CALIBRATION AND ACCURACY ASSESSMENT OF A MULTI-SENSOR ONLINE-PHOTOGRAMMETRIC SYSTEM

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ABSTRACT:

The Programmable Optical Measuring System (POM) was developed for use in non-contact 3D measurement applcations in industrial metrology. The system consists of different digital imaging sensors (high-resolution and standard CCD cameras), a digital rotary table and active light sources. The rotary table enables views from all around the object.
This paper reports on the calibration of the complete system, which includes the determination of exterior orientation as well as interior calibration of cameras and rotary table. The complete set of orientation values is calculated by self-calibrating bundle adjustment.
3D object information is obtained from spatial intersection or 3D element adjustment. The accuracy which can be achieved under practical conditions depends on the quality of calibration, the photogrammetric network configuration, and the quality of image measurement. Accuracy estimation is verified by independent measurements using calibrated reference objects such as scale bars. It is shown that an overall accuracy of 0.1mm for an object size of 2m can be obtained.

Key Words: on-line photogrammetry, digital high-resolution camera, self-calibration, rotary table

1. INTRODUCTION

LEICA's Programmable Optical Measuring System (POM) is a flexible multi-sensor digital photogrammetric system for automated industrial applications. Initially it has been developed for an application in quality assurance in the automobile industry. Due to its open system architecture, it can be adapted to a large variety of applications using appropriate sensor and light configurations in conjunction with a programmable software structure. The system includes algorithms for digital image processing and multi-image 3D-element adjustment. The system concept was first published in 1990 [Luhmann 1990], and a detailed description of the current installation is given in [Loser & Luhmann 1992].

A first prototype version was installed at VOLKSWAGEN for research and development applications (Fig. 1). The initial task was the 3D measurement in a production environment of a large variety of second-source parts of different sizes, shapes and surface materials. VW's own requirements for this system have been changed during the period of development, so that the system is currently used for internal services and investigations. The required accuracy was specified as ±0.1mm (95%) for a distance measurement in a measuring volume of 2.0m x 2.0m x 0.6m.

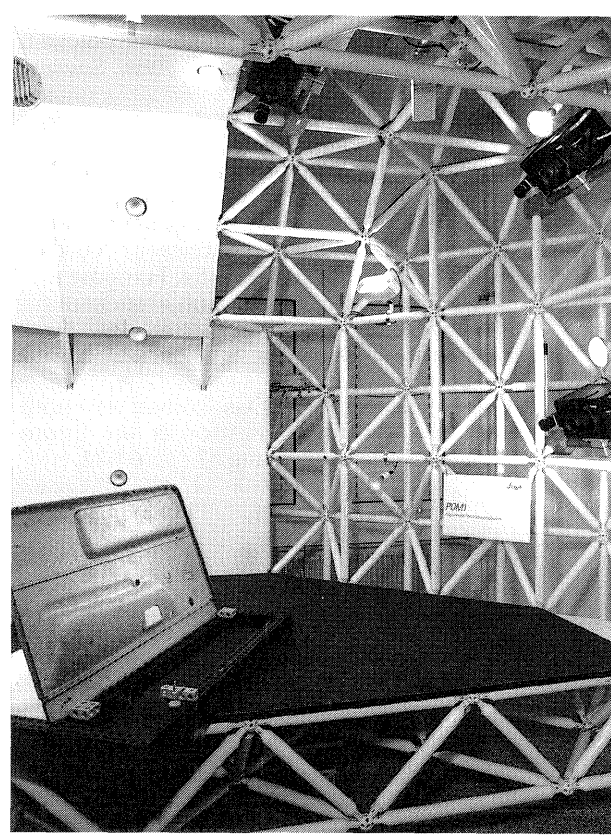


Fig. 1. POM prototype,Volkswagen version

1.1 Hardware Setup

The VW system consists of three Rollei reseau-scanning cameras (RSC) each equipped with a standard CCD array sensor which can be moved within the image space of the camera (scanning principle) [Riechmann 1990]. In addition there are three wide-angle CCD cameras for overview purposes. The RSC sensors are mounted in a vertical plane together with a digital rotary table, which carries a flexible part-mounting system. All devices are fixed in a very stable steel frame. A set of over 30 light sources is integrated in the measuring cell (Fig. 2).

