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Appendix A

Frequently Asked Questions about Photogrammetry

This section lists frequently asked questions about V-STARS, and photogrammetry. Click on the question, for an answer.

1. How accurate is V-STARS?

2. How many photographs are needed for a measurement?

3. How many points are needed for a measurement?

4. Do I need scale for the measurement? How do I get it?

5. How do I compensate for scale changes due to temperature?

6. Can the object move while it is being measured?

7. Do I need to use special targets with the system? Can I measure untargeted features?

8. What size should the targets be? Can I use different size targets on the same measurement?

9. How obliquely can I view the targets?

10. Do I need to provide special lighting for the system? Do I have to consider the lighting where the measurement is being taken?

11. Do I need to know where the camera is located when I take a photograph? How steady must the camera be when taking a picture?

12. How far away do I have to get from the object to measure it? Where should I locate the camera to get a good measurement?

13. How can I calibrate the camera and make sure the measurement is accurate?

How accurate is V-STARS?

The short answer is V-STARS is very accurate and provides accuracies comparable to those achieved by other large volume, high accuracy coordinate measurement systems such as Digital Theodolites, Co-ordinate

Measuring Machines (CMMs), and Laser Trackers. Typical accuracies are 25 to 50 microns (0.001" to 0.002") on a 3-meter (ten foot) object.

The long answer is a bit more complex since accuracy depends on several inter-related factors. The most important are:

1. The resolution of the camera you are using,
2. The size of the object you're measuring,
3. The number of photographs you're taking, and
4. The geometric layout of the camera stations (camera locations) relative to the object and to each other.

The effect of each of these factors is described briefly below.

Resolution
The resolution of the camera you're using is a major factor in determining the overall accuracy of V-STARS. V-STARS is able to measure the centers of images to better than 1/50th (0.020) of a pixel typically. For a 2,000 by 2,000 pixel camera such as the KODAK Megaplus 4.2, this represents an inherent accuracy of 1 part in 100,000 (2000/0.020). Other factors mentioned above will increase or decrease this inherent accuracy. Cameras with fewer pixels will have lower inherent accuracy. Cameras with more pixels have a higher inherent accuracy.

Object Size
The absolute accuracy of V-STARS depends on the size of the object being measured. Given the 1 part in 100,000 inherent accuracy mentioned above means a measurement accuracy of 50 microns (0.002") will be achieved on a 5 meter (15 foot) object (5 meters/100,000 = 50 microns), 100 microns (0.004") will be achieved on a ten meter (30 foot) object (10 meters/100,000 = 100 microns), and so on.

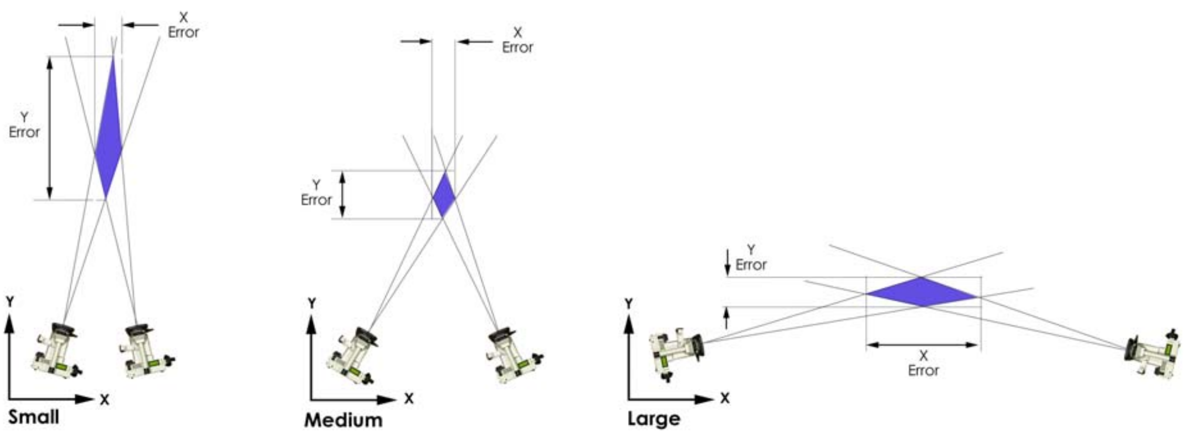
One technique you can use to increase accuracies is to move in closer, and photograph the object in sub-sections. For example, a ten meter object can be measured to an accuracy of 50 microns instead of 100 microns by photographing the object in five meter sections. Of course, this requires taking more photographs (usually at least twice as many) since the typical photograph sees only a fraction of the object. One can increase absolute accuracies considerably by using this technique, but the measurement becomes increasingly complex. One key to using this technique successfully is to ensure there is enough overlap among all the photographs to provide a good solution.

