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Terrestrial laser scanner and retro-reflective targets: an experiment for anomalous effects investigation

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Abstract

Artificial targets are generally used in the terrestrial laser scanner (TLS) practice for data georeferencing, since they are well recognized and modelled from the point cloud, and their positions can be contemporarily measured by topographical techniques. The accuracy of target identification directly influences the georeferencing quality. In particular, retro-reflective materials can cause anomalies in range measurement due to the too high amplitude of returned pulse. If the received pulse intensity exceeds the limits of the sensor dynamic range, the receiver saturates producing a truncated pulse preventing the correct time-of-flight computation. A series of experiments were performed in order to test the performances of a specific instrument (Optech ILRIS 3D) for the acquisition of artificial targets made of retro-reflective material resulting in very high reflectance. Dealing with ranges lower than about 300 m, two cases were clearly observed, that is wrong distance measurement of points over the high reflecting surfaces, and the presence of haloes around these surfaces. Neglecting these phenomena, has serious implications and can lead to a wrong georeferencing. The experiments were executed and data analyzed providing a qualitative and semi-quantitative phenomenon description. Finally, the design of a target that can be easily recognized and correctly modelled was ideated and proposed.
Keywords: Terrestrial Laser Scanner; Data Registration; Reflectance.

1. Introduction

Laser scanning represents a new frontier for topographical surveying and technical analysis. The use of high accuracy terrestrial laser scanners (TLS) was originally developed for studying individual architectural features, but it has now evolved into a complete morphological and structural surveying solution. Nowadays, there are available several commercial TLS, that can provide accurate and high-resolution data, from which very detailed digital models of the observed scene.

The most amazing factor of the TLS technique is the high accuracy and resolution that can be reached. For example, at a 50-m distance the spatial resolution of the Optech ILRIS 3D is 17.7 mm (Lichti and Jamtsho, 2006), and a sampling step of few centimetres can be considered also for an acquisition distance of about 700 m.

A TLS works a lot like ordinary radar, except that such a system sends out narrow pulses or beams of light rather than broad radio waves and it can acquire a huge amount of points randomly distributed on the observed surface. The product of a scan is the point cloud, consisting in coordinates of the acquired points, the corresponding intensity (normalized to the maximum value) and, optionally, the RGB colours.

If a large scene is observed by TLS, more than one viewpoint scan are necessary to acquire the entire surface without shading zones. In such a case, each one of the obtained partial point clouds is referred to its local instrumental frame (screw hole connected to the tripod), so these have to be registered, that is aligned within a same reference frame by means of rototranslation transformations. The alignment is generally obtained by means of...
automatic or semi-automatic ICP (Iterative Closest Points) algorithms (Besl and McKay 1992; Chen and Medioni 1992). These operate a surface matching of point clouds overlapped areas, with high accuracy and short computation time (Rusinkiewicz and Levoy 2001) leading to a global point cloud. It can be georeferenced using a series of control points (GCPs) that are natural or artificial targets contemporarily acquired by TLS and topographical techniques like total station or/and GPS. The absence of overlapping areas between different scans, requires a complete data registration by means of GCPs only. It is the case, for example, of a quarry or in general of a complex geometry (Scaioni et al. 2004). Moreover, the comparison of multi-temporal models allows the definition of a realistic displacement field and the evaluation of surface variations avoiding systematic effects only if the registration in the same reference frame is correct and accurate. This goal is reached measuring natural or artificial stable particulars (e.g., rocks, buildings) and verifying their stability means of accurate topographical measurements.

It is to underline that the final result, that is the model generated by the TLS data (Remondino 2003), is given by the addition of errors belonging to scan internal accuracy, quality of the point cloud alignment, and accuracy of the georeferencing, that is the transformation to pass from the local system of the model to the external reference frame, for example WGS-84 (WGS84 2006).

