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Analyzing shape deformation and rigid body movement of structures using commonly misaligned terrestrial laser scanners: the radio telescope case

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ABSTRACT

Terrestrial laser scanners (TLS) suffer from internal misalignments leading to systematic measurement errors. In most cases, these systematic errors surpass the magnitude of random errors. Hence, it is necessary to account for systematic errors within the deformation analysis in order to obtain unbiased results. Within this work, we present and compare several strategies for dealing with these TLS misalignments without the need of a previous calibration. These strategies are based on two-face measurements, an in-situ TLS calibration and a combination of both in a bundle adjustment. Furthermore, we analyze if changing measurement geometries, i.e., variations of the station of the instrument w.r.t. the object under investigation, improve the sensitivity of this bundle adjustment regarding the estimation of the calibration parameters.

We investigate these strategies based on a specific example: The elevation-dependent deformation analysis of radio telescopes that are used for geodetic very long baseline interferometry (VLBI). Within one measurement campaign, the radio telescopes rotate around their elevation axes. For this rotation, we need to know if the telescopes' reference points are stable and if the radio telescopes' main reflectors deform. While the first possible deformation equals a rigid body movement, the second one equals a shape deformation.

Our results demonstrate that the shape deformation as well as the rigid body movement are least affected by the TLS misalignments if measuring in two-faces, calibrating the scanner in-situ and varying the measurement geometry. Although we only draw our conclusions based on the empirical results of this specific example, they are transferable to other deformation analyses using terrestrial laser scanners.

I. Motivation

Regardless of the tremendous efforts of manufacturers, terrestrial laser scanners (TLS) are not geometrically perfect instruments. Hence, they are calibrated by the manufacturer right after assembly (Walsh, 2015). Due to different factors, e.g., long term utilization and suffered stress, the internal geometry of the device can be compromised so that the factory calibration is not valid anymore. The resulting mechanical misalignments are, e.g., the collimation axis error, trunnion axis error, vertical index offset and rangefinder offset, to name the most relevant ones (Lichti, 2010; Reshetyuk, 2009). These systematic errors misplace all points in the point cloud to some extent. That misplacement can significantly influence the deformation analysis (Holst und Kuhlmann, 2016):

- The geometry of the object under investigation might be estimated inaccurately. This might lead to biased conclusions about shape deformations.
- The position and orientation of the object might be estimated inaccurately. This might lead to biased conclusions about rigid body movements.

In both cases, the impact of the TLS's misalignments on the deformation analysis can be reduced either by (i) calibrating the instrument previous to its measurements or by (ii) using appropriate measurements strategies that reduce systematic measurement errors in-situ. Possibility (i) is not focused in this study since we do not want to include any assumption about the stability, which is questioned in the literature (Chan et al., 2013; Chow et al., 2012). Instead, we discuss possibility (ii) in order to present effective strategies that anyone can use in-situ at TLS-based deformation analyses. Consequently, this study answers the questions:

- What are possible in-situ strategies to deal with the terrestrial laser scanner misalignment at area-based deformation analyses and
- what are their advantages and disadvantages?

Possible strategies are presented in Section II. Section III analyses the benefit of each strategy related to one specific example: The deformation analysis of the Onsala Space Observatory (OSO) 20-m radio telescope. Section IV discusses the results, while Section V draws the conclusion.

Holst et al. (2018) already discussed the strategies presented hereafter regarding the shape analysis of the radio telescope while Holst et al. (2017) presented the final results. The corresponding rigid body movement was introduced in Holst et al. (2019). The present study combines the topics of these previous publications for the first time and it focuses on a more general context of TLS misalignments.