Sensors are individually controlled by a UNIX workstation (Sun SparcStation II) which is linked to a VME bus containing image processing hardware and sensor control devices.

1.2 Software Modules

The system is controlled by the Leica POM software package which integrates a number of independent processes and routines such as graphical user-interface, database management, program interpreter, photogrammetric and mathematical functions, sensor control and image processing. The overall system control is performed by an interpreter module which operates with a special programming language.

The interpreter reads a number of programming statements and is responsible for the synchronisation of all processes. It checks and executes the commands, calls required functions and stores information within a network database. The programming sequences can be generated by the user-interface, loaded from file or entered by the operator.

The photogrammetric routines include the CAP bundle adjustment program with self-calibration [Hinsken 1989], spatial intersection, resection, 3D coordinate transformation and a 3D element matching program [Andresen & Helsch 1990]. This element matching method is based on a grey level contour extraction in two or more images. In each image a list of non-corresponding edge points is generated which can then be matched to the 3D parameters of regular elements such as circles, cylinders, straight lines or spheres. This powerful algorithm is most often used for the current application since most of the objects can be completely described by a combination of these elements.

The input parameters of each observation (sensor position, illumination, area-of-interest etc) and the measurement results (image coordinates, 3D coordinates) are stored in the database and can be recalled at any time. This information is used to generate an automatic measurement program for batch testing which repeats the measurement performed manually during teach-in. The database enables SQL programming so that individual input and output formats of measurement results can be created (e.g. CAD or CAQ interfaces).

1.3 Technical Specifications

Measuring volume:	2.0m x 2.0m x 0.6m
Measured elements:	points (targets), circle, cylinder, line, sphere
Measuring speed:	approx. 30 sec per 3D element in sequential mode
Metric cameras:	3 Rollei RSC, image format: 50mm x 50mm
Overview cameras:	3 standard CCD video cameras
Rotary table:	Fribosa, accuracy: 5"
Sigma 0 of bundle:	1.5μm
RMS of object points:	< 0.04mm
Distance error:	< 0.1mm

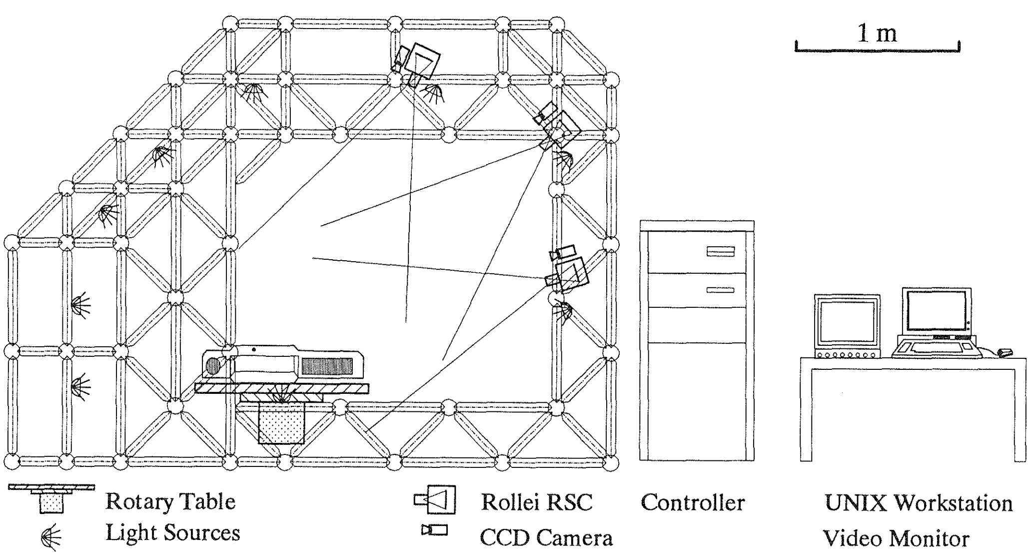


Fig. 2. POM hardware configuration of VW version

2. CALIBRATION AND ORIENTATION

The system calibration of POM provides the complete calculation of interior and exterior orientation of the RSC sensors. The spatial position of the axis of the rotary table within the machine coordinate system is also determined.

2.1 Camera Calibration

The determination of the interior orientation of the cameras can be performed by a suitable photogrammetric network using a testfield with sufficient point density. In this case the 3D coordinates of the testfield must not be known.

