CORRECTION OF THE CONCENTRATED SUNLIGHT SPOT´S DRIFT OF THE CIE-UNAM´S SOLAR FURNACE

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Abstract

This paper discusses the methods implemented for the solution of the drift andbackslash problems in the heliostat of the High Radiative Flux Solar Furnace recently built at the Center for Energy Research of the Universidad Nacional Autónoma de México, located at the geographical coordinates 18° 50' 24" North and 99° 15' 00" West. To solve the observed drift, various algorithms were analyzed for the calculation of the solar vector, and a closed loop through an electronic device was implemented which makes corrections to the position of the heliostat. Drift was corrected by means of unbalancing the heliostat.

Keywords: Concentrated sunlight spot´s drift, solar furnace, solar concentration system.

1. Introduction

In the Center for Energy Research of Universidad Nacional Autónoma de México (UNAM), a High Radiative Flux Solar Furnace (HRFSF) was built, which was inaugurated in August 2011. The optical design includes a total of 409 facets, divided into 5 different focal length groups [1]. In a previous work [2] the first results of the evaluation of the HRFSF were presented, were the first two focal lengths groups (with a total of 199 mirrors) and a 36 m heliostat were used. Now, the Solar Furnace has been completed and it includes the full optics of the concentrator and a heliostat with a reflective surface of 81 m , which was designed specifically for the furnace (see figure 1). Since the inauguration date, some problems detected during its operation have been solved.

The main problem observed was that the concentrated sunlight spot did not stay fixed at the focal zone throughout the day. This problem is detected when the solar furnace is in operation for a prolonged period of time. For the tests, the concentrated sunlight spot was projected onto a water cooled Lambertian target placed at the focus of the concentration system (3.68 m from the apex). In these tests, the concentrated sunlight spot shows a progressive displacement along the target surface with time.

Figure 1. High Radiative Flux Solar Furnace at CIE-UNAM.

As an example, Fig. 2 shows the melting of a refractory brick in the HRFSF. In this picture it can be observed how the melted region presents an oval shape, due to the drift of the spot during the experiment. The melting was made in December 15th, 2011, and the process lasted 4 minutes. The magnitude of the shift of the image varies depending on the day of the year in which the test is performed.

The shift of the concentrated sunlight spot is caused by the change in the direction of the solar radiation reflected by the heliostat and can be caused by many factors. These factors may include errors in the calculation of the solar vector, or the geo-location coordinates of the heliostat, or in the geographical North-south axis orientation. Also physical causes like an offset in the angles of the gearbox, or a tilt in the heliostat pedestal, as well as delay in the control system clock [3].

The heliostat has an azimuth mounting and its movement is produced with the help of a gear mechanism with two electric motors, one for the azimuth motion and the other for elevation. The control system that was initially installed in the heliostat is of the open loop type and the sun´s apparent position vector was calculated by using the equations from the book by Duffie and Beckman [4]. These were suspect of causing some of the drift problems, so a comparative analysis of various codes proposed by different authors was made in order to implement a better set of equations in the control system. The codes selected for the comparison were those proposed by Grena [5] and Reda [6]. This is described below.

In view of the comparison results, equations were changed for the ones proposed by Reda. With this modification, the drift was reduced significantly, but not completely so it was necessary to apply a closed loop control system, due to the difficult to identify and correct completely the physical causes of de residual drift. This is done by means of a device (peephole), which allows realizing adjustments in real time in the moment when a variation occurs in the direction of the rays reflected by the heliostat.

Figure 2. Photograph of the melting of refractory brick, showing the oval shape of the melted material.

Another important problem found in addition to drift, was backlash in the transmission mechanisms, due to gear clearances. Therefore, it was necessary to implement a mechanical system that prevents that the wind loads change the position of the heliostat.

2. Algorithms Comparison

To compare the algorithms presented by Dufie and Beckman (DB), Grena (ENEA) and Reda (also known as NREL´s Solar Position Algorithm, SPA), it was decided to do the theoretical analysis for the year 2012, taking into account the 1st and 15th of each month as the more significant days, on a schedule of 9 to 15 hours each hour in solar time. The comparison was carried out for the particular location of the HRFSF, at 18° 50' 24" north latitude and 99° 15' 00" west longitude. It must be pointed out that such a comparison of algorithms had not been carried out for such relatively low latitudes.

The variables that were compared are the zenith and the azimuth angles of the solar vector, taking as benchmark for the comparison the results generated by the SPA. In fig. 3 it is possible to estimate the comparative of the differences between the algorithms SPA ENEA and in fig. 4 the differences between the algorithms SPA-DB.