While the registration of partial point clouds is responsible for the internal precision of the model, and eventual registration errors can cause its deformation, georeferencing errors can cause systematic effects only. Nevertheless, there systematic errors can prevent a good interpretation in term of monitoring surface movements by means of comparisons between two or more multi-temporal digital models of a scene. For example, the Piecewise Alignment Method proposed in Teza et al. (2006) provides the displacement field of a landslide by using TLS multi-temporal data referred to a common reference frame, and the results critically depends on georeferencing quality. This happens for each
quantitative study on the time evolution of an observed phenomenon. As above shown, the georeferencing requires a series of artificial targets that can be easily recognized and modelled in the point cloud. The centres of these targets are the GCPs. Several targets exist with different shape, size and material (natural or artificial). In particular, a class of very high reflectance materials exists. They are the retroreflective materials, like the corner cube, and they can be easily recognized even if very long distances are considered. Nevertheless, a very high reflectance can lead to range errors, and/or other phenomena, as a test on TLS accuracy performed in the past has pointed out. In order to better understand the effects of retro-reflective elements for TLS data georeferencing, in this paper their influences on the performances of Optech ILRIS 3D laser scanner (Optech 2006; POB, 2006) are investigated. The principal aims are: the recognition of conditions in which bad-reflection phenomena happen, their analysis, they modelling (if possible), and the acquisition of useful elements for a target design.

2. Targets for data georefencing

Generally, the artificial target size and shape depend on the measurement range, and the colour is chosen to allow an easily identification in the point clouds thanks to the contrast between high and low reflective material. Actually, it does not exist a universal target suitable for each kind of laser scanner surveying, but each object is created to satisfy the demand of a specific application. Anyway it is possible to make a first discrimination between simple targets, made using common materials, and complex reflectors, formed by retro-reflective materials. The retro-reflective targets reflect the incident beam along the same direction and this behaviour is very different from the one of a natural material, where the incident radiation is diffused abroad a wide spectra of reflecting angle (partially Lambertian behaviour).
The artificial targets for georeferencing are modelled to determine their centres (or other), whose coordinates are acquired throughout the scanning session by means of topographical techniques. Clearly, this task is delicate because it directly affects the georeferencing accuracy. The modelling can be correctly done if the number of the points over the target surface is large enough, but it is quite impossible if the target size is small respect to laser spot size or if the TLS angular step is too large.

Figure 1 shows two TLS applications over the same landslide located near Bologna, (Italy), where different targets were used. These images belong to two surveys executed by means of Optech ILRIS 3D (Optech 2006, POB 2006) and Riegl LMS Z-420i (Riegl 2006; POB 2006). The targets used in the first survey was planar, with about 50 cm-by-50 cm size. These targets are quite visible in the point cloud, and can be easily modelled to obtain the circles fitting the bright areas, and therefore their centres. In the second survey, several cylindrical retro-reflectors were used. In this case, it is to notice that the very high reflectance makes the data points very bright in the point cloud, but the fact that the target have small size (few centimetres) should be considered. These special materials are very useful for a rapid detection of points, but a correct modelling of the target centres is impossible because the points are too few and, in addition, an halo can surround the obtained data (Pesci et al. 2006).

The registration of partial point clouds acquired by ILRIS TLS is generally performed using the surface-to-surface ICP algorithm (Bergevin et al. 2006) implemented in PolyWorks software (Innovmetric 2006). In particular, the GCPs are recognized and located only with georeferencing purposes.

A different strategy is adopted by Riegl: in this case, if one more viewpoints are considered, the registration of partial point clouds acquired by means of Riegl LMS Z-420i TLS are performed using specific Riegl targets and RiSCAN-PRO software. The
point clouds are linked together on the basis of the reciprocal spatial positions of the recognized targets.

The georeferencing is the main interest of the study, not the registration, although the two operations are correlated and, if no overlapping area exist, they can at least partially coincide. Here, the data registration is assumed, and the complete point cloud, already referred to a local reference frame, must be referred to an external reference frame by using GCPs.

3. Experiments

A comparative test was performed in March 2005 in order to verify the performance of the two laser scanners Optech ILRIS 3D and Riegl LMS Z-420i. Two artificial targets were created with this aim, and were acquired together with several rocks and reflectors to analyze also the radiometric returns (figure 2). In particular, also retro-reflecting material were used. Various effects appeared in the concerning retro-reflective elements, from halos to errors in range measurement, as shown in this figure. The obtained results were non completely unexpected, since some problems in acquisition by TLS of very high reflectance material was reported by various authors, e.g. Cheok et al. (2002). These results suggested the necessity of a further investigations about these materials.

[Insert figure 2 about here]

To perform a new experiment, a specific target was designed. Such a target is composed by a white wood panel on which a square box of retroreflective material by Rotbuchar (Rotbuchar 2006) was applied. A black zone surrounded the box to improve the contrast between high an low reflectance elements. The target size was chosen to allows its correct modelling also at long distances (figure 3).

