Impact of the 2022 Hunga Tonga–Hunga Ha‘apai Eruption on Cislunar Space Situational Awareness

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ABSTRACT

On January 15th 2022, the submarine volcano Hunga Tonga–Hunga Ha‘apai erupted and released an ash plume which reached the stratosphere. This is the largest eruption witnessed since the eruption of Mount Pinatubo in the Philippines in 1991, which famously cooled global temperatures due to the injection of volcanic aerosols into the stratosphere. Although much research studies the climatological impacts of large volcanic eruptions in which ash plumes reach the stratosphere, considerably less research exists on the impact of the inclusions of these new aerosols on night sky brightness and the impact to ground based optical telescope performance. Increased sky brightness due to volcanic aerosols can degrade optical capabilities significantly, especially when performing cislunar SSA in moonlight. Furthermore, modeling the impact of fresh volcanic aerosols is problematic, as radiative transfer modeling software such as MODTRAN generalizes volcanic ash and neglects considerations of specific plume properties; the same is true of astronomical models’ considerations of stratospheric volcanic ash.

While the recent Hunga Tonga eruption did not eject nearly as much material into the stratosphere as Mt. Pinatubo, satellites and ground-based instruments recorded an unprecedented amount of data which allows for comprehensive analysis of the eruption’s plume, and by extension it’s impact on ground-based optical SSA. Current optical instrument performance is designed to meet sensitivity requirements of a dark sky with little margin of error, so even small increases to night sky brightness due to aerosols could disrupt SSA coverage, particularly for cislunar space. This work begins with an overview of stratospheric volcanic aerosols and their impact on optical instruments and SSA, followed by a summarization of satellite and ground-based measurements of the Hunga-Tonga eruption specifically pertaining to fresh volcanic aerosol stratospheric injection and diffusion. These measurements include data from the following instruments: NOAA’s GOES-West satellite, NASA’s CALIPSO mission, ESA’s Copernicus Sentinel-5P mission, balloon-borne in-situ measurements made by an international collaboration of researchers, and AERONET which makes use of CIMEL photometers. This data is compared to a literature review of historical published information about the introduction of volcanic ash into the stratosphere by Mount Pinatubo in 1991.

Additionally, this study considers the night sky brightness in Tucson, Arizona using the University of Arizona’s Pomenis Observatory for the nights following the eruption of Hunga-Tonga, providing sufficient time for the plume’s stratospheric aerosols to travel globally. These night sky brightness measurements are compared to theoretical results derived from MODTRAN simulations as well as past results at similar lunar illuminations and photometric conditions to identify potential impacts of Hunga-Tonga’s stratospheric aerosols on cislunar SSA. Relevant values and plots are presented demonstrating this comparison, and differences between night sky brightness measurements are presented. Discussion of results emphasizes the need to consider unpredictable explosive volcanic eruptions in planning national and international cislunar SSA to improve resiliency of cislunar object tracking. Recommendations for the SSA community stemming from this research include advancing plume tracking research to better understand impact on ground-based optical instruments as large stratospheric ash plumes disperse over time and utilizing information of stratospheric plume chemical composition to improve stratospheric radiative transfer models from that data.

1. INTRODUCTION

Current SSA ground based optical telescope performance is designed to meet sensitivity requirements in dark sky with little margin. Increased sky brightness due to volcanic aerosols can degrade performance significantly, especially in moonlight. Increased concentrations of volcanics aerosols in the stratosphere increases the amount of backscattering light, leading to a brighter sky which can compromise SSA coverage, especially when observing resident space objects at low lunar elongation angles.

Many studies pertaining to this recent eruption, and other large eruptions in the last several decades, have focused specifically on the effect of local and global cooling related to increased volcanic aerosols in the atmosphere as opposed to atmospheric viewing conditions. This may be due to the interest of its effects of counteracting human-made climate change, which occurred with global cooling from Mount Pinatubo in 1991 [1]. Furthermore, astronomical models for calculating night sky brightness from radiative transfer calculations do not always consider the volume and chemical composition of extremely fresh and high-volume volcanic eruptions. It is only in recent years that the plethora of both ground-based and space assets have allowed for more intricate analyses of the multiple global impacts of explosive volcanic plumes that have global impacts.

The Volcanic Explosivity Index (VEI) is a logarithmic scale for bulk volume of ejected mass into the stratosphere, which might cause changes in night sky brightness [2]. The most recent volcano with significant stratospheric aerosol injection was Mount Pinatubo in the Philippines in 1991. That is a 6 out of 8 on the VEI scale; the last 7 out of 8 event was 1815 and the last 8 out of 8 event was in 26,500 BC [3]. The Hunga Tonga eruption reached a 5 out of 8 on the VEI scale, indicating that some stratospheric injection was possible [4]. The likelihood of lasting stratospheric aerosol injection from the Hunga Tonga eruption when considering that the stratosphere begins at 15 kilometers altitude, and the eruption's plume reached higher than 30 kilometers [5].

