Na LGS height profiles at Teide Observatory, Canary Islands.

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ABSTRACT

The Na Laser Guide Star (LGS) spots appear elongated in the adaptive optics (AO) wavefront sensors (WFS) because of the perspective subtended between the main and the launching telescopes. The LGS spots unveil the Mesopause Na vertical distribution and its variability impacts the WFS performance. To measure the absolute LGS height profile is important to get the total flux return and it can be obtained from an auxiliary telescope in a bistatic configuration.

In 2015-2016, the 20W CW ESO Wendelstein LGS Unit (WLGSU) was installed in the Teide Observatory (OT) to carry out an experiment to maximize the photon flux return from the Na LGS. The experiment included the LGS profiling from the IAC80 telescope. Here we are presenting some preliminary results.

Keywords: Laser Guide Star, LGS profiling, Na layer, Teide Observatory

1. INTRODUCTION

The overall Strehl ratio achieved by an adaptive optics (AO) system is depending on all the errors involved in the wavefront sensor (WFS) function. The use of Na Laser Guide Stars (LGS) references, based on the excitation of the Na atoms present in the mesopause ($\sim$ 90 km above the ground), contributes to this error through the LGS spot profile and the Signal to Noise Ratio (SNR).[1,2] An accurate knowledge of the height profile of the elongated LGS significantly contributes to improve both, the spot profile and the SNR.

The elongation shown by the LGS in the WFS is a consequence of the perspective and the finite thickness of the layer, being the elongation different for each WFS sub-aperture. Moreover, the Na layer is strongly variable, impacting the WFS performance.[3,4] The retrieval of Na height profiles are, therefore, important in two aspects:

- To give real time feedback for the AO system: WFS total flux calibration and focus adjust, and laser launching system waist/focus trimming.
- To characterize the mesosphere Na layer for AO simulations and design specifications.

Here we are presenting the preliminary results of a LGS height profiling experiment carried out at the Teide Observatory (OT; $\approx$ 2300 masl), Tenerife, Canary Islands.

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2. THE EXPERIMENT

In 2015-2016 we carried out a join experiment at the OT with the 20W CW ESO Wendelstein LGS Unit (WLGSU)[5] for the optimization of the LGS return flux.[6] The experiment also included the Na height profiling by using the IAC80 telescope (baseline = 121 m) (see Fig. 1). In summary we obtained around 3000 Na height profiles in 13 nights expanded in one year as follows:

- 2015-Sep: 6 nights
- 2015-Dec: 1 night
- 2016-Feb: 1 night
- 2016-Apr: 2 nights
- 2016-Jul: 3 nights

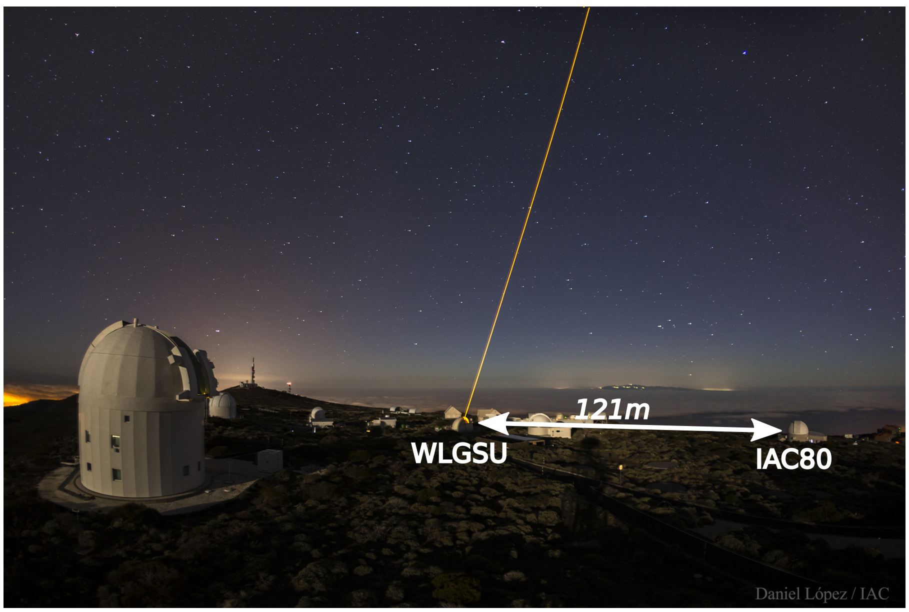

Figure 1. General view of the OT during the experiment with the WLGSU and the IAC80 telescope, separated by a baseline of 121 m

3. THE METHOD

All the schemes described for AO systems with LGS are based on bistatic or pseudo-bistatic configurations between the main and the launching telescope, also taking into account the unavoidable distance between the different points of the pupil and the beam launching point. Therefore, the subtended angle allows to measure distances by triangulation.