Number of Photographs
All other factors being equal, increasing the number of photographs will increase the accuracy of the measurement. Since V-STARS measures by triangulation, each target must be measured in at least two photographs for the point to be triangulated. If a target is seen in more than two photographs, the accuracy will increase. However, the accuracy increase is not linear. As a rule of thumb, the accuracy increases with the square root of the increase in the number of

photographs. Therefore, to increase the accuracy of a two-photo measurement by a factor of two, you must take not twice as many photographs but four time as many, or eight in this case. To increase accuracy by another factor of two, you would have to take 32 photographs. Obviously, one quickly reaches a point of diminishing returns when simply taking more photographs to increase accuracy.

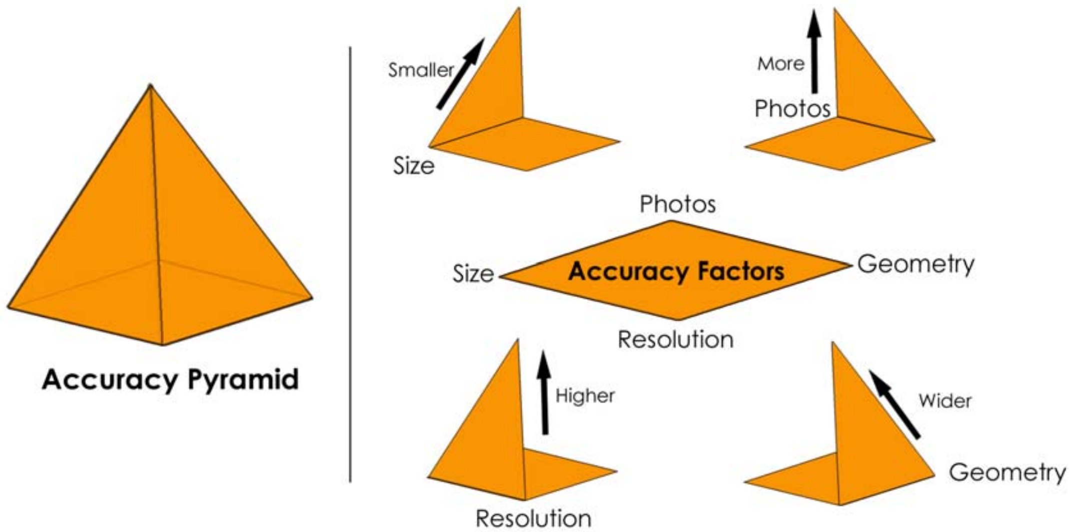
That said, it is worth mentioning that additional photographs also increase reliability because they reduce the influence of poor measurements. For that reason, we recommend trying to have each target seen in at least three (and preferably four) photographs. These pictures should be taken from different stations.

Geometry
Since V-STARS measures by triangulation, the geometry of the camera stations can have a considerable influence on measurement accuracy. Typically, one should try to get intersection angles of 90° or so between the lines of sight of the camera stations for the best results. Smaller intersection angles will progressively reduce accuracies. The figure below illustrates this. The thin lines around the thick lines show how errors in detecting the true centroid of target image produce errors in determining the location of the target.



Final Discussion on Accuracy
As you can see from the above discussion, accuracies can vary considerably. However, if you use the INCA camera, and take six to eight photographs with good geometry, and each photograph sees the entire object you should obtain accuracies of 25 to 50 microns (0.001" to 0.002") on a 15 foot object.

The effects of the four factors mentioned above on accuracy are illustrated by the diagram below. The diagram can be thought of as a pyramid with the four factors at the base of the pyramid and high accuracy at the top of the pyramid. To get higher accuracy (a higher pyramid) you need more of the items shown on the lines of pyramid (higher resolution, smaller size, more photos, wider (not too wide though) geometry).



How many photographs are needed for a measurement?

