

# Air-LUSI: An Autonomous Robotic Telescope for High-Altitude Lunar Spectral Irradiance Measurements

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## ABSTRACT

The airborne lunar spectral irradiance (air-LUSI) mission is an inter-agency partnership between the US National Aeronautics and Space Administration and the US National Institute of Standards and Technology. Air-LUSI aims to make SI-traceable measurements of lunar spectral irradiance at visible to near-infrared wavelengths with unprecedented accuracy. To minimize uncertainty, lunar spectra are acquired above 90% of the Earth's atmosphere aboard NASA's Earth Resources aircraft, a civilian descendant of the U-2 spy plane. The data collected by the air-LUSI instrument is poised to improve upon current lunar calibrations of Earth observing satellites.

The air-LUSI team recently completed their Operational Flight Campaign in Palmdale, California in March 2022. In addition to the Engineering Flight Campaign of August 2018 and the Demonstration Flight Campaign of November 2019, the air-LUSI instrument has been successfully deployed on over ten lunar spectral measurement flights at altitudes of roughly 21 km. This paper presents the simplified double gimbal design that was capable of recently tracking the Moon with a root mean square tracking error of less than  $0.1^\circ$ .

**Keywords:** Airborne science, target tracking, lunar irradiance, machine vision

## 1. INTRODUCTION

The air-LUSI mission continues efforts to establish the Moon as a calibration source for Earth observing satellites.<sup>1-6</sup> It is a partnership between the US National Aeronautics and Space Administration (NASA) and the US National Institute of Standards and Technology (NIST), in collaboration with the US Geological Survey (USGS), the University of Maryland, Baltimore County (UMBC), and McMaster University (formerly University of Guelph). The primary mission objective is to acquire measurements of lunar spectral irradiance with unprecedented accuracy. With this improved knowledge of the Moon, the accuracy of Earth observing satellites can be improved, contributing to better remote sensing capabilities of the orbiting radiometric sensors responsible for monitoring the health of our planet. The accuracy of previous, ground-based work aimed at characterizing the radiometric properties of the Moon has suffered in part because of atmospheric absorption. To improve the accuracy of lunar spectral irradiance (LUSI) measurements, one must reduce the effects of the atmosphere and enforce rigorous calibration controls. Air-LUSI solves the first problem by measuring from a high-altitude, airborne platform, NASA's ER-2 aircraft – a civilian descendent of the U-2 spy plane. At altitudes up to 21 km, LUSI measurements are captured above 90% of the Earth's atmosphere, thereby reducing the effects of scattering and absorption. The second problem is solved by deploying NIST-maintained radiometric artifacts to the ER-2 hangar for pre- and post-flight calibration, as well as by incorporating on-board radiometric validation sources in the measurement system.

The airborne instrument includes the IRradiance Instrument Subsystem (IRIS), which includes a spectrometer connected to a telescope and was designed and built by NIST using a commercially available spectrometer. The IRIS telescope is maneuvered from a stow position to a zenith view port, acquires and locks onto the Moon for measurement, and then moves back to the stow position when the observations are complete. To facilitate the

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telescope movement and lunar tracking, air-LUSI uses its Autonomous Robotic Telescope Mount Instrument Subsystem (ARTEMIS). The team at McMaster University developed the ARTEMIS to use a double gimbal, endowing the telescope with degrees of freedom in azimuth and elevation.<sup>7</sup> Linear actuators were used as a variable length linkages to incite rotation about each degree of freedom.<sup>8-10</sup> The ARTEMIS control system uses a simplified approach to control the pointing of the telescope when compared to other inertially stabilized systems that are commonly implemented for target tracking.<sup>11</sup> The simplified system treats both the azimuth and elevation axes as completely independent degrees of freedom and implements two distinct single input single output controllers for both axes. The control system relied entirely on the data obtained from a machine vision tracking camera which performed simplified image processing techniques to extract targeting information while keeping sampling rates high and overall delay low.<sup>12-14</sup>

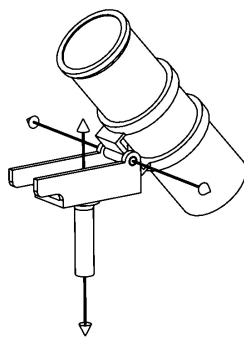
This brief paper presents the mechanical and control system design of the ARTEMIS, which is capable of tracking the Moon with a root mean squared error of less than  $0.1^\circ$ . Preliminary results of air-LUSI's Operational Flight Campaign are also shown, with an emphasis placed on actuator health and tracking performance.

