

# Stereo Plume Height and Motion Retrievals for the Record-Setting Hunga Tonga-Hunga Ha’apai Eruption of 15 January 2022

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## Abstract

Stereo methods using GOES-17 and Himawari-8 applied to the Hunga Tonga-Hunga Ha’apai volcanic plume on 15 January 2022 show overshooting tops reaching 50-55 km altitude, a record in the satellite era. Plume height is important to understand dispersal and transport in the stratosphere and climate impacts. Stereo methods, using geostationary satellite pairs, offer the ability to accurately capture the evolution of plume top morphology quasi-continuously over long periods. Manual photogrammetry estimates plume height during the most dynamic early phase of the eruption and a fully automated algorithm retrieves both plume height and advection every 10 minutes during a more frequently sampled and stable phase beginning three hours after the eruption. Stereo heights are confirmed with Global Navigation Satellite System Radio Occultation (GNSS-RO) bending angles, showing that most of the plume was lofted 30-40 km into the atmosphere. Cold bubbles are observed in the stratosphere with brightness temperature of  $\sim 173\text{K}$ .

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2 **Stereo Plume Height and Motion Retrievals for the Record-Setting Hunga Tonga-**  
3 **Hunga Ha’apai Eruption of 15 January 2022**  
4

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12

13 **Key Points:**

- 14 • The Hunga Tonga-Hunga Ha’apai eruption of 15 January 2022, lofted material above 30  
15 km to record-breaking heights of ~55 km.
- 16 • Our stereo-winds code retrieved height and motion vectors from GOES-17 and  
17 Himawari-8 every 10 minutes immediately after the event.
- 18 • Radio Occultation bending angles confirm plume altitudes.  
19

## 20 **Abstract**

21 Stereo methods using GOES-17 and Himawari-8 applied to the Hunga Tonga-Hunga Ha’apai  
22 volcanic plume on 15 January 2022 show overshooting tops reaching 50–55 km altitude, a record  
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25 ability to accurately capture the evolution of plume top morphology quasi-continuously over  
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28 every 10 minutes during a more frequently sampled and stable phase beginning three hours after  
29 the eruption. Stereo heights are confirmed with Global Navigation Satellite System Radio  
30 Occultation (GNSS-RO) bending angles, showing that most of the plume was lofted 30–40 km  
31 into the atmosphere. Cold bubbles are observed in the stratosphere with brightness temperature  
32 of ~173K.

## 33 **Plain Language Summary**

34 The Hunga Tonga-Hunga Ha’apai volcano in the South Pacific erupted violently on January 15,  
35 2022. A volcanic plume from the eruption was lofted into the stratosphere to altitudes that are  
36 unprecedented in the era of satellite observations. We observed the highest part of the plume at  
37 55 km and tracked the motion of the plume in 3D in the vicinity of the volcano for a seven-hour  
38 period, every 10 minutes, using imagery from the geostationary GOES-17 and Himawari-8  
39 satellites that are positioned at different locations on the equator. The apparent shift in the plume  
40 as seen from two different vantage points contains information about the plume height and the  
41 apparent movement of the plume as it is repeatedly observed by one satellite contains  
42 information about the plume velocity. We confirmed our height observations using radio  
43 occultation measurements that NOAA uses to profile the atmosphere. Radio waves are normally  
44 bent as they pass through the atmosphere from satellite to satellite, nearly grazing the Earth’s  
45 surface, but when radio waves pass through the volcanic plume, there is an anomalously large  
46 change in bending angle.

## 47 **1 Introduction**

48 The Hunga Tonga-Hunga Ha’apai eruptions of January 2022 culminated in a dramatic  
49 event on 15 January 2022. The plume from this underwater eruption was captured in imagery  
50 from the geostationary GOES-17 and Himawari-8 satellites beginning just after 04:00Z.  
51 Applying stereo methods to this imagery, we show that the 15 January 2022 eruption lofted a  
52 volcanic plume well above the tropopause and into the stratosphere, with the highest  
53 overshooting tops reaching altitudes of 50–55 km, a record in the satellite era. Determining the  
54 height of volcanic plumes has an important implication for their dispersion and transport in the  
55 atmosphere as well as their lifetime impacts on Earth’s climate. Although other observational  
56 techniques exist to estimate volcanic plume heights, including the temperature method, LiDAR  
57 (e.g., CALIOP), and UV limb sounding (e.g., OMPS), only stereo methods using geostationary  
58 satellite pairs offer the ability to accurately capture the evolution of plume top morphology  
59 quasi-continuously over long periods. We use manual photogrammetry to estimate plume height  
60 during the most dynamic early phase of the eruption and a fully automated algorithm to retrieve  
61 both plume height and advection every 10 minutes during a more frequently sampled and stable  
62 phase beginning three hours after the eruption. Global Navigation Satellite System Radio

63 Occultation (GNSS-RO) bending angles similarly show that the bulk of the plume was lofted 30–  
64 40 km into the atmosphere.