[Insert figure 3 about here]
The experiment was developed acquiring the object from different ranges from 10 to 300 metres with a step of about 10 m and from 300 to 800 meters with a 50 m step. For each one of the 40 scans, a suitable choice of the spot spacing allowed a correct modelling of the surface. The point clouds were analysed to estimate the discrepancies between the position of points relative to the natural surface of the panel (in the next, called NR points) and the ones belonging to the retroreflective material (in the next, called RR points).

Really, there are different effects that appears, depending on the range: a) the measure of the distance is shortened for near ranges and points are inside a box in front of the panel; b) the measure is both shortened and lengthened; c) the points are positioned behind the target.

Figure 4a shows the first effect (shortening) relative to the acquisition at a range of 10 m; the red points are clearly positioned outside the panel plane, nearer the scanner along the target-instrument direction, and are distributed inside a sort of box. The normal distance between the box centre and the panel is about 1 m, with a dispersion in range measurement of RR points of about 10 cm (box side).

Figure 4b describes the result of a 60 m range acquisition. In this case the shortening effect is still present but reduced to about 40 cm, but the more relevant error is a lengthen of several metres. Finally, figure 4c shows the point cloud obtained by a 260 m scan, in which only a lengthen effect can be observed.

In general, until a distance of about 300 m is reached, the ranges of RR points are wrongly measured. The offset is defined as the mean distance between the set of RR points and the plane modelled from NR points. Figure 5 shows the offset vs. distance plot. The error bars represent the dispersion of the measured RR distances. Neglecting the higher values, this plot presents a trend that starts with negative discrepancies, slowly decrease till positive values and finally goes to zero for ranges longer than 300 m. The
highest offset are about 10 m and are reached in the range from 30 m to 60 m, even if the offset range from -39 cm to +22 cm for a wide spectra of distances. If the data affected by offset exceeding 1 meter are excluded (arbitrary choice), the correlation between the range offset and dispersion (figure 6) is highlighted. A detailed analysis, shown in figure 7, shows that, at different scales, for the lengthen effect (positive offset), there is no a significant relation between the box wide and the offset, while in the negative part such a relation is more evident. Two correlation values were estimated for the two parts as -0.34 ± 0.05 and -0.56 ± 0.10 respectively. Despite low values, the differences seems indicate different behaviours probably caused by different effects.

The results depend on the used materials, so the experiment was partially repeated using a different retroreflective element, that is a “class 1” paper enclosing a lens retroreflective urethane film coated with a permanent acrylic adhesive, usually adopted for traffic signals usage (TTS 2006), see figure 8. This paper was applied on the target, and the scans were acquired over the 10 m, 30 m, 50 m, 60 m, 80 m, 100 m, 150 m, 200 m, 250 m and 300 m ranges. Also in this case the RR points are wrongly acquired, and the offset and data dispersion are related to the range, passing through negative to positive values (respect to the target plane), but differently respect to the other material. In figure 9, two scans are shown acquired respectively at 10 m and 60 m range. The effects are different depending on chosen reflective paper and this evidence prevent the estimation of a unique corrective function.

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A further test was performed to investigate a possible relation between the offset in point positioning and the size of retro-reflector. The paper sheet was divided in two parts, halving its dimension and some scans were performed. In this case the effect unchanged, as observed in figure 10. The data belonging to the experiments over the two different paper sheets were inserted in a single plot (figure 11) showing that, despite the different absolute values, the trends are very similar. The data of signal paper, in fact, are inside an interval ranging from -0.5 m to 6.5 m, while the Rotbucher ones range from -1.5 m to 12 m, but the coefficient of a simple polynomial interpolation indicate a scale factor (figure 11).

Another interesting effect is the halo obtained in the around of target, that is the instrument measured non-existing points that is the sensor detected arrivals over wrong angles along unexpected directions (figure 12). The halo appears especially using signal chart is used, whereas it is very reduces and disappears dealing with Rotbucher element.

The main results of this experiment are the following:

1) The wrong measurements are only related to error in time measurement because the bad measured points lie on the line defined by the laser beam;

2) A possible interaction between the elements (corner cubes, for instance) which form the retro-reflective material can be excluded because errors appears only when the target is lightened by the laser. This is also confirmed because the observed offset does not depend on target size;

3) Offsets are not easily modelled with the distance but, neglecting the dual effects in the near range region, the low variations allows the definition of a polynomial
second degree regression. In particular, offsets go from negative to positive values
and slowly converge to zero increasing the range.