II. Strategies for Dealing with Misalignments in TLS-based Deformation Analyses

In general, one could arrange a measurement configuration in a way that the instrument misalignments would not notably affect the results of the deformation analysis. This strategy could simply be to scan only from one station with an equal orientation of the laser scanner in each measurement epoch. In this case, the errors due to the misalignments impact the point cloud in each epoch similarly (similar direction and magnitude) so that they might not affect the deformation analysis between two epochs. However, this strategy is only feasible in special cases:

- We are not interested in the absolute position and orientation of the object,
- We are not interested in the object's absolute geometry, only in relative changes between the epochs,
- one laser scanner station is enough to acquire the complete object and
- we assume that the calibration parameters of the TLS do not change between the epochs.

An example satisfying all these requirements could be the high-frequency monitoring of a bridge that oscillates due to traffic using a profile laser scanner what is discussed, e.g., in Schill (2018). However, commonly, these requirements cannot be met.

Hence, we focus more general strategies that evolve out of two distinct thoughts:

- We just scan the deformed object twice in each epoch using two-face measurements (Holst et al., 2017). Then, all parts of the object are measured both in face 1 (front face or front side) as well as in face 2 (back face or back side). Afterwards, we just combine both point clouds into one dataset and perform the deformation analysis. The estimated deformations are not any more biased by the TLS systematic errors that switch signs between face 1 and face 2. The corresponding errors just average each other out. This holds true for all two-face sensitive misalignments (Medić et al., 2017; Muralikrishnan et al., 2014). This leads to Strategy S1.
- We know the desired physical construction of a TLS, all 18 possible misalignments (11 for the high-end TLS, which are typically used for deformation monitoring; Medić et al., 2017) as well as their functional model according to the National Institute of Standard and Technology of the USA (Muralikrishnan et al., 2015). Thus, we can just estimate these parameters in-situ for each epoch as also performed by Abbas et al. (2017) and Wang et al. (2016). This leads to a deformation analysis combined with an in-situ calibration of the TLS. We call this Strategy S2.

The advantages and disadvantages of Strategy S1 can be summarized as follows:

- The object needs to be scanned with two consecutive scans from each scanner station, i.e., in two cycles. In the first cycle, the scanner rotates horizontally from 0° to 180° and, in the second cycle, from 180° to 360°. Only then, the whole object is measured both from the front and also from the back side of the instrument. However, not all TLS are capable to do this due to the software limitations.
- It only covers the misalignments that are two-face sensitive (e.g., collimation axis error, trunnion axis error, vertical index error), not the ones that are not two-face sensitive (e.g., rangefinder offset and scale). However, in the case of the high-end TLS, only three parameters are not two-face sensitive (Medić et al., 2017). Thus, although it does not cover all possible errors, it covers most of them.
- Within this strategy, no in-situ calibration of the laser scanner is performed. Therefore, the mechanical construction of the laser scanner does not have to be known. Thus, it can be performed quite easily.
- Since the misalignments are not parameterized within the deformation analysis, they are not included in the functional model. Furthermore, they cannot be included in the stochastic model in an appropriate manner. Thus, the estimated residuals will most probably not be normally-distributed with expectation value zero. As a result of this inconsistent adjustment, the global test will fail and the a posteriori variance component analysis will be biased.

Regarding Strategy 2, we summarize the advantages and disadvantages as follows:

- The object needs to be scanned just once per station.
- Only those misalignments can be covered that are estimable by the given configuration of adjustment. Thus, the set of estimable calibration parameters very much depends on the shape of the deformed object, the knowledge about the deformed object, i.e., its parameterization, and the geometry between object and scanner station. Which parameters are estimable is, consequently, not easy to assess previous to the deformation analysis. For instance, a rangefinder offset will most probably not be estimable since it is hard to achieve an adequate measurement geometry within the typical deformation analysis. However, it will shift the absolute position of the scanned object and bias the estimation of rigid body movement parameters.
- The mechanical construction of the TLS needs to be known to include the corresponding transition between misalignment and resulting error in the functional model of the deformation analysis.

- Since the misalignments are parameterized within the deformation analysis, the adjustment might be consistent. Thus, assuming that the stochastic model is known (not discussed herein), the global test might be accepted.

