IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY

programme
to develop and test
solar heating
and cooling systems

TASK V - Use of Existing
Meteorological Information
for Solar Energy Applications

SUB-TASK 'C'
RECOMMENDATIONS CONCERNING METEOROLOGICAL NETWORKS FOR SOLAR ENERGY APPLICATIONS

Environment Canada
Atmospheric Environment Service
Climatological Applications Branch

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Task V
Use of Existing Meteorological Information for Solar Energy Applications

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RECOMMENDATIONS CONCERNING METEOROLOGICAL NETWORKS FOR SOLAR ENERGY APPLICATIONS

by

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June 1981

ABSTRACT

The dependence of solar energy applications studies on measured meteorological and solar radiation data is readily recognizable. This dependence, while large, is not general but is specific depending upon the application. The specificity of the dependence is reflected in the requirements for data, and the degree to which these requirements may be met are determined by the measurement program. This report describes the characteristics of the two main categories of measurement networks, routine and research oriented, and discusses recommended minimum desirable standards for supporting solar energy applications. Included in the appendices are: a survey of user requirements; a discussion of radiation network assessment and a discussion of measurement standards.

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an agreement on an International Energy Programme was formulated among a number of industrialized countries in November, 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty countries are currently members of the IEA with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme the participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA committee for energy, research and development (CRD), assisted by a small Secretariat, coordinates the energy research development, and demonstration program.

Solar Heating and Cooling Programme

In July, 1975 Solar Heating and Cooling was selected as one of the sixteen technology fields for multilateral cooperation. The objective was to undertake cooperative research, development, demonstrations and exchanges of information in order to advance the activities of all participants in the field of solar heating and cooling systems. Several tasks were developed in key areas of solar heating and cooling. A formal implementing agreement for this program, covering the contributions, obligations and rights of the participants, as well as the scope of each task, was prepared and signed by fifteen countries and the Commission of the European Communities. The overall program is managed by an Executive Committee, while the management of each task is the responsibility of an Operating Agent who acts on behalf of the other participants.

The tasks of the IEA Solar Heating and Cooling Programme and their respective Operating Agents (lead country responsible for the task) are:

- I Investigation of the Performance of Solar Heating and Cooling Systems -- Technical University of Denmark.
- II Coordination of Research and Development on Solar Heating and Cooling Components – Agency of Industrial Science and Technology, Japan.
- III Performance Testing of Solar Collectors – Kernforschungsanlage Julich, Federal Republic of Germany.
- IV Development of an Insolation Handbook and Instrumentation Package – United States Department of Energy.
- V Use of Existing Meteorological Information for Solar Energy Applications – Swedish Meteorological and Hydrological Institute.
- VI Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors – United States Department of Energy.
- VII Central Solar Heating with Seasonal Storage – Swedish Council for Building Research.

Collaboration in additional areas is likely to be considered as projects are completed or fruitful topics for cooperation are identified.

Task V – Use of Meteorological Information for Solar Energy Applications

Recognizing the importance of resource information, two of the seven tasks were designated as meteorological support tasks for solar heating and cooling research and applications. The objectives of Task V are to improve the availability of existing solar radiation and related meteorological data and to support the collection and presentation of such data in an effective manner for the solar energy community.

The project comprises the following subtasks:

A. Compilation of sources of solar radiation and relevant meteorological data;

B. Preparation of a handbook on estimation methods;

C. Recommendations concerning meteorological networks for solar energy applications; and

D. Preparation of a uniform format for presentation of data.

The following countries are participants in this task: Austria, Belgium, Canada, Denmark, Germany, Italy, The Netherlands, Spain, Sweden, Switzerland, United Kingdom, United States of America, and the Commission of European Communities.

Subtask C – Recommendations Concerning Meteorological Networks for Solar Energy Applications

This report documents work carried out under Subtask C of Task V of the IEA Solar Heating and Cooling Programme. It recommends a minimum network for routine measurements for solar energy applications and also contains recommendations concerning measurements for other scientific purposes.

These recommendations are intended for organizations dealing with solar energy measurements. It is suggested that the World Meteorological Organization consider them so that the national networks will be capable of directly providing the type of radiation data required for solar energy applications. Specifically, it is necessary to consider the need for:

1. Expansion of existing networks of radiation stations including the measurement of additional parameters, both regionally and globally;

2. Improvement of instruments used in radiation measurements; and

3. Increased reliability of data from existing and future stations.

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Recommendations Concerning Meteorological Networks for Solar Energy Applications

1. Introduction

To guide the design, development, and application of solar energy collection and conversion systems, and to evaluate their performance within a region, it is necessary to know the spatial and temporal distributions of the amount and characteristics of solar energy received. A significant and well developed body of knowledge and experience in solar radiation and related weather measurements already exist in many national and meteorological centres throughout the world. Many nations already have substantial networks of radiation stations. However, the time has been reached when existing networks need to be evaluated in the light of the increasing use of the data. Some spatial variations exist within the radiation field such that little suitable data are available. The establishment of a satisfactory network must be accomplished in the near future because of the financial significance of questions which have already been posed. As well, the user of data must recognize the limitations of even the best possible network. The users of meteorological data can be viewed as being of two types: designers and researchers. Designers include applications planners, manufacturers and operators who use data as input parameters in solving problems of siting, design, performance, reliability, etc., of solar energy systems. Research scientists include individuals who require data as inputs into detailed modelling studies of atmospheric and environmental interactions.

This note recommends a minimum network for routine measurements for solar energy applications and also contains recommendations concerning measurements for other scientific purposes. These recommendations are intended for organizations dealing with solar energy measurements. It is suggested that the World Meteorological Organization consider them so that the national networks will be capable of directly providing the type of radiation data required for solar energy applications. Specifically, it is necessary to consider the need for:

1.1 expansion of existing networks of radiation stations including the measurement of additional parameters, both regionally and globally;

1.2 improvement of instruments used in radiation measurements; and

1.3 increased reliability of data from existing and future stations.

A brief survey of the literature on user requirements for meteorological data is given in Appendix A; on radiation network assessment in Appendix B; and on radiation measurements in Appendix C.

2. Routine network measurements

The principal conclusions of this preliminary investigation are as follows:

2.1 A more rational approach should be taken to network design. A brief survey of current literature on radiation network assessment is given in Appendix B. No new stations should be added to the routine network until their need is established based on network optimization studies. Any organized design should be consistent with the objectives and decisions underlying present and future management and planning for solar energy systems, as well as for many other end users.

2.2 The *minimum* set of meteorological parameters required for solar energy applications, particularly for heating and cooling technology are listed in Table 1. Wherever possible meteorological and radiation measurements should be co-located. One of the most important improvements of the minimum routine measurement programme is the separation of the global radiation into direct and diffuse components. The recommended way of bringing about this separation is the continuous measurement of direct radiation. This will require the manufacture of a dependable, relatively inexpensive sun tracker. The alternative method of separation is the measurement of diffuse solar radiation by means of a shading device for occulting the direct solar beam. At present the diffuse radiation measurement is less costly and requires less routine adjustments, but on the whole the accuracy is less than measurement of direct radiation at normal incidence.

2.3 Dense measuring networks using pyranometers may not be economically viable in some regions. Therefore, the required solar radiation data must be estimated using observations from synoptic and climatological stations (and possibly satellite observa-

Table 1: Meteorological Observations at Routine Network Stations
(Adapted from Tables A-7 and A-9)

Parameter	Frequency	Accuracy of measurement
1. Global solar radiation	hourly total	$\pm 25 W/m^2$ or $\pm 5\%$, whichever is the greatest
2. Direct solar radiation **or** diffuse sky radiation	hourly total	same as above
3. Sunshine duration, and/or cloud amount	hourly total at synoptic intervals	± 0.1 hour in any hour $\pm 1/10$
4. Air temperature	hourly mean	± 1°C
5. Wind vector	hourly mean	speed = 1m/sec, direction $\pm 10°$
6. Humidity	hourly mean	$\pm 3\%$

tions) as inputs to numerical models. Item 3 (sunshine duration and/or cloud amount) in Table 1 is included to provide a means of computing the requisite radiation parameters.

2.4 Radiometric stations usually report in TST (true solar time), whereas, synoptic stations report in GMT and climatic stations in MST (mean solar time) or local standard time. It is recommended that meteorological services provide for the interpolation of synoptic, climatological, and radiometric observations to the appropriate time base requested by the user whenever these data are required for solar energy purposes.

2.5 The accuracy of radiation measuring equipment or systems at routine network stations should be on the order of ± 5 per cent. The objective should be to achieve a final data accuracy between ± 5 and ± 10 per cent. The accuracies given in Table 1 are compatible with WMO recommendations and with state of the art meteorological instrument technology. While improved instrumentation may be desired in certain circumstances, attention should also be concentrated on procedures for uniform data quality assurance across all stations in the routine network. Every effort should be made to maintain an uninterrupted series of observations since these are vital to derivation of single-parameter and combined frequency distributions. A very important aspect of network operation is the selection of instruments, test and quality control of instrument performance, calibration of sensors and instrument systems, siting of instruments, and field surveillance and maintenance. A brief review of the literature covering aspects of radiation measurement is given in Appendix C.

2.7 A central authority should be given responsibility for coordinating and/or monitoring the considerable growth in solar radiation data collection expected in the future. With the growing number of solar energy systems being placed in operation by government, business and individuals, the number of radiation (and conventional meteorological) measurement systems will increase rapidly in the future. Meteorological services or solar energy authorities may find it necessary to conduct periodic surveys of systems (networks) operating outside their control. Some organized system of collaboration in such areas as calibration of instruments, advice on exposure, operation and maintenance of meteorological monitoring systems, and standardization of instructions for data collection and quality control will be beneficial. The central authority should also act as a central location for collection, archiving and statistical treatment of data, and for providing necessary information services.

Meteorological data should be stored as far as possible in a manner such that the original records can be readily retrieved to meet any unforeseen future requirements.

3. Research network measurements

The principal conclusions of this preliminary investigation are as follows:

3.1 A programme of measurements for research related to solar energy applications is recommended in Table 2. This list includes measurements that are directly related to solar radiation monitoring for operations and technology research, as well as measurements required by atmospheric scientists in support of solar energy research in general.

3.2 Many of the parameters listed in Table 2 can be measured with current instruments. Other parameters require instruments which are not readily available from commercial sources. However, as an adjunct to any research programme every effort should be made to improve and refine the capabilities of instruments and/or measurement systems.

