USE OF NWS WEATHER MEASUREMENTS FOR CROSS-CHECKING LOCAL WEATHER MEASUREMENTS

Gregory D. Crowley and Jeff S. Haberl
Energy Systems Laboratory
Mechanical Engineering Department
Texas A&M University
College Station, TX

ABSTRACT

This paper discusses the use of an independent network of remote weather stations for building energy analysis to assist agencies participating in the Texas LoanSTAR Monitoring and Analysis Program. A review of the sensors and procedures is presented along with comparisons of local measurements against National Weather Service (NWS) measurements. Procedures are also presented for quickly determining when remote weather stations fail. Experiences from several years of operating the LoanSTAR weather network are provided, as well as examples of specific sensor failures and how the NWS comparisons provide a useful cross-check.

INTRODUCTION

Weather Measurement for Building Energy Analysis

The Texas LoanSTAR program is an eight year $98 million revolving loan program that funds energy conservation retrofits in state agencies. As of December 1993 the program has measured $7 million in savings from 46 buildings where retrofits have been completed which represents 120% of the audit estimated savings. One of the reasons the program has been successful is that the energy savings are measured hourly in the majority of the buildings. This has required local environmental conditions to be measured as well. In order to accomplish this, seven dedicated weather stations have been established at LoanSTAR sites around the state (Figure 1), including: Bryan/College Station, Austin, Houston, Galveston, Dallas/Ft. Worth, San Antonio, and Harlingen. LoanSTAR agencies at sites other than these were supplemented by weather data from over 35 National Weather Service stations throughout Texas.

Having data from both the NWS and LoanSTAR weather stations has proven helpful in cross-checking weather data from the same cities. In general, weather data from the LoanSTAR sites compares well with the data from the NWS sites. However, certain differences have been observed that can be traced to instrumentation and the location of the weather stations. This paper presents a comparison of weather data collected from different sources and comments on its usefulness in building energy analysis. It also discusses the development of procedures for processing, inspecting, and analyzing the data.

METHODOLOGY

National Weather Service data processing

The National Weather Service (NWS) has served the nation's weather information needs since 1870, when it was established as the Weather Bureau. Today, as a part of the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce, the NWS continues to collect and disseminate weather information using the latest in automated, high-tech instruments (Tannenbaum and Tannenbaum 1989).

For years surface weather observations have been conducted at airports around the country. At the sites, certified ground technicians work during three shifts around the clock to manually assemble current weather measurements. Upon collection the information is later utilized in conjunction with special visual observations (i.e., sky condition, precipitation, thunderstorms, tornadoes, etc.) to aid in aviation reporting and to broadcast environmental conditions for public knowledge.

Until the early 1990's many of these surface observing stations have relied on a collection of instruments arranged in a tower-like configuration at or near airport runways. Generally, the stations consist of a hygrothermometer (a dew point and ambient temperature sensor), an anemometer (wind speed and direction sensor), a ceilometer (cloud height sensor), and an altimeter reading indicator (pressure sensor). The remote sensors continuously observe the weather trends and forward the information to a visual display terminal located inside the nearby observation office. The offices are often attached to a Federal Aviation Administration (FAA) ground tower at the airport.

Proceedings of the Ninth Symposium on Improving Building Systems in Hot and Humid Climates, Arlington, TX, May 19-20, 1994

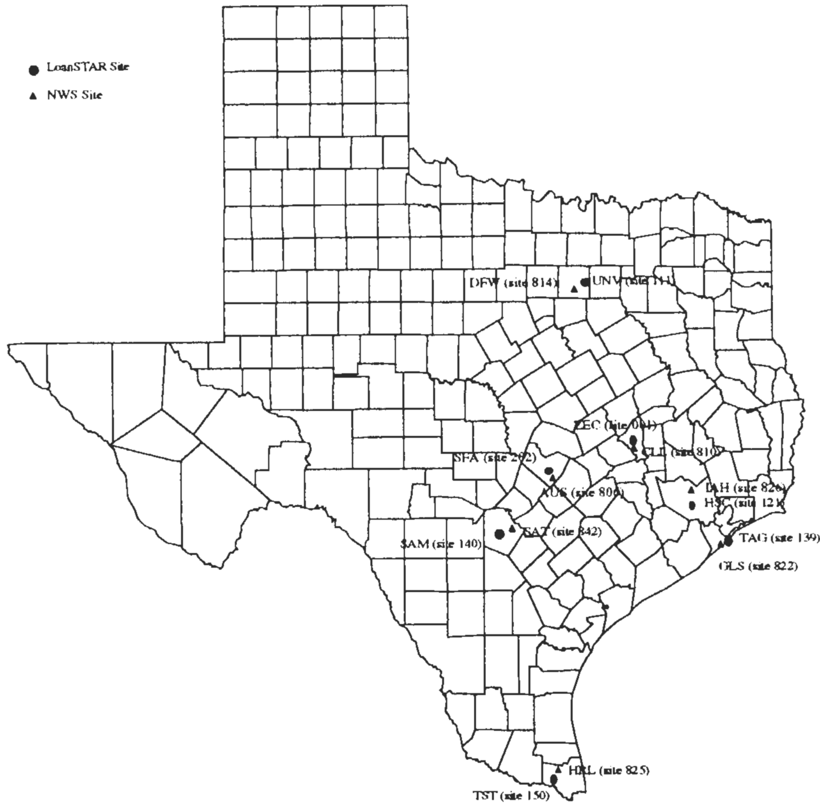

Figure 1. *Location of LoanSTAR and NWS weather station pairs within the state of Texas*

In the case of the hygrothermometer display unit, both channels of ambient and dew point temperature undergo a 5-minute averaging process. Maximum and minimum temperatures are also displayed. The remaining sensors rely upon analog gauges within the office to provide a visual representation of the coincident weather measurements. Table 1 provides a listing of the measurement equipment available at a typical NWS ground observation site.

The NWS observational procedures are defined in the Federal Meteorological Handbook (OFCM 1988). Certified ground technicians manually record local observations each hour, and whenever significant changes or occurrences are observed. These observations are written on Meteorological Form I-10 for documentation purposes. Immediately afterwards, the same report is then transmitted electronically to a NWS regional distribution site via the Automation Field Operations and Services (AFOS) network using a nearby computer terminal. According to procedures in the manual, these weather observations are to reflect only the conditions seen from the "usual point of observation," normally directly outside the front entrance of the weather reporting station, and unless otherwise specified, must have occurred within 15 minutes prior to the times recorded on the form, in other words, snapshot data.