## 2. DESIGN OVERVIEW

### 2.1 Mechanical Design

This section describes the mechanical design of ARTEMIS. A steel U-channel frame simplifies integration with the ER-2's science pod, which allows for rapid upload and offload of the robotics system. The robotics' load bearing structure is comprised of 1" x 1" aluminum 6061-T6 square tubing, for which a detailed mechanical design and loading analysis has been completed to satisfy the requirements of the Airworthiness Committee at NASA's Armstrong Flight Research Center.<sup>15</sup>

The robotic telescope employs two independently controlled linear actuators to automate the telescope's azimuthal and elevation viewing angles, the dynamics of which are a result of the double gimbal mechanism. One linear actuator is mounted on the structural frame that supports the outer gimbal, and uses a rod-end ball joint to attach to a spindle crank. This provides the moment arm that is used to adjust the telescope's azimuthal pointing angle. Another linear actuator was mounted within the inner gimbal and connects to the telescope's trunnion platform, allowing for the stroke position to adjust the pointing elevation of the telescope. Figure 1a and 1b below illustrate the rotational axes and in flight configuration of the ARTEMIS.



(a) Double gimbal rotational axes.



(b) CAD rendering of the ARTEMIS.

Figure 1: The Autonomous Robotic Telescope Mount Instrument Subsystem.

## 2.2 Control System Design

The control computer is an Intel<sup>®</sup> NUC running Ubuntu 16.04. The Robotic Operating System (ROS) middleware is responsible for message passing between the numerous software modules of the control system, which will now be explained. The control system is best described as Line of Sight (LoS) controller, which requires visual feedback to ascertain the error between the current viewing subject and the desired target.

ARTEMIS relies on a Basler 2.3 megapixel monochromatic machine vision camera to determine the location of the moon within a captured frame. A compressed grayscale image is passed to the image processing routine, which utilizes the open-source ROS package OpenCV.<sup>16</sup> The pixel error between the moon and a predetermined pixel coordinate is extracted through a series of simple image processing techniques.<sup>17</sup> The pixel error is then passed to a PID controller which calculates a pair of control signals – one for each axis. Recall that a pair of closed loop controllers are used to treat the elevation and azimuth degrees of freedom as independent single input single output systems, which greatly simplified the development of the control software. Figure 2 below illustrates the signal flow within the robot’s control software. Dotted lines represent outgoing status packets, namely the pixel error and actuator positions. The solid arrows show the transfer of control signals (such as target position, setpoint, and control effort) between software routines of the robot. The ellipses represent communication interfaces between subsystems and to the ground crew via the NASA-provided airborne science data and telemetry system (NASDAT).