3.3 A research station should be located in each national macroscale climatically homogeneous zones. These zones can usually be specified by a climate classification such as Köppen or Thornthwaite.

3.4 Original data should be collected and stored in a readily accessible form (magnetic tape or disc). A data set stored in this manner can be analysed in great detail. The analyses should impact on such questions as sampling frequency, network spacing, sensor development, sensor intercomparison and calibration, model development, and quality control of data.

3.5 A small number of mobile units equipped with the same kind pyranometer and pyrheliometer as those used at routine stations should be put into operation. These mobile units should be used to supplement network data for the purpose of microclimate characterizations in urban areas, coastal zones and areas of highly variable topography. In addition, these units can be used for verification studies of the practical limits of spatial interpolation.

Table 2: Meteorological Observations for Research Purposes
(Adapted from Table A-10)

Parameter	Sampling frequency for mean values
1. Global solar radiation	6 to 60 /hr
2. Direct solar radiation	6 to 60 /hr
3. Diffuse solar radiation	6 to 60 /hr
4. Reflected solar radiation	6 to 60 /hr
5. Global solar radiation on arbitrary surfaces	6 to 60 /hr
6. Upward and downward terrestrial radiation	6 to 60 /hr
7. Ultraviolet radiation	6 to 60 /hr
8. Spectral solar radiation	6 to 60 /hr
9. Atmospheric turbidity	6 to 12 /hr
10. Angular distribution of sky radiation	6 to 12 /hr
11. Circumsolar radiation	6 to 12 /hr
12. Sunshine duration	120 /hr
13. Air temperature	6 to 60 /hr
14. Humidity or dew point	6 to 60 /hr
15. Wind vector	6 to 60 /hr
16. Atmospheric pressure	1 to 6 /hr
17. Cloud cover	1 to 6 /hr
18. Precipitation	1 to 6 /hr
19. Snow cover, snow depth	1 to 2 /hr
20. Dust fall	1 /day
21. Soil temperature	1 /day
22. Soil moisture	1 /day

APPENDIX A

A SURVEY OF REQUIREMENTS FOR METEOROLOGICAL MEASUREMENTS FOR SOLAR ENERGY APPLICATIONS

1. There are a large number of actual or potential users of radiation and other meteorological data including those in agriculture, horticulture, forestry, hydrology, meteorology, climatology, architecture, and heating and cooling engineering. In the area of heating and cooling technology, which offers potential applications for water and space heating, cooling, crop drying and water desalination, the collector system is usually a flat plate or simple concentrating system which is coupled to a storage tank. The solar radiation is converted to low temperature heat, usually below 100°C.

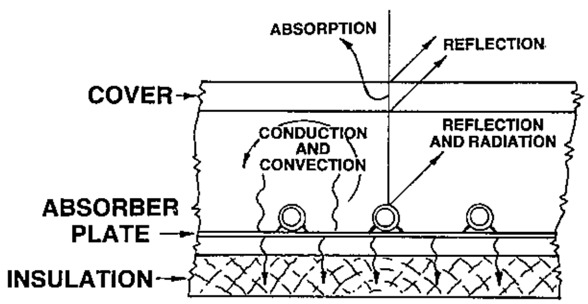


Figure (a) Flat plate

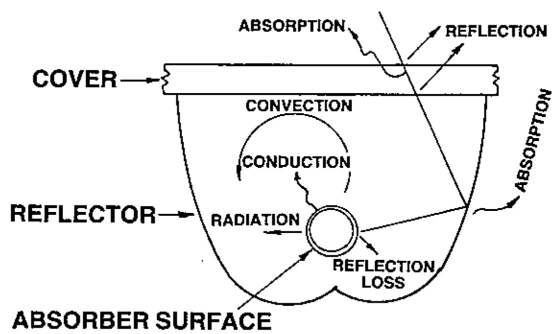


Figure (b) Concentrator

Figure A-1:
Showing the two Main Types of Solar Collector.

In Figure A-1 are schematics of typical solar collectors. Referring to Figure A-1 (a), the incident solar irradiance suffers losses by reflection at each of the cover surfaces and finally at the surface of the receiver.

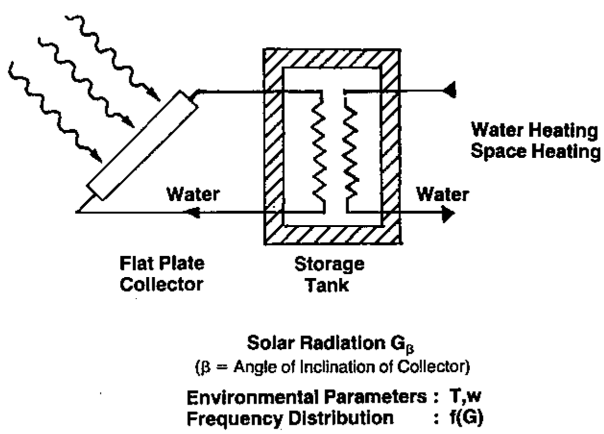
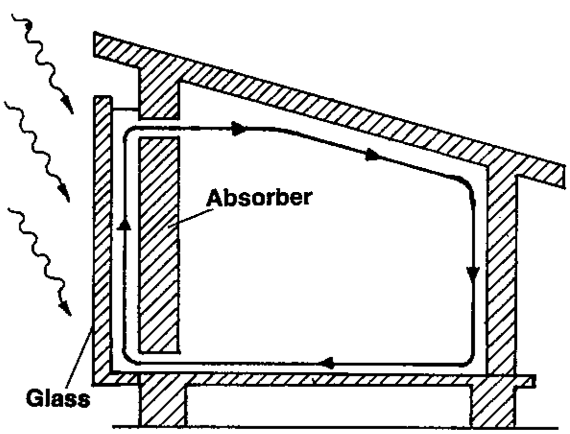


Figure A-2: *Flat Plate Collector System (Source: Bloss, 1978)*

The receiver absorbs the remaining radiation and is generally at a higher temperature than the local atmosphere. The collector loses heat by various processes (radiation, convection and conduction), but it turns out that in many cases the heat losses are proportional to the temperature difference between the receiver and the atmosphere. The energy collected also tends to be somewhat influenced by other environmental factors such as varying windspeed, proportions of direct and diffuse radiation, non-linear temperature dependence of losses, (e.g. by radiation) and others.

In order to design the heating system depicted in Figure A-2, detailed information on solar radiation G_β, on a surface inclined at angle β is required. In view of the temporal behaviour of the collector-storage system the frequency distribution f (G_β) of the collector irradiance must be known to the designer. The operating characteristics of this system depends also on the environmental parameters of temperature T and windspeed w. Since these values also exhibit variations with time, a cross correlation of G_β and T or w respectively is desirable (Swartman, 1967, 1971; Bloss, 1978).



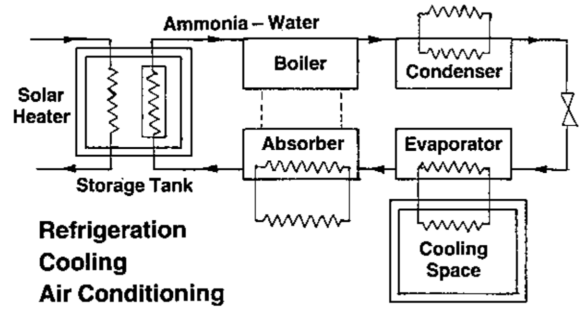
Trombe House Heating System

Solar Radiation $G_{90°}$
Upward Terrestrial Radiation L↑
Downward Atmospheric Radiation L↓
Environmental Parameters : T,w,h
Frequency Distribution : f(G), f(L)

Figure A-3: *Passive house heating system (source: Bloss, 1978)*

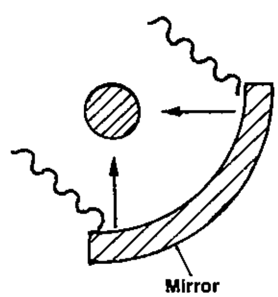
An example of a passive house heating system (Trombes house) is given in Figure A-3. Solar radiation is absorbed at a vertical wall which is usually south facing. Besides data on solar radiation G_{90}, information on long-wave terrestrial L↑, and atmospheric radiation L↓ must be available for evaluation of the performance of the system. This information must include the frequency distribution of radiation and of the environmental parameters, temperature, windspeed and humidity.

The radiation data required for designing a solar cooling sytem are listed in Figure A-4. In some cases concentrating systems are used to increase the temperature of the receiver. The designer of concentrating systems requires data on direct and diffuse radiation



Solar Radiation G_β
Upward Terrestrial Radiation L↑
Downward Atmospheric Radiation L↓
Environmental Parameters : T,w
Frequency Distribution : f(G), f(L)

Figure A-4: *Solar Cooling System (Source: Bloss, 1978)*



Linear Focus Collector
(Parabolic Trough)
Paraboloidal, Spherical
Collectors
Heliostats

Direct Solar Radiation	**I**
Diffuse Radiation	**D**
Frequency Distribution	**f (I,D)**

Figure A-5: *Concentrating System (Source: Bloss, 1978)*

Table A-1

Common Requirements for a Solar Radiation Data Network

Instrumentation	Accuracy			Frequency			Network	
	D	A	M	D	A	M	A	M
Pyranometer	1-2%	3%	5%	1 min.*	10 min.	1 hr.	300km	500km
Pyrheliometer	1%	–	2%	1 min.*	10 min.	1 hr.	500km	–

D – Desirable, better than this is not necessary
A – Acceptable, satisfies most applications
M – Mandatory, less than this is unsatisfactory
* – This may place too high a requirement for data storage, in which case on-line data compression should be used to give 10 min. and hourly sums.

(SOURCE: HAMILTON & THOMAS, 1976)

Table A-2

Relative Importance of Meteorological Measurement as a Function of Collector Type

Meteorological Measurement	Flat Plate	Low Concentration	Medium Concentration	High Concentration	Photo-voltaic
Sunshine	P	P	–	–	–
Cloud cover	P	P	–	–	–
Global radiation	P	–	–	–	P
Direct radiation	S	P	P	P	P
Diffuse radiation	S	S	–	–	–
Spectral distribution	S	S	–	–	P
Turbidity	S	P	P	P	P
Dry bulb temperature	S	P	P	P	P
Dew point temperature	S	–	–	–	–
Wind speed and direction	S	P	P	P	P
Precipitation	P	P	P	P	P

(P = primary measurement, S = secondary measurement)

(SOURCE: HAMILTON & THOMAS, 1976)

and their frequency distribution (Fig. A-5). Concentrating systems with high concentration factors and correspondingly high temperatures at the receiver are very sensitive to temporal variations. This means that the frequency distribution of direct radiation should take into account a temporal resolution of 1 minute of measurement.

