DIGITAL ZENITH CAMERA

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The studies of subsurface mass distribution is a major task for many branches of science and technologies – geology, seismology, volcanology, geophysics, geodesy and various other applications. Most often, for studies of subsurface mass distribution, gravity force measurements are applied using gravity measuring devices: absolute and/or relative gravimeters. Extreme concentrations of mass in the subsurface are characterised as gravity anomalies. Scattered sites of ground-based gravity measurements are distributed over most continents. Spaceborne and airborne gravity measurements also cover large areas, especially those inaccessible to the most accurate ground-based measurements. Gravimetric measurements determine the magnitude of gravity force at the measurement site. The gravity field and anomalous sites are determined by interpolation in the area of the measurements.

Additional information can be obtained by using the vertical deflection measurements by the digital zenith cameras (DZC). The DZC measures the direction of the vector of gravity. Distinctive mass distribution forms deep below the ground (funnel, cavity, various mass concentrations) and can be detected by developing densified network of DZC measurement points in the area of specific interest.

Efficient portable digital zenith camera (accuracy ~0.1 arcsec) was developed at the Institute of Geodesy and Geoinformatics (GGI) of the University of Latvia by a team that previously specialised in developing software and hardware for astrogeodetic cameras and satellite laser ranging devices. The innovation of Latvian DZC development is

Fig. 1.
Digital zenith cameras for observations at night

Fig. 2.
Two digital zenith cameras are exposed

based on recent achievements in various sciences – fast and accurate digital imaging technology, extremely accurate super-large reference star coordinate catalogues, very sensitive electronic tilt meter technologies, available high-precision Earth rotation parameters, and GNSS-based high-precision positioning and timing capabilities.

In GGI, development of the first model of the zenith camera and subsequent field tests began in 2009. However, the required measurement accuracy was achieved only in 2016. For several years, the last models were used for regular measurements, accompanied by regular work on improvements in software and hardware. Currently, several high-accuracy DZC instruments have been manufactured (Figs. 1–2).

The use of DZC offers the possibility of finding more anomalous sites without the need for accurate elevation values in distinction of gravimeters. Recently, DZC was purchased by Louisiana State University through a worldwide tender. Currently, this instrument is used in the USA for gravity field measurements in conjunction with absolute gravimeter.

A digital zenith camera compares the spatial direction of the local gravitational field normal (plumb line, measured with a very sensitive tiltmeter) and the direction to the geometric Earth ellipsoid zenith,

