

# On the Augmentation of Israeli GPS-BM Data with a Global Earth Geoid Model

Yaron A. Felus, Gershon Steinberg, and Yakov Tuchin, USA, Israel

**Key words:** GPS, Positioning, Geoid computation, Geostatistical interpolation

## SUMMARY

A variety of mathematical procedures can be employed to integrate long-wavelength geoid undulation information from a global Earth model with terrestrial measurements of geoid undulation taken as the difference between GNSS ellipsoidal heights and orthometric heights measured by leveling loops. These include methods based on second-generation wavelets, Spline interpolation, least-squares collocation (LSC), and kriging. In the following research, the co-kriging approach was used for the task of fusing these two different datasets.

The co-kriging approach is based on a geostatistical process which evaluates the covariance function of each dataset and uses this covariance function to perform the best prediction in the least-squares sense. This is different from the current remove-interpolate-restore process which does not take into account the proper characteristics of each surface. Experiments were carried out to test the new methodology in computing an accurate geoid for the state of Israel using the new global geoid model and the GPS/leveling data. The result of the integration process is a hybrid geoid model that is tied to the current state orthometric height system with its biases but employs the global model to fill-in gaps and holes of missing information specifically inside the leveling loops. A variance surface was also produced to provide an indication of the quality of the model. These experiments presented a potential for improvement of the geoid accuracy using the co-kriging approach.

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## 1. INTRODUCTION

Within the scope of preparing new survey regulations, the Survey of Israel (SOI) came to the conclusion that from a cost and benefits point of view there is no justification to maintain a countrywide vertical orthometric control network. The SOI has calculated a network of control points with ellipsoidal heights using Global Navigation Satellite System (GNSS) techniques. A combination of ellipsoidal heights with an official geoid undulation model (OGUM) will serve as a substitute to the countrywide vertical orthometric control network (Steinberg 2006, Steinberg and Even-Tzur, 2006).

The official Israeli undulation model (ILUM) is based on 833 points with given ellipsoidal and orthometric heights. Kriging, a Geostatistical approximation method, was used for the construction of a geoid undulation surface. The geoid undulation values were calculated on a grid with a resolution of 0.5 x 0.5 km. The accuracy of this calculation was estimated using the Kriging variance value on the same grid. The validity of the model was verified using a series of field measurements. These field measurements were independently surveyed and included GPS measurements on benchmarks and leveling observations on GPS stations. Discrepancies between the geoid model and the field measurements did not exceed 0.14 m in the evaluated areas (Tuchin 2006).

As from May 2007 surveyors in Israel enjoy the possibility to estimate orthometric heights in real time using a single GNSS receiver equipped with the official geoid model. Instead of occupying at least four benchmarks in order to define a local geoid, they can use just one benchmark for checking purposes only. Although many mapping and engineering projects may not require an accurate geoid model, the SOI seeks for ways to improve the official Israeli undulation model. This model is updated on a regular basis using additional measurements and due to minor datum modifications, or mistakes that are found. SOI have already released the third version (ILUM1.2) of the official model. Since this geoid model is based mainly on large loops of precise leveling along roads, its accuracy is decreasing with the distance from those roads to the center of the loops. Augmentation of the Israeli GPS-BM data with a global Earth geoid model as follows, is a simple and not expensive way to improve the geoid model in its weak parts. A variety of mathematical procedures can be employed to integrate long-wavelength geoid undulation information from a global Earth model with terrestrial measurements of geoid undulation taken as the difference between GNSS ellipsoidal heights and orthometric heights measured by leveling loops. These include methods based on second-generation wavelets (Soltanpour et al. 2006), spline interpolation, least-squares collocation (LSC) (Sjöberg and Featherstone 2004, and Featherstone 2007), and kriging. In the following research, the cokriging approach was used for the task of fusing these two different datasets. A study of digital elevation models integration using simple

cokriging was performed by Kyriakidis et al. (1999) but little research has been conducted on using cokriging for geoid modeling and development.

Cokriging is a geostatistical prediction technique that allows the use of additional information contained in secondary variables in the prediction of a primary variable. This technique is studied and experiments are performed to integrate GPS-BM points and a preliminary version of the world geoid model developed to degree 2160 by the US National Geospatial Intelligence Agency (Cf. Kenyon et al. 2007). The rest of the paper is organized as follows: The next section describes the Cokriging paradigm for data integration and an investigation of the geoid surface covariance function. The Cokriging principle is employed to integrate a set of GPS-BM points (points with measured geoid separation) with the Earth Geoid/Gravitational Model EGM2008 to degree 2160. A discussion about the limitations of the presented techniques and future method concludes this report.