2. The foregoing is a brief review of the meteorological data which the designer of heating and cooling systems will require. When we expand the requirement for data to satisfy other areas of application the list of parameters increases significantly. A number of surveys have been conducted where users were asked to indicate their preferences. The essentials of a report by Hamilton and Thomas (1976) on user preferences are given in Tables A-1, A-2 and A-3. Table A-1 gives the desirable, acceptable and mandatory requirements for pyranometer, and pyheliometer observations in terms of percentage error, frequency of observation and network spacing. A significant feature of these data is the mandatory requirement of 5 per cent accuracy, maximum integration time of 1 hour, and network spacing of 500 km, for pyranometer data. Table A-2

Table A-3

Measurement Requirements for Accuracy, Frequency, and Density of Geographical Coverage
Based on Collector Type and Data Use Category

		Collector Type			
Data Use	Data Requirements	Flat Plate	Low Concentration	Medium Concentration	Photovoltaic
Geographic environmental suitability	Accuracy	Low	Moderate	High	High
	Frequency	Monthly	Daily	Hourly	Hourly
	Coverage	Dense	Moderately dense	Limited	Limited
Engineering design	Accuracy	Moderate	Moderate	High	High
	Frequency	Daily	Daily	Hourly	Hourly
	Coverage	Moderately dense	Moderately dense	Limited	Limited
Performance evaluation	Accuracy	High	High	High	High
	Frequency	Hourly	Hourly	Continuous	Hourly
	Coverage	NA	NA	NA	NA
Short-term operational control	Accuracy	Moderate	High	High	High
	Frequency	Daily	Hourly	Continuous	Continuous
	Coverage	Dense	Site-specific	Site-specific	Site-specific
Scientific investigations	Accuracy		High		
	Frequency		Continuous		
	Coverage		Very limited		

(SOURCE: HAMILTON & THOMAS, 1976)

gives the relative importance of meteorological measurements as a function of solar collector type. Table A-3 summarizes in a relative and general manner the measurement requirements for accuracy, frequency and density of geographical coverage based on collector type and data use category.

A report prepared by Berdahl et al (1977) based on a questionnaire circulated in the state of California is summarized in Table A-4 and A-5. Table A-4 lists the data requested most strongly for each application category, while Table A-5 lists the data requested by each type of user.

The information in Table A-6 resulted from a survey (IEA, 1976) of user needs and data accuracy. Most users considered integrated solar radiation values over one hour as a minimum requirement, and, for special applications, 5 or 10 minute mean values as desirable. A questionnaire distributed among potential users in Switzerland showed primary interest for data in a form ready for application and in particular for single and combined frequency distributions, and information on persistence of the meteorological elements. As a consequence of developing design specifications for a portable meteorological instrument package, a minimum number of parameters required for heating and cooling applications were identified (Table A-7). The recommended data integration time was 10 minutes with other times optional.

A report of the WMO Solar Energy Meeting (1978) contains useful information on the meteorological aspects of solar energy problems. A table (reproduced here as Table A-8) prepared by the Organizing Committee gives the meteorological parameters related to the use of solar radiation as an energy source. Further in the report (Appendix H: Meteorological measurements for solar energy applications, by Michael R. Riches) two very useful tables are included. The first (Table A-9) gives the solar radiation parameters for a general network while the second (Table A-10) lists the solar radiation parameters for research purposes.

3. The potential user of meteorological data seeks information in order to reach a decision. The chain from data to decision is not always easily identifiable and making the wrong decision may be more harmful than useful. It is the final decision which governs the data collection requirements and many of the intermediate steps. It is the responsibility of the planner to

Table A-4

Data requested by application category. A plus sign signifies that a data item is requested by a significant number of individuals from the respective application category (A) through (E). The items in this table are listed in order of decreasing desirability, based on the number of requests from the various application categories.

(A) Heating and Cooling applications
(B) Agricultural applications
(C) Solar electric applications
(D) Photovoltaic conversion
(E) Biomass conversion

Data Item	Application Type (A)	(B)	(C)	(D)	(E)
Global radiation	+	+	+	+	+
Min./max. temperature	+	+	+	+	+
Daily temperature profiles	+	+	+	+	+
Daytime cloud cover	+	+	+	+	+
Daytime wind speed	+	+	+	+	+
Dry bulb temp. (24 hr. avg.)	+	+	+	0	+
Heating degree days	+	0	+	+	+
Cooling degree days	+	0	+	+	+
Nighttime wind speed	+	+	+	0	+
Direct radiation	0	+	+	+	0
Nighttime sky temperature	+	+	0	0	+
Sun charts	0	0	0	+	+
Freeze probability	+	0	0	0	+
Ground temperature	0	+	0	0	+
Sunshine hours	0	0	0	+	+
Wind direction distribution	+	+	0	0	0
Diffuse radiation	+	0	+	0	0
Rainfall	0	0	0	0	+
Total solar radiation, vertical surface	0	0	0	+	0
Nighttime cloud cover	0	0	0	0	+
Daytime wet bulb temp.	0	0	+	0	0
Nighttime wet bulb temp.	0	0	+	0	0

(SOURCE: BERDAHL et al, 1977)

Table A-5

Data requested by user category. A plus sign signifies that a data item is requested by a significant number of individuals from the respective user category (a) through (i). The items in this table are listed in order of decreasing desirability, based on the number of requests from the various user categories.

(a) agricultural engineer
(b) architect
(c) builder
(d) consultant
(e) developer
(f) engineer
(g) equipment manufacturer
(h) owner
(i) planner

Data Item	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Global radiation	+	+	+	+	+	+	+	+	+
Heating degree days	+	+	+	+	+	+	+	+	+
Daytime wind speed	+	+	+	+	+	+	+	+	+
Nighttime wind speed	+	+	+	+	+	+	+	+	+
Min./max. temperature	+	+	+	+	+	+	0	+	+
Daily temperature profiles	+	+	+	0	+	+	+	+	+
Cooling degree days	+	+	+	+	+	+	+	0	+
Daytime cloud cover	0	+	+	+	+	+	+	+	+
Dry bulb temp. (24 hr. avg.)	+	+	0	+	0	+	0	0	+
Direct radiation	+	0	0	0	0	+	+	0	+
Sunshine hours	+	0	+	0	+	+	0	0	0
Freeze probability	0	0	+	0	+	0	0	+	+
Sun charts	0	0	+	0	+	0	0	0	+
Wind direction	+	0	+	0	0	0	0	+	0
Diffuse radiation	+	0	0	0	0	0	+	0	0
Dry bulb temp. (daytime)	0	+	+	0	0	0	0	0	0
Wet bulb temp. (daytime)	0	0	+	0	0	0	0	0	+
Nighttime sky temperature	+	0	0	0	0	0	0	0	+
Ground temperature	+	0	0	0	0	0	0	+	0
Nighttime cloud cover	0	0	+	0	0	0	0	+	0
Rainfall	+	0	+	0	0	0	0	0	0
Total solar radiation, vertical surface	0	0	0	0	+	0	0	0	0
Dry bulb temp. (nighttime)	0	+	0	0	0	0	0	0	0
Wet bulb temp. (24 hr. avg.)	0	0	0	0	0	0	0	0	+
Wet bulb temp. (nighttime)	0	0	0	0	0	0	0	0	+
Daytime sky temperature	0	0	0	0	0	0	0	0	+
Absolute humidity profiles	+	0	0	0	0	0	0	0	0
Relative humidity profiles	+	0	0	0	0	0	0	0	0

(SOURCE: BERDAHL et al, 1977)

identify the most economical and efficient means of securing the information in the time available.

In many cases, users of meteorological data require that the information be representative of long-term conditions and that the data be applicable to specific surface conditions. Most currently published data fail to meet both these requirements. There is an unfortunate lack of radiation data for inclined surfaces. The sources of radiation data available to the user are based primarily on observing networks operated by National Meteorological Services. Such networks primarily measure what is termed global solar radiation (total diffuse and direct) on a horizontal surface. An alternative to the direct measurement of radiation for inclined sur-

Table A-6

User Meteorological Data Needs and Desired Accuracy

M = mandatory data
O = optional data
X = needed data (mandatory or optional)

Parameter	Japan	Germany	Belgium	Denmark	Sweden
Direct radiation	X	±2-5%	±1-5%	M	X
Diffuse radiation	X		±1-5%	M	X
Global radiation	X	±2-5%	±1-5%	M	X
Spectral direct radiation	X	±2-5%	±1-5%		X
Spectral diffuse radiation			±1-5%		
Spectral global radiation	X	±2-5%	±1-5%		X
Direct radiation on an inclined surface			±1-5%		X
Diffuse radiation on an inclined surface			±1-5%		X
Global radiation on an inclined surface		±2-5%	±1-5%		X
Net radiation, long was flux	X	±5%		M	X
Duration of bright sunshine	X			M	X
Turbidity, air pollution	X	±5%			X
Precipitation	X			O	
Wind velocity	X	±0.3m/s	±5%	M	X
Wind direction	X	10°	X	M	X
Air temperature	X	0.5°-1°	X	M	X
Air humidity	X	±5%	±10%	M	X
Atm pressure				O	X
Cloudiness	X			M	X
Weather	X			M	X
Snow cover and depth				O	

(SOURCE: IEA, 1976)

faces is to calculate the required values given the irradiance on a horizontal surface. In this way the long-term data for horizontal surfaces may provide a knowledge of the *average* radiant input for inclined surfaces (Kondratyev et al, 1978; Hay, 1977).

In the absence of radiation measurements, methods exist for estimating solar radiation using other meteorological parameters. A review of the relevant literature has been prepared by Dogniaux (1977).