This comparison between both strategies reveals that both suffer from certain disadvantages. The largest issue of Strategy S1 is its inevitable inconsistency due to the false functional model. Thus, this strategy S1 cannot be preferred since statistical testing of possible deformations is meaningless in this situation. The in-situ calibration of Strategy S2 is, on the contrary, more in the focus of this study. However, it suffers from the fact that the configuration of adjustment needs to allow for estimating all relevant calibration parameters. To improve this configuration, we introduce two further strategies:

- Strategy S3: In-situ calibration (S2) using two-face measurements (S1).
- Strategy S4: In-situ calibration (S2) using two-face measurements (S1) with improved configuration by scanning from different stations.

Strategy S4 includes a new aspect into the discussed scenarios: Scanning from different stations to improve the scanning geometry so that the configuration of adjustment is more sensitive regarding the calibration parameters. The corresponding adjustment can be realized as a bundle adjustment estimating the deformation parameters, the transformation parameters between the different stations as well as the calibration parameters – that are assumed to remain stable between the different scans – in one combined adjustment.

Herein, we do not specify whether scanning from different stations should be realized within each measurement epoch or if it is sufficient to use different stations between different epochs. The example provided in Section III will realize the latter possibility since the complete main reflector of the radio telescope is visible from one single station. In general, scanning in each epoch from different stations would also improve the predictability of the calibration parameters.

Fig. 1 depicts the ideas of all strategies. Tab. 1 focuses on the corresponding number of scans per station, the number of stations and the necessity to estimate calibration parameters.

III. The Radio Telescope Case

Detailed explanations regarding this deformation analysis in Holst et al. (2017, 2019). Here, only the most relevant information is given.

The scans of the OSO 20-m radio telescope were performed at seven elevation angles between 85 deg an 5 deg always measuring in two cycles. The laser scanner was positioned upside-down attached to the radio telescope's beams. Thus, the laser scanner moved together with the rotation of the radio telescope around its elevation axis but his orientation remained upside-down due to a flexible hinge (Fig. 2).

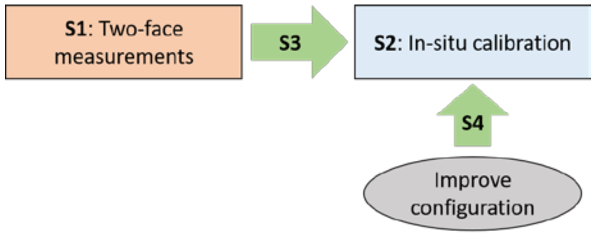

Figure 1. Strategies for dealing with TLS misalignments at deformation analyses

Table 1. Strategies to deal with misalignments

strategy	# of cycles	# of stations	Calibration
S1	2	1	No
S2	1	1	Yes
S3	2	1	Yes
S4	2	> 1	Yes

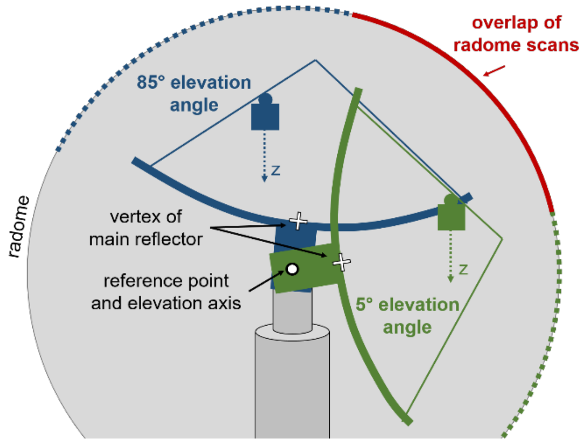

Figure 2. Measurement concept of scanning the OSO 20-m radio telescope; edited from Holst et al. (2019)

We sub-sampled the point clouds to a regular grid as proposed Holst et al. (2014) proposed. Afterwards, we parameterized the main reflector of the radio telescope as a rotational paraboloid estimating its form parameter (focal length f) and five transformation parameters (translations X_v, Y_v, Z_v; rotations φ_x, φ_y) between scanner and rotational paraboloid elevation-dependently (Holst et al., 2015).

