

## ABOUT THE CALIBRATION OF LIDAR SENSORS

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**ABSTRACT:**

Over the past years airborne laser-scanning has become the primary choice for gathering precise and dense digital elevation models (DEM) of large areas for a wide range of applications. It is presently the most efficient method for DEM acquisition, but it is far from being mature. Its reliability is confronted with erroneous data distracting potential customers. This paper intents to describe sources of the errors and to outline how they can be avoided, corrected and compensated.

### 1. INTRODUCTION

Users are frequently confronted with artifacts, miss-match of flight strips, smiley-face or pillow distortions and the like. A number of attempts have been made and described on how these distortions can be corrected on the ready data, how and which calibration might be required (may be at each flight) and how this calibration could be used.

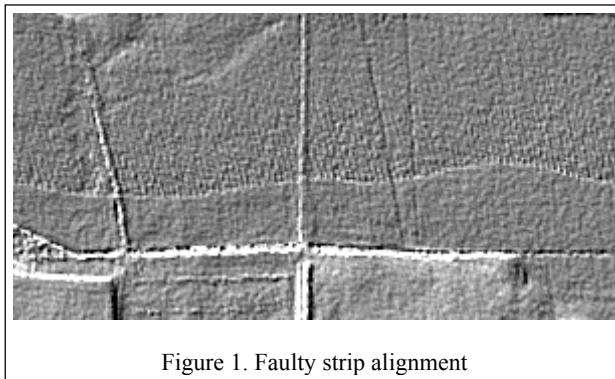


Figure 1. Faulty strip alignment

Figure 1 show a faulty alignment of adjacent strips leading to an elevation jump and a noisy model above this jump.

This paper shall provide an overview on error sources and shall give some hints about how to avoid these errors or how to correct them. It further will give information about at what level corrections or calibrations should be applied best.

### 2. GENERAL

The acquisition and production of a digital elevation model by laser-scanning is based on two vectorial data sets (Figure 2)

- sensor position P ( $p$ )
- distance and direction ( $a$ ) from P to the reflecting object R

Adding both leads to the vector to the reflecting object ( $r$ ) or the point R.

To establish the two basic vectors a few measurements have to be taken. First is the measurement of the position P and second the distance  $|a|$  and the direction from P to R (i.e. the instantaneous viewing direction)

For this all existing laser-scanning systems are composed of several basic components as depicted in figure 3. With respect to the basic parameters there are four essential components shown in bold lines.

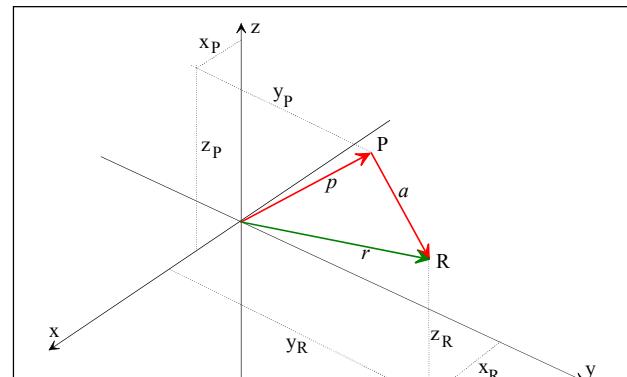
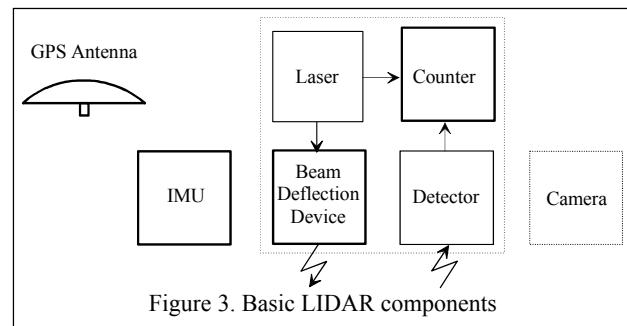


Figure 2. Sensor and Reflector Position



Within the following sections the measurements and calculations of the three basic elements

- sensor position
- distance to reflecting object
- viewing direction to reflecting object

and the associated errors and their consequences are outlined. For simplicity it is assumed that the IMU is the central part to which all other coordinates and orientations are transcribed.