The initial approach for camera calibration was as follow: Each camera was calibrated in the laboratory (IPB) outside the POM system. A suitable set of 7 images was taken of a testfield which carried 35 spatially distributed targets. After self-calibrating bundle adjustment the parameters of interior orientation were obtained with standard deviations less than 5µm. The mean accuracy of image measurement was about 1µm.

One shortcoming of this calibration procedure is that the cameras have to be dismounted from the measuring system if a new calibration is required. This situation occurs if, for instance, either a complete system re-calibration is necessary, a camera has to be replaced for service purposes or if the environmental conditions have been changed significantly. Therefore we have developed a method for complete system calibration *in situ*.

2.2 Complete System Calibration

The new method uses a calibration frame with 16 spatially distributed retro-reflective targets which is fixed on the part-mounting system (Fig. 3). In conjunction with 8 additional points which are located on the mounting base of the rotary table, a pyramid-shaped testfield with a total of 24 targets has been built. This object covers a large part of the measuring volume of the system.

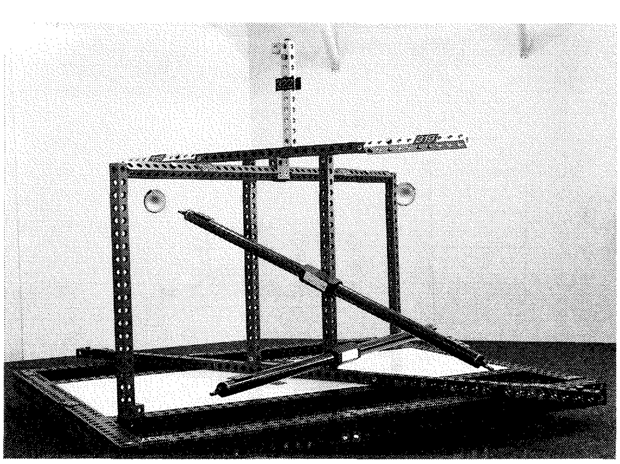


Fig. 3. Testfield for complete system calibration

The approximate 3D coordinates of the control points have to be known only to a few centimeters. In order to improve the determination of camera parameters, additional precisely known distances, in different coordinate directions, have to be introduced [Wester-Ebbinghaus 1985]. These distances serve also to determine the global system scale.

The turntable is rotated to 8 different positions in angular increment of approximately 45 degrees. In each position the testfield is recorded by all cameras, leading to an photogrammetric net of 24 images (see Fig. 4).

After bundle adjustment all parameters of interior orientation are given with standard deviations better than 10µm, whereby the mean error (sigma 0) of adjustment is equal to 1.5µm. The unknown coordinates of the testfield are calculated with an accuracy of < 0.04mm. The coordinates of these points are used to fix the machine coordinate system in which the exterior orientation of the cameras and the rotary table will be determined.

Using the calibrated values of interior orientation, as well as the adjusted target coordinates in the zero position (reference position) of the rotary table, a second bundle adjustment is computed. In this step, independent coordinates of target points are calculated for the other seven positions. As a result, the exterior orientation of the three cameras in the reference position are obtained. In addition there are eight sets of 3D coordinates which can then be transformed on to each other by a suitable spatial coordinate transformation. The parameters of this transformation define the position and orientation of the axis of the rotary table within the machine coordinate system.

