Llullaillaco and Paranal's Skyline

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The visibility of the volcano Llullaillaco from Paranal is discussed. That it can be seen at all depends on two circumstances: a fortunate geometry and the superb quality of the atmosphere over the Atacama Desert, stretching over a baseline of 190 kilometres, much longer than in any astronomical observation.

Figure 1. Llullaillaco as seen from the VLT platform. Close-up of a picture taken by Gianluca Lombardi on 19 December 2011.

If you have ever happened to visit Paranal you will have very likely recognised a majestic peak on the eastern horizon. This is Llullaillaco (pronounced You-ya-i-yaco, meaning "dirty lagoon" in Ketschua), at 6739 metres above sea level, the third-highest peak in Chile, the seventh highest in the Andes, and arguably the highest active volcano in the world. The view from Paranal is shown in Figure 1. The last eruption of Llullaillaco was recorded in 1877. It has beautiful lava flows extending both to the north and south. During most of the year it appears as snow-capped, although without glaciers: the snow limit in that part of the Andes is the highest in the world, at about 6500 metres. Even in that part of the Andes you would have to travel 265 kilometres to find a higher contour (Tres Cruzes, 6749 metres). It is impressive even by Chilean standards, and dwarfs Europe's highest mountain, Mt. Blanc at 4810 metres.

The first recorded ascent was in 1952[1], but there were earlier visitors: the mummies of three Inca children were discovered close to the summit in 1999, thus making Llullaillaco the highest archaeological site in the world.

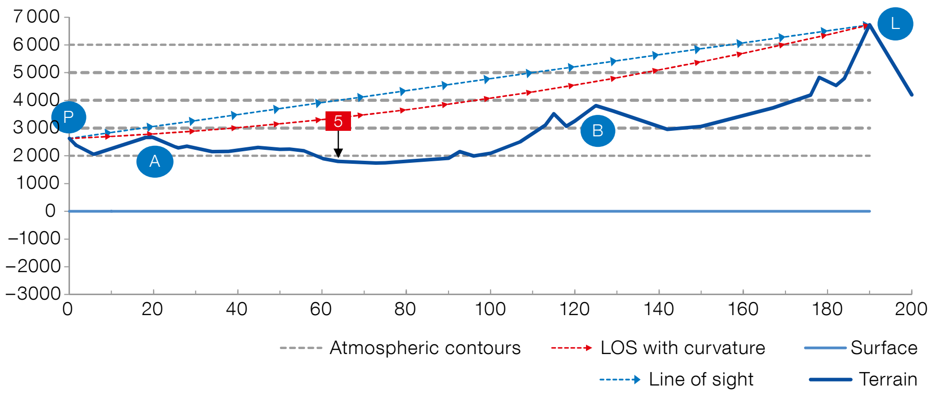
Visibility

There are several interesting aspects about Llullaillaco that are related to Paranal itself and its skies. First, as Google Earth confirms, the Paranal–Llullaillaco line of sight (LOS) spans 190 kilometres, starting on the Paranal platform at an elevation of 2600 metres and ending at 6739 metres, right at the Chilean–Argentine border. This is almost the entire width of Chile at this latitude.

If you take it for granted that one can spot a 6700-metre peak from a distance of 190 kilometres, then it is interesting to check the LOS profile (Figure 2, dotted blue line) from Paranal (P) towards Llullaillaco (L). There are two "critical" points: the nearby Sierra Vicuña Mackenna (A, 20 kilometres distant from Paranal, and including Cerro Armazones), and the distant Cordillera de Domeyko (B, 125 kilometres). For orientation, the ruta 5 is also marked (red square). It is clear that we have been lucky (or benefit from careful planning) with the siting of the Paranal platform: if it had been blasted just a few tens of metres lower, the view towards the Llullaillaco summit would have been vignetted by the nearby Sierra Vicuña Mackenna, as one can confirm by walking down from the platform along the road to the hairpin bend. The other element of luck is that the LOS crosses the Sierra just south of Cerro Armazones.

In addition to the purely fortuitous terrain morphology, there is another important effect to take into account: the curvature of the Earth. With distance D from the reference point P, the deviation of the tangential plane from the (ideal) surface curvature grows as $D^2/(2R)$, where R (6371 kilometres) is the mean Earth radius[2]. Figure 3 shows the LOS with curvature taken into account. Since the

Figure 2. The line of sight (in blue), the terrain, and atmospheric layers, neglecting surface curvature between Paranal (P) and Llullaillaco (L) . Intervening places are explained in the text. The terrain has been taken from Google Earth. Distances are in kilometres, elevation in metres.