As V-STARS measures by triangulation, in theory only two photographs are needed, for a measurement. However, we recommend you take a minimum of four to six photographs. With four to six photographs you can self-calibrate the camera. Self-calibration is a powerful technique in which the camera is calibrated as a by-product of the measurement. This allows the camera to be calibrated at the time of measurement under the conditions that exist at the time of the measurement. In order to self-calibrate the camera you must take a minimum of six photographs if the object is essentially flat, and a minimum of four photographs if the object isn't flat. Extra photographs also produce a more accurate and reliable measurement, and typically take little more time to measure so go ahead and take them. See Triangulation and Self-Calibration for more information.

How many points are needed for a measurement?

To get a good solution, we recommend measuring a minimum of twelve well-distributed points (and preferably fifteen to twenty) in each photograph. In addition, the entire measurement should have at least twenty (preferably thirty) well-distributed points. When in doubt add more points. It's quick and easy to do, so go ahead and do it.

Of course, measuring more points will lead to a better solution, however you quickly reach a point of diminishing returns. In most cases, measuring more than forty well-distributed points in each photograph, and more than sixty well distributed points overall will not significantly improve the solution.

Notice we always qualify the number of points with the term well distributed. The distribution of the points can often be much more important than the number of points. It is better, for example, to have twenty points which are spread out over the entire area being measured than to have fifty clustered in one small area and fifty more clustered in another small area. Points that are added only to improve the distribution of points are usually called "fill-in" points. See Resection and Self-Calibration for more details.

Do I need scale for the measurement?

Whether you need scale for the measurement depends on the application, but most applications do need to scale the measurement. To get scale, you must provide V-STARS with at least one known distance between two measured points. You can specify a virtually unlimited number of scale distances, and we recommend you use at least two scale distances, whenever possible, to provide redundancy. Of course, the scale points are like any other points; they must be measured and triangulated. They do not have to be measured in all the photographs to be triangulated, and they do not have to be seen in the same photographs. They simply must be seen in at least two of the entire set of photographs so they can be triangulated. Of course, for best results, you should try to see them in at least three or more photographs with good geometry.

Often, to get scale for the measurement, bars with targets located on them at precisely known distances are placed on or around the object. This is often not a trivial matter. Placing the Scale Bars on or near the object without obscuring other targets or being itself obscured can sometimes be difficult. One must also be careful to ensure the scale targets fit onto the photographs since they often are placed around the periphery of the object, or extend outside the boundaries of the object being measured. For the best results, the Scale Bar(s) should be comparable to the size of the object being measured.

Finally, it is very important to realize the Scale Bar(s) must be rigidly attached to the object being measured. That is, a Scale Bar **CANNOT** move relative to the object being measured while the object is being measured. If it does move during this time, the scale measurements will be corrupted, and can't be used. (If the Scale Bar has moved during the measurement, the operator will be able to detect the movement when looking at the measurement results).

How do I compensate for scale changes due to temperature?

If the Scale Bar is made of the same material as the object being measured, applying the scale distance(s) should scale the entire object to the temperature at which the Scale Bar was calibrated. If you want to scale the measurement to another temperature (for example, the ambient temperature at the time of measurement), you can apply the temperature coefficient of the Scale Bar material to the calibrated Scale Bar distance.

If the Scale Bar material is made of a different material than the measured material, then you must apply the temperature coefficient of the Scale Bar material to the calibrated Scale Bar distance to get the true distance at the ambient temperature. Then, you can scale the measured material to any temperature by applying the temperature coefficient of the measured material to the object measurement. However, in both cases, we have assumed the measured object and the Scale Bar are both at the same temperature. If the two have significantly different thermal masses, and the temperature has changed significantly, this assumption will not hold. Fortunately, most measurements are completed so quickly that there will be very little scale change due to temperature.

Can the object move while it is being measured?

Yes, under certain circumstances. The object can move during the measurement as long as it moves as a rigid body. That is, the entire object cannot undergo any deformation when it is moved. Sometimes, this feature of V-STARS can be used to simplify a measurement by moving the object relative to the camera, rather than moving the camera around the object. For, example if an object is mounted on a turntable, the camera can remain stationary and the object can be rotated to several positions with the turntable. Of course, the object must be rigid enough to maintain its shape when being rotated.

If the object is moved, it is important that the Scale Bars be mounted so that they move with the object. If not, the scale measurement is corrupted, and can't be used.

Do I need to use special targets with the system?