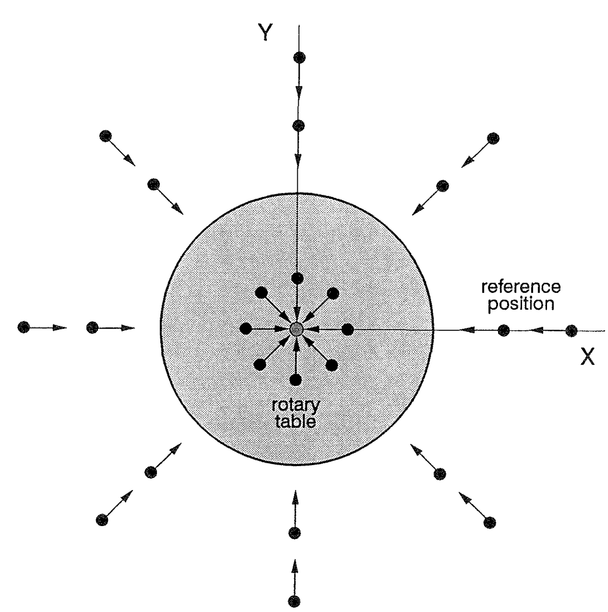


Fig. 4. Image network of system calibration

2.3 Re-Orientation of the System

Due to the internal construction of the RSC sensors, a complete calibration of the interior orientation does not have to be done very often. In order to avoid effects from environmental influences (temperature changes, mechanical deformations) and to maintain a stable system geometry, it is possible to determine only the exterior orientation of the cameras within certain time periods. This re-orientation can be performed with little effort using only a few well-known control points.

While the complete system calibration initially requires operator assistance (investigation of bundle results, blunder detection etc), the re-orientation process runs automatically. This procedure is used to check system geometry and, if necessary, to improve orientation parameters.

2.4 Point Measurement

The measurement of 3D points and elements is performed by spatial intersection and object-based element matching respectively [Loser & Luhmann 1992]. For a measurement a minimum of two images has to be taken of the object element. With POM it is possible to process an unlimited number of images for one object element using any combination of different camera and/or table rotations. It is even possible to use only one camera with two or more rotations in order to acquire images from different spatial directions.

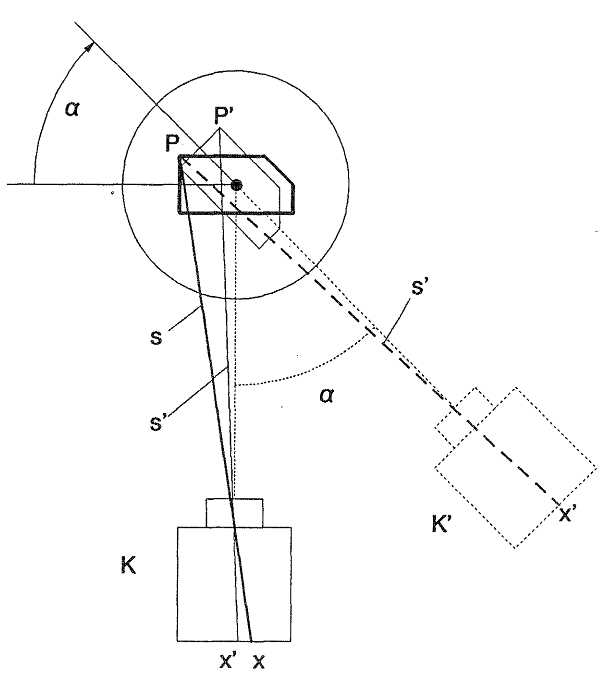


Fig. 5. Use of turn-table rotations
*For each camera the system calculates a virtual position in space **K'** (dashed) which depends on the rotation angle **α** of the rotary table. An object point **P** is then located at **P'** and is projected into the image at position **x'**. With this method the cameras apparently move round the object, enabling 3D measurements with only one camera in different rotations of the turntable.*

The measured angle of the rotary table is corrected by an internal correction functions which takes the adjusted rotary positions of the second bundle adjustment into account. For each rotation the system computes a set of virtual camera positions with new exterior orientations (Fig.5). With this method, an object point which is measured in different rotations with one camera appears exactly as it would if measured by the same camera, virtually moved around the object (virtual position K').

This procedure offers great flexibility for the photogrammetric measurement of complex shapes where, for instance, occlusions require a large number of different camera stations.

3. Investigation of Accuracy

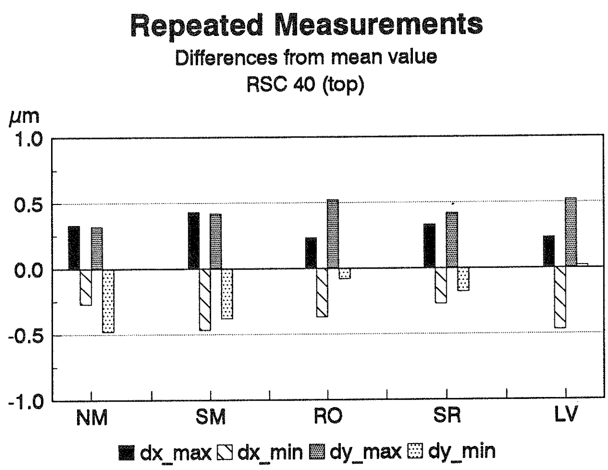
In order to investigate system accuracy under practical conditions, additional test measurements have been carried out. On the one hand, the inner accuracy of the sensors has been tested by a large number of repeated measurements. On the other hand, calibrated scale bars have been measured in different positions within the measuring volume using different combinations of sensors and rotary positions.