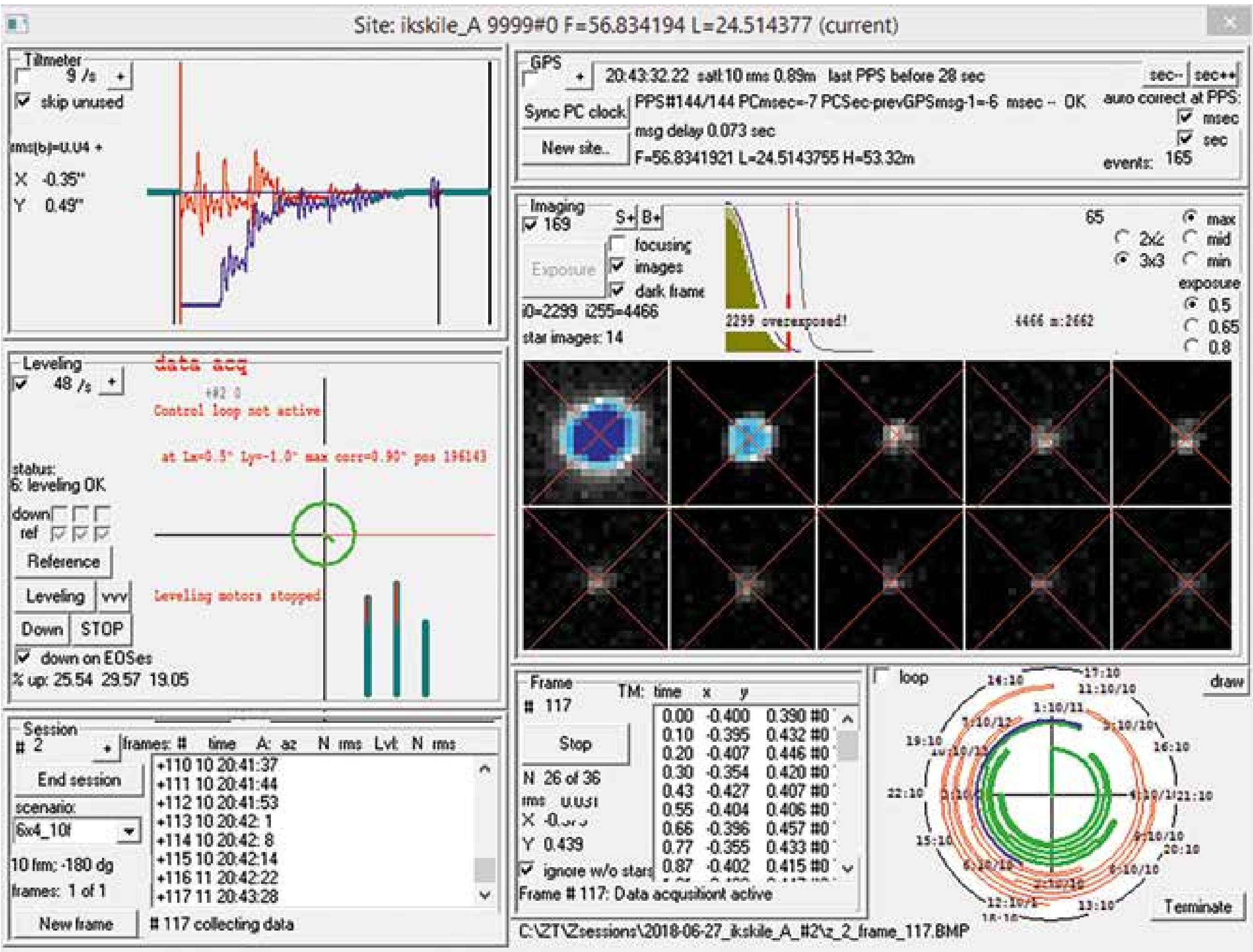

Fig. 3.
Session control panel. Clockwise from top left – tiltmeter controls, GPS and timing controls, CCD and star image controls, session scenario, frame data acquisition, session data acquisition, levelling and rotation controls

calculated from the instrument position in the inertial reference system defined by stars (Figs. 3–4). The obtained difference between these directions (vertical deflection) characterises the gravitational effect of nearby geological mass concentrations or deficits. Geometrically, the vertical deflection represents the angle between the surfaces of the geoid (based on gravity) and the reference ellipsoid at the measurement point on Earth.

DZC development is based on recent achievements in various sciences:

– Recently available charge-coupled devices (CCD devices) enabled to have the multiple images of star background with capability to use extremely accurate and extensive reference star catalogues like GAIA (2018, 1 billion stars, 0.1 arcsec accuracy). As a result, now it is possible to have accurate coordinates of practically all starlike objects up to magnitude of 20–21.

– Very sensitive tiltmeters were implemented using electronically controlled physical pendulums. That ensured very high sensitivity gain and also made these devices digital control and processing ready. Precision levelling using computer-controlled actuators is used.

– Accurate, near-real-time geocentric coordinates became widely available from GPS satellites.

– Time moments for exposure events (shutter open / close) also have been obtained from a GPS receiver through its event timing functionality. Timing accuracy itself (microsecond level or better) is more than good enough.

– Internationally supplied Earth rotation parameters enabling to find location of geocentric zenith relative to those stars in the moment of frame exposure. What then remains is to find where on this image ellipsoidal zenith is located.

Taking all the above functionalities together, we have a telescope equipped with a CCD camera, a tiltmeter, a GPS receiver, a set of levelling actuators, a rotation drive, and some auxiliary equipment, all of which produce the data we need (a lot of it). A control computer is installed to record the measurements and coordinate the activities of the hardware elements involved. Considering the sensitive nature of the measurements (even a small mechanical disturbance can cause unacceptable displacements in the instrument assembly) and the required mobility of the assembly, the control computer is fixed on board and communication with the remote-control equipment is wireless. Power is supplied by a onboard battery. An on-board control computer running Windows and remotely controlled via a Remote Desktop connection through Wi-Fi is provided. A single control programme controls all the hardware units involved. The process of measurements is fully automatic, except for the definition of the measurement settings and the scenario.

Since not all the required data are available at the time of the measurements, post-processing of the collected data files is necessary. Most of the computations are also automated, and the operator's tasks are usually limited to evaluating the results and, if necessary, removing some irregular data.

The next main problem is the calculation of the position of the ellipsoidal zenith position on the CCD. It includes the full extent of classical astrometric observational data reduction.