## 65 **2 Materials and Methods**

66 We rely on stereo methods previously developed at NASA for tracking wind tracers from  
67 multiple satellites (“stereo winds”). These tools have already been applied to stereo observations  
68 from Himawari-8 and MODIS of the 2019 eruption of Raikoke (Horváth et al., 2021a and  
69 2021b). The stereo-winds code for a geostationary pair is fully described in Carr et al. (2020). It  
70 offers the ability to retrieve both the height and the motion of a volcanic plume automatically and  
71 nearly continuously until the eruption dies down and the plume becomes too tenuous to track  
72 effectively. A similar approach has been applied to the study of an eruption of Mt. Etna in 2013  
73 using a pair of Meteosat satellites (Merucci et al., 2016).

74 We use geostationary satellite imagery from GOES-17 nominally stationed at 137.2°W  
75 and Himawari-8 nominally stationed at 140.7°E. Both satellites have nearly identical 16-channel  
76 imagers and capture the Earth’s Full Disk (FD) every 10 minutes. Both imagers have similar  
77 capabilities to acquire smaller sectors with shorter refresh times. In particular, GOES can acquire  
78 an approximately 1000×1000 km<sup>2</sup> Mesoscale (MESO) scene every 1 minute. NOAA centered a  
79 MESO scene over the eruption at 07:05Z to begin covering the volcano every minute. Before  
80 07:05Z, the volcano was only covered in the FD scenes repeating every 10 minutes. Stereo-  
81 winds feature tracking works better when the time between scene repetitions is shorter. At the  
82 beginning of this eruption, as the radius of the plume top expanded at a mean radial speed of ~50  
83 m s<sup>-1</sup> from ~20 km at 04:10Z to ~55 km at 04:20Z and to ~80 km at 04:30Z, features that  
84 otherwise could be tracked morphed quickly in the billowing and rapidly expanding plume. This  
85 made automated feature tracking more difficult using the 10-minute GOES-17 FD scenes.  
86 Therefore, we focused our use of the stereo-winds code on GOES-17 MESO scenes paired with a  
87 single near-simultaneous Himawari FD and used manual photogrammetry (stereo and shadow  
88 analysis) with FD pairs before 07:05Z. For example, the Himawari FD beginning at 07:00Z,  
89 starts above the North Pole and progresses towards the south, reaching the volcano around  
90 07:06Z; therefore, we pair GOES MESO scenes at 07:05Z, 07:06Z, and 07:07Z with the single  
91 07:00Z Himawari FD scene. This pattern repeats every 10 minutes. The sun has already set at  
92 the volcanic site by 07:00Z, so we use the long-wave Band 14 (B14) with a center wavelength at  
93 11.2 μm and spatial resolution of 2 km for both satellites.

94 Simultaneous stereo pairs are not required by the stereo-winds code as pixel acquisition  
95 times are used in the retrieval model. In our case, the 07:06Z GOES-17 MESO and the 07:00Z  
96 Himawari FD differ from exact simultaneity by either ~10 s, ~40 s, or ~70 s across the mesoscale  
97 domain depending on which of the three 30-s swaths of the Himawari FD that cover the  
98 mesoscale domain contain the pixel. The apparent displacement of a feature between images  
99 represents a combination of motion and geometric parallax that the model separates knowing the  
100 pixel times.

101 Our manual photogrammetry relies on the highest resolution (0.5 km) GOES and  
102 Himawari red band (0.64 μm) FD pairs with a typical non-simultaneity of ~30 s in each 10-  
103 minute slot. Prata and Grant (2001) and Horváth et al. (2021a) give a detailed description of the  
104 method. In short, the height of a feature visually matched in the two images is determined from  
105 the ellipsoid-projected parallax between the match points and the corresponding satellite  
106 view/azimuth angles. The method can also be applied to apparent shadows observed in a single

107 image. The second satellite view is effectively replaced by the solar-projected location of the  
108 feature, i.e., the shadow terminus. Note that the method can estimate the height but not the  
109 motion of a feature. The shadow variant has the advantage of only requiring a single image.  
110 Still, sampling is limited to shadowed areas, and it can be challenging to pinpoint the exact  
111 location of the shadow terminus due to the blurring effect of a penumbra.