According to ground technicians at the NWS site in College Station, TX., during a typical observation instantaneous dry bulb and dew point readings taken from the hygrothermometer display unit are rounded to the nearest degree Fahrenheit before tabulation in Form I-10. The remaining weather elements are visually determined from the respective gauges at the time that the Meteorological Form I-10 is filled in. Usually, the same technician records all the measurements during his/her respective shift in order to maintain uniformity within the measurement sets. Although the NWS specifies that a 15-minute window be allocated for manual input of data into its computer data bank prior to the start of each hour, most technicians complete this task in under 5 minutes.

Table 1. *Instrumentation used to measure weather data for the NWS.*

WEATHER ELEMENT:	TYPE OF INSTRUMENT:	RANGE:	ACCURACY:	MANUFACTURER:
AMBIENT TEMPERATURE	platinum RTD	-60 to 60 C	± 0.5 C	Technical Services Laboratory, Inc., Fort Walton Beach, FL
DEW POINT TEMPERATURE	optical chilled mirror system	-60 to 60 C	± 0.5 C	Technical Services Laboratory, Inc., Fort Walton Beach, FL
WIND SPEED AND DIRECTION	anemometer	0 to 80 knots	± 2 % of reading	Belfort Corp., Baltimore, MD
PRESSURE	altimeter	varies by site	± 0.02 in. Hg	AAI Corp., Hunt Valley, MD
RAINFALL ACCUMULATION	tipping bucket	8 in H_2O gauge std.	± 0.1 in. H_2O	Fischer & Porter Co., Warminster, PA
VISIBILITY	laser beam visibility sensor	1/4 mi. to 10 mi.	≤ 4 mi.; ± 1 mi. ≥ 5 mi.; ± 2 mi.	AAI Corp., Hunt Valley, MD
PRECIPITATION	laser beam precipitation identification sensor	light, moderate, heavy; rain/snow, freezing rain	allowable uncertainty (overlapping) on each limiting side based upon crystalline structure and intensity of precipitation	AAI Corp., Hunt Valley, MD
MINUTES OF SUNSHINE	photoelectric cell sunshine switch	varies by site and season of the year	N/A	N/A
CLOUD CEILING	laser beam ceilometer	0 to 12,000 ft.	0 to < 5,000 ft.; ± 500 ft. 5,000 to < 10,000 ft.; ± 1500 ft. 10,000 to 12,000 ft.; ± 2500 ft.	Vaisala, Inc., Woburn, MA

To cross-check the standard weather elements observed from the measurement devices, each station typically establishes one day per week to perform a rudimentary analysis of the instrumentation. For example at College Station airport, the attending technician checks the accuracy of the ambient and dew point temperature readings on Mondays at noon using an unshielded sling psychrometer in front of the weather office, often in the bright sunlight. If the readings produced by the sling psychrometer and the visual display agree within ± 2% of reading, the hygrothermometer is assumed to be working properly. The basis of this analysis stems from a correlation of wet bulb temperature with adiabatic saturation temperature (Threlkeld 1970). It was concluded that an unshielded wet bulb on the sling psychrometer will generally closely approximate the adiabatic saturation temperature, a hypothetical standard wet bulb temperature that can only be approached in practice. From the wet bulb value, a corresponding dew point temperature and/or relative humidity value can be calculated.

The remaining weather elements, in particular wind speed and direction, are checked by comparing information received from air traffic control tower operators who maintain a wind sock in the airfield. There is generally no specified level of accuracy associated between these comparisons. Occasionally significant differences in readings between the two agencies occur, yet acceptance of the discrepancy is usually based upon the ground technician's judgment in inspecting these instruments.

NWS Automated Surface Observing System

Over the past several years an automated on-line weather measurement system has been developed, and is currently being phased in by the NWS. The Automated Surface Observing System (ASOS) is the name given to this upgraded surface observation network. ASOS provides minute-by-minute performance and executes the basic monitoring functions necessary to generate a surface weather observation and other aviation weather information. The main difference between the new automated system and the human observation station is in the method used to collect and interpret visual weather elements (i.e., sky condition, visibility, and present weather). While the trained human observer utilizes a "fixed time, spatial-averaging technique," ASOS uses a "fixed location, time-averaging technique." In other words, when an attending technician goes outside to inspect a change in visual weather conditions, he bases his hourly report upon the present weather conditions occurring inside his visual horizon (i.e. 4 miles) at the instantaneous time of the inspection. On the other hand, ASOS reports any changes in precipitation within ten minutes of origination. The network then averages all of the continuous weather activity that it "observes" with respect to its stationary post during five minute intervals, and updates its reading to the local NWS station. Although these two methods are different, the NWS claims that the two methods do yield similar results within the limits of their respective capabilities (NOAA 1993).

The systems being installed at over 850 locations throughout the U.S. consist of four main components: individual weather sensors, data collection packages, acquisition control units, and peripherals and displays. Each collection of weather sensors contains a cloud height indicator, visibility sensor, precipitation identifier sensor, pressure sensors, temperature/dew point sensor, wind direction/speed sensor, rainfall accumulation sensor, and at many sites a freezing rain sensor. Figure 2 provides a detailed look at the ASOS. Although similar to the "old" surface observation sites, the newer set-up allows ASOS to detect significant changes and relay the signal via radio to the local Operator Interface Device (OID), a computer terminal where the attending technician may inspect incoming weather tracking data and distribute hourly and special observations via the NWS and FAA communications networks. During each hourly report special weather observation elements are also broadcast as they occur.

The advent of an automated system is intended to increase productivity in generating more consistent and accurate measurements. The system upgrade virtually eliminates the need for a ground technician to post his/her hourly watch of the weather, since all the measurements are performed and interpreted automatically by the computer system. However, in hopes of catching any "bugs," the NWS is cautiously integrating this network within their weather monitoring system. Upon the completion of installation of ASOS at a weather site, the system is integrated within the network and tested over an 18 month period of supervised weather measurements before it is utilized as the full-time initial weather response network. Up to 2 years can be allowed for a site to completely switch to a fully-automated unit, in case unusual difficulties occur. Meanwhile, the site's previous manual surface observation system becomes a back-up should anything go wrong with ASOS.