4) Results obtained observing two different retroreflective materials show similar
trends on the qualitative viewpoint, but a scale factor is present.

5) For distances longer than 300 m, no more effects are visible in the point cloud if the
incidence is normal. This fact suggest the use of retroreflective materials only if the
range is very long.

6) If the incident beam is not normal to the surveyed surface, problems in reflection
arises even if the acquisition distance exceeds 300 m (measurements with 30° and
60° was performed). In particular, a retroreflective plane surface cannot be correctly
modelled as a plane. For this reason, the use or targets observed with normal
incidence is strongly recommended.

7) Halo effects appear only for certain materials (e.g., the paper for traffic signals).

4. Data interpretation

4.1 Haloes

The presence of a halo around some retroreflective material can be justified taking in to
account the power distribution of the laser beam. A laser scanner operates with a Gaussian
beam, that is only the fundamental transversal electro-magnetic mode (TEM$_{00}$) is present
(Menzel 2001). The spot size (figure 13) is defined as the area at which the 86% of the
intensity content of the laser beam corresponds (the intensity is $I = c\varepsilon_0|E|^2$, where $c$ is the
speed of light, $\varepsilon_0$ is the dielectric constant in the vacuum, and $E$ is the electric field).

Dealing with amplitude ($E$) instead of intensity, the percentage is 68%. In this figure a 3-
cm diameter spot is shown, condition that corresponds to 100-m acquisition distance.
The light interacting with a natural material is reflected in a quasi-Lambertian way, that is it is diffuse. A rough computation shows that the returned intensity is about $10^{-8}$, detectable by the rangefinder. If a retro-reflector is present, it reflects the signal along the same direction of the incident beam with very low diffusive effects. So, also the Gaussian tails of the spot shape have to be considered, the spot size is greater. Clearly, even if a return is due to the Gaussian tail, and therefore is far some cm from the spot centre, the reflection is assigned to this centre, from which the halo. Note that, respect to central values of the spot function, the energy content of the external ring is reduced to about $10^{-5}$ to $10^{-6}$. So, if only a 1/10 or 1/100 part intersects the reflector, then the order of magnitude reached to the signal return intensity is about $10^{-7}$ – $10^{-8}$, comparable to expected returns values in standard conditions.

### 4.2 Range errors

Before the data interpretation, a brief introduction to the methods used in the identification of the time of flight of a laser pulse is presented. The accurate measurement of the time interval between the start of the emitted pulse and stop of the received pulse is very important, and a valid method for the recognition of the instant of pulse transit is necessary. Different methods can be used, as shown in figure 14.

They can provide different time intervals based over the waveform of the returned pulse, and can show different behaviour on the basis of the target cross-section (Wagner et al. 2004). The methods more used are the constant fraction, that is a pulse is considered passed when a certain fraction respect to the peak value is reached, and the inflection recognition, also called zero crossing because the inflection corresponds to the zero value
of the second derivative of the shape function. For example, in the case of Optech ILRIS 3D the 70% constant fraction is considered (Dario Conforti, Optech Inc., Personal Communication).

Probably, besides saturation effects that result in a truncated pulse due to the too high returned amplitude of the signal, what really happens is a wide modification of the returned waveform causing an uncorrected signal recognition and preventing the time of flight estimation.

A laser pulse in fact is a wave packet composed by some longitudinal modes, depending on the dimension of the resonant cavity were the light is amplified (Menzel 2001). Longitudinal modes are responsible for the impulse waveform and the impulsive emission is characterized by pulse duration and the time of pulse repetition. The power of the signal is a function characterized by a peaked shape. Generally, the interaction of the laser impulse with a physical surface generates a return wave very similar to the emitted one, but more flatter depending on distances, material reflectivity and interaction with the transmitting mean.