### 3. SENSOR POSITION

The position of the sensor is acquired by GPS applying DGPS on-the-fly algorithms at post processing (not real time). To achieve precise positions a number of requirements should be fulfilled.

- acquisition at 1 Hz, dual frequency, code and phase
- a stable spacecraft constellation evenly distributed ( $\text{PDOP} < 2.5$ )
- no disruption of the spacecraft signals

The GPS reference station should be positioned within the survey area and the rover should not depart by more than 25 km. At extremely stable (but rare) conditions of troposphere and ionosphere this distance might exceed 100 km.

If all conditions above are maintained one can expect that the position is accurate within 0.05 m in all directions.

The precision of the DGPS results depend strongly on how accurate the ambiguities are solved. As the rover moves fast in all directions this is not simple. Interruptions of a satellite's signal, rising and sinking space crafts, changing tropospherical conditions make this task more complicated.

Ideal conditions are rare and so one has to envisage a number of positioning errors:

- slight drift causing differences between adjacent strips
- strong drifts (or even jumps) caused by new solutions of the ambiguity (e.g. during turns)

For short surveys one can assume that the positioning error is stable and might be corrected by a simple shift (in most cases only in elevation). At survey flights exceeding one hour or extending for more than 30 km one will find all effects of changing ambiguity solutions.

Figure 4 show a typical example of a varying elevation error caused most probably by a DGPS error.

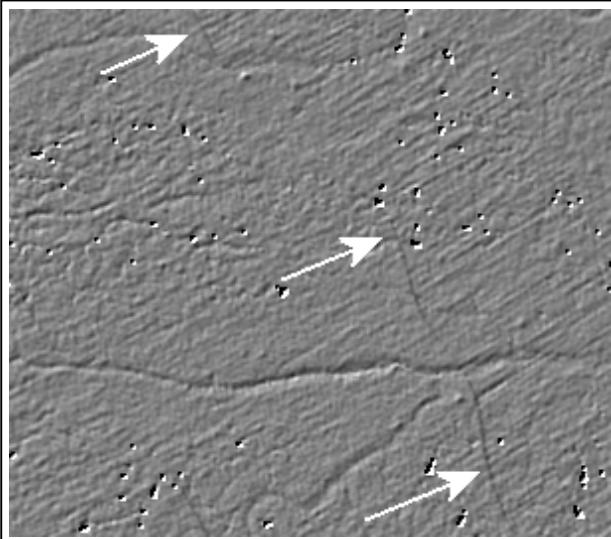


Figure 4. Varying elevation error

The calculated position is that of the GPS antenna. From this the position of the IMU is calculated using the vector from the IMU to the antenna (lever arm) in the coordinate system of the IMU.

#### 4. DISTANCE

The distance can not be measured directly, so the time from emitting a laser pulse till the reception of an echo (time of flight) is measured and converted into distance. Usually this measurement is done by counting the number of cycles ( $n$ ) of an oscillator operating at a frequency  $f$ . Time and distance follow then to be

$$t = \frac{n}{f} + \Delta t \quad \text{or} \quad s = \frac{n}{2f} \cdot c_a + \Delta s \quad (1)$$

where  $n$  = number of cycles (or counts)

$f$  = frequency of oscillator

$\Delta t$  or  $\Delta s$  compensate for delays and optical paths within the sensor

$c_a$  = speed of light within the atmosphere

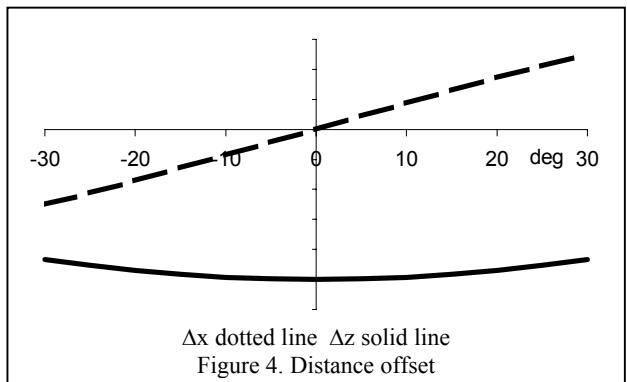
So far things look straight forward and should not cause problems. Lets look into some details:

$\Delta t$  or  $\Delta s$  can be taken as constant as far as the optical paths within the sensor is concerned. Delays caused by the electronic components might change with temperature and by aging effects. The aging effect can be controlled by regular calibration but the thermal effect might vary during a survey flight and has to be compensated (or better minimized) at the sensor's design phase.