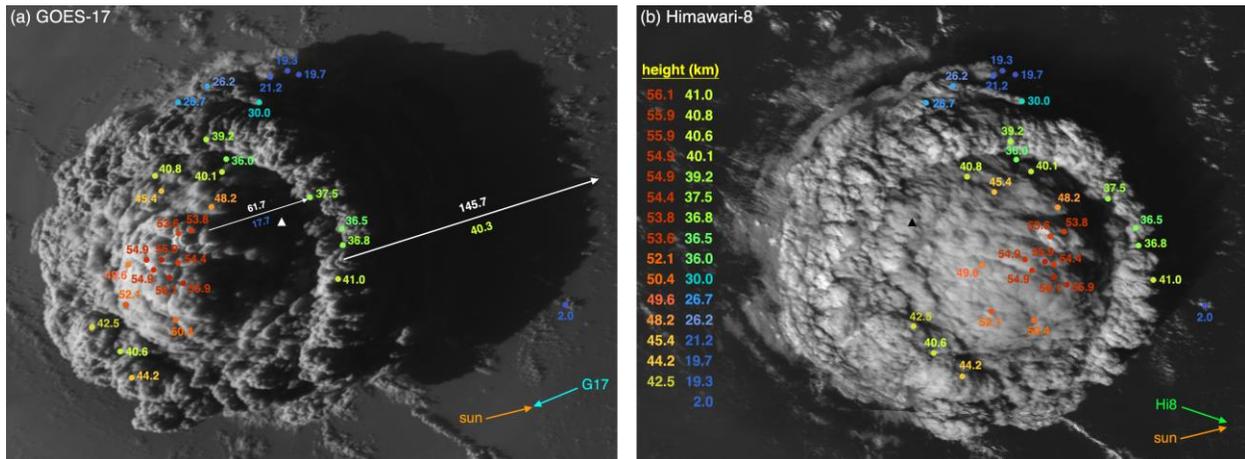
112 Manual feature matching between two satellite images of the plume is relatively  
113 straightforward; however, the horizontal and vertical motion of the feature introduces a height  
114 error due to any non-simultaneity between views. In our case, the GOES-17 and Himawari-8  
115 view zenith/azimuth angles are around  $50^{\circ}/66^{\circ}$  and  $55^{\circ}/71^{\circ}$ , respectively. This stereo geometry  
116 leads to a parallax almost precisely in the east-west direction, and a height error of  $\sim 0.4$  km for  
117 every 1 km parallax error (see Eq. 8 in Horváth et al., 2021a)—the corresponding height error  
118 sensitivity for our shadow geometry is  $\sim 0.3$  km per 1 km parallax. In the early phases of the  
119 eruption, the velocity of the fastest moving plume element is  $\sim 50$  m s<sup>-1</sup> in both the horizontal and  
120 vertical directions. During the 30 s between the satellite views, this results in a  $\sim 1.5$  km  
121 horizontal movement and a  $\sim 1.5$  km vertical rise, the latter of which translates to a  $\sim 3.7$  km  
122 parallax increase. In the worst case, when these motion parallax errors add up, the total parallax  
123 error is  $\sim 5.2$  km, amounting to a  $\sim 2$  km height overestimation. Vertical velocity can be negative  
124 (but smaller in magnitude) when overshooting tops collapse. There can also be partial  
125 cancellation between the motion parallax errors, depending on the direction of the horizontal  
126 velocity. Therefore, a  $\pm 2$  km height uncertainty is expected for the most dynamic plume features  
127 (although overestimation is more likely than underestimation), which is acceptable considering  
128 the extreme heights encountered. Both manual photogrammetry and stereo-winds methods are  
129 most accurate when the motion is predominantly perpendicular to the local vertical and stereo  
130 pairings are nearly simultaneous.

### 131 **3 Results**

#### 132 **3.1 Manual Photogrammetry**

133 Figure 1 shows the maximum height estimates found at 04:30Z. The plume resembled a  
134 stack of pancakes with several identifiable layers, capped by a large central dome (see the  
135 contrast-enhanced Supplementary Exhibit S1). Heights were calculated for thirty plume  
136 retrievals and one low-level cloud at 2 km altitude serving as a reference. The stereo retrievals  
137 indicate layers at 20–21 km, 26–27 km, and the massive topmost ring of  $\sim 80$  km radius at 38–40  
138 km. There are significant km-scale variations within this rugged topmost ring, demonstrating the  
139 sheer dynamism of the explosive rise. Most remarkably, the central dome reached an altitude of  
140  $\sim 55$  km. The retrievals show a systematic increase in height as sampling ascends from the base  
141 to the dome's peak. A rough estimate of peak height from applying the side view method of  
142 Horváth et al. (2021a) to the corresponding GEO-KOMPSAT-2A image is in Supplementary  
143 Exhibit S2. The GOES-17 view was favorable for applying the shadow method and is unaffected  
144 by motion effects. The long white arrow marks the apparent shadow of a local peak in the  
145 topmost ring, cast on the ocean surface. For a solar zenith/azimuth angle of  $68^{\circ}/108^{\circ}$ , the 145.7  
146 km shadow length corresponds to a plume edge height of  $\sim 40$  km, in good agreement with the  
147 nearby GOES-17–Himawari-8 stereo estimates. The shorter white arrow indicates the shadow of  
148 a dome feature cast on the ring. This 61.7 km long shadow corresponds to an  $\sim 18$  km height  
149 differential relative to the  $\sim 38$  km altitude of the ring feature at the shadow terminus, consistent

150 with a peak dome altitude of  $\sim 55$  km within the expected tolerance of  $\pm 2$  km. Shadow-based  
 151 plume height estimates for the 04:50–05:00Z time slots are also in Supplementary Exhibit S3.



