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Doppler Lidar Motion-Correction (DLMC) Value-Added Product Report

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ARM

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Acronyms and Abbreviations

2D	two-dimensional
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
DL	Doppler lidar
DLMC	Doppler Lidar Motion-Correction Value-Added Product
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NAV	Navigational Location and Attitude instrument
SNR	signal-to-noise ratio
UTC	Coordinated Universal Time
VAP	value-added product

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1.0 Introduction

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) second ARM Mobile Facility (AMF2) Doppler lidar (S/N 0319-160) was deployed on the German ice breaker *Polarstern* during the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) campaign during 2019-2020 (see Figure 1). This was the first deployment of the new AMF2 Doppler lidar, as well as the first ship-based deployment of a Doppler lidar (DL) by ARM. In contrast to land-based deployments, the lidar's heading (a.k.a. home point) and tilt are constantly changing, and lidar's radial velocity measurements are impacted by the ship's motion. Since the beam directions are reported relative to the instrument's frame of reference, derivation of higher-order data products such as wind speed and direction require that the lidar's attitude and translational velocity be properly accounted for.

The Doppler Lidar Motion-Correction (DLMC) Value-Added-Product (VAP) was developed specifically for ship-based deployments of the Doppler lidar. This VAP combines raw uncorrected data from the DL and simultaneous measurements from the ARM Navigation system (NAV) (Walton 2019) to transform the beam angles from the lidar coordinate system to an Earth-fixed coordinate system. The VAP also removes the contribution of the lidar's platform velocity from the radial velocity measurements. This report documents the methods used by the DLMC to perform these corrections.

2.0 Instrument Setup and Configuration

The DLMC VAP requires that certain parameters be prescribed ahead of time. These parameters describe the position and orientation of the DL coordinate system relative to the NAV coordinate system. During MOSAiC the DL was installed on top of the trailer that housed the ARM NAV system, as shown in Figure 1. The NAV is oriented such that it is 1-axis (x_{NAV}) point toward the bow, and it is 2-axis (y_{NAV}) points toward the port side. Thus, when the ship is heading due north, the positive y_{NAV} direction is west, and the positive x_{NAV} direction is north.

Figure 1. View of the *Polarstern*'s bow section as seen from the bridge. The location of the Doppler lidar is indicated.

The DL coordinate system is defined such that it is 1-axis (x_{DL}) point toward the front of the DL, it is 2-axis (y_{DL}) points toward the left side, and it is the 3-axis (z_{DL}) points toward the top of the DL. During set up on the *Polarstern* the DL was aligned (by eye) with its 1-axis facing the front of the ship, approximately parallel with the center line of the ship.

Figure 2 shows the position of the DL relative to the NAV during the MOSAiC campaign. For this deployment the displacement vector (in the NAV frame) was given by

$$\Delta\mathbf{r} = \begin{pmatrix} 1.52\text{ m} \\ 4.11\text{ m} \\ 1.68\text{ m} \end{pmatrix}, \tag{1}$$

as illustrated in Figure 2. Since the DL's 1-axis was oriented facing the front of the ship, we assume that the yaw offset between the NAV and the DL was negligible. The pitch and roll offsets were determined by comparing the NAV pitch and roll data to those obtained from DL's internal tilt sensor. Although data from the DL's tilt sensor was quite noisy, it was adequate for estimating the pitch and roll offset with sufficient averaging. Figure 3 shows a comparison between the NAV and DL pitch and roll data for 31 March 2020. Averaging the differences over the entire deployment resulted in a mean pitch offset of

$$\boldsymbol{\Delta\beta = -0.27^{o},} \tag{2}$$

and a mean roll offset of

$$\Delta\gamma = -1.77^{o}. \tag{3}$$

The yaw offset is assumed to be zero, i.e.

$$\Delta\alpha = 0. \tag{4}$$

We note that we did not observe any significant drift in the pitch and roll offsets over time.