For deformation analysis, this concept means:

- There are seven epochs, i.e., each elevation angle defines a new epoch.
- We know that, for each epoch, the focal length decreased and that the object moved relatively w.r.t. the position and orientation of the TLS. Hence, the object deforms in sense of a shape deformation as well as a rigid body movement.
- The measurement configuration varied notably between each epoch: While the TLS saw the the main reflector's vertex at 85 deg elevation angle approximately in direction of its local zenith, it saw the vertex at 5 deg elevation angle approximately in direction of its local horizon.

A. *Analyzing the Shape Deformation*

We implemented the four strategies listed in Tab. 1 according to the ideas presented in Section II. This means, for Strategy S1, we merged both cycles measured in each elevation angle together in one point cloud and estimated the six rotational paraboloid parameters individually for all elevation angles.

For Strategy S2, we only used scans from one cycle for all elevation angles and estimated the six parameters together with the calibration parameters accounting for the misalignments. Here, each elevation angle is handled separately meaning that the calibration parameters between different elevation angles are not functionally connected (i.e., they are not considered as being constant). Strategy S3 is realized in a similar way but with merged laser scans of cycle 1 and cycle 2 in each elevation angle.

For Strategy S4, we used Strategy S3 but connected all scans acquired in the different elevation angles in one combined adjustment estimating the calibration parameters only once (i.e., they are considered as being constant). This implementation leads to a bundle adjustment. In each case, the configuration of adjustment only allowed for estimating two-face sensitive parameters (Holst et al., 2018)

If no strategy is used and if Strategy S2 is used, only one scanning cycle is needed. Anyway, since both cycles were collected, the results are analyzed in these cases for both cycles (c1 and c2) separately.

Fig. 3 depicts the standard deviations of the estimated residuals for all four strategies and also for the case of no strategy. Herein, the residuals equal the discrepancies of the Gauß-Helmert adjustment model between each scan point and the estimated rotational paraboloid. It can be seen that the standard deviations vary between the different elevation angles for all cases. Additionally, Strategies S2-S4 minimize the residuals successfully compared to the case of not accounting for the misalignments.

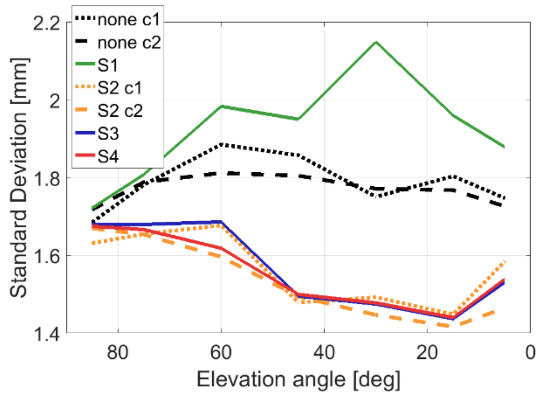

Figure 3. Standard deviations of the adjustment residuals using the different strategies

However, Strategy S1 leads to even larger residuals compared to the status quo. This is explainable by the fact that Strategy S1 incorporates measurements of two cycles. Thus, each part of the main reflector is scanned in face 1 as well as in face 2 leading to opposite signs in the systematic errors due to the misalignments. Thus, the histogram of these residuals reveals a bimodal normal distribution with opposite bias leading to apparently larger errors in sum (not shown here, for details see Holst et al., 2018).