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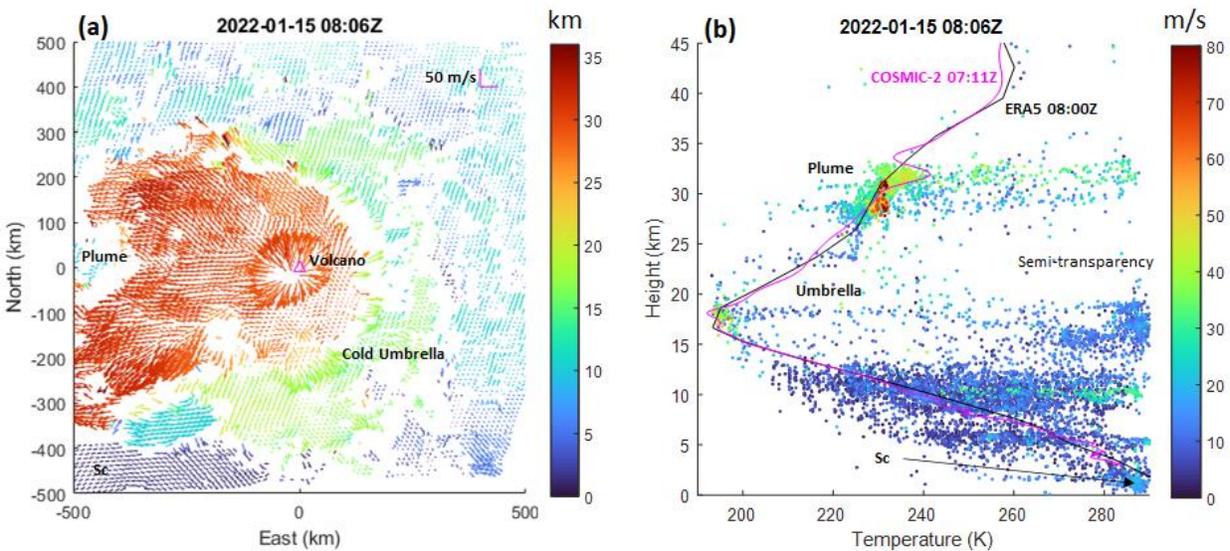
153 **Figure 1.** Image of the plume on 15 January 2022 at 04:30Z from (a) GOES-17 and (b)  
 154 Himawari-8. Colored dots mark manual stereo height estimates (in km), and the triangle shows  
 155 the volcano's location. The white arrows in panel (a) depict the shadow of a plume edge feature  
 156 and a dome feature, with the shadow length and the derived height given above/below the arrow.  
 157 Arrows in the lower right of each panel indicate the sun-to-pixel and satellite-to-pixel azimuths.

### 158 3.2 Automated Stereo-Winds Method

159 The stereo-winds method was applied after 07:05Z when NOAA placed the GOES-17  
 160 MESO1 scene on the volcano. The 1-minute cadence of the MESO scenes is nearly ideal as it  
 161 allows enough time for motion to be observed but leaves feature shapes sufficiently invariant to  
 162 be accurately tracked with subpixel precision. Figure 2a shows the jointly retrieved stereo  
 163 heights, and advection vectors for 08:06Z (uses GOES-17 MESO scenes at 08:05Z, 08:06Z,  
 164 08:07Z) paired with the Himawari 08:00Z FD. Smaller tracking templates allow for a higher  
 165 resolution characterization of the plume geometry and dynamics, but this must be balanced  
 166 against tracking accuracy. We selected 16x16 pixel templates (32 km feature spatial resolution)  
 167 and oversampled the scene 4:1 (8 km sampling). A lofted stratospheric plume mostly above 30  
 168 km is seen over a lower cold umbrella at  $\sim 18$  km near the tropopause. The expansion and  
 169 westward drift of the plume is evident from the advection vectors. Accompanying temperature  
 170 assignments have been made according to the Effective Blackbody Temperature (EBBT) of the  
 171 tracking templates taken from the 08:06Z MESO scene. Templates lower than 22 km (cold  
 172 umbrella and troposphere) are presumed to be cold targets over warmer backgrounds and are  
 173 assigned the mean temperature of the 20% coldest pixels. Templates 22 km and above are  
 174 expected to be warmer than the cold umbrella and are assigned the mean temperature of the 20%  
 175 warmest pixels because of the negative stratospheric lapse rate. However, where the plume  
 176 becomes optically thin (effectively semi-transparent) near its edges, heat from the troposphere  
 177 below makes the templates appear warmer than expected in the stratosphere up to 35 km ( $> 240$   
 178 K). In such cases, a colder pattern is being tracked over a warm background, and the 20%  
 179 coldest pixels are averaged to be more representative of the plume temperature. This approach to

180 temperature assignment is similar in concept to that proposed by Borde, et al. (2014) where the  
 181 assignment is being made based on the pixels that are most important for feature tracking.

182 ERA5 and GNSS-RO temperature profiles are provided in Figure 2b for context, which  
 183 may not be entirely accurate in the presence of volcanic ash; however, the EBBTs of both the  
 184 plume and tropospheric clouds broadly follow and cluster near both profiles. Deviations from  
 185 the profiles are indicative of challenges with temperature-based height assignment, which in  
 186 general is complicated by inversions, semitransparency, undercooling, temperature assignment  
 187 uncertainty, and targets with emissivity less than one. Additional confidence in the stereo  
 188 retrievals is gained by noting that the field of marine stratocumulus (Sc) clouds in the SW  
 189 quadrant of the mesoscale domain has stereo heights between 500 m and 1.5 km. These are  
 190 within expectations for such clouds and match well with the NOAA temperature-based cloud top  
 191 height product for this scene.

