

# Ballistic motion of dust particles in the “Collecting the Big Muley lunar rock” sequence of the Apollo XVI Footage

## ABSTRACT

This manuscript develops and integrates the previous study “*Analytical Methods for Tracking Bodies Motions on the Lunar Surface in Apollo XVI Footage*” <https://doi.org/10.32388/IA8MXE> in order to introduce a robust analytical method to trace and analyze the movement of dust shot during the Apollo XVI mission on the lunar surface. By employing both 2D and 3D analysis techniques, we aim to provide a detailed comparison of the observed kinematic events against theoretical models.

The paper extends a previous work focused on the kinematics of lunar dust utilizing footage from the “Grand Prix” sequence of the Apollo XVI mission "Ballistic motion of dust particles in the Lunar Roving Vehicle dust trails" published in 2012 in the American Journal of Physics by Mihaly Horanyi and Hsiang-Wen Hsu: <https://www.researchgate.net/publication/258468670> [Ann. 1 – Ann. 2].

In this further analysis, a sequence in which the astronaut Charles Duke collects an igneous rock (the so-called Big Muley) is tracked. A clearly visible trail of dust is kicked from the left foot of Duke and following a parabolic path, it will reach the lunar ground in the next 25 frames.

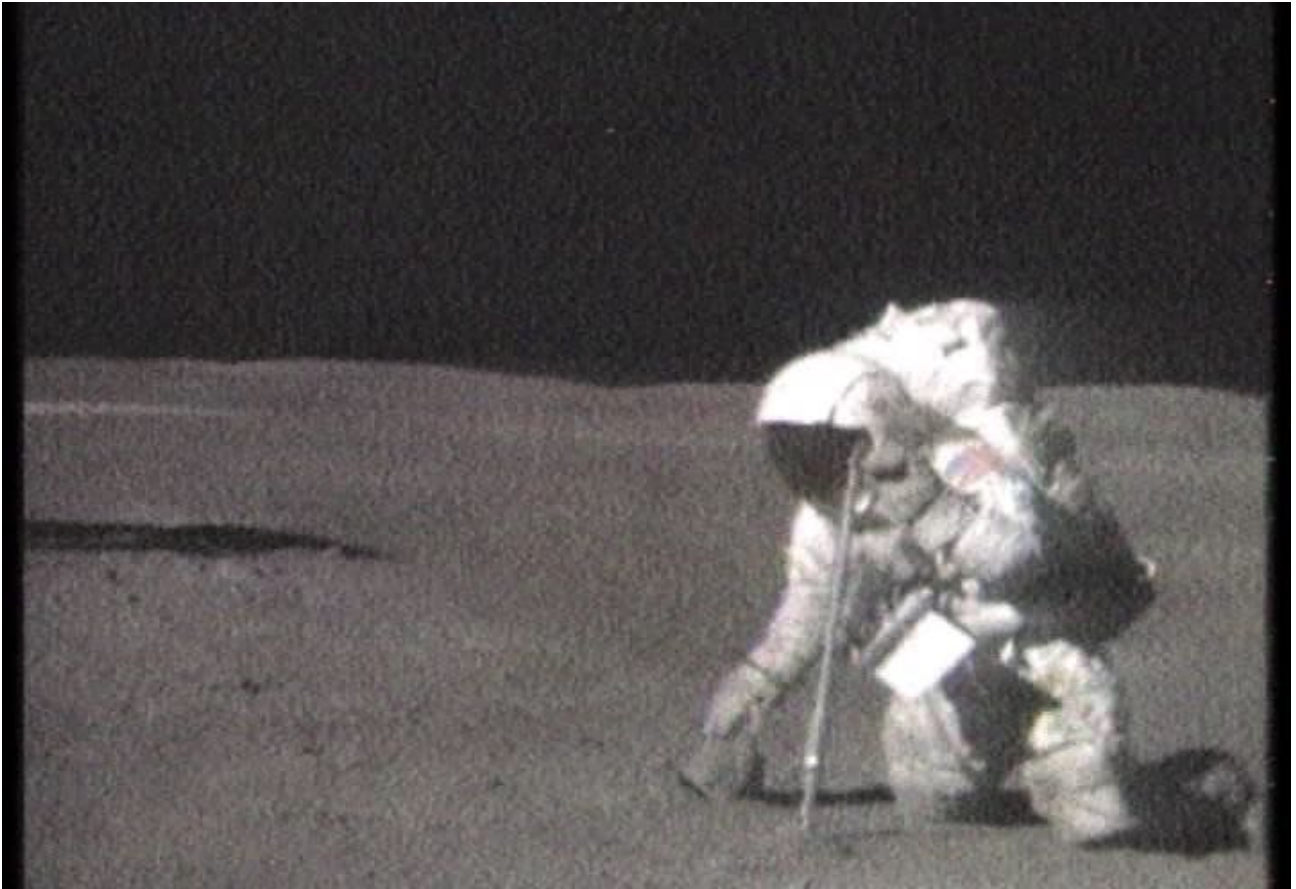
By tracking the motion of the dust, we obtain information on its grain size and mechanical behavior in the lunar environment, about the validity of the expected motion models, and - last but not least - about the integrity of the original films in the digital transpositions to which we have access, in particular with respect to the played framerate.

## Keywords:

Apollo 16, Lunar dust ballistic motion, Big Muley, Apollo footage

## SECTION C

### Big Muley



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Figure C1 – Charles Duke collects the Big Muley, a frame from the sequence taken by the CTV RCA during Apollo 16

#### C.1 DESCRIPTION OF THE SEQUENCE <sup>1</sup>:

*Houston asks Charlie to collect an 11.729-kilogram, football-sized, anorthosite rock from the rim of Plum Crater. It is the largest rock returned from the moon by any lunar mission and is a coarse-grained, nonvascular, crystalline, igneous rock composed largely of plagioclase. Duke later named it “Big Muley” after Bill Muehlberger, Apollo 16's principal investigator for geology.*

**C.1.1 Sources:** The images used for this study are taken from Apollo 16 Journey to Descartes, complete TV and onboard film © 2005 Spacecraft Film (courtesy NASA). The sequence "Big Muley" is published at this link: <https://youtu.be/REoy8eMVKIE>

#### C.1.2 Other official sources containing the same sequence:

- Apollo 16 Lunar Surface Journal Corrected Transcript and Commentary by Eric M. Jones 1997, last revised 16 March 2019. <https://www.nasa.gov/wp-content/uploads/static/history/alsj/a16/a16v.1240739.mov>
- “Nothing so Hidden” Published by NASA July 12, 2018

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<sup>1</sup> <https://www.hq.nasa.gov/alsj/a16/a16.sta1.html> 124:07:30, Apollo 16 Lunar Surface Journal Corrected Transcript and Commentary by Eric M. Jones 1997. Revised 7 April 2018

<https://plus.nasa.gov/video/apollo-16-nothing-so-hidden-2/>

### **C.1.3 Description of the sequence**

Charles Duke approaches the rock, that he is about to gather along the edge of the Plum Crater, in small leaps. The LRV is parked nearby and the RCA TV Camera, mounted on the vehicle for the shooting of EVA 1 activities, films the scene under the remote control of the Mission Control Center in Huston. About 8 meters from the camera, the astronaut makes a final lateral jump from the left to the right of the frame and then reaches the position in which he will bend over to collect the sample. After this leap, the astronaut's right foot approaches the left one, and in rapid succession the left moves away from the camera, advancing slightly to the right of the frame. Both raise a certain amount of dust. A clearly visible trail of dust detaches from the left foot just before it is placed on the ground again, following a parabolic path and reaching the lunar ground in the next 25 frames. Before reaching the ground, the dust spreads opening in a cloud at the end of its motion.

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### **C.2.1 Calculation of the focal length used for shooting.**

An image of the reference "set" in which the sequence was shot, comes to our support. In the Apollo 16 Image Library <sup>2</sup>, in fact, NASA makes the AS16-109-17800 high-resolution photo available: <https://www.hq.nasa.gov/wp-content/uploads/static/history/alsj/a16/AS16-109-17800HR.jpg>



*Figure C2 - Apollo Image Library AS16-109-17800*

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<sup>2</sup> <https://www.hq.nasa.gov/alsj/a16/images16.html> Apollo Image Library, Apollo 16 Figure Captions Copyright © 1996-2017 by Eric M. Jones, last revised 16 March 2019.

The image was taken with a 60mm lens<sup>3</sup> (therefore not subject to appreciable geometric aberrations). In the centre of the frame, it shows the Rover parked near the Plum Crater and the RCA CTV installed on the vehicle; on the far right there is a rock indicated in the description of the image as Big Muley (Lunar Sample 61016).

Through a perspective analysis performed with the Photoshop CS6 Vanishing Point Filter<sup>4</sup>, determining the distance between the lens and Big Muley is elementary. As has already been done in <https://doi.org/10.32388/IA8MXE> A.2.1.1, once the reference planes that characterize the perspective development of the image have been correctly identified, accurate measurements of the three-dimensional space can be performed. The known dimensions through which it is possible to set up a measuring system can be obtained, once again, from the wheel diameter of the LRV<sup>5</sup> (cm 81.8), which is the reference measurement for height and depth through which we can calibrate the measurement system for the prospective analysis of space.

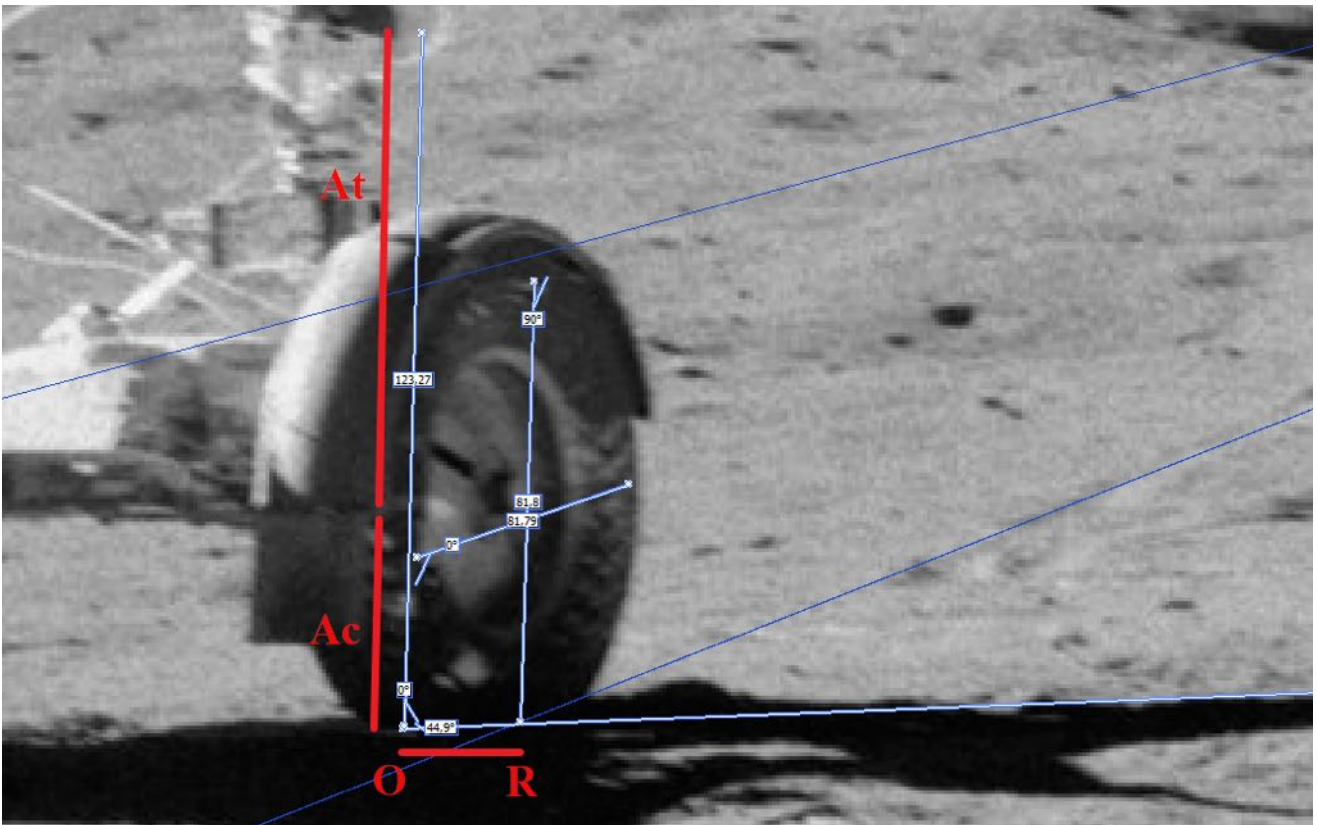


Figure C3 – AIL, ASI6-109-17800, calibration of measurement system with Photoshop CS6 Perspective Focus Filter

On the opposite side of the frame, the height that the portion emerging from the lunar soil of the Big Muley rock assumes in the set measurement system (16.4 cm) agrees with the scientific information

<sup>3</sup> [http://pdsimage.wr.usgs.gov/data/a16c-l-mc-2-scanned-images-v1.0/A16MC\\_0001/DOCUMENT/ap16\\_data\\_notes.pdf](http://pdsimage.wr.usgs.gov/data/a16c-l-mc-2-scanned-images-v1.0/A16MC_0001/DOCUMENT/ap16_data_notes.pdf) Apollo 16 Lunar Photography, NASA – National Space Science Data Center, Greenbelt MD 1973 [Ann. 3]

<sup>4</sup> <https://helpx.adobe.com/uk/photoshop/using/vanishing-point.html> Adobe Photoshop User Guide, Image transformations, Vanishing Point Copyright © 2019 Adobe 345 Park Avenue San Jose, CA 95110-2704

<sup>5</sup> [https://www.nasa.gov/wp-content/uploads/static/history/alsj/LRV\\_OpsNAS8-25145.pdf](https://www.nasa.gov/wp-content/uploads/static/history/alsj/LRV_OpsNAS8-25145.pdf) Lunar Roving Vehicle Operation Handbook, The Boeing Company LRV Systems Engineering, Huntsville (Alabama), April 19, 1971 [Ann. A6]

presented in the Lunar Sample Compendium published by NASA <sup>6</sup>, thus confirming the correctness of the scale and the perspective plans identified. Below we present in detail the steps performed and the results obtained.

### C.2.1.1 Relevant known dimensions.

We fix the lens's projection to the ground as the origin "O" of our system <sup>7</sup>, which is placed approximately in correspondence with the internal profile of the vehicle wheel <sup>5</sup>.

We indicate with R the ordinate that in our reference system is assumed by the external profile of the wheel, with  $A_t$  and  $A_c$  respectively the height of the CTV on the chassis <sup>7</sup> and the height of the chassis from the ground in the absence of load <sup>5</sup> (also the thickness of the chassis is considered); finally, with B, the position of Big Muley on the ground.

