GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-25-M09 R6168-0A0 GTRC/~~GIT~~ DATE 8 / 5 / 86

Project Director: Dr. Sheldon Jeter School/~~Lab~~ ME

Sponsor: Southern Company Services, Birmingham, AL

Type Agreement: Contract No. 195-86-002

Award Period: From 7/1/86 To ~~7/30/87~~ 6/18/88 (Performance) 7/30/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 10,000
Funded:	$ 10,000	$ 10,000

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: "Research and Development on Procedures for Solar Radiation Monitoring"

ADMINISTRATIVE DATA

OCA Contact E. Faith Gleason ext. 4820

1) Sponsor Technical Contact:	2) Sponsor Admin/Contractual Matters:
J.T. Petty, Research & Development	Joseph L. Coker, Contract Analyst
Southern Company Services	Southern Company Services
P.O. Box 2625	P.O. Box 2625
Birmingham, AL 35202	Birmingham, AL 35202
(205) 870-6241	(205) 877-7569

Defense Priority Rating: N/A

Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A

COMMENTS:

AUG 1986 RECEIVED SUPPORT SERVICES OCA

COPIES TO: SPONSOR'S I. D. NO. 02.218.000.86.005

Project Director	Procurement/GTRI Supply Services	GTRC
Research Administrative Network	Research Security Services	Library
Research Property Management	Reports Coordinator (OCA)	Project File
Accounting	Research Communications (2)	Other Jones

GEORGIA INSTITUTE OF TECHNOLOGY　　　　OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 4/21/88

Project No. E-25-M09　　School/~~Lab~~ ME

Includes Subproject No.(s) N/A

Project Director(s) Dr. Sheldon Jeter　　GTRC/~~GIT~~

Sponsor Southern Company Services/Birmingham, AL

Title Research and Development on Procedures for Solar Radiation Monitoring

Effective Completion Date: 6/18/88 (Performance) 4/18/88 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Copy of Last Invoice Serving as Final
- [ ] Release and Assignment
- [ ] Final Report of Inventions and/or Subcontract:
  Patent and Subcontract Questionnaire sent to Project Director [ ]
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ____________

Continues Project No. ____________ Continued by Project No. ____________

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E-25-M09

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THE GEORGE W. WOODRUFF SCHOOL OF MECHANICAL ENGINEERING

1 December 1986

Mr. J. T. Petty
Senior Research Engineer
Southern Company Services, Inc.
Post Office Box 2625
Birmingham, Alabama 35202

Dear Mr. Petty:

Enclosed is the report titled "Instrumentation Plan for a Regional Solar and Weather Monitoring System". This document constitutes the report of work done during the first quarter of the project titled "Procedures for Solar Radiation Monitoring". This project bears your Contract No. 195-86-002 and Work Order No. 8457-01. Georgia Tech has assigned Project No. E-25-M09.

A second quarterly report is due 31 December 1986. In view of the fact that work on this project is essentially complete, I hereby request that the requirement for two subsequent quarterly reports be waived. If you agree, please inform our Contracting Officer, E. Faith Gleason, Office of Contract Administration, Georgia Institute of Technology, Atlanta, GA 30332.

Thanks for your interest in and support of my research.

Sincerely,

Sheldon M. Jeter

CC: Dr. J. A. Brighton (cover letter only)
Mr. P. Dawkins (cover letter only)
OCA Reports Coordinator (2, complete report)

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

Instrumentation Plan for a Regional Solar and Weather Monitoring System

prepared for

Southern Company Services

prepared by

Sheldon M. Jeter
Assistant Professor

The George W. Woodruff
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

The Southern Company plans to implement a regional solar and weather monitoring system specifically designed to accumulate the data necessary for solar energy engineering and planning.

This report includes recommendations for the necessary transducers and data acquisition system. In addition, a proposed site layout is included.

Transducers

Transducers respond to the physical quantity being measured, such as temperature, with a convenient output, usually electrical, such as a voltage or change in resistance. For a network primarily devoted to establishing the solar radiation resources over the region, the most important transducers are those for measuring the solar radiant enery flux through a surface of interest. This quantity is called the "irradiation" and is just the time integral of the irradiance over an established interval. This interval or "period" is usually 1 hour or preferably 15 min. In practice the integral is evaluated by rapidly scanning the irradiances and accumulating the sum such that:

$$I = \int_{t_1}^{t_2} G \, dt = \Sigma \, G \, \Delta t$$

where:

I = irradiation (kJ/m^2)

G = irradiance (kJ/m^2 hr)

t_1 t_2 = time at start (t_1) and end (t_2) of period

Δt = interval between scans

Important surfaces of interest are:

(1) The horizontal plane

(2) The normal (to beam radiation) plane

(3) Tilted surfaces (especially tilted at the latitude angle pointing south)

(4) Various tracking planes (such as tracking on an east-west or north-south axis)

The transducers comprise three groups. The primary group includes standard high-quality thermopile radiometers on surfaces of traditional interest (horizontal, normal, and latitude tilt) measuring the beam, sky, and total radiation. A second group of radiometers measure the irradiation on surfaces of special engineering interest. For economy and flexibility, inexpensive photovoltaic (PV) detectors are used here. The third group of transducers measure the meteorological variables that are important to collector performance such as air temperature and wind speed and direction and variables such as humidity important for characterizing the performance of thermal converters and air conditioning loads.

Standard Solar Radiometers. These are the principal instruments in the system and as such should be selected from the "first class" of types as recognized by the Commission for Instruments and Methods of Observation of the World Meteorological Organization [1]. As a practical matter, this implies Eppley NIP's for pyrheliometers and Eppley PSP's for pyranometers. Redundancy in the more critical measurements (i.e. beam normal and global) is important. Recommended instruments are as follows (acrynom in parenthesis refers to placement on site layout):

(1) Beam Pyrheliometer (B1 and B2). Two Eppley NIP's should be used on separate Li-Cor 2020 mounts. Full redundancy is essential in this extremely important observation.

(2) Reference Beam Pyrheliometer (RB). Ideally, an Eppley or TMI absolute cavity radiometer (ACR) could be purchased for use as a field standard; however, an ACR is expensive and awkward to use. Maintenance of a true

field standard is even more demanding requiring participation in periodic intercomparisons. An extra NIP could instead be used to check for calibration drifts. This NIP would be commercially calibrated (e.g. by DSET, Inc.) and only occasionally exposed for comparison with the field instruments. If this practice is followed an Eppley ST-3, 3-position polar mount, should be on hand to use during intercomparisons.

(3) Global Pyranometer(GI and G2). Two Eppley PSP's should be used. This is perhaps the most important of all observations so redundancy is absolutely essential.

(4) Reference Global Pyranometer (GR). PSP's are known to degrade under continual exposure. A reference PSP should be kept on hand to serve as a field standard. Recalibrations should be conducted at least annually. The field standard should be commercially calibrated and exposed only during field comparisons.

(5) Inclined Pyranometer (IP). Measurement of the irradiation on a plane tilted at the latitude angle is important as this angle usually provides near the annual maximum for a fixed orientation. This data can also be used for studying the distribution of the sky radiation. Because foreground conditions are difficult to control, an artificial horizon should be provided. Further analysis and testing seems desirable to confirm or improve conventional artificial horizon design. An Eppley PSP should be used.

(6) Sky Pyranometer (S). An Eppley PSP with shading disc should be considered for the base station. Since the disc requires nearly daily adjustment, this device is unsuitable for remote stations. Shadow-band devices require less frequent adjustments but are much less accurate since the band occludes much of the sky rather than just the sun.

Since the sky radiation can be computed from the beam and global quantities, collection of this data is optional.

Special Radiometers. Data for surfaces of specific orientation is desirable for the planning and engineering of a variety of solar energy systems, especially PV and concentrator systems. For their low cost, and compact design PV detectors such as the Li-Cor Li-200SB, should be considered. The primary concern about such silicon PV-diode based instruments is their wavelength-dependent response, enhanced in the shortwave bands. This problem should be mitigated if the beam and global measurements made with the broadband radiometers are replicated by PV detectors to allow retrospective intercomparison. The recommended instrumentation is as follows:

(1) Global (GPV). A Li-Cor 200SB in 20035 Mount should be used.

(2) Beam (BPV). A Li-Cor 200SB in collimating tube should be used. A simple device of this type has been successfully used at the Shenandoah STEP, but some further design and development is recommended. No difficulty has arisen from "piggybacking" this lightweight apparatus on an NIP in a Li-Cor 2020 mount.

(3) Tracking Total (TT). Measurements of the total irradiation on the normal plane has many applications. This can be done by piggybacking a Li-Cor 200SB on an NIP carried by a Li-Cor 2020 as is being done at Shenandoah. An artificial horizon would be desirable but is difficult to implement.

(4) East-West Axis Tracking Radiometers (BEW,TEW). Measurements of the irradiation on a surface tracking the sun with a single east-west axis is important since this orientation gives rather even energy outputs over the seasons. A special tracker and control will need to be

developed. It seems feasible to control the tracker with a suitable site controller (e.g. IBM-PC/XT) and site DAS (e.g. DASCON-10). In fact, success with implementing these single-axis trackers, for which no suitable alternative is available, could lead to an economical two-axis design which could replace the expensive Li-Cor 2020's that are now necessary. On each mount should be a pyranometer for measuring the total irradiation and a "beam pyranometer". The proposed "beam pyranometer" comprises a pyranometer detector and shading discs to admit only the beam radiation and minimal sky radiation. An example used at the Georgia DOT's asphalt paving mix plant in Butler, Georgia, [2] is illustrated in Figure 1.

(6) North-South Axis Tracking Radiometers (BNS,TNS). Similar measurements for a surface with a north-south axis, which enhances the total annual and summertime energy production, is also desirable.

(7) Variable Tilt Pyranometer (VT). The near-instantaneous response of a PV detector would allow the measurements at several tilt angles while the instrument is in motion. Some development would be necessary but a wealth of useful data would be obtained. A very flexible DAS, such as the DASCON-10, would be necessary.

Meteorological Instruments.

(1) Dry Bulb Temperature (DBT). A platinum resistance temperature detector (RTD) is probably the most accurate and reliable device. The DASCON-10 includes 2 RTD ports of which one can be dedicated to this use.

(2) Relative Humidity (RH). There has been considerable dissatisfaction with RH probes in the past [3], and our experience at Shenandoah has

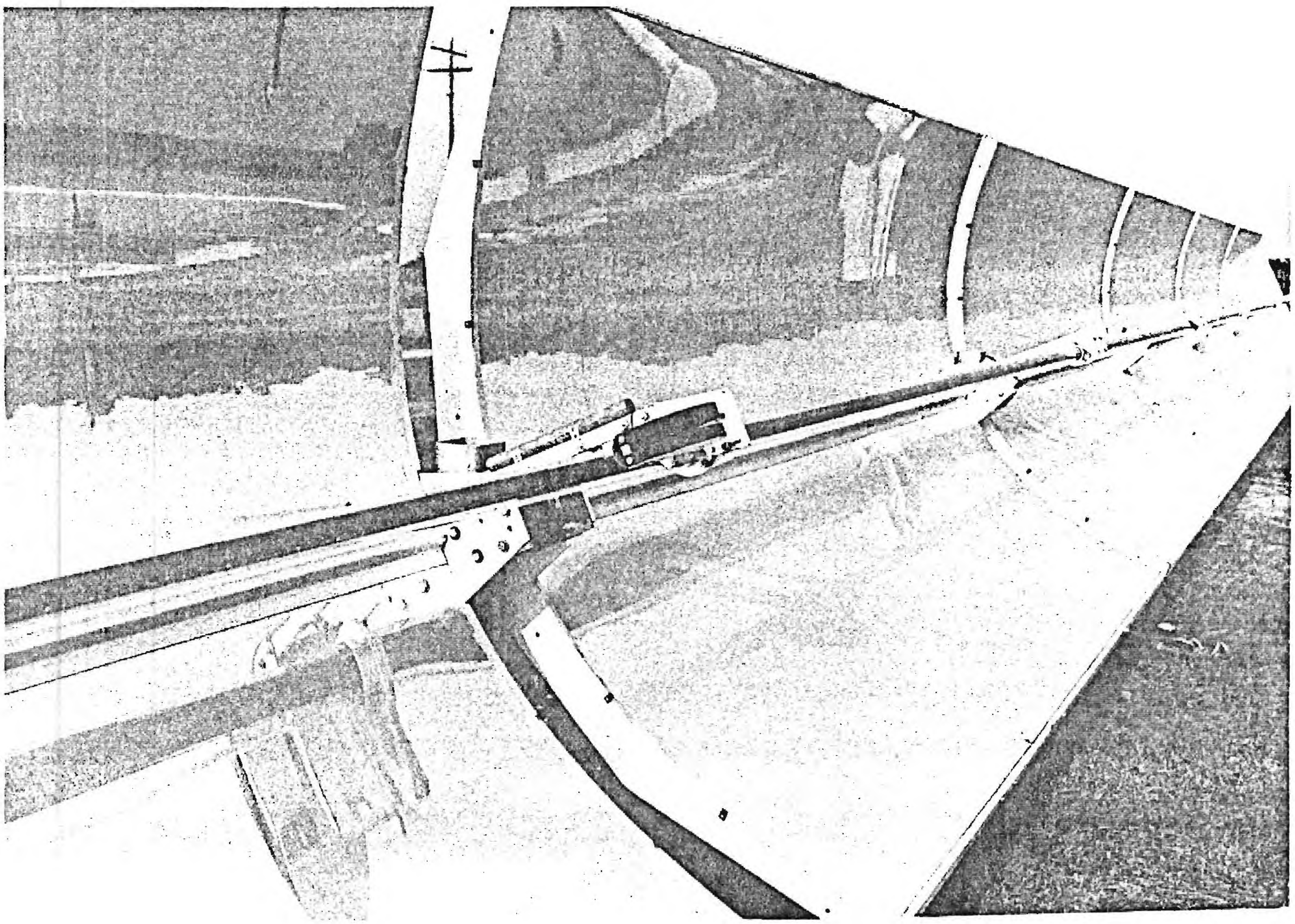

Figure 1. Beam Pyranometer Mounted on East-West Axis Parabolic Trough Collector Used at the Butler, Georgia, Asphalt Plant of the Georgia DOT.

been problematical. Indications are that contemporary devices are much improved. A good choice would be the Weathermeasure 5120-C which has a 0-100 mV output. An instrumentation amplifier can be used to make this output compatible with the DASH-8 or the DASCON-10.