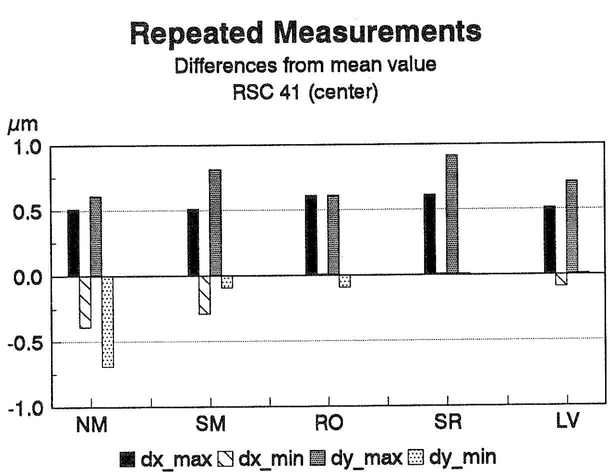
3.1 Repeated Measurements

The image coordinates of a retro-reflective target have been measured with the target located in 1m eccentrically from the rotary axis. In order to investigate the stability of the RSC and the potential influence of the CCD sensor movement, a total of 1100 measurements have been done with each camera under the following different conditions:

NM	300 measurements without sensor movement
SM	300 measurements, moving the CCD sensor to an arbitrary position in all directions (x, y, focus) and returning to the original position
RO	100 measurements, leaving the CCD sensor in constant position but rotating the turntable by about 90 degrees and returning to the original position
SR	100 measurements, moving both sensor and rotary table according to SM and RO
LV	300 measurement with constant sensor positions, with temporary variation of light intensity

Fig. 6 shows the measurement results. For each camera an average of the 1100 observations has been calculated, as well as the resulting deviation of each measurement value. The illustrations show the maximum differences between single measurement values and average values under different measuring conditions, tabulated separately in x and y. It can be proven that all deviations are under 0.9µm in image space, which is comparable to the internal accuracy of the RSC according to calibration results. With respect to a mean image scale of 1:30 an accuracy of repeated measurements of less than 30µm in object space is achieved.





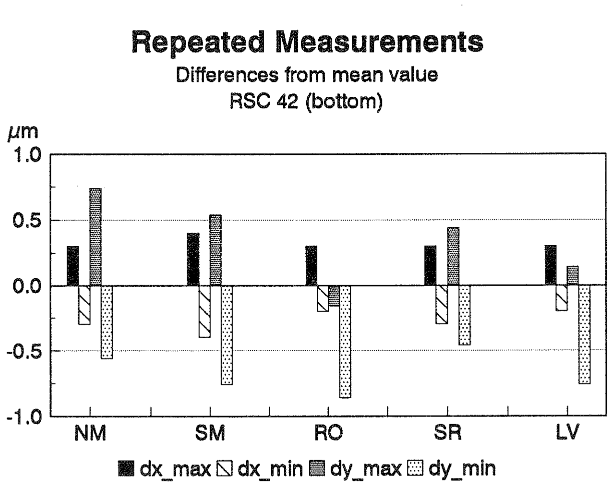


Fig. 6. Repeated measurements: image coordinates
NM: no sensor movement; SM: with sensor movement; RO: with rotary movement; SR: sensor and rotary movement; LV: light variations

3.2 Distance Measurements

In this part of the investigation the system accuracy for distance measurements shall be verified. For this purpose different distances (approximately 700mm and 1400mm) have been positioned at various locations within the measuring volume, oriented in different spatial directions. The nominal distances were measured using a first-order coordinate measurement machine (CMM). The distance bars are made of aluminium and cylindrical, retro-reflective targets are used for measurement.

The measurements are performed using a sub-pixel algorithm for the precise detection of ellipse-shaped targets [Zhou 1986]. The measured image coordinates are processed by an spatial intersection program which determines the 3D coordinates of the target.