We developed an algorithm to retrieve mesospheric Na profiles from the bistatic configuration and the Cartesian geometry. The method is explained in detail in Castro-Almazán et al. (2008 and 2016)[7,8] and summarized in the Fig. 2. The intersection of the *line of sight* (r_1) and the *plane of launching* (Π) defines an unique point in the space whose vertical coordinate is the height (except when the line of sight is embedded in the plane of launching, i.e., the launching azimuth equals the azimuth subtended by launcher and observer). After some algebraic manipulation, the following expression is obtained for the height h (see the inputs in the Fig. 2):

$$h = d \cdot \tan al_1 \frac{\tan az_2 \cos az_{12} - \sin az_{12}}{\tan az_2 \cos az_1 - \sin az_1} \tag{1}$$

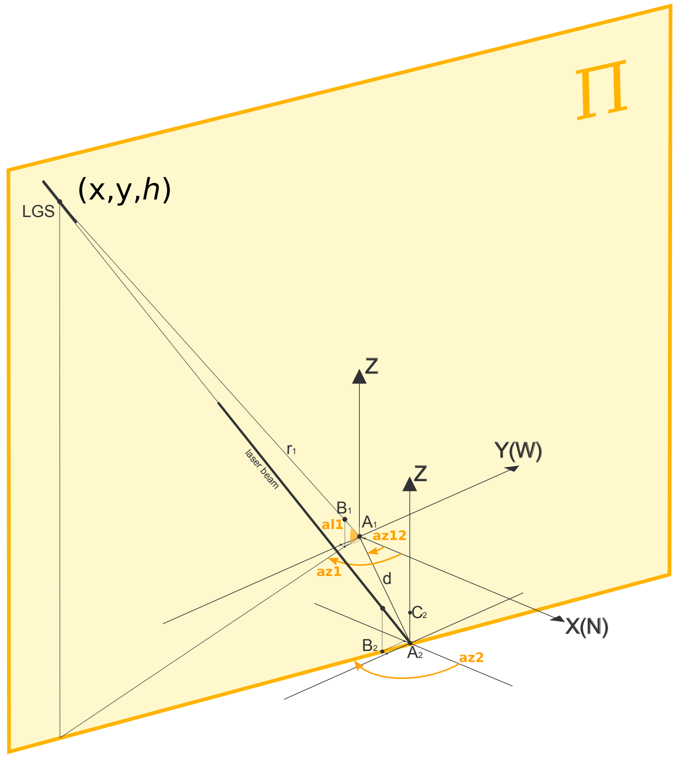

Figure 2. Cartesian geometry of the line-plane intersection model for LGS height (h) profile retrieval. The observer *line of sight* is represented by the line r_1 and defined as a function of the azimuth and altitude of the observer (az_1 and al_1). The launcher *plane of launching* (Π) is defined as a function of the azimuth of the launcher and the azimuth subtended with the observer (az_2 and az_{12}). Launcher and observer are separated by the baseline distance d.

In summary, the absolute height of each point of the LGS plume can be obtained free of perspective effects, with 3 main inputs:

- observer azimuth (az_1)
- observer altitude (al_1)
- launcher azimuth (az_2)

This means that the launcher altitude is not necessary and, thus, the heights obtained are not dependent on the refraction suffered by the laser or the differences in the topographic height between the launcher and the observer.

The observer coordinates az_1 and al_1 may be accurately obtained from the astrometry of the natural stars in the field of view (FOV) of the observer, after equatorial to horizontal conversion. This is important to overcome the fast error propagation induced by the small angles projected, as a consequence of the short baseline compared with the Mesopause altitude. In this work we have used the package Xparallax* for the astrometry.