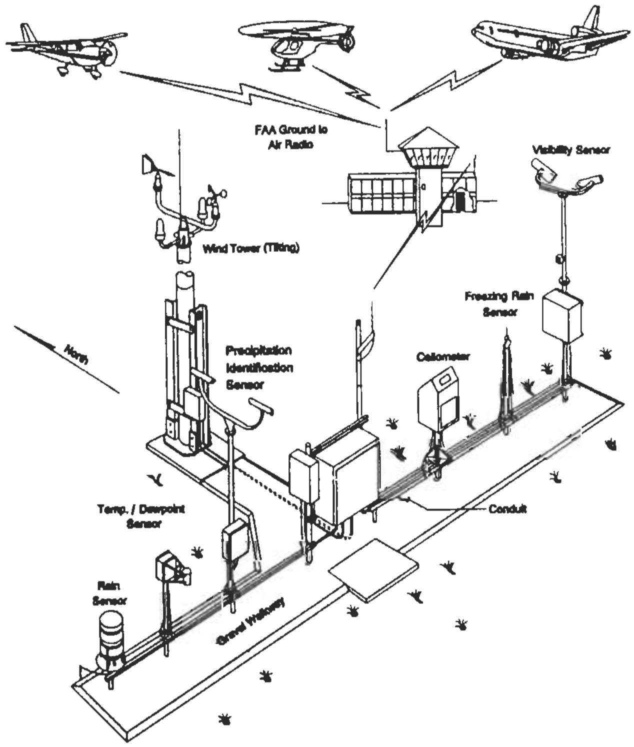

Figure 2. *Schematic of a typical ASOS sensor display* (Diagram reprinted with permission of National Oceanic and Atmospheric Administration).

LoanSTAR weather data processing

The NWS data are retrieved to assist in cross-checking the seven LoanSTAR weather stations at each of seven metropolitan cities throughout the state of Texas. Specifically, data from the NWS are used to cross-check ambient temperature, humidity, solar measurements, and wind speed. The LoanSTAR weather stations are usually perched atop the roof of one of the primary buildings being monitored within a region. Weekly polling of the weather stations is enabled through remote data loggers at the building sites. Meanwhile, NWS data is collected via a modem connection with AccuWeather, a wholesale weather information distributor. Once gathered both the LoanSTAR and NWS data are formatted and merged together utilizing a combination of public domain utilities, inexpensive commercial software, and routines written in-house as shown in Figures 3 and 4 (Lopez and Haberl 1992).

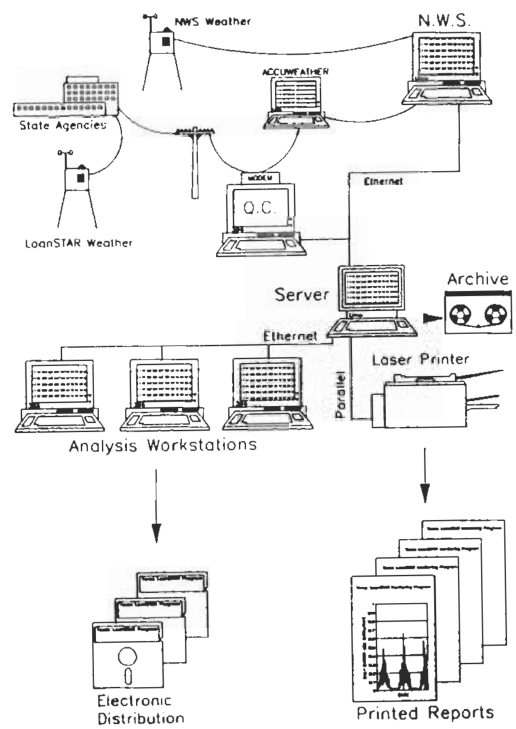

Figure 3. *Schematic of the data processing routine used to gather LoanSTAR and NWS weather data.*

Each week a collection of inspection plots are generated to allow for a simple visual quality control check of the various channels of data under analysis from the agencies and weather station as part of the Inspection Plot Notebook (IPN). The plots are key to visually identifying possible problems with the incoming data so corrective measures can be implemented. Included with this information are scatter plots of LoanSTAR weather data versus National Weather Service data which can be used to determine if a significant deviation has occurred between two stations in the same city.

Since the LoanSTAR program is primarily interested in analyzing the impact of weather parameters on buildings, hourly ambient, relative humidity, wind speed, and global horizontal solar radiation are being measured. Historically, LoanSTAR and NWS data tend to differ by only 5 to 10% on average. If LoanSTAR data begins to exceed this standard, support technicians are dispatched to the site to remedy the problem. In most cases failures to the remote weather stations are due to problems with individual sensors as shown in Table 2. Fast response is critical for maintaining the weather stations since one or more LoanSTAR building sites may be dependent on the data for various purposes. At some sites more than twenty buildings are dependent on the data from one weather station.

During 5 years of operation, the LoanSTAR program has experienced only 19 failures with the weather station sensors (Table 2). The most common problem experienced is bearing failure in the wind sensors. Due to a cheaply constructed bearing housing, these sensors have consistently proven to be unreliable performers. The most robust sensor of the group is the 2-wire platinum RTD used to measure ambient dry bulb temperature. These sensors tend to maintain long-term performance with fairly good accuracy as based upon comparisons with NWS dry bulb temperature.

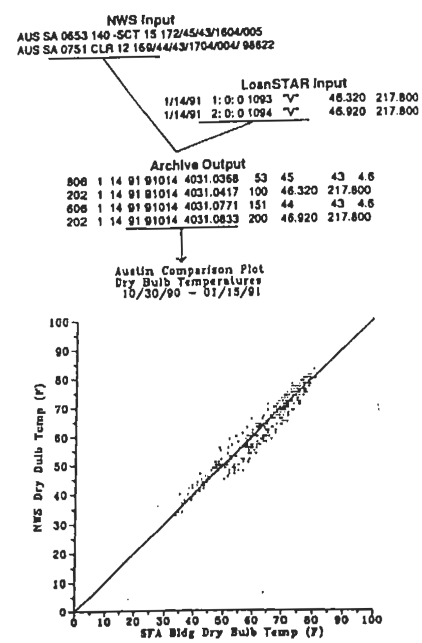

Figure 4. *Process for merging raw LoanSTAR and NWS data sets to produce comparison plots* (Lopez and Haberl 1992).