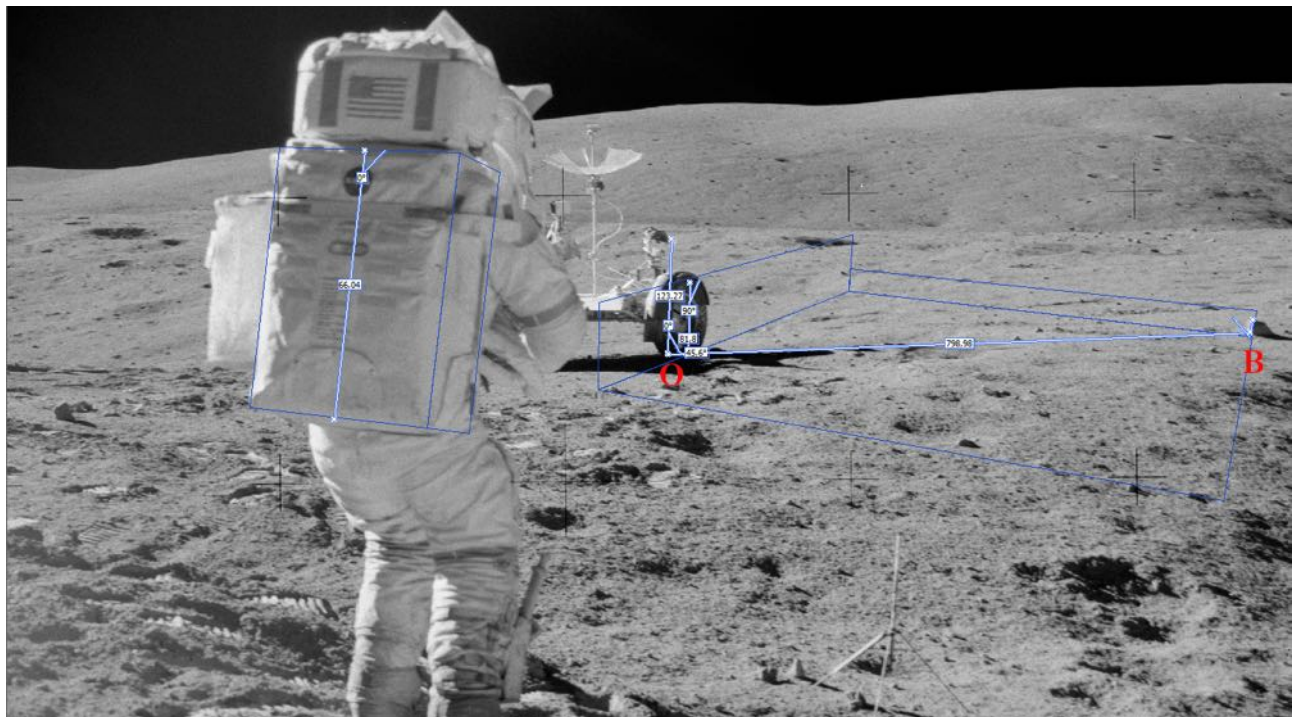


Figure C4 – AIL, AS16-109-17800, Distance of Big Muley from lens

The following measures are known:

Figure C3

- Rover wheel diameter <sup>5</sup>: 81.8 cm (32.2 inches)
- OR = Thickness of wheel <sup>5</sup> = 22.86 cm (9 inches)

The height of the camera on the ground A can be obtained from  $A = A_t + A_c = 123$  cm (48.41 inches)

The experimental error +/- 1.5 px (see C.3.7), on this measure, is calculated as +/- 0.97 cm

Figure C5

<sup>6</sup> <https://curator.jsc.nasa.gov/lunar/lsc/61016.pdf> 61016 Impact Melt Rock with Shocked/Melted Anorthosite Cap, Lunar Sample Compendium C Meyer 2009 [Ann. C1]

<sup>7</sup> <https://www.nasa.gov/wp-content/uploads/static/history/alsj/GCTA-Manual.pdf> RCA Government and Commercial Systems, Astro-Electronics Division, Princeton NJ 08540; Issued 24 May 1971, Revised January 1972 [Ann. A3]

- Big Muley above-ground height <sup>6</sup>: 16.4 cm

The position of the cube as a reference for the measurement also indicates the position that the rock had on the lunar soil, allowing us to identify the height of the above-ground portion.

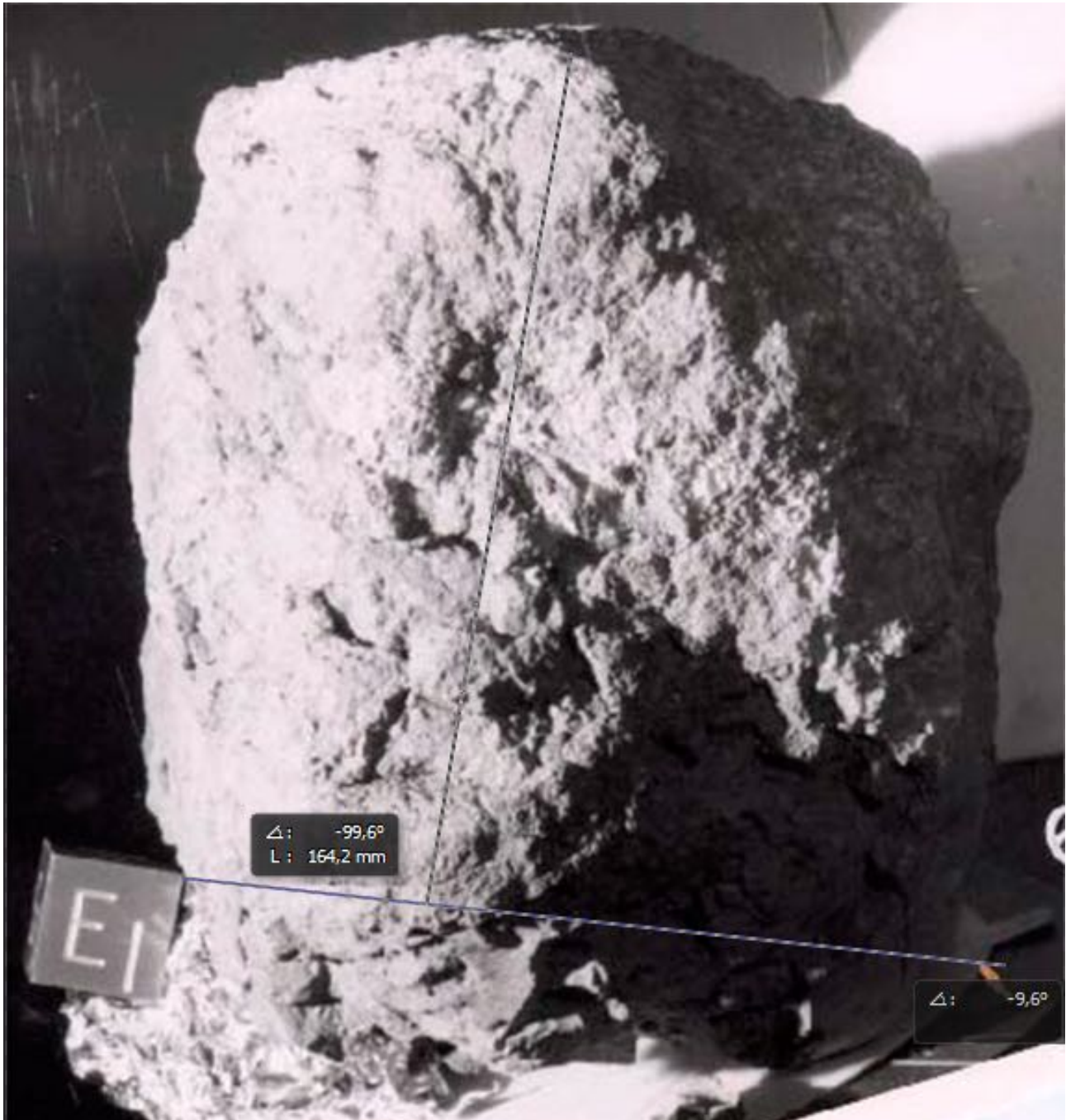


Figure C5 – Dimensions of Big Muley, Lunar Sample Compendium

### C.2.1.2 Identification of perspective measurement plans, instrumental error.

The line of contact of the wheel of the LRV with the lunar ground traces the base of the main plane on whose height we will rely on homologous points having the same heights on the circumference of the wheel itself. There is only one vertical plane that allows the measurements of the diameter of the wheel in width and height concordant. This one, once identified, will allow us to correctly express

the perspective. Once the main (vertical) plane, that we will extend up to Big Muley, has been identified, the Photoshop CS6 Vanishing Point Filter allows us to derive orthogonal planes. It will therefore be possible to proceed to derive the horizontal (ground) plane. At this point we derive a second vertical plane from the main plane, extending it to the end of the ground plane to measure the height of the Big Muley from the ground, and we actually obtain confirmation of the correctness of the system: the measure exactly matches the one published on the Lunar Sample Compendium.

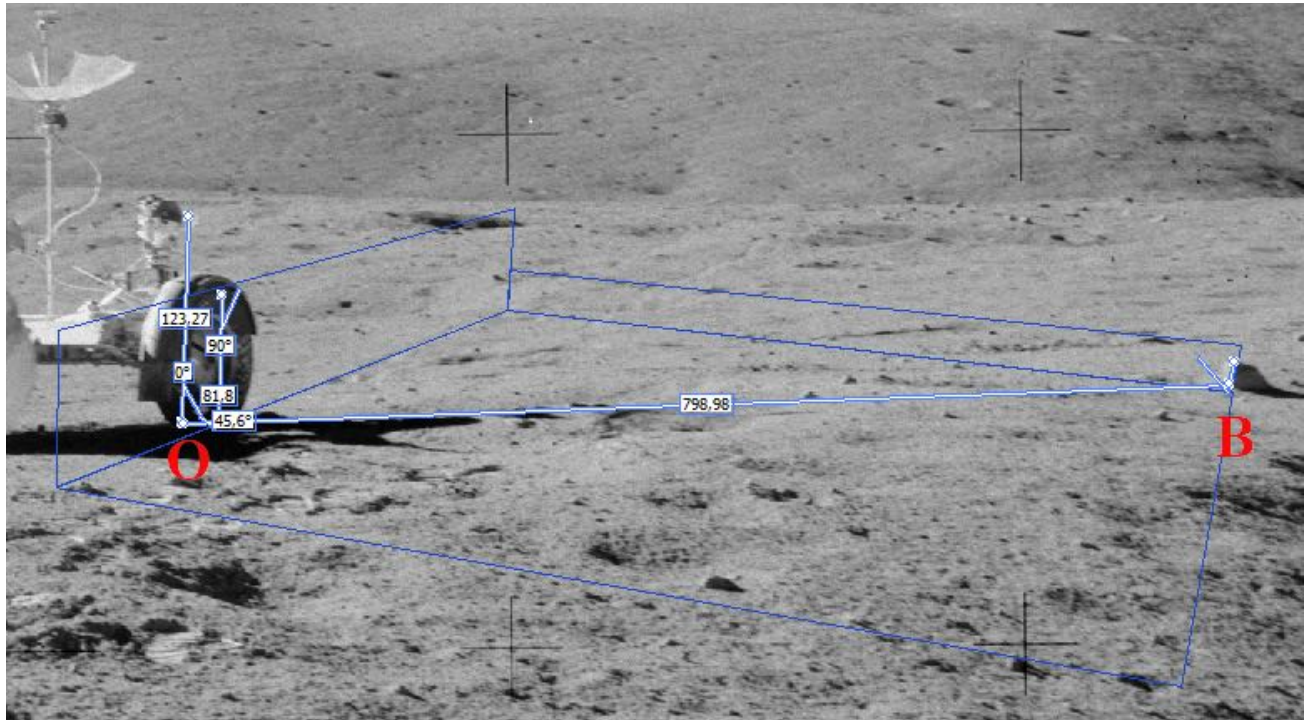


Figure C6 – AIL, AS16-109-17800, results of the measurement

**C.2.1.3 Measurement result**

Using the metric system just set, the OB distance turns out to be 799 cm. The instrumental error of +/- 1.5 pixels (see C.3.7) on this distance is +/- 1.82 cm. This measurement seems to agree with the available cartography (Figure C7 <sup>8</sup>)<sup>3</sup>

**C.2.1.4 Calculation of the distance between the lens and the object**

The distance D of the lens from the Big Muley is given by

$$D = \sqrt{(OB^2 + A^2)} = \sqrt{(799^2 + 123^2)} = 808 \text{ cm (+/- 1.95 cm)}$$

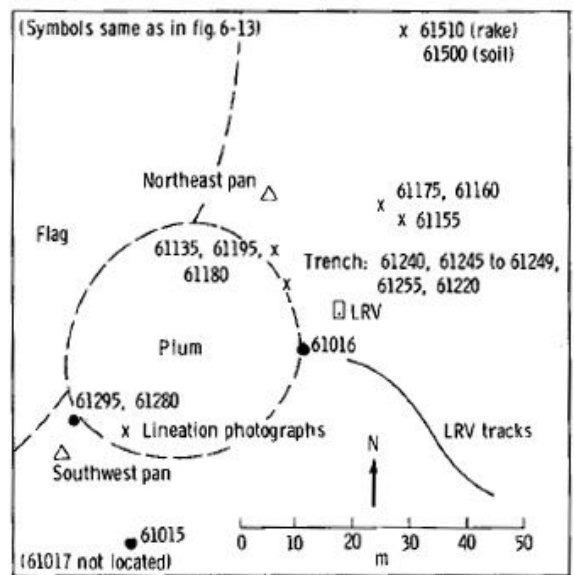


Figure C7 - Planimetry of Station 1, Eva 1, Apollo 16

<sup>8</sup> <https://www.nasa.gov/wp-content/uploads/static/history/alsj/a16/a16psrf6-21.jpg>  
 Apollo 16 Preliminary Science Report, NASA Manned Spacecraft Center, Scientific & Technical Information Office 1972

### C.2.1.5 Conclusions on the calculation of the focal length used for the shooting

Indicated as  $BM_t$  the height of Big Muley on the CTV sensor, and  $BM_l$  as the height of the rock on the lunar ground, the focal used  $F$  is given by the relationship

$$F = D \cdot \frac{BM_t}{BM_l}$$

By opening one of the images of the sequence being studied, and setting the sensor dimensions <sup>7</sup> (12.8 x 9.6 mm) as reference dimensions we can find  $BM_t = 0.6$  mm with an instrumental error of 1 pixel equivalent to +/- 0.05 mm



Figure C8 – Enlargement of Big Muley in the sequence taken from CTV RCA Camera

Therefore, we obtain:  $F = F = 8080 \cdot \frac{0,6}{164} = 29.56$  mm (+/- 2.53 mm)

To evaluate the percentage of distortion to be applied based on the focal length used, it is necessary to express the latter in terms of "equivalent focal length"  $F_e$ , comparing it to a standard sensor (36mm X 24mm full-frame, 35mm) instead of the sensor of 16 mm with which the scene was shot. If  $D$  is the diagonal of the 16 mm sensor and  $D_s$  is the diagonal of the standard format (43.3 mm), then:

$$F_e = F \cdot \frac{D_s}{D} = 29.56 \cdot \frac{43,3}{16} = 80$$
 mm (+/- 6.8 mm)

### C.2.2 Conclusions on the geometric aberration of the images

Since the typical distortion of CTV was estimated at 2% due to its spherical photocathode, and the equivalent focal length used for the sequence can be identified between 73 and 87 mm (light telephoto), it is appropriate to consider a percentage of distortion higher than 2% and less than 3% (maximum declared). The choice of the 2,5% value, as a percentage of positive distortion



(pincushion) to be corrected on the images of the sequence, was confirmed as the most accurate for the exact correspondence of the known dimensions within the measurement system that was built to obtain the spatial values of the sequence under study. The correction was made through the Photoshop CS6 Lens Correction filter <sup>9</sup>.

### C.3.1 Launch dynamics

With reference to the events already described in <https://doi.org/10.32388/IA8MXE> paragraph C.1.3, we analyse the elements and forces that make up the system filmed by CTV in the sequence of about 2 seconds that originates from the second 0:30 of the video already indicated, available at the address <https://youtu.be/REoy8eMVKIE>. There are two different motions of lunar dust raised respectively by the right foot and the left foot of the astronaut Charles Duke. The first trail of dust raised by the right foot in rapid approach to the left originates in the first frames of the sequence.