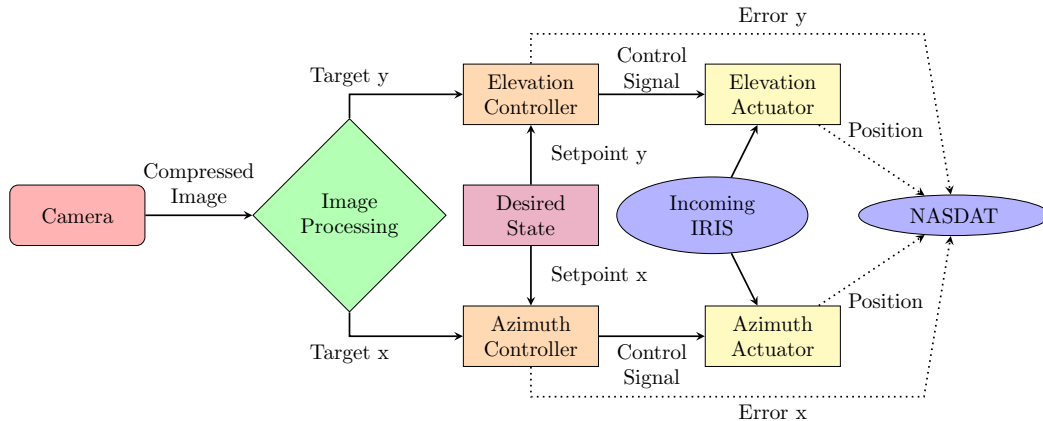


Figure 2: Signal flow diagram for the autonomous robotic telescope mount instrument subsystem.

## 3. OPERATIONAL FLIGHT CAMPAIGN: TRACKING RESULTS

From March 3<sup>rd</sup> to March 22<sup>nd</sup> 2022, the air-LUSI science team deployed to NASA’s Armstrong Flight Research Center (AFRC) in Palmdale, California to complete an Operational Flight Campaign. The air-LUSI instrument accomplished four high-altitude flights occurring over the nights of March 12<sup>th</sup>-16<sup>th</sup>, losing one flight opportunity to inclement weather. This section presents some issues encountered in the field as well as the robotic tracking performance during flight. For brevity, only results from the flight of March 14<sup>th</sup> 2022 are presented.

The following figures show the position, temperature, and torque profiles of each actuator during the 40-minute tracking window. Access to real-time data allowed the mission control team to have eyes on the actuators’ health and immediately address issues should something go askew – such as a drastic rise in temperature or a consistent over-torque error. The figures can be understood as a measure of the actuators’ health and performance during the lunar acquisition window.

The temperature profiles for each actuator are well within the expected range, which is -40 °C to +85 °C for the specific actuator models in use. The cyclic temperature profiles are due external heating elements which are controlled by the IRIS subsystem.

The azimuth position plot shows an azimuthal angle viewing bias. Note that an actuator position of 20000 corresponds with a “centered” azimuthal angle (i.e., perpendicular to the direction of aircraft travel). The