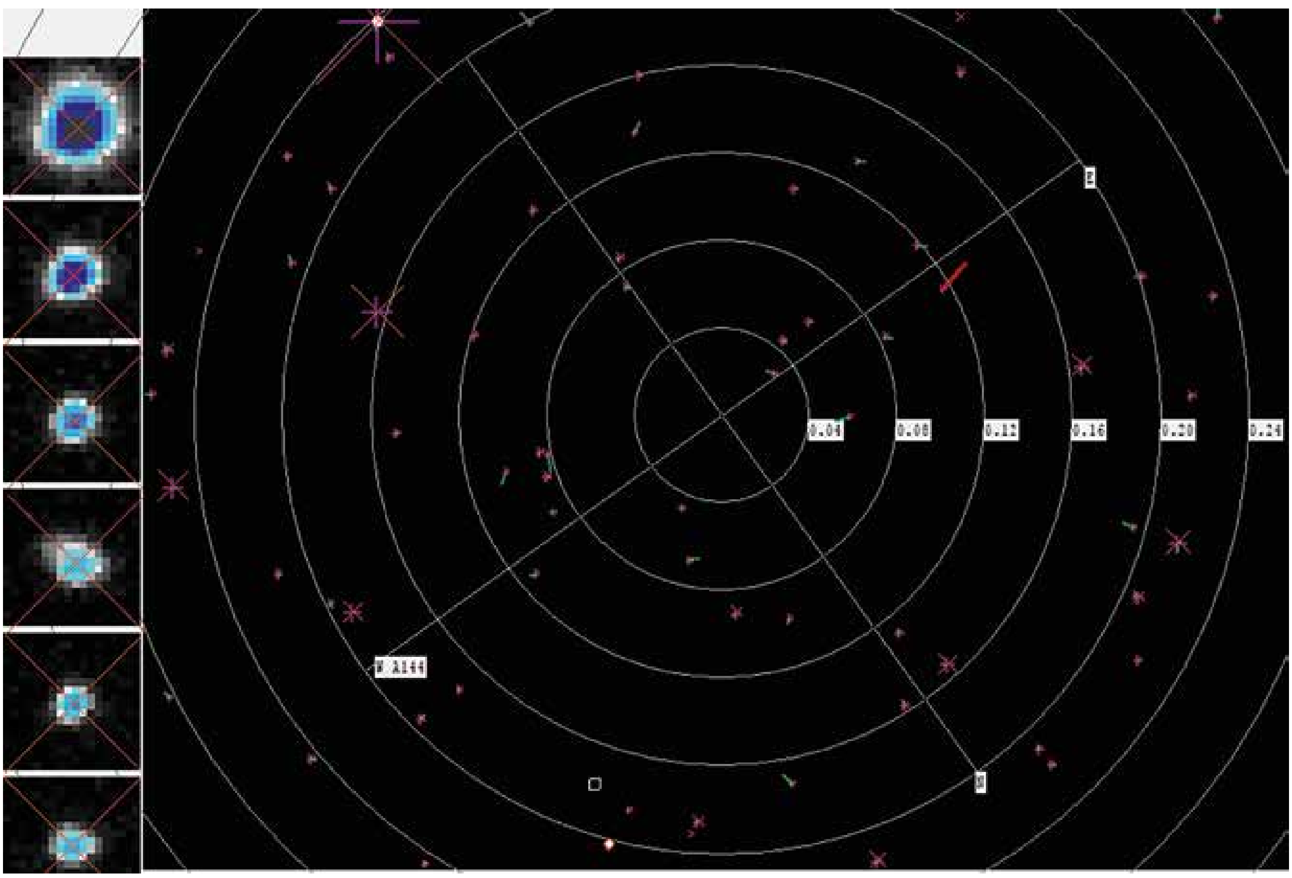

Fig. 4.
Astrometric processing of a frame. Right: frame image with superimposed calculated ellipsoidal zenith location (equal distance rings around it with degree notation) and orientation. Star images marked by slanted crosses, reference star position by straight crosses; green lines represent approximation residuals (red if rejected; magnified 20×). Left: magnified images of six brightest stars

Identifying star images with reference star catalogue (this task was generally handed over to the computer in the late photographic era), once the computer has received star image coordinates and the corresponding data of the reference stars, there are still some complicated steps of calculating the apparent places of the reference stars. This requires a very accurate (milli-arc-second level) Earth rotation theory. There are very few appropriate software packages that can accomplish this task, NOVAS (Navy Observatory Vector Astrometry System) package is used by DZC control software. In addition, actual values of the irregularities of the Earth's rotation (pole coordinates, Universal time correction) are necessary. Computing the parameters of the frame model to find the projection of gravity ellipsoidal zenith on CCD is the last step. Finally, the accuracy of the vertical deflection is 0.1 arc seconds (Fig. 5).