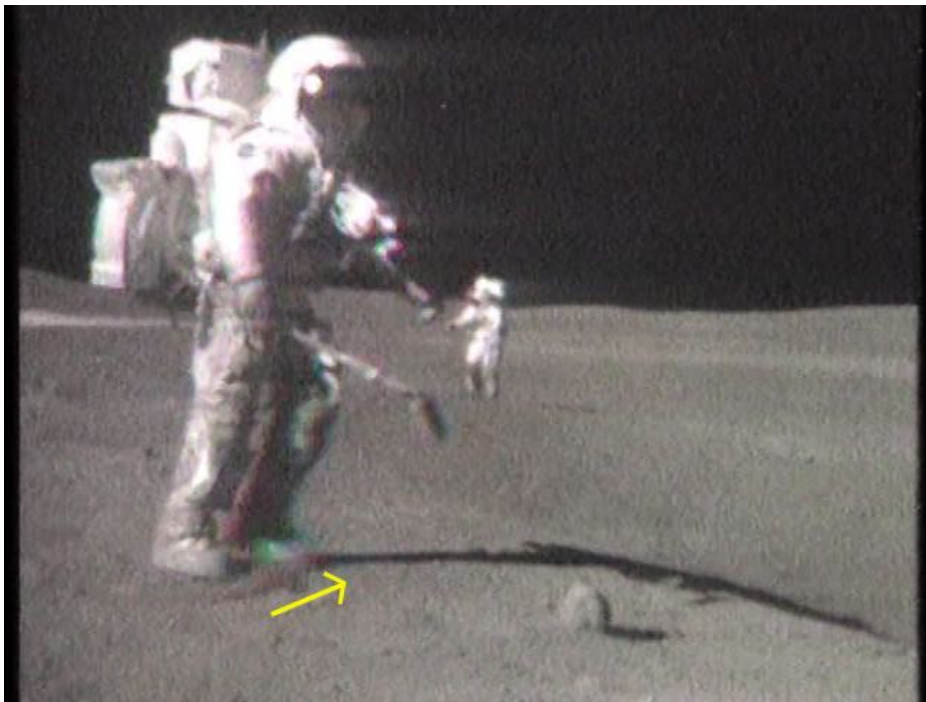


Figure C9 – Direction of first dust launch (right foot)

As soon as the left foot detaches itself from the ground, a second trail of dust, more evident, departs from Duke's boot in the direction of the Big Muley, falling back on the ground after about 20 frames: we will deal with this second trail. The direction of the second cloud of regolith can be determined thanks to its shadow cast on the lunar ground, which advances precisely towards the rock subject of the interest of the astronauts, moving away from Duke's shadow at an angle of about 5°. It was not possible to determine if this more persistent trail was lifted off from the ground by the astronaut's left foot, if the dust had already been deposited on the boot before launching, or if the same foot involuntarily kicked the dust raised by the right foot, diverting it from its original trajectory.

<sup>9</sup> <https://helpx.adobe.com/photoshop/using/correcting-image-distortion-noise.html> Adobe Photoshop User Guide, Image repair and restoration, Correct image distortion © 2019 Adobe 345 Park Avenue S. Jose, CA 95110-2704

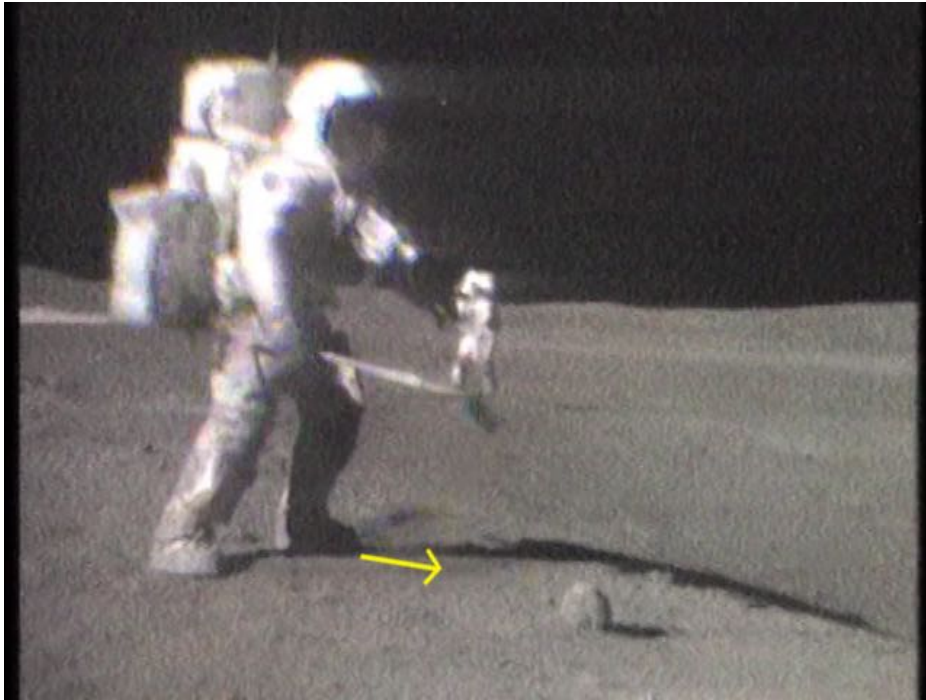


Figure C10 – Direction of examined dust launch

### C.3.2 Analysed frames

In the annex n° C2 [[Ann. C2](#)] there are the frames that refer to the motion studied, extracted from the video in uncompressed format. Among them, an interval of 20 frames was chosen, in which the position of the head of the dust train was evident. The most advanced point of this trail has been traced regardless of the chaotic shape that the cloud gradually assumed in its progression, similar to what was proposed by the authors of the study “Ballistic motion of dust particles in the Lunar Roving Vehicle dust trails” cited in the introduction. In fact, Mihaly Horanyi and Hsiang-Wen Hsu affirm: “For a tenuous dust cloud, where the inter-particle collisions are rare, a dust particle follows a ballistic path from its ejection until it returns to the surface”. The apical region of the cloud actually presents conditions that allow the model to be reduced to an independent material point, that is to a single ballistic particle. This choice was also made necessary in consideration of the particular production process suffered by the images, especially in relation to what is described in <https://doi.org/10.32388/IA8MXE> paragraph A.3.2. Only the most advanced part of the moving cloud can guarantee full compliance with the timeline, given that each frame consists of the superposition of 4 half-fields photographed within 1/15 of a second.

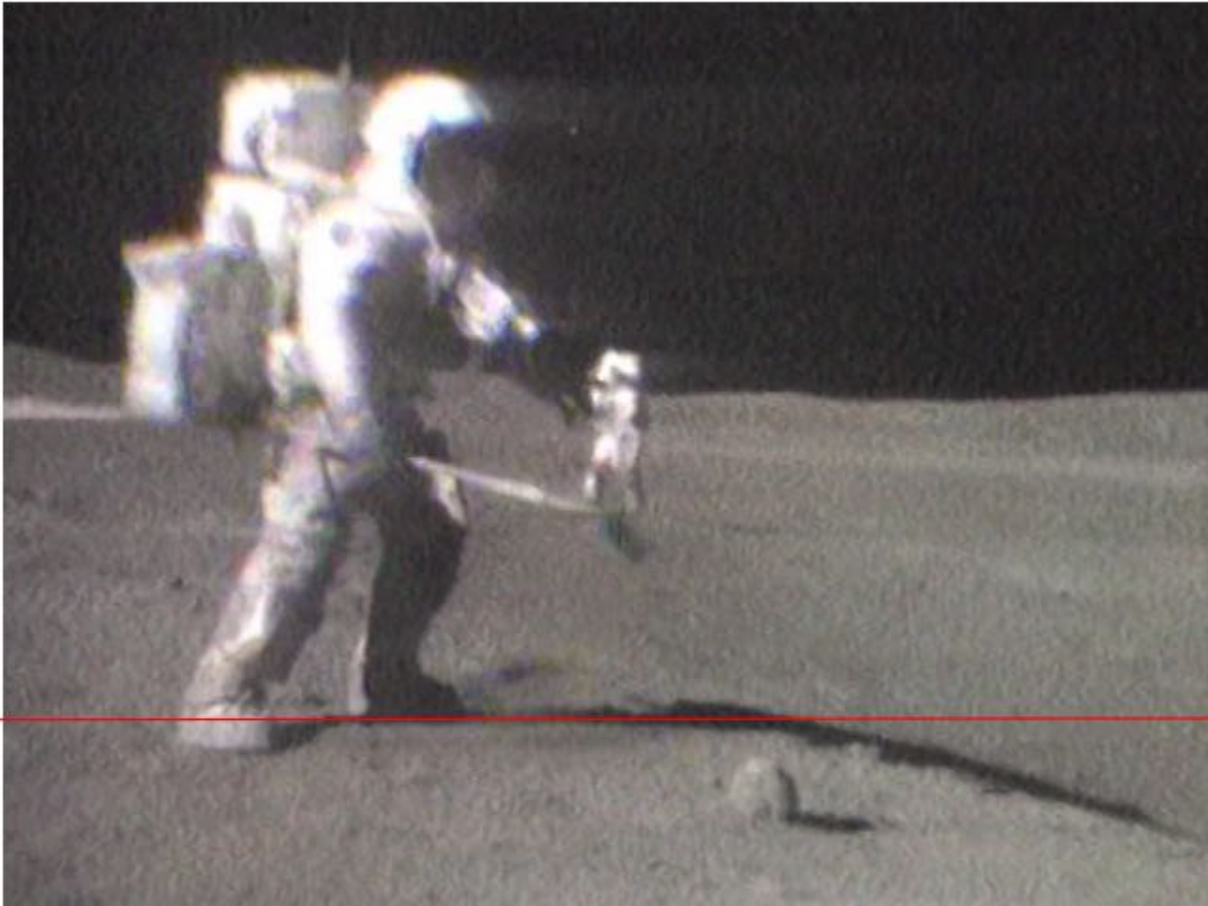
The cloud, in the descending part of its parable, denotes a progressive rarefaction, tending to fan out. The measurements continued to trace its most evident part, keeping the direction indicated by the shadow cast on the ground, a direction that is evidently followed by most of the material thrown.

### C.3.3 Measurement system set up [[Ann. C3](#)]

As in the case of determining the focal length used for shooting (see C.2.1), the Photoshop CS6 Vanishing Point Filter was used for the measurements <sup>10</sup>. To do this, the frames were exactly

<sup>10</sup> <https://helpx.adobe.com/uk/photoshop/using/vanishing-point.html> Adobe Photoshop User Guide, Image transformations, Vanishing Point Copyright © 2019 Adobe 345 Park Avenue San Jose, CA 95110-2704

superimposed in a multilevel project, which is very simple since we are in the presence of a sequence shot by a fixed camera. Then we proceeded to define the measurement system, through perspective analysis, first in 2D (monoscopic photogrammetry) <sup>11</sup> and then in 3D. Starting from frame 6 of the sequence, the Vertical Axis and the Ground Line have been identified.



*Figure C11 – Ground Line*

Considering that the camera is stably positioned on the same ground plane on which astronaut Charles Duke walks (as confirmed by Fig C6), it is possible to choose as reference system axes orthogonal to the plane of view. The ground line GL is suitably placed at the base of the astronaut's left boot and is extended so that it coincides with the flat part of the projection of his shadow. The first position detected by the tracked dust spurt head is chosen as the system origin.

<sup>11</sup> <https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1477-9730.2005.00343.1.x> *Manual of Photogrammetry*, American Society of Photogrammetry (Washington D.C.) and Remote Sensing (Bethesda Maryland), Fifth Edition 2004.

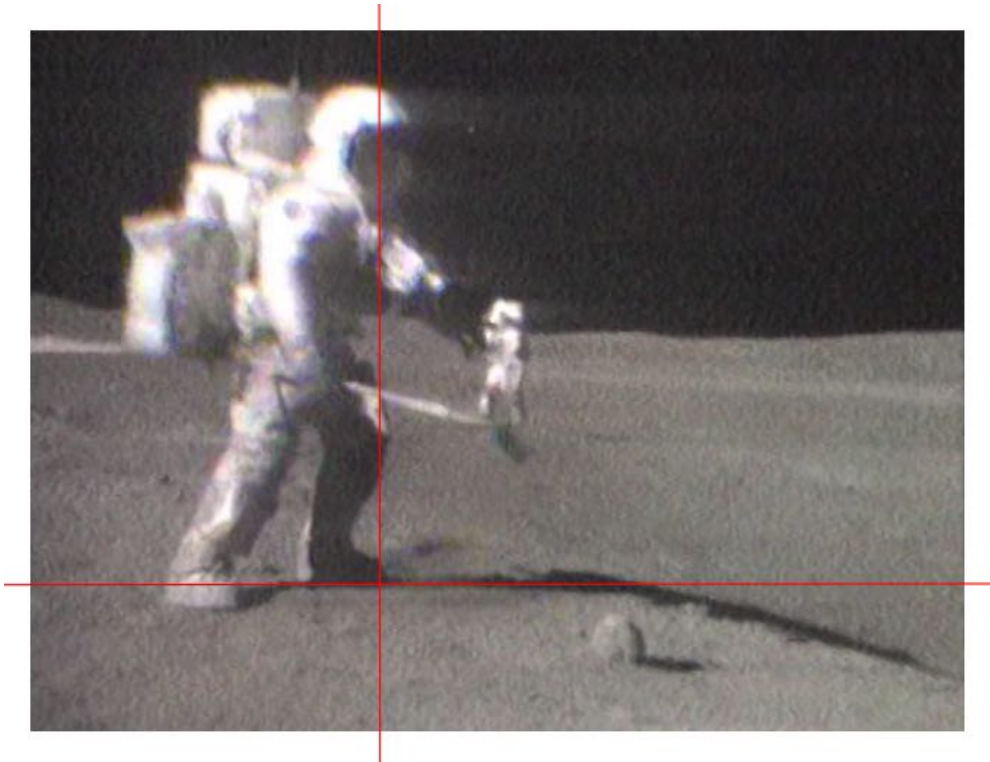


Figure C12 – Z axis orthogonal to the ground line GL

Finally, using frame 8 of the sequence, in which the apex of the shadow of the dust spurt is particularly evident, this point has been joined with the origin of the axes, identifying the trajectory of the motion of the dust in its projection on the lunar ground and thus obtaining the X axis.

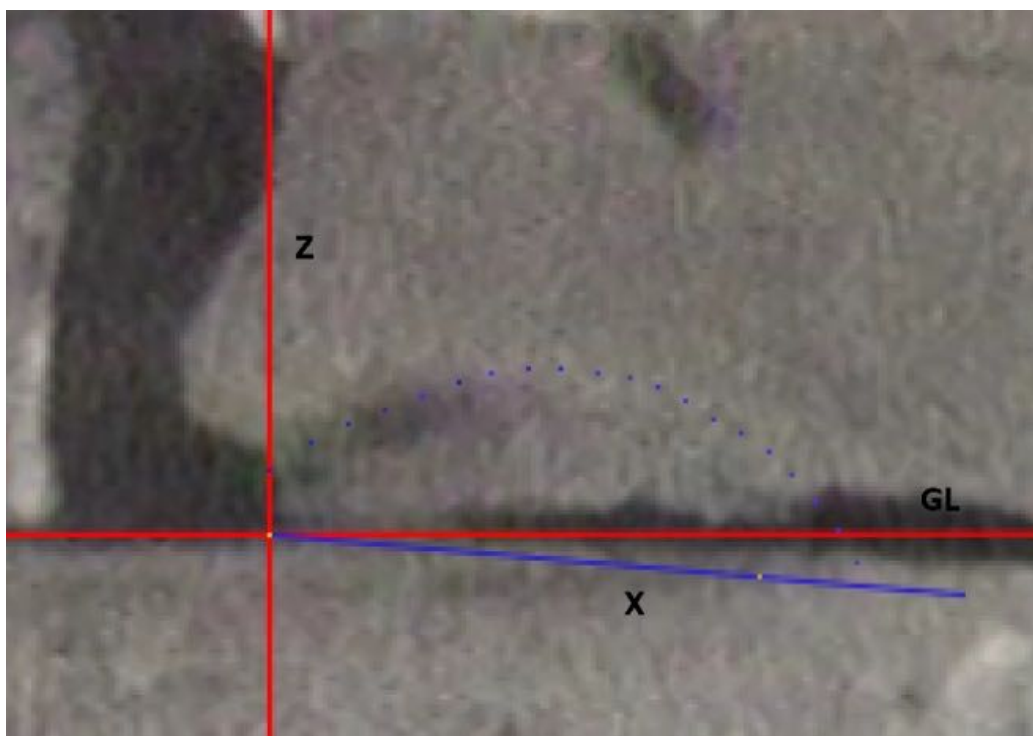


Figure C13 – Tracking of motion in space

At this point, from 2D analysis, we have moved to 3D analysis using the Photoshop CS6 Vanishing Point Filter. Starting from the lines identified in frame 6, the perspective planes necessary to define the 3D measurement system were defined. Plane A coincides with the plane of view. Plan B forms an angle of about 22 degrees with the latter and identifies the position of Duke's left foot (it will be used for system calibration). The C plane identifies the path followed by the dust and is inclined by a further 6 degrees (28 ° in total with respect to the plane of view).

