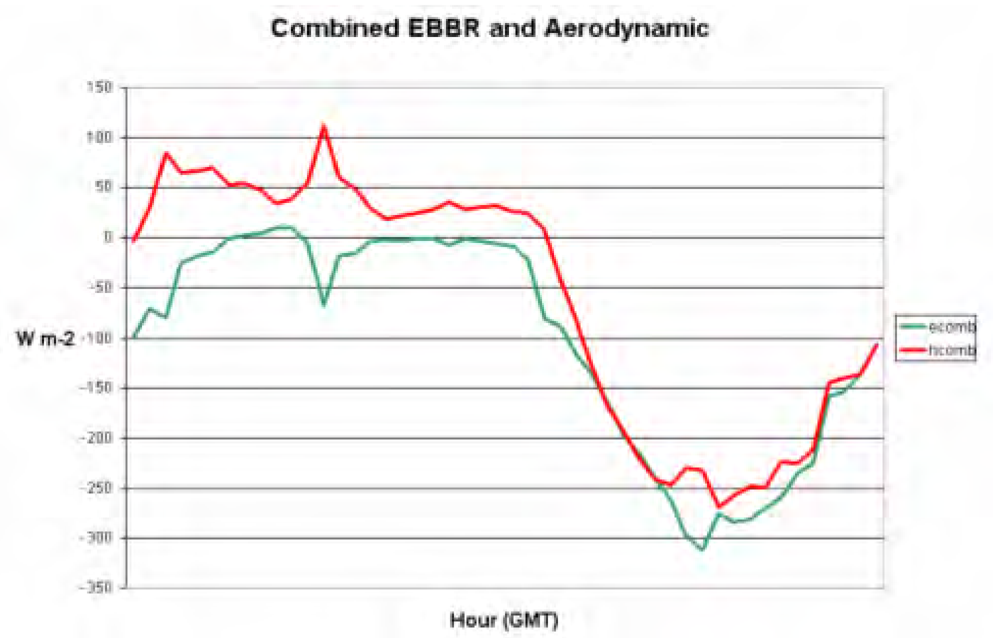

Figure 2.

5.3 User Notes and Known Problems

There are some conditions for which Data Quality Reports (DQR) are not written, as they occur somewhat frequently. These include: spikes in the sensible and latent heat fluxes when the Bowen ratio is near -1; short periods when the Automatic Exchange Mechanism (AEM) is not functioning properly (this can be detected from the QC checks in the data files); and short periods of missing data.

Common instrumentation problems include: condensation or frost on the net radiometer upper polyethylene dome (this can persist well into daylight hours); net radiometer desiccant degradation; holes in the net radiometer top dome caused by bird claws (this can result in water in the net radiometer if the dome is not replaced before precipitation occurs); soil sensors pulled from the ground or chewed by animals; a blown fuse in the AEM when the belt slides bind against the track; seized bearings in wind instruments; aging of sensors and electronic components; and loosened electronic connections. Preventative maintenance visits every two weeks and instrument mentor QA activities are designed to detect and correct these problems to reduce the amount of incorrect data collected.

5.4 Frequently Asked Questions

How are the latent heat flux and sensible heat flux derived?

The Bowen ratio technique is used to determine Bowen ratio, assuming that the transfer coefficients of heat and water vapor are the same. The Bowen ratio is then used in conjunction with net radiation and soil surface heat flux measurements to determine sensible and latent heat flux based on a budget approach. More details are provided in section 7.2, Theory of Operation, below.

What is the sign convention used for the energy flux densities?

All energy flux densities have a positive sign when directed toward the surface, and negative when directed away. For example, values of sensible (h) and latent heat flux (e) could be 0 to -600 watts per meter squared during the daytime in the summer.

In the design of the EBBR stations, which data are considered the most useful to ARM Science Team members?

The EBBR stations were designed primarily for computation of the sensible and latent heat fluxes. The soil temperature, moisture, and heat fluxes are measured in the upper 5 cm of the soil and therefore are not very useful for determining root zone soil moisture and soil heat flow. Other observations, such as air temperature, relative humidity, atmospheric pressure, and wind speed and direction are secondary measurements; Surface Meteorology Observation Station (SMOS) measurements, where available, should be used as the absolute measurements of these quantities. For example, the EBBR atmospheric pressure data is not measured with sufficient accuracy for many applications, whereas the SMOS pressure data has a smaller uncertainty and might be suitable for calculations of geostrophic winds. Other sources of reliable surface meteorological data are available as external data for the ARM Program from the Oklahoma Mesonet and from the Kansas network. The data user is encouraged to use the data from the SMOS for such observations.