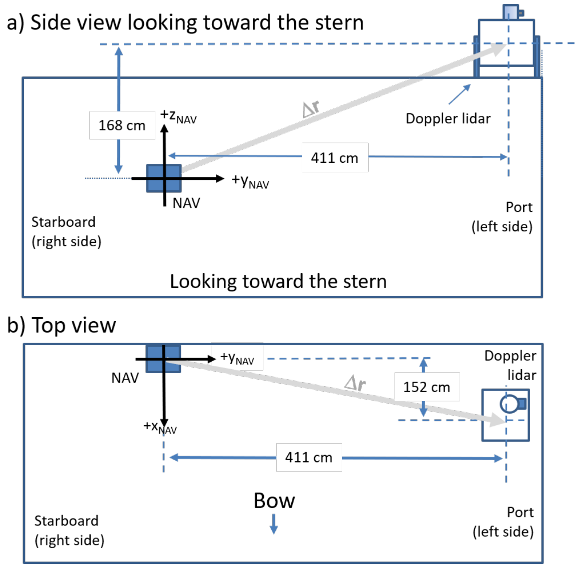

Figure 2. a) top and b) side views of the AMF2 lidar trailer during MOSAiC. The location of the DL relative to the NAV is defined by the displacement vector, Δ**r**.

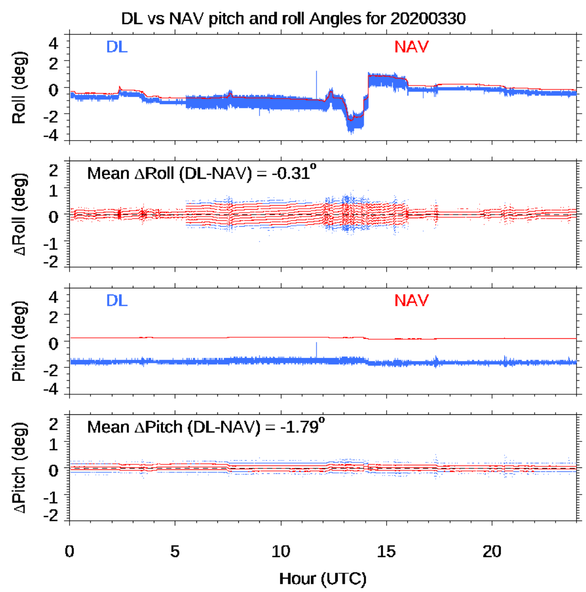

Figure 3. Comparison between the DL and NAV pitch and roll measurements for 20200331. The mean (NAV-DL) roll and pitch offsets were found to be -1.77° and -0.27°, respectively.

3.0 Input Data

The input data for the DLMC process includes the raw DL data from the <site>dl<scan_type><facility>.a1 datastream, and NAV data from the <site>nav<facility>.a1 datastream. We note that during the MOSAiC deployment, the DL was configured to acquire only “fpt” and “usr” scan-type data. Tables 1 and 2 list the input variables from the DL the NAV datastreams, respectively.

Table 1. Variables from the <site>dl<scan_type><facility>.a1 datastream used by the DLMC VAP.

Variable Name	Description	Units
base_time	Seconds since 1970-1-1 0:00:00 0:00	sec
time_offset	Time offset from base_time	sec
roll	Roll angle from lidar tilt sensor	deg
pitch	Pitch angle from lidar tilt sensor	deg
range	Distance from Lidar to center of range gate	m
relative_azimuth	Beam azimuth relative to true north	deg
relative_elevation	Beam elevation relative to local horizon	deg
relative_radial_velocity	Radial velocity (motion corrected)	ms^{-1}
attenuated_backscatter	Attenuate backscatter	$m^{-1}sr^{-1}$
intensity	Intensity (signal-to-noise ratio + 1)	unitless
Alt	Altitude above mean sea level	m
lat	Lidar latitude	deg
lon	Lidar longitude	deg

Table 2. Variables from the <site>nav<facility>.b1 datastream used by the DLMC VAP.