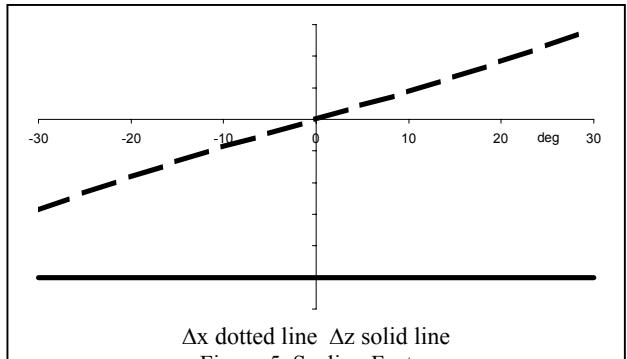
More essential is the effect caused by a false adjustment of the oscillators frequency  $f$ . Even minor deviations from the nominal frequency will cause reasonable deviations in calculated distance. For a distance resolution of 3 cm the nominal frequency has to be  $f = 10$  GHz.

The third parameter in the above equation is the speed of light  $c_a$  within the atmosphere. Even this seems to be simple, one has to take into account that it depends on the density of the atmosphere, that means it varies with pressure, humidity and temperature. Considering that survey flights with a LIDAR will be done only at clear atmospherical conditions, one can neglect humidity. But pressure has to be considered specifically if one is flying at various altitudes. Assume two survey flights one at a shore (0 m MSL) and one at a high elevation area (2000 m MSL) both 2000 m above ground. Taking the speed of light valid at the shore also for the high region will lead to calculated distances which are about 0.12 m too short (twice the error one would accept for DGPS elevation).

The effects of these two errors on an elevation model are outlined in figures 4 and 5 below. The dotted line shows the lateral error across track. A positive gradient means widening of the swath. The solid line shows the elevation error.



Δx dotted line Δz solid line  
Figure 4. Distance offset



Δx dotted line Δz solid line  
Figure 5. Scaling Factor

An offset ( $\Delta s$ ) will cause a shift of the elevation model (which might be corrected) but also a slight pillow distortion and a widening of the swath width. If the offset is negative, then the elevation model becomes higher than it should be, the pillow distortion goes downward at the edges and the swath width becomes narrower.

A scaling factor caused by a false frequency or speed of light will result in widening (or narrowing) the swath and an elevation shift but no pillow distortion.

## 5. BEAM DIRECTION

Here we have to make a clear distinction between the orientation (or attitude) of the sensor itself and the direction of the individual beam. To avoid any misunderstanding we use the following terminology:

Sensor orientation (or attitude) is understood as the attitude of the IMU.

Beam deflection is understood as the direction the laser beam has with respect to the deflection device

Beam direction is the direction of the laser beam w.r.t. the IMU.

### 5.1 Sensor attitude

All LIDAR systems use some kind of navigation system including a GPS receiver and an inertial measurement unit (IMU). The IMU comprises accelerometers and gyros. Integrating twice the accelerations leads to the position and integrating the angular rates from the gyros leads to the attitude. But neither gyros nor accelerometers are free of errors and thus simple integration will lead to a drift of the results. Taking the continuous DGPS position and the movement direction and speed derived from subsequent positions one can correct the drift and achieve a very precise attitude. The procedure to take additional sensors to correct the drift of gyros and accelerometers is usually called "strap down" and requires a constant lever arm. If the IMU is mounted on a gimbal and moves in relation to the GPS antenna, the "strap down" and thus the attitude might become erroneous.

Depending on the price for an IMU one can expect that the error for roll and pitch will be

from 0.004 deg to 0.02 deg.

The error for the heading (i.e. deviation from true north) is about twice that of roll.

### 5.2 Beam Deflection

There are presently three different types of electro-optical components in use to deflect the laser-beam across the flight path. The principal effects shall be shown in more detail for an oscillating mirror. For a rotating mirror (polygon) and a fiber-scanner these effects shall be outlined only.

**5.2.1 Oscillating Mirror:** A mirror oscillates between two positions, driven by a galvanometric motor controlled by a sine-wave generator. The principle components of such a device is shown in fig. 7.