EBBR data are collected only at the Southern Great Plains (SGP) extended facilities, including one at the Central Facility and some that are co-located with boundary facilities, and where the local surface is not tilled. Eddy correlation stations exist at nearly half of the extended facilities to sample the latent heat, sensible heat, and momentum fluxes above tilled cropland.

EBBR data can be used to compute momentum fluxes with a bulk aerodynamic approach. This approach is used as the basis for the calculation of sensible and latent heat fluxes by the BA EBBR VAP. This technique is briefly summarized in an extended abstract titled “Surface Heat Flux Data from Energy Balance Bowen Ratio Systems” by M. L. Wesely, D. R. Cook, and R. L. Coulter in Preprints, Ninth Symposium on Meteorological Observations and Instrumentation, Charlotte, NC, 27-31 March 1995, American Meteorological Society, Boston, MA, pp. 486-489.

What do the AEM (Automatic Exchange Mechanism) home signals indicate?

The AEM home signal outputs in the 5, 15, and 30 minute data streams are in units of millivolts DC. The circuitry producing the millivolt output is fairly rudimentary and therefore the millivolt value is proportional to the DC voltage output of the EBBR power supply (solar/AC charged battery). The home signal can therefore vary significantly diurnally and can fall to unacceptable levels for the 15 minute value if battery performance degrades too much.

During the first and third quarter hours, the right side (looking from behind the AEM) aspirated radiation shield (housing temperature and relative humidity probes) is normally in the “bottom” (lowest elevation) position, and the left side is in the “top” (greatest elevation) position. During this AEM state, the 5 minute “home”, 15 minute “mv_home”, and 30 minute “home_15” values should be between 40 and 55.

During the second and fourth quarter hours, the left side (looking from behind the AEM) aspirated radiation shield (housing temperature and relative humidity probes) is normally in the “bottom” (lowest elevation) position, and the right side is in the “top” (greatest elevation) position. During this AEM state, the 5 minute “home”, 15 minute “mv_home”, and 30 minute “home_30” values should be between 15 and 30.

What soil measurements are made by the EBBR stations?

Five soil heat flow sensors are located at a depth of five cm from the surface, five long platinum resistance temperature detectors (PRTD) integrate the temperature from the surface to a depth of five centimeters, and five soil moisture probes are located at a depth of 2.5 cm. Each set of five soil sensors is averaged. Since soil is not horizontally homogeneous, the sensors are spaced out in the soil locally to provide representative samples.

The purpose of these sensors is to compute one term, the surface soil heat flux. The soil temperature and moisture probes allow calculation of energy storage in the layer of soil between the surface and the heat flow plate depth of five centimeters. The soil moisture probes allow the soil heat flow measurements to be adjusted for the conductivity of the soil.

The sensible and latent heat fluxes are computed by the EBBR data logger with the standard energy balance equation, in which the surface soil heat flux is usually a relatively small term. The surface soil heat flux term cannot be precisely recalculated from the raw information because of the way that the soil energy storage term is computed with the EBBR data logger, but, in principle, the raw information can be used to recompute the sensible and latent heat fluxes with only a few percent error.

Can the sensible and latent heat fluxes be recalculated if some of the soil probes are not working?

Yes. The remaining working soil probe sets can be used to calculate an average surface soil heat flux. See the procedure in section 7.2, Theory of Operation.

What type of diurnal trends should appear in the EBBR data?

Some examples of diurnal trends can be seen in various textbooks and articles. For example, some data are shown in the special FIFE issue of the Journal of Geophysical Research (Vol. 97, pp. 18,343-19,110), e.g., the article by Fritschen et al. starting on p. 18,697. The ARM Program uses a Fritschen-type EBBR station.

What can be said about the quality of the EBBR data?

The EBBR systems sometimes experience hardware problems. For example, the automatic exchange mechanism will sometimes malfunction. Some problems, like this one, can be discerned by looking at the data quality flags.

The following information should be useful for interpretation of the quality of data from the EBBR stations. Data quality flags should be used to detect when the automatic exchange mechanism (AEM) is functioning properly. The rate of AEM failure has been high at times. When it is not working, the estimates of sensible and latent heat flux are unreliable and should not be used for any scientific investigations, even if the flux estimates appear to be reasonable.