The practical application of the above considerations led us to the DZC instrument shown in Figure 1 in operation at night and Figure 2 where two DZC are exposed. The path to this point was neither straightforward nor simple; many iterations and revised variants were tested until a satisfactory design emerged.

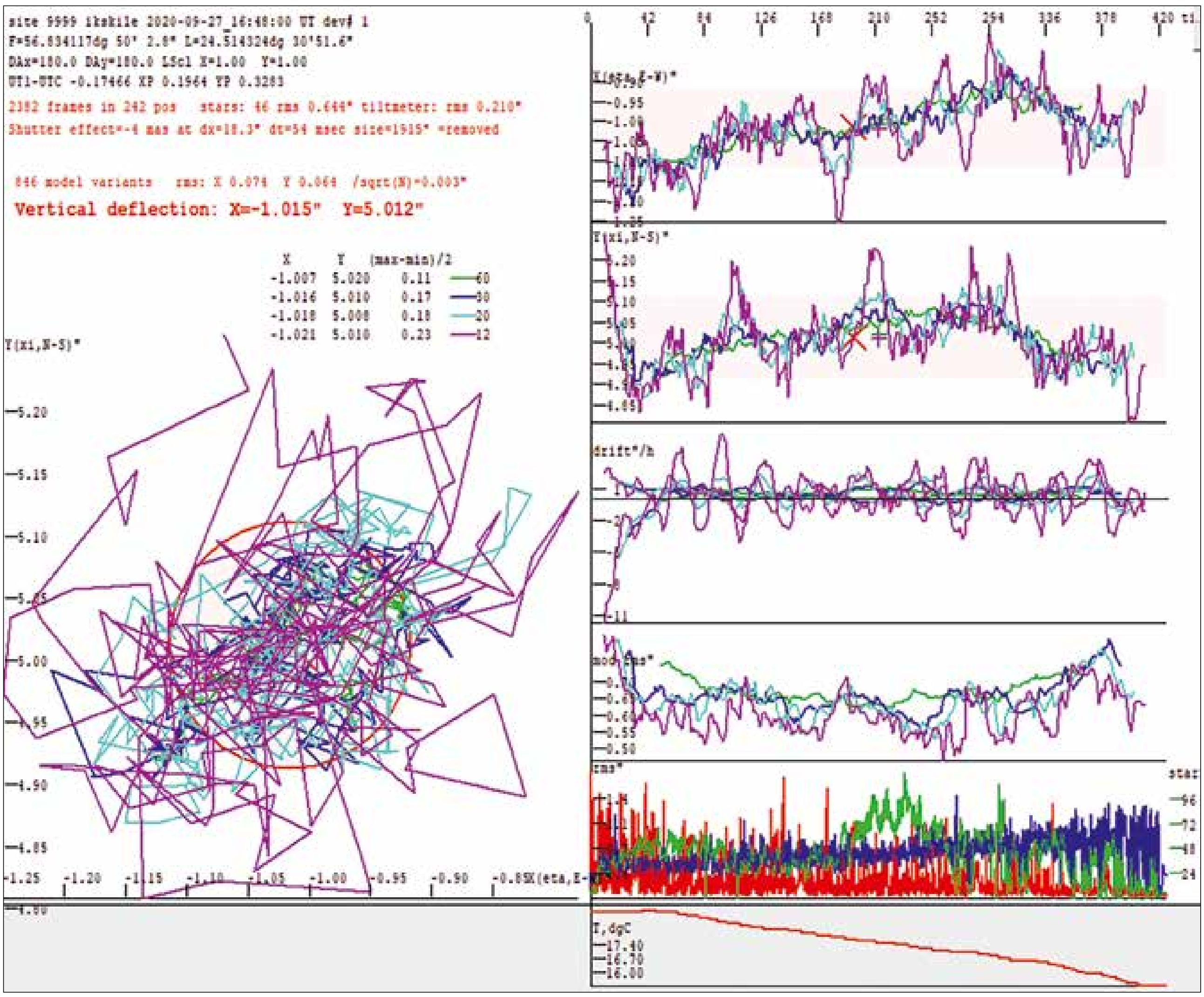

Fig. 5.

Session results analysis panel. Left – X&Y trajectories of calculated vertical deflections for various models; each colour represents a model made of indicated number of consecutive positions, each bend represents DoV values for one of these models. Right (top to bottom) – time dependencies of DoV X and Y components, thermal drift estimates, RMS estimates for various models; RMS of star residuals and tiltmeter positions for each frame and number of stars per frame; ambient temperature and cyclogram of sessions

Fig. 6.
From the left: Augusts Rubans, Inese Vārna, Gunārs Silabriedis, Ansis Zariņš, and Jānis Balodis