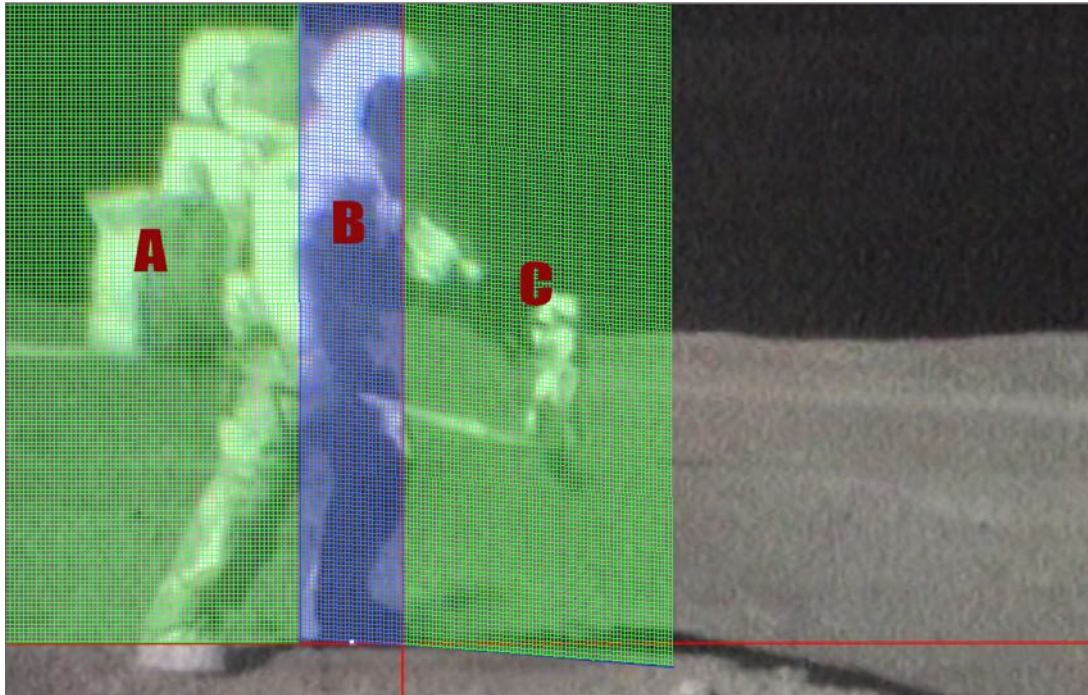


Figure C14 – Measurement planes

The measurements of the dust spurt head tracking are carried out on the C plane identifying the vertical and horizontal coordinates by positioning perfectly orthogonal segments on the same plane.

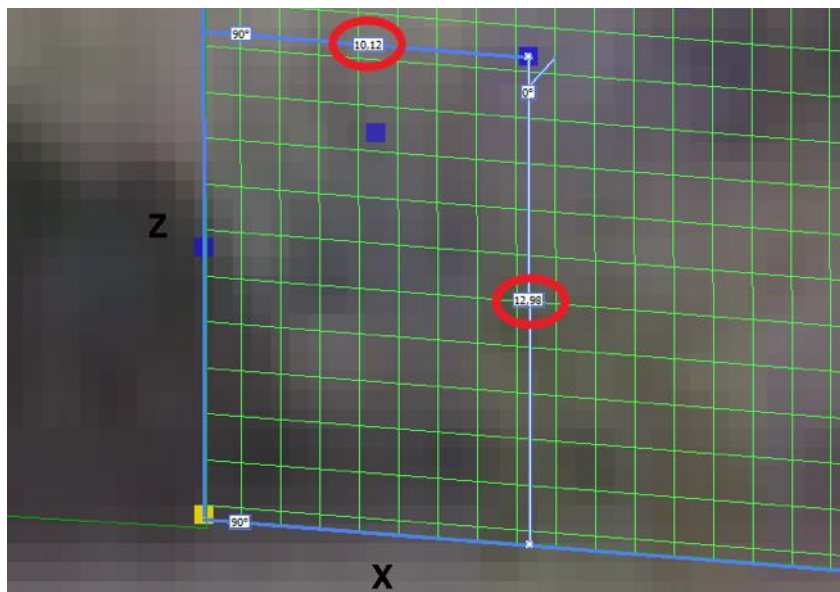


Figure C15 – Example of measurement, frame 2

### C.3.4 Configuration of the perspective scale starting from known measures.

The planes shown in Figure C14 are connected in a single system, and thus they maintain correct proportions. It is necessary to introduce at least one known measure to define the scale. In this regard, we use the technical data of the astronaut equipment already identified in <https://doi.org/10.32388/IA8MXE> A.2.1.1.1: the Training PLSS Unity worn by Charles Duke (height 66.04 cm, top thickness 22.22 cm)<sup>12</sup>. Following the appropriate corrections of the display aspect ratio and pixel aspect ratio (see <https://doi.org/10.32388/IA8MXE> A.3.4.1 and A.3.4.2), and the identification of the right measurement plans, the first confirmation that the system set up is correct with respect to the real proportions is implicit in the fact that these two known measures are compatible with the detectable ones on the examined images (see Figure C16).

Further confirmations, about the correctness of the system in the proportions and interpretation of the perspective, come from two other elements in the image of which we can find the real size. The first is the length of the boot worn by Charles Duke. The production measures of the Moon Boot were two: Omed (336 mm long) and Olge (368 mm long). The smaller size corresponds exactly to the one we can check in the image (see Figure C18)<sup>13</sup>.



Figure C16 – Apollo 16, dimensions of the Training PLSS unity in the images of the examined sequence

<sup>12</sup> Measurements of Apollo 16 Training Unit, Courtesy Dean Eppler, NASA, Lyndon B. Johnson Space Center, Houston Texas, USA. The PLSS Unity measurements do not include the OPS module placed above.

<sup>13</sup> [https://issuu.com/moonandspace/docs/moon\\_boot](https://issuu.com/moonandspace/docs/moon_boot) The story of the Apollo lunar overshoe and the race to walk on the moon, © David H. Mather 2014 – Published by Space Effects Limited (Durley UK)

## Boot sizes

The moon boot was produced in two sizes – OMED and OLGE, and the difference can be seen in the number of ribs on the sole of the boot - there are eight on the OMED and nine on the OLGE.

The soles measure 13¼" (336mm) x 6" (52mm) for the smaller size and 14½" (368mm) x 6½" (165mm) for the larger size.

Astronauts that wore a street shoe of size 11(US) or larger would use the OLGE size. For example, Jim Lovell of Apollo 13 wore a size 11(US) shoe, whilst Neil Armstrong's shoe size was 9½(US).



Figure C17 – The production measures of the Moon Boots

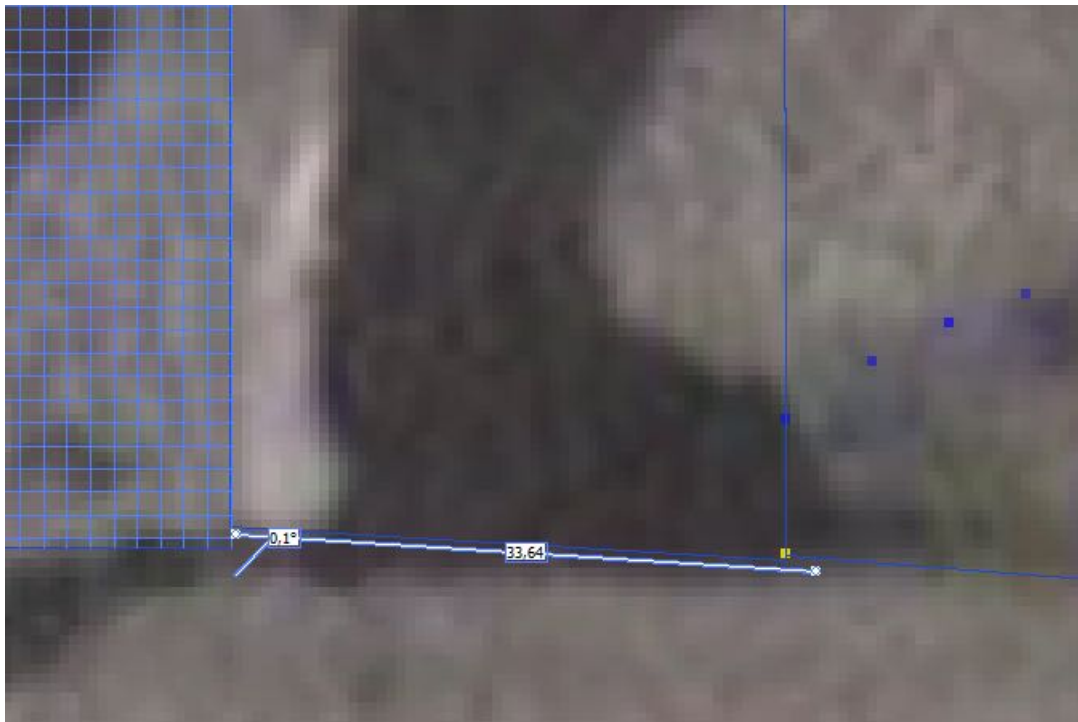


Figure C18 – Measurement of the left Moon Boot of Charles Duke in the examined sequence

The second element is the height above the ground of the Big Muley: 16,4 cm (see Figure C5), which is confirmed with excellent approximation by the relief on the CTV image.

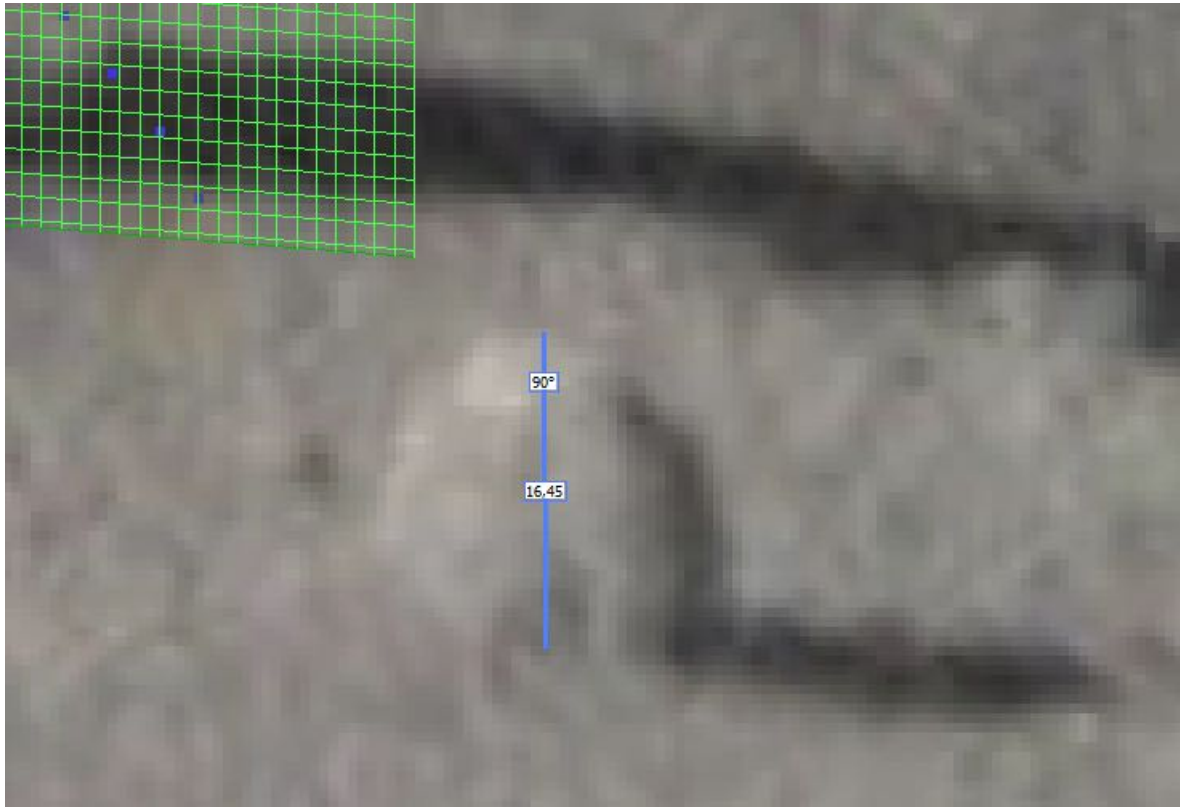


Figure C19 – Height above the ground of the Big Muley

### C.3.5 Finding the position of the material point in the frames of the sequence.

With reference to what has already been described in C.3.1 about the dynamics of the launch and the reasons that led to the measurement of the most advanced part of the cloud of dust launched by the boot of the astronaut Charles Duke in the analysed sequence, we present the graphic elaborations collected in Annex n° 32-33 [[Ann. C4](#) – [Ann. C5](#)] which describe how the head of the aforementioned cloud, reduced to a material point, was identified frame by frame.

The identification took place without the use of particular filters, so as not to condition the result with artefacts and noise reduction processes that could reduce or alter the information available within the images. Before positioning the point, whose coordinates were subsequently collected thanks to the measurement system implemented, particular lines, able to describe the most advanced front of the spurt, were identified with the Photoshop CS6 “Magnetic Lasso” automatic selection tool.

In some cases, when evident, the positioning of the point did not present any particular problem. For example, the positions of the cloud head recorded at frame 0 and frame 19 are very evident, so much that these frames have been adopted as the beginning and end of the sequence.





*Figure C20 – Graphic elaboration for identifying the head of the dust trail: frame 3/20*

Some frames do not allow a sufficiently certain identification of the dust trail tip, so they were left out in the final tracking. These are the frames: 10-11-13-14-15-17-19. Frame 0 does not seem to correspond with the instant of the launch: probably the launch point can be identified in the two previous frames, even if the detection is difficult given the interpretative difficulties that these images present (probably due to the superposition of the two spurts of dust kicked by the Astronaut, first with the right foot and then with the left one).

The darker area of the cloud does not necessarily represent the most densely populated with particles and therefore more compact and advanced. Due to the superposition of the sequential fields recorded by the CTV camera within the analysed frames, it most likely corresponds to the position of the trail of dust resumed in the intermediate fields forming the single frame, which appeared in it twice (see <https://doi.org/10.32388/IA8MXE> A.3.2).