To use the metadata on the AEM, the user should become familiar with the field and global attributes described in a dump of the netCDF header. The fields are defined there, and, in data sets recently provided, the configuration of the data quality flags is briefly described at the end of the list of the global attributes. The flags themselves are contained in numbers at the end of the data listing. The next paragraph provides some suggestions on the quality control numbers (qcmin# and qcmax#) and the imbedded flags relevant to the AEM.

Quality control (QC) flags in the standard, 30-min data interval indicate when the AEM is working for each half hour in the time series. The particular QC flags of interest are the sixth and seventh bits of the 24-bit binary numbers representing qcmin49-72 and qcmax49-72. The sixth bit of qcmin49-72 is set to zero when the home_15 is greater than 35 mV, and to unity when less. The sixth bit of qcmax49-72 is set to zero when the home_15 is less than 70, and to unity when greater. A similar set of criteria are applied to the seventh bit, but with a minimum of 15 and maximum of 34.999999. Alternatively, if you choose not to convert the quality control numbers to binary form, you can inspect the values of home_15 and home_30 to determine if they fall in the desired range. Because the limit checks on the home signals were not properly set prior to April 7, 1993, you must inspect home_15 and home_30, rather than qcmin# and qcmax# for data collected prior to that date.

The QC flags should routinely be used for all of the variables. For some variables, however, QC flags have not been set, and for some variables (e.g., average soil heat flux [ave_shf], latent heat flux [e], and sensible heat flux [h]) flags were not set until late May 1998, as is evident in the listing of the field attributes. Nevertheless, some information can be obtained by inspection of the data if you are familiar with typical values. For example, Bowen ratios tend to be positive during the day and negative at night. Daytime values are usually between 0 and 2, and nighttime values can vary widely between positive values and -50. A negative Bowen ratio during daylight hours should be considered as possibly indicating suspect sensible and/or latent heat flux values. During transition times lasting up to two half hours near sunrise and sunset, the magnitude of the Bowen ratio can sometimes be quite large, in which case the sensible and latent heat flux values should be viewed as suspect. Although no QC flags were set for latent and sensible heat flux, values smaller than -1000 watts per meter squared and larger than 200 watts per meter squared are clearly suspect.

Routine checks reveal an expected offset drift of the relative humidity (RH) probe of about +2% per year caused by aging and dirt contamination of the RH sensing element. This drift has also been observed in the Tower and SMOS RH probes. Although this affects the absolute accuracy of the RH measurement, it does not adversely affect the 30 minute vapor pressure difference calculated from the RH and temperature measurements because the RH probes drift at approximately the same rate and the AEM exchanging Bowen ratio technique reduces offset effects. Recalibration after two years use is usually recommended to keep the RH probes within their "as new" absolute accuracy specification; this is the goal of the EBBR recalibration program conducted every two years.

The absolute value of the home signals varies with the voltage of the battery that powers the EBBR data acquisition system. When the battery condition is good, the home_15 value is typically between 40 and

55; the home_30 value is typically between 15 and 30. When battery condition is low, the home signals can be slightly lower, but then the data from some individual sensors are questionable. Instances have occurred where low battery condition allowed some sensors to function while others did not. Data Quality Reports (DQRs) are written to identify such problems.

Unfortunately, the AEM does not always switch and occasionally hangs up. Four cases are common:

1. AEM fuse blown. The housing positions on the AEM when the fuse blows (usually a result of too much friction on the exchange mechanism resulting from freezing rain or snow, built up dirt, or an electrical or electronic failure) is uncertain and usually yields home_15 and/or home_30 values of zero, although E15 at Ringwood, OK showed -2.0 in this condition in May 1994.

2. AEM stuck at one position. Usually the right housing will stick in the down position (sometimes referred to in site operations log messages as the home position). When this happens, the home_15 and home_30 signal outputs are usually both equal to the proper home_30 value, if the AEM fuse has not blown. There are exceptions to this of course, which included a period at the Central Facility EBBR in late 1992 when both home signals were 35.

3. AEM stuck between the 15 and 30 min positions. This situation usually produces a very small negative home value for both home_15 and home_30, such as -0.2.

4. AEM removed for service. Occasionally, an AEM has been removed from service for repair when no replacements were available. A good example of this situation is when the EBBR at E9, Ashton, KS, was removed on April 5, 1994. A resistor in the AEM circuitry had burned out, leaving the left housing in the bottom position (a rarity). This had resulted in both home signals showing somewhere from 67 to 73. After the AEM was removed, the aspirated housings were tied to the EBBR frame, approximately a meter apart. Without the AEM circuitry being present, the home signals floated to the thousands. On April 19 a refurbished AEM was installed and the home signals returned to normal.