Table A-7

Portable Meteorological Instrument Package

Parameter	Accuracy	Tolerance
Direct Radiation (normal incidence)	±25 w/m^2 or ±5% (whichever is largest)	2%
Global Radiation (direct plus diffuse)	±25 w/m^2 or ±5% (whichever is largest)	2%
Solar on Inclined Surface	±25 w/m^2 or ±5% (whichever is largest)	2%
Incoming IR	±10% or ±25 w/m^2	2%
AirTemperature	±1.0°C	±0.5°C
Wind Speed	±1m/sec or ±5% (whichever is largest)	±0.5m/sec
Wind Direction	±10°	±5°

(SOURCE: IEA, 1977)

Table A-8

Meteorological Parameters* related to the use of Solar Energy

			(1)**	(2)**	(3)**	(4)**	(5)**	(6)**	(7)**	(8)**	(9)**
A. Heating and cooling domestic water heaters, dryers, stills, etc.	Non-concentrating devices		X	(X)	X	X	X	(T),N,SS	hourly	X	
	Focusing devices			X	X	X	(X)	T,N,SS	¼ hour		
B. Power generators	Ocean thermal power plants										
	Thermodynamic conversion	(Non-concentrating devices)	X		X	X	X	(T),N,SS	hourly	X	
		Focusing devices		X	X	X	X	T,N,SS	¼ hour		
	Photovoltaic conversion	(Non-concentrating devices)	X (spectr)		(X)	(X)	(X)	T,N,SS	hourly	(X)	
		Focusing devices		X	X	X	(X)	T,N,SS	¼ hour		
C. Photosynthesis	C.1. ground		X (spectr)		X	X	X	N,SS			X
	C.2. water		X (spectr)					N,SS			
D. Photochemistry, biology					?						

Notes: *Symbol "(X)" indicates that the meteorological parameter in question may be useful for the purpose.

** (1) Global and diffuse radiation
(2) Direct radiation
(3) Air temperature
(4) Wind speed
(5) Air humidity
(6) Turbidity T
Cloud amount N
(7) Frequency distribution
(8) Terrestrial radiation
(9) Precipitation

(SOURCE: WMO, 1978)

Table A-9

Solar Radiation Parameters for a General Network

Parameter	Priority	Frequency	Accuracy
GLOBAL RADIATION	1	hourly integrals (1)	±25 w/m^2 or ±5% whichever is largest
SUNSHINE DURATION	1	hourly	10% of an hour
DIRECT **OR** DIFFUSE RADIATION (2)	2	hourly integrals (1)	±25 w/m^2 or ±5% whichever is largest
GLOBAL RADIATION INCLINED SURFACE (3) This may be omitted in tropics. The foreground should have a known uniform neutral albedo. A grid of black slats may be used for this purpose.	3	hourly integrals (1)	±25 w/m^2 or ±5% whichever is largest

Priority

1 required
2 recommended
3 desired

(1) If digital recording equipment is used, 10 minute (or less integrals should be collected for quality control and engineering analyses; if strip chart recorders are used, the chart recorder speed and chart width should be such that 10 minute integrals can be computed to desired accuracy. (Electrically sensitive paper or other suitable chart recorder system should be used so that the 10 minute integrals can be obtained by automatic chart reading devices). The time reference desired is that the solar radiation integrals match the meteorological data, i.e. local standard time. However, if true solar time is used the meteorological data must be interpolated to this base. It is recommended that the meteorological service provide the interpolations rather than have the engineer make his own. If 10 minute integrals (or less) are used this problem essentially disappears.

(2) For the comparability of direct solar radiation data the receivers used should have identical apertures defined as the whole angle subtended at the centre of the receiver by the limiting diaphragms. Presently the common apertures on standard receivers used for continuous records are 5.7° and 10.2°. Future applications involve the possibility of designing special apertures to meet the requirements of standard types of solar energy concentrators.

(3) Station Latitude or Latitude + 15° for heating season and -15° for cooling season.

(SOURCE: RICHES, 1978)

Table A-10

Solar Radiation Parameters For Research Purposes

Parameter	Priority	User	Frequency	Application
Global Radiation	(1)	1, 2, 3	1 minute integrals	non-concentrating devices, model development, climatology
Sunshine Duration	(1)	1, 2, 3	% per hour	
Direct Radiation	(1)	1, 2, 3	1 minute integrals	concentrating devices
Diffuse Radiation	(1)	1, 2, 3	1 minute integrals	
Global Radiation on Arbitary Surfaces*	(1)	1, 2, 3	1 minute integrals	device design, building design
Albedo	(1)	3, 2, 1	1 minute integrals	model development
Infrared (I R) Down	(1)	1, 2, 3	1 minute integrals	device design, cooling to night sky
Infrared (I R) Up	(1)	1, 2, 3	1 minute integrals	
Ultraviolet (UV)	(1)	1, 2, 3	1 minute integrals	material degradation
Spectral (direct, diffuse, albedo)	(2) (1 for PV)	1, 2, 3	1 minute integrals	photovoltaic designs, photochemical processes photosynthesis
Turbidity	(1)	3, 2, 1	1 minute integrals	model development, climatology
Tracking Pyranometer	(2)	2, 3, 1	1 minute integrals	mildly concentrating device design
Solar Cell Device (horizontal, direct tilted)	–	1	1 minute integrals	to determine utility
Angular Distribution of Diffuse Radiation	(3)	2, 3, 1	1 minute integrals	model development, system design
Circumsolar Radiation	(3)	2, 3, 1	1 minute integrals	highly concentrating system design, model development.

Table 10 (continued)

Air Temperature	(1)	1, 2, 3	1 minute integrals	climatology, device design
Dew Point	(1)	1, 2, 3	" "	
Wind Speed	(1)	1, 2, 3	" "	
Wind Direction	(1)	1, 2, 3	" "	
Atmospheric Pressure	(1)	3, 2, 1	hourly	
Cloud Cover **	(1)	3, 2, 1	hourly 10 minute during special studies	model development
Weather	(1)	3, 2	as appropriate	climatology, model development
Precipitation	(1)	3, 2, 1	10 minute samples	
Snow Cover	(1)	3, 2, 1	as appropriate	
Snow Depth	(1)	3, 2, 1	as appropriate	
Precipitable Water	(1)	3	hourly	
Dust Fall	(2)	2, 3	daily	special applications
Soil Temperature	(2)	2, 3	daily mean value	biomass production
Soil Humidity	(2)	2, 3	daily mean value	biomass production

Priority:

1. Necessary
2. Recommended
3. Desired

User:

1. Designer
2. Solar researcher
3. Atmospheric scientist

Assumptions:

- Accuracy is state of the art

* To include sensors tilted at latitude facing South (or North) with neutral albedo, latitude ±15°, and vertical south, north, east and west.

** Recommend an all sky camera or television camera (can be digitized directly) be used to monitor clouds as well as observer reports.

(SOURCE: RICHES, 1978)

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APPENDIX B

RADIATION NETWORK ASSESSMENT

1. Meteorological data are used increasingly for a wide variety of practical problems and much of the data must be supplied, either directly or indirectly, from networks of observing stations. The increased use of the data and its significance to such problems as the design of solar energy systems warrants special attention to sampling, spatial, and temporal aspects of the data and to the adequacy of existing networks. Unfortunately, such questions have received little attention in the past, so only a limited amount of experience is available on which to draw upon.

Meteorological measurements are samples of local ambient conditions. The primary errors involved are sampling errors (errors inherent in the instrument and measurement), spatial errors (errors in interpolating between stations), and temporal errors (errors in sampling times due to variability of the parameter with time). The goal is to minimize these errors. The meteorological approach to data sampling is first to determine the amount of acceptable and reasonable error. In this regard it is necessary to assess both the error levels of the parameters and the economic losses caused by insufficient knowledge of meteorological conditions. It is then possible to seek an optimum network design to give maximum benefit (minimum costs and losses).

Measurement errors are minimized by improving instrument quality, and by strict attention to maintenance and calibration requirements. However, this should be accomplished with cost effectiveness in mind. Sampling times must meet the needs, but must not be overestimated. Hourly, daily, monthly and annual data are the usual time intervals requested by the user. The researcher may request data as frequently as 1 minute. A continuous analog record or a record at 1 minute intervals has been found to be very useful for quality control of data. It is a common practice to request the best resolution possible, although in many cases such requests are not justified.

2. The problem of spatial coherence of network data is one that has been studied by Gandin (1970). The formulation is based on an isotropic homogeneous field structure of a meteorological element.* A quantity, ϵ, called the optimum interpolation error, is defined for 3 cases:

(a) for the center of an equilateral triangle formed by three stations

$$\epsilon = 1 - \frac{3\mu^2 (\rho/3^{\frac{1}{2}})}{1+\eta+2\mu\rho}$$

(b) for the midpoint of a line segment between two stations

$$\epsilon = 1 - \frac{2\mu^2 (\rho/2)}{1+\eta+\mu\rho}$$

(c) for the center of a square of 4 stations (square grid station network)

$$\epsilon = 1 - \frac{4\mu^2 (\rho/2^{\frac{1}{2}})}{1+\eta+2\mu\rho+\mu(\rho/2^{\frac{1}{2}})}$$

where ρ = station-to-station distance

μ = the correlation coefficient (the auto correlation function)

and $\eta = \frac{\sigma^2}{D}$, the measure of observational error (the square error to the variance of the interpolated magnitudes)

*The supposition of an isotropic, homogeneous field structure of the meteorological element is very often not valid.

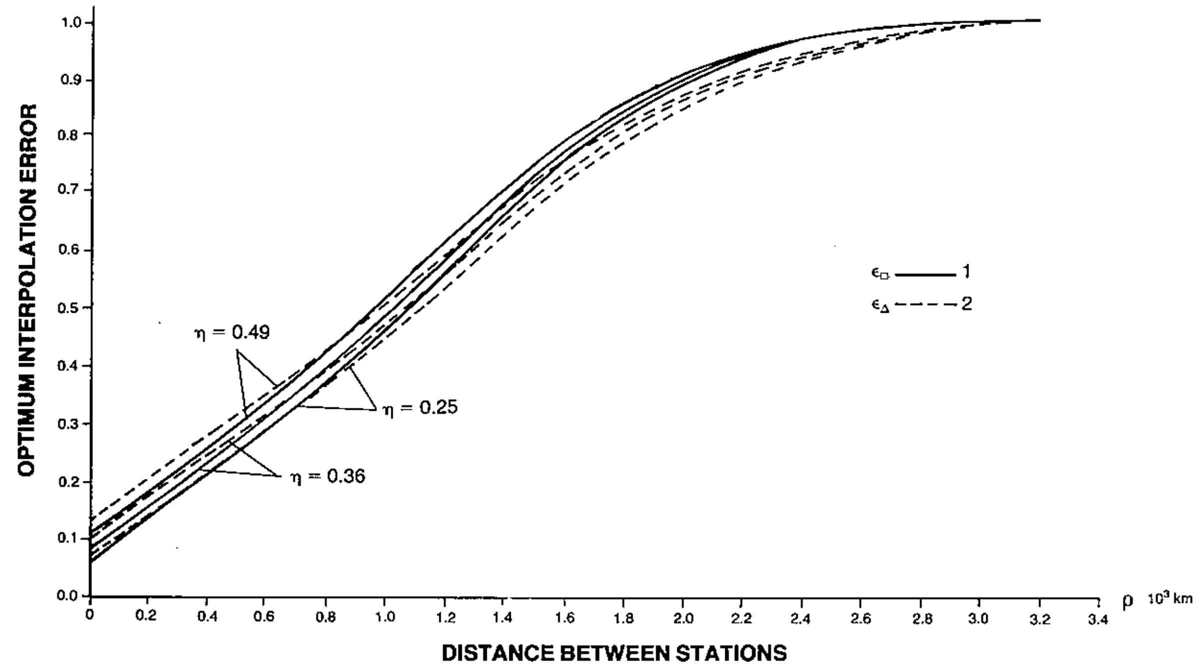

Figure B-1:

The relationship of measure of optimum interpolation error in the center of square, $\epsilon_\square$ and of triangle, ϵ_Δ, to ρ for different values of the measure of observation error η. Stations are supposed to be situated at the apices of the indicated squares and triangles. (from Gandin).