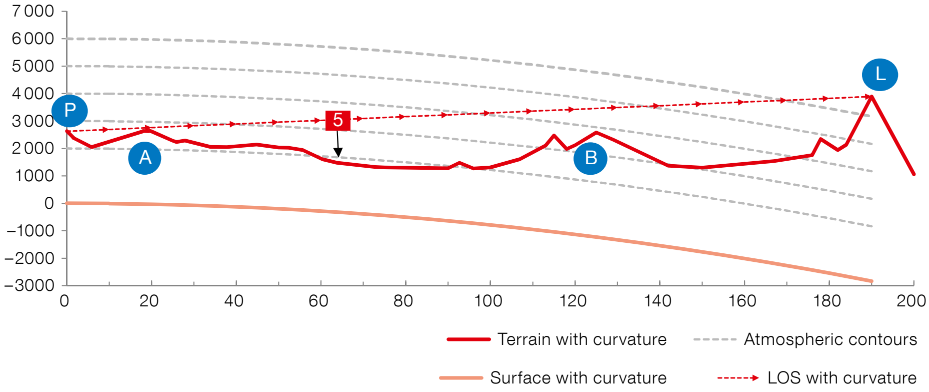


Figure 3. Same line of sight as Figure 2 but now considering surface curvature of the Earth. The LOS intersects with lower atmospheric layers than in Figure 2. This LOS with curvature is also sketched in Figure 2 (red dotted line).

curvature effect grows with D^2 it affects Sierra Vicuña Mackenna by 30 metres and the Cordillera de Domeyko, 125 kilometres away, by 1.2 kilometres. At the distance of Llullaillaco (190 kilometres) the surface curves down by an amazing 3.1 kilometres with respect to the tangential plane! So that the summit has effectively only an elevation of 3600 metres as seen from Paranal.

A careful analysis would also take atmospheric refraction into account: objects in the far distance are effectively lifted up and the effect of curvature is thus reduced. This is usually accounted for by choosing a 10% higher value for *R* in the above formula, lifting Llullaillaco by the same 10% to 4.1 kilometres. This effect is neglected in the following discussion.

Figure 4. Llullaillaco in winter, displaying a spectacularly rich contrast and wealth of details (taken on 14 July 2012 by Dimitri Gadotti).

The curvature effect is strongest for the most distant points, and much less so for the nearby and intermediate terrain. So, surface curvature makes it much easier for the Sierra Vicuña Mackenna to mask Llullaillaco, although it is only at the same altitude (2645 metres, curvature-corrected) as Paranal itself. The curvature-corrected LOS requires 2763 metres at that distance, giving a clearance of just 120 metres (point A in Figures 2 and 3), which could indeed be called a near-miss given the geometrical dimensions of the problem. The much higher Cordillera de Domeyko (3882 metres and 125 kilometres distance away; point B in Figures 2 and 3) is less critical for the LOS, since it is itself curvature-reduced by 1.2 kilometres, giving a comfortable clearance of more than 800 metres.

Transparency

With the geometry sorted out, now we need to look at sky transparency: how is it possible to look through the atmosphere along a 190-kilometre baseline and still retain excellent contrast (as evident from Figure 4)?

Light travelling through the atmosphere, no matter whether it is starlight or sunlight scattered off Llullaillaco towards Paranal, is both absorbed and scattered. We are discussing here much stronger effects than are usual in astronomy: lines of sight towards the stars traverse the atmosphere roughly vertically, with a typical scale height of 8 kilometres, and the first, and worst, 2.6 kilometres have already been truncated by Paranal's elevation. Here, we look through 190 kilometres of air, almost tangentially. What is the typical atmospheric elevation across that LOS? The blue LOS in Figure 2 steadily increases from 2600 to 6700 metres, but that needs to be corrected since the atmospheric layers follow the gravitational curvature (Figure 3). This is the red LOS in Figure 3, repeated in Figure 2: all points except the two end points cross lower atmospheric layers than the uncorrected LOS, with the maximum difference of about 600 metres in the middle, 95 kilometres from Paranal. Assuming constant density in the atmosphere, the effective average altitude in the uncorrected LOS would be 4700 metres, and 4200 metres with curvature correction. A more realistic description of the atmosphere would take into account its exponential structure, with a much higher weighting given to the lowest layers. Since these are close to Paranal, where curvature is smallest, we can keep things simple and ignore the curvature-induced correction in the following.