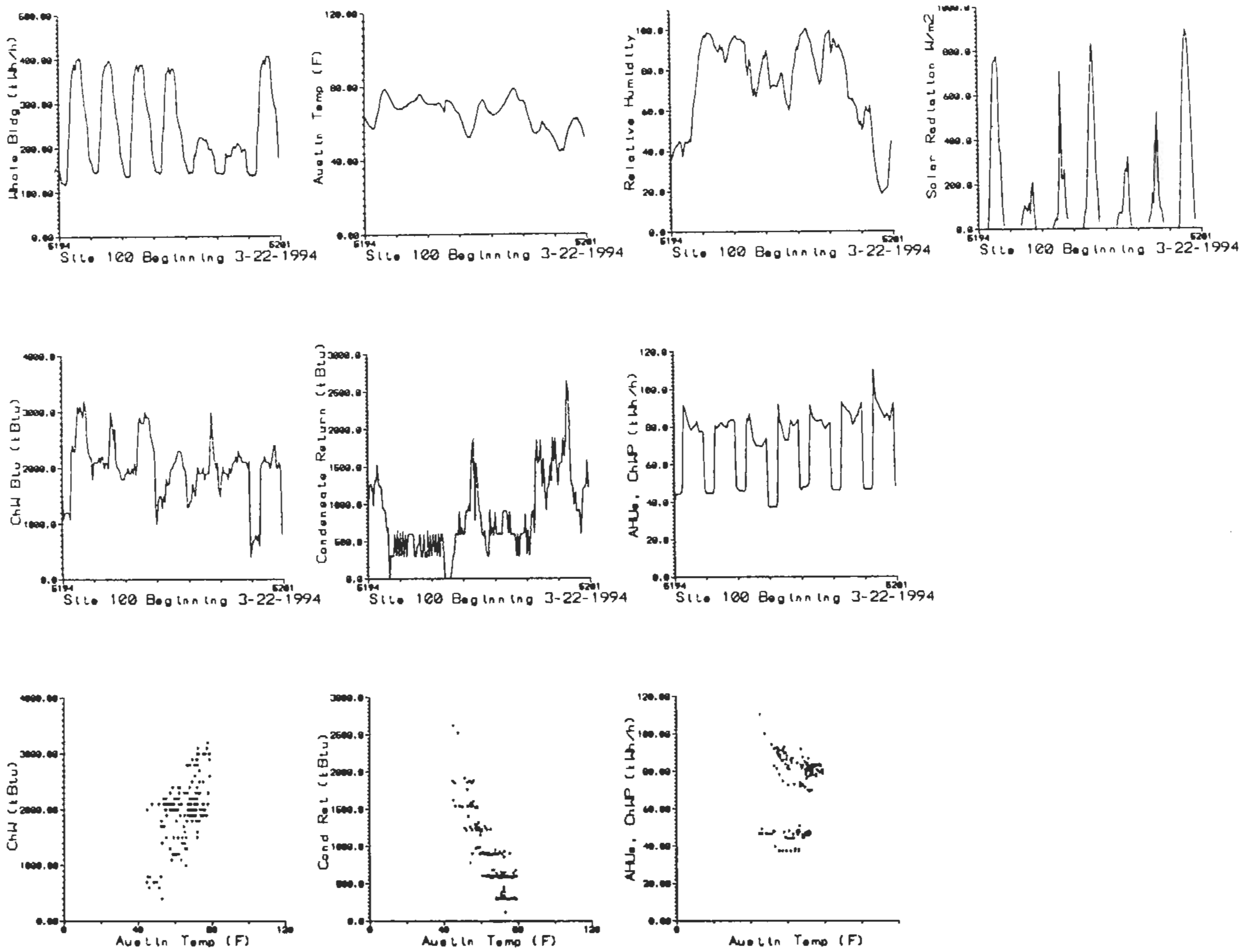

Figure 5. *A typical page from the Inspection Plot Notebook (IPN).*

Typically, notification of potential problems with a sensor are detected from observation of IPN cross plots, however, many instances occur where some failures are detected in the field. In the first few years of the LoanSTAR Monitoring and Analysis Program, technicians were dispatched to sites to repair faulty sensors only after a failure had been detected. Accordingly, many sensors operated for extended periods, up to a year, without experiencing periodic maintenance and cleaning. As a result some sensors experienced an unnecessary drop-off in performance. One example is highlighted by the experience in utilizing an optical dew point sensor at the weather stations. Following the example of the NWS, LoanSTAR incorporated dew point sensors in all their weather stations near the gulf coast to determine humidity. Because the optical chilled mirror device is highly sensitive to tiny particles resting on its surface, the sensor is prone to giving false or misleading dew points readings when not regularly maintained. In the case of the LoanSTAR weather stations, most of the dew point sensors proved to be reliable for only two months before significant degradation developed with the sensor readings. Unfortunately, many of the stations are physically too remote from College

Station to warrant the dispatching of technicians with the frequency required by these sensors. Consequently, LoanSTAR has recently replaced each of the dew point sensors with an electronic relative humidity sensor, and is currently achieving better long term results in determining humidity. Today, LoanSTAR seeks to maintain the vitality of the sensors by implementing a regular periodic inspection schedule where each weather station is visited every 6 months for regular maintenance, cleaning, or upgrading, along with visits for failures.