Variable Name	Description	Units
base_time	seconds since 1970-1-1 0:00:00 0:00	sec
time_offset	Time offset from base_time	sec
roll	roll angle	deg
pitch	pitch angle	deg
yaw	yaw angle	deg
roll_angular_rate	roll angular rate	deg s-1
pitch_angular_rate	pitch angular rate	deg s-1
yaw_angular_rate	yaw angular rate	deg s-1
surge_velocity	bow-ward velocity	$m\ s^{-1}$
sway_velocity	port-ward velocity	$m\ s^{-1}$
heave_velocity	upward velocity	$m\ s^{-1}$
alt	Altitude above mean sea level	m
lat	Lidar latitude	deg
lon	Lidar longitude	deg

4.0 Algorithm and Methodology

Figure 4 displays (schematically in 2D) the relationship between the Earth-fixed, NAV, and DL reference frames. The 1-axis (x_E or x'_E) of the Earth frame points north, and the 2-axis (y_E or y'_E) points west. The displacement and attitude of the DL relative to the NAV are known, as discussed previously. Together with the NAV data this gives us all the information we need to transform a vector (position or velocity) from the DL frame to the Earth frame.

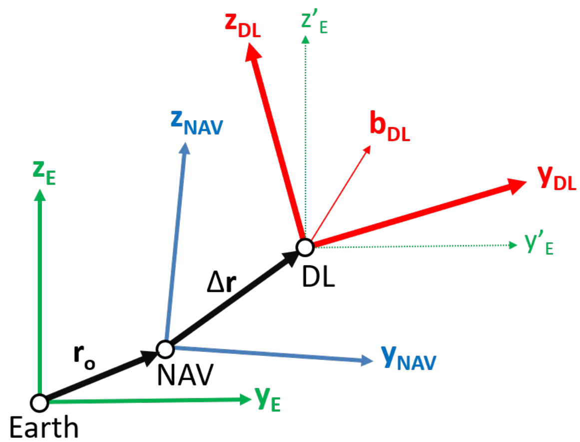

Figure 4. Relationship between the Earth-fixed (green), NAV (blue) and DL (red) coordinates.

From Figure 4 we see that the relationship between NAV and DL coordinates is given by

$$\mathbf{r}_{NAV} = \Delta\mathbf{r} + \mathbf{B}\mathbf{b}_{DL}, \quad (5)$$

Where $\mathbf{B}$ is a matrix that transforms a vector, $\mathbf{b}_{DL}$, from the DL to the NAV coordinate system. The "beam" vector $\mathbf{b}_{DL}$ specifies the lidar beam direction. The specific form of $\mathbf{B}$ is given in Section 4.1. The relationship between the Earth-fixed and NAV coordinates is given by

$$\mathbf{r}_E = \mathbf{r}_o + \mathbf{A}\mathbf{r}_{NAV}, \quad (6)$$

Where $\mathbf{r}_o$ is a vector that defines the origin of the NAV relative to a fixed point on the Earth, and $\mathbf{A}$ is a matrix that transforms a vector from the NAV to the Earth frame. Substituting equation (5) into equation (6) gives

$$\mathbf{r}_E = \mathbf{r}_o + \mathbf{A}\Delta\mathbf{r} + \mathbf{A}\mathbf{B}\mathbf{b}_{DL}. \quad (7)$$

The velocity of the DL in the Earth frame (for $\mathbf{b}_{DL} = 0$) is given by

$$\dot{\mathbf{r}}_E = \dot{\mathbf{r}}_o + \dot{\mathbf{A}}\Delta\mathbf{r}. \quad (8)$$

Thus, the net velocity of the DL is given by the linear velocity of the NAV ($\dot{\mathbf{r}}_o$) plus the linear velocity due to rotation about the NAV, $\dot{\mathbf{A}}\Delta\mathbf{r}$. The linear velocity of the NAV (in the Earth frame) is given by

$$\dot{\mathbf{r}}_o = \mathbf{A}\mathbf{v}_{NAV}, \quad (9)$$

where the NAV velocity vector (in the NAV frame) is given by

$$\mathbf{v}_{NAV} = \begin{pmatrix} v_{surge} \\ v_{sway} \\ v_{heave} \end{pmatrix}. \tag{10}$$