The list above illustrates only some of the possibilities. It can be generally said that, whatever their absolute values, if the home_15 and home_30 values are practically the same in the 30 min data, at least one of them is incorrect, indicating that the sensible and latent heat flux estimates are suspect. Unless both of the home_15 and home_30 values are within proper ranges, the sensible and latent heat values must be considered incorrect. No other interpretation is appropriate. Even if we know the AEM position situation and could thus recalculate fluxes from the available data, those fluxes would still be corrupted with calibration offsets, which are normally removed via the AEM switching process.

Most users of the EBBR data only receive the 30 min data and not the 5 or 15 min data. The QC flags in the 15 min data might be useful for a comprehensive evaluation of each EBBR sensor. For example, the qcmin# check for battery condition in the 15 min data is set to the lowest value at which the sensors will typically operate reliably. Also, soil moisture resistance ratios (rr_sm#, used before April 1996) or soil moisture resistance (r_sm#, used beginning in April 1996) could be examined to help determine when individual soil moisture values are reliable. We do not, however, expect every user of the EBBR to obtain the 15 min data for such analyses. Finally, users of the data are cautioned that the reliability and accuracy of some individual sensors, such as soil moisture sensors, may be not optimal. The EBBR system was not designed to observe all quantities extremely well because its primary purpose is to provide sensible and latent heat flux estimates, which are not particularly sensitive to the uncertainties of some of the variables. If, for example, accurate, reliable estimates of barometric pressure and air temperature are needed, the values supplied by SMOS or from external data sets such as those from the Oklahoma Mesonet should be used. For soil moisture and temperature, we consider the EBBR observations to be mostly inadequate for use in landsurface process and hydrological models or submodels. On the other hand, we expect high quality data on net radiation from EBBR stations because it is crucial in the energy balance calculations; we expect soil heat flux values to be fairly good because they enter directly into the surface energy balance calculations (but are typically small in magnitude compared to net radiation). Unforeseen types of failures sometimes occur, e.g., the ventilator for one of the temperature and humidity sensors stops. Such problems are usually described in data quality reports (DQRs) that are available for data users.

When the Bowen ratio is between -1.6 and -0.45, “spikes” can occur in the latent and sensible heat flux values.

What are likely difficulties in comparing surface heat fluxes measured by EBBR stations to results of numerical modeling efforts?

One of the greatest difficulties in comparing model versus field data on surface heat fluxes is caused by model calculations requiring soil moisture information. The soil moisture across the SGP site can be quite variable for summertime conditions. EBBR soil moisture data provide measurements of average moisture content only in the top 5 cm. An effort led by Jeanne Schneider at the University of Oklahoma and supported by the National Oceanic and Atmospheric Administration for GCIP installed soil moisture and temperature profiling instrumentation (SWATS) at every SGP extended facility, including every location that has an EBBR station, during 1996 and 1997. SWATS soil moisture and soil temperature data should be used for modeling efforts, not the EBBR soil moisture and temperature data.

At least three science team groups have tried to compare model outputs with SGP site data (as of summer 1995): Jim Liljegren working with Chris Doran at Pacific Northwest Laboratory; Marina Zivkovic working with Jean-Francois Louis at Atmos. & Environ. Research, Inc., in Cambridge, MA; and Sarah Fox working with Lee Harrison and others at the State University of New York at Albany.

A cooperative program of sorts that has looked extensively at this type of modeling is PILPS (Project for Intercomparison of Land-surface Schemes). Some information on PILPS can be found in the paper by Sellers et al. (Bulletin of the American Meteorololgical Society, Vol. 74, pp. 1335-1349; 1993). One conclusion of PILPS is that more observational data is needed for developing large-scale models. For example, an article by Betts et al. (Quarterly Journal of the Royal Meteorololgical Society, Vol. 119, pp. 975-1001, 1993) carries out a fairly critical evaluation of European Center for Medium Range Weather Forecasting (ECMWF) model outputs by using FIFE data.

Some other potentially informative articles are as follows:

Shuttleworth, W. J. 1991. 1. Insight from Large-scale Observational Studies of Land/Atmosphere Interactions. *Surveys in Geophysics*, **12**, 3-30.

Dickinson, R. E. et al. 1989. A Regional Climate Model for the Western United States. *Climatic Change*, **15**, 383-422.