Due to the diffusive light reflection, the signal intensity is really reduced but, depending on the sensor precision and sensibility, it can be detected throughout ranges of the order of 1 kilometre or longer. Dealing with a complex and artificial material as a retro-reflector, the waveform of returned pulse could be highly deformed because some modes are favoured and the internal sensor cannot recognize correctly the impulse arrival time. Unfortunately, the lack of information about the real system device, probably due to all reserved rights, do not allow a satisfactory description of the problem, but it is possible to formulate some hypothesis and justify results. Optech Inc. only asserted that anomalies of range measurements were due to “saturation” of the signal into the internal sensor but, as widely described, variations and errors are related to the range and the empirical function describing offset behaviour is well defined, not random. The offset is the same
for all the high-reflectance points at the same distance, suggesting that the pulse waveform is the same, resulting in the same saturation effect but the behaviour changes when the range changes. Despite the poor information about the laser device and the internal scanner rangefinder, a waveform hypothesis is attempted following laboratory experiments performed in 2004 (figure 15).

[Insert figure 15 about here]

In this figure, a double peak shape is used supposing the sensor recognize the maximum intensity value on longer time demonstrating the lengthening effects while, for very close ranges, the shortening is justified if the first peak is high enough. Moreover, this effect in fact is not obtained using TLS based on different signal detection approaches like threshold or inflection point, while halo effects are always present, as the test performed in 2005 using also Riegl LMS Z-420i evidenced. This kind of material can be also used to check for the spot size outside the 86%. Anyway, avoiding the usage of retroreflectors for short ranges (< 300 m) no other problems are evidenced.

5. Suggestion for an artificial target

The described phenomena are relevant if the scene is observed from a distance lower than about 300 m. Note that they are negligible only if the incident beam is normal to the object, that is if the LOS direction is orthogonal to the target surface. If the target is rotated, assuming a different orientation, an error is present also if the distance is larger than 300 m, probably due to the previously described halo effect. For example, if the inclination between the LOS and the normal to the surface is 60°, wrong reflection can be seen also if a 400 m range is considered. For this reason, a planar target is suggested, and the distribution of the targets on the scene must be designed in order to have a normal (or at least a quasi-normal) incidence.
The target must be easily recognized in the point cloud, so a high-reflectance material is often necessary. It could be created using a planar white panel, like the one for the experiment, black painted in the internal area using a well defined square shape, to obtain a contrast intensity zone, and a small retro-reflective paper could be applied on its centre as attraction. In this way, the high-reflectance points allows the identification of the target in the scene, and an easy recognition of its low-reflectance points, that can be modelled, due to the simple geometric shape, to obtain for example the precise coordinate of the centre. The target can be also acquired with total station previously calibrated to correctly measure that kind of reflectors.

Moreover, in absence of a specific calibration, the error in range measurement arises also in the case of the rangefinder of a total station, and a target in a hardly accessible landslide cannot be temporarily covered during the topographical acquisition. For this reason, four doilies for total station are traced on the not retroreflective material. Clearly, the total station has to operate in reflector-less measurement mode. The coordinates of the centre of target can be computed from the coordinates of the four points. In this way, the problems that arise when high reflectance material are used, can be overcome. The proposed target is shown in figure 16.

[Insert figure 16 about here]

6. Conclusion

Artificial targets, well distributed on the observed scene, are important objects for georeferencing of the models obtained from laser scanner data, since a point cloud can be referred to a chosen external reference frame by means of the topographical localization and measurement of the centres of these targets. In order to obtain good results, a target must be easily recognized and modelled, from which, sometimes, the necessity of a high-
reflecting material, as well as adequate size on the basis of the considered range, since the modelling of a primitive such as a bright circle or square requires some tent of points. In particular, targets constituted by retroreflective materials (corner cubes, micro-lenses,...) can be easily recognized in a point cloud, but some undesired effects can degrade the results. The Optech ILRIS 3D laser scanner, for example, if working at ranges lower than 300 m from the object, leads to wrong coordinate estimation of retro-reflective elements, showing also haloes in the point cloud.

For this reason, a series of experiments were performed, using two different retro-reflective materials (Rotbucher target and traffic signal paper). The point cloud analyses show offsets between -1 m and +12 m in the case of the first material and between -0.5 m and +6 m for the other. The obtained trends demonstrate that data are not casually distributed but subjected to a specific behaviour. Nevertheless, an accurate modelling of the phenomena cannot be general, since different materials cause different offsets, even if the shape functions offset vs. range are very similar.

The results advise careful in the use of retroreflective material, whose use should be leaved to the very long range measurements and in conditions of normal incidence by the laser beam, since the inclination amplifies the undesired effects. Finally, in order to effectively help the TLS user, a unified target has been proposed. Since this target contains both retroreflective and natural reflecting materials, it can be easily recognized in the point cloud, correctly modelled, and correctly localized by a total station in any case.