Despite the height of the volcanic plume from the Hunga Tonga eruption, without knowing the chemical composition of the plume, it possible that the majority material ejected into the stratosphere was just water vapor, not sulfuric-based aerosols which cause light-backscattering. As a result, measuring changes of global night sky brightness requires instrumentation and measuring programs.

This study features *in-situ* results of cislunar night sky brightness results from University of Arizona's Pomenis astrograph located in Tucson, Arizona. By comparing the results before and after the eruption at similar moon illuminations, we can determine if there is any significant observable difference in brightness magnitude, and by extension potential impact on cislunar space situational awareness capabilities. Prior to assessing these results and comparing them to MODTRAN radiative transfer modeling results, we shall present and summarize various global impacts of the Hunga Tonga undersea eruption as a means of summarizing research efforts on this eruption thus far.

2. LITERATURE REVIEW

Because of the timing of this paper's publication relative to the eruption (roughly eight months after the event), most information sources related to ongoing studies from the undersea eruption derive from non-peer reviewed science communication articles. Perhaps the most famous result of the Hunga Tonga eruption was the shockwave heard around the world: the sheer force of the eruption, equivalent to ten megatons of TNT, generated pressure waves in the atmosphere that rippled globally, passing over the Earth multiple times before finally dissipating in the atmosphere [6]. These pressure waves acted as a low frequency 'ringing'; the Earth's atmosphere rang like a struck bell. This event had not been witnessed in prior eruptions and provided evidence for the theories posited by mathematician Pierre-Simon de Laplace following the 1883 eruption of Krakatoa [6].

Evidence for this global atmospheric phenomenon is available in never-before possible resolution thanks to the variety and quality of scientific instruments always monitoring the globe. One example of such an instrument the atmospheric infrared sounder (AIRS) aboard NASA's Aqua satellite, which yielded temperature data that researchers at the Jülich Supercomputing Centre in Germany used to create Figure 1 [7]. This figure helps visualize the pressure waves rippling from the Hunga Tonga undersea eruption by using temperature in the stratosphere as a proxy for atmospheric pressure propagation [7]. While these pressure waves might not directly influence night sky brightness magnitude globally, this phenomenon acts as an example of the global reach of this volcanic eruption and the necessity to delve deeper into the lesser understood impacts of volcanic eruptions and plume dissipation.

Another representation of these pressure waves can be seen in Figure 2, derived from another space-borne mission: NOAA's GOES-West satellite, which produces infrared radiance data spaced 10 minutes apart. The sequence of images in Figure 2 was generated at the University of Massachusetts Lowell and shows a time-lapse of the progression of the pressure wave [7]. This wave moved much faster than the volcanic plume which contains the aerosols that might impact cislunar SSA. That being said, pressure waves such as these might also have impacts on SSA if the stratospheric composition in a region is changed from this phenomenon, finally observed after over 200 years [6].