The NAV system provides 10 Hz measurements of the surge, sway, and heave velocity components. In an Earth frame moving with the DL we have

$$\mathbf{r'}_E = \mathbf{r}_E - (\mathbf{r}_o + \mathbf{A}\Delta\mathbf{r}) = \mathbf{ABb}_{DL}. \tag{11}$$

The unit vector describing the beam direction (in the DL frame) is given by

$$\mathbf{b}_{DL} = \begin{pmatrix} \cos(az_{DL})\cos(el_{DL}) \\ -\sin(az_{DL})\cos(el_{DL}) \\ \sin(el_{DL}) \end{pmatrix}, \tag{12}$$

Where az_{DL} and el_{DL} are the azimuth and elevation angles measured by the DL, as illustrated in Figure 5.

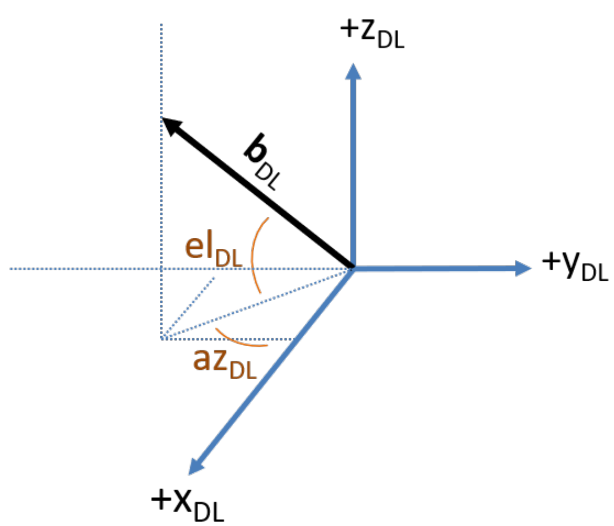

Figure 5. Geometry of the beam vector, $\mathbf{b}_{DL}$, in the DL frame of reference. The azimuth and elevation angles from the DL are az_{DL} and el_{DL}, respectively.

The beam vector expressed in the Earth frame is given by

$$\boldsymbol{b'}_E = \boldsymbol{ABb}_{DL}. \tag{13}$$

Thus, the beam azimuth as measured counterclockwise from true north is given by

$$az = -atan(b'_{E2}/b'_{E1}), \tag{14}$$

and elevation angle relative to the local horizon is given by

$$el = asin(b'_{E_3}). \tag{15}$$

The along-beam (i.e., radial) component of the DL's velocity is given by the following scalar product

$$u_r^{DL} = (\boldsymbol{b'_E})^{\boldsymbol{T}} \dot{\boldsymbol{r}}_E. \tag{16}$$

The motion-corrected radial (air) velocity measured by the DL is given by

$$u_r^{cor} = u_r^{obs} - u_r^{DL}, \tag{17}$$

Where u_r^{obs} is the observed radial air velocity from the DL, and u_r^{cor} is the corrected radial air velocity.

4.1 Doppler Lidar to NAV Transformation

The transformation from the DL to the NAV frame is given by

$$\mathbf{B} = \mathbf{R}_3(\Delta\alpha)\mathbf{R}_2(\Delta\beta)\mathbf{R}_1(\Delta\gamma), \tag{18}$$

where $\Delta\alpha$, $\Delta\beta$, and $\Delta\gamma$ are the yaw, pitch, and roll offsets between the NAV and the DL, respectively. The rotation matrices are given by

$$\boldsymbol{R}_1(\varphi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{pmatrix}, \tag{19}$$

$$\boldsymbol{R}_2(\varphi) = \begin{pmatrix} \cos\varphi & 0 & -\sin\varphi \\ 0 & 1 & 0 \\ \sin\varphi & 0 & \cos\varphi \end{pmatrix}, \tag{20}$$

and

$$\boldsymbol{R}_3(\varphi) = \begin{pmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{21}$$