For the launcher azimuth, we carried out a Montecarlo simulation to estimate the error propagation and the accuracy required. We imposed an error in the launcher pointing azimuth az_2 of 1". A typical result is in the Fig. 3. With an accuracy of 1" in az_2, the absolute Na heights can be obtained with a resolution better than ~ 200 m, for the conditions in the experiment here described. The abrupt increase in the error around the azimuth

*Xparallax was developed by Juan José Sanabria (IAC) at the Valencian International University under the supervision of Olga Zamora (IAC) http://vivaldi.ll.iac.es/OOCC/wp-content/uploads/2016/08/master_juanjo.pdf

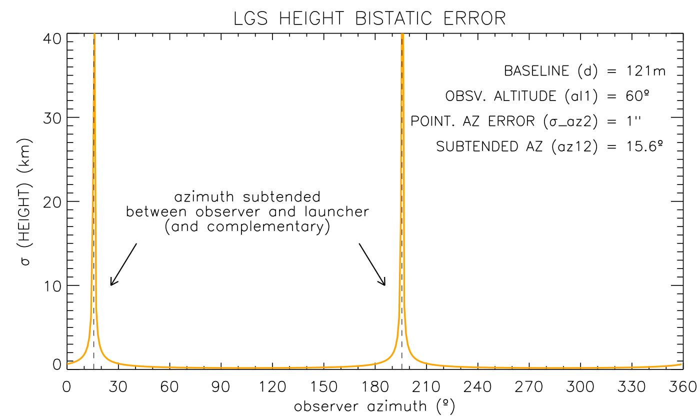

Figure 3. Montecarlo error propagation for the geometry of the ESO-IAC LGS experiment at OT. The input error is $\sigma(az_2) = 1''$. The abrupt increase in the error around the azimuth 15.6° and $15.6^\circ + 180^\circ$ (the azimuth subtended between the launcher and the observer, and the complementary) are the no domain points of eq. 1.

15.6° and $15.6^\circ + 180^\circ$ (the azimuth subtended between the launcher and the observer, and the complementary) are the mathematical no domain points of eq. 1. To achieve the required accuracy for az_2 implies an accurate ad-hoc pointing model for the launching telescope and an auto-guiding tracking mode that were not implemented for this experiment. For this reason the absolute height retrieval was not available. Instead we obtained relative heights.

In the relative heigh retrieval mode we impose the LGS peak to be at 90 km and solve the inverse problem to obtain the launcher azimuth az_2. Once estimated az_2, the eq. 1 is applied to retrieve the heights in the profile. It is important to note that the method corrects the perspective effect and, therefore, the relative heights obtained are accurate related to the fixed level of 90 km.

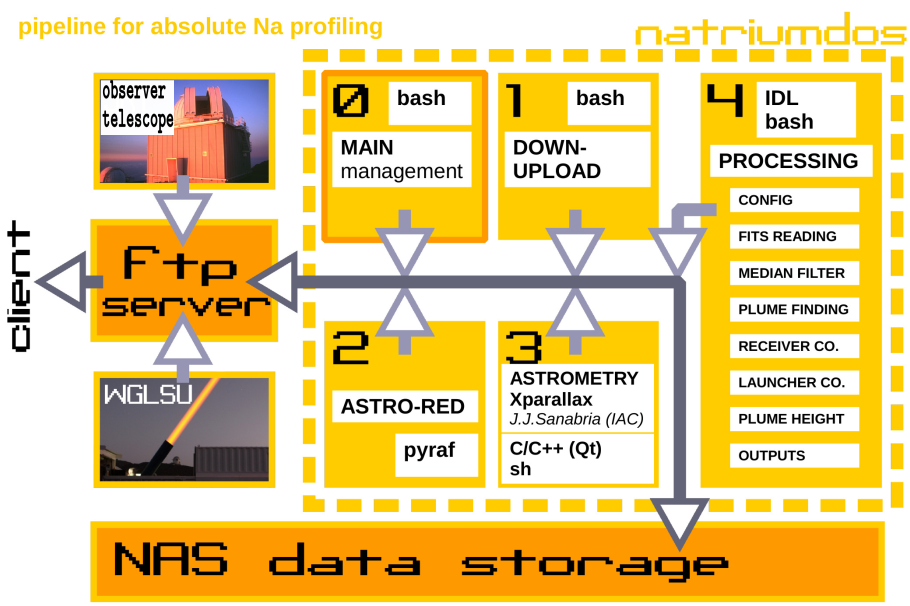

Figure 4. Block diagram of the pipeline *natriumdos* for absolute Na heigh profiling from LGS.

4. THE natriumdos REDUCTION PIPELANE

We developed the *natriumdos* pipeline for LGS Na profiling. The procedure is based in different modules to automatically retrieve the height profiles from the raw fits images obtained by the observer telescope. The Fig. 4 shows a block diagram summarizing the operation of the pipeline and detailing the programming languages. A more detailed scheme of the steps in the block 4 (Processing) is in the Fig. 5.