Avissar R., and M.M. Verstraete. 1990. The Representation of Continental Surface Processes in Atmospheric Models. *Reviews of Geophysics*, **28**, 35-42.

6. Data Quality

6.1 Data Quality Health and Status

The status of the measurements made by the EBBR system can be found by going to the ARM DQ HandS web site at http://dq.arm.gov.

6.2 Data Reviews by Instrument Mentor

Monthly reviews of the EBBR data are prepared by the mentor and posted here.

6.3 Data Assessments by Site Scientist/Data Quality Office

The Data Quality Office performs checks of EBBR data quality and prepares a weekly report. The mentor reviews the report and the data and makes suggestions for changes, additions, or deletions to the weekly report.

6.4 Value-Added Procedures and Quality Measurement Experiments

The BA EBBR VAP represents a recalculation of sensible and latent heat fluxes using wind speed and temperature gradient information in conjunction with a bulk aerodynamic estimation technique; it has been implemented, and 30 minute average files are available in the Data Archive beginning from 1995. Vegetation height and wind speed are used to determine aerodynamic quantities that allow the calculation of sensible and latent heat flux independent from measurements of net radiation and soil surface heat flux. These calculations help to produce more reasonable estimates of fluxes when the Bowen ratio is between -1.6 and -0.45 (the Bowen ratio technique often produces unreasonable flux values under this condition). Data source names take the form “sgp30baebbrE13.c1”. Presently the files can be found in the Archive by looking under c1 data sources. Results from the BA EBBR VAP can be seen in the second plot in section 5.2, Annotated Examples, above.

A second VAP involves the recalculation of sensible and latent heat fluxes using Solar and Infrared Station (SIRS) net radiation information; however, this VAP has not been implemented. This approach may help to improve flux estimates during times when the EBBR net radiation data is corrupted by dew, frost, or condensation inside or outside of the net radiometer domes.

EBBR-related quality measurement experiments (QMEs) could include:

- Comparison of EBBR-measured net radiation and SIRS-calculated net radiation. Comparisons plots of EBBR net radiation and SIRS-calculated net radiation are produced by the Data Quality

Office and displayed on the DQ HandS website. These comparison plots reveal significant differences between these two systems at times. A QME has not been performed as yet.

- Comparison of sensible and latent heat fluxes from EBBR and eddy correlation (ECOR) systems (only for comparisons between the EBBR and ECOR systems at the SGP Central Facility, and then only for very limited wind directions); no ECOR systems are co-located with EBBR systems over the same vegetation surface.

7. Instrument Details

7.1 Detailed Description

7.1.1 List of Components

Vaisala T/RH probes at two heights (1 m separation), in aspirators
PRTD temperature probes at two heights (1 m separation), in aspirators
REBS Q*7.1 Net Radiometer (at 2 m typical)
REBS SMP-2 (5 sets) Soil Moisture Probes at 2.5 cm depth
REBS HFT-3 (5 sets) Soil Heat Flow Plates at 5 cm depth
REBS STP-1 (5 sets) Soil Temperature Probes, integrated 0 to 5 cm
Met One Instruments 090C or 090D Barometric Pressure sensor (in enclosure)
Met One 020C Wind Direction sensor at 2.5 m
Met One 010C Wind Speed sensor at 2.5 m
PRTD Reference temperature of control box
REBS Automatic Exchange Mechanism (AEM)
Pipe network structure for mounting of the instrumentation
Solar panel, battery, AC charger power source
Enclosure holding Campbell CR10, multiplexers, J-panels, communication equipment

7.1.2 System Configuration and Measurement Methods

The EBBR sensors (except for soil probes) are mounted on a triangular pipe framework that sits on the soil surface. The net radiometer mount extends from the south end of the EBBR frame.

A unique aspect of the system is the automatic exchange mechanism (AEM), which helps to reduce errors from instrument offset drift. The AEM extends from the north end of the frame. Aspirated radiation shields (which house the air temperature and temperature/relative humidity probes) are attached to the AEM. The openings of the aspirated radiation shields face north to reduce radiation error from direct sunlight.

The soil probes are buried just outside the view of and in an arc to the south of the net radiometer.

The heights of the AEM aspirators are different at different extended facilities and are dependent on maximum vegetation height; the vertical separation between the two aspirators is 1 m at all extended facilities. The heights or depths of all other sensors are the same at all facilities.