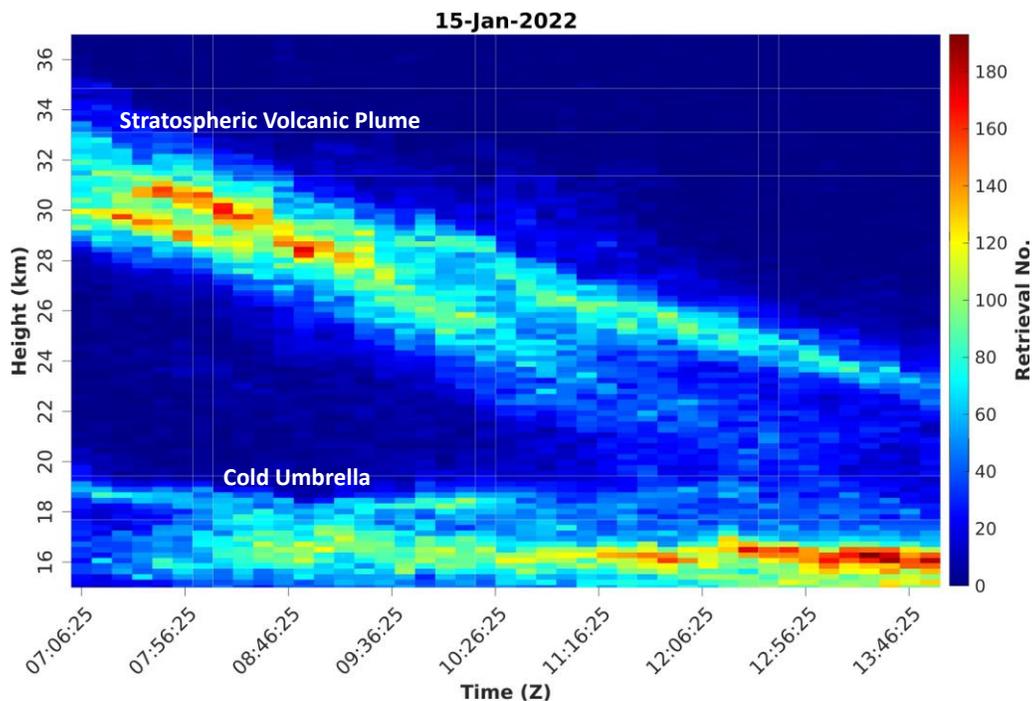


192

193 **Figure 2.** Panel (a) shows the jointly retrieved heights and horizontal advection vectors at their  
 194 parallax corrected locations centered on the volcano (20.536°S, 175.382°W). The vector scale at  
 195 the upper right indicates a  $50 \text{ m s}^{-1}$  wind in each direction. Panel (b) shows the assigned  
 196 temperatures for each retrieval and the associated advection speed. Temperature profiles from  
 197 ERA5 at 08:00Z and COSMIC-2 RO at 07:11Z have been added for context.

198 The 08:06Z scene was selected for Figure 2 as an interesting case because it clearly  
 199 shows an eruption of volcanic ash overshooting the plume top centered over the marked volcanic  
 200 site (Global Volcanism Program, 2013). All stereo-winds product files are found in the  
 201 supplement, along with animations of the IR imagery, height-coded advection fields, and height  
 202 versus temperature profiles for the complete set (Exhibits S4ff). At 08:41Z, an overshooting  
 203 plume core reached the upper stratosphere with an EBBT of  $\sim 173\text{K}$ , significantly colder than the  
 204 surrounding stratospheric plume. This cold bubble has an EBBT  $\sim 15\text{K}$  colder than the lower  
 205 umbrella near the tropopause, which can be explained by adiabatic cooling during plume  
 206 convection (Woods and Self, 1992). Atmospheric gravity waves are also evident in the  
 207 animations.

208 The evolution of the mesoscale plume height statistics from 07:06Z to 13:46Z for 15  
 209 January 2022 is detailed in Figure 3. At each time, this density plot presents the distribution of  
 210 retrieved heights. Optically thick parts of the plume at a higher altitude can block the view of  
 211 elements underneath, which explains the lower number density in the cold umbrella when the  
 212 upper-level plume has a higher number density. If the upper volcanic plume were a mix of  
 213 optically thin and thick layers, the height retrieval count profile would indicate an approximate  
 214 upper-plume thickness of 4-5 km. However, as noted, optically thick parts will obscure material  
 215 below. From 07:06Z to 10:06Z, the upper volcanic plume obscures the lower cold umbrella,  
 216 decreasing its retrieval numbers, but as the upper volcanic plume moves out of the mesoscale  
 217 domain, retrievals increase for the slower evolving cold umbrella. Subsequent activity is seen in  
 218 the volcanic plume retrieval peaks between 07:00Z and 09:00Z that do not surpass height of the  
 219 initial eruption, for which earlier plume material has advected out of the mesoscale domain. This  
 220 interpretation is supported by the animation of the stereo retrievals provided in the supplemental  
 221 material. Overall, the plume ceiling within the mesoscale domain is observed to fall nearly  
 222 linearly at a rate of  $\sim 1.7$  km/h.