Figure C21 – Graphic elaboration for identifying the head of dust trail: frame 12/20

An animation that exemplifies the motion of the material point at 1fps is available at <https://youtu.be/tOg70CDvzbE> [Ann. C6]

### C.3.6 Measurements [Ann. C7]

Table C1 on the right displays the measurements obtained in relation to the 20 frames of the sequence. We refer to Annex C8 for the consultation of the screenshots that document the measurements made. [Ann. C8]

### C.3.7 Experimental Error and its propagation

The measurements taken were expressed by the Photoshop CS6 Vanishing Point Filter directly on the real scale. The accuracy of the identified values, however, depends both on the calibration of the scale, carried out by associating the known dimensional value (see C.3.4) to a detected segment, and on the individual measurements. In both cases, the sensitivity of the instrument (which we will call  $u$ ) is equal to 1 pixel equivalent to 0,005 m in reality:

$$u = +/- 0.5 \text{ px} = +/- 2.5 \cdot 10^{-3} \text{ m.}$$

Frame	Time (s)	X (m)	Z (m)
0	0,000	0	0,071
1	0,033	0,053	0,106
2	0,067	0,101	0,13
3	0,100	0,148	0,148
4	0,133	0,195	0,166
5	0,167	0,243	0,185
6	0,200	0,285	0,199
7	0,234	0,333	0,207
8	0,267	0,374	0,209
9	0,300	0,422	0,208
10	0,334	0,463	0,205
11	0,367	0,5	0,198
12	0,400	0,535	0,185
13	0,434	0,571	0,167
14	0,467	0,607	0,154
15	0,501	0,643	0,136
16	0,534	0,673	0,113
17	0,567	0,702	0,084
18	0,601	0,732	0,055

Tab. C1 – Big Muley: metric data collected

#### C.3.7.1 Evaluation of the calibration error.

Therefore, the calibration by identifying known measurements requires us to consider a first experimental error equal to the minimum division of the system. Each dimension, enhanced and broken down into its Cartesian components, identifies the scale of the measurement plane on which

it resides. Being orthogonal planes, they collectively contribute to defining the measurement system as a whole. The software used, therefore, associates to each point of the plane a pair of coordinates  $P(x, y)$  so that the distance between two points will be expressed by the relationship:

$$f(x, y) = P_2(x_2, y_2) - P_1(x_1, y_1) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

in which the components  $x$  and  $y$  obtained from the difference between  $x_2 - x_1$  and between  $y_2 - y_1$  are affected with an error  $2u = +/- 1 \text{ px} = +/- 5 \cdot 10^{-3} \text{ m}$ . The distance between points that reside on different planes (provided these planes are orthogonal to each other) can be expressed by a similar relationship. The uncertainty on the distance calculated by the software can be determined starting from the uncertainties of each variable, by calculating the partial derivatives of the function  $f$  with respect to them:

$$\Delta f = \Delta f(\Delta x, \Delta y) = 2u * \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}$$

With  $u = 1$ , the distance can be expressed as follows:

$$D_1 = \left(\frac{\partial(\sqrt{x^2+y^2})}{\partial x}\right)^2 = \frac{x^2}{x^2+y^2}$$

$$D_2 = \left(\frac{\partial(\sqrt{x^2+y^2})}{\partial y}\right)^2 = \frac{y^2}{x^2+y^2}$$

Therefore, the distance will be  $D = \sqrt{x^2 + y^2}$  with uncertainty  $2u = 1$ . This demonstrates that, given an identical initial uncertainty on the coordinates of two points, the uncertainty of their distance maintains the same value.

### C.3.7.2 Evaluation of the error in the measurement.

At this point, we want to identify the position of the material point on the measurement plane. We must therefore consider again the error  $u$  due to the minimum division of the instrument. The experimental error of each measurement can therefore be quantified in

$$3u = +/- 1.5 \text{ px} = +/- 7.5 \cdot 10^{-3} \text{ m}.$$

In order to express the maximum error which burdens each measurement, the module of experimental error will be composed with the module of accuracy error, through the quadrature sum method:

$$ErrMax = \pm \frac{\sqrt{(u^2 + Err^2)}}{2}$$

### C.3.8 Discussion of results

The analysis of the results in order to identify the best fit of the expressed parabolic curve is carried out with the professional software Origin Pro 2018 [[Ann. C9](#)]. The equations of motion represented by the model described above are the following:

$$E_1) X_{mod}(t) = X_0 + (V_{X_0} \cdot t)$$

$$E_2) Z_{mod}(t) = Z_0 + (V_{Z_0} \cdot t) - \left(\frac{1}{2} \cdot g \cdot t^2\right)$$

$$E_3) X_{ErrMax} = \pm \frac{\sqrt{u^2 + (X_x - X_{x+1})^2}}{2}$$

$$E_4) Z_{ErrMax} = \pm \frac{\sqrt{u^2 + (Z_x - Z_{x+1})^2}}{2}$$

Equation:  $X = \text{Intercept} + \text{Slope} \cdot t$

Equation	y = a + b*x				
Report Status	New Analysis Report				
Weight	Instrumental				
Special Input Handling					
Data Filter	No				

Input Data

Masked Data - Values Excluded from Computations

Bad Data (missing values) -- Values that are invalid and thus not used in computations

Parameters

		Value	Standard Error	t-Value	Prob> t
x	Intercept	0,03479	0,00981	3,54531	0,00403
	Slope	1,19835	0,02687	44,59834	1,04361E-14

Slope is significantly different from zero (See ANOVA Table).  
Standard Error was scaled with square root of reduced Chi-Sqr.  
Some input data points are missing.

Statistics

	x
Number of Points	14
Degrees of Freedom	12
Residual Sum of Squares	5,89134
Pearson's r	0,997
R-Square (COD)	0,994
Adj. R-Square	0,9935

Summary

	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
x	0,03479	0,00981	1,19835	0,02687	0,9935

ANOVA

	Model	DF	Sum of Squares	Mean Square	F Value	Prob>F
x	Model	1	976,49463	976,49463	1989,01191	1,05471E-14
	Error	12	5,89134	0,49094		
	Total	13	982,38597			

At the 0.05 level, the slope is significantly different from zero.

Equation:  $Z = \text{Intercept} + B1 \cdot t + B2 \cdot t^2$

Equation	y = Intercept + B1*x^1 + B2*x^2						
Report Status	New Analysis Report						
Weight	Instrumental						
Special Input Handling							
Data Filter	No						

Input Data

Masked Data - Values Excluded from Computations

Bad Data (missing values) -- Values that are invalid and thus not used in computations

Parameters

		Value	Standard Error	t-Value	Prob> t
z	Intercept	0,07407	0,00256	28,89181	1,00382E-11
	B1	0,93393	0,01854	50,36791	2,33147E-14
	B2	-1,62066	0,02995	-54,10735	1,06581E-14

Standard Error was scaled with square root of reduced Chi-Sqr.  
Some input data points are missing.

Statistics

	z
Number of Points	14
Degrees of Freedom	11
Residual Sum of Squares	0,77657
R-Square (COD)	0,99628
Adj. R-Square	0,99561

Summary

	Intercept		B1		B2		Statistics
	Value	Standard Error	Value	Standard Error	Value	Standard Error	Adj. R-Square
z	0,07407	0,00256	0,93393	0,01854	-1,62066	0,02995	0,99561

ANOVA

	Model	DF	Sum of Squares	Mean Square	F Value	Prob>F
z	Model	2	208,05863	104,02931	1473,5593	4,34097E-14
	Error	11	0,77657	0,0706		
	Total	13	208,8352			

At the 0.05 level, the fitting function is significantly better than the function y=constant.

Figure C22 – Fit of the motion curve with Origin Pro: parameters obtained on the two axes

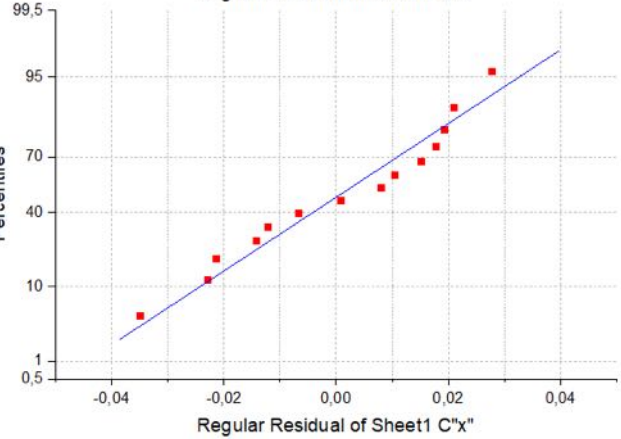
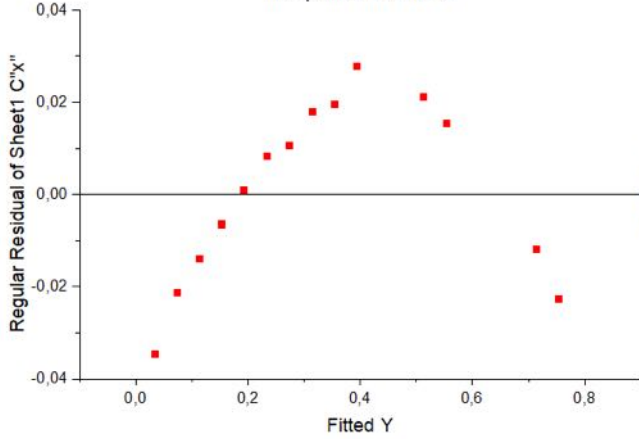
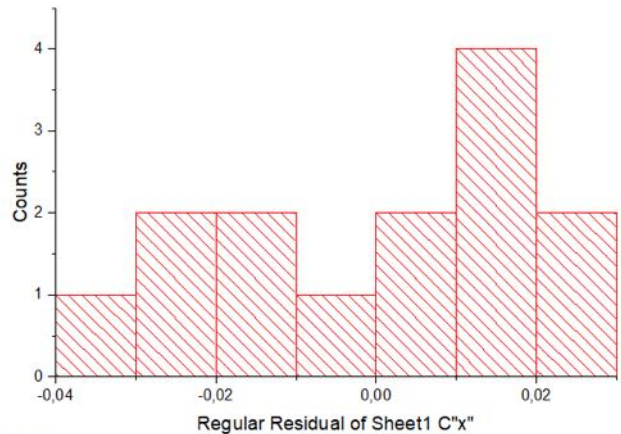
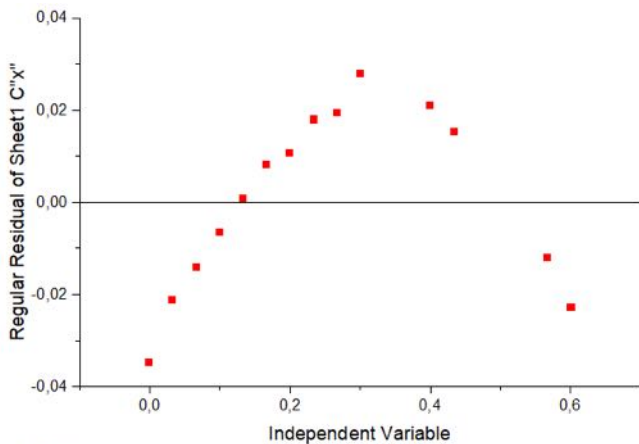
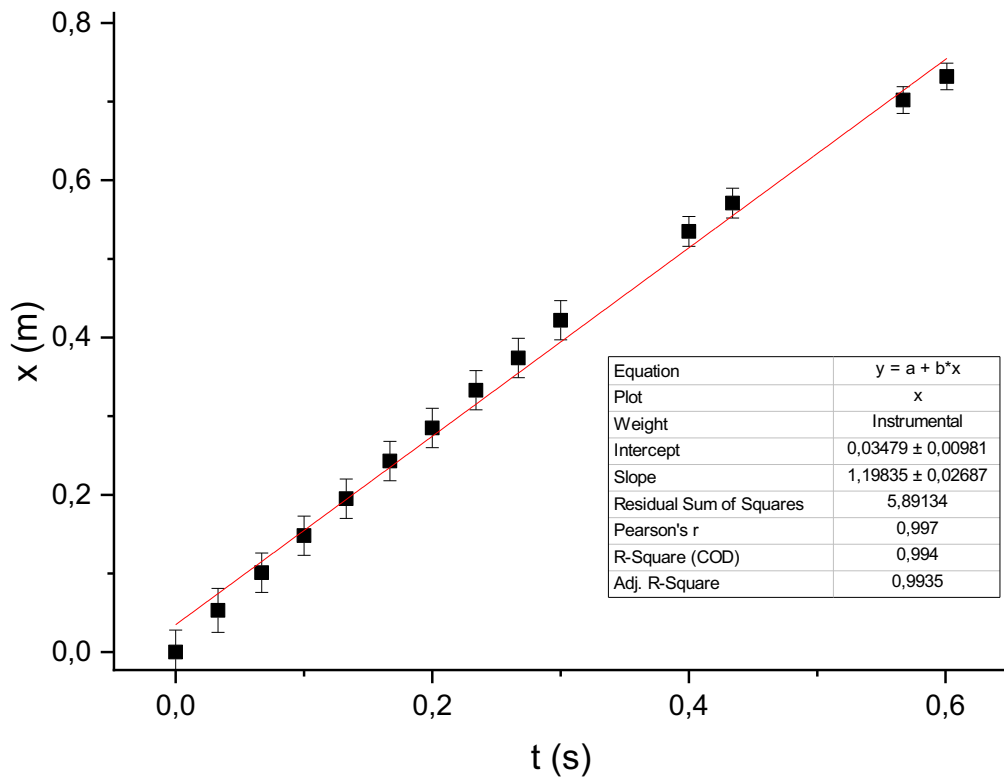


Figure C23 – X-axis fit with maximum error range and data variability analysis (Origin Pro)

As regards the X axis the fit software proposes a horizontal speed of the dust trail of approximately 1.20 m/s, but the problem is that the data collected only partially validates the linear model.

The best estimation of Z-axis gravity acceleration in the tracked sequence is  $g_{or} = -3.24 \pm 0.060 \text{ m/s}^2$  (Standard Err). A value significantly higher than the one obtained in the previous chapter but above all increasingly far from the expected one:

$$\frac{|g_{or} - g_m|}{\sigma} = \frac{|-3.24 + 1.62|}{0,060} = 27.00 > 3$$

The analysis of the data variability proposed by the Origin Pro 2018 software and reported in Figure C25 highlights that the distribution of the residues is sufficiently disordered; the random error is normally distributed with the exception of the interval of residuals between +0.004 and +0.002 m, in which 5 values are included; the variance is approximately linear. It is therefore a model strongly validated by the data, but which does not prove consistent with the context of a lunar event.

