UMR-MEC Conference on Energy

09 Oct 1975

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Recommended Citation

Durbin, Ronald C.; Boone, Jack L.; and Kern, Frank J., "A Combined Digital-Analog Tracker for Terrestrial Applications" (1975). *UMR-MEC Conference on Energy*. 80.
https://scholarsmine.mst.edu/umr-mec/80

A COMBINED DIGITAL-ANALOG TRACKER
FOR TERRESTRIAL APPLICATIONS

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ABSTRACT

A combined Digital-Analog Tracker is suggested to allow maximum efficiency in a solar-electrical energy converter, utilizing a twelve-foot parabolic collector. The analog tracker compares solar beam radiation to ambient (diffuse) light to obtain optimum placement of the collector when the sun is visible. The digital portion of the tracker utilizes a wired program which derives information on solar position from a non-volatile random-access semiconductor memory. This arrangement allows accurate mapping of the sun even when the sun is obscured by atmospheric phenomena which would make mapping impossible.

INTRODUCTION

In order to optimize the collection of direct solar radiation, it is necessary to maintain the orientation of the collection surface normal to the sun's rays. The Solar-Kine[1] project at the University of Missouri - Rolla involves the collection and concentration of solar energy as a part of a solar energy conversion process. Studies[2,3] relating to the optimization of collector-absorber efficiency, collector concentration ratio and useful energy indicates the requirement for very precise tracking whenever the sun is visible. Reisbig[4] has shown that, for concentrating systems, the maximum allowable tracking error during normal operation is approximately 0.5 degrees in both azimuth and elevation.

This paper describes a combined digital-analog system which will maintain accurate tracking of a visible sun and limited tracking (±2°) of an obscured sun. The system is economical, reliable and simple to operate.

Analog Tracking System

The technique used to track the sun in normal operation of the system employs an analog comparator. The comparator consists of three major subsystems: a mechanical collimator; a photoresistive bridge, error detecting circuit and amplifier; and a hysteresis switch (Fig. 1).

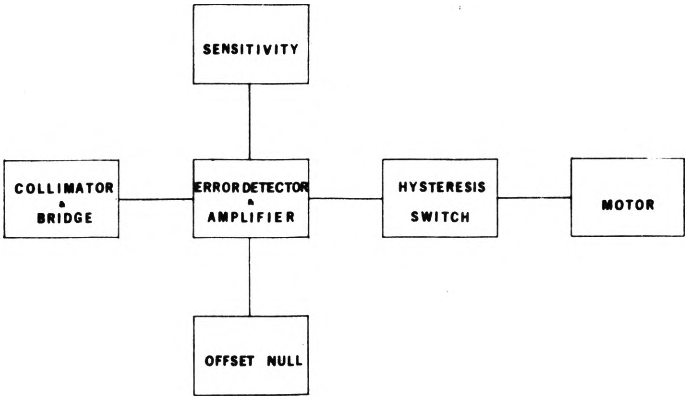


Fig. 1. Block Diagram of the Analog Tracking System

The mechanical collimators (Fig. 2) are constructed around a length of brass waveguide of rectangular cross-section. The end of the waveguide which is normally oriented toward the sun, is covered by a piece of clear plexiglass which has been taped to leave only a small (approx. 1/8") slit through which light may pass. The length of the waveguide has been experimentally determined to enhance the directional properties of the slit. The net "lock-on," or tracking range of the collimator system has been found to be very close to a ± 2.5°[5]. By restricting the lock-on range of the analog tracker (that is, the portion of the sky in which the sun must exist to cause tracking) to ± 2.5 degrees the selectivity of the tracker is greatly improved. Good selectivity minimizes the effects of extraneous light sources such as glare, reflected sunlight, and artificial light.