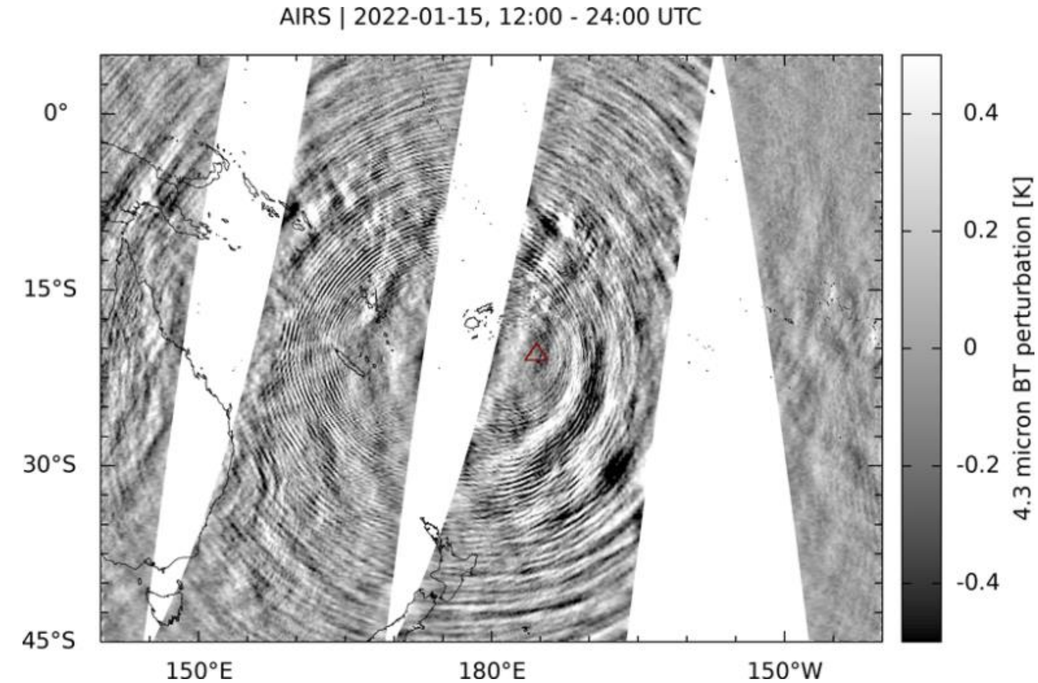

Fig. 1. NASA Aqua Satellite data mosaic from the Jülich Supercomputing Centre in Germany showing temperature reading ripples in the stratosphere above Hunga Tonga–Hunga Haʻapai that may be acoustic-gravity waves [7].

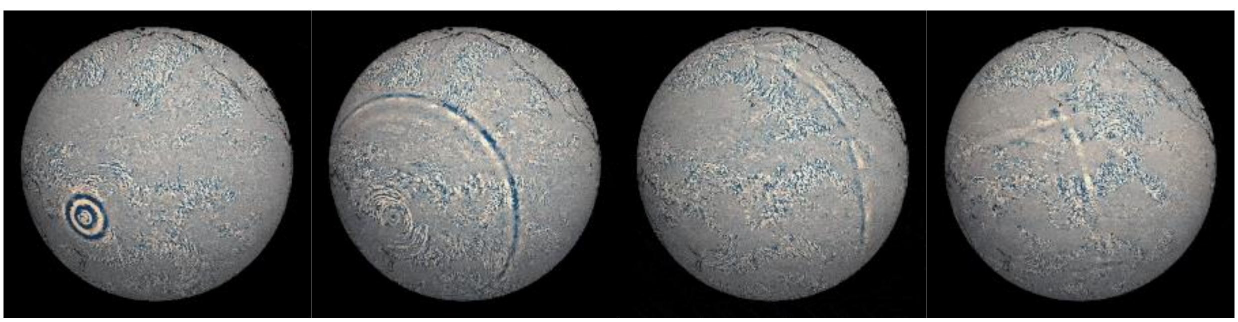

Fig. 2. NOAA Goes-WEST Satellite data compiled at the University of Massachusetts Lowell demonstrating the global pressure wave and its back-propagation until attenuation using infrared radiance data [7].

Some space-borne instruments were able to investigate the compositional properties of the Hunga Tonga eruption plume, though they do not speak of the plume's potential impact on either localized or global night sky brightness changes, or even more specifically for a moon-light sky while observing objects at low lunar elongation angles. Having compositional information on the plume's ash can help with modeling potential effects. The Copernicus Sentinel-5P satellite monitors air pollution, specifically sulfur dioxide [8]. Sulfur dioxide could be a good proxy to study newly added volcanic sulfuric aerosols and the path of the volcanic plume, as shown in Figure 3.

Another space-borne instrument was able to measure aspects of the Hunga Tonga eruption plume. Figure 4 shows data compiled from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission [5]. Not only does this figure show the low height of the stratospheric boundary near Tonga, but it also demonstrates that the volcanic plume did in fact reach well into the stratosphere, increasing the potential that this specific volcanic eruption, and those like it, could affect cislunar space situational awareness through altering night sky brightness. that was able to characterize the height of the plume. The NOAA has estimated that approximately .4 teragrams of sulfuric dioxide weas injected into the stratosphere, roughly 2% of the amount introduced by the eruption of Mt. Pinatubo in 1991 which decreased temperature globally [5].

Fig. 3. Sulfur Dioxide from Tonga eruption spreads over Australia as the plume travels West in the stratosphere. Data captured by the ESA Copernicus Sentinel-5P mission [8].

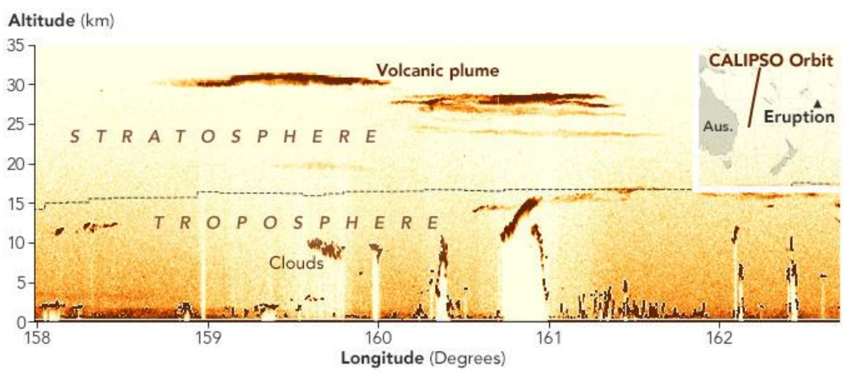

Fig. 4. Graph compiled from the NASA CALIPSO space-based LIDAR instrument showing that the height of the Hunga Tonga eruption plume introduced ash and sulfur dioxide gas aerosols well into the stratosphere [5]