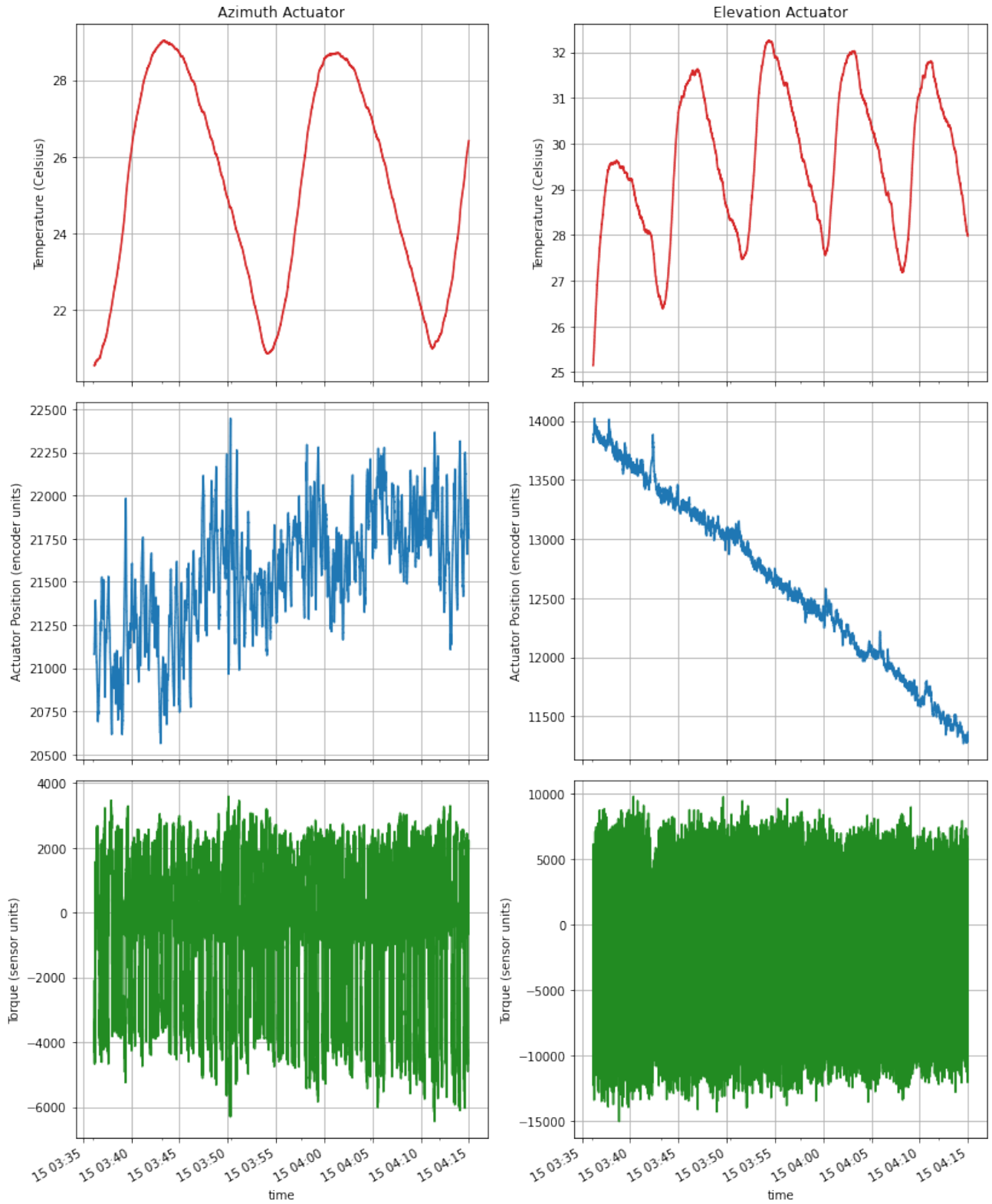


Figure 3: Actuators' data feedback during the March 14<sup>th</sup> tracking window. Times are in UTC.

kinematics of the system are such that a stroke position greater than 20000 corresponds to an azimuthal viewing angle that tends toward the front of the aircraft. The flight lines are designed such that the moon should always be perfectly  $90^\circ$  to the aircraft's direction of travel. The slight forward bias is an indication that the airplane may not be travelling in the direction of its heading, which is known as drift and may be a result of cross-wind. There is another source of angular displacement inherent to the aircraft that is unknown, such as misalignment of the supporting rack in the wing's science pod (e.g., it is not perfectly aligned with the aircraft frame). This is a significant source of risk as the forward positional limit for the azimuth actuator is 23000, which means the actuator will lock out at this position and a manual recovery is required – which is costly in terms of resources and time.

The torque profiles offer little information other than to confirm that no dangerous levels of torque were encountered. The maximum continuous torque for the actuator models is 14000 arbitrary units, which was not approached in the azimuth. However, it was likely exceeded in the elevation actuator. Note that the actuators are capable of handling short (2 s) bursts of torque up to 28000 units provided they are not sustained over a long period of time.

Tracking performance data from the March 14<sup>th</sup> flight will now be presented. The tracking error is evaluated by the  $(x, y)$  pixel offset in the machine vision camera frame, corresponding to the azimuthal and elevation error respectively. The total tracking error is then given by the radial offset between the Moon's center coordinates and the pixel setpoint coordinates. For the particular camera and lens combination used on the ARTEMIS, the conversion from pixel space to angle space is  $0.053^\circ/\text{pixel}$ . This conversion factor is applied to the radial pixel offset to determine if the ARTEMIS was satisfying the less than  $0.5^\circ$  offset requirement. The next plots illustrate the tracking accuracy of ARTEMIS.

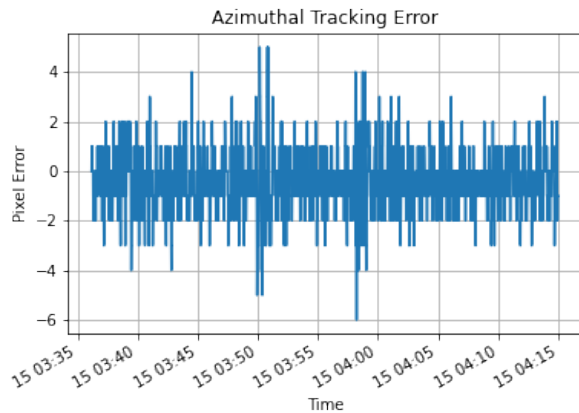


Figure 4: Azimuthal pixel error.