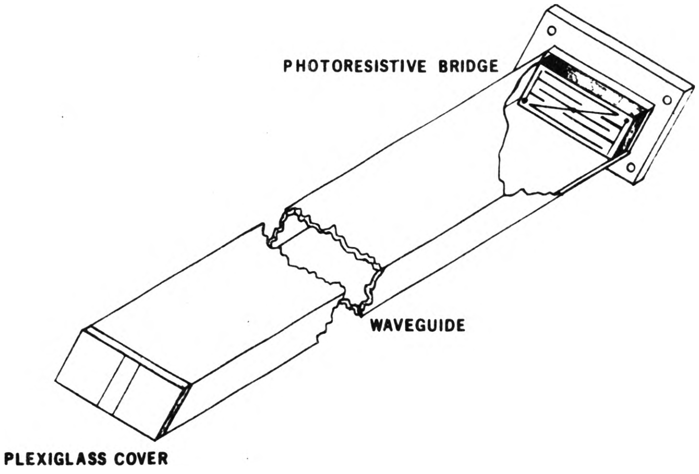
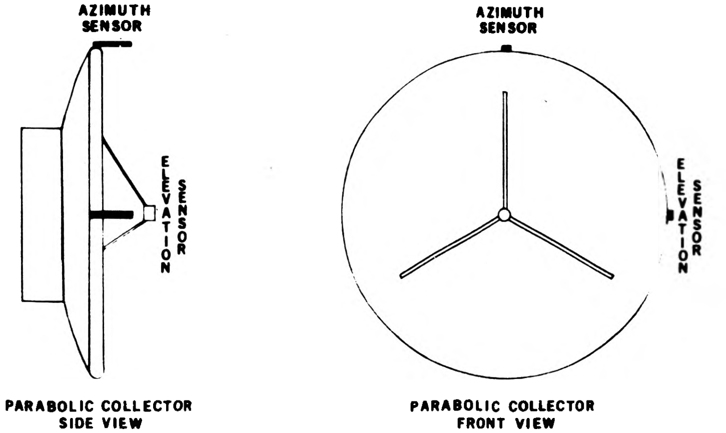


Fig. 2a. Collimator and Photobridge



PARABOLIC COLLECTOR SIDE VIEW

PARABOLIC COLLECTOR FRONT VIEW

Fig. 2b. Location of Comparator Units on the Dish

The actual analog comparator is made up of a photoresistive bridge, and an error detector-amplifier connected, as shown in Fig. 3.

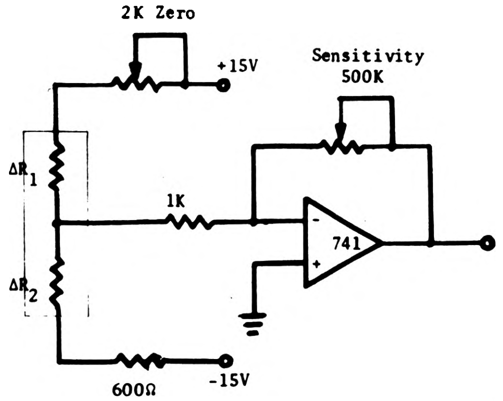


Fig. 3. Diagram of the Analog Comparator Unit

The photoresistive bridge sits snugly in the waveguide, at the end opposite the plexiglass lens. The three non-trivial conditions which describe the operation of the comparator are:

(1) Solar beam radiation equally incident upon both sides of the bridge.
(2) Solar beam radiation unequally distributed over the bridge.
(3) Diffuse radiation <u>only</u> present on bridge.

In the first case, the intensity of the light is equal on both sides of the bridge, making the resistance of both sides equal. With both resistances equal, the error voltage at the amplifier input is zero. Assuming that the output null is adjusted to yield zero output for zero input, the output voltage of the amplifier for equal beam irradience will be zero. In the second case, one side of the bridge is better illuminated, making the resistance of that side lower than the resistance of the other side. Hence, the error voltage will be driven either positive or negative as one side or the other receives more beam radiation. The polarity of the error voltage corresponds to the polarity of the poorly illuminated side, while the magnitude of the error voltage indicates the difference in areas illuminated. The error voltage is amplified and a portion of the output is fed back into the input through the gain control. Adjustment of the gain control determines the output voltage for a given error voltage or a given positional error, and hence determines the <u>sensitivity</u> of the error detecting circuit.

The third case to be considered occurs when the sun is outside the tracker's lock-on range and both sides are exposed to diffuse light. Since the diffuse light will be equally incident upon both sides of the bridge the error voltage, and hence the output voltage, will be zero. This result is important, as it insures that the analog tracker will not engage in a random search for the sun throughout the limits of the tracker's motion. If the sun is outside the lock-on range the analog tracker is essentially inoperative until some other system brings the sun within its tracking range of ± 2.5 degrees.