For a network of ground stations the statistical structure of ground-level fields is controlled by physical and geographical conditions. Two locations on the Earth's surface receive differing amounts of solar radiation because of differences in latitude, altitude, atmospheric properties, and orientation and slope of the receiving surface.

The suitable location of a new station depends on the peculiarities of the terrain and on the need for operational servicing. For these reasons, it is preferable only to indicate admissible distances between stations and not to calculate the optimum location of new stations. Figure B-1, taken from Gandin, gives the relationship of the measure of optimum interpolation error in the center of a square and of a triangle to the distance between stations for different values of observation error. Figure B-2, taken from Pivovarova (1978), gives the auto correlation function for monthly and daily totals of global radiation in the Soviet Union in summer.

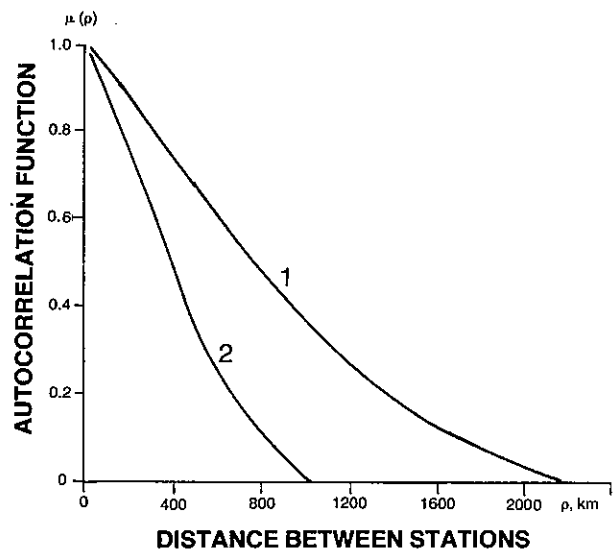

Figure B-2:

Correlation function of global solar radiation totals for summer months
Curve 1 – monthly totals
Curve 2 – daily totals
(Pivovarova, 1978).

3. Wilson and Petzold (1972) investigated the spatial variability of measured global solar radiation for selected stations in southern Canada for the summers 1967 to 1971. Suckling and Hay (1976) have investigated the spatial variability of daily values of global solar radiation for British Columbia and Alberta, Canada. Figure B-3 indicates that there is a strong relationship between the correlation of measured solar radiation for station pairs and distance between stations. Figure B-4 shows the relationship for a number of studies (Wilson and Petzold, 1972; Wilson and Petzold, 1976; Hay and Suckling, 1977) between the coefficient of variability (standard deviation/mean solar radiation) and distance between stations. Suckling and Hay (1976) found average errors of up to ±5 MJ m^{-2} day^{-1} and at least ±3.5 MJ m^{-2} day^{-1} can be expected when observed solar radiation data are extrapolated for distances of 600 to 250 km, respectively. The results of

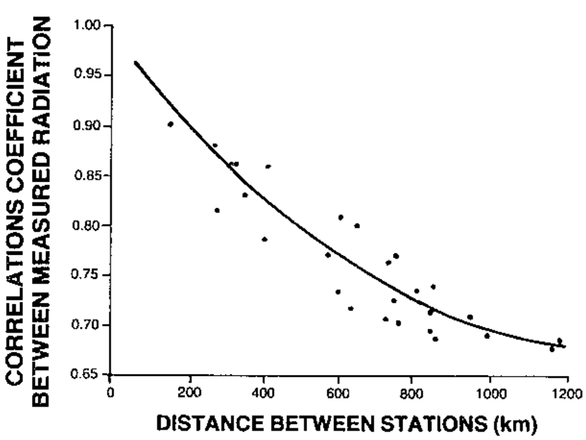

Figure B-3:

Variation of correlation coefficient for daily solar radiation between stations with distance between station pairings. (Suckling and Hay, 1976).

these analyses show that there is a marked tendency for displacement of the error-distance relationship depending on the mean incoming solar radiation (Figure 4). Hay and Suckling (1977) also found that synoptic conditions influenced the rationship considerably such that relative errors were smaller than average under anticyclonic conditions and larger under cyclonic conditions. Thus, relationships such as those in Figure B-4 can be expected to change not only within a region, but also from region to region depending on the differences in synoptic climatology.

The Hay and Suckling (1977) relationship suggests that extrapolation should not exceed 60 km in order to maintain the error within ±15 per cent. It is possible to improve the extrapolation distance by using averaged or accumulated radiation totals for periods of more than one day. The results of varying the data accumulation period from one to fifteen days for the Hay and Suckling (1977) data are shown in Figure B-5. An instrumental accuracy of 7.1 per cent has been indicated, this latter being the expected error in a measurement of the difference between two sites if each measurement has an error of ±5 per cent. It can be noted that the ±15 per cent coefficient of variability at a distance of 60 km for a single day can be expected to be maintained to a distance of 180 km if data are accumulated for a 3-day period, and a distance of 500 km for a 7-day accumulation, assuming, of course, that the radiation regime remains homogeneous for that distance. Figure B-6 illustrates the effect of multiplying the values of Figure B-5 by a value of 1.64 to achieve a 90 per cent confidence level in the data. This has the effect of reducing the possible extrapolation distance but increases the probability that the extrapolation error will actually be within the stated value. For example, it would be expected that 90 per cent of extrapolation errors would fall within ±15 per cent at a distance of about 70 km when using 3-day accumulated data, compared to 180 km at the 67 per cent level.

4. Accuracy of solar radiation data and the density of a network of solar radiation stations has been studied by Pivovarova (1978). Estimates were derived based on a study of spatial-temporal variability of the radiation balance components using a technique developed by Drozdov and Sepelevskij (1946). Table B-1 gives the rms errors of solar radiation totals. For daily totals of global radiation throughout a year, or direct, diffuse or radiation balance during the summer, the error is 10 to 15 per cent. The error becomes large in winter and can achieve 30 to 50 per cent. In terms of the standard deviation the rms error comprises 0.25 to 0.35. The error in the mean daily total averaged over a month is considerably less, being 3 to 5 per cent during the summer season and 10 to 20 per cent during winter.

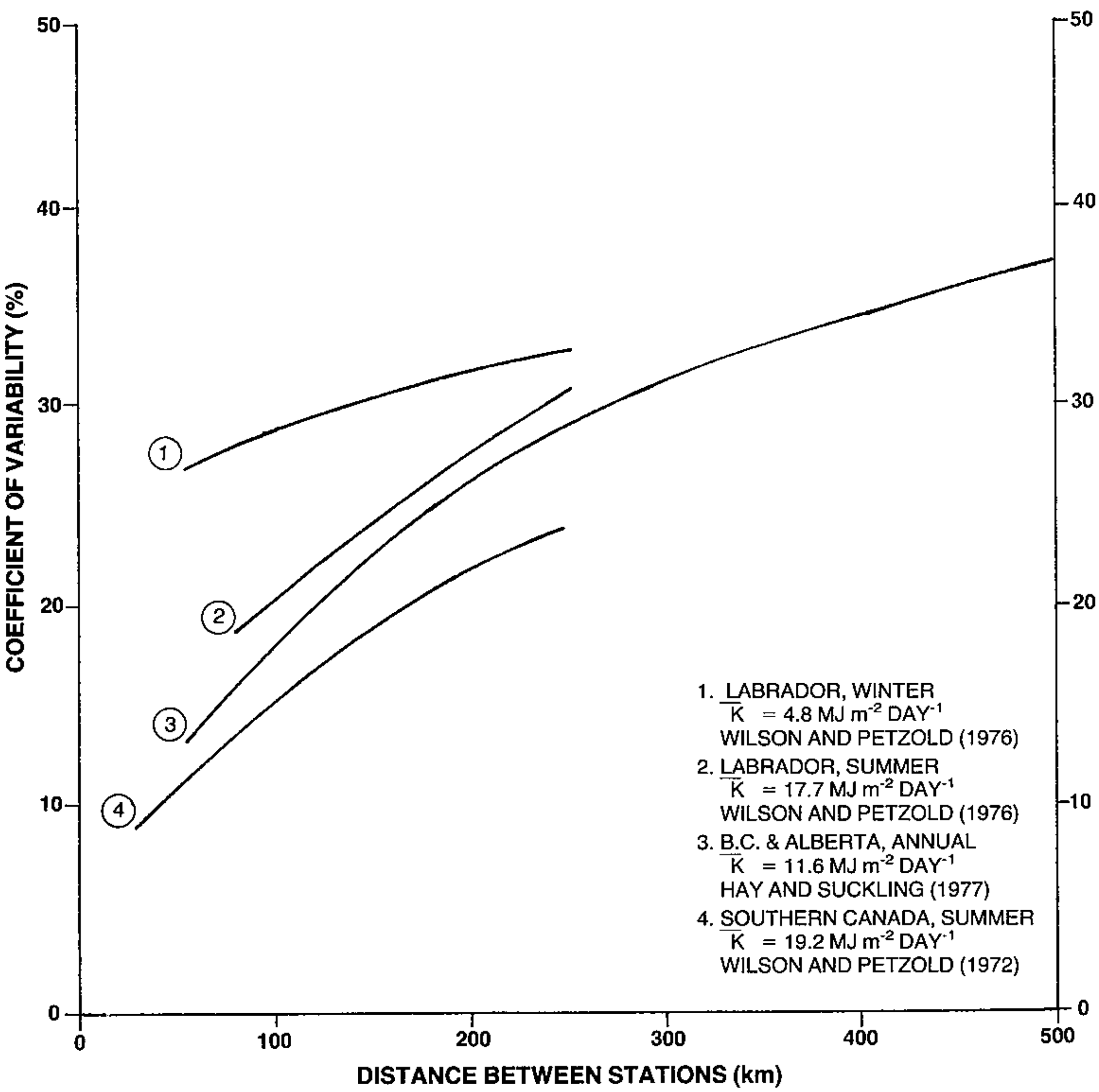

Figure B-4:

Various relationships between station separation and the coefficient of variability for daily differences in total incoming solar radiation. (Wilson, 1978).