Fig. 4 depicts the estimated focal lengths separated for each strategy. Based on the known mechanical behavior, we expect a smooth decrease of the focal length with decreasing elevation angle. Such a decrease is only notable for Strategies S1 and S4 – disregarding the estimates at 75 deg elevation angle – this scan was partially disrupted (Holst et al., 2017). For Strategies S2 and S3 and for the case of not accounting for the misalignments, the estimates are significantly biased. This is partially highlighted by the fact that the deviations from the expected smooth decrease change the sign when using cycle 1 or cycle 2 measurements in the no-strategy case.

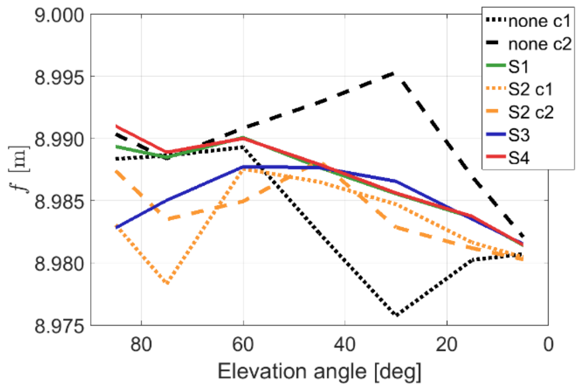

Figure 4. Estimated focal lengths using the different strategies

B. *Analyzing the Rigid Body Movement*

Analogous to Figs. 3 and 4, Fig. 5 depicts the estimated translation vector in X-direction between the TLS station and the paraboloid vertex as a representative for the rigid body movement. This parameter changes significantly between the elevation angles since the relative position between the instrument and the radio telescope changes due to the flexible hinge holding the TLS. Thus, for better interpretation, the mean translation of all strategies is subtracted from the translation estimated for each elevation angle in Fig. 5.

When analyzing the results for cycle 1 and cycle 2 without any strategy, it is revealed that the deviations from the mean are mirrored between cycles at each elevation angle. This implies again that the systematic errors are mainly two-face sensitive. At Strategies S1, S3 and S4, these deviations are mostly eliminated. These strategies all rest upon two-face measurements. Thus, although this is only a validation regarding relative deviations without any absolute reference – since the rigid body motion is due to the flexible hinge of the laser scanner mounting –, we attest the transformation parameters of all "two-face" strategies to be less affected by the TLS misalignments.

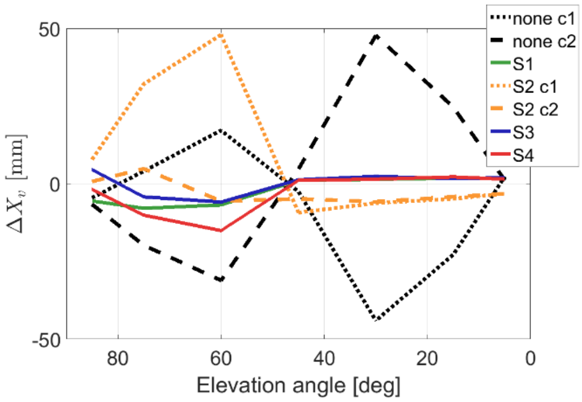

Figure 5. Relatively estimated translations in X-direction between laser scanner station and vertex of the main reflector.

Based on this insight, the determination of the reference point's stability rests upon the results of Strategy 4. Thereafter, each vertex coordinate of the main reflector is first transformed into the local coordinate system of each corresponding scanner station using the previously estimated five transformation parameters of each elevation angle (translations X_v, Y_v, Z_v and rotations φ_x, φ_y). Afterwards, the overlapping laser scans of the radome are used to determine the transformation parameters between all laser scanner stations in the seven elevation angles by a plane-based registration (Wujanz et al., 2018). These latter transformation parameters transform each point cloud into a stable reference coordinate system that is fixed for all elevation angles (Fig. 6).