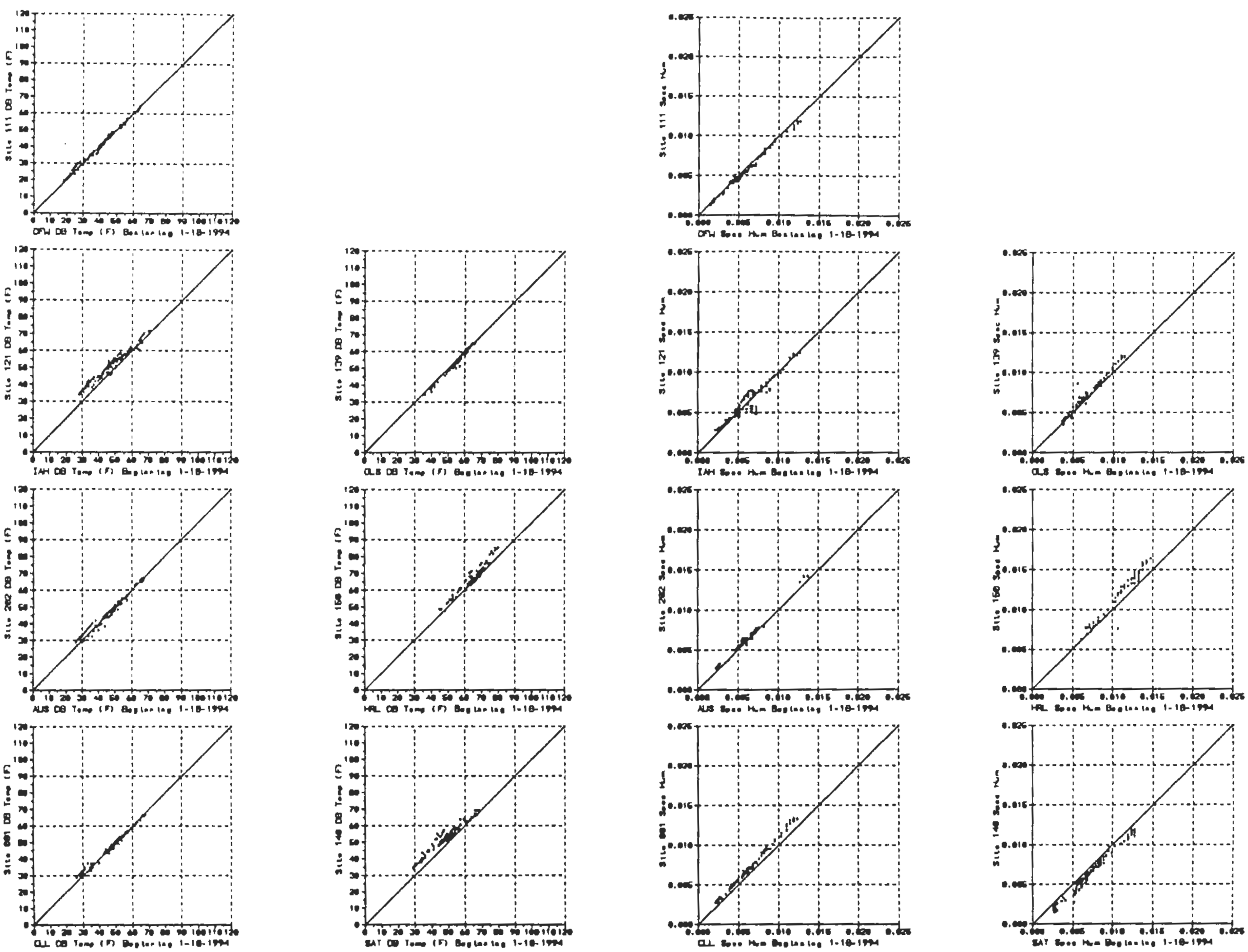

Figure 6. *A collection of scatter plots for corresponding LoanSTAR and NWS weather sites used in the IPN.*

Table 2. *Sensor failures detected at seven LoanSTAR weather stations during the period May 8, 1989 to December 31, 1993.*

LoanSTAR Sensor	Failure Mode	Number of Occurrences	Method of Detection; Remedy
Electrical resistance dry bulb temp.	loss of calibration	1	IPN/cross plots with NWS; recalibration at ESL
Optical dew point	collects scale deposits on mirror surface	3	Visual observation during periodic inspections; cleaned and recalibrated at ESL
	loss of calibration	1	IPN/cross plots with NWS; recalibration at ESL
Electronic relative humidity	collects debris from dirt and insects	2	Visual observation during periodic inspections; cleaned on site
	loss of calibration	3	IPN/cross plots with NWS; recalibration at ESL
Wind speed	develop bearing failure	6	Visual observation during periodic inspections; fixed or replaced on site
Solar radiation	loss of calibration	1	IPN/cross plots with NWS; recalibration at ESL
Aspiration fan	develop bearing failure	1	Visual observation during periodic inspections; replaced on site
	loss of power (120 volt)	1	IPN/cross plots with NWS or visual observation during periodic inspections; fixed on site
	TOTAL:	19	

NOTE: ESL stands for the Energy Systems Laboratory at the Riverside Campus of Texas A&M University.

Table 3. *Instrumentation presently used to measure weather data at LoanSTAR weather stations.*

WEATHER ELEMENT:	TYPE OF INSTRUMENT:	RANGE:	ACCURACY:	MANUFACTURER:
TEMPERATURE (1)	1000 ohm, 2 wire platinum RTD	-50 to 212 F	± 0.6 F	HY-CAL Engineering, El Monte, CA
RELATIVE HUMIDITY (1)	thin film capacitive RH sensor	0 to 100% RH	± 2% of reading	Vaisala, Inc., Woburn, MA
WIND SPEED (2)	low-threshold contact anemometer	1 mph to 100 mph	Note (2)	Fowlkes Engineering, Bozeman, MT
SOLAR RADIATION (1)	LI-200SA pyranometer	0 to 3000 W/m^2	± 3% of reading ± 5-10% of reading at large incidence angles, not cosine corrected.	Licor, Inc., Lincoln, NE

NOTES:

1. The values for the range and accuracy are from the manufacturer's literature.
2. The manufacturer of this device only cites the low threshold wind speed.

RESULTS

Comparison of weather measurements from the LoanSTAR and NWS weather stations

As revealed in Figures 6 and 7, considerable differences exist between the weather data recorded at sites that are often only a few miles apart. Unfortunately, there can be up to 20 miles between LoanSTAR and NWS weather stations. Although previous studies have argued for or against using local or NWS weather data, very little advice exists as to what the differences are, and how those differences can be factored into a procedure that can indicate to what extent a local weather station agrees with the nearest NWS weather station (Dufner et al. 1993). A closer look at the weather data from LoanSTAR and NWS for Houston provides some guidance as to what comparisons can be made and how useful they are.

From Figure 7 it is clear that during certain periods, readings of the LoanSTAR average daily dry bulb temperature and specific humidity agree reasonably well with those recorded by the NWS even though those sites are separated by 20 miles. Total daily global solar horizontal radiation reported by the LoanSTAR solar sensor agrees somewhat with the minutes of sunshine information listed by the NWS.

The comparison of the two solar readings appears to yield a relationship that may furnish enough evidence to catch major errors with the sensor. The x-axis represents percentage of possible sunshine per day as measured with a Foster sunshine switch (Duffie and Beckman 1990; Foster and Foskett 1953). Along the y-axis, the sky clearness, K_t, is the ratio of the total global horizontal solar radiation to the extraterrestrial horizontal radiation. The line that is drawn through the data represents a simple linear regression as suggested by the Angstrom-Lof equation (Kreider and Kreith 1981). The equations for calculating the sky clearness and percentage of possible sunshine are listed in the appendix.

In the case of the wind speed there is virtually no agreement between the LoanSTAR data and the NWS data. There are several reasons for this problem. First, the NWS records the peak wind gust that occurs during each hour, whereas the data logger at the LoanSTAR site records an average wind speed. Second, the wind sensors under operation in the LoanSTAR stations are a less expensive and less durable brand than that utilized by the NWS. Unfortunately, the sensor specifics for the LoanSTAR wind sensor have a higher cut-in wind speed and are prone to premature bearing failure. Although the wind sensor at LoanSTAR Houston weather station HSC (site 121) was rotating during the last inspection of the site on May 5, 1993, the attending technician observed that there was considerable bearing friction in the unit. This situation probably contributed significantly to the lack of agreement shown in Figure 7. However, it should be noted in hind-sight that this much lack of agreement probably should have been cause for alarm.