Soon after the eruption on January 15th 2022, researchers from University of Houston and St. Edwards University launched a balloon from an island in the Indian ocean called La Réunion to study the plume after it had traveled 8,000 miles West [5]. The balloon's maximum altitude was 30km, close to where the volcanic plume is shown in Figure 4. The researchers developed a sulfur dioxide detector to better understand how the volcanic plume impacts stratospheric aerosol composition [5]. This research can be very helpful for estimating night sky brightness when conducting feasibility studies for ground-based cislunar space situational awareness systems which have the stratosphere in their optical path. This data may be available in the future for atmospheric radiative transfer modelers; for the meantime, it remains a work in progress due to the recentness of the Hunga Tonga eruption.

Aside from space-borne or balloon-borne instruments measuring plume height and composition, some research has leveraged ground-based photometers and the international program for aerosol measurements, AERONET. AERONET comprises of photometers located nationwide produced by the company CIMEL and a central repository maintained by NASA to hold historical data on both a local and global scale [9]. During the time that the Hunga Tonga plume travelled across Australia, AERONET used its photometers to coordinate observations on daytime solar data, not night-time sky brightness. They were able to produce results measuring the Aerosol Optical Depth of the plume, as well as aerosol particle volume size distribution as seen in Figure 5 [10]. The variation in aerosol optical depth and particle size may indicate an ongoing process of sulfur dioxide gas conversion into sulfate particles which may disappear as the plume travels West and the chemical reaction has had more time to complete [10].

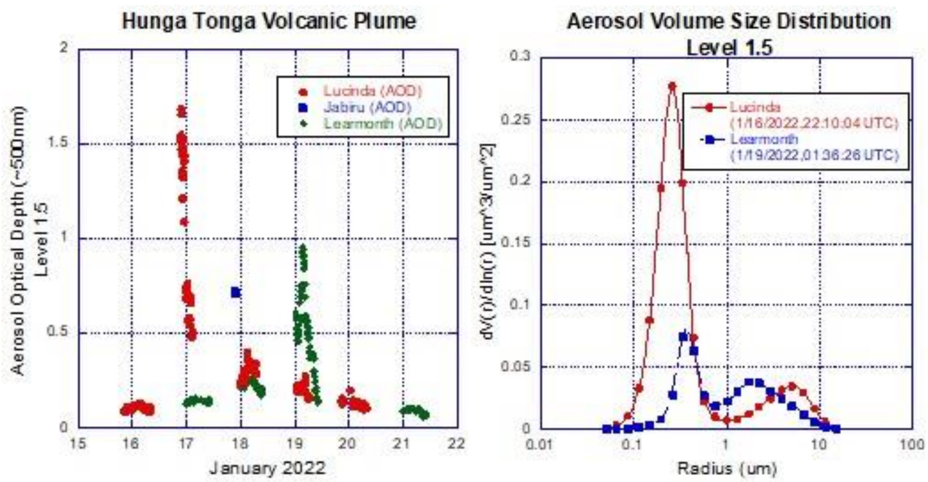

Fig. 5. Left plot shows the aerosol optical depth as a function of time at each of three CIMEL sun photometers AERONET sites in Australia. Right plot shows aerosol size distribution at two of the stations [10].

3. METHODOLOGY

With the knowledge gained from the measurements of space-borne, balloon-borne, and ground-based systems of the Hunga Tonga eruption, we can say that there is potential for a noticeable global increase of stratospheric aerosol content composition, and by extension an increase in night sky brightness due to longer photon attenuation times due to more backscattering. To check if there is a noticeable difference, this paper leverages the University of Arizona Pomenis astrograph observation program which enables high-speed multi-color photometry [11]. Pending favorable observing conditions, Pomenis takes cislunar night sky brightness measurements by choosing points radially around the lit moon and interpolating results in-between those points for night sky brightness magnitude.

An example of the results of this process is shown in Figures 6 and 7 for the night of February 9th, 2022, several weeks following the Hunga Tonga undersea eruption. This is the date used to determine the potential impact of brightness before and after the eruption on January 15th, 2022. While Figure 6 shows a polar plot showing the expected decrease of night sky brightness further away from the moon (centered within the saturated zone), Figure 7 shows the sky points observed on a rectilinear representation of right ascension and declination.