(3) Dew Point Temperature (DPT). A dew-point temperature measurement should be considered as an alternative to a RH measurement. It is recommended that a Li Cl dew cell be included in at least the base station and the relative merits of the two instruments be assessed prior to selecting one for the remote stations. The Weathermeasure 5321 would be a good choice. Its RTD sensor is compatible with the DASCON-10. It will require a 24 VAC power supply such as included in the Weathermeasure 53211 Housing.

(4) Atmospheric pressure (AP) The Weathermeasure 7105-A barometer with piezoresistive sensor should be adequate. It 4.83 mV/mb sensitivity should be compatible with a 0-5V input on the DASH-8 at most locations.

(5) Wind Direction (WD). The Weathermeasure 2020 Micro Response Vane should be adequate. Its transducer is a 0-5 KOhm potentiometer which can be excited to produce a signal compatible with a 0-5V input on the DASH-8.

(6) Wind Speed (WS). A three-cup anemometer is the conventional choice of detector. At least three distinct rotation to electrical signal transducers are available. The reed-relay pulse generator is obsolete. The DC-generator transducer has a large threshold (c.1 mph). This threshold is unimportant for wind-energy or weather measurements, but could be significant in predicting PV cell temperature. The preferred choice is Weathermeasure 2030 Micro-

Response Anemometer with the low torque light chopper (900 Hz at 89 mph) output. The resulting pulse train with frequency proportional to wind speed can be monitored in several ways. A standard VFC chip can be used in the frequency-to-voltage conversion mode to provide a 0-5V input for the DASH-8. Alternatively, available timer circuits can be used for measurements of period or frequency with the DASCON-10 or DASH-8. Some experimentation should be conducted before selecting a method. If wind energy flux measurements (proportional to ρV^3) are desired, such can be implemented in software using the available pressure, temperature, and speed measurements.

(7) Sunshine Duration (SD). Commercial "sunshine sensors" are available but none appear to be identical to the USWB's Foster Sunshine Switch. Since the WMO defines presence of sunshine as beam-normal irradiance exceeding 210 W/m^2 [4], it is recommended that this rather expensive instrument not be included but that the duration of sunshine be implemented with software.

Data Acquisition System

The Data Acquisition System (DAS) must be reliable capable, and inexpensive. General experience indicates that principal causes of reliability problems have been electrical transients, degradation of magnetic recording media, and operation at excessively high temperatures. The most important capabilities are as follows:

1. Adequate mass data storage.
2. Flexibility to handle various input signals and transducers.
3. Reasonably high data rates to allow time-averaging as a tool to eliminate spurious periodic noise and to minimize the effect of spikes and other transients and to allow fast-sequence measurements such as required for a variable-tilt pyranometer.
4. Communication ability to allow data telemetry.
5. Ability to control sophisticated instruments and do on-line software implementation of measurements such as "presence of sunshine" and wind energy flux density.
6. High level language programming.
7. Active temperature control with mechanical or thermoelectric cooling.

For the present application a microcomputer based system rather than a special-purpose data logger appears to be the best choice. Overall, a microcomputer such as the IBM PC/XT or compatible should provide a low cost system since less peripherial equipment will be required. The data format will be an industry standard and compatible with mainframes and other PC's used for data analysis. The reliability and maintainability of the system is enhanced since for field maintaintance defective or questionable cards can be switched and repaired later commercially.

Admittedly the selection of a data logger or a computer-controlled DAS is problematical. One important consideration is the widespread dissatisfaction with contemporary solar monitoring programs, especially in the U.S. In contrast historical data and data from less-developed countries seems rather more reliable and nearly free of gap even when poor performance transduces are used. Many investigators blame this situation on the poor feedback available to the site operator. Data on a circular chart with mechanical integrator is easy to review and instrument problems are apparent. In contrast a data logger may persist for long periods accumulating erroneous data. The on site display of data and on line generation of error messages is an important feature that is only available with a computer-controlled system.

The system outlined in Table 4 is recommended. The controller is an IBM PC/XT. No monitor is recommended for field units although the attendant should have a monitor available to display on-line diagnostics.

Mass storage is a critical function. Contemporary data-loggers are plagued with problems from their tape recording systems. Since tapes and tape decks are sensitive to temperature and contamination they should be avoided. Relocatable or "floppy" disks may provide better service but remain questionable. Better service should be expected from more contemporary devices. Internal fixed or "hard" disks are readily available. Alternatively an enhancement board carrying semiconductor or magnetic bubble memory should be considered. A hard disk would run continuously and is sealed against contamination. Semiconductor or bubble memory, if used, could be in the form of a memory bank organized like a sequential access device, the so-called "RAM disk" concept. For this application, an non-volatile RAM disk is mandatory. Bubble memory is non-volatile while semiconductor components can have on-board battery power back-up. Either would not lose data during the brief power outages that must be anticipated. Selection of hard disk versus RAM disk is problematical. Both would appear to be adequate, and they cost about the same. The RAM disk is perhaps more sensitive to electrical transients while the hard disk is somewhat prone to mechanical failure. Either component would serve the same logical funtion, an extra non-volatile disk drive. Since it does seem more likely that a hard disk drive would fail and fail catastrophically over the several years we expect these systems to operate, a RAM disk is recommended.

The IBM PC/XT is self-booting and will return to operation in the advent of a power interruption; therefore, no auxiliary power supply is required or recommended. A surge suppressor should be provided for protection against transients and impressed voltages.

An internal modem is used for data telemetry. Alternatively, data from the RAM or hard disk can be dumped to a relocatable disk. It is also recommended that raw data on floppies be archieved permanently after the data is transferred to the system to be used for data processing.

A variety of data conversion and control components are available for the IBM PC/XT. One highly regarded series is produced by Metra Byte Corp. The components shown on Table 4 are recommended. The DASCON-10 provides RTD capability and includes a non-volatile clock/calendar circuit. The DASCON-10 can also perform many control functions that may be required now and in the future. Most of the other analog to digital conversions (ADC) can be accomodated with the DASH-8 fast ADC card. One 16-input submultiplexer for the DASH-8 can accomodate all the radiometer channels. Other DASH-8 channels can accomodate the remaining inputs. Table 5 shows the allocation of data channels among the I/O devices. Figure 2 is a schematic representation of the DAS.

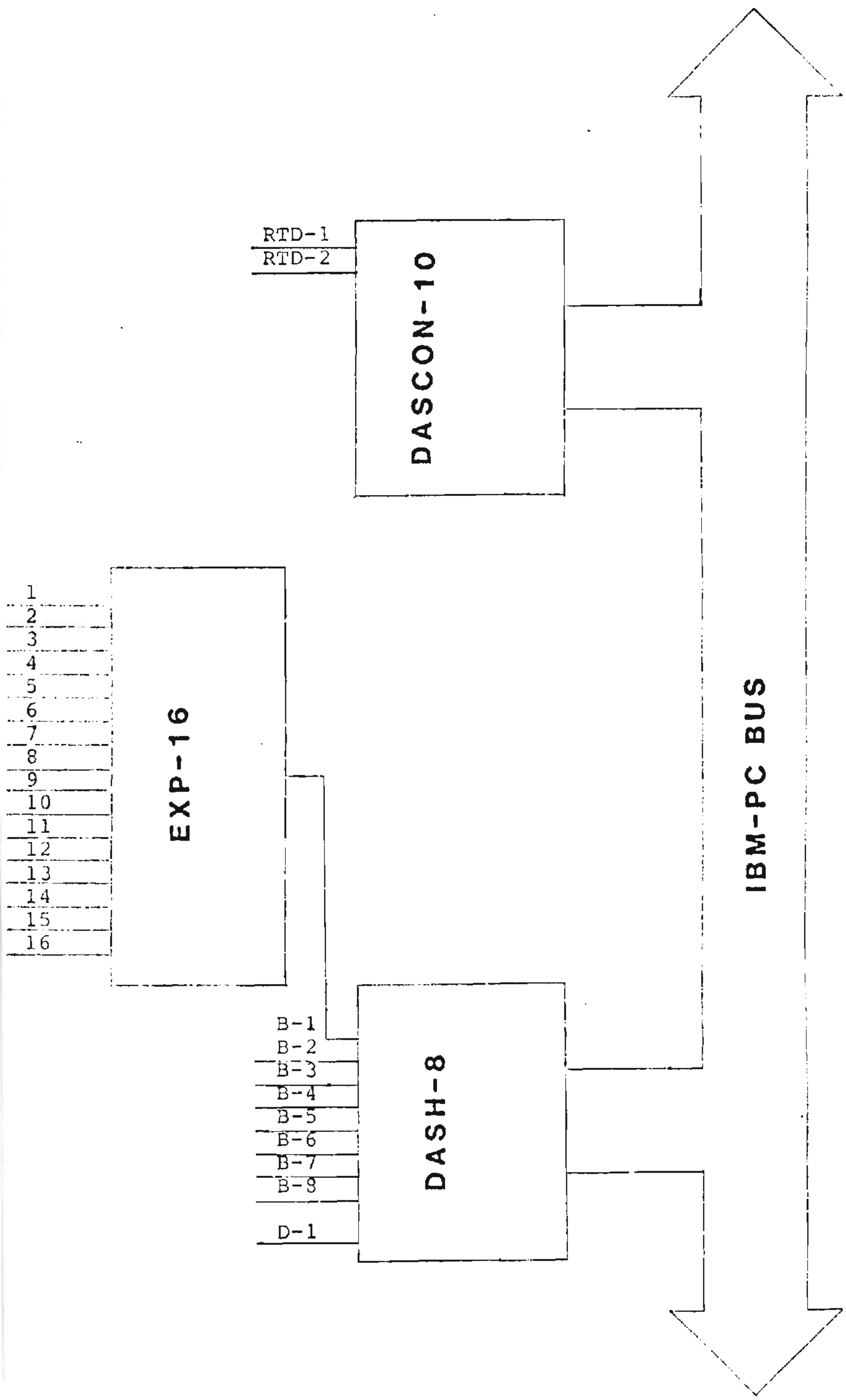

Figure 2. Schematic of Data Acquisition System

The performance and accurary of the DAS should be carefully evaluated before being placed in routine service. At a minimum each ADC channel should be tested over its operating range for stability and accuracy. The measured gain must be either adjusted to the prescribed nominal value or the observed calibration be maintained for use in data processing. Radiometer channels should be calibrated at 0 and 10 mV inputs. Other channels should be appropriately calibrated. The Georgia Tech Solar Lab has access to a stable high-precision Fluke voltage source and a highly-accurate Hewlett-Packard microvoltmeter which have been used for similar calibrations.

The DAS should not be expected to operate reliably at all ambient temperatures which after all range from under 0 F to over 100 F in this region. Nor should its own enclosure be used as weather protection. While DAS units are marketed as having these capabilities, it is doubtful that field performance will meet these assertions. Previous experience with the very expensive EG and G data logger at the Shenandoah STEP has revealed many problems from operation at high temperature. The extra expense of equipment rated for high and low ambient temperature and for direct exposure to the weather seem especially unwarrented since they are unlikely to perform as advertised over the many years this network will operate.

Local fabrication of an equipment enclosure is recommended. A dust and rain proof insulated enclosure should be provided for the DAS. One possible concept is an enclosure fabricated from weather resistant insultating board such as properly-coated Manville Maronite (R), with a gasketed door. This inner enclosure should be protected by an outer metal envelope. An air space between the two is desirable and the metal envelope should be louvered. This assembly should be much less expensive that the typical foam-filled fiberglass all-weather enclosure. It should also be safe as no combustible materials need be used. A packaged fire suppression device should be considered for the interior.

Active cooling is a must. Equipment for high temperature operation is very expensive and disappointing in use. Either vapor-compression or thermoelectric cooling is possible. A small vapor-compression unit is very inexpensive and should be very reliable. Thermoelectric cooling might be considered for critical locations.

Site Plan

The proposed site plan is shown in Figure 3. Instruments are positioned so as to minimize or eliminate interference and facilitate maintenance. A model of the layout is pictured in Figure 4.

Note that the prime global pyranometer G1, is mounted at the highest level to preclude interference. Similarily, the prime pyrheliometer, B1, is positioned to avoid obstruction; however, it can be lower than G1. Other radiometers are similarily situated to minimize obstruction of their fields of view.

The surface instrumentation mast is mounted north of the radiometers to minimize any shading of the solar radiation instruments. The position is illustrated in the photo of the scale model shown in Figure 4.

All radiometers can be reached from a short step ladder for maintenance. Note that the principal instruments are the six in the main diagonal and are arranged to provide clear fields of view. Additionally, as illustrated by the model figure, all instruments are located so they can be reached for cleaning, adjustments, and other maintenance. The weather mast can be pivoted to provide safe and easy access.

