Actinometric system for measuring the intensity of direct solar radiation

D.K. Davydov, A.P. Plotnikov, and T.K. Sklyadneva

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received October 11, 2000

An automated system for measuring the intensity of direct solar radiation with the use of an AT–50 actinometer is described. Hardware and software of the system are discussed. Some measurement results demonstrating the system performance are presented.

The net solar radiation and radiation budget have been measured continuously since 1995 at an automated post (TOR station) put into operation at the Institute of Atmospheric Optics SB RAS in 1992 (Ref. 1). The data on the direct solar radiation (S) are needed for thorough understanding of the radiation budget of the atmosphere and the factors determining it. The direct solar radiation is usually measured manually with an AT–50 actinometer. This device is visually sighted on the Sun by an operator. Therefore, the actinometer cannot be operated as a part of an automated measuring system.

In this paper, we describe an automated system for measuring the intensity of the direct solar radiation with an AT–50 actinometer operating as a part of the TOR station. Some measurement results demonstrating the system performance are presented.

The system consists of the hardware and software parts. The hardware part, in its turn, consists of a mechanism for aiming the actinometer at the Sun and an electronic unit for linking it to a computer. The actinometer is driven with two stepper motors with reduction gears. One of them is set inside the device body (Fig. 1) and serves a driver of a movable platform. The platform, turning around its axis, moves the actinometer by the azimuth from 0 to 320° accurate to 0.25°. The second stepper motor is set in the upper part of the platform and serves for moving (rotating) the actinometer in the elevation angle plane from −20 to +90° accurate to 0.156°. Terminal switches for determining the starting and final positions of the actinometer are set at the positions of 0 and 320° on the base and −20 and +90° in the upper part of the platform.

The electronic unit set inside the body receives the information from the computer, controls the stepper motors, and tracks the positions of the terminal switches. The computer controls the device through an expanded input/output board.[2] The supply voltage is fed and the device is controlled through a 5-wire line: wire 1 is the ground; wire 2 is for the supply voltage (+ 12 V); wire 3 is for the control pulses to the stepper motor that sets the azimuth; wire 4 is for control pulses to the stepper motor that sets the elevation angle; wire 5 is for the reverse signal for both motors. The electronic circuitry is designed so that wires 3 and 4 execute double functions. On the one hand, they transmit control pulses. On the other hand, in the intervals between control pulses they transmit signals from the terminal switches. Thus, the connecting cable is used economically taking into account that the system is controlled remotely at a rather long distance from the TOR station.

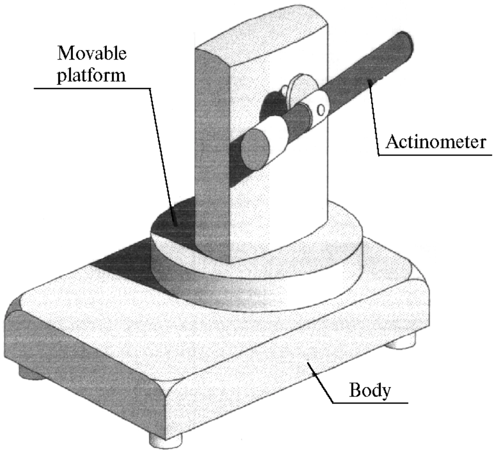


Fig. 1. The appearance of the device.

The software consists of three main blocks for:

1. Determining the Sun coordinates at a given place and time;
2. Counting the azimuth and elevation control pulses;
3. Controlling the Sun tracking system.

It is a rather complicated problem to determine the exact position of the Sun. Several equations are

0235-6880/00/11 947-04 $02.00

now available for calculating the main astrophysical parameters. Many of these parameters can hardly be determined on a personal computer in real time. That is why we used semiempiric equations from Ref. 3 to calculate the position of the Sun.

The azimuth (A) and elevation (h) of the Sun are determined by the equation of conversion of equatorial coordinates to horizontal ones:

$$\tan A = \frac{\sin H}{\cos H \sin\varphi - \tan\delta \cos\varphi};$$

$$\sin H = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos H,$$

where H is the local hour angle; φ is the latitude of the observational site; δ is the solar declination.