4.2 NAV to Earth Transformation

The transformation matrix from the NAV to the Earth frame has the same form as the transform from the DL to the NAV frame, i.e.

$$\mathbf{A} = \boldsymbol{R}_3(\alpha_{NAV})\boldsymbol{R}_2(\beta_{NAV})\boldsymbol{R}_1(\gamma_{NAV}), \tag{22}$$

where α_{NAV}, β_{NAV}, and γ_{NAV} are the yaw, pitch, and roll angles output by the NAV. The time derivative of $\mathbf{A}$ is given by

$$\dot{\boldsymbol{A}} = \dot{\boldsymbol{R}}_3(\alpha_{NAV})\boldsymbol{R}_2(\beta_{NAV})\boldsymbol{R}_1(\gamma_{NAV}) + \boldsymbol{R}_3(\alpha_{NAV})\dot{\boldsymbol{R}}_2(\beta_{NAV})\boldsymbol{R}_1(\gamma_{NAV}) + \boldsymbol{R}_3(\alpha_{NAV})\boldsymbol{R}_2(\beta_{NAV})\dot{\boldsymbol{R}}_1(\gamma_{NAV}), \tag{23}$$

where

$$\dot{\boldsymbol{R}}_1(\gamma_{NAV}) = -\dot{\gamma}_{NAV}\begin{pmatrix}1 & 0 & 0\\ 0 & \sin\gamma_{NAV} & -\cos\gamma_{NAV}\\ 0 & \cos\gamma_{NAV} & \sin\gamma_{NAV}\end{pmatrix}, \tag{24}$$

$$\dot{\boldsymbol{R}}_2(\beta_{NAV}) = -\dot{\beta}_{NAV}\begin{pmatrix}\sin\beta_{NAV} & 0 & \cos\beta_{NAV}\\ 0 & 1 & 0\\ -\cos\beta_{NAV} & 0 & \sin\beta_{NAV}\end{pmatrix}, \tag{25}$$

$$\dot{\boldsymbol{R}}_3(\alpha_{NAV}) = -\dot{\alpha}_{NAV}\begin{pmatrix}\sin\alpha_{NAV} & \cos\alpha_{NAV} & 0\\ -\cos\alpha_{NAV} & \sin\alpha_{NAV} & 0\\ 0 & 0 & 1\end{pmatrix}, \tag{26}$$

and $\dot{\alpha}_{NAV}$, $\dot{\beta}_{NAV}$, and $\dot{\gamma}_{NAV}$ are the yaw, pitch, and roll rates from the NAV, respectively.

4.3 Computational Steps Summarized

The steps in the DLMC procedure are summarized as follows:

1. Initialize the displacement vector, $\Delta\mathbf{r}$.
2. Initialize the roll and pitch offsets ($\Delta\beta$ and $\Delta\gamma$).
3. Read in a DL a1-level data file.
4. Read in the 10Hz NAV a1-level data that spans the same period as the DL data.
5. For each beam (profile) in the DL file, do the following:
    a. Average the NAV data (roll, pitch, yaw, roll rate, pitch rate, yaw rate, surge velocity, sway velocity, and heave velocity) over the pulse integration time of the DL beam. Use vector averaging for the yaw angle to avoid problems caused by the cyclic nature of this variable.
    b. Compute the velocity of the DL in the Earth frame from Equations 8, 9, and 10.
    c. Compute the beam vector in the Earth frame from Equation 13.
    d. Compute the along-beam (i.e., radial) component of the DL's velocity from Equation 16
    e. Compute the motion compensated radial velocity from Equation 17
    f. Compute the beam azimuth and elevation angles in the Earth frame from Equations 14 and 15, respectively.
6. Write the results to an output file.