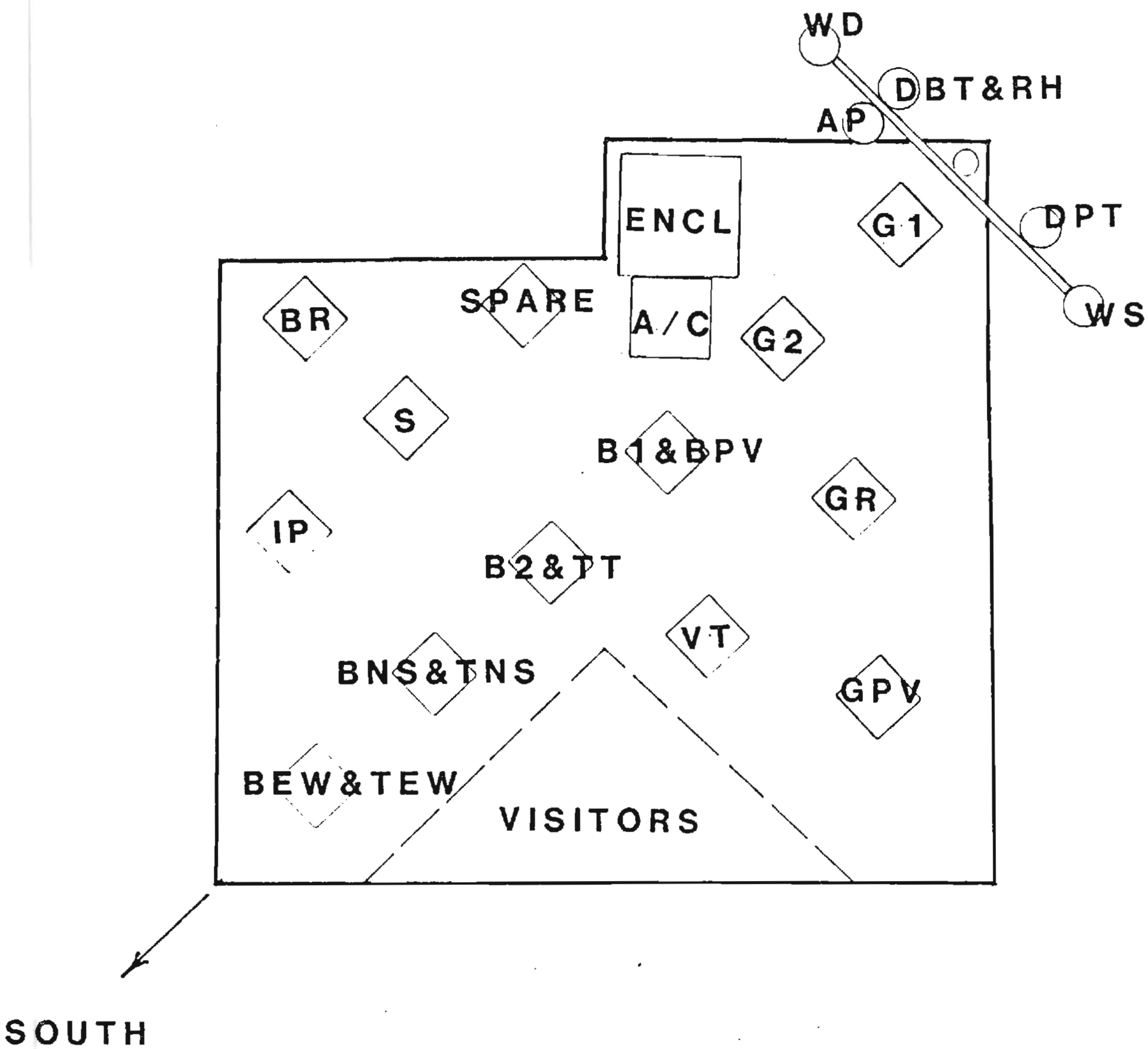

Figure 3. Site Plan. Instruments are identified by acronym defined in the text.

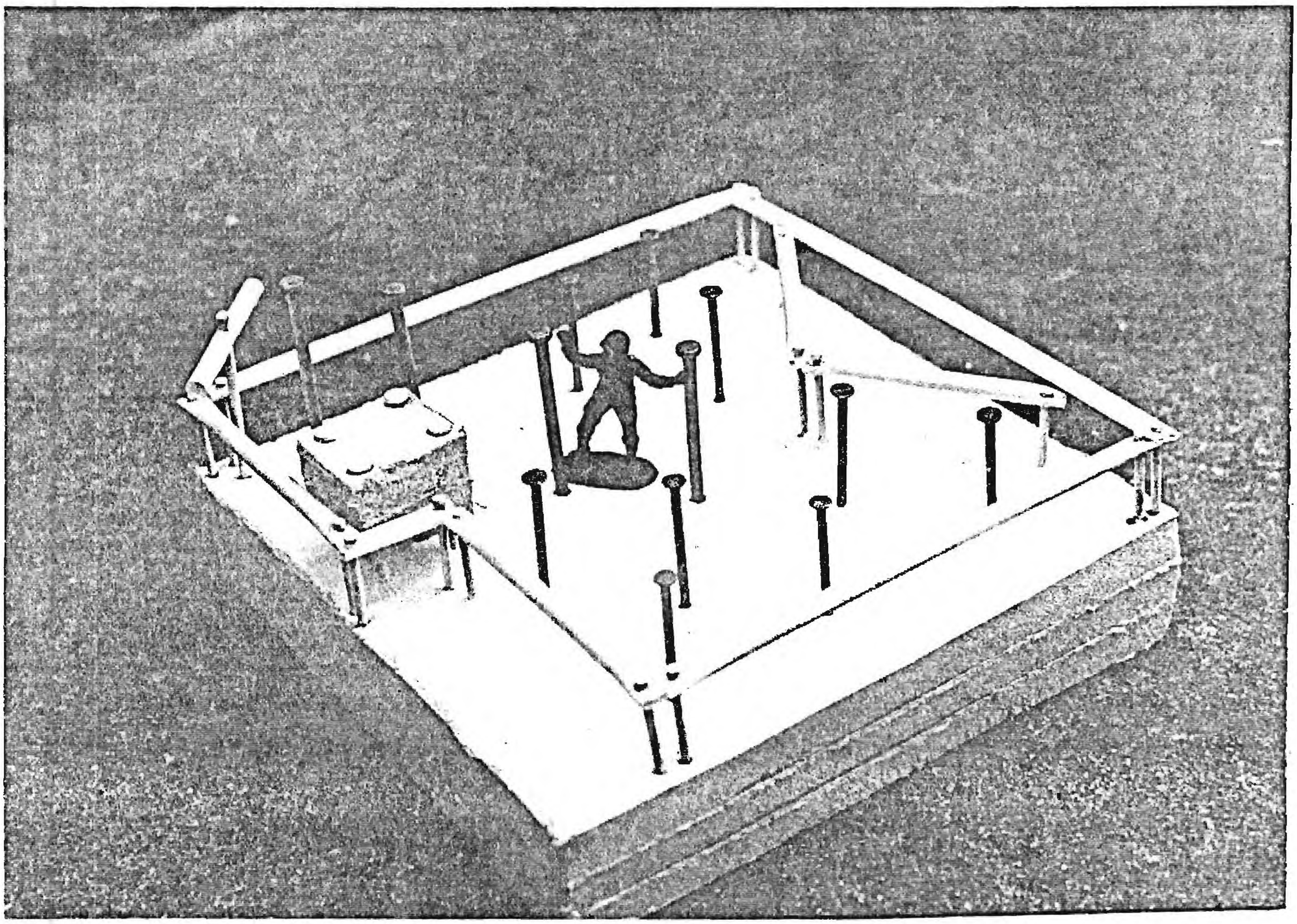

Figure 4. Scale Model of Solar Monitoring Site Proposed for Southern Company Services.

References

(1) E. A. Carter, et al, "Solar Radiation Data Sources, Applications and Network Design," Report No. HCP/T5362-01, April, 1978.

(2) S. M. Jeter, "Final Report: Solar Heat Supply for an Asphalt Paving Plant," Project DTFH-71-81-GA-02, 1985.

(3) D. J. McKay, "A Sad Look at Commercial Humidity Sensors for Meteorological Applications," Atmospheric Environment Service (Canada).

Table 1

Standard Radiometers

symbol	description	quantity	vendor*	model	output range	aprox cost each
B1, B2	Beam Pyrheliometer	2	E	NIP	0-8 mV	1575
	Automatic Solar Tracker	2	L	LI-2020 (note - 1)		3200
RB	Reference Pyrheliometer (optional)	1	E	NIP	0-8 mV	1575
	Solar Tracker	1	E	ST-3		1900
G1, G2	Global Pyranometer	2	E	PSP	0-9 mV	1590
RG	Reference Pyranometer	1	E	PSP		1590
TP	Inclined Pyranometer	1	E	PSP	0-9 mV	1590
	adjustable mount	1	DC**			200
	artificial horizon	1	DDC**			400
S	Sky Pyranometer	1	E	PSP	0-9 mV	1590
	Shading Disc	1	E	special		c.3000
	or Shadow Band	1	E	SBS	0-9 mV	1300

*vendor

E: Eppley Laboratory
12 Sheffield Avenue
Newport, R.I.
(401) 847-1020

L: Li-Cor, Inc.
4421 Superior Street
P. O. Box 4425
Lincoln, Nebraska 68504
(402) 467-3576

WM: Weathermeasure
P. O. Box 41039
Sacramento, CA 95841
(800) 824-5873

notes:

** DC design and construct

*** DDC develop, design and construct locally

1. Requires 110 VAC power, has battery back-up

Table 2

Special Radiometers

symbol	description	quantity	vendor	model	output range	aprox cost/each
GPV	Global PV-P**					
	detector	1	L	note - 1	0-10 mV	180
	mount	1	L	note - 2	0-10 mV	29
BPV	Beam PV-P					
	detector	1	L	note - 1	0-10 mV	180
	mount/ collimator	1	DC	note - 3		150
TT	Tracking Total PV-P					
	detector	1	L	note - 1	0-10 mV	180
	mount/ collimator	1	L	note - 3		150
BEW, TEW	Single-Axis (EW) PV-P					
	detector	2	L	note - 1	0-10 mV	180
	tracker	1	DDC	note - 4		2000
	shading dics	1	DC	note - 4		100
BNS, TNS	Single-Axis (NS) PV-P					
	detector	2	L	note - 1	0-10 mV	180
	tracker	1	DDC	note - 4		2000
	shading disc	1	DC	note - 4		100
VT	Variable Tilt PV-P					
	detector	1	L	note - 1	0-10 mV	180
	mount	1	L	note - 2		29
	tilting mount	1	DDC	note - 5		1500

notes:

1. Li-Cor 200SB-50 detector with 50' cable recommended for all special radiometers.

2. Li-Cor 20035 mount to be used.

3. Combination mount/collinating tube used for both beam PV-P and tracking PV-P. Will be used for calibration of TT against NIP.

4. Similar single axis mount can be used for both EW and NS. Distributed control from IBM-PC/XT anticipated.

5. A motorized continuously varying tilted mount is recommended. Development is required.

**PV-P: Photovoltaic Pyranometer or Pyrheliometer

Table 3
Meteorological Instruments

system	description	quantity	vendor	model	output range	aprox cost/each
DBT	Dry Bulb (Air) Temperature	1	WM	4470-A	100 Ohm	135
	Platinum RTD	1	WM	4470-A	100 Ohm	135
	Radiation Shield	1	WM	8140-A		155
RH	Relative Humidity					
	Capicitance Sensor (note 1)	1	WM	5120-C	0-100 mV	595
	Radiation Shield	1	WM	8140-A		155
	RH Calibration Set					
	Calibration Chamber	1	WM	5150-A		225
	Li Cl salt	3.5%oz	WM	5135	13% RH	20
	K_2SO_4	3.5 oz	WM	5136	97% RH	15
	Na Cl salt	3.5 oz	WM	5137	75% RH	15
DPT	Temp. Dew Point Temperature					
	Li Cl Dew Cell (w/RTD sensor)	1	WM	5321	100 Ohm	450
	Protective Housing	1	WM	53211	100 Ohm	625
	Shade and Rain Cover	1	DC			50
AP	Atmospheric Pressure					
	Analog Barometer	1	WM	7105 A		590
WD	Wind Direction					
	Micro-Response Vane	1	WM	2020	0-5 k Ohm	430
	Cross arm	1	WM	2023		130
WS	Wind Speed					
	3-cup Anemometer (chopper output)	1	WM	2032	pulse	360

notes:

1. Required 5-20VDC, 15mA, excitation.

Table 4

Data - Acquisition Equipment

1. Controller	
IBM PC/XT	
256 kB user memory	
DOS 3.1	
360 kB diskette drive adapter	
360 kB diskette drive	
package price	1559
monochrome/printer adapter	175
2 Mb non-volatile RAM disk	485
surge protector (EMI and RFI filtered)	44
2. DAS Components	
DASCON-10 A and D I/O	495
STA-01 terminal board	109
DASH-8 ADC and timer I/O	395
EXP-16 sub-MUX	395
STA-08 terminal board	109
3. Enclosure and Environmental Control	
insulated enclosure	400
metal envelope	200
fire suppressor	150
vapor-compression cooler	250

Table 5

DAS Survey

symbol	excitation	output range	input module	input channel*
B1	none	0- 8mV	EXP - 16	B-1 (1)
B2	none	0- 8mV	EXP - 16	B-1 (2)
RB	none	0- 8mV	EXP - 16	B-1 (3)
G1	none	0- 9mV	EXP - 16	B-1 (4)
G2	none	0- 9mV	EXP - 16	B-1 (5)
RG	none	0- 9mV	EXP - 16	B-1 (6)
S	none	0- 9mV	EXP - 16	B-1 (7)
IP	none	0- 9mV	EXP - 16	B-1 (8)
GPV	none	0-10mV	EXP - 16	B-1 (9)
BPV	none	0-10mV	EXP - 16	B-1 (11)
TT	none	0-10mV	EXP - 16	B-1 (11)
BEW	none	0-10mV	EXP - 16	B-1 (12)
TEW	none	0-10mV	EXP - 16	B-1 (13)
BNS	none	0-10mV	EXP - 16	B-1 (14)
TNS	none	0-10mV	EXP - 16	B-1 (15)
VT	none	0-10mV	EXP - 16	B-1 (16)
DBT	none	100 Ohm RTD	DASCON-10	A RTD-1
RH	5-20 VDC 15 ma	0-100mV	DASH - 8	B-2
DPT	24 VAC	100 Ohm RTD	DASCON-10	A RTD-2
AP		0-5V	DASH-8	B-3
WD		0-5 k Ohm	DASH-8	B-4
WS		0-800 Hz	DASH-8	B-D1

*see schematic

E-25-M09

Instrumentation Plan for a Regional Solar and Weather Monitoring System

prepared for

Southern Company Services

prepared by

Sheldon M. Jeter
Assistant Professor

The George W. Woodruff
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The Southern Company plans to implement a regional solar and weather monitoring system specifically designed to accumulate the data necessary for solar energy engineering and planning.

