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# Optical model and calibration of a sun tracker

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ABSTRACT

Sun trackers are widely used to investigate scattering and absorption of solar radiation in the Earth's atmosphere. We present a method for optimization of the optical altazimuth sun tracker model with output radiation direction aligned with the axis of a stationary spectrometer. The method solves the problem of stability loss in tracker pointing at the Sun near the zenith. An optimal method for tracker calibration at the measurement site is proposed in the present work. A method of moving calibration is suggested for mobile applications in the presence of large temperature differences and errors in the alignment of the optical system of the tracker.



## 1. Introduction

Investigation of the Earth's atmosphere using the Sun as a source of wideband radiation is very urgent. Spectroscopic analysis of stratospheric ozone, greenhouse gases, and the presence of traces of other gases are goals of atmospheric research [1–8]. Moreover, taking advantage of the Sun's diurnal motion, light scattering and absorption at different angles can be investigated in the atmosphere. To perform this research, a sun tracker is used for pointing at the Sun and its subsequent tracking. At present, altazimuthal trackers whose output radiation direction is aligned with the axis of a stationary spectrometer are more and more widely used [9–11]. Sun is tracked by rotating two mirrors at elevation and azimuth angles, respectively. To fix the direction of output radiation, the optical system of the tracker contains additional mirrors. As a rule, a portion of radiation is deflected by a beam-splitter plate to the position sensor consisting of a lens and a quadrant or multi-element radiation detector (called sensor hereinafter) in the image plane.

Tracker pointing within the angular dimensions of the position sensor is first performed. More precise pointing at the Sun and its subsequent tracking are performed in the active (close-loop) mode. Pointing at the sun (open-loop mode) and its subsequent support are performed with a position controller also called Proportional-Integral-Differential (PID) controller. The position controller is based on a synthesized optical tracker model and parameters (the Euler angles) describing the tracker position with respect to the Earth's surface.

A number of works are devoted to synthesis of optical tracker models and tracker calibration [12–16]; however, this subject of research is far from being exhausted. In trackers with fixed output radiation direction, the optical model introduces significant errors in operation of the position controller near the zenith. As indicated in [12], the tracker cannot track the Sun position for about an hour. Optical, mechanical, and electronic parameters of the tracker affect the accuracy of estimation of the Euler angles. The problem of tracker calibration for mobile applications without refinement of the tracker position parameters is especially urgent.

The present work solves problems of calibration and optimization of the optical tracker model. An altazimuthal tracker with fixed output radiation direction is taken as a

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basis. Within the framework of the General Agreement on Scientific Cooperation between V. E. Zuev Institute of Atmospheric Optics (Siberian Branch of the Russian Academy of Sciences) and Hanbat University (Republic of Korea), we have developed a sun tracker and evaluated its efficiency using optimal calibration methods and optical tracker model.

Theory of operations, problem formulation, and method for optimization of the optical tracker model are stated in Section 2. The optimal calibration method is described in Section 3. Results of experimental testing of the optimization methods are presented in Section 4.

## 2. Optimal optical tracker model

### 2.1. Theory of operation and problem formulation

Altazimuthal trackers with fixed output radiation direction intended for atmospheric spectrometry are based on a system with one or more rotating mirrors. These trackers to a lesser or greater extent implement the idea of two axis altazimuth mount for tracker pointing at the sun. For this reason, optical tracker models have a common feature. Let us illustrate synthesis of an optical tracker model on an example of simple altazimuth tracker mount at the measurement site in the altazimuth coordinate system.

The Sun vector is described by two (*Altitude and Azimuth*) angles. The altazimuth coordinate system is convenient for positioning, but all coordinate transformations are performed in the Cartesian coordinate system and spherical coordinate system attached to it. Hereafter we assume that the $x$-axis of the Cartesian coordinate system is aligned with the south, whereas the $z$-axis is aligned with the zenith. The unit vector $(x, y, z)$ specifies the Sun's position. The angles $(\psi, \varphi)$ of the Sun in the spherical and altazimuthal coordinate systems are related by expressions

$$\begin{cases} \psi = Altitude \\ \varphi = 180 - Azimuth \end{cases} \quad (1)$$

The zenith angle in the spherical coordinate system is $\theta = 90 - \psi$.