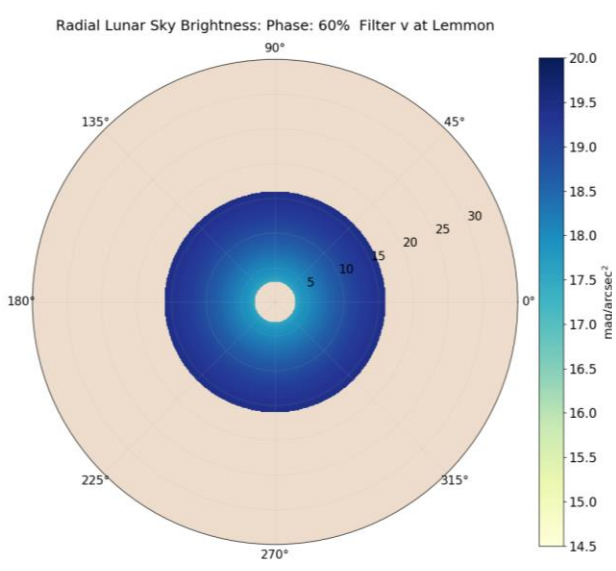

Fig. 6. Plots the average brightness in each observed V-filter ring with interpolation between each ring.

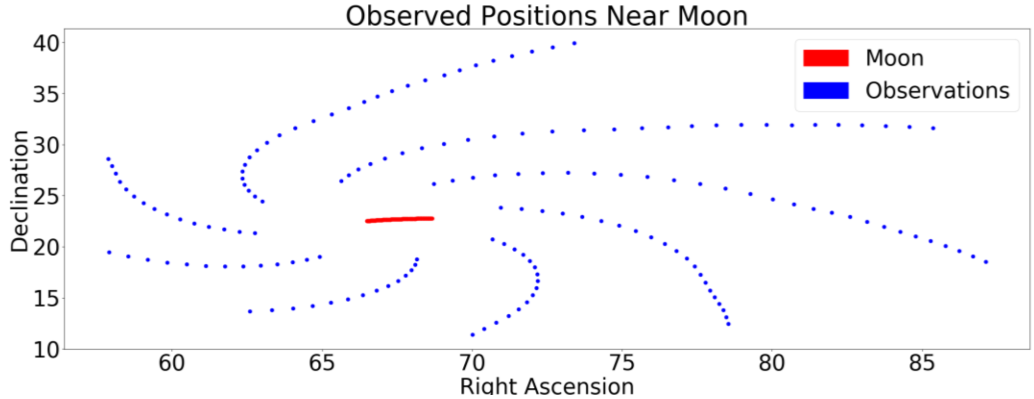

Fig. 7. Plots the sky points observed on a rectilinear representation of right ascension and declination.

We compare the night sky brightness measurements taken on this night to nights prior to the eruption, but with a similar moon phase or illumination percentage. For each night, plots are generated to show the magnitude of each point measurement taken in each color band with respect to its angle of separation from the moon, as well as a comparison of actual values of night sky brightness to theoretical results from the Krisciunas moon model [12]. An example of this plot for the night of February 9th-10th is shown in Figure 8. This figure is particularly helpful for comparison to other computationally intensive radiative transfer modeling software that might produce different results to both the Krisciunas moon model and the actual results, highlighting a shortcoming in our understanding of fresh volcanic stratospheric activity on cislunar night sky brightness.

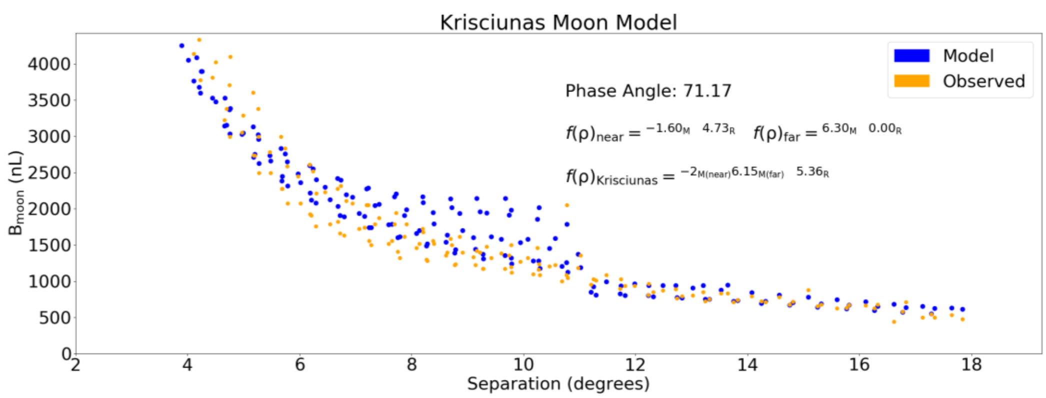

Fig. 8. Plots the expected brightness values of the Krisciunas model with the observed values generated from his equations using the V-filter only.