This report includes recommendations for the necessary transducers and data acquisition system. In addition, a proposed site layout is included.

Transducers

Transducers respond to the physical quantity being measured, such as temperature, with a convenient output, usually electrical, such as a voltage or change in resistance. For a network primarly devoted to establishing the solar radiation resources over the region, the most important transducers are those for measuring the solar radiant enery flux through a surface of interest. This quantity is called the "irradiation" and is just the time integral of the irradiance over an established interval. This interval or "period" is usually 1 hour or preferably 15 min. In practice the integral is evaluated by rapidly scanning the irradiances and accumulating the sum such that:

$$I = \int_{t_1}^{t_2} G \; dt = \Sigma \; G \, \Delta t$$

where:

I = irradiation (kJ/m^2)

G = irradiance (kJ/m^2 hr).

t_1 t_2 = time at start (t_1) and end (t_2) of period

Δt = interval between scans

Important surfaces of interest are:

(1) The horizontal plane

(2) The normal (to beam radiation) plane

(3) Tilted surfaces (especially tilted at the latitude angle pointing south)

(4) Various tracking planes (such as tracking on an east-west or north-south axis)

The transducers comprise three groups. The primary group includes standard high-quality thermopile radiometers on surfaces of traditional interest (horizontal, normal, and latitude tilt) measuring the beam, sky, and total radiation. A second group of radiometers measure the irradiation on surfaces of special engineering interest. For economy and flexibility, inexpensive photovoltaic (PV) detectors are used here. The third group of transducers measure the meteorological variables that are important to collector performance such as air temperature and wind speed and direction and variables such as humidity important for characterizing the performance of thermal converters and air conditioning loads.

Standard Solar Radiometers. These are the principal instruments in the system and as such should be selected from the "first class" of types as recognized by the Commission for Instruments and Methods of Observation of the World Meteorological Organization [1]. As a practical matter, this implies Eppley NIP's for pyrheliometers and Eppley PSP's for pyranometers. Redundancy in the more critical measurements (i.e. beam normal and global) is important. Recommended instruments are as follows (acrynom in parenthesis refers to placement on site layout):

(1) Beam Pyrheliometer (B1 and B2). Two Eppley NIP's should be used on separate Li-Cor 2020 mounts. Full redundancy is essential in this extremely important observation.

(2) Reference Beam Pyrheliometer (RB). Ideally, an Eppley or TMI absolute cavity radiometer (ACR) could be purchased for use as a field standard; however, an ACR is expensive and awkward to use. Maintenance of a true

field standard is even more demanding requiring participation in periodic intercomparisons. An extra NIP could instead be used to check for calibration drifts. This NIP would be commercially calibrated (e.g. by DSET, Inc.) and only occasionally exposed for comparison with the field instruments. If this practice is followed an Eppley ST-3, 3-position polar mount, should be on hand to use during intercomparisons.

(3) Global Pyranometer(GI and G2). Two Eppley PSP's should be used. This is perhaps the most important of all observations so redundancy is absolutely essential.

(4) Reference Global Pyranometer (GR). PSP's are known to degrade under continual exposure. A reference PSP should be kept on hand to serve as a field standard. Recalibrations should be conducted at least annually. The field standard should be commercially calibrated and exposed only during field comparisons.

(5) Inclined Pyranometer (IP). Measurement of the irradiation on a plane tilted at the latitude angle is important as this angle usually provides near the annual maximum for a fixed orientation. This data can also be used for studying the distribution of the sky radiation. Because foreground conditions are difficult to control, an artificial horizon should be provided. Further analysis and testing seems desirable to confirm or improve conventional artificial horizon design. An Eppley PSP should be used.

(6) Sky Pyranometer (S). An Eppley PSP with shading disc should be considered for the base station. Since the disc requires nearly daily adjustment, this device is unsuitable for remote stations. Shadow-band devices require less frequent adjustments but are much less accurate since the band occludes much of the sky rather than just the sun.

Since the sky radiation can be computed from the beam and global quantities, collection of this data is optional.

Special Radiometers. Data for surfaces of specific orientation is desirable for the planning and engineering of a variety of solar energy systems, especially PV and concentrator systems. For their low cost, and compact design PV detectors such as the Li-Cor Li-200SB, should be considered. The primary concern about such silicon PV-diode based instruments is their wavelength-dependent response, enhanced in the shortwave bands. This problem should be mitigated if the beam and global measurements made with the broadband radiometers are replicated by PV detectors to allow retrospective intercomparison. The recommended instrumentation is as follows:

(1) Global (GPV). A Li-Cor 200SB in 20035 Mount should be used.

(2) Beam (BPV). A Li-Cor 200SB in collimating tube should be used. A simple device of this type has been successfully used at the Shenandoah STEP, but some further design and development is recommended. No difficulty has arisen from "piggybacking" this lightweight apparatus on an NIP in a Li-Cor 2020 mount.

(3) Tracking Total (TT). Measurements of the total irradiation on the normal plane has many applications. This can be done by piggybacking a Li-Cor 200SB on an NIP carried by a Li-Cor 2020 as is being done at Shenandoah. An artificial horizon would be desirable but is difficult to implement.

(4) East-West Axis Tracking Radiometers (BEW,TEW). Measurements of the irradiation on a surface tracking the sun with a single east-west axis is important since this orientation gives rather even energy outputs over the seasons. A special tracker and control will need to be

developed. It seems feasible to control the tracker with a suitable site controller (e.g. IBM-PC/XT) and site DAS (e.g. DASCON-10). In fact, success with implementing these single-axis trackers, for which no suitable alternative is available, could lead to an economical two-axis design which could replace the expensive Li-Cor 2020's that are now necessary. On each mount should be a pyranometer for measuring the total irradiation and a "beam pyranometer". The proposed "beam pyranometer" comprises a pyranometer detector and shading discs to admit only the beam radiation and minimal sky radiation. An example used at the Georgia DOT's asphalt paving mix plant in Butler, Georgia, [2] is illustrated in Figure 1.

(6) North-South Axis Tracking Radiometers (BNS,TNS). Similar measurements for a surface with a north-south axis, which enhances the total annual and summertime energy production, is also desirable.

(7) Variable Tilt Pyranometer (VT). The near-instantaneous response of a PV detector would allow the measurements at several tilt angles while the instrument is in motion. Some development would be necessary but a wealth of useful data would be obtained. A very flexible DAS, such as the DASCON-10, would be necessary.

Meteorological Instruments.

(1) Dry Bulb Temperature (DBT). A platinum resistance temperature detector (RTD) is probably the most accurate and reliable device. The DASCON-10 includes 2 RTD ports of which one can be dedicated to this use.

(2) Relative Humidity (RH). There has been considerable dissatisfaction with RH probes in the past [3], and our experience at Shenandoah has

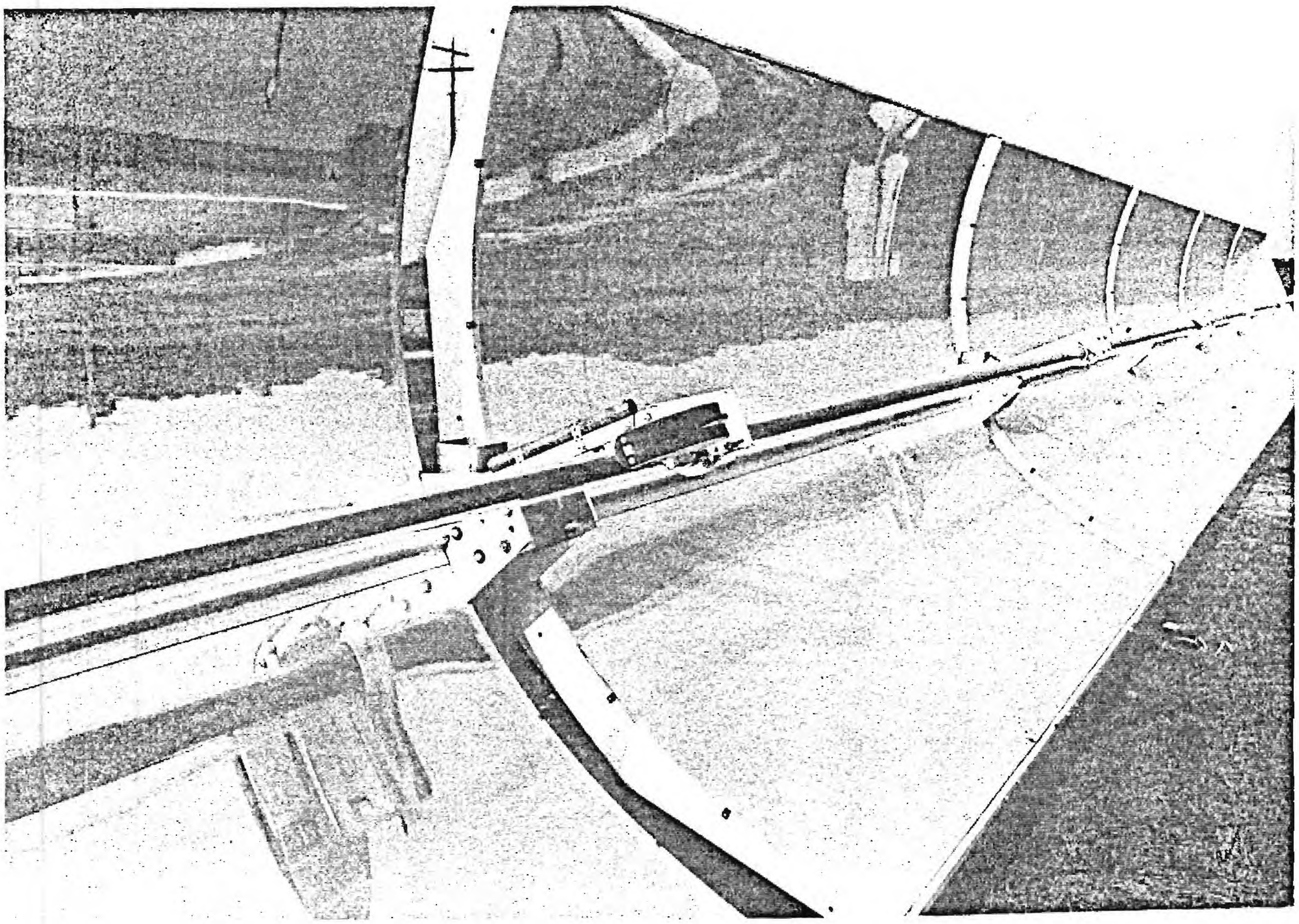

Figure 1 . Beam Pyranometer Mounted on East-West Axis Parabolic Trough Collector Used at the Butler, Georgia, Asphalt Plant of the Georgia DOT.

been problematical. Indications are that contemporary devices are much improved. A good choice would be the Weathermeasure 5120-C which has a 0-100 mV output. An instrumentation amplifier can be used to make this output compatible with the DASH-8 or the DASCON-10.

(3) Dew Point Temperature (DPT). A dew-point temperature measurement should be considered as an alternative to a RH measurement. It is recommended that a Li Cl dew cell be included in at least the base station and the relative merits of the two instruments be assessed prior to selecting one for the remote stations. The Weathermeasure 5321 would be a good choice. Its RTD sensor is compatible with the DASCON-10. It will require a 24 VAC power supply such as included in the Weathermeasure 53211 Housing.

(4) Atmospheric pressure (AP) The Weathermeasure 7105-A barometer with piezoresistive sensor should be adequate. It 4.83 mV/mb sensitivity should be compatible with a 0-5V input on the DASH-8 at most locations.

(5) Wind Direction (WD). The Weathermeasure 2020 Micro Response Vane should be adequate. Its transducer is a 0-5 KOhm potentiometer which can be excited to produce a signal compatible with a 0-5V input on the DASH-8.

(6) Wind Speed (WS). A three-cup anemometer is the conventional choice of detector. At least three distinct rotation to electrical signal transducers are available. The reed-relay pulse generator is obsolete. The DC-generator transducer has a large threshold (c.1 mph). This threshold is unimportant for wind-energy or weather measurements, but could be significant in predicting PV cell temperature. The preferred choice is Weathermeasure 2030 Micro-

Response Anemometer with the low torque light chopper (900 Hz at 89 mph) output. The resulting pulse train with frequency proportional to wind speed can be monitored in several ways. A standard VFC chip can be used in the frequency-to-voltage conversion mode to provide a 0-5V input for the DASH-8. Alternatively, available timer circuits can be used for measurements of period or frequency with the DASCON-10 or DASH-8. Some experimentation should be conducted before selecting a method. If wind energy flux measurements (proportional to ρV^3) are desired, such can be implemented in software using the available pressure, temperature, and speed measurements.