223

224 **Figure 3.** A time series of the distribution of plume height retrievals shows the evolution over a  
 225 nearly 7-hour period. Advection out of the mesoscale domain and thinning of the higher-level  
 226 plume causes more of the cold umbrella near the tropopause to be revealed as time progresses.

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#### 4.3 Radio Occultation Results

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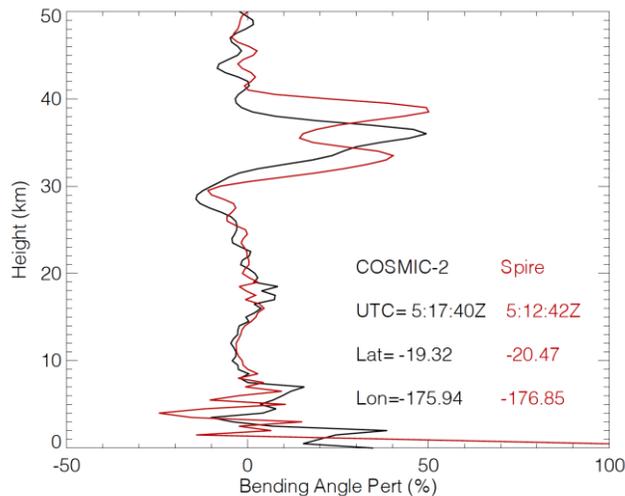
The GNSS-RO technique has been used operationally in numerical weather prediction to provide temperature information in the lower stratosphere and upper troposphere through the bending induced by atmospheric refractivity (Healy et al., 2005). Bending Angle (BA) is the critical parameter used to profile atmospheric variability from GNSS-RO and increases exponentially as the surface approaches. This study uses near real-time data from the

233 Constellation Observing System for Meteorology, Ionosphere and Climate-2 (COSMIC-2), and  
 234 Spire under NOAA's Commercial Weather Data Pilot (CWDP) program.

235 To detect volcano-induced BA perturbations on January 15, we first derive a BA  
 236 reference profile for the latitude band (15°S to 25°S) using all BA profiles from January 14 and  
 237 16. Then, we take the difference between individual profiles from January 15 and the reference  
 238 BA to find anomalies near the Tonga eruption region. The BA perturbation is measured in  
 239 percentage from the difference divided by the reference BA. Typically, a BA profile varies  
 240 within 10% about the reference at heights between 20-40 km.

241 As shown in Figure 4, two strong BA perturbations are observed around 05:17:40Z (from  
 242 COSMIC-2) and 05:12:42Z (from Spire), indicating an ~50% deviation from the reference. The  
 243 top heights of the BA perturbations are approximately 41 km and 38 km, respectively for these  
 244 cases. The GNSS-RO technique has a relatively good (< 2 km) vertical but poor (~300 km)  
 245 horizontal resolution. Thus, the bending is sensitive to the refractivity change induced by a large  
 246 volcanic plume like that of the Tonga eruption. The top of the BA perturbation indicates the first  
 247 height where the RO line-of-sight encounters the volcanic plume. Starting with the average of  
 248 the two RO measurements, 39.5 km at 05:15Z, and extrapolating forward with the fall rate of 1.7  
 249 km/h (identified in Figure 3) until 07:06Z predicts a maximum plume top of 36.4 km. This  
 250 agrees with the highest retrievals in the 07:06Z histogram to the expected vertical resolution of  
 251 the RO observations.

252



253 **Figure 4.** Perturbations of the Bending Angle (BA) profile observed by COSMIC-2 and Spire  
 254 GNSS-RO from 15 January 2022 with respect to the reference profile. The sharp BA change in  
 255 the stratosphere indicates the impact of the volcanic plume on radio-wave propagation. The plot  
 256 indicates the locations and times of the RO profiles.

#### 257 4 Conclusions

258 We used GOES-17 and Himawari-8 geostationary satellite imagery to study the 15 January 2022  
 259 eruption of the Hunga Tonga-Hunga Ha'apai volcano shortly after 04:00Z. Manually measured  
 260 parallaxes between near-simultaneous visible images from each satellite and the lengths of  
 261 shadows cast by the plume provided information about plume structure in the earliest phases of

262 the eruption. We applied a stereo-winds tracking method starting at 07:06Z to automatically  
263 generate a high-density representation of plume advection jointly retrieved with plume height.  
264 This powerful method provided a detailed mesoscale description of advection and vertical  
265 structure for nearly seven hours every 10 minutes.