Frames	T (s)	X <sub>ps</sub> (m)	X <sub>ErrMax</sub> (m)
0	0.000	0.000	±0.028
1	0.033	0.053	±0.028
2	0.067	0.101	±0.025
3	0.100	0.148	±0.025
4	0.133	0.195	±0.025
5	0.167	0.243	±0.025
6	0.200	0.285	±0.025
7	0.234	0.333	±0.025
8	0.267	0.374	±0.025
9	0.300	0.422	±0.025
10	0.334	-	-
11	0.367	-	-
12	0.400	0.535	±0.019
13	0.434	0.57	±0.019
14	0.467	-	-
15	0.501	-	-
16	0.534	-	-
17	0.567	0.702	±0.017
18	0.601	0.732	±0.017
19	0.634	-	-

Table C2 – “Big Muley” sequence: X<sub>photoshop</sub> quotas and maximum associated error

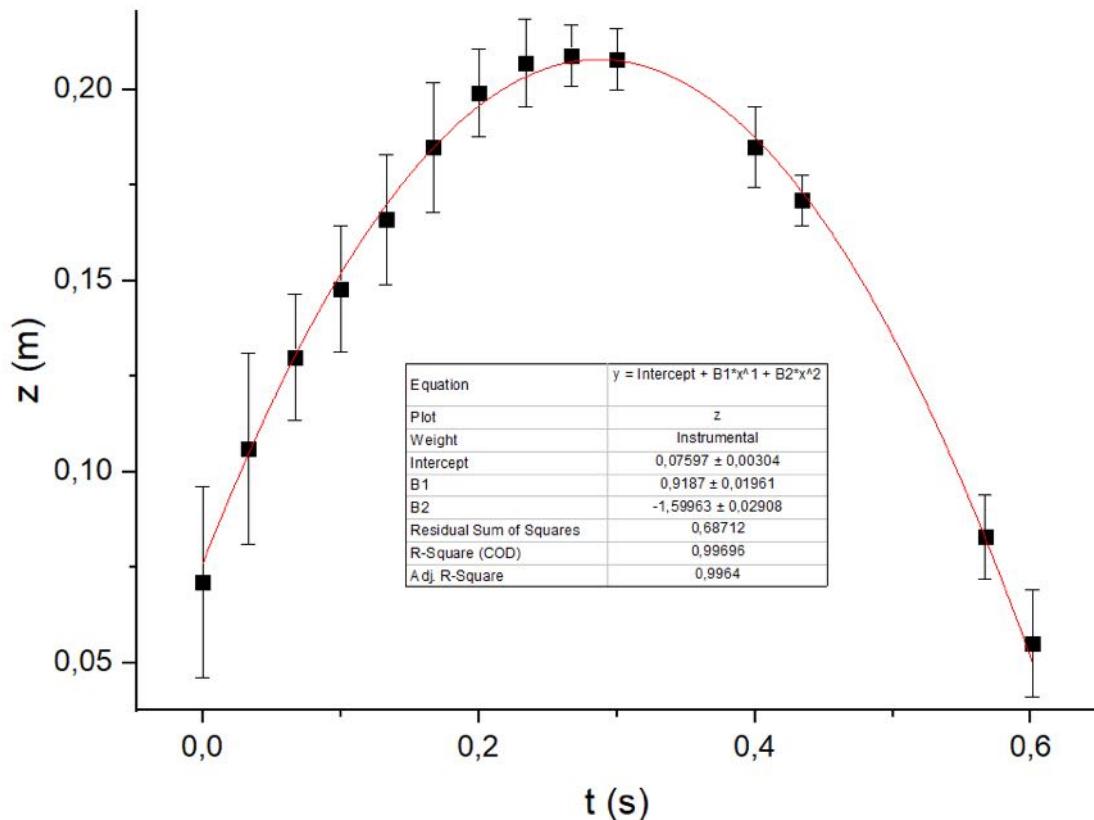


Figure C24 – Z-axis fit with maximum error range

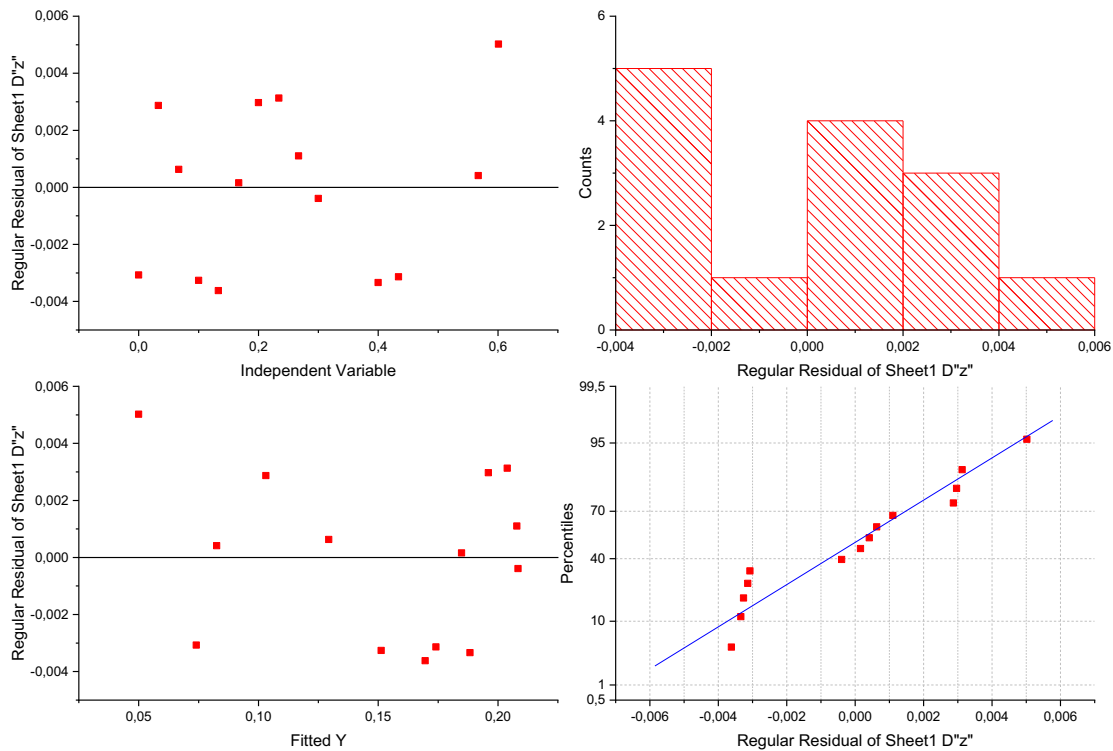


Figure C25 – Z-axis fit analysis of data variability (Origin Pro)

In an attempt to identify a better model, the data collected are proposed for a new fit, this time also on the X-Axis according to a non-linear equation [Ann. C10]. To introduce this choice, we must clarify some basic assumptions.

**C.3.9 Hypothesis of motion with air resistance.**

Getting inspiration once again from the study “Ballistic motion of dust particles in the Lunar Roving Vehicle dust trails” by Mihaly Horanyi and Hsiang-Wen Hsu, and in particular from the section “IV. Discussion”, a motion model with air resistance is adopted on the X-axis.

Abandoning the model that saw dust particles reduced to a material point, let's consider a braking action originating from the viscous resistance of the air, which, given the relatively low speed (Reynolds number  $Re < 1$ ), prevails over the pressure resistance.<sup>14</sup>

Frames	T (s)	Z <sub>ps</sub> (m)	Z <sub>ErrMax</sub> (m)
0	0.000	0.071	±0.019
1	0.033	0.106	±0.019
2	0.067	0.13	±0.012
3	0.100	0.148	±0.012
4	0.133	0.166	±0.012
5	0.167	0.185	±0.012
6	0.200	0.199	±0.009
7	0.234	0.207	±0.009
8	0.267	0.209	±0.008
9	0.300	0.208	±0.008
10	0.334	-	-
11	0.367	-	-
12	0.400	0.185	±0.010
13	0.434	0.171	±0.010
14	0.467	-	-
15	0.501	-	-
16	0.534	-	-
17	0.567	0.083	±0.016
18	0.601	0.055	±0.016

Table C3 – “Big Muley” sequence: Z<sub>photoshop</sub> quotas and maximum associated error

<sup>14</sup> Fundamentals of Physics and Chemistry of the Atmosphere  
Guido Visconti, Copyright Springer Science & Business Media, 2001.

The equations representing the motion will be <sup>15</sup> :

$$E_5) X_{\text{airdrag}}(t) = X_0 + V_{x0} * \tau * (1 - e^{-\frac{t}{\tau}})$$

$$E_6) Z_{\text{airdrag}}(t) = Z_0 + (V_{z0} + (g * \tau)) * \tau * (1 - e^{-\frac{t}{\tau}}) - (g * \tau) * t$$

where  $\tau = \frac{m}{\beta * d}$  is the time which horizontal velocity takes to reach  $\frac{1}{e}$  of its initial value.

Figures C26 – C27 – C28 represent the results of the fit of the data collected on the X-axis with equation E5

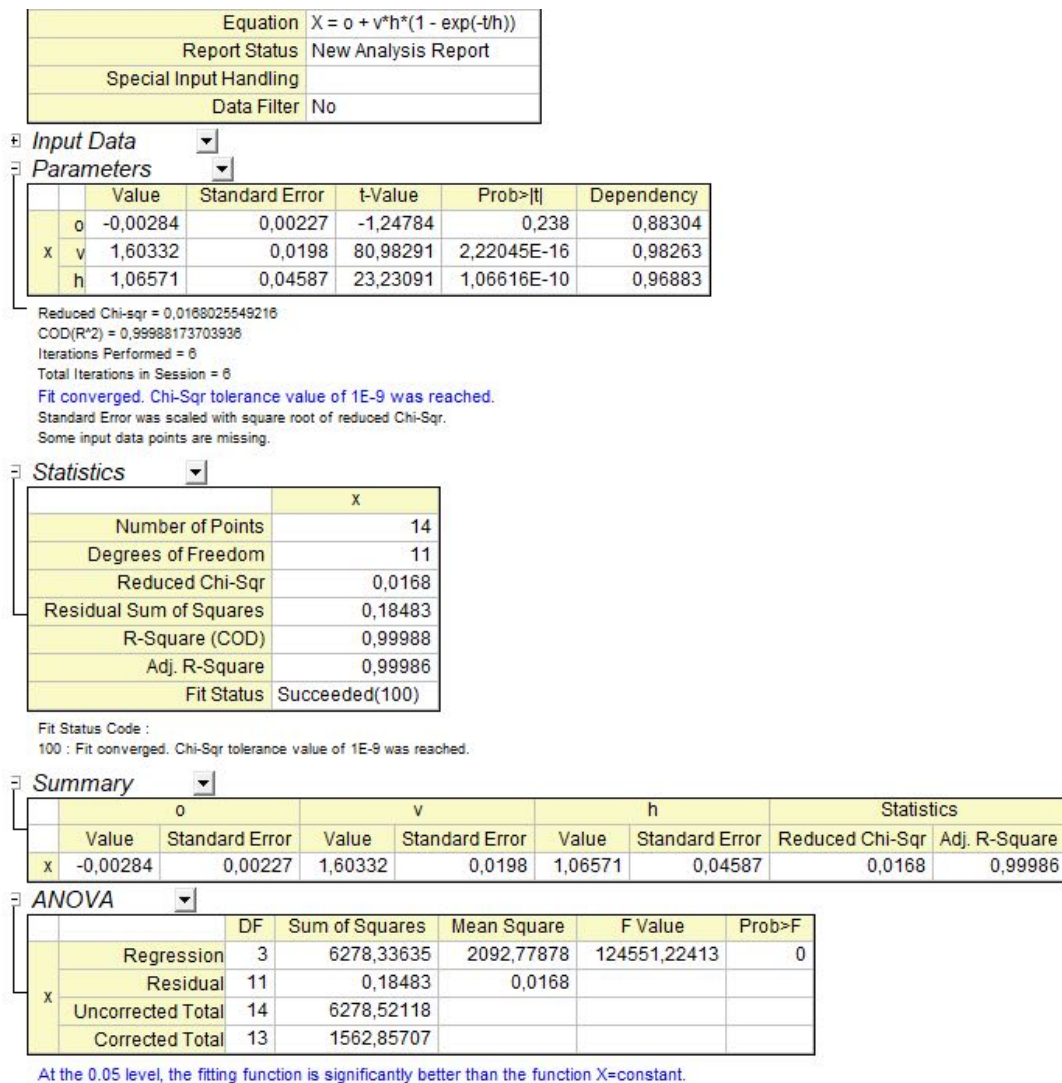


Figure C26 – X-axis, non-linear fit: parameters obtained and their reliability

<sup>15</sup> <https://www.researchgate.net/publication/258468670> - M. Horanyi e Hsiang-Wen Hsu, "Ballistic motion of dust particles in the Lunar Roving Vehicle dust trails", American Journal of Physics, 2012



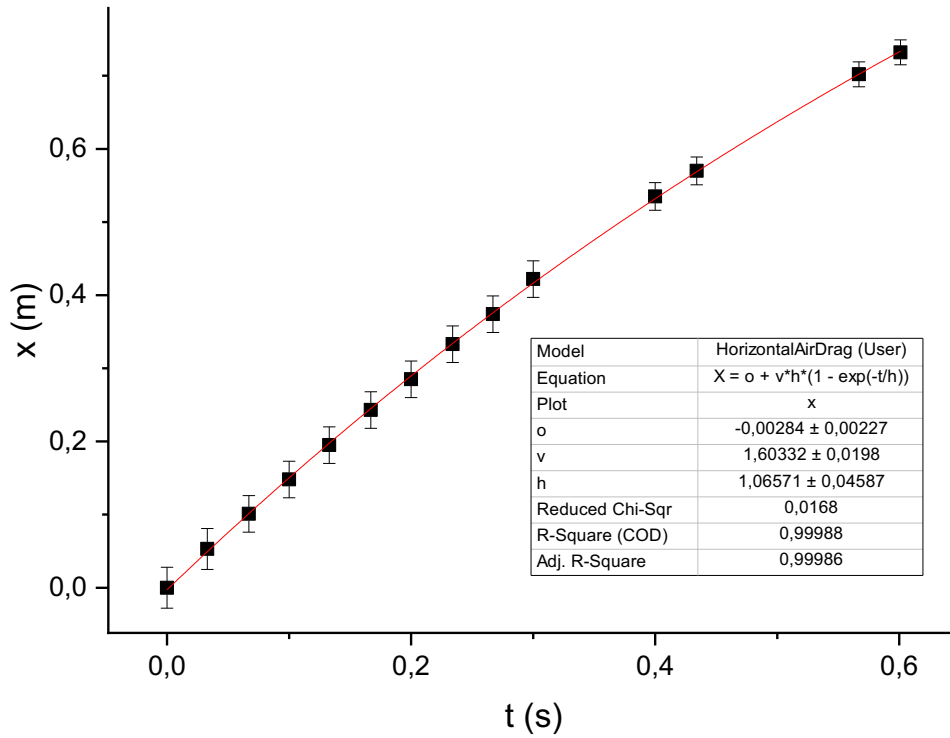


Figure C27 – X-axis, motion plot with air resistance

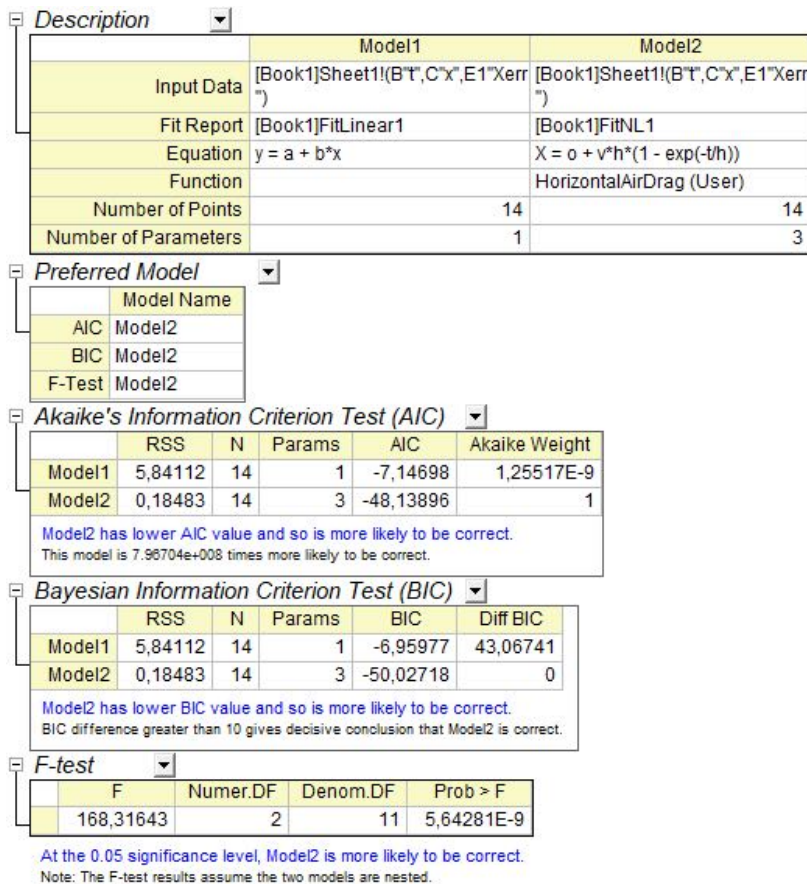


Figure C28 – X-axis: comparison between linear model and model with air resistance

As can be seen from Figure C28 on the X-axis, the model with air resistance proves to be more effective than the linear one. The time  $\tau$  which in the software analysis is indicated with the parameter  $h$ , is identified by the fit with the approximate value of 1.1 seconds (Figure C27).