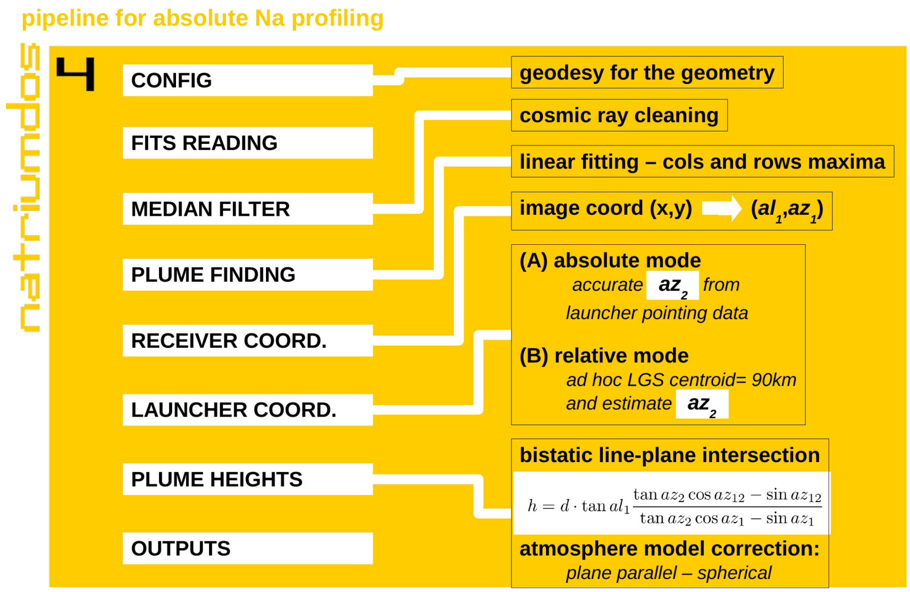

Figure 5. Detail of the steps in the Processing module (module 4) of *natriumdos* for absolute Na heigh profiling from LGS (see Fig. 4).

5. RESULTS

Contrary to the simple Gaussian shaped profile with a width of 10 km used as a first approximation in the models, the Na LGS typically shows a more complicated profile with two or more sporadic or doubled layers (see Fig. 6, rows 1 and 2) and ~ 20 km width. Nevertheless, the profile is still *Gaussian* many other times (see, for example, Fig. 6, row 3). This complexity remarks the importance of a real time profiling for an efficient operation of the WFS in AO. The layer also shows spatial anisotropy and temporal instability in short time periods (see Fig. 7, e.g.).

The vertical resolution achieved depends on the zenith distance due to the perspective projection. This means that the closer the pointing is to the horizon, the lower the resolution, but, because of the design of the method, the layer will be still resolvable and not impacting the layer width, making easier the WF reconstruction. For example, in the Fig. 8 we show a LGS pointing to the Galactic Centre from the OT (al $\sim 33°$) with a vertical resolution of 326 m (compared to the ~ 100 m close to the zenith) making the plume to appear smoothed.

As shown in the Fig. 3, an abrupt increase in the error is found around the azimuth subtended between the launcher and the observer (and the complementary angle). These points correspond to the no domain points in the eq. 1. Therefore, the method diverges when the laser is propagated in that direction (see Fig. 9). This limitation may be overcome by the use of two observer telescopes shifted 90°.[8]