(7) Sunshine Duration (SD). Commercial "sunshine sensors" are available but none appear to be identical to the USWB's Foster Sunshine Switch. Since the WMO defines presence of sunshine as beam-normal irradiance exceeding 210 W/m^2 [4], it is recommended that this rather expensive instrument not be included but that the duration of sunshine be implemented with software.

Data Acquisition System

The Data Acquisition System (DAS) must be reliable capable, and inexpensive. General experience indicates that principal causes of reliability problems have been electrical transients, degradation of magnetic recording media, and operation at excessively high temperatures. The most important capabilities are as follows:

1. Adequate mass data storage.
2. Flexibility to handle various input signals and transducers.
3. Reasonably high data rates to allow time-averaging as a tool to eliminate spurious periodic noise and to minimize the effect of spikes and other transients and to allow fast-sequence measurements such as required for a variable-tilt pyranometer.
4. Communication ability to allow data telemetry.
5. Ability to control sophisticated instruments and do on-line software implementation of measurements such as "presence of sunshine" and wind energy flux density.
6. High level language programming.
7. Active temperature control with mechanical or thermoelectric cooling.

For the present application a microcomputer based system rather than a special-purpose data logger appears to be the best choice. Overall, a microcomputer such as the IBM PC/XT or compatible should provide a low cost system since less peripherial equipment will be required. The data format will be an industry standard and compatible with mainframes and other PC's used for data analysis. The reliability and maintainability of the system is enhanced since for field maintaintance defective or questionable cards can be switched and repaired later commercially.

outages that must be anticipated. Selection of hard disk versus RAM disk is problematical. Both would appear to be adequate, and they cost about the same. The RAM disk is perhaps more sensitive to electrical transients while the hard disk is somewhat prone to mechanical failure. Either component would serve the same logical funtion, an extra non-volatile disk drive. Since it does seem more likely that a hard disk drive would fail and fail catastrophically over the several years we expect these systems to operate, a RAM disk is recommended.

The IBM PC/XT is self-booting and will return to operation in the advent of a power interruption; therefore, no auxiliary power supply is required or recommended. A surge suppressor should be provided for protection against transients and impressed voltages.

An internal modem is used for data telemetry. Alternatively, data from the RAM or hard disk can be dumped to a relocatable disk. It is also recommended that raw data on floppies be archieved permanently after the data is transferred to the system to be used for data processing.

A variety of data conversion and control components are available for the IBM PC/XT. One highly regarded series is produced by Metra Byte Corp. The components shown on Table 4 are recommended. The DASCON-10 provides RTD capability and includes a non-volatile clock/calendar circuit. The DASCON-10 can also perform many control functions that may be required now and in the future. Most of the other analog to digital conversions (ADC) can be accomodated with the DASH-8 fast ADC card. One 16-input submultiplexer for the DASH-8 can accomodate all the radiometer channels. Other DASH-8 channels can accomodate the remaining inputs. Table 5 shows the allocation of data channels among the I/O devices. Figure 2 is a schematic representation of the DAS.

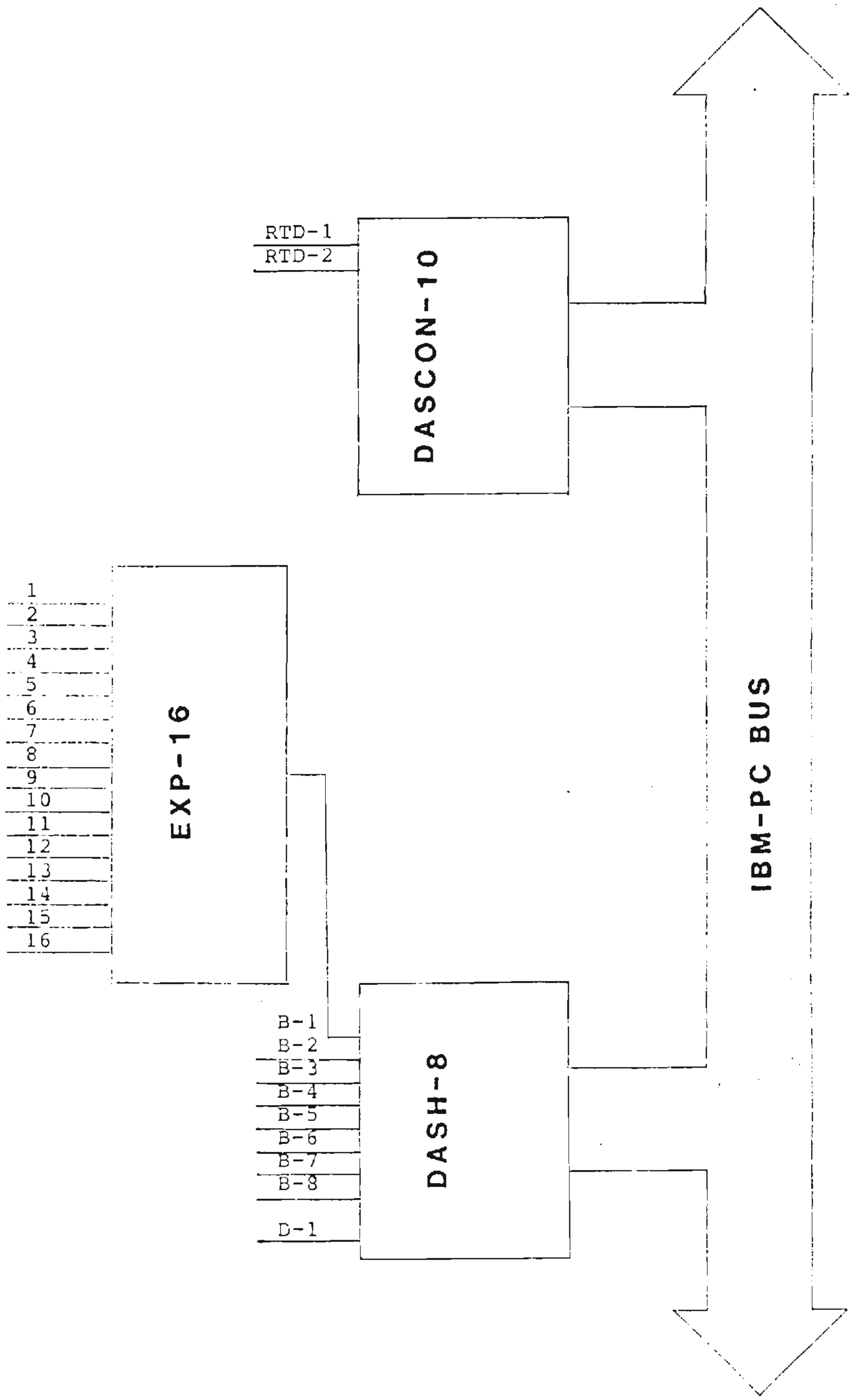

Figure 2. Schematic of Data Acquisition System

The performance and accurary of the DAS should be carefully evaluated before being placed in routine service. At a minimum each ADC channel should be tested over its operating range for stability and accuracy. The measured gain must be either adjusted to the prescribed nominal value or the observed calibration be maintained for use in data processing. Radiometer channels should be calibrated at 0 and 10 mV inputs. Other channels should be appropriately calibrated. The Georgia Tech Solar Lab has access to a stable high-precision Fluke voltage source and a highly-accurate Hewlett-Packard microvoltmeter which have been used for similar calibrations.

The DAS should not be expected to operate reliably at all ambient temperatures which after all range from under 0 F to over 100 F in this region. Nor should its own enclosure be used as weather protection. While DAS units are marketed as having these capabilities, it is doubtful that field performance will meet these assertions. Previous experience with the very expensive EG and G data logger at the Shenandoah STEP has revealed many problems from operation at high temperature. The extra expense of equipment rated for high and low ambient temperature and for direct exposure to the weather seem especially unwarrented since they are unlikely to perform as advertised over the many years this network will operate.

Local fabrication of an equipment enclosure is recommended. A dust and rain proof insulatd enclosure should be provided for the DAS. One possible concept is an enclosure fabricated from weather resistant insultating board such as properly-coated Manville Maronite (R), with a gasketed door. This inner enclosure should be protected by an outer metal envelope. An air space between the two is desirable and the metal envelope should be louvered. This assembly should be much less expensive that the typical foam-filled fiberglass all-weather enclosure. It should also be safe as no combustible materials need be used. A packaged fire suppression device should be considered for the interior.

Active cooling is a must. Equipment for high temperature operation is very expensive and disappointing in use. Either vapor-compression or thermoelectric cooling is possible. A small vapor-compression unit is very inexpensive and should be very reliable. Thermoelectric cooling might be considered for critical locations.

Site Plan

The proposed site plan is shown in Figure 3. Instruments are positioned so as to minimize or eliminate interference and facilitate maintenance. A model of the layout is pictured in Figure 4.

Note that the prime global pyranometer G1, is mounted at the highest level to preclude interference. Similarily, the prime pyrheliometer, B1, is positioned to avoid obstruction; however, it can be lower than G1. Other radiometers are similarily situated to minimize obstruction of their fields of view.

The surface instrumentation mast is mounted north of the radiometers to minimize any shading of the solar radiation instruments. The position is illustrated in the photo of the scale model shown in Figure 4.

All radiometers can be reached from a short step ladder for maintenance. Note that the principal instruments are the six in the main diagonal and are arranged to provide clear fields of view. Additionally, as illustrated by the model figure, all instruments are located so they can be reached for cleaning, adjustments, and other maintenance. The weather mast can be pivoted to provide safe and easy access.

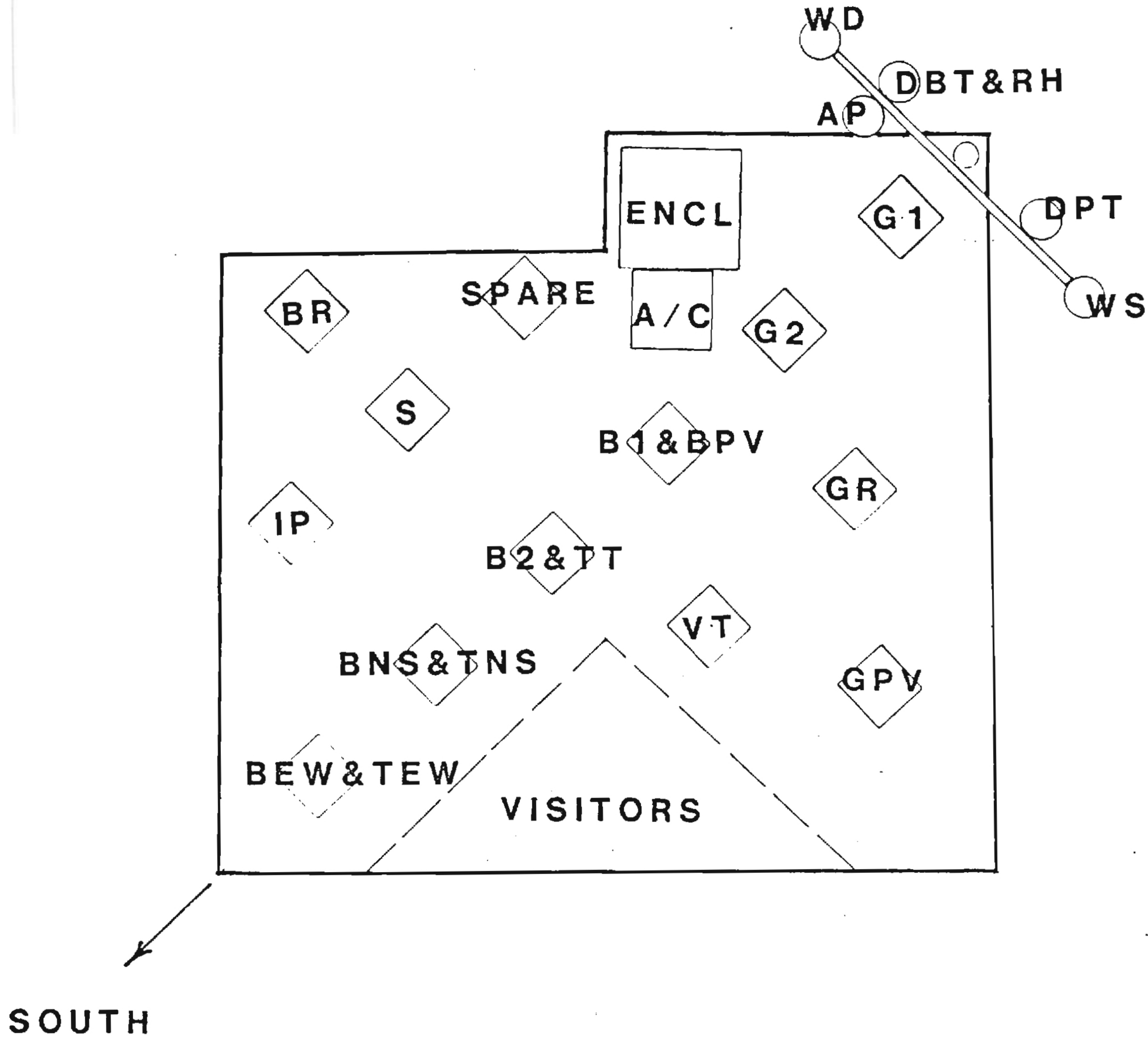

Figure 3. Site Plan. Instruments are identified by acronym defined in the text.