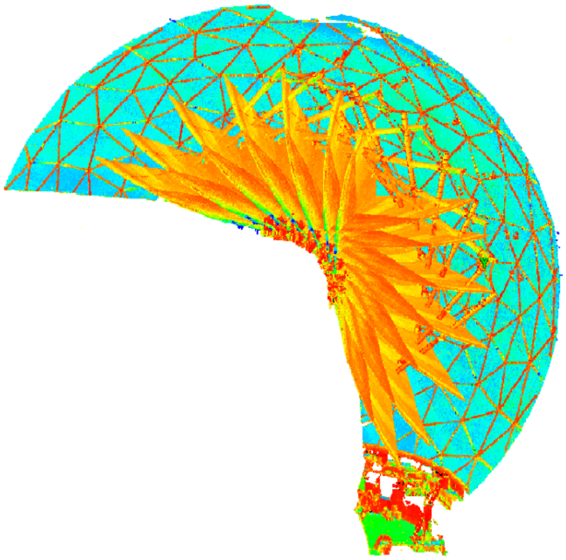

Figure 6. Transformed point clouds (all 7 elevations) into one stable reference coordinate system (Holst et al., 2019)

Based on these reference point clouds, we estimate the center of rotation of the main reflector whose stability over all elevation angles is to be analyzed (Fig. 7). Therefore, we parameterized the vertice's movement as a circle whose normal axis equals the elevation axis (horizontal rotational or trunnion axis) of the main reflector. The estimated residuals of the circle estimation, that are not any more affected by the TLS misalignments due to adopted strategy, are in the range of up to 0.4 mm indicating that the reference point's stability cannot be disproved. For more details, see Holst et al. (2019).

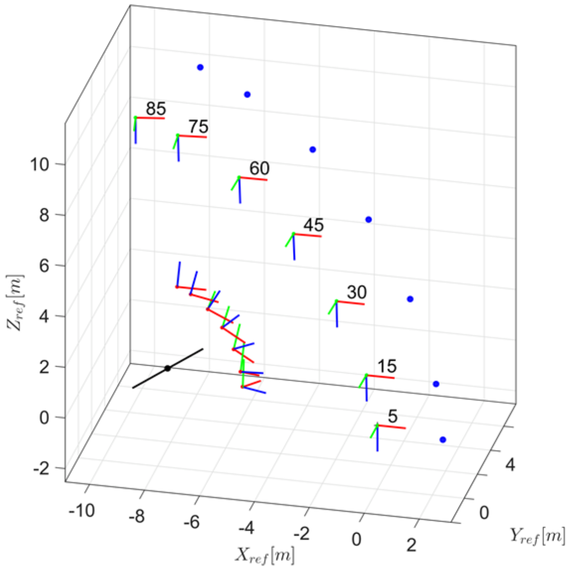

Figure 7. Estimated elevation axis (black line), reference point (black dot), vertices of the main reflector (tripods without labels of elevation angles), laser scanner stations (tripods with label of elevation angles) and focal points of main reflector (blue dots) (Holst et al., 2019; edited from Holst et al., 2019)

C. *Summary of Results*

The results are quite similar for Strategy 1 (two-face measurements) and Strategy 4 (two-face measurements combined with an in-situ calibration using different configurations) regarding the estimated parameters – for the shape deformation as well as for the rigid body movement. However, this does not hold true for the estimated residuals since they reveal the inconsistency in Strategy 1 that does not account for the misalignments in the functional model.

Nevertheless, in principle, both strategies S1 and S4 could be suited for estimating the focal length decrease of the main reflector as well as for analyzing the reference point's stability. This holds true since in both cases the estimated deformation parameters are in the main focus, while the inconsistencies in the estimated residuals can be eventually parameterized and eliminated (not shown here, see Holst et al., 2018).

IV. Discussion

In Section II, we introduced four different strategies that could potentially deal with the terrestrial laser scanner misalignments at deformation analyses. These strategies evolved out of two thoughts: Either the majority of the relevant errors are eliminated by introducing two-face measurements by scanning in two consecutive cycles or the instrument is calibrated in-situ. The numerical results of Section III can be discussed in a general manner – not restricted to the given example – as follows.

