GEODETIC SURVEYING
(continued)

7. New Techniques in Geodetic Surveying

The traditional methods of geodetic control, namely angular, edm and astronomic measurements, can be replaced by the following new methods. A first method, using Doppler Receiver,is suitable for primary and may be secondary control and is already widely used. A second method, suitable for secondary and tertiary control as well as for a lot of other survey tasks is based on a Inertial Surveying System and is not yet in wide use. Although both methods could provide full geodetic control of smaller or large countries, in general they will have to be supplemented by the traditional methods.

7.1 Doppler Receiver of Satellite Signals and their Use

Portable Doppler Receivers consist of an antenna, which can be set-up over a survey mark on its tripod and the actual receiver with recording facilities (e.g. cassette tape) and power supply by its side. Signals of several passes of a special type of satellite are recorded and these allow the subsequent computation of the station coordinates.

7.11 History and Introduction

The development of the Doppler-Measuring-System started about 1938, when this technique was used by Germans for rocket orbit tracking. Further developments were executed in the U.S.A., finally by the Applied Physics Laboratory (APL) of the John Hopkins University in Washington D.C. The latter used the principle to determine the orbit data of the first (Russian) Satellite in 1957, with the use of the radio signals transmitted by the satellite.

APL is the author of the U.S. Navy Navigation Satellite System (N.N.S.S.), used at present by the U.S. Navy. Ships and submarines can determine their position anywhere in the world and at any time to an accuracy between ±50 m and ±100 m. (Raw) satellite orbit data are stored in the satellite and transmitted periodically. Doppler receivers on the ships receive the satellite signals and feed them (on line) into an on-board-computer, which calculates the position. Five to six satellites (NAVSAT) in polar orbits and at an altitude of about 1100 km provide the world wide navigational cover (see figure 1). These satellites are tracked by a basic network of 13 tracking stations (TRANET = TRAcking NETwork System) which are distributed all over the world in order to determine the actual precise satellite ephemeris (±3 m) and to predict the future orbits, which form the broadcast satellite ephemeris or the raw ephemeris (±25 m). The latter is transmitted to the satellites periodically for storage. In this first

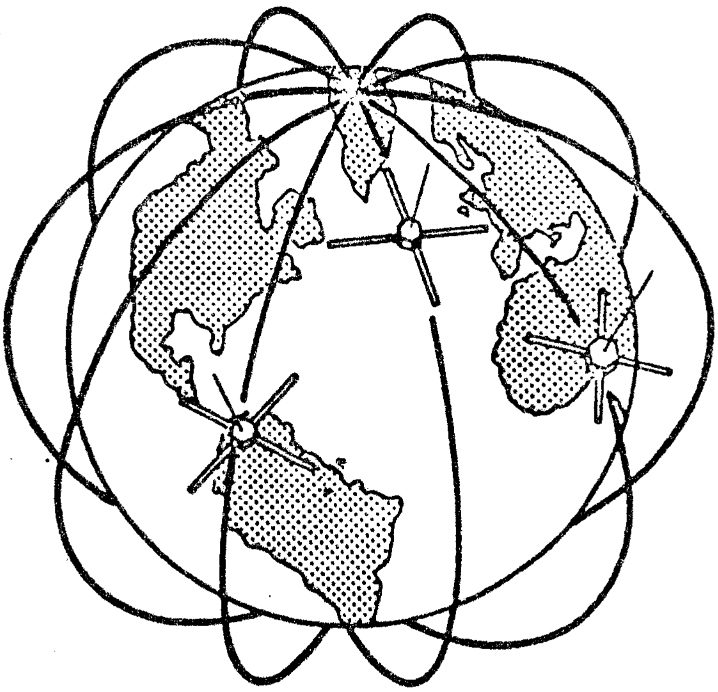

Figure 1: Worldwide NAVSAT cover

step, unknown satellite orbits are computed from known coordinates of ground (TRANET) stations, using a sophisticated model of the earth's gravitational field. A second step provides unknown coordinates of ground stations from, now known, time dependent satellite positions. This second step is very interesting for surveying, especially after the NNSS became "generally" available to non-military users in 1967 and after portable receivers became available in 1971 (Geoceiver).