The comparison of humidity readings suggests a good agreement for these two sites even though a look at the hourly time series data from the LoanSTAR sensor reveals many hours of saturation (Figure 5). The use of the specific humidities can be problematic for certain sites because it involves the potential error of four measurements (i.e., two dry bulb temperatures, one relative humidity from the LoanSTAR sites, and a dew point measurement from the NWS). The data for Figure 7 required preprocessing with a psychrometric program (AIR 1992) that converts dry bulb and relative humidity pairs into specific humidity values. The correlation of specific humidities appears to be site specific as shown in Figure 6, where there is fair agreement for six of the seven sites, and a strong drift at one of the sites, (San Antonio, SAT). In general, this comparison has proven useful for determining if a sensor is $\pm$ 20% or more out of calibration.

The comparison of the dry bulb temperatures requires a closer look. The dry bulb data displayed in the upper left graph of Figure 7 show two groupings, which are caused by a failed dry bulb temperature sensor. Figure 8 shows 52 week time series data displayed as connected box whisker mean plots (Abbas 1993). The upper graph shows the LoanSTAR station, the middle graph shows the NWS station, and the lower graph shows the differences in the weekly hour-by-hour comparisons.

It should be noted that a recalibration of the LoanSTAR weather station took place during week 40. At that time it was determined that the 1000-ohm RTD sensor was not working properly, since a temperature difference of 15 degrees was being reported in the IPN. Clearly, the plot of the $\pm$ residual in Figure 8 confirms that the average for weeks, 7 through 40, was 5 ^{o}F and higher which is approaching the RMSE annual difference of 5.5 °F between the two sites that is shown in Table 4.

In Table 4 the hourly LoanSTAR data are compared to hourly, daily-averaged, and min/max daily-averaged NWS data. Surprisingly enough, the hourly and daily-averaged CV(RMSE) are virtually identical for the Houston weather stations. However, the comparison of min/max daily-averaged LoanSTAR dry bulb temperature to min/max daily-averaged NWS data seems to be slightly worse than daily-averaged and hourly comparisons in the same city.

Figure 9 shows a comparison of the daily averaged LoanSTAR data to the daily averaged hourly NWS data. The filled symbols indicate data taken after the recalibration. The un-filled symbols are data taken before the recalibration. The dashed lines on either side of the solid direct comparison line represent ± CV(RMSE). Clearly a simple filter that sets a flag whenever the daily average difference consistently exceeds the RMSE would have indicated that there was a problem at this site. Figure 10 shows that a similar comparison to NWS min/max average data would have yielded a similar, yet slightly less clear indicator.

CONCLUSION

This paper has shown that a continuous comparison to NWS data can be useful in detecting sensor degradation in local weather stations for ambient temperature, humidity, and solar data. Comparisons between local average hourly wind speed and NWS peak hourly wind speed are not recommended.

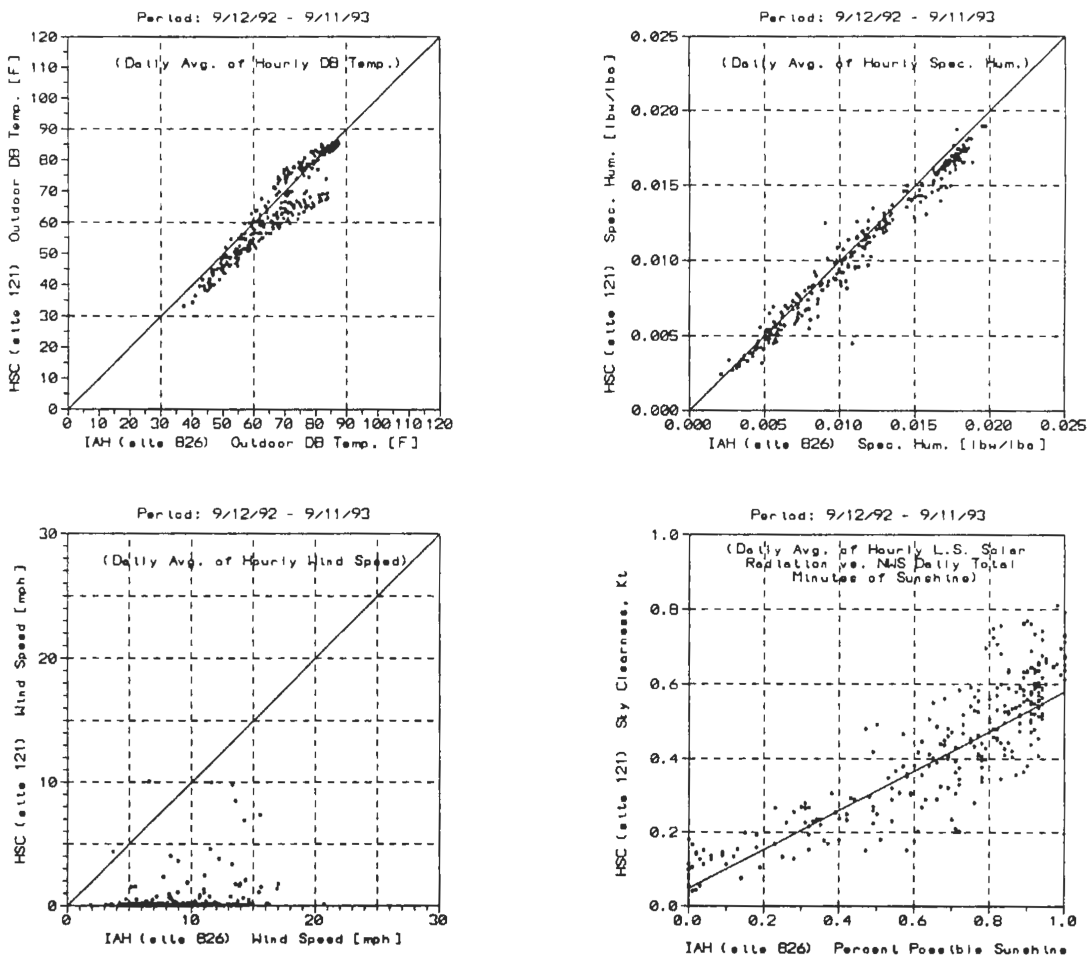

Figure 7. *Daily averaged LoanSTAR weather data versus NWS weather data for Houston during the period September 12, 1992 to September 11, 1993.*