Oscillating frequency and maximum angular position ( $\pm \Theta/2$ ) are controllable within some (mechanical and dynamical) limits. The instantaneous angle is described in general by

$$\vartheta(t) = \frac{\Theta}{2} \cdot \sin(\omega t) \quad (2)$$

Please recall that the maximum scan-angle ( $\pm \Theta$ ) is twice the maximum angle of the mirror.

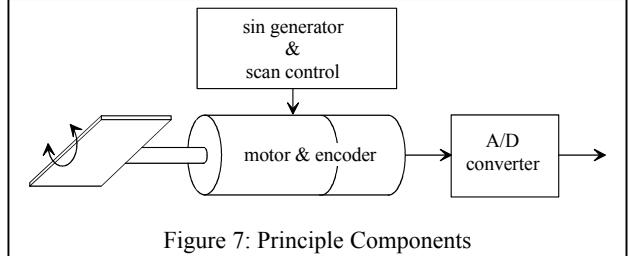


Figure 7: Principle Components

The instantaneous angular position  $\vartheta$  is read by an encoder and converted to a digital representation  $\vartheta_D$ . Only the latter one is used for the processing of a DEM.

We have to consider two errors, each of them might have several reasons.

One error is a zero-offset causing that  $\vartheta_D$  becomes

$$\vartheta_D(t) = \vartheta(t) + \Delta\vartheta \quad (3)$$

Reasons for this can be a mechanical miss-alignment of mirror and encoder or a zero-shift within the A/D converter.

A second error is a scaling factor leading to

$$\vartheta_D(t) = \vartheta(t) \cdot (1 + \varepsilon) \quad (4)$$

The most probable reason for this error is a false gain-control within the A/D converter, but it might also be caused by the encoder itself.

Figure 8 show in general the geometry of the actual laser beam (dotted line) and of its calculated direction (solid line) for an

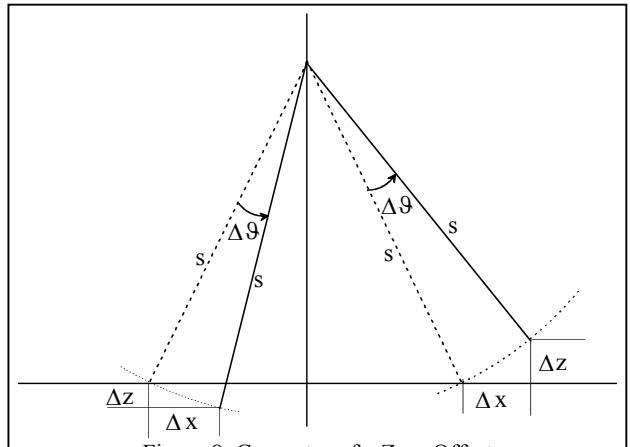
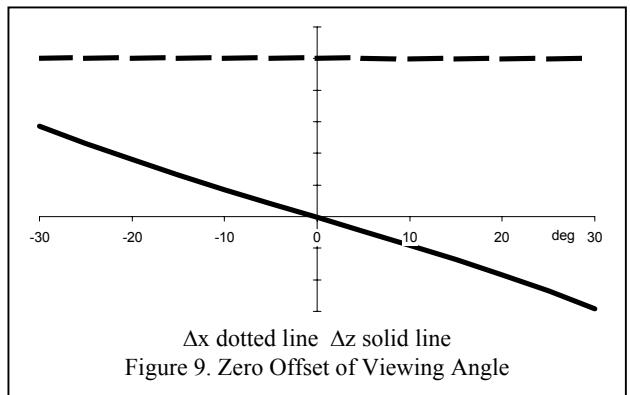


Figure 8. Geometry of a Zero Offset

offset (equation (3)).



The zero-offset results in a nearly constant lateral shift of the DEM and in a tilt of the DEM (figure 9).

