New Astronomy 47 (2016) 105–110

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Modeling and calibration of pointing errors with alt-az telescope

Long Huang[a,b,*], Wenli Ma[a], Jinlong Huang[a]

[a] *Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China*
[b] *University of Chinese Academy of Science, Beijing 100039, China*

HIGHLIGHTS

- I/we use the Denavit-Hartenberg convention to analyze kinematics of an alt-az telescope.
- A physical model is established to illustrate the effects of geometric errors.
- An improved hybrid model denoted as SPRM model is developed to compensate for remaining nonlinear errors.
- The measured experiment confirmed that the proposed SPRM model provides higher accuracy than does the conventional KM.

ARTICLE INFO

Article history:
Received 24 October 2015
Accepted 24 February 2016
Available online 3 March 2016

Communicated by E.P.J van den Heuvel

Keywords:
Pointing error
Alt-az telescope
Error analysis
SPRM

ABSTRACT

This paper presents a new model for improving the pointing accuracy of a telescope. The Denavit–Hartenberg (D–H) convention was used to perform an error analysis of the telescope's kinematics. A kinematic model was used to relate pointing errors to mechanical errors and the parameters of the kinematic model were estimated with a statistical model fit using data from two large astronomical telescopes. The model illustrates the geometric errors caused by imprecision in manufacturing and assembly processes and their effects on the pointing accuracy of the telescope. A kinematic model relates pointing error to axis position when certain geometric errors are assumed to be present in a telescope. In the parameter estimation portion, the semi-parametric regression model was introduced to compensate for remaining nonlinear errors. The experimental results indicate that the proposed semi-parametric regression model eliminates both geometric and nonlinear errors, and that the telescope's pointing accuracy significantly improves after this calibration.

1. Introduction

Telescopes and similar Electro-Optical systems are used for a wide variety of scientific, military, and commercial applications. Good repeatability and low jitter are necessary requirements of modern telescopes, but accuracy required for telescopes far exceed the capability of most manufacturing processes. In order to lower machine costs and improve telescope's pointing accuracy, the pointing process should be studied in detail. Therefore, modeling and calibration techniques appropriate for determining the terms of mechanical errors and improving pointing accuracy are necessary. Pointing errors may affect the operational efficiency in a tracking system (Keitzer et al., 1991), system accuracy for laser ranging (Chen and Yan, 2009), or throughput in a communication system (Prabu et al., 2014).

Common software used for astronomical telescopes, STARCAL (Keitzer et al., 1991) and TPOINT (Wallace, 1993), are used in many other large telescopes. Both methods use a physical error approach. The TPOINT program also includes arbitrary polynomial and harmonic terms. Lewis et al. (1994) described the mount modeling process utilized for the W. M. Keck telescopes, which are currently the largest in the world. That process uses five physical errors and three empirical harmonic corrections. From first light to November 1993, predicted pointing performances was ~7.5" rms. At TPOINT calibration, its modeled pointing improved to about 3" rms. The Multiple Mirror Telescope (MMT) is similar to those used for large radio telescopes and presented results from a pointing model fitted for the MMT using observations made through a small auxiliary telescope. Meeks (2003) analyzed the telescope mechanical error using the pointing data and explored four methods to make a precise estimate of the physical errors that affect telescope pointing. Hong et al. (2013) used a semi-parametric regression method to analyzed and model nonlinear parameters, improving the pointing accuracy of inertially stabilized platforms. Donato et al. (2007) used single pixel method and star track method to accurately determine the absolute pointing of the fluorescence detector telescopes. Tang et al. (2014) analyzed the contributions of integrant geometric error sources using of quaternions, and established a

* Corresponding author at: Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China. Tel.: +86 18682770976; fax: +86 2885100033.
E-mail address: cdhuanglong@163.com (L. Huang).