7.12 Construction and Principle

The most compact Doppler Receivers available to surveyors in 1976 consist of two components for transport (carrying case with receiver and folded antenna and a 12 Volt Battery) and three for operation (Receiver, Antenna, Battery). The weight of receiver and antenna is about 20 kg (JMR-1). The antenna is connected to the receiver by a cable during operation. The instrument has only to be set up and switched on. It automatically searches for the satellite signals, locks onto them, takes the measurements and records them on magnetic tape (cassettes). Instruments of the first generation are:

Geoceiver (GEOdetic Doppler ReCEIVER) by Magnavox (USA)
ITT 5500 by International Telegraph and Telephone (USA)

Instruments of the second generation:

Magnavox 702 by Magnavox (U.S.A.)
JMR-1 by JMR - Instruments Inc. (USA)
Marconi CMA-722 by Marconi (Canada)

One JMR-1 instrument costs 1976 \$43000 to give an idea about prices.

We know from physics, that the frequency of the satellite signal recorded by the receiver will change with time due to the relative motion between satellite and ground station. The frequency variation can be detected by the receiver, when the received signal is compared with an internal frequency standard. The integral of the frequency variation over a certain time period is proportional to the change in distance between satellite and ground station. One obtains the differences of the distances to the satellite positions at the beginning and at the end of the time interval by the summation of the frequency variation with time between two satellite time pulses (e.g. every 4.6 sec).

The locus of points with equal distance differences to two points of the satellite orbit is a hyperboloid of revolution. The coordinates of the doppler receiver antenna can be computed by least-squares as an intersection of numerous hyperboloids of revolution, if the measurement is repeated during several time intervals. (A satellite pass takes a maximum of 18 minutes, so that up to a total of two hundred and thirty five 4.6 sec intervals may be obtained). The computations lead to the absolute position of the receiver antenna with respect to a coordinate system with an origin at the earth's centre of mass, in which the satellite orbit data are given.

The geometry of the determination of Doppler Receiver positions is somewhat similar to well known navigation systems as e.g. DECCA and TORAN, where the (two-dimensional) position is obtained from intersection of two hyperbolae. In the case of Doppler Receiver however, we face a three-dimensional problem with large sets of data. Figure 2 depicts a very simple case, where the two satellite positions S_1 , S_2 and the Doppler Receiver are exactly in the X, Z plane of a local coordinate system with the origin at the midpoint between S_1 and S_2. Such local systems would have to be transformed into a common system, for an adjustment of all the numerous Doppler measurements on a station. Figure 2 gives all the same an introduction into the mathematics of the problem.

$$\frac{Z^2}{c^2} - \frac{X^2}{a^2} - \frac{Y^2}{a^2} = 1 \qquad \text{Hyperboloid of revolution}$$

S_1, S_2	Satellites position at time t_1, t_2
d_1, d_2	Distances, Satellite (S) - Receiver(R), at time t_1, t_2
e	Linear eccentricity

$e^2 = a^2 + c^2$ (definition)

$d_1 - d_2 = 2c$ (definition)