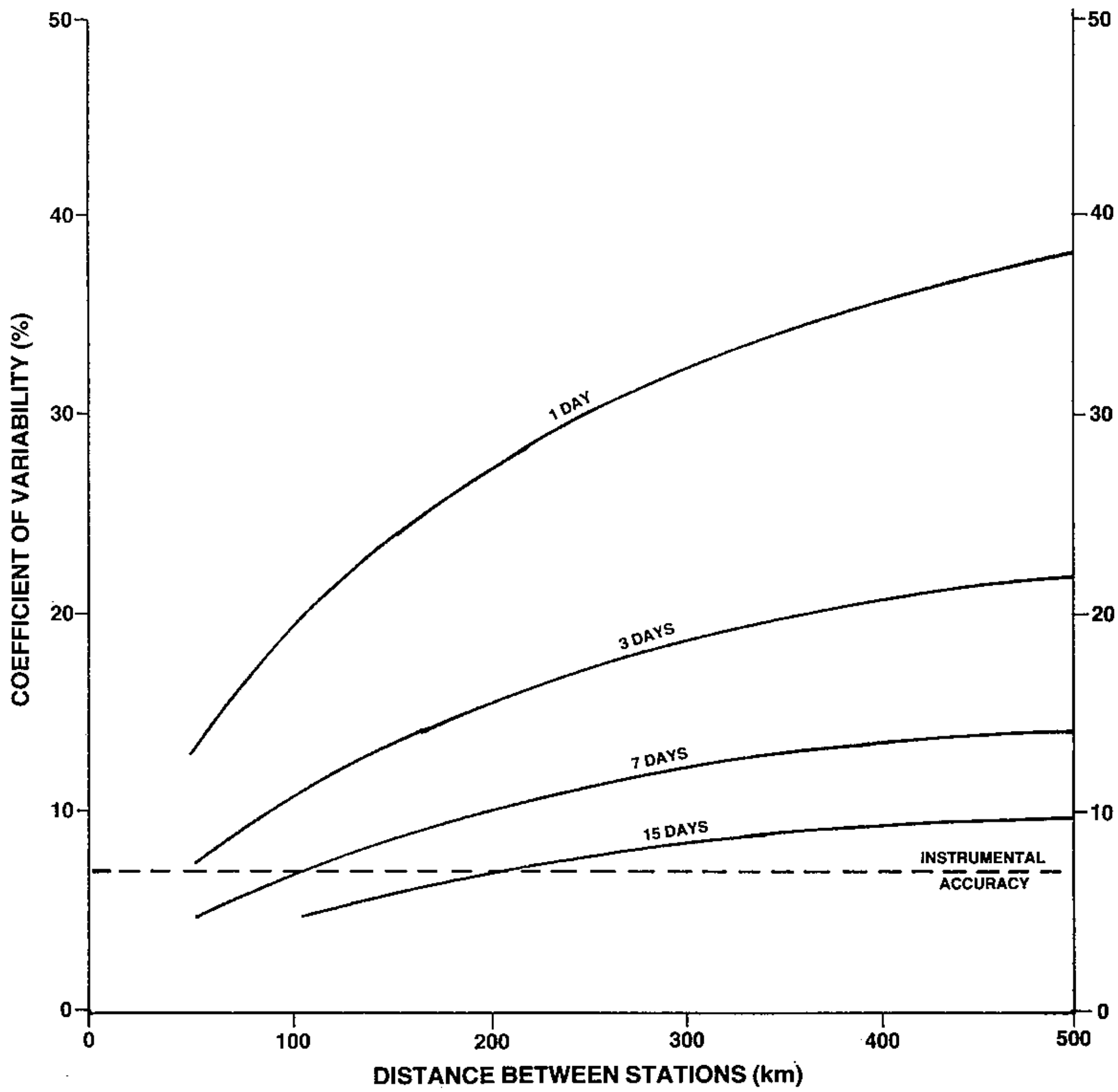

Figure B-5:

Estimated Effect of Accumulation Period on Co-efficient of Variability at 67% Confidence Level, Assuming a Normal Distribution of Daily Differences Between Stations Located in a Uniform Solar Radiation Climate. (After Hay and Suckling, 1977).

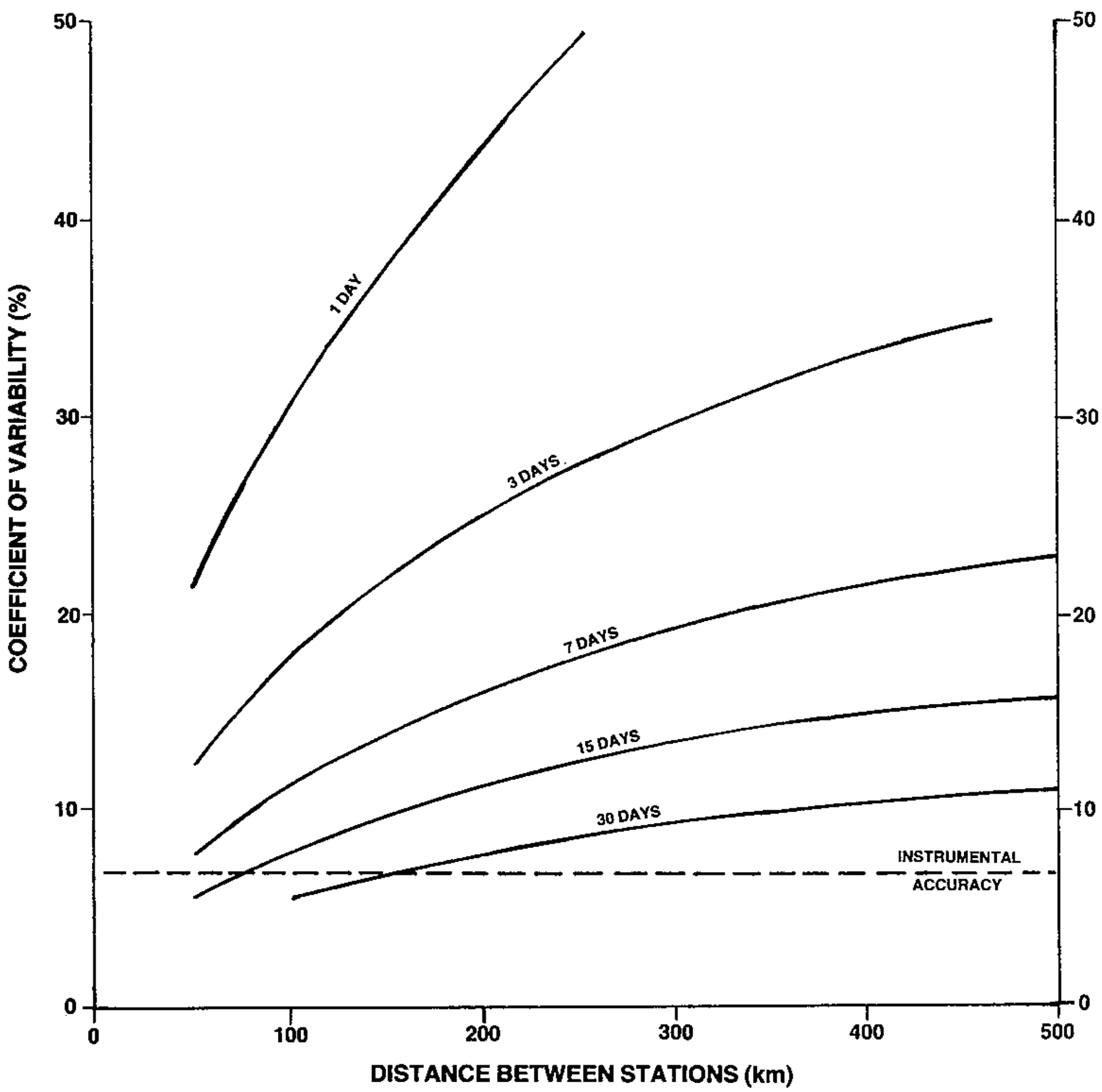

Figure B-6:

Estimated Effect of Accumulation Period on Co-efficient of Variability at 90% Confidence Level, Assuming a Normal Distribution of Daily Differences Between Stations Located in a Uniform Solar Radiation Climate.
(After Hay and Suckling, 1977).

Table B-1

Rms errors of daily, monthly and annual totals of solar radiation obtained from network stations in the USSR on even terrain, in per cent.

Component	Jan.	Apr.	July	Oct.	Year
	Monthly and annual totals				
Direct radiation	12	5	5		3
Diffuse radiation	6	4	3		2
Global radiation	8	4	3	5	1.5-2
Radiation balance	20-30	7	5	15	3-4
	Daily totals				
Direct radiation	40	20	15	30	
Diffuse radiation	20	11	9	11	
Global radiation	15	9	8	12	
Radiation balance	50	17	10	35	

(SOURCE: PIVOVAROVA, 1978)

Table B-2 gives the rms errors of linear interpolation between anomalies of daily radiation totals for distances of 100, 200, and 400 km, respectively. These results refer to even terrain in the USSR European Territory. Accordingly, an estimate of the maximum permissable distances between solar radiation stations, measuring monthly totals (or daily totals averaged over a month) of global radiation for a square grid station net in planning the world solar radiation network is 500 km (WMO, 1970).