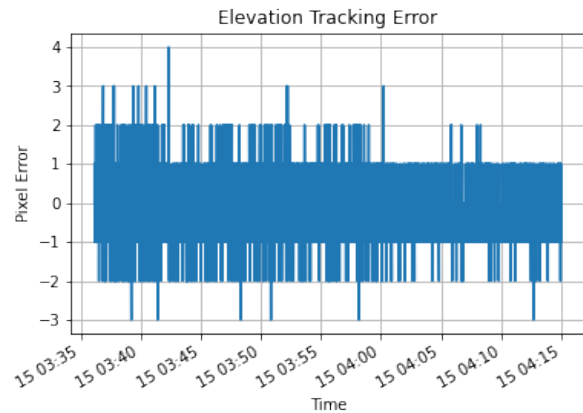


Figure 5: Elevation pixel error.

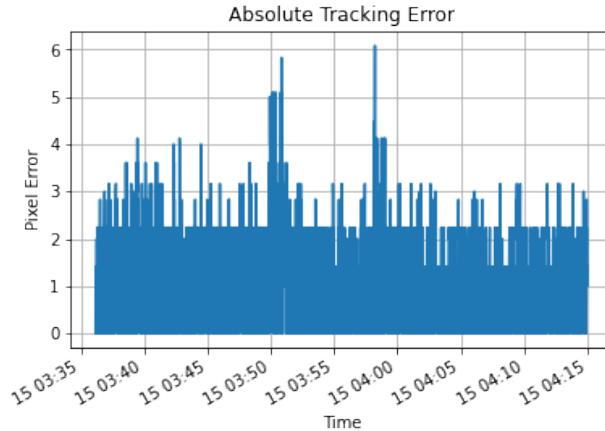


Figure 6: Total pixel error.

The pixel error plots demonstrate a successful lunar tracking window on the night of March 14<sup>th</sup> 2022. The elevation axis tracked slightly better than the azimuthal axis, but there were no off-target measurements made during the 40-minute window as evidenced by Fig. 6. The pixel/angle conversion factor stated above corresponds to a maximum of 9 pixels offset, which was not exceeded. The average tracking error for this flight was  $0.059^\circ$ , with a median error of  $0.053^\circ$  (1 pixel) and a root mean square error (RMSE) of  $0.071^\circ$ . This surpasses the mission constraint of  $0.5^\circ$  of accuracy. ARTEMIS has contributed to the acquisition of some of the first high-altitude lunar spectral data sets used within the science community.

#### 4. CONCLUSIONS

The air-LUSI system was deployed on an Operational Flight Campaign from March 3<sup>rd</sup> to March 22<sup>nd</sup> 2022. During this time, the ARTEMIS subsystem tracked the Moon with an RMSE tracking accuracy of less than  $0.1^\circ$ . This was the third deployment of the air-LUSI system, with successful field campaigns in August 2018 and November 2019. The stability of the tracking system during these deployments enabled the first ever measurements of lunar spectral irradiance from a high-altitude platform.

The simplified approach of treating the two telescope axes as independent by using two single input and single output controllers proved effective and greatly simplified the control software development. Although treated independently, the two closed-loop controllers for azimuth and elevation axes compensated for most of the aircraft and lunar motions, and produced tracking accuracy that exceeded the design team's expectations.

Radiometric characterization of the telescope is ongoing. The air-LUSI instrument is expected to be used throughout the coming years to compile several lunar irradiance data sets for a wide range of lunar phases relevant to satellite calibration. With enough data, a highly accurate lunar spectral irradiance model can be created. This model can be used to further calibrate Earth observing satellites and allow for more accurate monitoring of our planet.

#### 5. ACKNOWLEDGMENTS

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