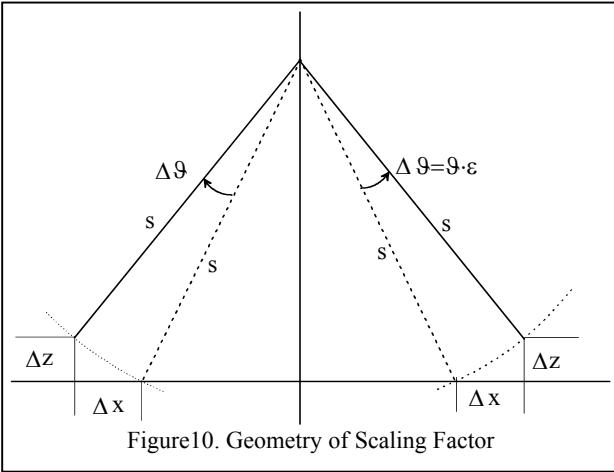
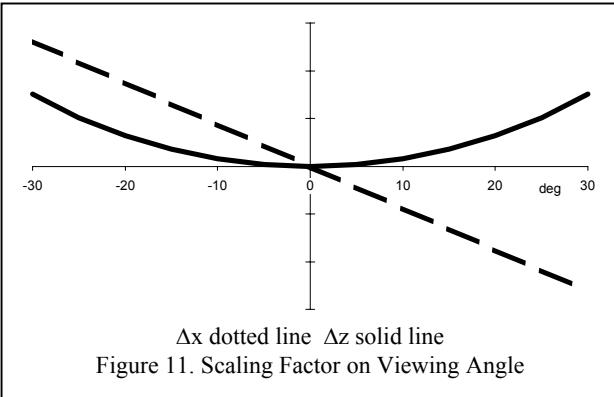


Figure 10 shows the geometry of the beams in case of a false scaling of the viewing angle. Depicted is a positive error according to equation (4).



The false scaling factor results in a scaling of the swath width (wider or narrower) and in a pillow distortion of the elevations (edges up or down) depending on the sign of the error (figure 11).

Whether these errors can be corrected or calibrated or not depends only on whether these errors are stable or whether they change with time. If they are of a mechanical nature one can assume that they are stable, but if they are of electrical nature then one has to assume that they change with time even within a survey flight and thus are not correctable by simple calibration procedures.

**5.2.2 Rotating Mirror:** For a rotating mirror we have nearly the same conditions. The angular orientation is read by an encoder and converted to a digital representation.

For a regular polygon one has to consider that the individual polygon surfaces are slightly tilted against their nominal direction (manufacturing tolerances) and thus each polygon surface might have an individual zero-offset which needs to be calibrated once.

At the processing one needs to know which polygon is active to apply the respective correction.

**5.2.3 Fiber Scanner:** For a fiber scanner the individual beam direction is given by the number of the fiber. The center of the scan is defined by the alignment of the fiber array and the field optics. Both are calibrated once and are stable over the life-time of a fiber scanner.

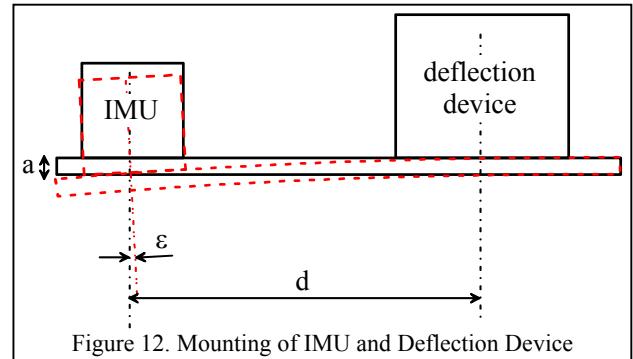
### 5.3 Scan Direction

In most cases one can assume that the scan direction is perpendicular to rotation axes of the oscillating or rotating mirror and that this stays stable. This applies also to the orientation of a fiber scanner.

### 5.4 Beam Direction

At an initial calibration of IMU and deflection device a bore sight alignment of both will be established. By this one can transfer the angles of the beam deflection into the direction of the IMU and so establish the beam direction.

Depending on how the IMU and the deflection device are mounted this bore sight alignment is not necessarily very stable. Lets assume that both are mounted on a strong plate (or any other similar structure) as shown in figure 12. Due to some bending forces during mounting the sensor into the aircraft or during flight or from thermal effects the carrying plate might be deformed slightly. Lets assume that the center of the IMU and the optical center of the deflection device are separated by the distance  $d$  and that both center lines are parallel. If now the plate gets slightly deformed (red dotted lines in figure 12), then the orientation of the IMU changes. Depending on the type of deformation the orientation(s) of the deflection device or of both might change.