Assuming R in x, z plane: $y = 0$

$2e$ = distance between two satellite positions (known) = $\overline{S_1S_2}$

$2c$ = measured by Doppler measurements

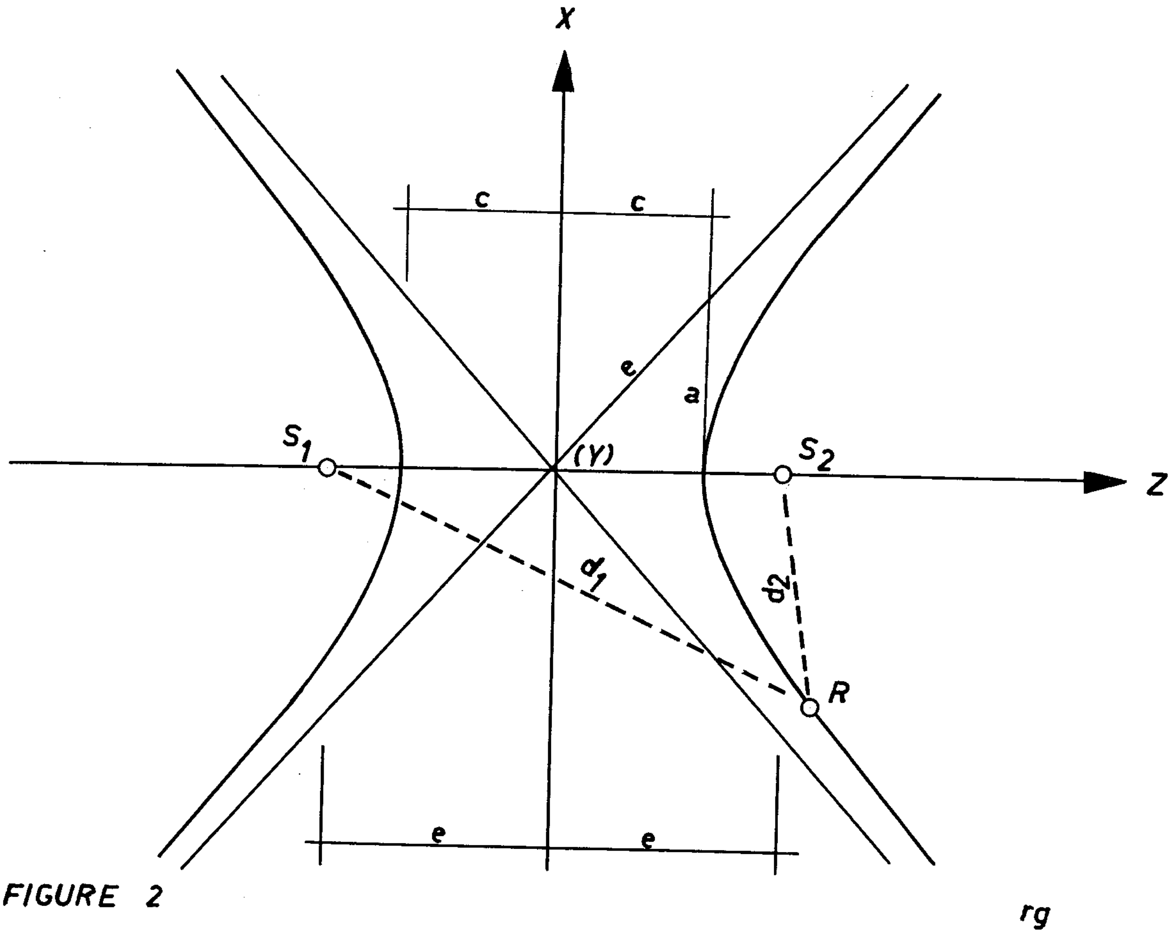

FIGURE 2

$$\frac{Z^2}{\left(\frac{d_1-d_2}{2}\right)^2} - \frac{X^2}{\left(\frac{\overline{S_1S_2}}{2}\right)^2 - \left(\frac{d_1-d_2}{2}\right)^2} = 1$$

(Equation for position coordinates of Receiver)

It can be seen from the above equation, that at least three Doppler measurements have to be made to determine all three coordinates X, Y, Z of a receiver station.

Different methods can be employed with doppler receivers for position fixing. These methods differ only in fieldwork program and computation but not in the equipment used.

(1) Single Point Positioning

All Doppler Receiver Stations are computed independently, using precise satellite ephemeris for geodetic purposes. The main advantage of this method is the fact, that only one instrument is needed.

(2) Translocation

This concept is used to determine the relative position of two stations. Observations are done simultaneously with two or more instruments, recording the same satellite passes on all stations.

The station coordinates are computed as in (1), but the coordinate differences between stations will be more accurate than the absolute station coordinates, because systematic errors in orbit parameters are cancelled to a certain degree. Improvements are possible by Orbit Relaxation (determination of some orbit parameters).

(3) Short Arc

Several Doppler Receivers are required for this solution. Some instruments are set-up on known stations, other on unknown stations. Simultaneous observations of identical satellite passes are executed. In a least square solution, the unknown ground station coordinates as well as the parameters of the satellite orbits of all used satellite passes are determined.

(4) Long Arc

Again, several known and unknown stations are occupied by Doppler Receivers. No restrictions are made about identical satellite passes and position of stations. Satellite orbits have to be computed world wide which causes a decrease in precision of orbit parameters.

Methods (3) and especially (4) are scientific approaches and can be used also for other purposes.