266 Our results show that the Hunga Tonga-Hunga Ha'apai volcano ejected material as high as 55  
267 km, with a substantial amount of material injected above 30 km. Such peak altitudes exceed the  
268 maximum column altitudes of 40 km reported for the 1991 Mount Pinatubo eruption by Holasek  
269 et al. (1996). As the eruption progressed and later died down, advection carried much of the  
270 injected stratospheric plume outside the mesoscale domain studied. The plume remaining in the  
271 mesoscale domain would have thinned or collapsed to render it untrackable in the IR imagery.  
272 Our analysis of GNSS-RO bending angles confirms that material was lofted between 30 km and  
273 40 km approximately one hour after the initial eruption.

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283 Computing (HEC) Program through the NASA Center for Climate Simulation (NCCS) at  
284 Goddard Space Flight Center.

## 285 **Competing interests**

286 The authors declare that they have no conflict of interest.  
287

## 288 **Open Research**

289 All mesoscale stereo retrievals are included in the supplementary material submitted with  
290 this paper. GOES-17, Himawari-8, and GNSS-RO are publicly available at  
291 <https://class.noaa.gov>, <https://registry.opendata.aws/collab/noaa/>, and [https://cdaac-  
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**Stereo Plume Height and Motion Retrievals for the Record-Setting Hunga Tonga-Hunga Hai'apai Eruption of 15 January 2022**

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**Additional Supporting Information (Files uploaded separately)**

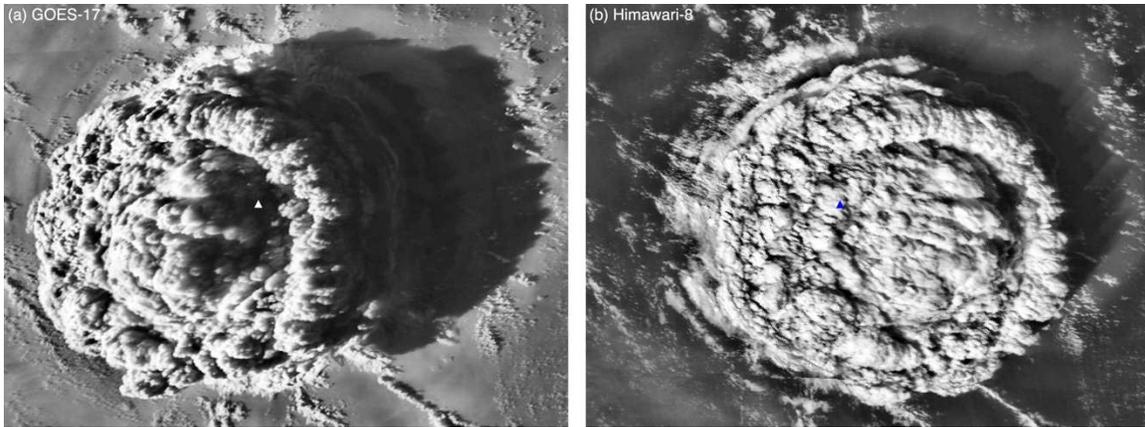
Captions for Movies S4 to S6 corresponding to files ms01, ms02, and ms03.

**Introduction**

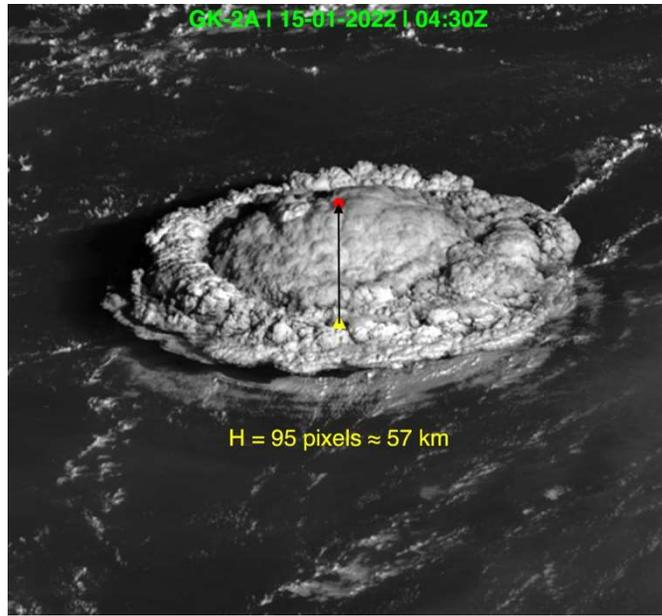
This supporting information (SI) provides contrast-enhanced versions of the GOES-17 and Himawari-8 visible images in Figure 1 of the article (S1), an independent geometric estimate of the maximum plume height at 04:30Z obtained by applying the side view method to the corresponding GEO-KOMPSAT-2A image (S2), and additional shadow-based height estimates for the 04:50–05:00Z time slots (S3). The SI also provides the following animations on 15 January 2022 of 20-hour GOES-17 Full Disk infrared contrast-enhanced brightness temperature (ms01), 7-hours of jointly retrieved GOES-17 MESO and Himawari-8 heights, horizontal advection vectors (ms02), and assigned temperatures (ms03).