The reference temperature sensor, barometric pressure sensor, data logger equipment, and communication equipment are located in a control box (weatherproof enclosure), which is attached at the northeast corner of the EBBR frame.

The local area of influence upon Bowen ratio measurements is contained within a horizontal distance of approximately 20 times the height of the top aspirated radiation shield on the AEM. This distance varies among the different extended facilities and for different times of the year because of differences in maximum vegetation height, and therefore the height at which the AEM is installed.

The manufacturer's (REBS) name for these systems is SEBS (Surface Energy Balance System); this name appears in their systems documentation.

7.1.3 Specifications

The accuracies cited below are generally those stated by the manufacturer. They are sensor absolute accuracies and do not include the effects of system (i.e., data logger) accuracies. Although it is not known how some of the manufacturers have determined sensor accuracy, it is properly the root square sum of any nonlinearity, hysteresis, and non-repeatability, usually referenced as percentage of full scale.

The detection limit is normally restricted to the range (sometimes called Calibrated Operating Range) over which the accuracy applies. In the case of the EBBR, some of the detection limits are those determined by the vendor (REBS) who performed the calibration, not by the manufacturer of the sensor. Some manufacturers also specify an Operating Temperature Range in which the sensor will physically and electronically function, even though the calibration may not be appropriate for use throughout that range. When no detection limits have been listed by the manufacturer or the calibrating vendor, none are stated below.

Air temperatures: Chromel-constantan thermocouple, Omega Engineering Inc., REBS Model # ATP-1, Detection Limits -30 to 40 deg C, Accuracy +/- 0.5 deg C.

Temperature/Relative Humidity Probe: Operating Temperature Range -20 to 60 deg C. Temperature: Platinum Resistance Temperature Detector (PRTD); Detection Limits -30 to 40 deg C, Accuracy +/- 0.2 deg C Relative Humidity: Capacitive element, Vaisala Inc., Model #s HMP 35A and HMP 35D; Detection Limits 0% to 100% RH, Accuracy +/- 2% (0-90% RH), +/- 3% (90-100%), uncertainty of RH calibration +/- 1.2%.

Soil Temperature: Platinum Resistance Temperature Detector, MINCO Products, Inc., REBS Model # STP-1, MINCO Model # XS11PA40T260X36(D), Detection Limits -30 to 40 deg C, Accuracy +/- 0.5 deg C.

Soil Moisture: Soil Moisture Probe (fiberglass and stainless steel screen mesh sandwich), Soiltest, Inc., REBS Model # SMP-2, Soiltest Model # MC-300, Accuracy not specified by manufacturer (varies significantly depending on soil moisture and soil type). Detection limits for this sensor are limited by the ability to fit a polynomial to the calibration data; for the SGP site, the detection limits are approximately 1% to 50% by volume.

Soil Heat Flow: Soil Heat Flow Probes, Radiation & Energy Balance Systems, Inc., Model #s HFT-3, HFT3.1, Accuracy not specified by manufacturer.

Barometric Pressure: Barometric Pressure Sensor, Met One Instruments, Model #s 090C-24/30-1, Detection Limits 24 to 30 kPa; 090C-26/32-1, Detection Limits 26 to 32 kPa; 090D-26/32-1, Detection Limits 26 to 32 kPa; Accuracy for all +/- 0.14 kPa.

Net Radiation: Net Radiometer, Radiation & Energy Balance Systems, Inc., Model Q*6.1 or Q*7.1, Accuracy +/- 5% of full-scale reading.
Wind Direction: Wind Direction Sensor, Met One Instruments, Model #s 5470, 020C, Detection Limits 0 to 360 deg physical (for greater than 0.3 ms-1 wind speed), 0 to 356 deg electrical, Accuracy +/- 3 deg.

Wind Speed: Wind Speed Sensor, Met One Instruments, model #s 010B and 010C, Operating Temperature Range -50 to 85 deg C, Detection Limits 0.27 to 50 ms-1, Accuracy +/- 1% of reading. Operational Limit on speed 60 ms-1.

Datalogger: Campbell Scientific, Inc., Model CR10, Detection Limits vary by voltage range selected, Accuracy +/- 0.1% of full scale reading.

7.2 Theory of Operation

The EBBR stations use a standard Bowen ratio approach that has been described by textbooks and articles. A general description can be found in the book titled *Evaporation in the Atmosphere* by W. H. Brutsaert (D. Reidel Publishing Company, Dordrecht, Holland, 1982, pp. 210-212). For an article, see p. 18,549 of the special FIFE issue of the Journal of Geophysical Research (Vol. 97, pp. 18,343-19,110).