5. In considering a basic strategy for radiation networks, it is clear that at least two types of networks must be identified, differentiated on the basis of purpose and probably responsibility as well. Firstly, there must be a basic network which provides data for all regions with significantly different radiation climates. These data must be suitable for a variety of uses but its basic purpose should be to define the radiation climate of the region. Secondly, there will be requirements for additional measurements of smaller networks to satisfy special needs where the data from the basic network are not adequate. Essentially, this second category would be necessary if data are required within a region where there are significant variations in the solar irradiance and/or in the character and aspect of the radiation surfaces between stations of the basic network, or where the required time frame in the data is shorter than that which could be achieved by extrapolation from the existing network. Except for the last case, it is probable that some type of modeling will be required to augment the measured data.

In designing a basic network two questions must be asked:

(1) Do the existing stations provide adequate regional coverage, allowing for the effects of latitude, regional climatic differences, and basic elevation effects?

(2) If so, will there be basic requirements for data within the major climatic zones which require further measurements?

Table B-2

Rms errors of linear interpolation between anomalies of daily radiation totals (megajoules m^{-2} day^{-1}) and the mean distance between stations.

Component	Distance in km: January 100	January 200	January 400	July 100	July 200	July 400
	(Daily totals, individual values)					
Diffuse radiation				1.2	1.3	1.8
Global radiation	0.3	0.5	0.7	2.2	2.7	3.1
Radiation balance	0.6	0.8	0.8	1.4	1.8	2.2
	(Daily totals averaged over a month)					
Direct radiation	0.1	0.1	0.2	0.8	0.9	1.0
Diffuse radiation	0.2	0.2	0.2	0.3	0.3	0.5
Global radiation	0.2	0.2	0.2	0.8	0.9	1.0

(SOURCE: PIVOVAROVA, 1978)

The first question is probably the easiest to answer and incorporate into a network design. In planning the location of new stations, any existing radiation data can be taken into account and then surrogate data can be used, including small-scale maps of radiation, sunshine duration data, cloud and precipitation data. The second question is more difficult because judgments must be made as to how closely the radiation climate should be differentiated in a basic network. Because climatological data must be accumulated for a number of years to be meaningful, and because of typical uses of radiation data, extrapolation of data from a basic network of solar radiation stations should be able to satisfy an error level of $\pm 15\%$ at a 90% probability level with an accumulation or averaging period not exceeding 7 days. This would mean extrapolation for a distance of about 170 km (Figure B-6), and a station separation of about 340 km in regions with similar radiation climates. This distance compares with a value of 200 km recommended by Gandin (1970) for separation of stations measuring sunshine duration. It would also provide estimates with an error level within $\pm 10\%$ for bi-monthly intervals. Networks for other radiation parameters may not need to be as dense since they may be produced from global solar radiation values. In this regard it is also important to locate as many as possible of the actual stations for global solar radiation and other parameters at existing stations where adequate meteorological data are collected for modeling purposes, so that models can be tested and developed for application at other locations.

The strategy outlined above would mean that the second category of networks would serve the purpose of determining the larger-scale variations between and within the regions, and special measurements also would be required if the time period required was less than a week.

6. Gandin (1970) has formulated a general scheme for a network of climatological stations. The network is, first of all, divided into a basic network (long-term sites, 30 years or more) and special stations (short-term, a few years). Stations belonging to the basic network are divided into three groups (corresponding roughly to a classification adopted by WMO). The first group of stations carry out observations of atmospheric phenomena, visibility, cloud amount, precipitation, snow cover, air and soil temperature, humidity of the air, wind, pressure and sunshine duration. The rational distance between stations of this group is, on average, 150 to 200 km and should be specifically adapted to the physical and geographical conditions of the region. It is also suggested that approximately every fourth or fifth station of this group should be a reference station (300 to 400 km apart). Reference stations serve essentially two purposes: the study of long-term climatic changes and the correcting of data series from other stations. Aerological stations and stations where geophysical observations are carried out (including measurements of radiation, heat balance, ozone, atmospheric electricity etc.) fall within this first group.

The volume of observations is reduced for a second group of stations separated on the average about 50 to 60 km. Synoptic stations presumably fall within the first and second group. The third group are stations where precipitation observations (snow, rain) are mainly carried out and on average are spaced 25 to 30 km in flat country and more often in mountainous areas.

Other schemes have been advanced. For example, Riches (1978) proposed dividing the user community into two basic groups, the researcher, and the designer. The data requirements of the designer (individuals working to plan, design and operate solar energy systems) would be fulfilled by augmenting the normal national programme of meteorological observations by an appropriate selection of solar radiation parameters. The recommended network density is that station to station spatial correlation of data be at least 0.7 (0.9 should be easily attainable over homogeneous areas) for mean monthly values of daily totals of global solar radiation for any given month. Except in regions with strong gradients (such as coastal and mountainous regions) stations would be located on a square grid approximately 500 km in separation. Short-term mobile stations would be used to better define data requirements.

The researcher would have his requirements satisfied by a number of special stations measuring a large number of parameters. These experimental research and development stations should provide the data sets necessary to solve future potential problems, or present needs not satisfied by existing stations. The spatial density of the research network should be sufficient to have one station in each major climatic zone as specified by a broad climatic classification system (e.g. Köppen).

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APPENDIX C

RADIATION MEASUREMENT

1. The generally recognized authority on meteorological measurement is the World Meteorological Organization: *Guide to Meteorological Instruments and Observing Practices*. The Guide covers the nature and exposure of meteorological instruments and accuracy requirements for the measurements. Table C-1 gives a summary of accuracy requirements for surface measurements (DOE, 1978), while Table C-2 gives the classification and accuracy of radiometers (WMO, 1971). A number of very useful reference sources for those pursuing the art and science of radiation measurement require special mention:

(a) IGY Instruction Manual: *Radiation Instruments and Measurements*. Part VI, Pergamon Press, 1958.

(b) Robinson, N.: *Solar Radiation,* Elsevier Publishing Company, 1966.

(c) Kondratyev, K.Ya.: *Radiation in the Atmosphere* Academic Press, 1969.

(d) Drummond, A.J.: *Precision Radiometry*. Advances in Geophysics, Vol. 14, Academic Press, 1970.

(e) Coulson, K.L.: *Solar and Terrestrial Radiation: Methods and Measurements*. Academic Press, 1975.

2. Chapter IX of the WMO Guide gives the system of radiation quantities, their definitions and symbols, and the instruments employed for measurements. More recently a system of units and symbols (which has not at this time been accepted by atmospheric scientists) has been published by Beckman et al (1978). A much improved system has been devised by Perrin de Brichambaut in collaboration with Page and Kasten which is included in a new WMO Technical Note (see section 6). The system of units known as Système International d'Unités, abbreviated SI, is now generally preferred. It is an extension and refinement of the traditional metric system. The unit of energy (including heat) is the joule and the unit of power is the watt. The various different calories or the Langley (1 cal cm^{-2}), are therefore not used.

The preferred SI unit for radiative flux per unit area is the watt per square metre (W m^{-2}), and for quantity of radiation per unit area, the joule per square metre (J m^{-2}). Convenient fractions and multiples of these preferred units are also allowed. However, use of the centimetre (cm) is discouraged.

For meteorological usage WMO prefers milliwatt per square centimetre (mW cm^{-2}) for radiative flux per unit area, and for radiation amount per unit area, either joule per square centimetre (J cm^{-2}) or milliwatt-hour per square centimetre (mWh cm^{-2}). The SI units that adhere closest to WMO preference are the watt per square metre (W m^{-2}) and the watt-hour per square metre (Wh m^{-2}), respectively.

Routine radiation measuring instruments are usually calibrated by comparison with a "standard" radiation instrument whose response factor is calculable for more fundamental quantities. Radiation measurements are based on two main instruments, the Angström and the Smithsonian standard pyrheliometers, which do not exactly agree because of small systematic errors and other differences. In 1956 an International Radiation Conference recommended the adoption of a new scale, the International Pyrheliometric Scale (IPS) 1956, which was brought into effect 1 January, 1957.

To express measurements on the IPS 1956, measurements made according to the Angström scale of

Table C-1
Summary of Accuracy Requirements for Surface Measurements
(from U.S. DOE 1978)

Element	*Climatology*	*Aeronautical meteorology §*	*Synoptic meteorology*	*Maritime meteorology*	*Hydrometeorology*	*Agricultural meteorology*
I. *Cloud*						
1. Cloud amount	±⅛ or ±1/10	* ±⅛	±1/10	—	—	—
2. Height of cloud base	* ±30 m up to 1 500 m ±300 m from 1 500 m to 9 000 m ±1 500 m from 9 000 m to 21 000	* ±15 m up to 150 m ±10% from 150 m to 300 m ±20% above 300 m	+ ±10 m up to 100 m + 10% above 100 m	—	—	—
3. Direction of cloud movement	—	—	* ±10°	—	—	—
II. *Atmospheric pressure*						
1. Pressure	§ ±0.3 mb	±0.5 mb	±0.1 mb	+ ±0.1 mb	—	—
2. Tendency	—	—	' ±0.2 mb	* ±0.2 mb	—	—
III. *Temperature*			§			
1. Dry bulb temperature	' ±0.1°C	±1.0°C	±0.1°C	±0.1°C	—	' ±0.1°C
2. Extremes	±0.5°C	—	±0.5°C	—	—	±0.5°C
3. Sea surface temperature	0.2°C	—	±0.1°C	±0.1°C	—	—
IV. *Humidity*			§			
1. Wet bulb temperature	±0.1°C	—	±0.1°C	—	—	* —
2. Relative humidity	±3%	—	±5% up to 50% ±2% above 50%	—	—	±1%
3. Dew point	±0.5°C	' ±1°C	—	±0.1°C	—	±0.1°C
4. Vapor pressure	±0.2 mb	—	—	—	—	'

Climatology:

* A mean value of one minute is needed.

§ The value is to be obtained from a single reading.

' The minimum lag of the sensor for all temperature and humidity measurements is to be such that not more than 90% of a change which is equal to the required accuracy is indicated in 3 minutes.

Aeronautical meteorology:

§ Aeronautical requirements for meteorological observations for take-off and landing and accuracy attainable appear in more detail in Attachment G. Chapter 12. Technical Regulations.

* Observations to be representative of *(a)* ILS middle marker site, or *(b)* Final approach, initial missed approach, circling approach and landing area.

' Observations to be representative of the whole runway (at average height of turbine-engined aircraft).

+ Observations to be representative of the whole runway (for piston-engined aircraft as required).

Synoptic meteorology:

+ Mean values over 1 minute are required but means of 5 individual values taken at 1 minute intervals would be acceptable.