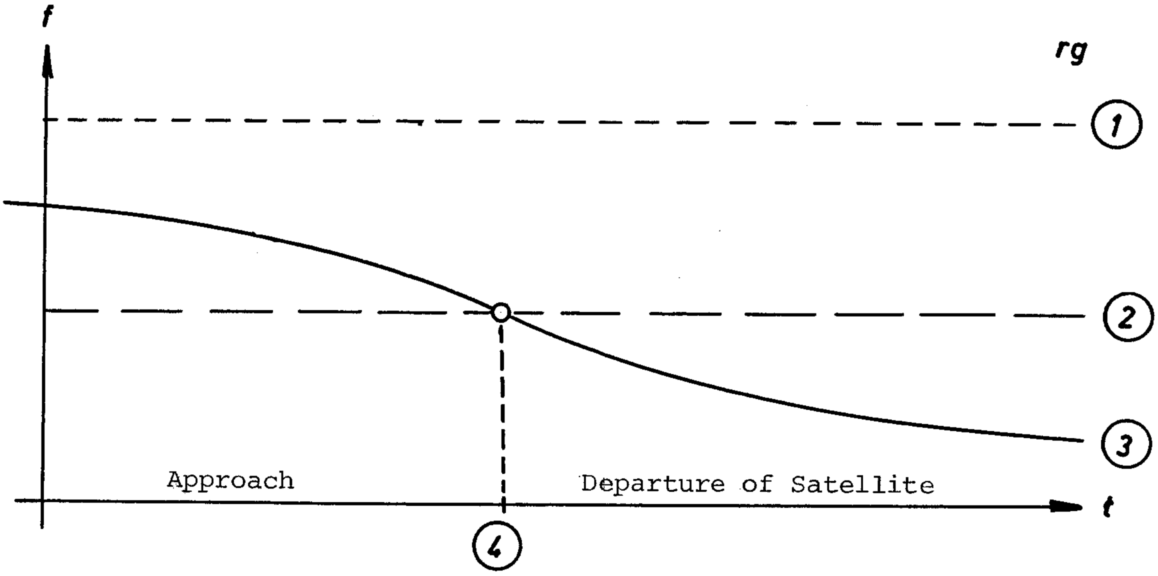

Figure 3: f = frequency, t = time. 1 = Constant Doppler Receiver reference frequency. 2 = Constant frequency emitted by the satellite. 3 = Doppler shifted satellite frequency received by Doppler receiver. 4 = Time of closest approach of satellite with respect to Doppler receiver.

7.13 Observations and Processing

The navigation satellites (NAVSAT) transmit information and 2-minute time pulses on two phase locked frequencies (400 MHz, 150 MHz), thus providing a means of eliminating ionospheric refraction from the data. Because of the relative movement of the satellite with respect to the receiver, the emitted constant frequency is Doppler shifted upon arrival at the receiver to a continuously variable frequency. See figure 3. The latter is mixed with a constant reference frequency in the receiver and the number of cycles of the beat frequency (Doppler counts) are counted in the receiver for every 4.6 second time interval. The integrated Doppler counts are stored for the high and the low frequency, together with date, time, satellite number, number of passes, ambient temperature and pressure on the cassette for laterprocessing. Final computations are done later, after the precise satellite ephemeris is released, if the latter is necessary. Otherwise, the broadcast ephemeris can be used as approximate values for short and long are solutions, and even for the translocation mode improved by orbit relaxation. All methods of processing using broadcast (raw) ephemeris are much faster, being independent of the release of the precise ephemeris. The latter is only available for one or two satellites and is subject to a special agreement with the U.S. Department of Defence.

About 2-5 days of measurement are needed for geodetic purposes, and should include a total of 25 to 50 acceptable passes.

7.14 Applications and Experiences

Doppler Satellite Receiver open new possibilities in Geodetic Surveying:

(1) Relative point positioning on existing control networks for the purpose of deriving datum transformations between independent networks and/or readjusting and possibly improving the accuracy of existing control networks.

(2) Establishment of coordinates relative to an earth-centred coordinate system for providing worldwide ties between datums.

(3) Point positioning in remote areas lacking any control for future control extensions by conventional methods.

(4) Point positioning in support of mapping, particularly in remote areas.

(5) Point positioning on existing astronomic positions for obtaining deflections of the vertical.