By comparing the results from each observed night, we can see if there are any observable differences after the eruption in night sky brightness across multiple photometric color bands.

4. RESULTS & DISCUSSION

On the night of February 9th-10th, the moon was illuminated by roughly 66%. The night with the that illumination that was measured closest to but still before the eruption was either 11/11/21 or 11/12/21, illuminated at roughly 50% and 66% respectively. For a simple preliminary analysis, Table 1 summarizes the average night sky brightness from all measured observations on each night, with their corresponding number of measurements. In this table, because magnitude scales logarithmically, a lower number indicates a brighter sky. As such, the results from Table 1 are expected with or without a volcanic eruption: the lowest illumination has the weakest magnitude, while the highest illumination has the highest magnitude.

Night	Night Sky Brightness Average Magnitude	Number of Measurements	Illumination
11/11/2 – 11/12/21	18.401	465	50%
11/12/21 – 11/13/21	18.258	537	66%
2//9/22 – 2/10/22	18.261	640	60%

Table 1. Summarization of nights sky brightness average results taken with the University of Arizona Pomenis astrograph on three different nights, before and after the eruption of the Hunga Tonga-Hunga Ha'apai.

From this information is not possible to determine whether there is any impact to night sky brightness from volcanic injection of stratospheric aerosols. To determine if there are any band-specific observable differences, Figure 9 shows a side-by-side comparison of the measurements with respect to their lunar separation angle in degrees. For the most part, these plots are largely similar. While the night of 2/10 may have data that appears closer together in magnitude range, that night has the most observations out of the three nights may create an illusion of density.

