On the derivation of zonal and meridional wind components from Aeolus horizontal line-of-sight wind

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Response to Anonymous Referee #1

Dear Anonymous Referee #1,

Thank you very much for reviewing our manuscript and for your helpful comments. We added a section to discuss the impact of our methods on possible future Doppler-Wind-Lidar scenarios and applied some minor changes to the manuscript. Please find detailed answers on all your comments below.

Sincerely,

Isabell Krisch on behalf of all Co-Authors

1. **Eq. 11 is expressed in a slightly different way as Eq. 10 in the first line. It's better to rewrite the Eq.11 for consistency.**

   Both equations (10 & 11) were slightly amended for consistency, as also proposed by Anonymous Referee #2:

$$\begin{aligned} u_3^* &= -0.5 \cdot \left(\frac{w_{HLOS,asc}}{\sin\theta_{asc}} + \frac{w_{HLOS,dsc}}{\sin\theta_{dsc}}\right) \\ &= -0.5 \cdot \left(\frac{-u_{asc}\sin\theta_{asc} - v_{asc}\cos\theta_{asc}}{\sin\theta_{asc}} + \frac{-u_{dsc}\sin\theta_{dsc} - v_{dsc}\cos\theta_{dsc}}{\sin\theta_{dsc}}\right) \\ &= 0.5 \cdot (u_{asc} + v_{asc}\cot\theta_{asc} + u_{dsc} + v_{dsc}\cot\theta_{dsc}) \\ &= 0.5 \cdot (u_{asc} + u_{dsc}) + 0.5 \cdot \cot\theta_{asc} \cdot (v_{asc} - v_{dsc}), \end{aligned} \tag{10}$$

$$\begin{aligned} v_3^* &= -0.5 \cdot \left(\frac{w_{HLOS,asc}}{\cos\theta_{asc}} + \frac{w_{HLOS,dsc}}{\cos\theta_{dsc}}\right) \\ &= -0.5 \cdot \left(\frac{-u_{asc}\sin\theta_{asc} - v_{asc}\cos\theta_{asc}}{\cos\theta_{asc}} + \frac{-u_{dsc}\sin\theta_{dsc} - v_{dsc}\cos\theta_{dsc}}{\cos\theta_{dsc}}\right) \\ &= 0.5 \cdot (u_{asc}\tan\theta_{asc} + v_{asc} + u_{dsc}\tan\theta_{dsc} + v_{dsc}) \\ &= 0.5 \cdot \tan\theta_{asc} \cdot (u_{asc} - u_{dsc}) + 0.5 \cdot (v_{asc} + v_{dsc}). \end{aligned} \tag{11}$$

2. All three methods produce reliable zonal wind estimates between 70° S and 70° N with absolute errors typically below 5 ms^{-1}. Method 3 is the only method able to produce reliable meridional winds at all latitudes. It's straightforward that the error of Method 1 and Method 2 depends on how well the zonal and meridional wind components is projected onto Aeolus Line-of-sight measurement. It's a latitude related error different from the equator to the poles. Method 3 is based on the combination of two measurements in the collocated analysis region, the error of which relies on temporal and spatial interpolation. This method can be analogous to the velocity-azimuth processing technique, so called VAP method for single weather radar and wind lidar. The colocation analysis would be instructive for future Aeolus follow-on mission, for instance the two-satellite constellation to provide two independent measurements for zonal and meridional wind components. It would be great if authors can comment on that two points above.

Yes, method 3 is inspired by the VAP or more commonly VAD (velocity azimuth display) method. A note on this has been added to the manuscript:

The third method is inspired by the velocity–azimuth display (VAD) technique for single ground-based or airborne radar or lidar instruments (e.g. Browning and Wexler, 1968; Reitebuch et al. 2001; Witschas et al., 2017): The laser or radar beam is actively stirred in different azimuth directions to retrieve a horizontal wind vector by combining different LOS measurements. Aeolus cannot stir its LOS, but we can use the geometrical differences between ascending and descending orbits and combines measurements from both to more accurately estimate the true zonal and meridional wind over a specific region.