The surface energy balance equation is used:

q + ave-shf + h + e = 0,

where q is net radiation, ave_shf is the ground surface heat flow, h is sensible heat flux, and e is latent heat flux. The units for the terms in the equation above are watts per meter squared.

ave_shf is measured with five sets of soil heat flow, soil temperature, and soil moisture probes; soil heat flow at 5 cm (shf1, shf2, shf3, shf4, shf5) measured with soil heat flow plates) and soil energy storage (ces1, ces2, ces3, ces4, ces5) in the 0-5 cm layer (measured as the change in temperature with time) are added to obtain surface soil heat flow, as follows:

g1 = shf1 + ces1,

etc.,

where shf1 and ces1 are, respectively, the soil heat flow from the soil heat flow plate and the change in energy storage measured from the soil temperature probe of soil set #1. The expressions for g2, g3, g4, and g5 are similar. Soil moisture is used to adjust the measurements for soil thermal conductivity, which affects the calibrations of the sensors.

Surface soil heat flow is then

ave_shf = (g1 + g2 + g3 + g4 + g5)/5,

When data from one or more soil set(s) is incorrect, that soil set(s) can be eliminated and the average soil heat flow determined from the remaining sets.

The Bowen ratio is measured as the ratio of the gradients of temperature and vapor pressure (the latter calculated from relative humidity and temperature) across two fixed heights within three meters of the surface.

The Bowen ratio (B = h/e) is computed on the basis of the gradients and the following computations are performed:

e = -(q + ave_shf)/(1 + B)

h = B * e

More detailed information on these and other equations can be obtained elsewhere, including from David Cook at Argonne National Laboratory. A large manual provided by the manufacturer, REBS, Inc., describes the general theory, gives rather complete information on each type of sensor, and explains procedures for installation, operation, and maintenance.

7.3 Calibration

7.3.1 Theory

Standard calibration procedures are employed by the vendor(s) of the sensors and equipment used in the EBBR system when each EBBR unit is returned for recalibration, approximately every two years.

7.3.2 Procedures

The following are the factory recommended calibration procedures.

Humidity: Three-point calibrations (at approximately 11%, 75%, and 97%) above saturated salt solutions are used. (Factory calibration at 0% and 75% referenced to NIST.)

Temperature Sensors: There are ten temperature sensors in the EBBR system: two platinum resistance temperature detectors (PRTD) in the exchanging aspirated radiation shields, two thermocouples in the exchanging aspirated radiation shields, one reference PRTD in the control box, and five PRTD soil probes. All temperature sensors are subjected to an eight-point calibration (-30 to 40 deg C) in a XLT Heat Transfer Fluid (a silicon fluid) bath. A laboratory standard NIST-traceable PRTD is used for the reference. The laboratory standard PRTD data are acquired with a Campbell Scientific CR10 Datalogger, using the CR10 resistance-to-temperature function. Sensor PRTD normalized resistance ratio is measured with a CR10 Datalogger and regressed versus laboratory standard temperatures to obtain polynomial coefficients for the EBBR CR10 software. Thermocouple output is measured with a CR10 analog channel and the Campbell Thermocouple Function; the CR10 panel reference platinum element is used as the reference temperature sensor, located at the point where the thermocouples connect to the multiplexer. Deviations between the Laboratory Standard and thermocouple temperatures are recorded.

Soil Moisture Probes: Soil moisture probes are calibrated in a ceramic pressure plate extractor, in Kennewick, WA, soil. (Note: 1995 calibrations for E20 in Meeker, OK, and for E7 in Elk Falls, KS, were initially performed in soil from the respective site. These sensors were replaced in early 1996 with sensors calibrated in Kennewick, WA, soil). The extractor pressure gauge is traceable to NIST. Soil moisture probe and pressure gauge data are acquired with a CR10. Until April 1996, regression analyses were used to determine polynomial coefficients for the relationship between the normalized resistance ratio and the natural logarithm of pressure. A second polynomial converted pressure into soil moisture percent by weight using empirically determined polynomial coefficients for clay loam soil. The polynomial coefficients were used in the EBBR CR10 software.

In April 1996, the method of calibrating soil moisture probes from the probe and pressure plate data was modified. Soil moisture is now calculated directly from probe resistance, normalized to 25 degrees C. This produces a nearly linear relationship that requires the use of only one polynomial in the CR10 software and results in a significantly extended range of measurement of soil moisture.