The tracker is pointed at the Sun by rotation about the horizontal axis at the zenith angle $\theta$ and about the horizontal axis at the azimuthal angle $\varphi$. The optical tracker model of the pointing controller in the open loop mode is described in the matrix form $\mathbf{M}_{tr}$ by two rotations $\mathbf{R}_z(\varphi)$ and $\mathbf{R}_y(\theta)$ [17]:

$$\mathbf{M}_{tr} = \begin{pmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}. \quad (2)$$

These rotations describe transition from the Earth's coordinate system at the observation site to the coordinate system attached to the tracker whose unit vector $(x_t, y_t, z_t)$ points at the Sun:

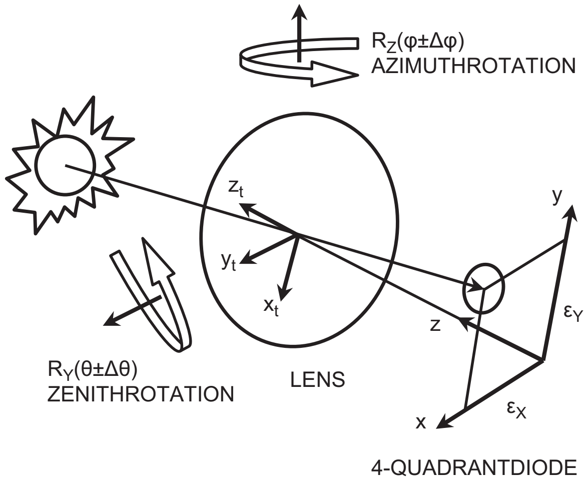


**Fig. 1.** Optical system of the position sensor of the altazimuth tracker (view from the north side). Small angular deviations of the tracker form Sun's position appear as small deviations $\varepsilon_x$ and $\varepsilon_y$ of the Sun image in the $xoy$ coordinate system of the quadrant photodiode.

$$\begin{pmatrix} x_t \\ y_t \\ z_t \end{pmatrix} = \mathbf{M}_{tr} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \quad (3)$$

Exact pointing at the Sun and its tracking support in the controller are carried out in the close-loop mode. Fig. 1 shows a simple optical scheme of the position sensor of the altazimuth tracker. The optical axis of the position sensor is aligned with the optical axis of the tracker. In this pointing system, a 4-quadrant photodiode is placed on the same axis with the lens in the image plane. Rotation of $\mathbf{R}_z(90^\circ)$ at $90^\circ$ about the $z$-axis transforms the coordinate system of the tracker into the coordinate system of the sensor. Small angular deviations $\Delta\varphi$ and $\Delta\psi$ of angles $\varphi$ and $\psi$ in tracker pointing at the Sun are perceived as small displacements, $\varepsilon_x$ and $\varepsilon_y$, of the solar image in the $xoy$ coordinate system of the photodiode. This close-loop model is simple, and the paraxial optics approximation can be used for its synthesis. In the first approximation, the control signals $d_\theta$ and $d_\varphi$ of the position controller can be considered linear in $\Delta\varphi$ and $\Delta\psi$:

$$(\Delta\theta, \Delta\varphi) \propto (\varepsilon_x, \varepsilon_y) \propto (d_\theta, d_\varphi). \quad (4)$$

The optical scheme of the altazimuthal tracker is complicated because of the necessity of Sun tracking and aligning of the radiation incidence direction with the input spectrometer axis. The special feature here is the fixed position of the sensor. We designed, manufactured, and tested the sun tracker whose scheme is shown in Fig. 2 (the technical details are given in Section 4). It consists of two 45° mirrors $M1$ and $M2$ rotatable about the orthogonal axes. Additional mirror $M0$ directs the light beam to the spectrometer along its input optical axis. The position sensor comprises a fixed lens and a 4-quadrant photodiode. Signals from the 4-quadrant photodiode are used