The experiment here described was focalized on the Optech TLS. Nevertheless, it will be repeated using instruments provided by other manufacturers and also using other retro-reflecting materials.
Acknowledgments

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References


Figure captions

**Figure 1.** Two different target used during the same landslide surveying and their recognition on a landslide. Upper panel: case of a simple planar object of 0.5 m size painted with black and their white colours to provide high contrast and to allow a correct definition of the white circle shape. Lower panel: case of a cylindrical panel covered by high reflectance material.

**Figure 2.** Targets used in an experiment conceived to test accuracy and resolutions of two TLSs (left), and the corresponding point clouds acquired by Optech ILRIS 3D from a 25-m distance (right). Note the artefacts due to the retroreflective elements (reflectors 1 and 2 in figure), pointed out by dashed rectangles.

**Figure 3.** The target built for the experiment consists in a wood panel white painted with an internal black rectangle and a 30 cm size square retroreflective paper.

**Figure 4.** Point cloud acquired at a 10 m (a), 60 m (b) and 260 m range (c). Red points are bad measured. Note that a 60 m some points of the retroreflective surface have a measure range larger than the true, whereas the contrary effect is observed for the most part of the points of this surface.

**Figure 5.** Offset vs. range map. The error bars represent the dispersion in range measurement of the points belonging to the retroreflective target.

**Figure 6.** Relation between offset and dispersion
**Figure 7.** Positive and negative offsets respect to errors. The right panel shows a low values zoom or the entire chart.

**Figure 8.** Another retroreflective elements (paper for traffic signals) has been applied on the upper part of the panel (A), while the Rotbucher square is in the centre (B).

**Figure 9.** Wrongly measured points of two retroreflectors. Distances between instrument and target: 10 m (left) and 60 m (right).

**Figure 10.** The traffic signals paper is divided in two parts to investigate if the offset is related to the object size. Left: point cloud acquired at 50 m range. Right: point cloud at 100 m range. No effect have been detected.

**Figure 11.** Offsets belonging to the first experiment (black squares) and to the second one (blue squares). A simple interpolation was performed by means of a second degree polynomial is shown. Trends are very similar, but a scale like effect seems to exist.

**Figure 12.** The halo effects. The halo is well visible if the intensity is not used in the point cloud representation.

**Figure 13.** Left panel: Power and spatial view of a laser spot. The retro-reflector is depicted with black and white squares, and the yellow ring is an area of the plane at which a very little fraction on the total incident power is associated. This ring partially intersects the retro-reflector. On the right panel, a Gaussian and its cumulative function are represented. The first intervals (rings whose width is \(\sigma\)) shows the corresponding power
content as fraction of the entire power of the laser beam. This configuration can explain the halo effects.

Figure 14. Methods used for pulse emission and arrival recognition. T: threshold value (generally not used); F: inflection point of the pulse (or zero crossing); C: constant fraction respect to the maximum; P: pulse peak; M: median value, that is the pulse’s centre of mass. The most considered approaches are zero crossing and constant fraction.

Figure 15. Hypothesis for a modified pulse waveform. Such a pulse shape could justify the lengthening effects. Emitted and received pulses are not in scale (the order of magnitude of the received pulse is lower than the one of the emitted pulse).

Figure 16. Target for georeferencing with both retroreflective and not retroreflective surfaces.
Fig. 1
Fig. 2
Fig. 4
Fig. 5
Fig. 6
Fig. 7
Fig. 8
Fig. 9
Polynomial Weighted Regression

\[ Y = A + B_1 X + B_2 X^2 \]

First experiment
\[ A = -0.63 \pm 0.04 \]
\[ B_1 = 0.015 \pm 0.0015 \]
\[ B_2 = -6.6E-5 \pm 1.3E-5 \]
\[ R\text{-Square}(COD) = 0.99508 \]

Second experiment
\[ A = -0.98 \pm 0.08 \]
\[ B_1 = 0.012 \pm 0.001 \]
\[ B_2 = -2.9E-5 \pm 0.3E-5 \]
\[ R\text{-Square}(COD) = 0.83862 \]

Fig. 11
Fig. 12
Fig. 13
Fig. 14
Fig. 15
Fig. 16