(6) Point positioning on existing vertical control to determine the height of the geoid directly. Coordinates of points are computed first in a earth centred coordinate system, as described earlier. They can be transformed later into an existing datum based on a specified spheroid. Spheroidal heights are obtained and can be compared with orthometric heights from levelling or trigonometric levelling. The difference is the height of the geoid.

(7) Point positioning in support of geophysical surveys as well as oil drillings in remote areas and also off-shore oil wells.

(8) Determination of large soil and ice movements.

(Above list according to E.H. Rutscheidt)

Early observations in the USA in 1971 and 1972 with first generation receivers proved the high accuracy of this method as compared with high precision traverses (AGA Geodimeter 8). Standard deviations of the determined longitudes, latitudes and heights were between ±0.75 m and ±1.6 m, depending on the processing mode and the number of field days. The internal precision of a single pass solution is now better than ±0.1 m, according to V. Ashkenazi. The use of several satellites and/or passes increases naturally the accuracy of position fixing, although the precision may be less than the ±0.1 m mentioned above due to systematic errors in orbit parameters. Instrumental errors were found with early instruments as for example additional constants in the height information and multipath effects caused by nearby trees. Field calibrations are therefore advisable.

In Australia, four JMR-1 receivers are used by NATMAP since 1975 for point positioning in the primary control. Short arc methods are expected to give finally a relative accuracy (between points) of between ±0.2 and ±0.4 m. Geoceivers are used by the Royal Australian Survey Corps in the point positioning mode using precise ephemeries.

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7.2 Inertial Surveying Systems

Inertial Surveying Systems are still in the stage of 1st generation instruments and have been available since about 1975. They are not yet portable and have to be built in station wagons or helicopters. The system consists of five different components (metal cases) and provides longitudes, latitudes, heights, azimuths, deflection of the vertical and possibly gravity and gravity anomalies with high accuracy.

7.21 History and Introduction

Inertial Navigation Systems are in wide use with aircrafts and missiles since several years, providing continuous information as to direction and position. Litton Systems Inc(USA) built in 1972 a first prototype of a "Position and Azimuth Determining System" (PADS) for the US Army (Artillery). A highly refined version of the PADS gave later the "Inertial Positioning System" (IPS) with outputs of latitude, longitude, elevation, gravity anomaly and deflection of vertical. The commercial version of the IPS, called "Auto-Surveyor" by the manufacturer and "Inertial Surveying System" (ISS) by others does have all outputs of the IPS apart from gravity. A few "Auto-Surveyors" are in operation and give accuracies in coordinates and elevation of about ±1 m (standard deviation) and deflections of the vertical to about ±2". Inertial Surveying systems are highly efficient because they are all-weather and day-or-night systems with no line-of-sight constraints and because their output includes the whole package of geodetic measurements. There is no longer any need for separate and costly horizontal, vertical, astronomic and gravity field work. All these can be done in one operation and with the speed of a vehicle or a helicopter. The only restriction is that the survey mark is accessable by road or by air and that the vehicle or helicopter can be centred over it. The high cost of the system, about $200,000, is compensated by the high efficiency.

7.22 Construction

The system has five components. The Inertial Measuring Unit contains basically a precise inertial platform which is stabilized in space by two gyroscopes with perpendicular axis. Three very sensitive accelerometer (one each for North, East and Vertical) are also fixed on this platform. The sensitivity of these accelerometers lies between 1 mgal and 10 mgal. The On-Board-Computer has a large storing capacity and has a double function of controlling the system and of calculating the results. Data of up to thirty new stations can be stored and adjusted. The high performance of the system is based on a statistical process called Kalman filtering or error budgeting. It compares actual propagation of errors with a priori data of 40 major systematic errors (and their standard deviations). It also updates the a priori knowledge and the error budget, if necessary, thus providing more or less error free survey data. A new adjustment or smoothing of all survey data is executed after the input of coordinates of a known closing point. The Display and Command Unit (near the driver or pilot) serves as input/output unit for data, initializes and controls the system and monitors the status and quality of each survey. The Cassette-Recorder stores the measurement data calculated by the computer and records the operational condition of the entire system every two seconds. The cassette is later read and processed on a desk-top computer. The Power Supply supplies a 24-Volt current to the system.