Soil Heat Flow Plates: The soil heat flow plates are calibrated in a water-saturated glass bead medium that is located between hot and cold temperature baths. Heat transfer across the medium is determined from the temperature gradient between the baths. Bath temperatures are determined with NIST-traceable PRTD probes. Corrections are made in the CR10 software for the difference between the calibration medium thermal conductivity and the plate thermal conductivity.

Net Radiometer: Calibration is performed in a temperature-controlled chamber against a net radiometer transfer standard. The light source is a tungsten-halide lamp. The transfer standard is calibrated against an Eppley precision pyranometer. The transfer standard is traceable to NIST through the Eppley pyranometer using a shading technique. Note: some difference in calibration for short and long wavelengths has been noted by REBS and ARM, and is partially the result of calibrations versus a standard that is itself calibrated only against a pyranometer (which measures primarily short wavelengths), and partially a result of net radiometer design.

Barometric Pressure: The barometric pressure sensor is calibrated by the manufacturer at three pressure levels (27, 29 and 31) inches of mercury. Two models manufactured by the same company are presently in use. Electronic adjustments are made to bring the sensor within specifications. In the past, the sensors were calibrated at two ranges of pressure. However, recalibration of all sensors at the range indicated above is being performed in 2002.

Wind Direction Sensor: Calibration consists of alignment of the potentiometer and drive coupler to produce a voltage output corresponding to 180 degrees when the sensor hub and column marks are lined up. The manufacturer uses a precision degree wheel, pointer assembly, and digital voltmeter for the procedure.

Wind Speed Sensor: Calibration consists of spin tests by the manufacturer at various rotation rates to ensure that the sensor meets frequency-versus-speed specifications. Wind Tunnel calibrations are not performed.

CR10 Datalogger: All connections to the CR10 are removed and reference voltages or frequencies inputted to determine if outputs are as specified by the manufacturer.

7.3.3 History

The EBBR systems are returned to REBS approximately every two years for calibration of all sensors and data logger equipment. Some of the calibrations are performed by REBS themselves while some are performed by manufacturers of the equipment. For various reasons (the need to provide and calibrate spare sensors, frequent AEM failures, etc.) the time between recalibrations of EBBR units has sometimes been greater than two years; REBS is a small company and has little flexibility to rapidly reprioritize for individual customers.

7.4 Operation and Maintenance

7.4.1 User Manual

A user manual is available from REBS for the SEBS systems. A copy is kept at the SGP Central Facility and one is kept by the mentor.

7.4.2 Routine and Corrective Maintenance Documentation

Preventative maintenance, corrective maintenance, and engineering logs are maintained by SGP Site Operations (Site Ops) personnel. Maintenance and system checks are performed in accordance with a set of procedures written by Site Ops and the mentor. These procedures are maintained in print form at the SGP Central Facility and in digital form on Site Ops laptops taken into the field during preventative maintenance visits to the EBBR systems.

7.4.3 Software Documentation

EBBR programs are maintained on SGP Site Ops computers at the SGP Central Facility, on laptops used by Site Ops during preventative maintenance visits, and at REBS. Print copies and some digital copies are maintained by the mentor.

7.4.4 Additional Documentation

Six month EBBR checks are maintained on the SGP OMIS website.

7.5 Glossary

Bowen Ratio - The ratio of the sensible heat flux to the latent heat flux.

Sensible Heat Flux - The transfer of sensible heat (enthalpy) between the surface and the air, or vice versa.

Latent Heat Flux - The transfer of latent heat (heat released or absorbed by water) between the surface and the air, or vice versa.

Net Radiation - The net difference in downwelling and upwelling solar plus terrestrial radiation.

Soil Heat Flow - The transfer of sensible heat (enthalpy) in the soil, towards the surface or away from the surface.

7.6 Acronyms

AEM: Automatic Exchange Mechanism
BA: Bulk Aerodynamic Technique
DQR: Data Quality Report
EBBR: Energy Balance Bowen Ratio
ECOR: Eddy Correlation System
MDS: Meta Data System
PRTD: Platinum Resistance Temperature Detector
QME: Quality Measurement Experiment
RH: Relative Humidity
SEBS: Surface Energy Balance System
SIRS: Solar and Infrared Station (Broadband Radiometers)
SMOS: Surface Meteorological Observation Station
VAP: Value Added Product

Also see the ARM Acronyms and Abbreviations.

7.7 Citable References

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