The LOS towards Llullaillaco is dominated by atmospheric layers well above the atmospheric boundary layer, sometimes also called the inversion layer. Most of the atmospheric dust, aerosols and humidity are trapped below that boundary zone. Astronomical observations with Paranal

Dimitri Gadotti/ESO

instruments measure the quality of the atmosphere by the extinction, the fraction of light being absorbed or scattered by the atmosphere. In the *V* passband (visual, centred around 550 nm) the extinction towards the zenith is about 0.12 mag, or about 12% on a good Paranal night, occurring in the roughly 4–5 kilometre-long column of air effectively contributing above the observatory. Most of the extinction is caused by scattering, whereby the wavelength of the photon is preserved, but its directional information is lost, degrading the contrast. (Light is scattered out of the LOS, but light from other sources is also randomly scattered into the LOS. Blue daylight is an example of the scattering of blue sunlight, completely disassociated from its original direction.)

In clear skies, mountains turn blue in the distance, just like the open sky, and eventually can't be distinguished from the sky. So what do you need to see a target at 190 kilometres, apart from visibility? Contrast! Llullaillaco is very cooperative with visible snow fields on dark lava rocks throughout the year, and in particular during the winter months (Figures 4 and 7).

Still, with 12% contrast loss over 5 kilometres, less than 1% of "quality" light (with preserved directional and colour information) would remain over a 190-kilometre baseline, while a rule-of-thumb suggests that a minimum of 2% contrast is required[3]. Looking at Figure 4, the contrast of Llullaillaco must be much better than 2%: one can distinguish crisp white and dark bands that can readily be identified with features visible on satellite imagery presented by Google Earth (Figure 6). Visibility of this quality is not a rare exception, as confirmed by quotes from frequent Paranal observers (Gadotti, 2013; priv. comm.) and by other pictures, like the one by Gerd Hüdepohl (Figure 7).

The apparent contradiction between these photographs with their amazing contrast, and the estimates from astronomical observations can likely be explained by assuming that most of the atmospheric extinction actually happens even closer to the ground than assumed above, in the densest parts of the atmosphere just above the Observatory. It seems that beyond roughly

Figure 5. Summer view of Llullaillaco taken by the author, from Cerro Armazones, in November 2009.

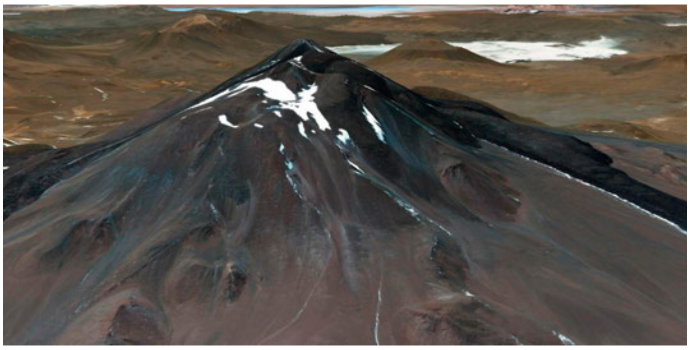


Figure 6. Satellite picture of Llullaillaco, rendered in 3D by the author using the information available from Google Earth (view towards the east into Argentina, north is left, with Paranal behind the viewer). This close-up view is from almost the same direction as from Paranal.

3500–4000 metres, the Atacama atmosphere does not contribute significantly to the extinction, and the larger part of the LOS towards Llullaillaco suffers virtually no extinction.

The very long baseline must also be essentially free of dust; a significant assertion given all the open-pit mining and industrial activity taking place in the Atacama Desert. The main dust source in that direction, the Escondida copper mine (currently the largest on Earth), is comfortably north of the LOS to Llullailliaco.

Are there other peaks visible from Paranal, constituting a true "skyline"? There are some other candidates in the "summit 6000" club, like Socompa (6050 metres at 222 kilometres); Lastarria (5700 metres, 202 kilometres; not quite 6000 metres, but close); or Pular (6230 metres, 244 kilometres). However, all of these are hidden behind the Sierra Vicuña Mackenna as seen from Paranal. But moving just a bit higher, as Gerd Hüdepohl did for his famous aerial photo (Figure 7), helps a lot when trying to spot the volcano Socompa. This mountain to the north of Llullaillaco is also visible from Cerro Armazones. Possibly Cerro Pular is also visible (6230 metres, 244 kilometres), but this is unconfirmed. None of them offers the same spectacular view as Llullaillaco since they are lower in altitude, further away, and have few if any snow fields.