5.0 Output Data

The datastream name for DLMC output is <site>dlmc<scan_type><facility>.c1. We note that during the MOSAiC deployment, the DL was configured to acquire only "fpt" and "usr" scan-type data. Primary variables in the output datastream include the georeferenced beam angles (azimuth and elevation), the motion-corrected radial velocity, the Euler angles, angular rates, and the lidar's linear velocity, including the component along the beam. We note that the uncorrected radial velocity can be reconstructed by simply adding ‘lidar_velocity_radial’ to ‘radial_velocity’. Table 5 lists variable names and their descriptions.

Table 3. DLMC output variable names, descriptions, and units.

Variable Name	Description	Units
base_time	seconds since 1970-1-1 0:00:00 0:00	s
time_offset	seconds since 00 UTC	s
range	Distance from lidar to range gate center	m
azimuth	beam azimuth relative to true north	deg
elevation	beam elevation relative to local horizon	deg
radial_velocity	motion-corrected radial velocity	m s-1
intensity	SNR + 1	-
attenuated_backscatter	Attenuated backscatter	m-1 sr-1
lidar_velocity_west	West component of DL velocity	m s-1
lidar_velocity_north	North component of DL velocity	m s-1
lidar_velocity_z	vertical component of DL velocity	m s-1
lidar_velocity_radial	Along-beam component of DL velocity	m s-1
nav_roll	Roll angle from NAV	deg
nav_pitch	Pitch angle from NAV	deg
nav_yaw	Yaw angle from NAV	deg
nav_roll_rate	Roll rate from NAV	deg s-1
nav_pitch_rate	Pitch rate from NAV	deg s-1
nav_yaw_rate	Yaw rate from NAV	deg s-1
lidar_nav_displacement_bow	Bow-ward displacement of DL relative to NAV	m
lidar_nav_displacement_port	Port-ward displacement of DL relative to NAV	m
lidar_nav_displacement_up	Upward displacement of DL relative to NAV	m
lidar_nav_roll_offset	Lidar-NAV roll difference	deg
lidar_nav_pitch_offset	Lidar-NAV pitch difference	deg
lidar_nav_yaw_offset	Lidar-NAV yaw difference	deg
lidar_roll	Roll angle from DL tilt sensor	deg
lidar_pitch	Pitch angle from DL tilt sensor	deg
lat	North latitude	deg
lon	East longitude	deg
alt	Altitude above mean sea level	m

6.0 Summary

The DLMC VAP was developed specifically for the MoSAiC deployment but is general enough to be used for most ship-based deployments provided proper installation of the DL. The VAP performs motion correction on the raw DL measurements. Specifically, it uses the output from the DL.a1 and NAV.a1 datastreams to transform the DL beam angles from their native coordinate system to an Earth-fixed frame of reference such that the beam azimuth is measured relative to true north and the beam elevation is measured relative to the local horizon. The VAP also removes the contribution of the platform velocity (see "lidar_velocity_radial" in Table 2) from the lidar's measurement of radial velocity. These corrections enable the development of higher-order data products such as profiles of wind speed and direction.

The DLMC VAP requires some set up before it can be run. The VAP requires prescribing the three components of displacement vector between the DL and the NAV, expressed in NAV coordinates. Additionally, the orientation of the DL coordinate system relative to the NAV system must be prescribed. This is done by specifying roll, pitch, and yaw offsets between the two coordinate systems. During MOSAiC the 'x' axes of the NAV and the DL were approximately aligned with the centerline of ship. Thus, we assumed that the yaw offset was zero. The pitch and roll offsets were determined by comparing the NAV data to the DL's internal tilt sensor. For future deployments we highly recommend that efforts be made to ensure coalignment of the DL and NAV 'x' axes. That will make life a lot easier.

7.0 References

Newsom, RK, and R Krishnamurthy. 2020. Doppler Lidar Handbook. U.S. Department of Energy, Atmospheric Radiation Measurement User Facility, Richland, Washington. DOE/SC-ARM/TR-101.

Walton, SM. 2019. Navigational Location and Attitude (NAV) Instrument Handbook. U.S. Department of Energy, Atmospheric Radiation Measurement User Facility, Richland, Washington. DOE/SC-ARM/TR-226.

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