A final point of the error detector-amplifier which should be considered is the use of the offset null control. It became obvious early in the construction of the analog tracker that perfect mechanical alignment between the collimators (one each for azimuth and elevation) and the collector would not only be costly but unreliable, and would require handling that could not reasonably be expected in the devices' anticipated operating environment. The offset null provides, instead, an <u>electrical</u> means of obtaining precise alignment between the collimators and the collector. Fine adjustments may be made on a periodic basis, if necessary, in a matter of a few minutes by simply changing the setting of a potentiometer.

The Hysteresis Switch is a digital switch which employs hysteresis: that is, a certain value of voltage must be exceeded to cause switching to occur. The hysteresis switch employed in the analog tracker is bipolar; voltages exceeding the hysteresis level will trip one switch or the other, depending on the input polarity. For example, assuming a hysteresis of ± 0.8 volt, the output voltage of the error detector-amplifier must exceed 0.8 volt to activate one switch, or must exceed -0.8 volt to activate the other switch. Obviously the switches are mutually exclusive: one or the other may be on, or both may be off; however, both may not be on simultaneously. Each hysteresis switch drives a bi-directional motor and gear train. The two functions of the hysteresis switch are:

(1) to prevent oscillation of the collector around the point of zero tracking error, and
(2) to allow an "error zone" about the zero tracking error point, the zone width is determined by adjusting the sensitivity of the error detector-amplifier.

The hysteresis switches are connected to the motors in such a way that, when engaged, the motors tend to drive the collector towards zero tracking error. The motors used in the drive system, because of their internal gearing and, consequently, slow shaft speed, allow very accurate positioning of the collector and minimize the chances of overshoot. These advantages are obtained at the expense of a very slow slew rate, in both azimuth and elevation, of roughly 3°/minute.

Limitation of Analog Tracker

The Analog Tracker, while boasting the advantages of simplicity and great accuracy, has one unavoidable limitation. To minimize tracking error and to prevent interference from extraneous light sources, only a comparatively small cross section of sky is seen by the photoresistive bridge. Should the sun be obscured by rain, dust, fog, or some other atmospheric phenomena for more than a very few minutes, the sun will have passed out of the lock-on range and analog tracking rendered impossible. The need for the accuracy mentioned in the introduction dictates the need for an auxiliary tracking system to maintain coarse positioning at all times during the solar day.

Choice of Auxiliary Tracking System

It became apparent that the narrow-range analog tracking system, described previously, required an additional coarse positioning scheme to keep the collector's attitude within lock-in range of the sun. The nature of the movement of the sun in azimuth and elevation, is described for 21 December, 21 March, and 21 June, in Figure 4.

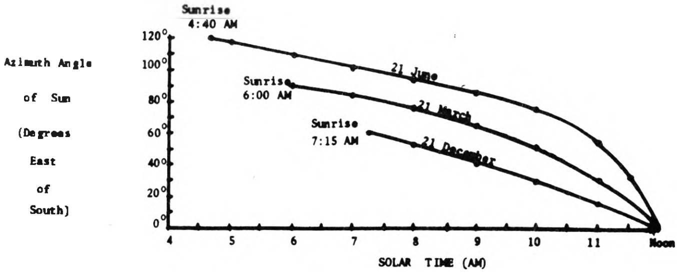


Fig. 4a. Sun Azimuth vs Time-of-day for Selected Days.[6]

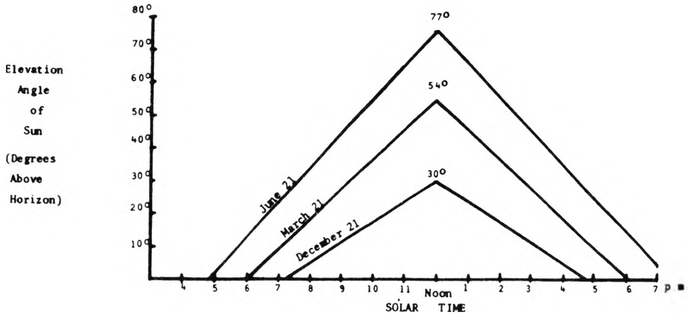


Fig. 4b. Sun Elevation vs. Time-of-day for Selected Days[6].