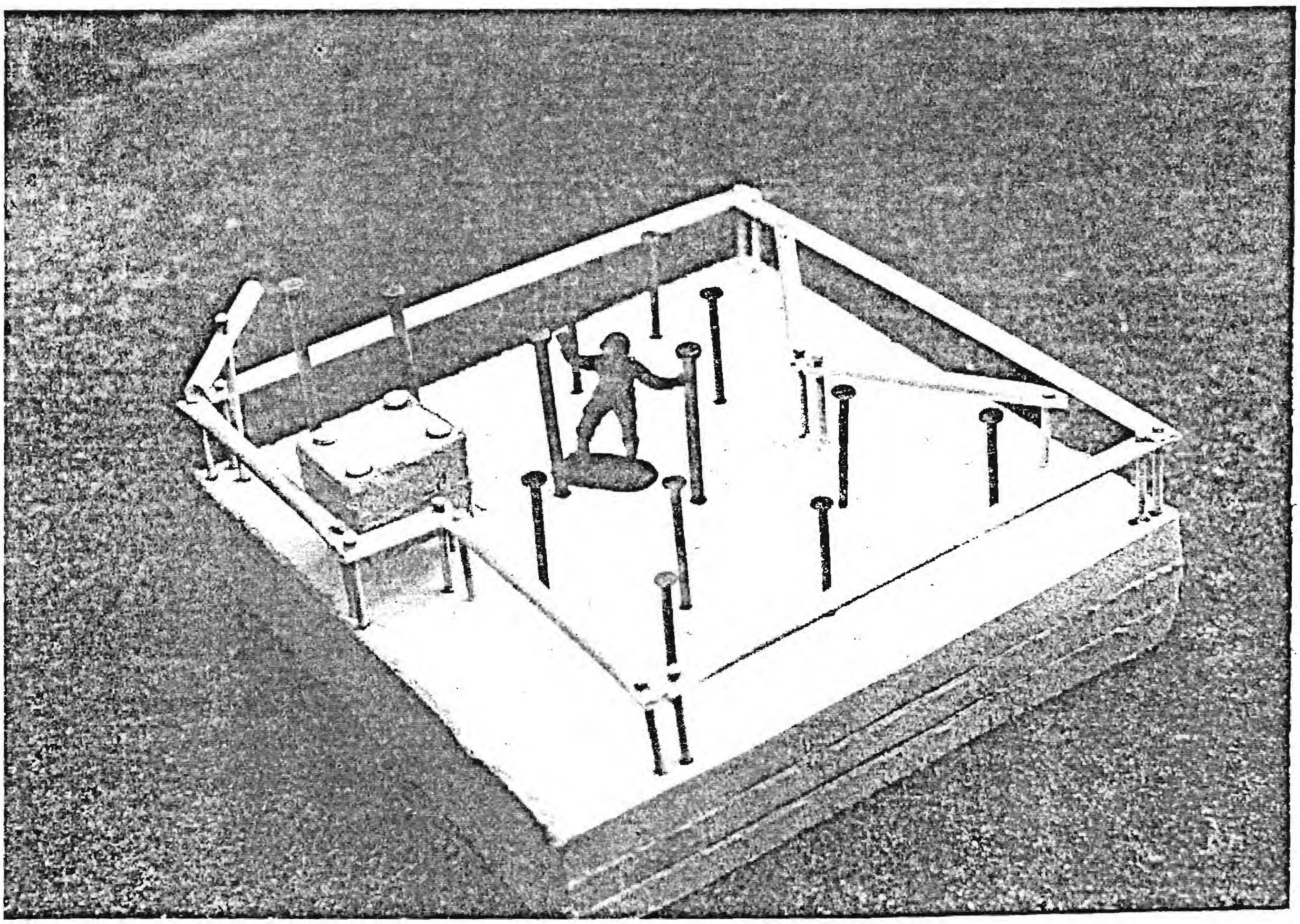

Figure 4. Scale Model of Solar Monitoring Site Proposed for Southern Company Services.

References

(1) E. A. Carter, et al, "Solar Radiation Data Sources, Applications and Network Design," Report No. HCP/T5362-01, April, 1978.

(2) S. M. Jeter, "Final Report: Solar Heat Supply for an Asphalt Paving Plant," Project DTFH-71-81-GA-02, 1985.

(3) D. J. McKay, "A Sad Look at Commercial Humidity Sensors for Meteorological Applications," Atmospheric Environment Service (Canada).

Table 1

Standard Radiometers

symbol	description	quantity	vendor*	model	output range	aprox cost each
B1, B2	Beam Pyrheliometer	2	E	NIP	0-8 mV	1575
	Automatic Solar Tracker	2	L	LI-2020 (note - 1)		3200
RB	Reference Pyrheliometer (optional)	1	E	NIP	0-8 mV	1575
	Solar Tracker	1	E	ST-3		1900
G1, G2	Global Pyranometer	2	E	PSP	0-9 mV	1590
RG	Reference Pyranometer	1	E	PSP		1590
TP	Inclined Pyranometer	1	E	PSP	0-9 mV	1590
	adjustable mount	1	DC**			200
	artificial horizon	1	DDC**			400
S	Sky Pyranometer	1	E	PSP	0-9 mV	1590
	Shading Disc or	1	E	special		c.3000
	Shadow Band	1	E	SBS	0-9 mV	1300

*vendor

E: Eppley Laboratory
12 Sheffield Avenue
Newport, R.I.
(401) 847-1020

L: Li-Cor, Inc.
4421 Superior Street
P. O. Box 4425
Lincoln, Nebraska 68504
(402) 467-3576

WM: Weathermeasure
P. O. Box 41039
Sacramento, CA 95841
(800) 824-5873

notes:

** DC design and construct

*** DDC develop, design and construct locally

1. Requires 110 VAC power, has battery back-up

E-25-M09

GEORGIA TECH 1885-1985

DESIGNING TOMORROW TODAY

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

tp01jan.87

29 December 1986

Mr. Tim Petty
Senior Research Engineer
Southern Company Services Inc.
P. O. Box 2625
Birmingham, Al 35202

Quarterly Progress Report
Contract 195-86-002
Georgia Tech Project E-25-M09

1. Preliminary work on rehabilitating the Shenandoah solar and weather monitoring system is progressing smoothly. A rugged, industrial version PC-compatible computer has been purchased for this application along with interface cards. The wind instruments have been returned to the manufacturer for refurbishment and calibration.

2. The data quality control program has been reviewed. Only a few questions about minor details have been raised including the following:

a. Should TIME correspond to end or middle of data period?
b. Is the newest version of EXTRAD being used?
c. Is the current version of TLTCHK complete and correct?
d. Should a set of variables be established to represent all the error limit spans?
e. Are further checks needed on nighttime data?

I anticipate that the questions can be resolved within a couple of weeks.

Sincerely,

Sheldon M. Jeter
Associate Professor
Principle Investigator

GEORGIA TECH 1885-1985

DESIGNING TOMORROW TODAY

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

tp25feb.87

25 February 1987

Mr. Tim Petty
Senior Research Engineer
Southern Company Services Inc.
P. O. Box 2625
Birmingham, Al 35202

Quarterly Progress Report
Contract 195-86-002
Georgia Tech Project E-25-M09

1. Preliminary work on rehabilitating the Shenandoah solar and weather monitoring system is still underway. The temperature and humidity instruments have been returned to the manufacturer. Software and hardware development for the data acquisition system are well underway.

2. The enclosed material relating to the maintenance of shadow-band radiometers and correcting for the portion of the sky radiation blocked by the band has been assembled.

Sincerely,

Sheldon M. Jeter
Associate Professor
Principle Investigator

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

dP22SEP.87

22 September 1987

Mr. Tim Petty
Senior Research Engineer
Southern Company Services, Inc.
P. O. Box 2625
Birmingham, AL 35202

Quarterly Progress Report
Contract 195-86-002
Georgia Tech Project E25-M09

General Progress:

The Shenandoah STEP station will be getting more attention. I hope to have it operational around the end of October. I hope to have the Eppley Smart Tracker running sooner so we can begin to evaluate its performance and reliability.

I will be available to assist you in reviewing the maintenance and QC procedures for the SCS station. I suggest that we try to arrange a visit for a full day sometime in October or November.

On 3 September we met with Alabama Power personnel to discuss their proposed solar monitoring. Their proposal has several problem areas specifically:

1. Location near fossil power plants will degrade the radiation measurements and effect atmospheric measurements such as temperature and humidity to an unknown degree.

2. Remote operation of solar radiometers is problematical both for adjustment of trackers and cleaning and maintenance of the instruments, especially the pyrheliometer. My recommendation is that remote operation of NIPs not be attempted. We must keep in mind that substandard operation will always produce measurements that are biased <u>low</u>. This situation is serious for future use of the data in planning, marketing, and engineering.

3. We discussed some technical solutions to the beam monitoring problem including:
model for the global
model from multi-PSP installation (report attached)
Eppley Smart Tracker
Li-Cor Tracker
PSP with shadow band

None of these solve the cleaning problem. The Li-Cor tracker has not proved itself to be completely reliable. The Eppley tracker is untested. Neither tracker is likely to be commercially available in the future.

Despite the technical problems, the institutional and management problem of manual operation of a solar data network seem so immense that a technological solution (a reliable self adjusting and cleaning system) should be sought.

Also attached are copies of some recent research here at Tech on related topics.

Sincerely,

Sheldon M. Jeter

DEVELOPMENT OF MODELS FOR THE BEAM RADIATION BASED ON DATA FROM SHENANDOAH, GEORGIA, U.S.A.

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Constantinos A. Balaras, Research Assistant

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ABSTRACT

Of special importance in the investigation of solar radiation are the development of models to predict the beam radiation from the measured global radiation and to calculate the clear sky radiation. In the following, a seasonally - dependent beam radiation with improved predictive power model is presented. Also described is a simple model for the air-mass dependence of the clear-sky radiation which may be useful for design or correlation studies.

DEVELOPMENT OF SEASONAL REGRESSION MODEL

Various unattended stations operate across the United States that collect global irradiation data using pyranometers which are dependable and economical instruments. This situation dictates the need to develop regression models that allow the estimation of the beam radiation from the global radiation without any dependency on meteorological observations. Such relationships are expressed in terms of the irradiations which are the time integrals (i.e. one hour) of the radiant flux or irradiance. A convenient representation is the relationship between two dimensionless numbers, the beam transmittance of the atmosphere,

$$\tau_b = \frac{I_{bn}}{I_{on}} \qquad (1)$$

where I_{bn} = hourly or short period beam irradiation
I_{on} = corresponding extra-terrestrial normal irradiation,

and the short-period clearness index,

$$k_t = \frac{I}{I_o} \qquad (2)$$

where I = hourly or short period global irradiation
I_o = corresponding extraterrestrial horizontal irradiation.

Relationships between these variables have been presented by several authors. Especially notable among this work are the pioneering efforts of Boes, et al [1], and the highly-regarded results of Randall and Whitson [2]. The present authors have also prepared a similar model [3] based on measurements conducted since 1979 at the site of the Shenandoah Solar Total Energy Project in west-central Georgia, U.S.A. (33.40°N, 84.75°W). The basic data set consists of irradiation values integrated over fifteen minute periods recorded at the end of each period) and assembled on an hourly basis.

A seasonal dependence in the relationship between the bean and global irradiations has been apparent in the Shenandoah data. The present study deals with the investigation of the observed seasonal dependence and the development of an improved regression model for the beam irradiation.

Two procedures have been used to reveal the seasonal dependence of the correlation between the beam and global hourly irradiations. The more straightforward procedure is to assemble seasonal collections from the five years of data and then perform a regression analysis on each such seasonal data base. An alternative procedure is to evaluate a seasonally-dependent multiplicative factor which modifies the basic five-year regression model. The latter procedure returns a single number for each seasonal subset. This simple result is desirable since the factor can be plotted to illustrate graphically the seasonal dependence of the correlation.

It is of capital importance to prepare a high-quality data base since, as demonstrated in [3], spurious data can have a substantive effect on the resulting correlation. A rather intensive routine data-quality control procedure, described in [4], has been instituted for the Shenandoah data. The procedure is summarized in [3]. Additional screening and processing was conducted during the development of the five-year regression model with the ultimate result of producing a long term record of hourly irradiations which appears to be quite reliable.

The seasonal regression studies were based on monthly intervals. Data for each month of the calendar was selected from the entire five-year data base for individual analysis. The analysis followed the same procedure as used to develope the five-year model. The principal features were that a piecewise continuous linear model was selected. The same piecewise bands were used as were used by Randall and Whitson in [2]. The initial band (k_t < .05) was devoid of data as a result of the screening out of very low irradiation hours caused by darkness or overcast skies. The standard least-squared error fit to a homogeneous linear model was applied over the remaining bands resulting in a regression model of the form:

$$\tau_{bj} = F_m(k_{tj}) + \varepsilon_j \qquad (3)$$

where F_m is the regression model for month m and ε_j is the residual for datum (τ_{bj}, k_{tj}).

Representative results are illustrated for two months in Figures 1 and 2. It is notable that the beam transmittance is higher for the winter months than the summer months. This could be expected on account of the prevalent sky conditions. During winter the typical condition for middling clearness index is intermittent clouds in an otherwise clear sky. This results in intermittent beam radiation. In contrast the typical summer sky for an intermediate k_t is a hazy condition with much greater attenuation of the beam radiation. Note also that the beam transmittance reaches higher values for clear skies during winter. This is explained by the reduced water vapor and turbidity in the cold continental air masses that dominate clear weather conditions during winter in the southeastern U.S.A.. A summary of the regression coefficients for all twelve months is presented in [5].
The monthly regression models clearly demonstrate a seasonal dependence in the correlation between transmittance and clearness index. This dependence cannot be a hidden effect of the optical path length since the air-mass ratio is higher in winter than summer and by increasing the beam attenuation would cause a variation opposed to that actually observed.