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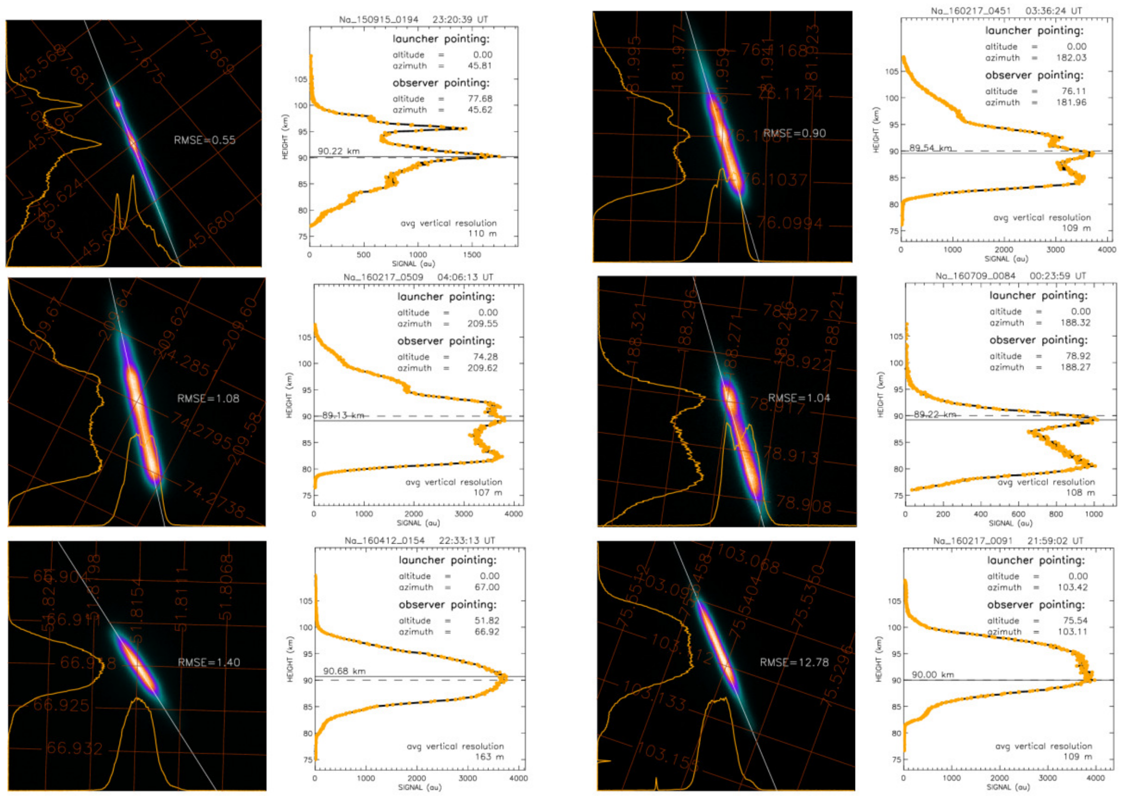

Figure 6. Some preliminary results of Na LGS height profiling obtained with *natriumdos* at the OT.

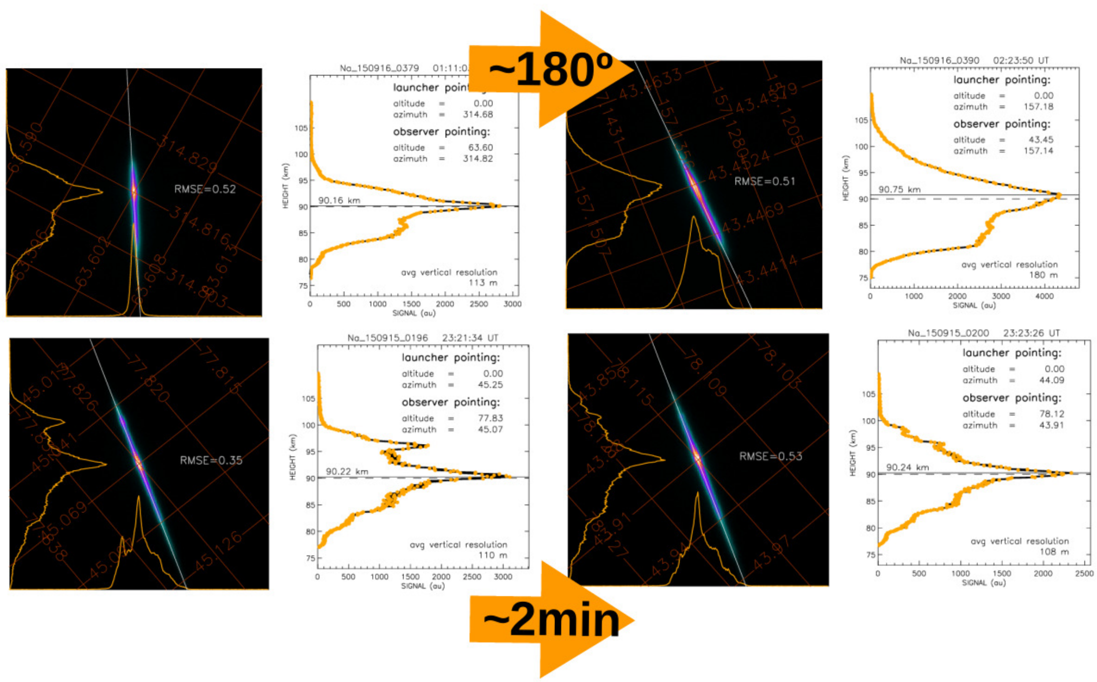

Figure 7. Anisotropy and temporal instability of the Na LGS height profiles.