A. *Using Two-Face Measurements*

The only requirement for two-face measurements is that the used instrument allows scanning in two consecutive measurement cycles, which holds true for all panoramic type terrestrial laser scanners due to their assembly. The only limiting factor can be in-built software. However, this could be overcome by a coarse rotation of the instrument around the standing axis for a half circle, allowing cycle 1 and cycle 2 scans from a single station. Thus, the inclusion of two-face measurements is largely applicable, regardless of the individual characteristic of the specific geodetic task.

Using two-face measurements can completely remove the influence of all two-face sensitive scanner misalignments and, therefore, improve the accuracy of estimating deformation parameters. Thus, the estimated parameters indicating the shape deformation and the rigid body movement might be quite similar to the ones if performing an in-situ calibration. However, the adjustment will be inconsistent since the systematic errors due to the laser scanner misalignments are not accounted for, neither in the functional nor in the stochastic model. Thus, the global test will be rejected.

This bears two problems: Other potential inconsistencies within the deformation analysis might be undetectable and the estimated residuals cannot be inspected for further local deformations of the object since they will also contain the misalignment errors. Distinguishing between local deformations and misalignment errors in residuals is not a straightforward task.

Further problems are the identification and modeling of laser scanner misalignments not sensitive to two-face measurements. This might require an additional calibration of the laser scanner – either in-situ or not (Medić et al., 2017).

B. *Using In-Situ Self-Calibration*

The success of the in-situ calibration strongly depends on the configuration of adjustment, which mainly depends on the measurement geometry, i.e., the position and orientation of the instrument w.r.t. the scanned object and the object's shape. The more versatile the measurements during the deformation analysis are, the better is the possibility of estimating accurate TLS calibration parameters. This procedure takes advantage of the presumption that the calibration parameters do not change during one assignment. That allows all scans collected on the job scene to be bundled in one adjustment procedure with enhanced sensitivity regarding the TLS misalignment detection. For that, two prerequisites must be fulfilled:

1. the object needs to be scanned from several scanner stations with altering measurement geometry and
2. some a priori knowledge about the object geometry is needed.

Herein, the altering measurement geometry could be achieved within one measurement epoch or between different measurement epochs.

In our case study, both prerequisites are fulfilled: (1) each telescope's elevation angle is measured with a different measurement configuration and (2) the telescope´s main reflector is designed as a rotational paraboloid.

Generally, the first prerequisite is usually accomplished without any extra effort because many geodetic monitoring tasks aim at objects that are too complex to be scanned from one scanner station. Those are for example dams, tunnels, bridges, and tall rise building. The second prerequisite is also fulfilled if the object of interest can be geometrically parameterized in some way. For instance, man-made buildings might be parameterized as geometric primitives. If not, assumptions about the object's smoothness might be incorporated to link the different point clouds together.

V. Conclusion

With the example of analyzing the elevation-dependent deformations of a radio telescope's main reflector, we demonstrated that not considering the terrestrial laser scanner misalignments can significantly bias the results of the deformation analysis. This conclusion is directly transferable for the deformation monitoring with TLS in general. Several strategies for overcoming the latter problem are proposed and analyzed in detail.

The outcome of the analysis can be summarized as follows. Including two-face measurements in the deformation monitoring task can significantly reduce the bias of the results caused by the majority of the TLS misalignments. This strategy is simple and it does not pose any special prerequisites. The main shortcoming is a difficult analysis of the local deformations.

As an alternative, the in-situ calibration can theoretically mitigate the effect of all TLS misalignments and, if successful, it allows a straightforward analysis of local deformations. However, it requires both a versatile configuration of adjustment as well as prior knowledge about the investigated object. The combination of two-face measurements and an in-situ calibration of the TLS assures the most comprehensive and accurate deformation monitoring, least affected by TLS misalignments.

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