The local hour angle, in its turn, is determined by the Smart's equation of time[3]:

$$H = m - 12 - E,$$

where $m = t - N + \lambda - 1$ for winter time, $m = t - N + \lambda - 2$ for summer time (N is the number of the time zone; t is the current time; λ is the longitude of the observational site); E is the equation of time:

$$E = y \sin 2L - 2e \sin M + 4ey \sin M \cos 2L - \frac{1}{2} y^2 \sin 4L - \frac{5}{4} e^2 \sin 2M;$$

$$y = \tan^2 (\varepsilon/2),$$

where ε is the obliquity of the ecliptic; L is the mean longitude of the Sun; e is eccentricity of the Earth's orbit; M is the mean anomaly of the Sun.

The solar declination (δ) can be found as

$$\sin\delta = \sin\varepsilon \sin\theta.$$

Here θ is the visible longitude of the Sun corrected for nutation and aberration:

$$\theta = L + C - 0.00569° - 0.00479° \sin\Omega;$$

$$\Omega = 259.18° - 1934.142° \, T,$$

where T is the time interval measured from the epoch of January 0.5 1990 in Julian centuries each 36525 ephemeris days long; C is the equation for the center of the Sun:

$$C = (1.91946° - 0.004789° \, T - 0.000014° \, T^2)\sin M + (0.020094° - 0.0001° \, T) \sin 2M + 0.000293° \sin 2M.$$

The mean geometric longitude of the Sun, mean anomaly, eccentricity of the Earth's orbit, and obliquity of the ecliptic are calculated by the following semiempiric equations:

$$L = 279.69668° + 36000.76892° \, T + 0.0003025° \, T^2;$$

$$M = 385.47583° + 35999.04975° \, T - 0.00015° \, T^2 - 0.0000033° \, T^3;$$

$$e = 0.01675104° - 0.0000418° \, T - 0.000000126° \, T^2;$$

$$\varepsilon = 23.452294° - 0.0130125° \, T - 0.00000164° \, T^2 + 0.000000503° \, T^3 + 0.00256° \cos\Omega.$$

Using this technique for calculating the position of the Sun, we avoided the use of the reference data on Astronomic ephemeris and achieved a sufficient accuracy. The comparison of the above technique with the well-known Astro Meeus package of astronomic programs and the data on Astronomic ephemeris showed that the error of our technique is less than 10^{-3}%.

The number of azimuth and elevation control pulses is calculated by semiempiric equations. Thus, additional errors connected with installation of the stepper motors and the system as a whole are avoided. The equations were determined as follows. In the solstice days, the coordinates of the Sun were calculated and the needed number of azimuth and elevation control pulses was determined. The calculated values were compared with the actual ones determined for the platform set in on-position with the actinometer aimed at the Sun for the same instant of time. Then the equation for the number of azimuth and elevation control pulses was fitted using the method of least squares.

The tracking system control program operates in the background mode, leaving the computer resources for calculation of the Sun position by the proposed technique. The time quantum of an IBM/PC computer well agrees with the technical requirements to stepper motor control. The period between the control pulses should be no less than 50 ms. The timer interrupt mode allows the period between pulses to be set as 55 ms without additional programming of the 8253/8254 timer chip. The program is developed so that it traces the signals from the terminal switches with the interval of 55 ms and controls the stepper motors in accordance with the calculated coordinates of the Sun.[4]

The software for the Sun tracking system is a Turbo Pascal 7.0 program with some Assembler fragments.[5]

The time diagram of operation of the Sun tracking system is shown in Fig. 2.

Initially, the actinometer is in a zero position corresponding to the coordinates 0 and −20° (azimuth and angle of elevation, respectively). The program calculates the coordinates of the Sun at the time of beginning of the measurements and determines the number of control pulses for both motors then the actinometer is aimed at the Sun. The measurements last 10 min, therefore the device is continuously adjusted, because the position of the Sun changes with time. Once the measurements are completed, the actinometer comes back to the initial position.