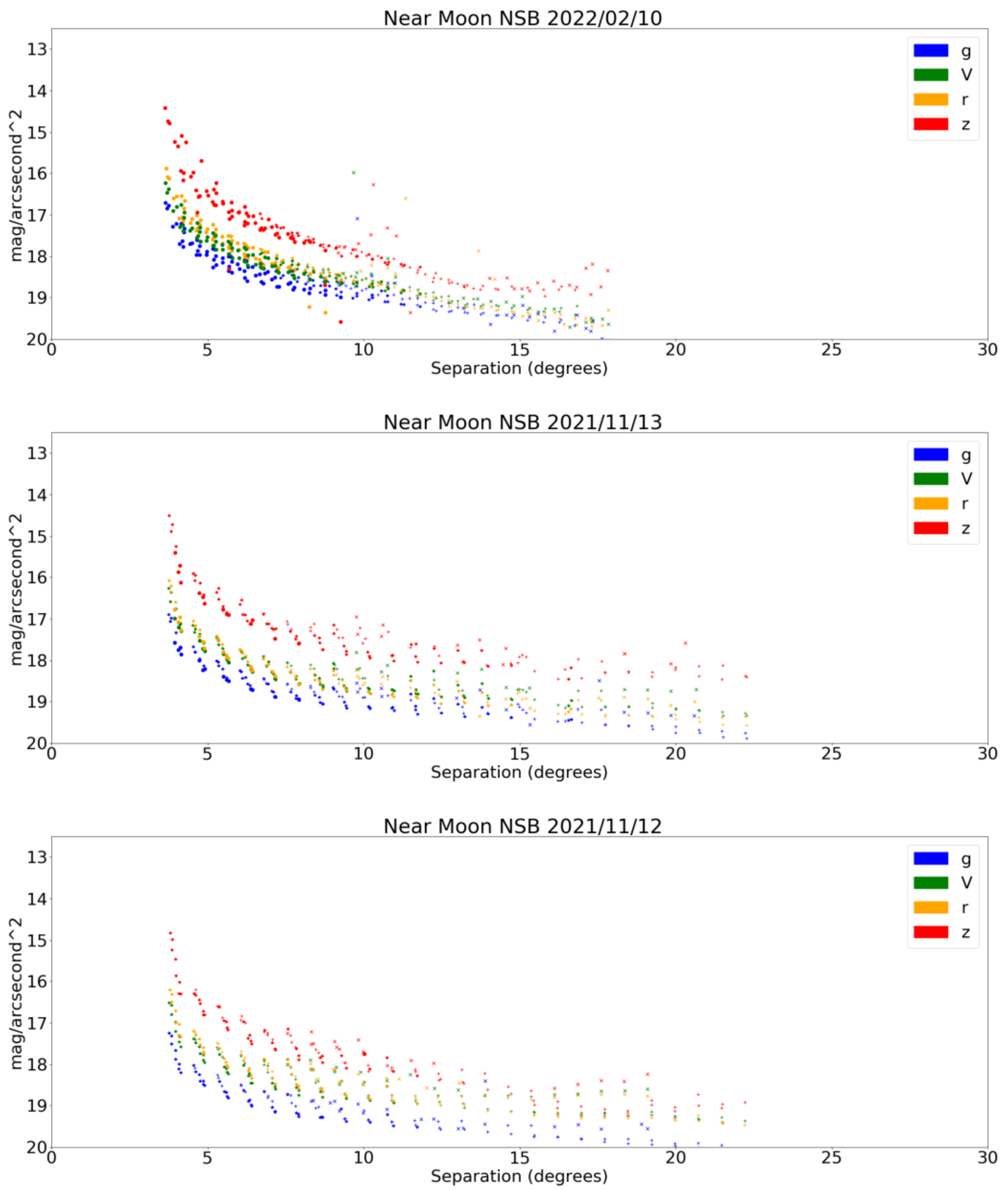

Fig. 9. Plots the magnitude of each filter with moon separation for similarly illuminated nights pre/post-eruption.

The results presented in figures 7 and 8 do not provide conclusive evidence of increased aerosol content or by extension in increased night sky brightness post-eruption. Pomenis' sky quality monitor did not show any abnormalities on the night of 2/10 compared to 11/11 or 11/12 in terms of sky temperature and humidity, which would impact results. However, this information is the inception of a study of stratospheric plume impact on cislunar space situational awareness, a phenomenon which until now was unobservable due to a lack of instrumentation. Using a network of photometers like AERONET and its daytime observations might help determine changes in global night sky brightness due to significant volcanic events.

MODTRAN radiative transfer modeling software can replicate night sky brightness measurements under similar conditions to those on 2/9/22. MODTRAN is one of the most advanced radiative transfer software available [13], containing the ability to simulate multiple scattering in the atmosphere, and the ability to swap between different atmospheric models rapidly and determine the most accurate representation of the experimental setup of Pomenis in Tucson.

A MODTRAN model comparable to Pomenis' 2/9/22 measurements might include the following settings: a band model in lunar irradiance run mode with DISORT multiple backscattering pointed at the observer, a mid-latitude winter atmospheric model to simulate Tucson, Arizona in February, a desert aerosol model (or a custom model), one of multiple volcanic stratospheric models (i.e. high volcanic fresh, extreme volcanic fresh, etc.), and viewing geometries based on a the location of the Pomenis astrograph as shown in Figure 10.

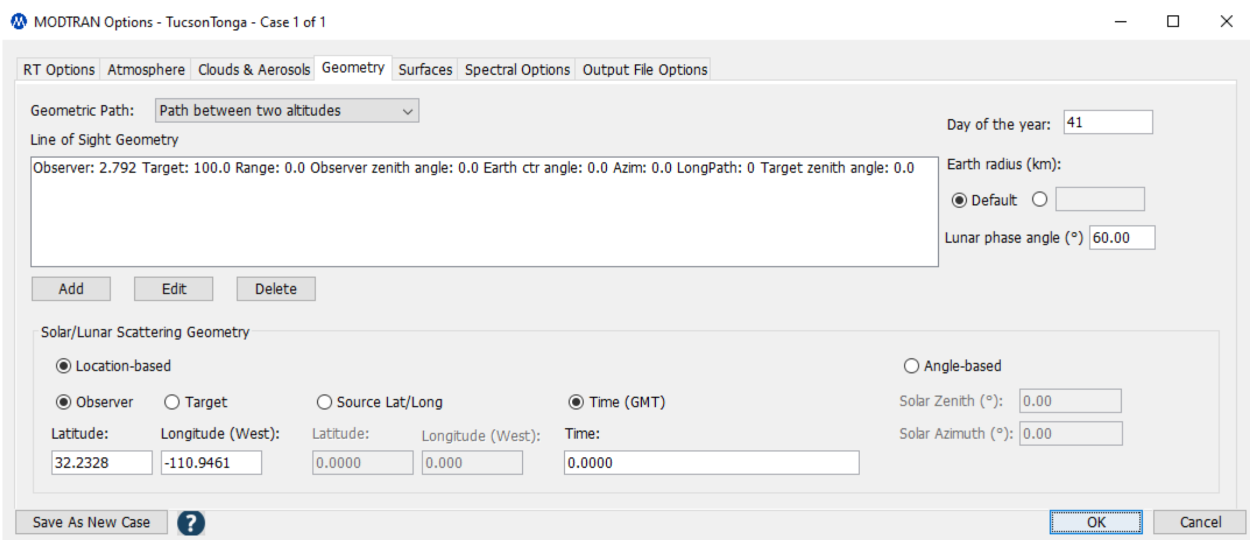

Fig. 10. MODTRAN GUI Geometry panel demonstrating an observer at the location of the Pomenis astrograph in Tucson, Arizona, pointing at its local zenith to take one measurement.