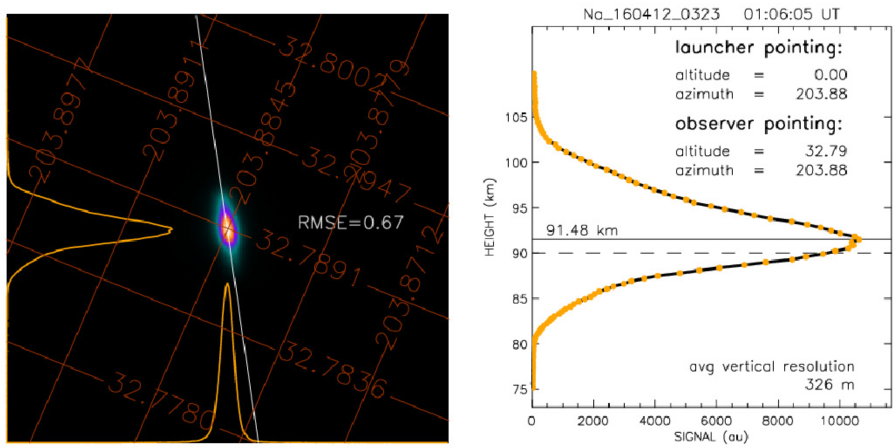

Figure 8. LGS pointing to the Galactic Centre from the OT (al $\sim 33^{\circ}$)

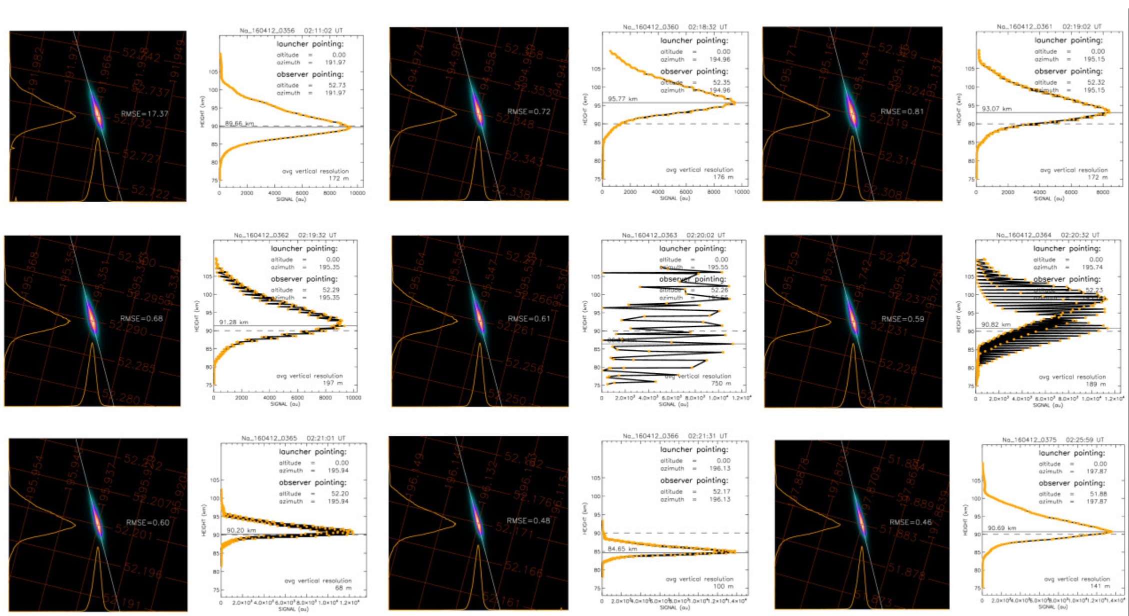

Figure 9. Sequence of LGS profiles showing the divergence of the method around the mathematical no domain points of eq. 1 (the launcher azimuth az_2 equals the azimuth subtended between launcher and observer az_{12}).

the helpful discussions and contributions. We have made use of the ESO Wendelstein LGS Unit (WLGSU) and the telescope IAC80 at the Teide Observatory, belonging to the IAC. We implemented the Xparallax astrometry package developed by Juan José Sanabria (IAC) at the Valencian International University under the supervision of Olga Zamora (IAC); we thank them the ease access to it.

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