Regarding possible Aeolus follow-on scenarios and additional section has been added to the manuscript briefly touching this issue:

Impact of possible future Doppler-Wind-Lidar scenarios on the accuracy of Method 3

Although a detailed discussion of possible future Doppler-Wind-Lidar (DWL) scenarios (e.g. Marseille et al., 2008; Baker et al., 2014) is beyond the scope of this paper, we would like to briefly comment here on the impact of dual-perspective and multiple satellite constellation scenarios on the accuracy of derived winds from our Method 3.

A dual-perspective DWL would provide two LOS wind measurements under different azimuth angles from one satellite (e.g. Baker et al., 2014, their Fig. 12). This would be ideal, because the time difference and spatial distance between these two wind measurements would be negligible and the systematic errors of our Method 3 would become very small.

Another scenario discussed for a future DWL mission is a multi-satellite constellation. In this scenario, the accuracy of our Method 3 strongly depends on two key characteristics of such a constellation: how far apart in time and space are the two (or more) satellites, and do the different instruments have the same LOS with respect to flight-direction?

In a constellation with two identical satellites that both have the same LOS direction in the same orbit plane and only a small shift in time and space (e.g. Tandem-Aeolus scenario of Marseille et al., 2008), errors in our Method 3 would only be slightly reduced compared to a single satellite constellation. This is because although the spatial distance between the nearest neighbours would decrease by a factor of two (or more, for more satellites) in such a constellation due to the shift in orbit, the time difference would remain large.

However, if the tandem constellation described above was amended such that one of the satellites had a different LOS viewing direction, errors in our derived winds would be strongly reduced and their reliability greatly increased. This is because, in addition to the close spatial separation of the different LOS measurements, there would only be a small time difference.

Thus, for deriving the zonal and meridional winds from spaceborne DWL measurements, a dual-perspective DWL would perform best, followed by a multiple satellite constellation with differing LOS. A multiple satellite constellation with similar LOS for all satellites is expected to only slightly improve the derivation of zonal and meridional wind components compared to Aeolus.

Response to Anonymous Referee #2

Dear Anonymous Referee #2,

Thank you very much for reviewing our manuscript and for your helpful comments. We applied some minor changes to the manuscript as proposed. Additionally, we added a section to discuss the impact of our methods on possible future Doppler-Wind-Lidar scenarios, as it was requested by Referee #1. Please find detailed answers on all your comments and the text of the new section below.

Sincerely,

Isabell Krisch on behalf of all Co-Authors

1. **Sect. 3.1: For Method #1 it should be clarified that this method assumes that the wind direction and the LOS direction are always "accidentally" the same. For testing a simple method to derive wind vectors, this assumption makes absolutely sense, but you should mention that strictly speaking this is not a physically well-reasoned assumption.**

   The authors completely agree with the referee on this topic, but some scientific studies (preprints) have used this method, so we thought it was important to be included. We added a more detailed explanation on this topic to the manuscript:

   This very simple approach is nothing else than assuming that the horizontal wind direction is aligned with HLOS, which is not a physically well-reasoned assumption. Nevertheless, it is already used in the community (e.g. preprint of Wright et al., 2021, and Chou et al., 2021) and we will show later that under certain conditions it provides reasonable estimates for the zonal wind.

2. **l.182: Why did you select 20hr of miss-time? Is there a reason?**

   20hrs of miss-time was chosen to make sure the nearest neighbours in time (which are due to the orbit geometry around 10-14hrs away) are included, but at the same time to reduce the data amount for calculation as much as possible. For better reasoning this miss-time has been increased to 24hrs now (sun-synchronous orbit geometry of Aeolus). The results did not change. An explanation has been added to the manuscript:

   Twenty-four hours of miss-time are chosen due to the sun-synchronous orbit geometry of Aeolus.

3. **l.186: Interpolation in time is also linear?**

   Yes, the interpolation in time is also linear. This has been clarified in the manuscript.