7.23 Operation

The method of operation shall be explained for a normal mission with a vehicle operated system. We assume that the starting point of a mission shall be in relative proximity of the survey office. The system is turned on about one hour before departure time to allow for the automatic alignment. The computer calculates and checks all the biases, levels the platform into the local horizon and aligns the north axis into the meridian. The observer will then drive to the starting point of the Inertial Surveying System "traverse", where the vehicle has to be centred over the survey mark (not without problems!). A zero velocity updating (ZUPT) is then initiated. This procedure will be described later. Coordinates and elevation of the starting point are fed into the system. The computer calculates then the exact distance travelled in E-W as well as in N-S direction and the change in height every 17 ms during the subsequent run. All three informations are obtained by a double integration of measured accelerations with time, followed by a reduction to sea level for the horizontal components. The computer also calculates the necessary curvature of the reference spheroid (e.g. Australian National Spheroid) and commands the platform gimbal torques to torque the platform so that the horizontal plane remains horizontal (more or less tangential to the geoid) and that the North gyroscope axis remains pointed towards the North. The effects of the earth's rotation are also compensated for.

The vehicle must be stopped every 4 to 6 minutes for twenty seconds on the run between any two survey marks. This provides a possibility of calibration for the accelerometers, which should read zero if the vehicle is not moving (N-S, E-W accelerometers only). This step is therefore called ZUPT for Zero Velocity Updating. The Platform is relevelled automatically into a perpendicular plane to the direction of local gravity. The amount of torque used for this relevelling describes the change in the direction of the deviation of the vertical (plus uncompensated gyroscope drifts in the horizon) since the last stop. The vertical accelerometer measures naturally the local gravity during the stop. After arriving on a survey mark of unknown coordinates etc., a ZUPT process is executed. The storage of all station data (coordinates, elevation, components of the deflection of the vertical and, if the IPS is used, gravity and gravity anomalies) is then initiated or the data are called to the display and command unit and booked in the usual way.

The system provides further the facility of an optical azimuth output through a built-in porro-prism-system. A theodolite is simply set up behind the car and is pointed to the prism which also has to be orientated. The angle between the prism and any target is measured and then entered into the key board. The computer calculates the azimuth between theodolite and target. The coordinates of the theodolite can also be obtained if the distance between prism and theodolite is measured and fed into the system. A similar procedure can be used to align the inertial system with a known azimuth on the starting point of a mission. Transferred azimuths have a maximum accuracy of ±20" (standard deviation).

On the endpoint of a mission, the system is again updated (ZUPT) and the newly calculated station data are stored. The known coordinates and the known elevation are entered into the system and an "adjustment" is initiated. The previous error budgeting is updated in this smoothing process according to the misclosures of the mission and smoothed adjusted data of intermediate stations of the mission are computed.

7.24 Test Measurements and Experiences

Several tests were carried out and published by the manufacturer, Litton Systems Inc., USA. Standard deviations of ±0.3 m in longitude and latitude and ±0.2 m in elevation were obtained in missions up to 9 km. As ISS levelling test over half a mile gave a standard deviation of ±8 mm in height.

A more comprehensive study was executed by the Research and Geodesy Section of the Geodetic Survey of Canada (Department of Energy, Mines and Resources EMR), being one owner of such a system, in 1975. The ISS was tested in a mountainous area on lines with large differences in height and large deflections of the vertical. A "Valley Line" was 34 km long with 300 m height difference, a "Mountain Line" was 41 km long and went over 2400 m vertically. Numerous intermediate stations were repeatedly surveyed in these two closed traverses and gave standard deviations of ±0.3 to ±0.5 m in longitude and latitude, ±0.2 m to ±0.3 m in elevation and ±1.4" in the components of the deflection of the vertical. All standard deviations are valid for one single mission of a closed traverse (after adjustment) and are computed from deviations between measured and given values. Such good results were obtained by a good preliminary adjustment of the instrument, a well trained team, careful driving and stopping of the vehicle (thus avoiding potholes), an improved centring system, an improved mathematical model (conversion of astronomic to geodetic azimuth), a revised adjustment procedure and good test networks for calibration.

This Inertial Surveying System which was improved by the user to give these high accuracies in mountainous areas, was not as easy to handle as expected. But it can be expected that better models will be produced and will be easier to handle. These Inertial Surveying Systems, in a refined and may be smaller form, will have a great impact on all branches of surveying in future. The feasibility of their use in large survey projects should therefore always be investigated.

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