Note on Symmetry of Sun's Motion: Motion of sun in azimuth and elevation is symmetrical by day with respect to Solar Noon, and by year with respect to 21 Dec. All positional data for Rolla, Mo: 36°N. Lat, 92°W. Long.

To make the system as simple as possible, it was decided to make both auxiliary trackers (azimuth and elevation) identical in design and construction. The limits thus imposed on the system are a function of the motion of the sun. Since on any given day, the velocity of the sun in elevation with respect to a fixed point on earth is constant, no problem is encountered. The velocity of the sun is azimuth, however, is not constant for any day of the solar year. The apparent acceleration of the sun in azimuth is the limiting factor in the design of the auxiliary tracker. After careful consideration, possible solutions were studied: an analog wide-range tracker, a mechanical (motor-driven cam) system, an infrared sensitive tracker, an analog tracker using piecewise linear approx., and a digital tracking unit, using stored data. Of these alternatives, only the digital system satisfied all the requirements under all circumstances.

As may be seen from Fig. 4, the 21st of June has some unique qualities. June 21st is the longest solar day of the year, has the largest azimuth excursion and the sun reaches its maximum elevation all on this first day of Summer. By choosing this day as the worst-case design example, it was insured that the system would work on any other day in the solar year. In the description of the digital system, which follows, all data refers to the 21st of June.

The Digital Tracker

The entire operation of the digital tracker may be summed up in the following words: Stored positional data for the sun is periodically compared with the position of the collector, and if a difference exists, a motor-driven gear train is engaged to drive the error to zero. This description serves to illustrate the simplicity of the tracker's overall operation, but does not hint at the methods used to achieve its function. In considering the digital tracker, two principal topics will be covered in detail. The first of these topics will be the memory, or more importantly, the significance of the memory's concents, while the second topic will be the control sequence which describes in detail the operation of the digital tracker.

To sense the significance of the contents of the non-volatile semiconductor Random Access Memory (RAM) it is necessary to consider what information must be stored there. As shown previously, positional data for the sun is desired, and from the discussion of the analog tracker, the digital tracker is constrained to an accuracy of better than $\pm 2.5^{\circ}$. By considering the data in Figure 4, it becomes apparent that the maximum velocity of the sun is very nearly one degree/minute in azimuth (on June 21st) and 0.175 degrees/minute in elevation (also on June 21st). Since it is desired to make the azimuth and elevation systems identical, only the azimuth system, the limiting case, need be considered. Therefore, it is known that to meet worst case velocity conditions and accuracy restraints, the maximum sampling rate (rate at which positional data is compared and updated) is once every 2 minutes. In 2 minutes the sun can, at worst, have moved 2 degrees, 0.5 degree less than the maximum tolerable error; in general, the sun will have moved much less than 2 degrees, in 2 minutes. The graph of Azimuth Angle of the Sun vs. Solar Time (Fig. 4a) may be modified by enlarging it and breaking the Solar Time Axis up into 220 - 2-minute increments. (The time between sunrise at 4:40 AM and Solar Noon on June 21 is 7 hours and 20 minutes, or 440 minutes, or 220 - 2-minute increments.) Each of these 2-minute intervals is assigned a value, either a logical 1 or a logical 0. The presence of a logical 1 indicates that the sun has moved 2 degrees in azimuth since the last similar movement, while a logical 0 indicates that the sun has not yet moved 2 degrees. (The same procedure is applied to elevation, using Fig. 4b and will, from this point, be ignored.) Since it is known that the sun's excursion in azimuth on June 21st is 120° between sunrise and Noon, 60 logical 1's may be expected, corresponding to 60 - 2-degree increments. By the same reasoning, 160 logical 0's may be expected, making up the remainder of the 220 intervals. The next step requires that each of the 220 intervals be identified by a binary number, starting with sunrise as binary 0, 2 minutes later being binary 1, and so on, up to Solar Noon (219 in binary). Since the maximum value of an 8-bit binary number is 256, an 8-bit word will suffice to account for the 220 invervals. However, the 8-bit binary words corresponding to intervals, containing logical 0's convey no information -- they are 'no-action' words and may be neglected. On the other hand, the 60 binary words corresponding to logical 1's are 'action' words and must be stored. The necessary positional information is now ready to be stored in memory in the form of 8-bit binary words which indicate the times when the collector should have moved 2 degrees. The memory used was a 1 k bit oriented memory. It was rearranged artifically by use of counters and storage registers to appear electronically as a memory made up of 128 - 8-bit words. The positional data which has been gleaned from Fig. 5, may now be inserted in this memory after encoding, as described.