The V-STARS system measures special targets made of a thin 0.1mm thick (0.004"), flat, grayish colored retro-reflective material. This material has several advantages over conventional targets (typically a white circle on a black background). The retro-reflective material returns light very efficiently to the light source (they are similar in principle and operation to highway reflectors only much more efficient), and is typically 100 to 1000 times more efficient at returning light than a white target. A relatively low-powered strobe located at the camera lens is used to illuminate the targets, and makes exposure of the targets independent of the ambient light level. This means the object can be photographed in bright light or total darkness, and the target exposure will be the same.

Furthermore, the strobe power is low enough that the strobe does not normally significantly illuminate the object. Thus, the target and object exposure are largely independent with target exposure provided by the strobe, and object exposure provided by the ambient light. By setting the shutter exposure time appropriately, you can expose the object to whatever level you desire. You can make a normal exposure, but usually you will want to underexpose the object significantly to make the target measurement easier and more reliable. Then, you can use the enhancement features available in V-STARS to enhance the object.

What size should the targets be? Can I use different size targets on the same measurement?

The target size depends on the distance from the camera to the object. A rough rule of thumb is to use a target 2 millimeter (0.080") in diameter for every meter of object size. For example, you should use a 6 mm diameter target for a 3 meter object. If necessary, you can use smaller target sizes by increasing the strobe power. For best results, we recommend you try to use the same size targets on a measurement whenever possible. However, target sizes that vary by up to 2 to 1 in size are usually acceptable. See Target Sizes for more information.

How obliquely can I view the targets?

Although retro-reflective targets have several advantages over conventional targets (see question above) they tend to lose their special reflective properties when viewed too obliquely and become dim and unmeasurable. The targets shouldn't be viewed from more than 60 to 65° off-axis for the best results. See Target Angle for more details.

Do I need to provide special lighting for the system? Do I have to consider the lighting where the measurement is being taken?

The strobe system provided with V-STARS is all that is needed to illuminate the targets, and the target exposure is independent of the ambient light. However, you should set the shutter time to underexpose the background. This makes the targets easier to find and measure. See Background Exposure for information on how to expose the background.

Do I need to know where the camera is located when I take a photograph? How steady must the camera be when taking a picture?

You don't have to know where the camera is since V-STARS figures out where the camera is located automatically using GSI's AutoStart procedure. With AutoStart, the operator only has to measure four known points (which can't be collinear) on the image and V-STARS will figure out where the camera is. If you don't have good coordinates for any points on the object (a first time measurement, for example) you can use our AutoBar to get the camera location.

Since the targets are illuminated by a nearly instantaneous flash from the strobe, the camera doesn't have to be steady. This is one of the greatest advantages of photogrammetry over other large-volume, high-accuracy measurement technologies. The camera can be used on scaffolding, lifts, ladders, etc. and can be used in environments where movement or vibration is occurring.

How far away do I have to get from the object to measure it? Where should I locate the camera to get a good measurement?

The distance from the camera to the object is very easy to determine. Simply get back far enough to see the object you want to measure (or the part of the object you want to measure if you are measuring the object in sections). As a rule of thumb, you will need to get the same distance back from the object as the size of the object. For example, you will need to get about ten feet back to measure a ten foot object. See Field of View for more details.

If you haven't done so already, read question 1 above about factors affecting accuracy, especially the fourth factor regarding geometry. Of course, getting good geometry isn't the only consideration when considering where to locate the camera for a good measurement. You must also locate the camera so every target is ultimately seen in at least two (preferably four) photographs with strong geometry. On objects with lots of blockage and or complex surfaces, figuring out where to locate the cameras to get a good measurement can be a challenge.

How can I calibrate the camera and make sure the measurement is accurate?

V-STARS normally automatically calibrates the camera as a byproduct of the measurement in a process called self-calibration. Self-calibration is a very powerful technique that allows the camera to be calibrated at the time of measurement under the conditions that exist at the time of the measurement. In order to self-calibrate, the camera you must take a minimum of six photographs if the object is essentially flat, and a minimum of four photographs if the object isn't flat. If self-calibration can't be used on a particular measurement, pre-calibrated values can be used but accuracies may be somewhat lower. See Self-Calibration for more details.

V-STARS also provides internal estimates of accuracy for each measured point. These internal estimates of accuracy have been extensively compared to external measures of accuracy (repeatability, artifacts, known distances, measurements by other systems, etc.) and have been found to be consistent and reliable. This is important because often in everyday measurements one does not have access to external measures of accuracy and must rely on the internal accuracy estimate as a quality indicator.