* Instantenous value is required.

' Difference between two instantaneous measurements of pressure.

§ All temperature and humidity measurements are to be instantaneous in the sense that this is the time required for taking an observation.

Maritime meteorology:

+ An Instantaneous value is required but the instrument is to be sufficiently damped to provide a value within the required accuracy.

* The difference between two such values obtained as above.

Agricultural meteorology:

+ The minimum lag of the sensors for temperature measurement are to be such that not more than 90% of a change equal to the required accuracy will be indicated in 1 minute. Sampling errors are considered to exceed instrument errors.

* Required to be of sufficient accuracy to give stated relative humidity accuracy.

' Equivalent to ±0.1°C in dew point.

Table C-1 (continued)

Element	*Climatology*	*Aeronautical meteorology*	*Synoptic meteorology*	*Maritime meteorology*	*Hydrometeorology*	*Agricultural meteorology*
V. *Wind*	*		+			
1. Direction	±10°	* ±10°	±5°	+ ±5°	—	* ±10°
2. Speed	$\pm 0.5\ m\ s^{-1}$	—	* $\pm 0.5\ m\ s^{-1}$ up to 5 m/s ± 10% above $5\ m\ s^{-1}$	+ ±1 kt up to 20 kt + ± 5% above 20 kt	—	±10% above $1\ m\ s^{-1}$
3. Speed components	$\pm 0.5\ m\ s^{-1}$	* ±1 kt up to 10 kt and ±10% thereafter	as for speed	—	—	—
VI. *Precipitation*						
1. Total amount between two observations	0.1 mm up to 10 mm 2% larger amounts	—	±0.2 mm up to 10 mm, ±2% above 10 mm	±0.2 mm up to 10 mm ±2% above 10 mm	±1 mm	0.2 mm up to 10 mm ±2% for greater amounts
2. Intensity	§ $\pm 0.5\ mm\ h^{-1}$ up to $25\ mm\ h^{-1}$ 2% for greater amounts	— —	$\pm 0.02\ mm\ h^{-1}$ below $2\ mm\ h^{-1}$ $\pm 0.2\ mm\ h^{-1}$ between 2 mm and $10\ mm\ h^{-1}$ ±2% above $10\ mm\ h^{-1}$	—	* $\pm 1\ mm\ h^{-1}$	±5% over periods of 15 minutes
3. Depth of snow	ˣ ±1 cm	—	±1 cm below 20 cm ±5% above 20 cm	—	§ ±1 cm	±10% of absolute value
4. Density of snow	$\pm 0.01\ g\ cm^{-3}$					
VII. *Evaporation*	±0.1 mm up to 10 mm ±2% for larger amounts					
VIII. *Radiation*						
1. Sunshine duration	±0.1 h in any hour					
2. Solar radiation	$\pm 1\ cal\ cm^{-2}\ h^{-1}$					
	* Mean values are required over periods varying from 3 seconds to 1 hour. Sensor response is to be such that not more than 90% of a change is indicated in 3 seconds. § Mean value over 1 minute is required. ˣ Reported depth is to be the mean of several readings taken in different places. Snow cover less than 0.5 cm must be reported.	* Measurements required to be representative of *(a)* the lift-off and touch-down areas (at 6-10 m height above the runway level). *(b)* the whole runway (at 6-15 m height above the runway level).	+ Mean values over 10 minutes are required. * For forecasting purposes these limits could be relaxed to $\pm 1\ m\ s^{-1}$. · Mean values over 10 minutes are required. If precipitation is not continuous then actual rate at the time of precipitation is acceptable.	+ Mean values over 10 minutes are required.	· Required over 6- and 24-hour periods. * Mean values every 5, 10, 15, 30 and 60 minutes are required together with a mean value over 2 minutes if this proves possible. § Amount over 24 hours.	* Mean values over 2-minute periods are required.

Table C-1 (continued)

Element	*Climatology*	*Aeronautical meteorology*	*Synoptic meteorology*	*Maritime meteorology*	*Hydrometeorology*	*Agricultural meteorology*
IX. *Visibility*	+0.1 km up to 5 km 1 km from 5 km to 30 km 5 km from 30 km to 70 km	±50 m up to 500 m ±10% from 500 to 1 500 m ±20% above 1 500 m	+ ±10%	—	—	—
X. *Runway visual range*		* ±50 m up to 500 m ±100 m between 500 m and 1 000 m ±200 m above 1 000 m				
XI. *Waves*						
1. Wave period	—	—	—	±0.5 seconds	—	—
2. Wave height	—	—	—	±10%	—	—
	+ 1½ minute mean value is required. The minimum values are to be observed in all directions.	* Measurements required to be representative (1) for take-off, of the whole runway, (2) for landing, of the runway from the threshold up to 1 500 m.	+ To be observed instantaneously in the sense detailed under temperature.			

1905 were increased by 1.5 per cent and measurements made according to the Smithsonian scale of 1913 were decreased by 2.0 per cent (IGY, 1958).

As this is being written (1979) conversion is underway to an absolute scale (WRR). The relation between the various systems of measurement have been discussed by Latimer (1973) and Fröhlich (1973). The primary standard instruments have an absolute accuracy of ±0.3 per cent. The accuracy of radiation measurements relative to this standard varies with the type of radiometer and the nature of the measurement. For example, it has been demonstrated that for a continuous record of global solar radiation an accuracy of better than ±5 per cent represents the result of good and careful work.

There are a variety of methods of calibrating radiometers using the sun, and using laboratory sources:

(a) directly against a primary or (more customarily) a working standard pyrheliometer using the sun as source,

(b) by comparison with a standard radiometer of either the same or different type using the sun as source, or under other natural conditions of exposure (e.g. a uniform cloudy sky),

(c) in the laboratory on an optical bench with an artificial source (lamp) replacing the sun, either at normal incidence or at some specified azimuth and elevation, by comparison with a similar radiometer previously calibrated outdoors,

(d) in the laboratory with the aid of an integrating system simulating diffuse sky radiation by comparison with a similar radiometer previously calibrated outdoors,

Table C-2

The classification of accuracy of radiometers
(from WMO Guide to Meteorological Instruments and Observing Practices (1971))

	(a) Sensitivity (mW cm^{-2})	(b) Stability	(c) Tempera-ture	(d) Selectivity	(e) Linearity	(f) Aperture	(g) Time constant (max.)	(h) Cosine response	(i) Azimuth response	Errors in auxiliary equipment: Gal-vano-meter	Milliam-meter	Chrono-meter
		%	%	%	%			%	%		%	
Reference standard pyrheliometer	± 0.2	± 0.2	± 0.2	± 1	± 0.5	(1)	25 s	—	—	0.1 unit	0.1	0.1 s
Secondary instruments												
1st class pyrheliometer	± 0.4	± 1	± 1	± 1	± 1	(1)	25 s	—	—	0.1 unit	0.2	0.3 s
2nd class pyrheliometer	± 0.5	± 2	± 2	± 2	± 2	(1)	1 min	—	—	0.1 unit	± 1	—
										Errors in recording apparatus		
1st class pyranometer	± 0.1	± 1	± 1	± 1	± 1	—	25 s	± 3	± 3		0.3	
2nd class pyranometer (2)	± 0.5	± 2	± 2	± 2	± 2	—	1 min	± 5-7	± 5-7		± 1	
3rd class pyranometer	± 1.0	± 5	± 5	± 5	± 3	—	4 min	± 10	± 10		± 3	
											Errors due to wind %	%
1st class net pyrradiometer	± 0.1	± 1	± 1	± 3	± 1	—	½ min	± 5	± 5		± 0.3	± 3
2nd class net pyrradiometer	± 0.3	± 2	± 2	± 5	± 2	—	1 min	± 10	± 10		± 0.5	± 5
3rd class net pyrradiometer	± 0.5	± 5	± 5	± 10	± 3	—	2 min	± 10	± 10		± 1	± 10

Notes: The letters heading the columns refer to the subdivision of paragraph 9.2.4.
(1) See Annex 9.B.
(2) For spherical Bellani, with regard to daily sums only.

(e) in the laboratory with the aid of standard sources, such as standard lamps, blackbody cavities.

(Drummond and Greer, 1966; Hill, 1966; Latimer, 1966; Latimer, 1972; Drummond, 1970).

3. A high standard of network data can only be realized by frequent evaluation and calibration of network instruments and recording systems. Special attention must be given to the exposure, installation and routine care of radiometers. Useful guidance has been given by Latimer (1972) and by DOE (1978). A new information source on instruments is the *Catalog of Solar Radiation Measuring Equipment*, Carter (1977). The IEA has prepared an improved questionnaire with instructions, which should be used in compiling a revised catalog of commercially available solar radiation equipment (IEA, 1979, Appendix 1).

4. The IEA has developed specifications (Table C-3) for a low cost, portable instrumentation package to measure solar radiation and other meteorological data, both prior to and during operation of solar energy systems.

5. At the time of this writing (1979) the WMO is preparing a technical note dealing with meteorological aspects of the utilization of solar radiation as our energy source. The IEA has in preparation a handbook: An introduction to meteorological measurements and data handling for solar energy applications. Both publications should provide adequate guidance to those concerned with the meteorological measurements for solar energy purposes.

Table C-3

Final Specifications

For a Portable Meteorological Instrument Package

Parameter	Accuracy [3]	Tolerance	Time of Integration
Direct (Normal incidence)	±25 w/m^2 or ±5% [1]	2%	10 Minutes Continuous [2]
Global (Direct Plus Diffuse)	± 25 w/m^2 or ±5% [1]	2%	
Solar on Inclined Surface	±25 w/m^2 or ±5% [1]	2%	
Incoming IR (Inclined)	±25 w/m^2 or ±10% [1]	2%	
Output of Inclined Solar Cell (Optional)			
Air Temperature	±1.0°C [4]	±.5°C [4]	
Wind Speed	±1 m/sec or ±5% [1]	±.5 m/sec	
Wind Direction	±10°	±5°	
Humidity (Optional)			

Notes:
Recording Method-Optional
Record: Date, Time, Station Identity, Electronic Calibration Reference
Battery Takeover for Clock, No Other Power Specification
Final Data Output in S.I. Units (from Computer Processing or Possible Unit Itself)
Must have a "Jack" for on Station Data Readout Equipment
(1) Whichever is the Largest
(2) Other Integration Times Optional
(3) Mean Values When in Absolute Units
(4) Higher Accuracy or Precision Optional

(SOURCE: IEA, 1979)

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