4. **Fig.4: Please clarify: This figure combines data from all latitudes? Why do the lon. dist. curves in Fig.4 not show steps, similar to the time diff. curves? Would the statistics look quite different if only a limited latitude range is considered?**

   Yes, this figure combines data from all latitudes. The longitudinal distance curves would show steps when looking at single latitudes only. When looking at Fig. 5c, it becomes obvious why no steps are observed when all latitude bands are included: The distances between the ascending and descending orbits is smoothly decreasing and increasing again when following one track from north to south or vice versa. For the temporal distance this is different: One orbit takes around 1.5h and during half of the orbit, the satellite is on the other side of the Earth (= in the same orbit phase as the comparison orbit), before reappearing again. During this time period, no collocated measurements are counted and thus the step. This has been clarified in the manuscript:

For this figure, all latitudes are used. This leads to the continuous transition of the spatial distance from 0% to 100%. When looking at single latitudes this transition would be step-wise, but the overall evolution would be similar. For the temporal distance this is different: One orbit takes around 1.5h and during half of the orbit, the satellite is on the other side of the Earth, before reappearing again. During these roughly 45min no collocated measurements are acquired, which explains the steps in the temporal distance distribution. For a single point / latitude these steps would be more emphasised, but, again, the overall evolution would not change.

5. **l.199: What are "Rayleigh clear measurement locations"? Do you mean cloud-free, or locations where Rayleigh wind observations of Aeolus show only small errors?**

   Yes, only cloud-free Rayleigh measurements are used. Within the Aeolus L2B products a flag exists to filter for “cloudy” or “clear” measurements. This is why we used the word “clear” in the text as well. No additional filtering on the product quality (e.g. error estimates) is used, as the measurement points are anyway populated with synthetic measurement data from ERA5.

6. **Sect.6: Error estimation is only performed for the month of January. As the error depends on the angle between the real wind and the Aeolus LOS, do you think that error estimates will be significantly different for other months/seasons?**

   The error estimation has been performed also for other months (March, June, October) with no significant differences in the results. For method 1, the mean bias slightly changes its structure with respect to latitude with the season, but no change in bias magnitude is observed. A sentence explaining this has been added to the manuscript:

   Processing of data from other months (not shown) did not lead to significant differences in the results are discussed compared to the January 2021 dataset. Thus, in the following, the results for zonal and meridional wind are discussed only for the January 2021 dataset.

7. The following section has been added to the manuscript:

   Impact of possible future Doppler-Wind-Lidar scenarios on the accuracy of Method 3

   Although a detailed discussion of possible future Doppler-Wind-Lidar (DWL) scenarios (e.g. Marseille et al., 2008; Baker et al., 2014) is beyond the scope of this paper, we would like to briefly comment here on the impact of dual-perspective and multiple satellite constellation scenarios on the accuracy of derived winds from our Method 3.
   A dual-perspective DWL would provide two LOS wind measurements under different azimuth angles from one satellite (e.g. Baker et al., 2014, their Fig. 12). This would be ideal, because the time difference and spatial distance between these two wind measurements would be negligible and the systematic errors of our Method 3 would become very small.
   Another scenario discussed for a future DWL mission is a multi-satellite constellation. In this scenario, the accuracy of our Method 3 strongly depends on two key characteristics of such a constellation: how far apart in time and space are the two (or more) satellites, and do the different instruments have the same LOS with respect to flight-direction? In a constellation with two identical satellites that both have the same LOS direction in the same orbit plane and only a small shift in time and space (e.g. Tandem-Aeolus scenario of Marseille et al., 2008), errors in our Method 3 would only be slightly reduced compared to a single satellite constellation. This is because although the spatial distance between the nearest neighbours would decrease by a factor of two (or more, for more satellites) in such a constellation due to the shift in orbit, the time difference would remain large.
   However, if the tandem constellation described above was amended such that one of the satellites had a different LOS viewing direction, errors in our derived winds would be strongly reduced and their reliability greatly increased. This is because, in addition to the close spatial separation of the different LOS measurements, there would only be a small time difference.

Thus, for deriving the zonal and meridional winds from spaceborne DWL measurements, a dual-perspective DWL would perform best, followed by a multiple satellite constellation with differing LOS. A multiple satellite constellation with similar LOS for all satellites is expected to only slightly improve the derivation of zonal and meridional wind components compared to Aeolus.

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