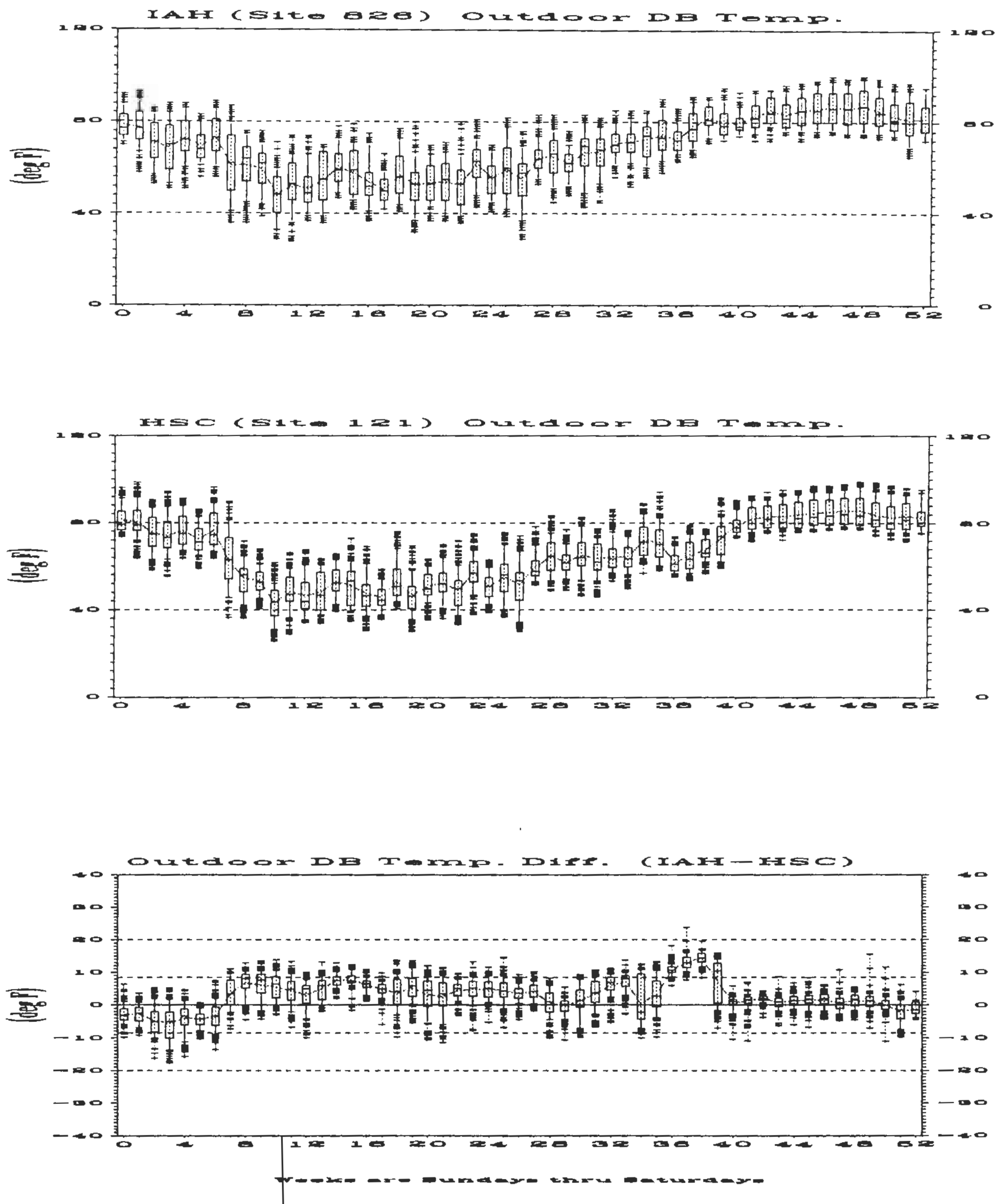

Figure 8. *Box-whisker-mean comparison plots of the Houston based LoanSTAR and NWS weather stations.*

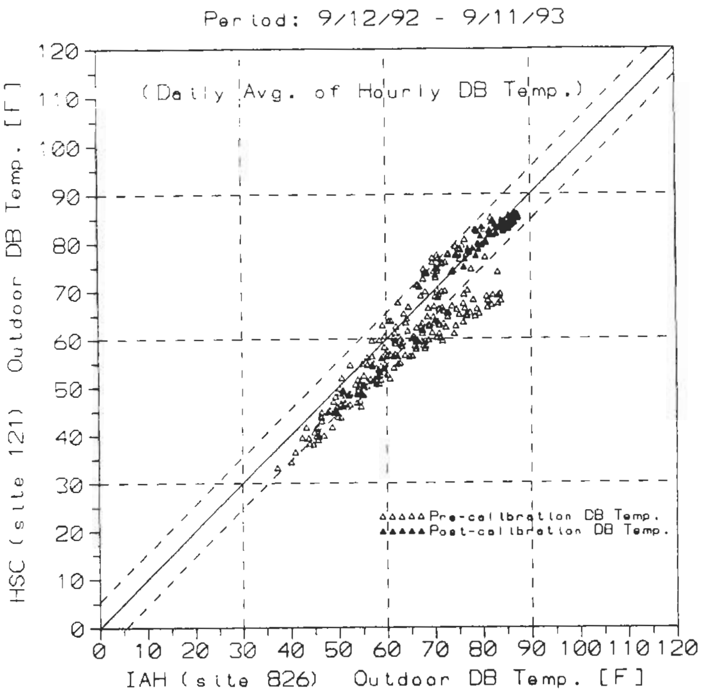

Figure 9. *Comparison plot of average hourly dry bulb temperature from the Houston based LoanSTAR and NWS weather stations.*

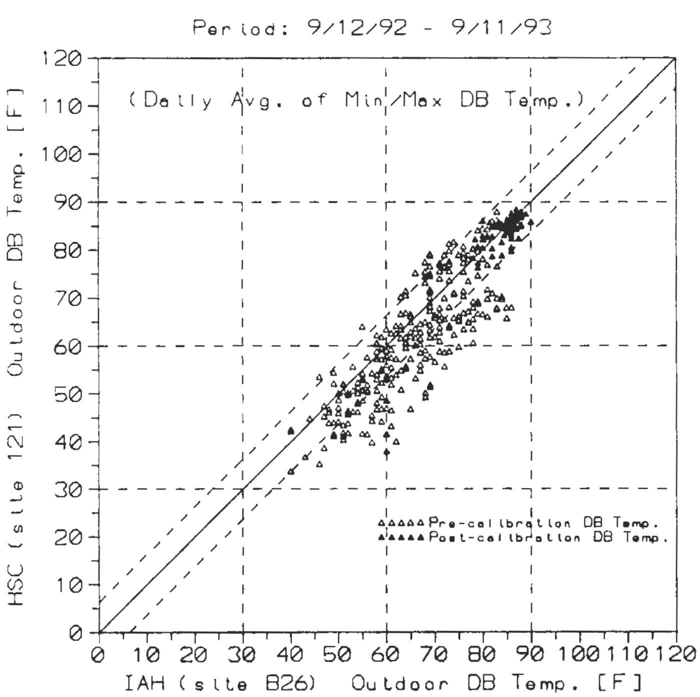

Figure 10. *Comparison plot of average daily min/max dry bulb temperature from the Houston based LoanSTAR and NWS weather stations.*