The distance points have been measured in different configurations:

NR	measurements with different cameras, without rotations
WR	measurements with one camera and various rotations
CO	measurements with combinations of cameras and rotations
2 obs	measurements with 2 images
3 obs	measurements with 3 images
> 3 obs	measurements with more than 3 images

The number of observations per point varies between 2 and 9 images. Fig. 7 shows a few results from different points of view. The first three clusters show the dependency of accuracy on the number of observations. The last three clusters show the results of different configurations. In each cluster the mean deviation is displayed, as well as the minimum and maximum deviations. Deviations are computed from the calculated distance between measured points and the nominal value measured by the CMM.

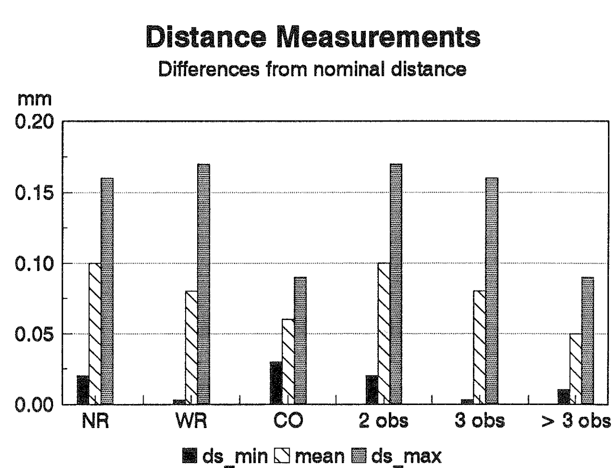


Fig. 7. Distance measurements
NR: different cameras, no rotation; WR: one camera and rotations; CO: camera/rotary combinations; 2 obs: two images per point; 3 obs: three images per point; >3 obs: more than three images

These results make clear that the maximum deviations are always less than 0.1mm if more than three observations are used for 3D point measurement. If the minimum number of two images is used for point measurement, the maximum differences are always less than 0.2mm.

A similar interpretation of the results can be made for the effect of different imaging configurations. Optimal ray intersection angles are obtained if different cameras are combined with different rotations. It is obvious that a reliable and accurate point determination depends on the intersection angle in space. For combined measurement sufficient results can be obtained even with 2 or 3 images. Using other configurations the maximum deviations are again less than 0.2mm.

The investigation of distance accuracy show that higher accuracies (< 0.1mm) can be achieved if suitable configurations of sensors and rotations are used. If less accuracy is required (< 0.2mm), one can work with the minimum number of images using 2 or 3 observations.

4. SUMMARY

The prototype installation of the Programmable Optical Measuring System (POM) is equipped with three Rollei RSC digital high-resolution cameras and a digital rotary table. The calibration of the system and its accuracy in this configuration were investigated.

System calibration and orientation is performed using a non-calibrated testfield with retro-reflective targets combined with calibrated spatial distances within the measuring volume. With a set of 24 images the complete calibration of interior and exterior orientation of the cameras and the rotary table is provided. The self-calibrating bundle adjustment leads to an RMS (sigma 0) of 1.5µm, and an accuracy of 0.04mm in object space.

Repeated measurements of targets have been carried out in order to judge the inner accuracy and stability of the RSC sensors. These tests have shown that a high accuracy of < 1.0µm in image space is permanently achievable. This result is even confirmed if the rotary table is involved. This inner accuracy leads to an accuracy of < 30µm in object space.

The measurements of calibrated distances show that the final accuracy of the system is less than the calibration results from bundle adjustment if a spatial intersection is applied under practical conditions. The specified accuracy of 0.1mm for a distance measurement can be obtained if a larger number of images (> 3) or a sufficient image configuration (different cameras and turntable rotations) is used. With the minimum number of observations (2-3 images) the resulting accuracy is always better than 0.2mm.

The results from calibration process are better than those from practical measurements, showing that there is still a possibility of improving system accuracy. Additional effects (temperature changes, longterm characteristics, different algorithms, influences of light) will be investigated in the near future.

It has been shown that an accuracy of < 0.1mm in an object space of about 2.0m x 2.0m x 0.6m can be obtained. The relative system accuracy ranges between 1:20,000 (for spatial intersection) and 1:40,000 (using bundle adjustment) of object size.

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