The GEO-KOMPSAT-2A geostationary satellite, stationed at 128.2°E, Advanced Meteorological Imager (AMI), virtually identical to ABI and AHI, observed the plume at a ~67° view zenith angle. Although not ideal, the side view allows a rough estimate of peak height using the method described in Horváth et al., 2021a. In the highest-resolution red band, the vertically projected instantaneous field of view (VIFOV) is ~550 m. The foreshortening due to the deviation from the perfect 90° side view is  $\text{COS}(23^\circ)$  or ~8%.

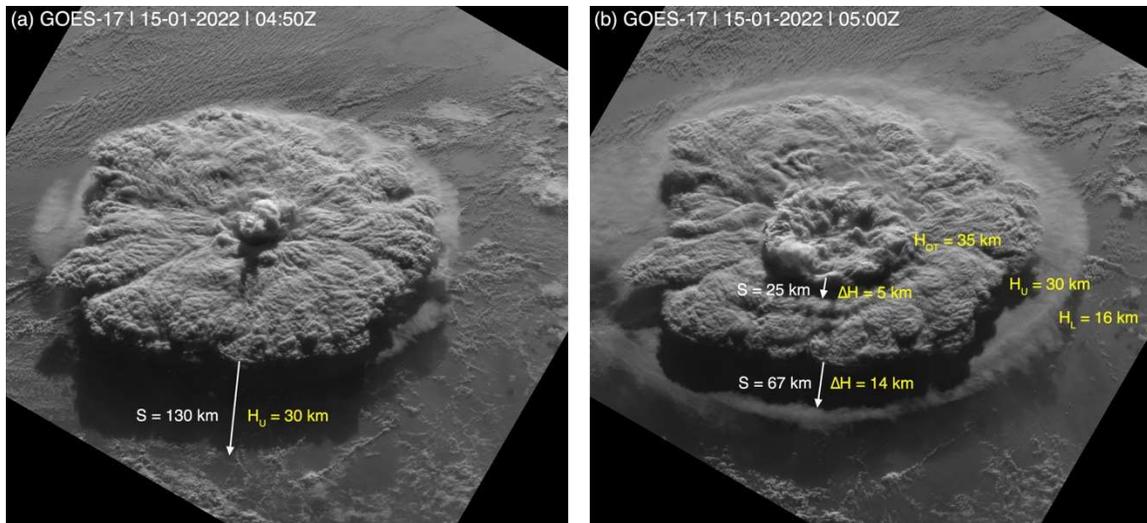
Height estimation near the vent can be done by counting the pixel numbers between the known volcano base location and the dome top, assumed to be above the vent along the local vertical. The base-to-top distance is approximately ~95 pixels, corresponding to a foreshortening corrected height of ~57 km. This is consistent with the maximum GOES-17 and Himawari-8 stereo retrievals height presented in the paper.



**Figure S1.** Image of the plume on 15 January 2022 at 04:30Z from (a) GOES-17 and (b) Himawari-8, enhanced by the Contrast Limited Adaptive Histogram Equalization (CLAHE) plugin of the Fiji package (Schindelin et al., 2012). Compared to Figure 1 of the paper, the enhanced images better reveal the layered plume structure in the shadowed areas.



**Figure S2.** Red band ( $0.64 \mu\text{m}$ ) image of the plume on 15 January 2022 at 04:30Z from GEO-KOMPSAT-2A. The image was rotated by the geodetic colatitude. The yellow triangle and the red dot mark the volcano base and the top of the dome, respectively. The black arrow indicates that the base–top distance is 95 pixels, which corresponds to a height of  $\sim 57 \text{ km}$  at the GK-2A view zenith angle of  $67^\circ$ .



**Figure S3.** Plume structure deduced from GOES-17 (a) 04:50Z and (b) 05:00Z red band images (rotated by the geodetic colatitude), showing the development and collapse of an overshooting top (OT) at the center of the plume. From the length of shadows ( $S$ ) cast on the ocean surface or lower-level plume layers, we identified a lower umbrella spreading near the tropopause at  $H_L = 16$  km altitude, an upper umbrella at  $H_U = 30$  km altitude, and parts of the collapsing OT at  $H_{OT} = 35$  km altitude.

**Movie S4.** Movie of the GOES-17 Full Disk infrared ABI Band 14 (11.2  $\mu\text{m}$ ) brightness temperature (K) shows the progression of the volcanic plume edge and dome features on 15 January 2022 from 02:50Z through 23:50Z. Darker colors indicate lower brightness temperatures, whereas lighter colors indicate higher brightness temperatures.

**Movie S5.** Movie panels show the jointly retrieved GOES-17 MESO and Himawari-8 heights and horizontal advection vectors at their parallax corrected locations on 15 January 2022 from 07:06Z through 14:06Z. The retrievals are centered on the volcano (20.536°S, 175.382 °W) indicated by the magenta triangle. The magenta vector scale at the upper right indicates a 50 m s<sup>-1</sup> wind in each direction. Arrow color indicated height on the same scale as Figure 2a.

**Movie S6.** Movie panels show the assigned temperatures for each GOES-17 MESO and Himawari-8 retrieval and the associated advection speed on 15 January 2022 from 07:06Z through 14:06Z. Dot color indicates advection speed on the same scale as Figure 2b.