Assuming that  $d = 300$  mm and the deformation  $a = 1$  mm then the orientation error becomes about  $\epsilon = 3$  mrad. At a measuring distance of 1000 m this will result in a displacement of 3 m. Whether this error is stable over time or whether it changes from flight to flight or even within a flight can be assessed only if details about the mounting of these components within the sensor are known.

## 6. SYNCHRONIZATION OF MEASUREMENTS

The above showed that there are several individual measurements which need to be combined for a precise final result: Among these individual measurements the most essential are

- position
- sensor attitude
- distance
- beam deflection

These measurements are taken by different parts of the sensor system and are not taken at the same instant. So one needs to

know precisely the time at which each individual measurement has been taken or the time difference between measurements to associate each correctly with all others.

The criticality of the timing of measurements may be outlined by one example. To calculate the proper beam direction one needs the attitude and the deflection angle at the same instant. Both are measured by independent components governed by their internal timing. The IMU (providing the attitude) runs on its timing at about 200 Hz while the deflection device will be synchronized to the laser and its pulse rate of 20 kHz to 80 kHz. We have to consider that there might be a small delay between both measurements. If the attitude is stable (i.e. it does not change over time) then there is no error in the beam direction. If the attitude varies fast (e.g. during a roll maneuver) the beam direction will become wrong. A roll rate of 2 deg/sec and a delay of 4 msec will cause an error of 0.008 deg leading to a displacement of the measurement of 0.28 m at a distance of 2000 m.

A survey flight at very calm air will not show this error, but at bumpy conditions this error will happen frequently and vary continuously.

## 7. COUNTERMEASURES

Under normal conditions one has to expect that several of the errors described above will apply at the same time. Most of the errors (if known) can be corrected only at the level of the measured data: distance, attitude, and beam deflection. A correction at the level of the produced DEM is nearly impossible even if the DEM is available in strips.

Best is to avoid the errors by a proper design of the sensor system.

We have taken all measures to avoid these basic errors:

### 7.1 Beam Deflection

Within a fiber scanner the individual beam direction is defined by the number of the fiber in use. As these fibers are tightly coupled the deflection can not vary over time.

### 7.2 Beam Direction

As shown above one of the essential elements is how IMU and deflection device are mounted. We have placed IMU, fiber scanner and push-broom camera tightly together on a very stiff carbon reinforced plastic (CFRP) plate. This ensures that the bore sight alignment will not vary, unless one of the components has been re-mounted. Mounting the sensor system into an other aircraft does not change the bore-sight alignment.

### 7.3 Distance

The distance measurement is influenced by the speed of light, the counting frequency and delays within the electronics. Within the fiber scanner there is one fiber going directly from the transmitting device to the receiving device. This fiber has a calibrated optical length of about 1100 m which does not vary. The distance over this reference fiber is measured once each scan and used to monitor the behavior of the electronics and to correct the measured distances.

Within the processing the average flight height is used to correct the speed of light applying the ICAO model of the atmosphere.

### 7.4 Timing

Each component doing a time critical measurement has its own stable timing circuit which is synchronized to the GPS time each second by the PPS signal. So timing errors can be held below about 10  $\mu$ sec.

### 7.5 Remaining Errors

There are primarily two errors remaining:

The DGPS positioning will be erroneous specifically if a survey flight has been performed at adverse conditions. As there is not a stable offset but a varying error it is extremely difficult to correct for.

The distance measurement is based on detecting the edge of an echo and is accurate for flat, homogenous surfaces. Uneven surfaces (spruce stand, corn-field, etc.) reflect echoes with widely varying shapes, causing variations in the edge detection. Measurement of such surfaces will remain erroneous.

## 8. CONCLUSIONS

The above shows that most of the corrections, which might be applied have to be used at a very early stage of the data processing. Even if so called "raw data" (i.e. all echo coordinates) are available, the correction is limited to GPS (or positioning) errors.

The usual calibration flights (at the beginning and at the end of a survey) over flat terrain do not allow the detection of distance errors, of varying deflection errors, of time delays between measurements, etc.

It seems that it is much more essential to understand the composition of a sensor system and what the manufacturer has done to avoid most of the effects described above. Further the above outlines why a general software for processing real raw data (i.e. position, orientation and distance) will never exist. It would have to take into account a large number of parameters assigned with the individual manufacturing of a sensor system and which can not be generalized.

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