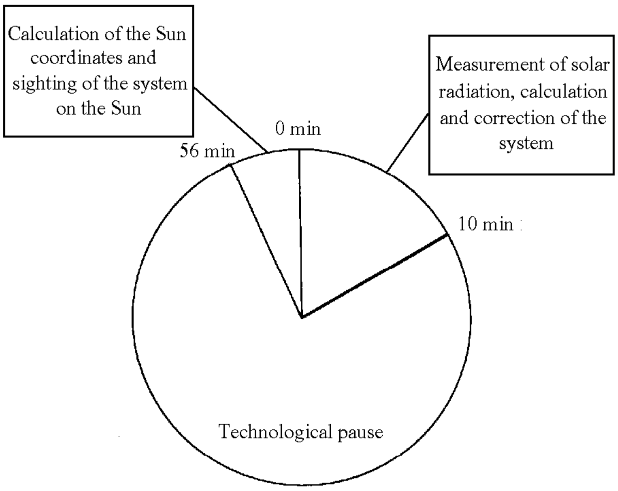
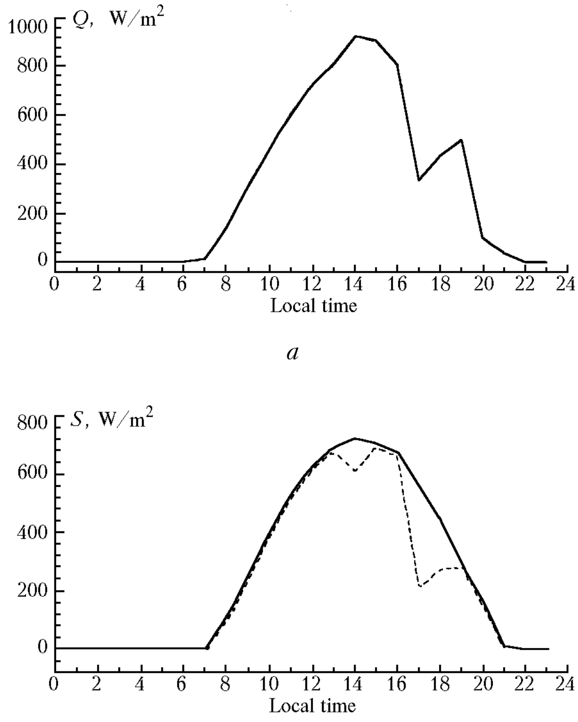


Fig. 2. Time diagram of actinometer operation.

One more problem arises in connection with the automated measurement of the direct solar radiation. This problem is due to the presence of clouds in the atmosphere. In manual observations, an operator stops the measurements for the time when the solar disk is screened by clouds. However, it is difficult to monitor Sun screening by clouds automatically. So, we have to develop new methods for automated measurement of the direct radiation.

In this work we used the following method. To exclude the influence of clouds on measurement of the direct solar radiation, the value of S was measured every second during 10 min. The measured values were used for determination of the mean and maximum values. Under conditions of broken clouds, the maximum values correspond, with rare exceptions, to the intensity of the direct solar radiation under clear sky conditions. This is illustrated in Fig. 3, which shows the diurnal behavior of the net and direct solar radiation incident on a horizontal surface on August 12, 2000. In that day, the conditions of broken clouds were observed at 14:00, 17:00, and 18:00 LT. It is seen from the figure that the maximum value of S corresponds to the direct solar radiation under clear sky, and the mean value of S reflects the presence of clouds during some periods of observation. The resulting text file included the measured mean and maximum intensities of the direct solar radiation for 10 min and their values recalculated to the horizontal surface. Under overcast conditions the measurements were not conducted.

The operation of the system in the monitoring mode is illustrated by Fig. 4, which shows the measurement results on the intensity of the net and direct solar radiation incident onto the horizontal surface in August 2000. In fine days the intensity of the direct solar radiation on the horizontal surface achieved 700–800 W/m^2. The presence of clouds in some periods of the observations decreased the intensity of the direct solar radiation by several orders of magnitude.



a

b

Fig. 3. Diurnal behavior of the net radiation Q (*a*) and direct radiation calculated onto the horizontal surface (*b*) on August 12, 2000: maximum S for 10 min (——) and mean S for 10 min (- - - -).