Determining the MODTRAN settings which would best replicate conditions following the Hunga Tonga eruption requires additional trade studies between different atmospheric and aerosol models for locations where the plume was experimentally monitored. For an area like Tucson where global impacts of stratospheric aerosol injection are less understood, even further investigation is required to alter factors such as aerosol optical densities to move beyond the preset models available through MODTRAN and fine-tune details. The results from these MODTRAN simulations would produce transmittance and radiance values which are used to calculate values for simulated night sky brightness given the provided scenario conditions. These MODTRAN simulation results serve as an important foil to experimental results and theoretical mathematical moon model results to examine the disparities between expected values between models of different fidelities, and the actual observed results.

With the data obtained through multiple nights of observations both before and after the Tonga eruption, and evaluation of the capabilities of MODTRAN radiative transfer simulation software, it is not possible to state definitively that there was an SSA impact seen in Tucson, Arizona due to introduction of volcanic aerosols into the stratosphere from the Hunga Tonga eruption. However, a change in cislunar sky brightness still may have occurred.

5. **CONCLUSION**

The eruption of Hunga Tonga–Hunga Haʻapai in early 2022 created a never-before possible opportunity to study the impact of significant volcanic aerosol introduction into the stratosphere. Generally, adding these large aerosols increases photon backscattering, by extension increasing sky brightness. Many cislunar space situational awareness systems operate with very small margins of error when considering atmospheric properties and night sky brightness; understanding the changes in cislunar sky due to volcanic activity is imperative to ensure total coverage of resident space objects of interest. Failure to properly accommodate for stratospheric changes in an SSA instrument's optical path can lead to potential loss of target tracking.

Perhaps the most reported observed phenomenon related to the Hunga Tonga eruption was the atmospheric pressure wave ripple effect visualized in Figures 1 and 2 using thermal data. There have never been sufficient satellites and ground-based stations to observe this low-frequency 'ringing' effect, which was first theorized hundreds of years ago but never witnessed. While these atmospheric pressure waves might impact localized and global concentrations of stratospheric aerosols, this effect would be much less than the more direct impact of volcanic aerosol stratospheric injection.

The Hunga Tonga plume reached well into the stratospheric boundary with clear sulfur dioxide contributions as measured by multiple space systems as seen in Figures 3 and 4. After eruption, the Hunga Tonga plume moved West over Australia, where researchers were able to leverage the international AERONET photometry system to determine optical properties of the plume shown in Figure 5. This type of data is invaluable for generating localized MODTRAN simulations to determine changes to night sky brightness; a photometry network like the daytime photometers used by AERONET could help study the impact of global volcanic activity on cislunar night sky brightness worldwide.

The beginning of such a network exists with the Pomenis astrograph in Tucson, Arizona which captured data for night sky brightness in multiple color bands on nights of similar illuminations both before and after the Hunga Tonga eruption. The methodology behind the data capture was to observe point values of sky brightness at increasing elongation angles radially distancing from the moon, creating concentric rings with interpolated values in between. This process is shown through Figures 6 and 7. The measured values are compared to expected values for equivalent conditions run through theoretical Krisciunas moon model, shown in Figure 8, as a means of demonstrating the disparity between the more complex, less understood conditions in actual observations compared to expected values.

The results from the Pomenis observations averaged and summarized in Table 1 do not show conclusively that a change occurred due to an increase of stratospheric volcanic aerosols due to different lunar illumination levels on the different nights. The individual color bands separated in Figure do have some visible differences, but his might be caused by the different quantities of measurements taken on each night. Expanding this analysis to include additional nights in the past with similar illuminations and expected atmospheric conditions may yield more insights into whether there was a noticeable change in night sky brightness magnitude after the Tonga eruption, after the plume and its associated sulfur dioxide had time to travel globally.

Experimenting extensively with MODTRAN radiative transfer modeling software may yield values for transmittance radiance matching either observed values or theoretical Krisciunas moon model expected values; however, this would require inputting custom aerosol models deriving from localized aerosol optical density measurements such as those shown in Figure 5. Adding multiple geometries for observer viewing paths would replicate the Pomenis observation schedule, generating a simulated ring measurement to compare to Figure 6.

The exact impacts of significant explosive volcanic activity on global night sky brightness and cislunar space situational awareness remain unknown. Evidence exists that increased backscattering can occur, but without knowledge of the concentration gradients through the global stratosphere as the plume travels, pinpointing numerical changes of magnitude remains difficult. Additional research is required of the scientific community to ensure that space situational awareness of cislunar resident space objects is not lost due to unpredicted explosive volcanic activity. Coordinating efforts of worldwide photometers like the AERONET system can achieve the goal of adequately preparing cislunar SSA operators for future volcanic eruptions.

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