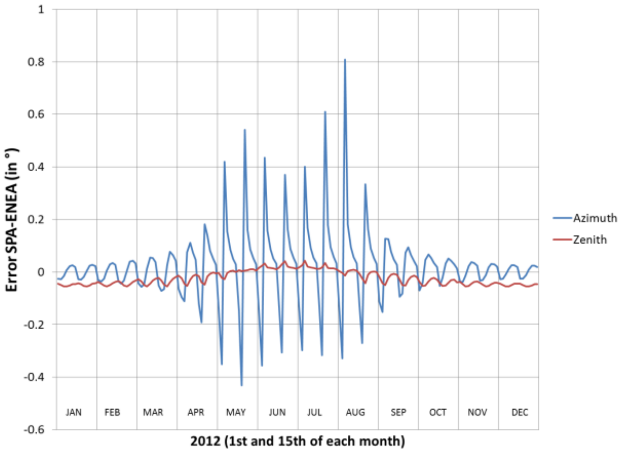

Figure 3. SPA-ENEA difference for azimuth and zenith angles.

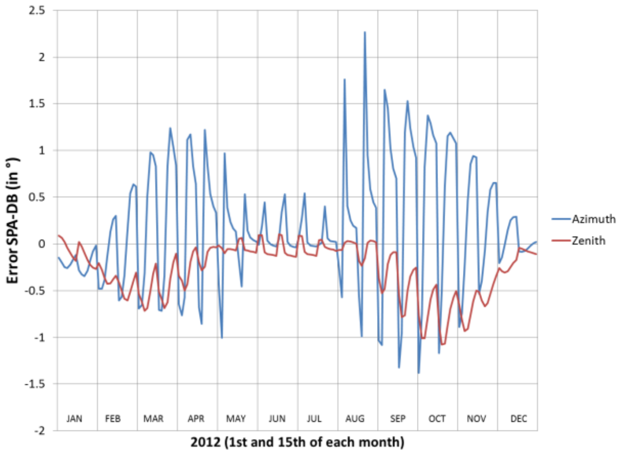

Figure 4. SPA-DB difference for azimuth and zenith angles.

As can be seen in the graphs of Figs. 3 and 4, the algorithm DB presents significant errors, which can be as high as 2.33 degrees in the azimuth angle and 1.08 degrees in the zenith angle. Nevertheless, the results of the ENEA algorithm are also not good for the considered conditions, as errors in azimuth can reach 0.6 degrees. This is clearly not acceptable as compared to the 0.5 degrees size of the solar disc. Therefore, it was decided to replace the algorithm for the SPA. Even though this algorithm requires more computation time than the other two, this fact does not represent a problem, and the gain in accuracy is substantial.

With the change of algorithm for the calculation of the solar vector the drift of the heliostat decreased significantly. This was observed by comparing the position coordinates of the centroid of the spot of concentrated sunlight at the beginning and the end of two tests realized on 14 and 15 of June 2012. The first test was carried out with the DB algorithm and the second with the SPA: The shift of the spot decreased approximately by half. The reduction in the displacement in horizontal direction was 3 cm and in the vertical one it was 1 cm approximately. We can see that this is an important reduction, if we take into account as the diameter of the spot is approximately 6 cm. Moreover, these values are similar to theoretical error obtained from the difference between the SPA and the DB algorithm. Figure 5 shows the theoretical behavior of the difference in the calculation of the zenith and azimuth angle of the sun vector between the SPA and DB algorithms for the 16 June 2012, in a solar time of 8:00 a.m. to 11:00 a.m.

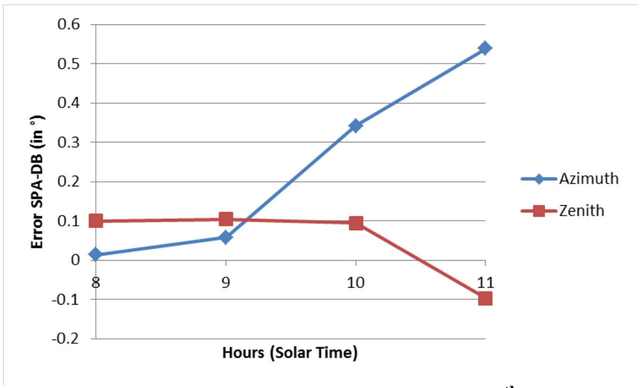

Figure 5. SPA-DB difference for June 6th 2012.

As seen in Figure 5, the errors in the calculation amount to 0.55 degrees for azimuth, and 0.20 degrees for zenith angle. This corresponds to a horizontal displacement of the spot of 3.65 cm and a vertical displacement of 1.28 cm, taking into account that the screen where the spot is projected has a distance of 368 cm from the vertex of the concentrator.

3. Backlash Correction

As mentioned above, besides the drift presented along a certain period of time of operation, intermittent oscillatory movement was also observed during testing. This backlash effect is produced by the clearances of the transmissions mechanisms, in azimuth as well as in elevation movement. This oscillation is provoked by the wind loads over the heliostat. The angular displacement registered by the solar spot due to this cause was of 1° in azimuth and 1° in elevation.