To verify the consistency of this data we refer to the mechanical characteristics of the dust particles starting from those of the simulant of the lunar regolith used. Apollo program engineers and geologists developed 5 lunar soil simulants (LSS). In 1970 in Dayton, Ohio, the LSS-4 simulant was used in a series of mechanical tests on the wheels of the Lunar Rover because researchers considered it to be particularly suitable for representing the characteristics of the lunar soil for the Apollo 15 mission.<sup>16</sup>

About Apollo 16 it was then ascertained that the soil characteristics of the stations visited during the EVAs did not differ from those of previous missions. Figure C29 shows the comparison of the grain size distribution of the lunar soil in the lunar landing areas chosen for the various missions.<sup>17</sup>

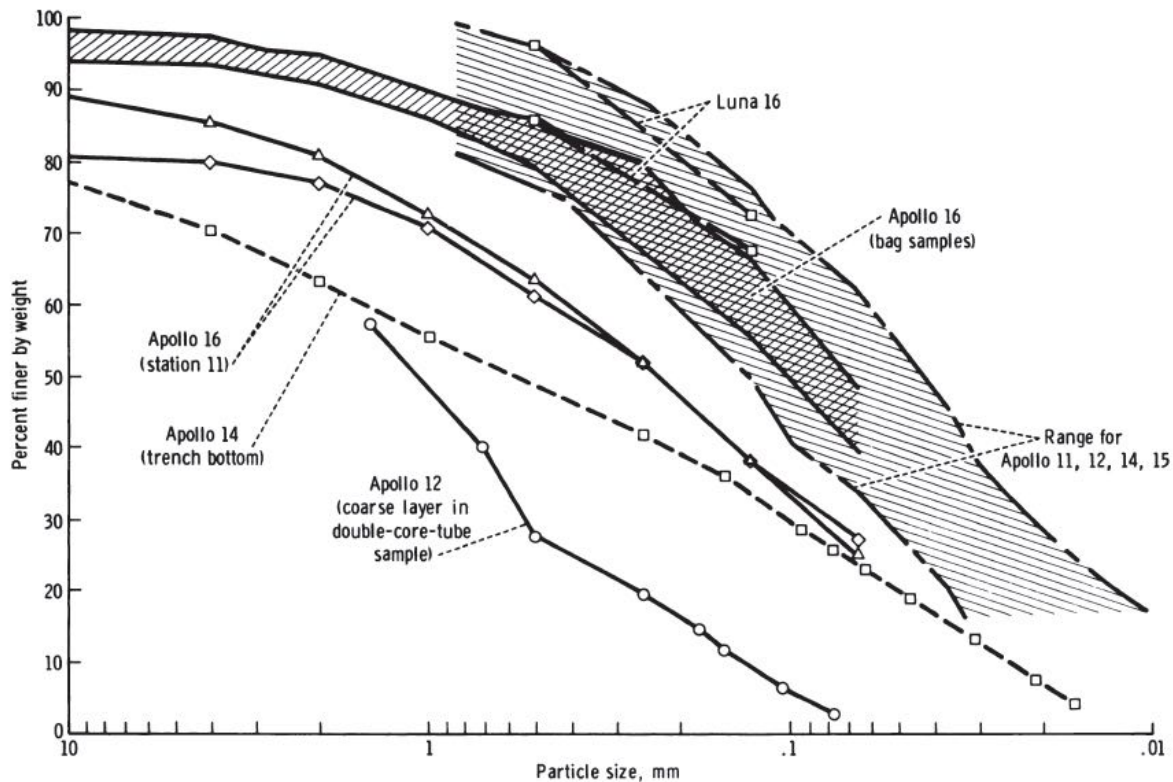


Figure C29 - Comparison of the grain size distribution of lunar soil in the Apollo missions

As can be seen from the graph, the distribution found in the Apollo 16 mission constitutes a subset of the distribution range relating to the previous missions. It is therefore plausible that the LSS-4 simulant was also used in relation to Apollo 16, or at least it was considered eligible to replicate the characteristics of the lunar soil for the Descartes Highlands and the Plum Crater. Below are its mechanical characteristics<sup>17</sup>:

<sup>16</sup> <https://www.lpi.usra.edu/lunar/documents/NASA%20CR-121075.pdf> A Study and Analysis of the MSFC Lunar Roving Vehicle Dust Profile Test Program by C. Howell Mullis, November, 1971 - College Of Engineering University Of Alabama [Ann. B8]

<sup>17</sup> <https://www.nasa.gov/wp-content/uploads/static/history/alsj/a16/as16psr.pdf> Apollo 16, Preliminary Science Report, NASA 25 May 1973 (pag 8.5)

**LSS-4**

*Official Name: Lunar Soil Simulant 4*

*Parent Rock Source: Basalt Rock Company, Napa, California*

*Material: Crushed Basalt*

**Grain Size Distribution:**

*D60 = 0.19 mm*

*D10 = 0.0065 mm*

*Cu (Uniformity coefficient) D60/D10 = 29.3*

*Distribution Classification: Well-Graded*

*Color: Cement Gray*

*Manufacturer and Test Laboratory:*

*U.S. Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi*

Once the physical characteristics of the simulant are known and their compatibility with those of the lunar soil is verified, we proceed with the construction of the mechanical model of dust particles, approximating it to a sphere in order to identify the best value of  $\tau$  indicated by the Origin Pro software in the fit model with air resistance. With the help of the spreadsheet [[Ann. C7](#)], the results obtained are the following:

Particle Diameter	344	$\mu\text{m}$
Surface of Particle Section	0.093	$\text{mm}^2$
Particle Volume	$2.13144 \cdot 10^{-11}$	$\text{m}^3$
Basalt Density	2950	$\text{Kg}/\text{m}^3$
Particle Mass	$6.28776 \cdot 10^{-8}$	$\text{Kg}$
Viscosity Air Coefficient	$1.81000 \cdot 10^{-5}$	
Constant Sphere resistance	9.42478	
$\beta$	$1.70588 \cdot 10^{-4}$	
$\tau$	1.07149	s

*Table C4 – Mechanical data characteristic of the dust particles*

To obtain  $\tau = 1.07 \text{ s}$  it is therefore necessary to assume that the particles had a diameter of 344 microns. This is a value that can be considered consistent with the scientific data available, relating to the simulant used for the tests and to the lunar soil in question. This grain size value is positioned in the graph in Figure C29 as indicated in the following figure C30.

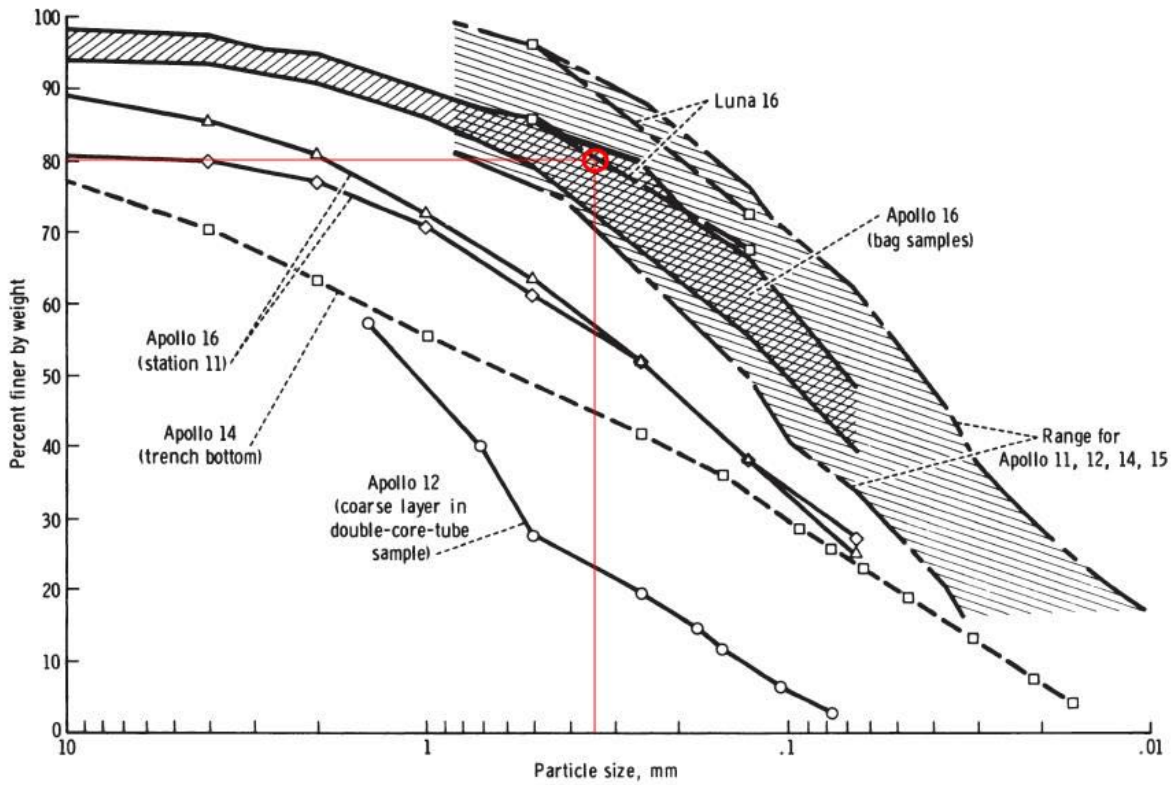


Figure C30 – Consistency of the particle size result

In fact, according to the scientific information available, approximately 20% of the particulate in question (present on the lunar soil or simulated in the laboratory) had a diameter equal to or greater than that taken into consideration for the model. And then it is legitimate to determine a higher-than-average value, since we are tracing the head of the dust spurt: the biggest particles tend to be less subject to the braking action of the air and therefore to have a longer trail.

We, therefore, perform the fit of the data collected on the Z-Axis by setting  $\tau = 1.07$  s as the fixed parameter of the E6 equation and we observe that the fit is excellent also in this case (Figures C31, C32, and C33).

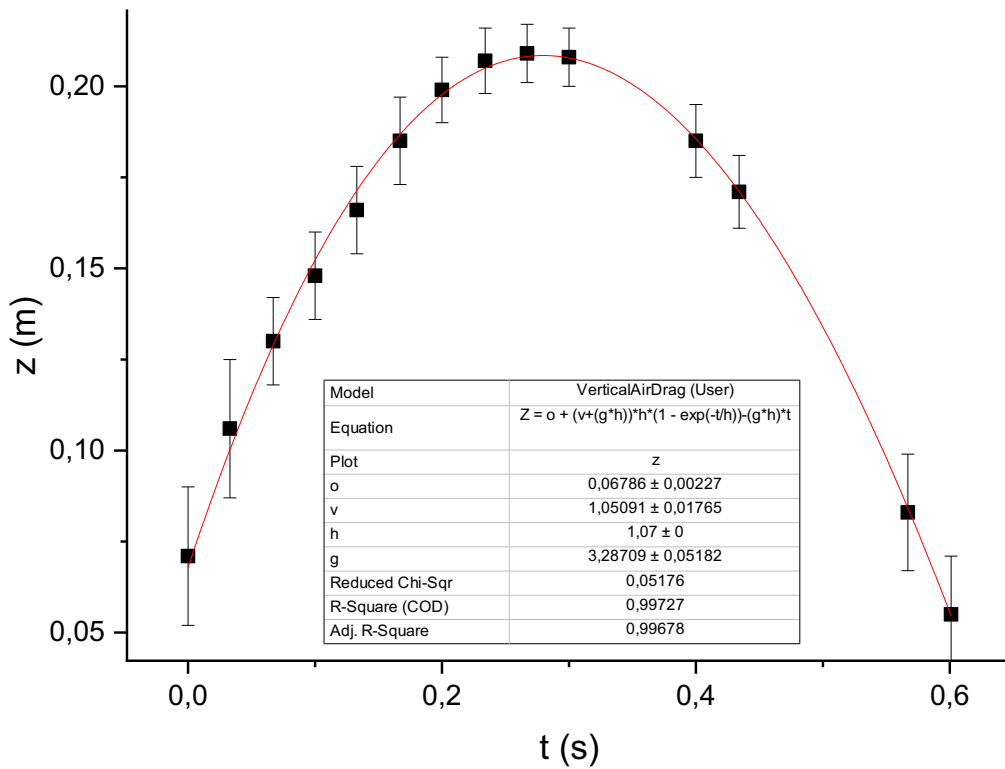


Figure C31 - Plot of data collected from tracing on the Z-axis with fit equation E6