Consequently, our results do not support the assertion of Garrison [6] that there is no seasonal dependence of the relationship. One explanation of this disagreement is that Garrison's data excluded hours for which the solar elevation exceeded 50°. As a consequence most winter hours are included but many summer hours around solar noon are excluded. This exclusion could have a systematic impact on his results because, in the southeast at least, one experiences many summertime days that are clear in early morning and late afternoon but cloudy in midday; therefore, it may well be that summer hours when the elevation is less than 50° have sky conditions similar to winter hours.

Our monthly regressions are also in general accord with the results of Randall and Biddle [7]. Their work involved not the beam transmittance but its ratio to an air-mass dependent clear-sky beam transmittance; consequently, the present work is not strictly comparable.

The monthly regressions should accurately account for the observed seasonal dependence; however, monthly models have some shortcomings. They are awkward to program and are not concise. A single variable accounting for the seasonal dependence would be easy to program and concise in presentation. Inspection of Figures 1 and 2 indicates that a simple multiplicative factor should be sufficient. This suggest a model of the form

$$\tau_{bj} = b_n F_5(k_{tj}) + \varepsilon_j \qquad (4)$$

where F_5 is the basic five-year model of reference [3], namely:

$$(\tau_{bj} - y_{oi}) = \beta_i(K_{tj} - x_{oi}) + \varepsilon_j \qquad (5)$$

where
x_{oi} = lower limit of band i,
y_{oi} = regression model at x_{oi},
β_i = five-year regression coefficient
ε_j = residual error of data (K_{tj}, τ_{bj}).

As usual b_n is selected to minimize the unexplained variation; therefore, for a given period, selected to be monthly, b_n is given by

$$b_n = \frac{\Sigma\, F_5(k_{tj})\ \tau_{bj}}{\Sigma(F_5(K_{tj}))^2} \qquad (6)$$

Seasonal factors can be efficiently computed using monthly data bases. For the Shenandoah data results illustrated in Figure 3 are obtained.

To quantify the results, pertinent statistics were computed for the simple five-year model, the seasonal five-year model, and each annual seasonal model. These statistics include the following:

1. The total variation,
$SYY = \Sigma\ (\tau_{bj} - \tau_{b,ave})^2$,
2. The residual variation,
$RSS = \Sigma\ (\tau_{bj} - y_j)^2 = \Sigma\ \varepsilon_j^2$
where y_j = regression model at τ_{bj},
3. The explained variation
$SSR = SYY - RSS$,
4. The coefficient of determination,
$r^2 = SSR/SYY$.

Each of the less inclusive models was compared to the five-year seasonal model in order to determine the significance of the difference between the available models. For this decision-making procedure the null hypothesis is that an annual seasonal model is tenable while the alternative hypothesis is that the five-year seasonal model is more tenable based on the available five year data. The most appropriate test statistic for comparing regression lines is the Fisher F-statistic, given by:

$$F = \frac{(RSS_0 - RSS_A) \;/\; (d_0 - d_A)}{RSS_A / d_A} \qquad (7)$$

Representative results from the analysis of variation are given in Table 1. The high values of the F-statistic tend to support the alternative hypothesis. Thus, one can reject all the annual seasonal models and five-year model in favor of the seasonal five-year model. Also shown in Table 1 are the probabilities $P\ (Z < F)$ that a random variable Z would have a value <u>less than</u> the computed value for F. Again, all the hypothesized models have P aproximately 1.0. The literal interpretation is that there is essentially no chance that a long-period model would have the same regression model as any of the short-period, annual seasonal models or as the five-year model. The high probabilities that an adequate model would have lower RSS than observed for the limited models is convincing evidence that all, including the five year-model, be rejected in favor of the new five-year seasonal model.

The proceeding analysis has shown that the seasonal five-year model is clearly preferable than any of the more limited models. This was of course only to have been expected of a more flexible model. However, the coefficient of determination has only been increased from 88.6% to 90.3%. This slight improvement seems hardly worth any additional effort to implement. In practice however, because of the other seasonal variations, the effect can regain importance. The longer length of days dictates more extraterrestrial normal irradiation during summer. If the model overpredicts the beam transmittance during this season, the error is compounded.

In summary we can report conclusive evidence of a seasonal dependence in the relationship between beam transmittance and clearness index. Either distinct seasonal regression models or an inclusive regression model modified by a seasonal factor can be used to quantify this effect; however, the seasonal factor appears to be the most concise and convenient means of including the seasonal effect in a regression model for the beam transmittance.

DEVELOPMENT OF CLEAR SKY RADIATION MODEL

Beam radiation may be attenuated by scattering or absorption during interaction with the molecules and particles in the atmosphere. Since these interactions are independent events, the net attenuation as the beam traverses an infinitesimal layer of the atmosphere is proportional to the incident irradiance and an atmospheric extinction according to a Bouguer's Law type formulation. Integrating through the depth of the atmosphere and including an air-mass independent factor, τ_o, that is best justified for its improvement in fitting the statistical data, one obtains the following formula for the beam transmittance:

$$\tau_b = \frac{I_{bn}}{I_{on}} = \tau_o \exp\ (-Kp) = \tau_o \exp\ (-\kappa m) \qquad (8)$$

where p = path length (km),
K = extinction coefficient (km^{-1}),

and the path length is replaced by the air mass ratio, m, such that

$$m = \frac{p}{d},$$

d = depth of the atmosphere,
κ = normalized extinction coefficient.

The air-mass ratio can be related to the inverse of the sine of the solar elevation, $m = 1/\sin\alpha$, until the curvature of the atmosphere becomes significant at low elevation angles where a Lagrangian interpolation of data from [8], was substituted.

The variation of τ_b and m is shown in Figure 4. Air-mass values range from unity up to 6.5. Higher values of air-mass were not attained since at very low sun angles pyrheliometer data cannot be considered reliable due to refraction and interference from objects near the horizon. The envelope of the τ_b distribution exhibits the expected variation, high values at low air-mass and lower values as the air-mass increases in value since the energy attenuation caused by the atmosphere increases.

To identify the limiting values that represent the clearest sky conditions, the distribution was disaggregated into bands (0.1 wide up to an air-mass value of 5.1) and the largest τ_b in each band was identified. Using a least square error curve fit through these sample data the following expression for the clear sky beam transmittance was determined:

$$\tau_{bc} = 0.8426\exp(-0.0939m) \qquad (9)$$

Along with the scatter plot of the five year data, Figure 4 shows the resulting clear sky beam transmittance (CSBT) model, Equation (2). Also illustrated is a model developed by Randall and Whitson (R-W) [9] which is $\tau_b = 0.8847\exp(-0.106m)$.

Results of the statistical comparison of the two models are given in Table 2. The pertinent statistics used to determine the degree of correlation between the two models and the maximum data of (τ_{bj} and m_j) are as stated previously.

The present model, Equation (9), can explain 94% of the clear sky τ_b variation as a dependence on air-mass. This is a slight, but significant, improvement over the 86% explained by the Randall-Whitson [9] correlation.

The probability P(Z<F) in Table 2 is the likelihood that a random variable Z with the F-distribution would attain a value lower than the computed F. This probability is nearly unity asserting that there is essentially no chance that a random selection of data from the population represented by the Shenandoah data base would result in a model yielding such a high value of F as computed for the hypothesized, R-W, model. Consequently, the CSBT model is statistically preferred over the R-W model for the Shenandoah data with a confidence of nearly 100 percent.

While the large value of the F-statistic can be viewed as simple evidence against the R-W model and in favor of the CSBT model, a more significant interpretation is to recognize that the R-W model is presumably a best fit to its underlying data just as is the case for the CSBT model. The large value of the F-statistic is then evidence that there is little chance that the two models represent identical underlying distributions.

On the other hand, in an absolute sense the two curves vary by less than four percent (Figure 4). This is a very important observation which shows that two models developed from distinctly different populations (with statistically different underlying distributions) are practically identical. As a matter of fact, either model could be applied with satisfactory results. One can then conclude that clear sky conditions actually represent a universal behavior. Models of similar nature can be used with confidence on different data samples for determining limiting sky conditions. Any observed discrepancies can be attributed to varying climate, sampling techniques and/or instrumentation errors and variations that could bias the corresponding measurements. Equations (8) and (9) will now enable us to model the beam radiation under clear skies in the following form:

$$I_{bnc} = I_{on}\tau_{bc} \qquad (10)$$

where I_{bnc} = periodic (e.g. hourly) beam irradiation under clear skies,

τ_{bc} = beam transmittance computed for the mid-point of the period.

The modeled data from Equation (10) was compared with measured data for several representative clear days throughout the year of 1979. The general trend of the modeled data was found to be in good agreement with the measured data. Statistical analysis and representative results illustrate that the CSBT model, Equation (9), is an adequate representation of the clear sky beam irradiance as a consequence of the purely air-mass dependence of the beam transmittance. The method described here could be employed with data for a specific site. However, since the very clearest skies are not necessarily site specific, the present model could be applied generally for purposes such as to predict extreme beam irradiance and to remove the air-mass dependence in beam transmittance correlations.

TABLE 1

STATISTICAL RESULTS FOR THE SIMPLE FIVE-YEAR MODEL, FIVE-YEAR SEASONAL MODEL AND 1979, 1980 SEASONAL MODELS, INCLUDING FISHER'S F-STATISTIC

	SIMPLE 5-YR MODEL	5-YR (SEASONAL MODELS)	1979 (SEASONAL MODELS)	1980 (SEASONAL MODELS)
SYY	418.32	418.32	418.32	418.32
RSS	47.47	40.36	47.94	44.13
SSR	370.85	377.96	370.38	374.19
r^2	0.8865	0.9035	0.8854	0.8945
F	118.68		126.65	62.93
P(Z<F)	1.0		1.0	1.0

TABLE 2

STATISTICAL RESULTS FOR THE PRESENT CLEAR SKY BEAM TRANSMITTANCE MODEL (CSBT) AND THE RANDALL-WHITSON MODEL (R-W), INCLUDING FISHER'S F-STATISTIC

PARAMETER	CSBT	R-W
SYY	0.0686	0.0686
RSS	0.0038	0.0096
SSR	0.0648	0.0590
r^2	0.9439	0.8596
F		15.01
P(Z<F)		0.9999

REFERENCES

1. E. Boes, H. E. Anderson, I. J. Hall, R. R. Prairie, R. T. Stromberg, SAND 77-0885, August, 1977.

2. C. Randall and M. E. Whitson, The Aerospace Corporation, Final Report ATR-78(7592)-1 (1977).

3. S. Jeter and C. Balaras, Solar Energy, 37, pp. 7-14, 1985.

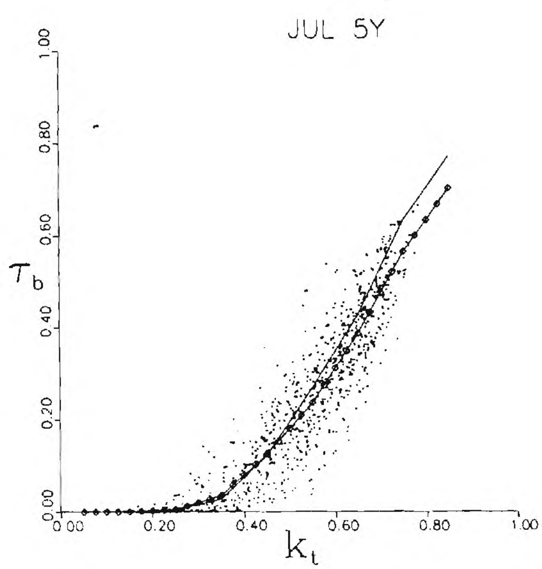
4. C. Phan, M.S. Thesis, School of Mechanical Eng., GA. Tech., 1980.

5. C. Balaras, M.S. Thesis, School of Mechanical Eng., GA. Tech, 1985.

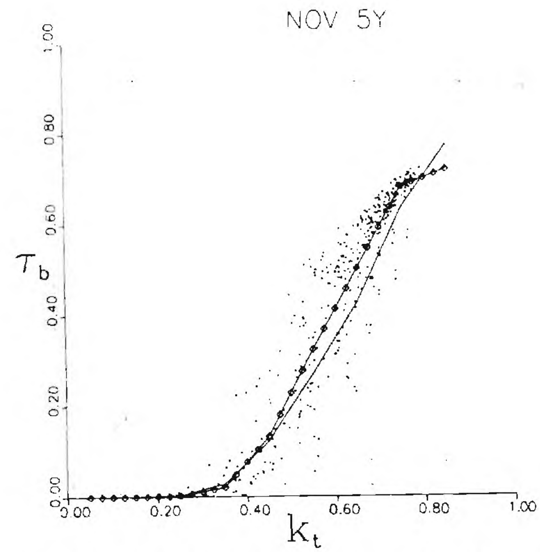
6. J. Garrison, Solar Energy, 37, pp. 7-14, 1985.

7. C. Randall and J. M. Biddle, The Aerospace Corporation Report ATR-81(7878)-1, 1981.

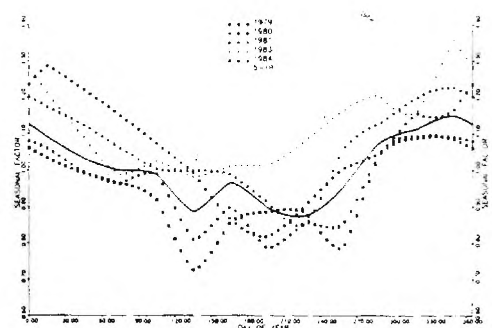
8. J. F. Kreider and F. Kreith, "Solar Energy Handbook", McGraw Hill, 1981.