To reduce this oscillation, a weight unbalance is provoked in the heliostat through counterweights, so as to counteract wind loads. To determine the weight of the loads, an analysis of the wind speed measured by the meteorological station located in the CIE-UNAM was done.

4. Residual drift Correction

Due to the fact that the algorithm have changed for the calculation of the solar position only reduced the drift of the solar concentrated light, it was necessary to implement a closed loop control by means of a device which detects the horizontal deflection (azimuth) and vertical (elevation) of the solar radiation reflected by the heliostat and sends a signal to the computer for making the required correction. This device is called an electronic eye or peephole. The peephole is composed of four photo-resistors connected in series with fixed resistors. When a voltage difference is detected between two of them, it indicates indicate that the solar radiation reflected by the heliostat presents a change of direction. Whenever the peephole sends a signal, it is recorded in a file that indicates the direction and magnitude (in degrees) toward which the correction was made. Fig. 6 shows the graph of azimuth adjustments made to the heliostat from 13:00 to 16:00 hours (standard time), on July 11 2012. In Fig. 7 the adjustments to the elevation angle at the same time and date are shown.

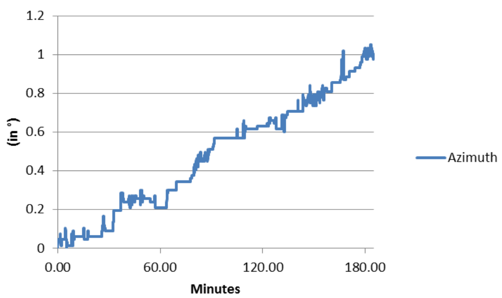

Figure 6. Adjust the azimuth angle correction recorded by the peephole.

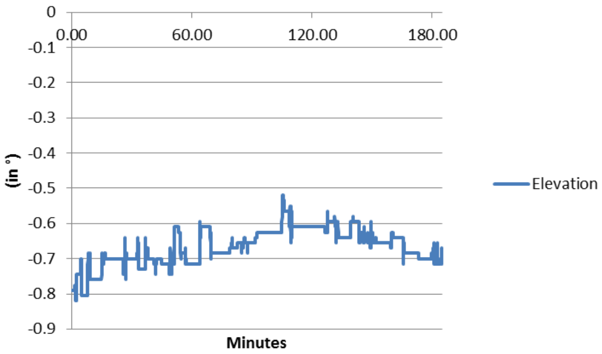

Figure 7. Adjust the elevation angle correction recorded by the peephole.

According to the corrections file generated during the test, the displacement observed in the sun spot, if the closed loop was not implemented, would have been 6 cm estward, and 2 cm down. However, the error that would have been incurred juts by not changing the sun´s position algorithm (with can be obtained theoretically) would have been 3 cm to the east and 1 cm down. Fig. 8 shows the error in the calculation of the theoretical solar vector algorithm comparing SPA and DB for this particular date. Therefore the whole error would be 9 cm est and 3 cm down if none of the corrections was implemented.

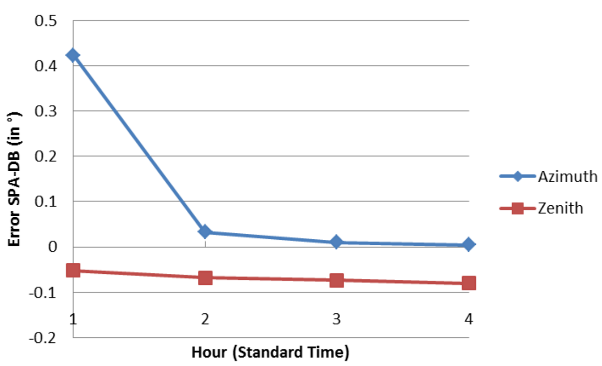

Figure 8. Theoretical error in the calculation of azimuth and zenith angle of the sun vector produced by the algorithm DB for July 11, 2012.

5. Conclusions

With the change of the algorithm DB algorithm for the SPA a significant drift reduction was achieved for the solar spot. However, residual drift remained, and it was necessary to implement a closed loop system to eliminate it. This was achieved by means of a electric eye device that detects the change of direction of the solar radiation reflected by the heliostat, allowing real-time corrections and thereby achieving a fixed spot of concentrated sunlight at the focus of the system. Furthermore, with the weight unbalance in azimuthal and elevation movement, we were able to achieve intermittent counter oscillatory motion caused by wind loads.

Acknowledgements

We appreciate the technical support provided by Javier Licurgo during the performance testing, and support in the design of the system of weights to unbalance the mechanisms.We also appreciate the support of the CIE machine shop for the counterweight system manufacture.

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