The control sequence (Fig. 5) may be divided, for purposes of explanation, into 3 main parts: (a) Memory Associated Logic; (b) Time Compare Logic; and (c) Position Compare and Control Logic. The main control signal in the sequence is 'scan.' Scan is generated once on every 2-minute decode of a solar time clock (a simple 24-hour digital clock set to local solar time). Upon generation of scan, each 8-bit word in memory is sequentially extracted and placed, one word at a time, into the Memory Information Register (MIR). This binary word is then digitally compared, bit by bit, with the Solar Time Counter(STC). The Solar Time Counter starts at count 0 at sunrise and is incremented by a count of 1 every scan pulse.

If the comparison fails, then another word is checked and so on, until every word has been checked or a comparison found. At the end of an unsuccessful comparison, the control sequence is terminated, as it is not time to check the position of the collector. On the other hand, if a comparison is successful, then the sun's position has moved 2 degrees and the position of the dish must be checked. A shaft angle encoder connected to the base of the collector increments a binary counter, called the Azimuth Position Register (APR), by a count of 1 for every 2 degrees of rotation. When a valid time comparison is made, the contents of the APR are compared to the contents of the Desired Azimuth Register, which contains the number of 2-degree movements the sun has made up to that time. If the DAR and APR compare, then the Analog Tracker is functioning normally and no action is taken - the control sequence terminates. Conversely, if the contents of the APR and DAR are <u>not</u> identical, then the motor is engaged and remains enable until the two position registers do agree. At that point the control sequence is terminated.

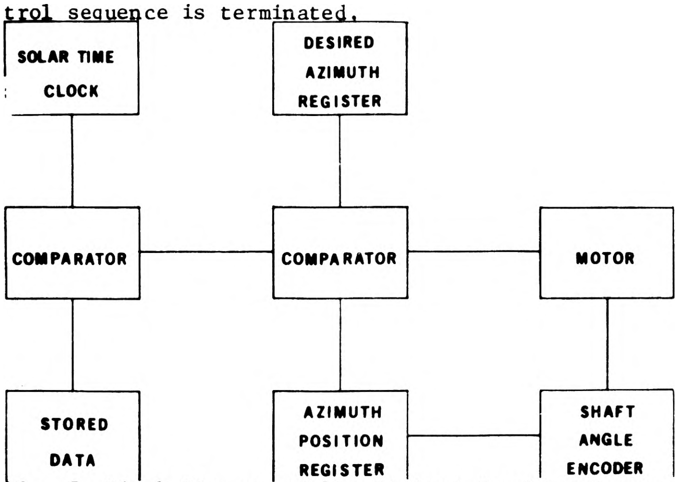


Fig. 5. Block Diagram of the Digital Tracking System

The digital control sequence which defines the operation of the Digital Tracking Unit was written originally in a computer language developed by Hill and Peterson[7], called 'A Hardware Programming Language,' AHPL. The language was intended for use in designing control sequences and simple instructional computers, and has as its chief advantage the fact that the AHPL program may be translated <u>directly</u> into hardware in the form of off-the-shelf TTL packages. No intermediate design phases were required, resulting not only in a great reduction in the number of engineering man hours required and savings in component costs, but most importantly, in making it possible to program the control sequence as a microprocess or unit using today's LST CMOS technology.

Conclusion

By using a combined Digital Analog Tracking Unit, the best advantages of both systems may be exploited. The Analog System results in superb accuracy during normal tracking of the visible sun, while the Digital System keeps the Analog Tracker within lock-on range of the sun at any time during which the sun may become obscured. The combination allows for maximum efficiency in extraction of electrical energy from sunlight even when using collectors with high (1000:1) concentration ratios and critical focusing.

The Analog Tracker is simple in design, requires a minimum of components and is inexpensive to construct. The Digital Tracker employs a straight forward control sequence which may be built with off-the shelf TTL components or, in volume applications, manufactured as a microprocessor on a single LSI CMOS chip.

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