http://dx.doi.org/10.1016/j.newast.2016.02.007
1384-1076/

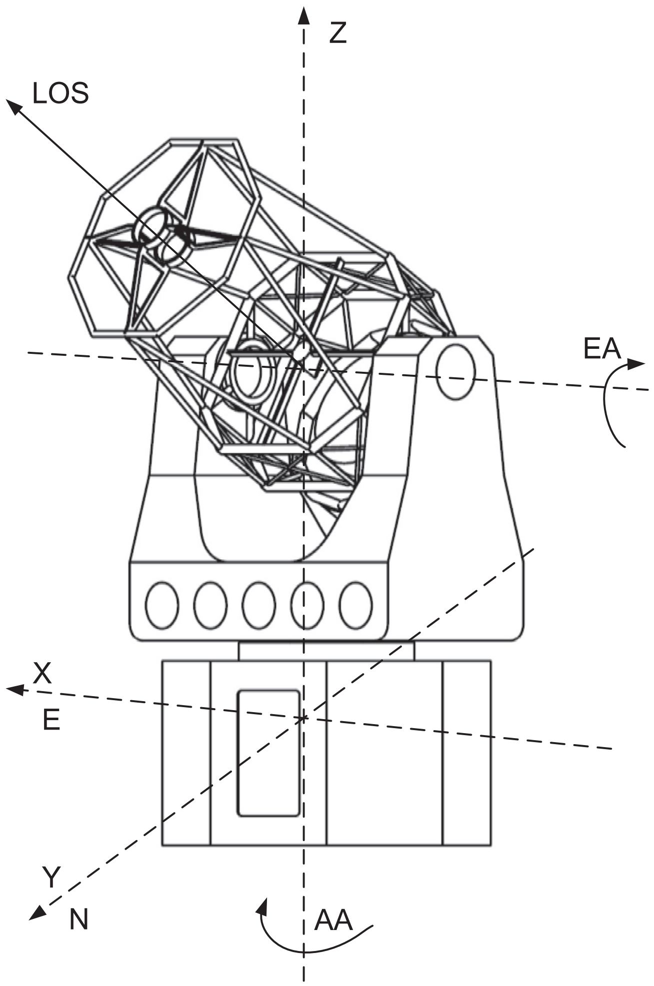

Fig. 1. Model of telescope and references coordinate.

parametric model. There are two main methodologies regarding modeling and calibration pointing errors, the first is based on a numerical analysis of the pointing data, like the Spherical Function. The second approach is based on the analysis of error sources during the machining processes, which includes identifying the physical relationships of the pointing errors and developing a physical mathematical model using a kinematic method.

Determining the coefficients for correction model of pointing error is a type of parameter identification problem. The solution to a parameter identification problem is a set of values for the parameters that best achieves a stated objective. When making corrections of pointing, the goal is to find a set of parameter that optimizes the performance of model. This is a common approach to many optimization problems and is referred to as the least squares method. For its objective the TPOINT program uses the sum of the squared pointing errors from the reference stars. In his work, Everett (1993) suggests a weighted least squares approach and describes an objective function that accounts for the amount of workspace each measurement represents. The research of the semi-parametric regression model has existed a lot of estimate methods, such as partial spline estimations (Engle et al., 1986), kernel smoothing estimations (Hardle, 1991), and Penalized Least square Estimations (Green and Silverman, 1994). This work employed PLS to estimate the appropriate parameters of SPRM.

2. Telescope modeling and error analysis

The telescope mount is illustrated in Fig. 1. A telescope performs two basic functions: pointing to an object of interest and redirecting light from a source into an instrument or detector. A wide variety of telescope designs are currently in use, but most of them share this function commonality, which is reflected in a uniform architecture seen in most modern telescopes. A telescope employs a two degrees-of-freedom motion system. The basic kinematic representations consist of two rotation motions (rotation about the azimuth axis and the elevation axis). Similar kinematic modeling has been employed in the robotic and radar fields, though they have different numbers of degrees-of-freedom (Hsu and Wang, 2007). The goal of telescope mount modeling is usually to predict the pointing error at a particular location and use it to determine appropriate corrections to apply to eliminate the error in the future.

Errors that affect pointing arise during a telescope's manufacturing, assembly, installation, and operation. The major error sources (Zhang and Wu, 2001; Zheng et al., 2004) are shown in Fig. 2. Estimating or measuring the individual parameters, and

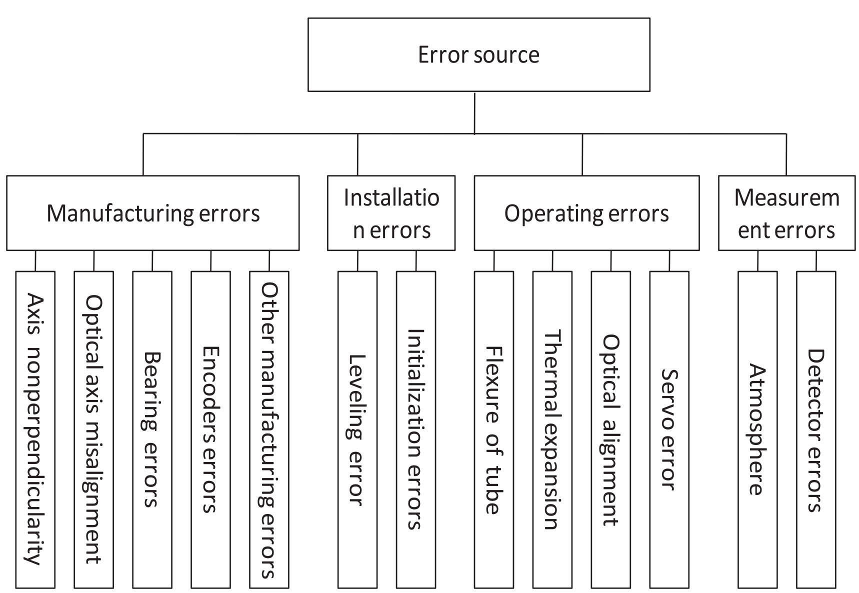

Fig. 2. Telescope error sources.