Finally, there is another interesting question: could one spot Paranal from Llullaillaco? The issue is contrast, again. Seen from Cerro Armazones, Paranal is mainly visible by its structures, and the contrast is poor even at short distances, at least for most of the day. Spotting Paranal from the summit would require climbing to at least 5500 metres (roughly the altitude of the lowest part of Llullaillaco visible from Paranal). The best contrast could be expected in the morning, so you would need to stay overnight, at temperatures reported by mountaineers to be as low as –20 or –30°C. Just before morning

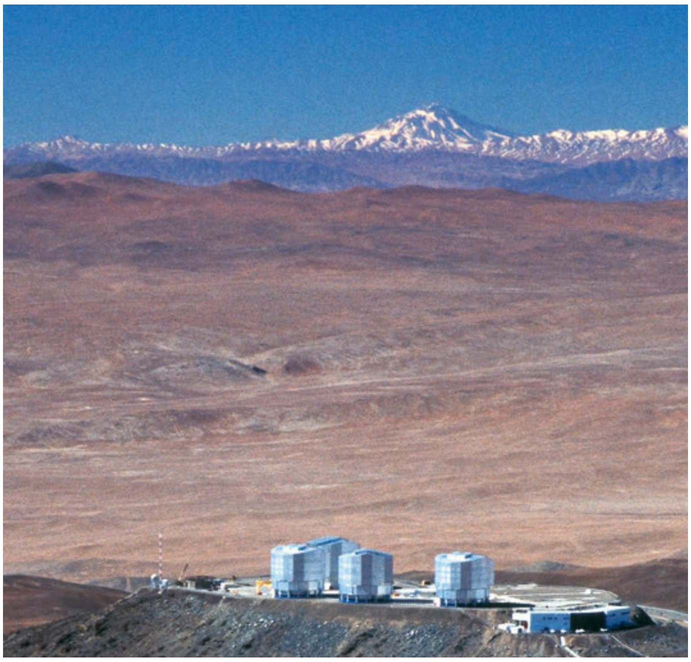


Figure 7. Winter view of Llullaillaco, taken by Gerd Hüdepohl in July 2002 from an aeroplane, i.e., with a slightly different LOS than in the other pictures, but from a similar distance. The volcano Socompa is the peak close to the lefthand edge.

coffee you could probably spot the first rays of the Sun reflected off the silver domes in a spectacular flash, as in Gianluca Lombardi's picture of Paranal taken from Cerro Armazones[4]. Probably the three Inca children could tell, as they might have enjoyed this view every morning for a few years. Not for too long though, since their mummies were discovered in 1999 and taken to a museum in Salta/Argentina.

Links

[1] Cerro Llullaillaco: http://en.wikipedia.org/wiki/Llullaillaco
[2] Mean radius of the Earth: http://en.wikipedia.org/wiki/Horizon
[3] Contrast of distant objects: http://en.wikipedia.org/wiki/Visibility
[4] View of Paranal from Armazones: http://www.eso.org/public/images/potw1205a/

Hännes Heyer Retires

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Figure 1. Among the gifts received by Hännes Heyer at his farewell reception on 6 December 2012 was a mounted print of one of his photographs signed by his colleagues. He is shown holding this trophy aloft.

Hännes, or Hans Hermann, Heyer was at ESO for 25 years and experienced the remarkable coincidence of being honoured for both his retirement and celebrating his 25th anniversary at ESO on the same day. On the morning of 6 December 2012 the Director General hosted a small ceremony for Hännes as well as two other staff members, Hélène Neuville and Enzo Brunetto, and in the afternoon Hännes was at the centre of a reception in the Council Room in Garching (see Figure 1).

There is hardly anyone at ESO who does not know Hännes. He has played an important role in taking and curating our photographs since the days of the ESO Information and Photographic Service (IPS, reflecting the origins of key staff in the former ESO Sky Atlas Laboratory). The IPS was created in 1986, during the exciting time of the 1985–86 Halley apparition. At that time, science communication as a profession hardly existed and a fully developed conceptual framework