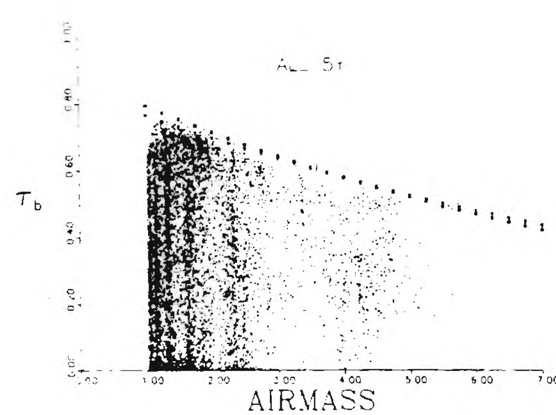
1. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Julys. The Simple Five-Year Model is Shown by the Plain Line.



2. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Novembers. The Simple Five-Year Model is Shown by the Plain Line.



3. Seasonal Factors Computed from Five-Years of Data Compared with Factors Computed from Annual Data Sets



4. Beam Transmittance Dependence on Air Mass Using Five Year Data from Shenandoah, Georgia. Triangles Indicate the Simple CSBT Model, Squares Indicate the Randall-Whitson Model.

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A NEW METHOD FOR THE DETERMINATION OF DIRECT INSOLATION*

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Abstract—A method of determining direct normal insolation by using two fixed pyranometers was developed and tested. Experimental data for two different configurations are presented. The results are such that the method presented could reasonably be substituted for the standard tracking pyrheliometer in situations in which the use of such a pyrheliometer is not practicable.

1. INTRODUCTION

The solar resource is composed of three types of insolation: direct, diffuse, and reflected. A knowledge of the distribution of the solar resource available at a given location among these three components is essential to accurately predict conversion efficiencies for different collector technologies. The direct component measured by a sensor oriented normal to the beam (I_{DN}) is commonly referred to as the direct normal insolation. It is usually measured by a pyrheliometer. To insure proper alignment, the pyrheliometer requires frequent corrections in orientation which can make its use inconvenient. As a routine part of its daily measurements, our research group monitors, among others, the direct normal insolation using a pyrheliometer known as an Epply Normal Incidence Pyranometer (NIP). Since this is our only measure of I_{DN}, we became interested in the possibility of determining I_{DN} by other indirect means. Such a method, if reliable, would provide a backup for the NIP and in addition would provide a quality control monitor on the data provided by the NIP.

This is a report of the results of a method which has worked well for our group, and which other facilities may also find useful because of its simplicity and lack of solar tracking. The equipment required is commonly available at many solar monitoring sites and may be left in situ indefinitely without alignment or adjustment (adjustment is necessary for other back-up methods, such as shadow band devices).

The method uses two pyranometers, which measure global insolation, mounted at different orientations to yield data for a set of equations which may be solved for I_{DN}. A similar technique for a different purpose was pursued by Steinmuller[1]. Monitoring sites which maintain two pyranometers typically measure the total insolation on a horizontal sensor and on a sensor mounted north-south and tilted from the horizontal at the local latitude. We have applied the method to such an arrangement with good results. Analysis of the model however shows that there is a better choice of tilt for the second pyranometer for the purpose of this study, and we also have applied our method to this angle with improved results.

2. THE MODEL

The model assumes that the total insolation received on any sensor may be written as the sum of direct, diffuse and reflected components. If θ is the angle of incidence measured from the sensor normal, then the beam or direct insolation received on a sensor can be written as follows:

$$I_D = I_{DN} \cos \theta. \tag{1}$$

The diffuse insolation received on a sensor is difficult to express analytically due to its dependence upon highly variable atmospheric conditions. However, it is assumed that the diffuse insolation on any surface (I_d) can be written in terms of that on a horizontal surface (D_o) as

$$I_d = dD_o. \tag{2}$$

The diffuse coefficient d and its influence on the model are discussed in the following section. The reflected insolation reaching any sensor is also difficult to express analytically, but it is assumed that the reflected insolation reaching a sensor of arbitrary orientation (I_r) can be written in terms of the total insolation on the horizontal (I_o) as

$$I_r = rI_o, \tag{3}$$

where r is the reflection coefficient, which depends on the geometry and reflectivity of the surroundings. This relationship assumes that the reflecting environment is horizontal so that no reflected insolation would be received on a horizontal sensor, as was the case in this study due to the elevation we used for our sensors. In order to strengthen this

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* Portions of this paper were presented at the American Solar Energy Society Meeting in Minneapolis, 1983.
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other than the purpose of this study; and therefore we utilized the 8-48 for the tilted data. To allow for its tilt dependence, the 8-48 was calibrated against an identically tilted PSP at the tilt angles of interest. Once the calibration was obtained, the 35° tilt experiment was performed in the period 26 February through 9 March, 1982, and the −80° (80° North-facing) tilt experiment was performed in the period 22 March through 7 April, 1982. Seventy-three (73) data points were obtained in the first study and ninety (90) data points were obtained in the second study.

5. ANALYSIS OF THE DATA AND RESULTS

A typical relationship between the predicted values $\langle I_{DN}\rangle_{ISO}$ and $\langle I_{DN}\rangle_{COM}$ (from the isotropic and combination models, respectively), and the actual $\langle I_{DN}\rangle$ values as measured by the NIP for the 35° tilt experiment can be seen in Fig. 1. Similarly, sample results for the −80° experiment are given in Fig. 2. In general, it can be observed that both models at both tilt angles tracked the actual NIP readings. It also can be observed that the isotropic model was significantly better than the combination model for both tilt angles. Finally, overall the −80° tilt data is somewhat better at fitting the actual NIP values than the data taken at 35°. However, for either the 35° or the −80° data the typical maximum daily error (for the period within two hours of solar noon) is on the order of ±5%.

6. CONCLUSIONS

It should be recalled that a tilt angle of −80° was chosen to minimize the effect of errors and at least in the data reported here we see that this is born out. In fact the average error at −80° for all the data was less than 3% for the middle six hours of the day. Given that the NIP has a nominal accuracy of ±2%, this result is surprisingly good.

The results for the −80° experiment are expected to be applicable at a variety of locations, assuming the tilt angle is chosen, based on the local latitude and season in such a way that little or no direct insolation is received or the tilted sensor during the time period of interest. The same may or may not be true of the experiment performed with the tilt angles chosen to equal the local latitude. While the model is well behaved for this choice of tilt, an analysis of the model shows that there is a distinct dependence of the model upon latitude, and therefore a confident prediction of how variation in latitude would affect the results cannot be made without experimental testing at the latitude of interest. Similarly, tests were only made at one season of the year. The equations predict that the model's results should be portable to other seasons but this has not been experimentally verified.

The results obtained in this study are encouraging. It would seem that two static pyranometers can predict with fair accuracy the direct normal insolation under clear sky conditions. As was mentioned, there are two circumstances for which this

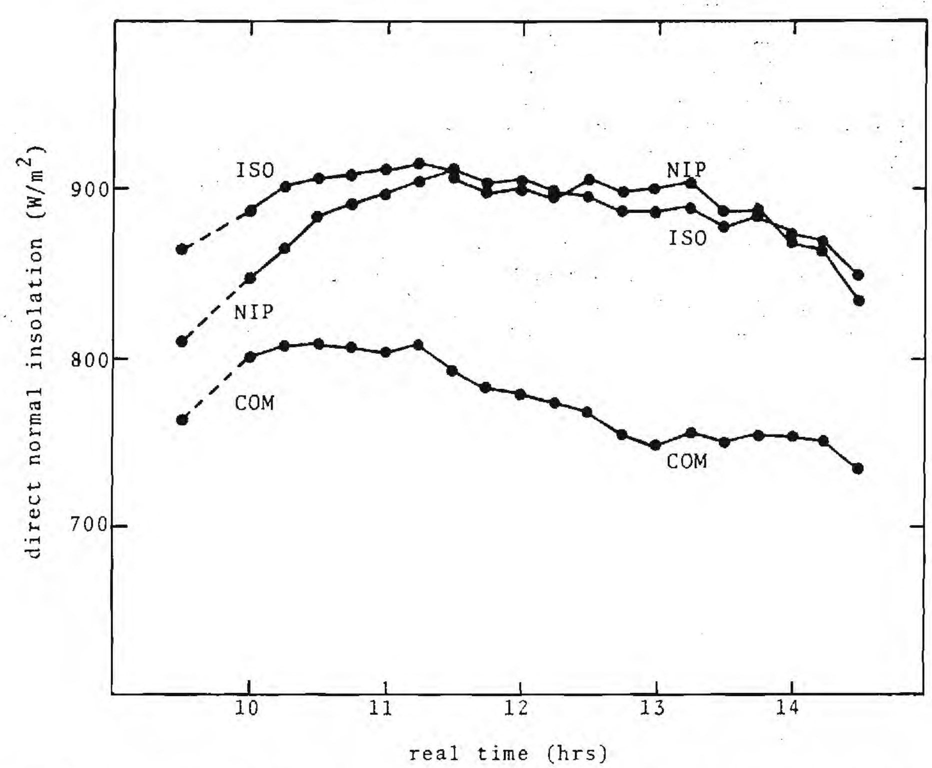

Fig. 1. Direct normal insolation for Julian day $N = 61$, tilt angle $\beta = 35°$. Actual values from NIP, predicted values from ISO and COM models.

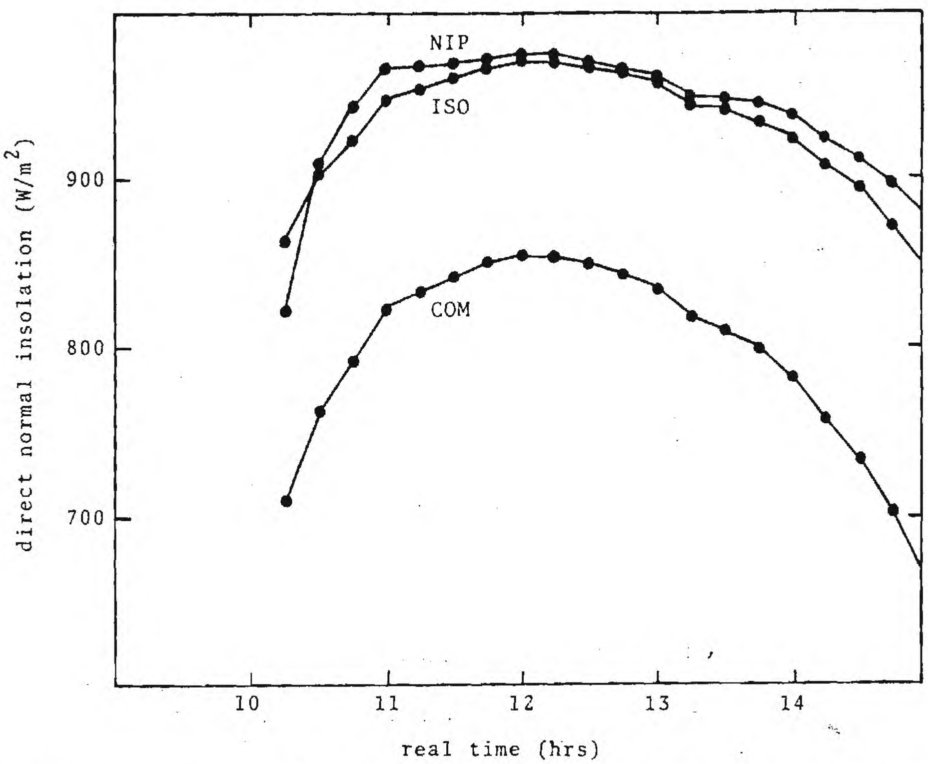

Fig. 2. Direct normal insolation for Julian day N = 85, tilt angle $\beta = -80°$. Actual values from NIP, predicted values from ISO and COM models.

technique would be most helpful and for which the accuracy we have obtained should be satisfactory. First, if one is already taking direct normal data and horizontal data the utilization of a second pyranometer (and not necessarily a high quality one) can be used to provide data sufficient to monitor the quality of the direct normal data and, in fact, to serve as backup to this data. Second, for the locations where it is not practical to have a NIP or similar instrument this technique would be useful for closely estimating direct normal insolation during the midday period. The midday data are probably sufficient for most uses but as already mentioned, this data can be extrapolated to other hours if needed.

REFERENCES

1. B. Steinmuler, The two-solarimeter method for insolation on inclined surfaces. *Solar Energy* **25**, 449 (1980).
2. L. O. Lamm and C. Adler, A generalized technique for evaluating reflection coefficients for ground-plane systems. *Solar Energy* **35**, 243 (1985).
3. D. Rapp, *Solar Energy*, pp. 63–69. Prentice-Hall, Englewood Cliffs, New Jersey (1981).
4. E. C. Flowers, Solar radiation facility report for 1978. NOAA/ERL-ARL, Boulder, Colorado (1978).
5. L. O. Lamm, C. Adler, A. Larkins, S. Kelly, The elimination of cosine errors in the calibration of tilted pyranometers. *Proceedings of ISES Montreal Conference* (1985).
6. F. Loxsom and W. Hogan, Estimating insolation on tilted surfaces. Trinity University Solar Data Center, San Antonio, Texas (1980).

Georgia Tech

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Final Report, Deliverable No. 6
Contract 195-86-002
Georgia Tech Project E25-M09

As noted previously, all required deliverable on this project have been submitted concluding with the Site Selection Memorandum on 2 November 1987.

This project will continue to support your activity with residual funds and cooperative support from Georgia Power Company's Solar Operations Department.

As discussed yesterday, the following are current priorities:

1. Update and upgrade the solar monitoring software.

2. Complete the rehabilitation of the STEP monitoring station.

We can plan to meet to discuss these activities during April 1988.

Respectively submitted,

Sheldon M. Jeter