Since no regular measurements of the direct solar radiation was performed earlier in the Tomsk Region, it is interesting to compare our results with those published for neighboring stations. These data are given in the Table. One can see that our results agree with the results of long-term observations[6] for some periods of observation. The monthly sum of the direct solar radiation near Tomsk in August is 368 MJ/m^2. This value is close to the monthly mean sum of the direct solar radiation in August for the station Ogurtsovo – 393 MJ/m^2 (Ref. 7).

Table. Intensity of direct solar radiation, in W/m^2, incident on horizontal surface for 56°N (Ref. 6) and TOR station at clear sky in August

Time of observation (local time)	56°N	TOR station
09:30	516.52	459.28
12:30	621.22	658.35
15:30	404.84	506.74

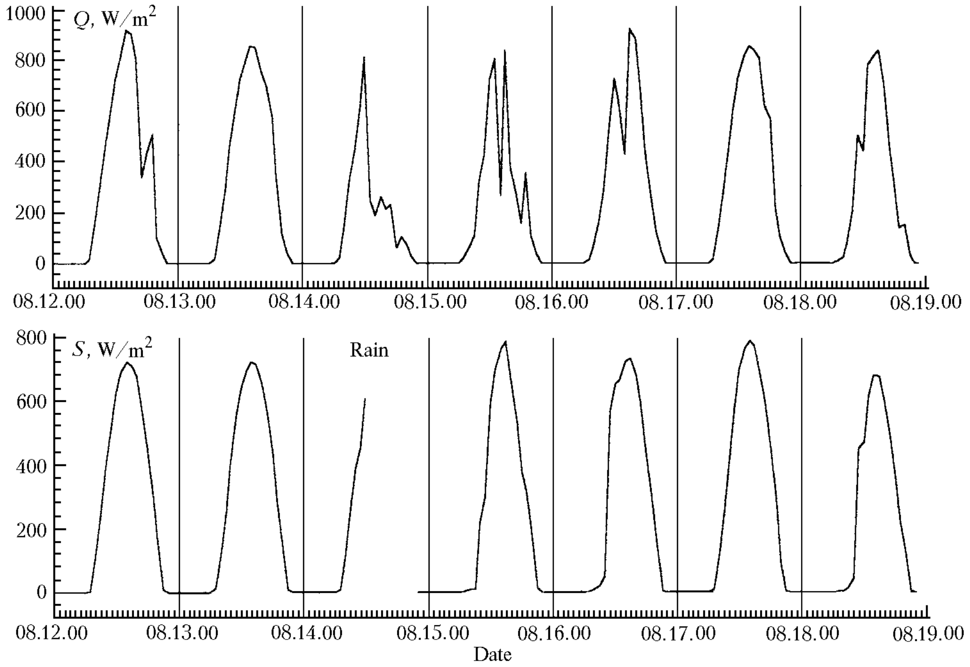


Fig. 4. Intensity of the net (Q) and direct (S) solar radiation incident on the horizontal surface in August 2000.

Acknowledgments

The work was partially supported by the Russian Foundation for Basic Research, Grant No. 00–05–72014.

References

1. M.Yu. Arshinov, B.D. Belan, D.K. Davydov, V.K. Kovalevskii, et al., Meteorol. Gidrol., No. 3, 110–118 (1999).

2. B.D. Belan, V.K. Kovalevskii, A.P. Plotnikov, and E.V. Pokrovskii, Prib. Tekh. Eksp., No. 1, 156–157 (1999).

3. G. Meeus, *Astronomic Equations for Calculators* [Russian translation] (Mir, Moscow, 1988), 168 pp.

4. A.V. Frolov and V.G. Frolov, *IBM PC Hardware* (DIALOG–MIFI, Moscow, 1992), Part 1, 208 pp.

5. V.V. Faronov, *Turbo Pascal*. Vol. 1. *Principles of Turbo Pascal* (MVTU–FESTO DIDAKTIK, Moscow, 1992), 304 pp.

6. Z.I. Pivovarova, *Radiative Characteristics of Climate in the USSR* (Gidrometeoizdat, Leningrad, 1977), 335 pp.

7. Z.I. Pivovarova and V.V. Stadnik, *Climatic Characteristics of Solar Radiation as an Energy Source at the USSR Territory* (Gidrometeoizdat, Leningrad, 1988), 291 pp.