Table 4. *LoanSTAR weather site, location, approximate distance to NWS site, and setup.*

LoanSTAR site:	Latitude, Longitude:	Distance to NWS site:	Comments:
UNV (site 111)	32°54' N 96°05' W	12 miles	Located atop University Hall (8 stories) on the campus of U.T. Arlington
ZEC (site 001)	30°35' N 96°21' W	1 mile	Located atop Zachry Engineering Center (4 stories) on the main campus of Texas A&M Univ.
TAG (site 139)	29°24' N 94°30' W	5 miles	Located atop Physical Plant Bldg. (3 stories) on the campus of Texas A&M University-Galveston
HSC (site 121)	30°00' N 95°00' W	20 miles	Located atop the Medical School Building (12 stories) at the Houston Medical Center
TST (site 150)	26°12' N 97°48' W	3 miles	Located atop the TSTC Building (1 story) in Harlingen
SAM (site 140)	29°30' N 97°48' W	5 miles	Located atop the Medical School Building (3 stories) at the U.T.H.S.C. complex in San Antonio
SFA (site 202)	30°18' N 97°24' W	3 miles	Located atop the Stephen F. Austin Bldg. Capitol Complex (12 stories) in Austin

Table 5. *Statistical temperature variation between the LoanSTAR weather stations and NWS weather stations.*

WEATHER STATIONS (LoanSTAR & NWS):	HOURLY DRY BULB TEMPERATURE:		AVERAGE OF TOTAL HOURLY (DAILY) DRY BULB TEMPERATURE:		AVERAGE OF DAILY MIN/MAX DRY BULB TEMPERATURE:	
	RMSE(CV) °F	MBE	RMSE(CV) °F	MBE	RMSE(CV) °F	MBE
HSC (site 121) & IAH (site 826)	5.5 (8.3%)	-4.3%	6.3 (9.4%)	-4.2%	5.4 (8.0%)	3.9%
ZEC (site 001) & CLL (site 810)	2.9 (4.3%)	0.2%	1.3 (1.9%)	0.2%	1.3 (1.9%)	0.1%
UNV (site 111) & DFW (site 814)	2.4 (3.8%)	-0.7%	1.5 (2.2%)	-0.8%	1.5 (2.3%)	-0.6%
SFA (site 202) & AUS (site 806)	3.2 (4.7%)	1.2%	2.2 (3.2%)	1.3%	2.3 (3.3%)	0.9%
SAM (site 140) & SAT (site 842)	3.1 (4.6%)	-1.4%	1.7 (2.5%)	-1.4%	1.7 (2.5%)	-1.1%
TST (site 150) & HRL (site 825)	3.8 (4.8%)	5.1%	3.2 (4.1%)	4.0%	3.5 (4.4%)	6.5%
TAG (site 139) & GLS (site 822)	2.2 (2.9%)	-0.6%	0.9 (1.2%)	-1.9%	4.3 (5.9%)	-1.8%

APPENDIX
Statistical formulae used to analyze the weather data (SAS 1990):

1. Coefficient of Variation, CV (%):

$$CV \equiv \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(y_{pred,i} - y_{data,i}\right)^2}{n-p}}}{\bar{y}_{data}} \times 100$$

2. Mean Bias Error, MBE (%):

$$MBE \equiv \frac{\frac{\sum_{i=1}^{n}\left(y_{pred,i} - y_{data,i}\right)}{n}}{\bar{y}_{data}} \times 100$$

where,

$y_{data,i}$ = a data value of the dependent variable (LoanSTAR) corresponding to a particular set of the independent variables (NWS).

$y_{pred,i}$ = a predicted dependent variable (NWS) value for the same set of independent variables (LoanSTAR) above.

n = the number of data points in the data set.

p = the number of regression parameters in the model (which was assigned as 0 for all models).

Equations used to develop the solar radiation cross-plots (Lof et al., 1966a,b):

1. sky clearness index, K_t:

$$K_t = \frac{H}{H_o}$$

2. percent of possible sunshine, PP:

$$PP = \frac{A}{N}$$

3. extraterrestrial solar radiation on a horizontal surface, H_0 (MJ/day):

$$H_o = \frac{24 \times 3600 G_o}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right) \times \left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right)$$

4. maximum possible minutes of sunshine, N:

$$N = \frac{2 \times 60}{15}\cos^{-1}\left(-\tan\phi \cdot \tan\delta\right)$$

where,

H = the measured solar radiation on a horizontal surface in MJ/day.

A = the recorded sunshine duration for the day in minutes.

G_0 = the mean solar constant (=1367 W/m^2).

n = the day of the year, (i.e. January 1; n=1).

ϕ = the latitude angle for the site.

δ = the solar declination angle for the day,

$$\delta = 23.45\sin\left(360 \cdot \frac{284 + n}{365}\right)$$

ω_s = the sunset hour angle,

$$\omega_s = \cos^{-1}\left(\tan\phi \cdot \tan\delta\right)$$

ACKNOWLEDGMENTS
Support by the State of Texas Energy Office, as part of Texas A&M's LoanSTAR Monitoring and Analysis contract is gratefully acknowledged.

The Texas LoanSTAR program is an eight-year, $98 million revolving loan program for energy conservation retrofits in Texas state, local government and school buildings funded by overcharge dollars. Currently, the program is monitoring 3,000+ channels of hourly data from over 200 buildings. Additional information concerning the program can be found in Claridge et al. (1991).

Thanks to the following people at the Energy Systems Lab for their assistance with this paper: Chuck Bohmer, Curtis Boecker, Ron Chambers, Robert Sparks, Pat Tollefson, Mustafa Abbas, and Jinrong Wang.

Special thanks goes to Steven Baker, electronics technician at the NWS in Waco, TX, and Dr. Mickey Flynn at the NWS in College Station for their help in gathering insightful information concerning NWS weather data collection.

Software used during the course of this project include: Grapher and MapViewer software from Golden Software, Golden, Colorado; the Statistical Analysis Software from the SAS Institute, Cary, North Carolina; and file transfer software from FTP Software Inc., Wakefield, Massachusetts. Public domain software includes GAWK (FSF 1989).

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