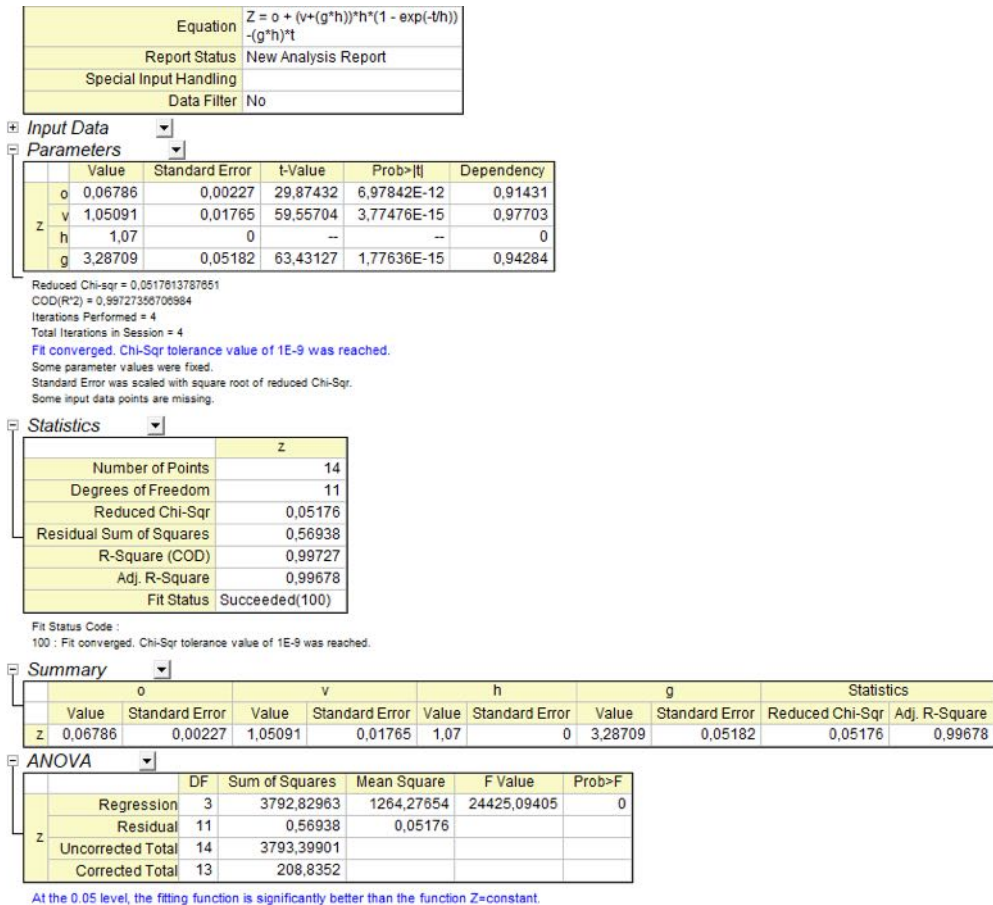


Figure C32 - Fit values, data relating to the Z-Axis with fit equation E6

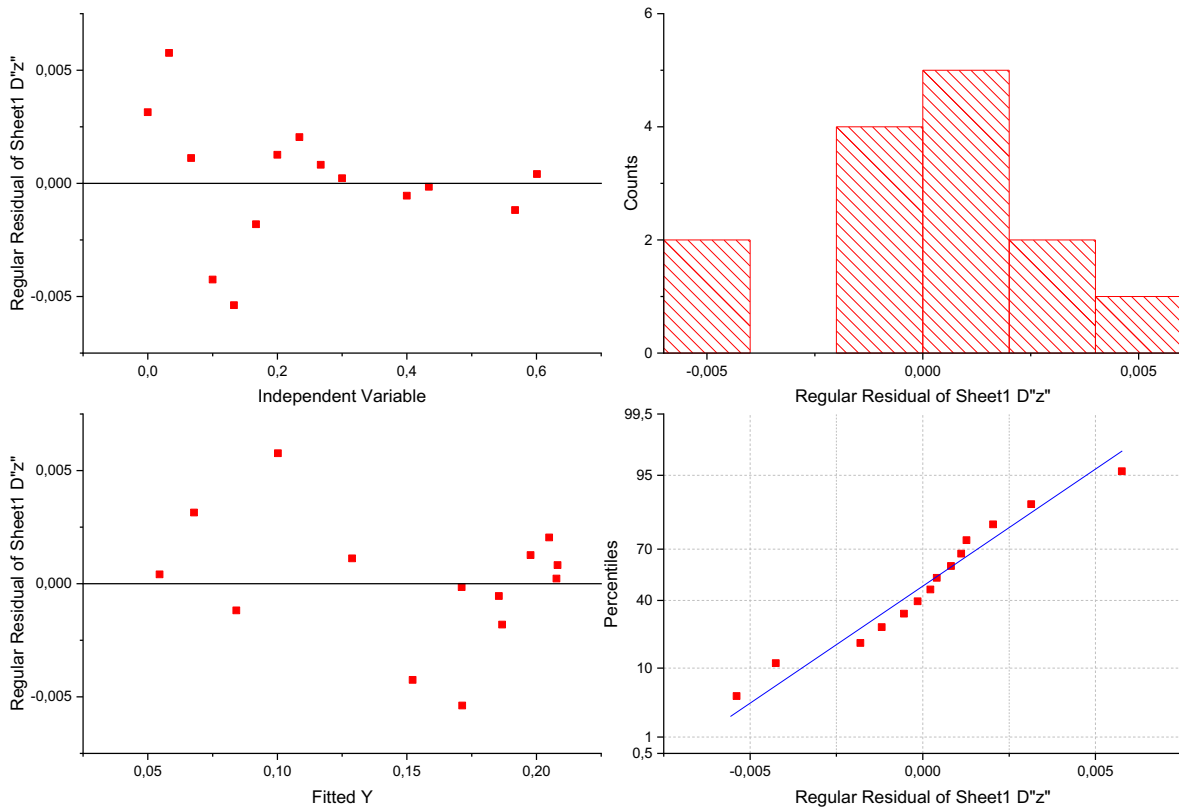


Figure C33 – Analysis of residuals, fit of data relating to the Z-Axis with fit equation E6

### C.4.1 Framerate Correction

By applying what has already been used in B.3.4.2 we can calculate an appropriate framerate correction factor so as to be able to bring g back to the expected values:

$$Z(t) = Z_0 + (V_{z0} + (g * \tau)) * \tau * (1 - e^{-\frac{t}{\tau}}) - (g * \tau) * t \text{ is equivalent to}$$

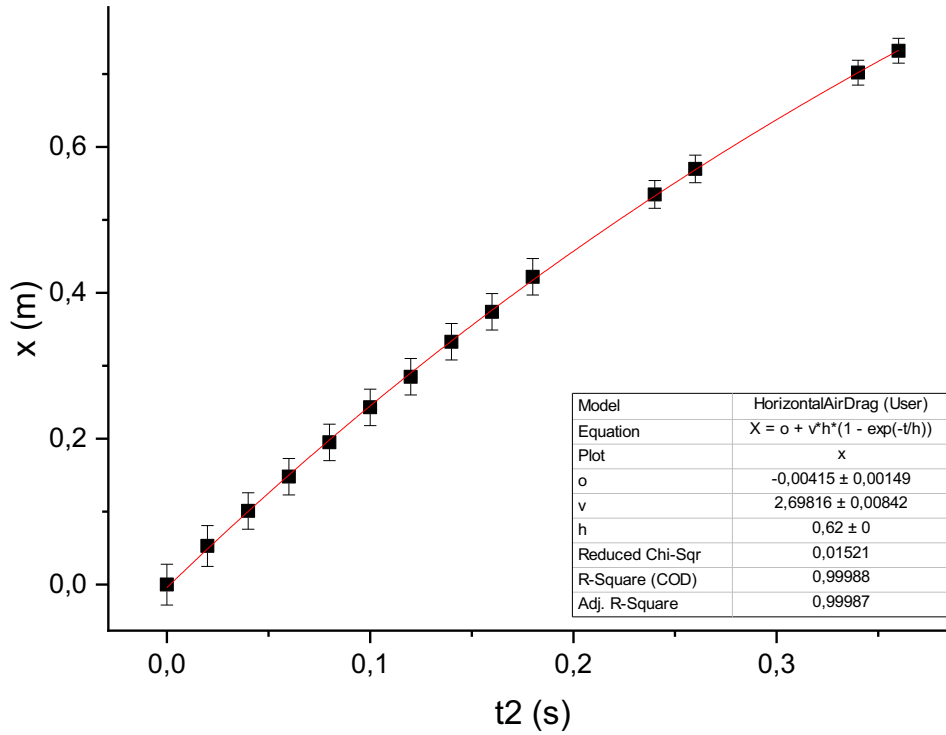
$$Z'(t) = Z_0 + (V'_{z0} + (g' * \tau')) * \tau' * (1 - e^{-\frac{t'}{\tau'}}) - (g' * \tau') * t' \text{ when}$$

$$t' = \frac{t}{\alpha}; \quad \tau' = \frac{\tau}{\alpha}; \quad v'_{z0} = \alpha \cdot v_{z0} \quad \text{e} \quad g'_{av} = g_{av} \cdot \alpha^2$$

Considering that in the fit carried out, the results are consistent only with the models with air resistance, the correction factor is calculated considering the value of terrestrial  $g = 9.81 \text{ m/s}^2$ :

$\alpha = \sqrt{\frac{9.81}{3.29}} = 1.73$  in this case, therefore, the correct shooting framerate is 51.75 fps, and the time  $\tau'$  takes on the value of 0.62 seconds, obtainable with particles of at least 262 microns diameter, a value that is fully admissible in the studied context.

Even approximating the framerate to the more plausible value of 50 fps, the fit [Ann. C11] performed according to E6 with fixed parameters  $g = 9.81 \text{ m/s}^2$  and  $\tau' = 0.62 \text{ s}$  always proves to be excellently effective on both axes (Figures C34 and C35).



Equation	$X = o + v \cdot h \cdot (1 - \exp(-t/h))$
Report Status	New Analysis Report
Special Input Handling	
Data Filter	No

Input Data

Parameters

	Value	Standard Error	t-Value	Prob> t	Dependency
o	-0,00415	0,00149	-2,77664	0,01675	0,75483
x	v	2,69816	0,00842	320,51365	0
	h	0,62	0	--	0

Reduced Chi-sqr = 0,0152116199123  
 COD(R<sup>2</sup>) = 0,99988320145043  
 Iterations Performed = 4  
 Total Iterations in Session = 4  
 Fit converged. Chi-Sqr tolerance value of 1E-9 was reached.  
 Some parameter values were fixed.  
 Standard Error was scaled with square root of reduced Chi-Sqr.  
 Some input data points are missing.

Statistics

	x
Number of Points	14
Degrees of Freedom	12
Reduced Chi-Sqr	0,01521
Residual Sum of Squares	0,18254
R-Square (COD)	0,99988
Adj. R-Square	0,99987
Fit Status	Succeeded(100)

Fit Status Code :  
 100 : Fit converged. Chi-Sqr tolerance value of 1E-9 was reached.

Summary

	o		v		h		Statistics	
	Value	Standard Error	Value	Standard Error	Value	Standard Error	Reduced Chi-Sqr	Adj. R-Square
x	-0,00415	0,00149	2,69816	0,00842	0,62	0	0,01521	0,99987

ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
x	Regression	2	6278,33864	3139,16932	206366,5368	0
	Residual	12	0,18254	0,01521		
	Uncorrected Total	14	6278,52118			
	Corrected Total	13	1562,85707			

At the 0.05 level, the fitting function is significantly better than the function X=constant.

Figure C34 - Plot and data related to the X-Axis with E5 fit equation and framerate of 50 fps

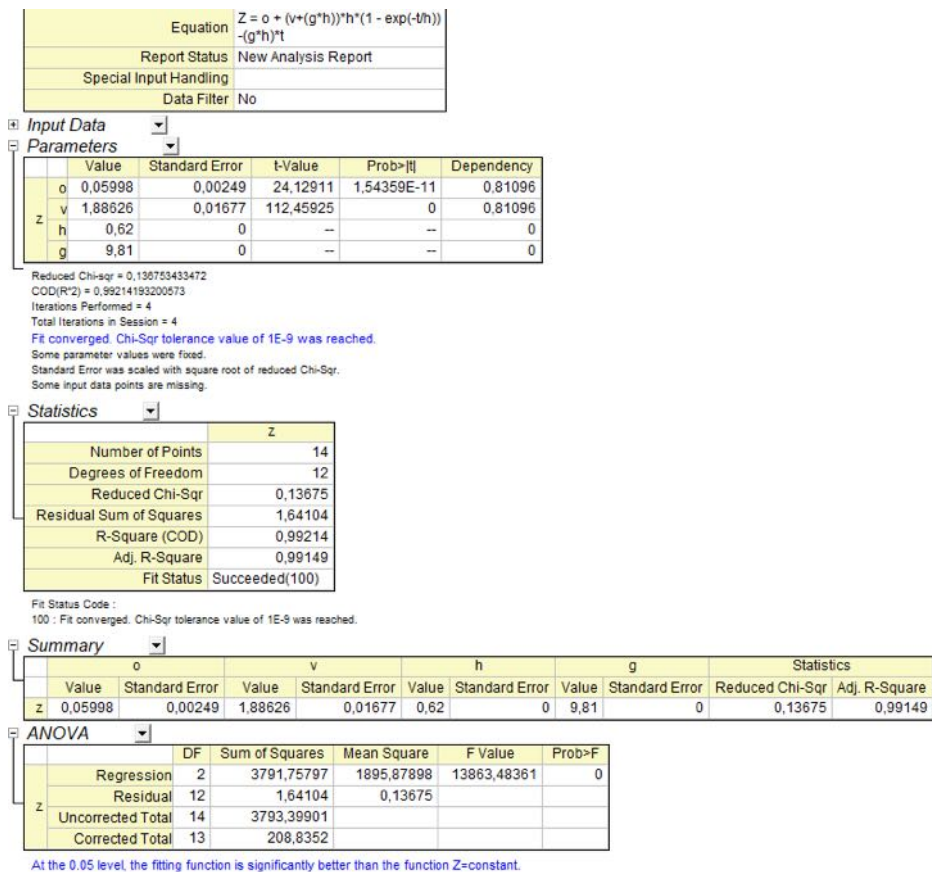
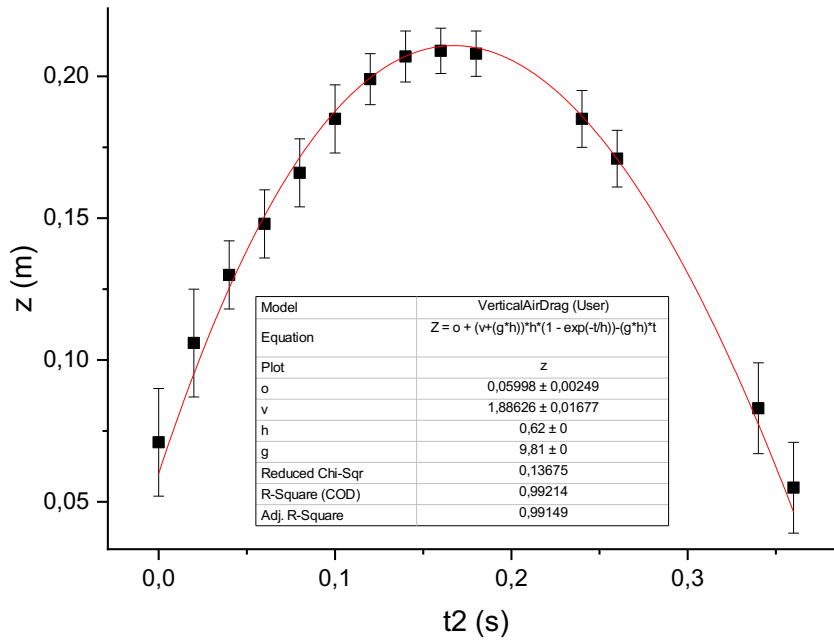


Figure C35 - Plot and data related to the Z-Axis with E6 fit equation and framerate of 50 fps

The theoretical model so obtained, relating to a terrestrial parabolic motion of basalt particles in the presence of viscous friction caused by air, finds substantial identity with the experimental results for granulometric values of the dust compatible with those of the simulants used in technical tests conducted for the preparation of Apollo missions, if we accept that the camera recording framerate was 50 fps instead of 29.97 fps.



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## Authors contribution

- Alessio Michelotti: Conceptualization, Data curation, Investigation, Project administration, Visualization, Writing – original draft
- Andrea Simon: Conceptualization, Formal Analysis, Methodology, Software, Supervision, Validation

## Conflict of interests

The authors declare that there are no conflicts of interest.

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- **Andreas Märki**, Zurich (CH); Master of Engineering, Swiss Aerospace Industry Technician.  
Revised sections: Preamble; Sections A, B, C, D.

- **Andrea Simon**, Vittorio Veneto (IT); Physics teacher and headmaster at Scuola Superiore “Novalis”, San Vendemiano (Treviso, IT). Revised sections: Preamble; Sections A, B, C, E.

- **Luis Bilbao**, Buenos Aires (ARG); PhD at the Physics University of Buenos Aires; more than 100 publications in international journals; reviewer for the American Journal of Physics and other major scientific journals. Revised sections: Sections B, E.

- **Dwight Steven-Boniecki**, Köln (DE); Author of Space History: NASA Skylab and Soyuz Mission Reports Editor/Compiler. Revised sections: Preamble; Section A.

- **David Chandler**, Denver, Colorado (USA); Teacher at Porterville College, Porterville, CA / Physics, Mathematics, and Engineering; publications in American Journal of Physics and other Journals. Served on “The Physics Teacher” Editorial Board as a reviewer.  
Revised sections: Preamble.

- **Francesco Vinci**, Avola (IT); Order of Architects P.P.C. Siracusa province; Teacher at Università degli Studi di Catania, Facoltà di Scienze dell’Architettura e dell’Ingegneria Edile. Creator of “Brunelleschi” software for prospective restitution. Revised sections: Preamble; Section A.

Their contribution to the review process is documented in the specific appendix (not attached here).

The previous study “**Analytical Methods for Tracking Bodies Motions on the Lunar Surface in Apollo XVI Footage – An analysis method**” has been reviewed as Preprint on the **qeios.com** platform the 22nd April 2024: <https://www.qeios.com/read/IA8MXE>

The following researchers further revised that work:

Dr. **Jens Biele German** (h-index 36) Aerospace Center (DLR), Köln (DE) – Astronomy, Geophysics, Experimental Physics and Thermodynamics Researcher. Revised sections: Sections A, B, C.

Dr. **Alexey Artamonov** (h-index 9), National Research Nuclear University MEPhI - Moscow Engineering Physics Institute, Moscow (RU). Revised sections: Sections A, B, C.

(English translation by Roberto Leopardi)