## 2. THE COKRIGING PARADIGM FOR DATA INTEGRATION

**2.1 Kriging** is a class of interpolation techniques, which provide the best linear unbiased prediction (BLUP) of an attribute value at an unmeasured point. Given a set of  $n$  observed data points  $z(s_1), z(s_2), \dots, z(s_n)$ , at locations  $s_1, s_2, \dots, s_n$ , a list of optimally unbiased weight coefficients  $\lambda_1, \lambda_2, \dots, \lambda_n$ , is calculated such that the unknown value,  $z(s_0)$  at location  $s_0$  can be predicted by:

$$z(s_0) = \lambda_1 \cdot z(s_1) + \lambda_2 \cdot z(s_2) + \dots + \lambda_n \cdot z(s_n) \quad (1)$$

Unlike other weighted average methods, kriging uses the spatial dependence function (e.g. variogram or covariance functions) to calculate the weight coefficients (i.e.  $\lambda_1, \lambda_2, \dots, \lambda_n$ ).

**2.2 Cokriging** is an extension of the kriging technique that allows the use of additional information contained in secondary variables in the prediction of a primary variable. Let the secondary variables be a set of  $m$  observations  $y(s_1'), y(s_2'), \dots, y(s_m')$  at locations  $s_1', s_2', \dots, s_m'$ . Note these locations ( $s_1', s_2', \dots, s_m'$ ) may or may not be identical to the locations of the primary variable. Once again a set of optimally unbiased weight coefficients  $\lambda_1, \lambda_2, \dots, \lambda_n$ , and  $\kappa_1, \kappa_2, \dots, \kappa_m$  is calculated such that the unknown value,  $z(s_0)$  at location  $s_0$  can be predicted using a linear combination of the primary and secondary variables as follows:

$$z(s_0) = \lambda_1 \cdot z(s_1) + \dots + \lambda_n \cdot z(s_n) + \kappa_1 \cdot y(s_1') + \dots + \kappa_m \cdot y(s_m') \quad (2)$$

For the ordinary cokriging, the optimal cokriging weights are obtained by solving the following equation (Hohn, 1999, and Ver Hoef. and Cressie 1993):

$$\begin{bmatrix} C(z, z) & C(y, z) & I & 0 \\ C(z, y) & C(y, y) & 0 & I \\ I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \bar{\lambda} \\ \bar{\kappa} \\ \mu_1 \\ \mu_2 \end{bmatrix} = \begin{bmatrix} c[z, z(s_0)] \\ c[z, y(s_0)] \\ 1 \\ 0 \end{bmatrix} \quad (3)$$

where

- $\bar{\lambda}$  and  $\bar{\kappa}$  are vectors that include the weight coefficients.
- $C(z,z)$  and  $C(y,y)$  are the covariance function matrices with elements that describe the spatial dependence of the same variable at different locations (e.g.,  $[C(z(s_1),z(s_1))], [C(z(s_1),z(s_2))]\dots [C(z(s_1),z(s_n))]$ ).
- $C(z,y)$  and  $C(y,z)$  are the cross-covariance function matrices with elements that describe the spatial dependence between the two variables at different locations (e.g.,  $[C(z(s_1),y(s_1'))], [C(z(s_1),y(s_2'))]\dots [C(z(s_1),y(s_m'))]$ ).
- $\mu_1$  and  $\mu_2$  are Lagrange multipliers that guarantees the unbiasedness of the solution
- $c(z, z(s_0))$  and  $c(z, y(s_0))$  are the covariance function vectors with elements that describe the spatial dependence between the primary variables  $z$  at different locations and the  $z(s_0)$  and  $y(s_0)$  the primary and secondary variable at the unmeasured location.

The Mean Squared Prediction Error (MSPE) or cokriging variance is given by:

$$\sigma_{ck}^2(z(s_o)) = c(z(s_o), z(s_o)) + \mu_1 - \sum_{i=1}^n \lambda_i \cdot c(z_i, z(s_o)) - \sum_{i=1}^m \kappa_i \cdot c(y_i, z(s_o)) \quad (4)$$

The interpolation mean squared prediction error is a useful gauge for the accuracy of the cokriging results. Cokriging approach would be ideal for the integration of local GPS-BM data with the EGM2008 since there is a bias difference between the two surfaces and the ordinary cokriging approach utilize the bias of the primary variable and not the bias of the secondary variable. Proper calculation of the covariance and cross-covariance functions is essential to the success of the cokriging procedure and will be described in detail in the next section.

### 2.3 Covariance and cross- covariance functions

The spatial dependence function describes mathematically the correlation between data points as a function of their separation distance. Typical this spatial dependence function expresses the first law of geography which states that “two data points close to each other are more likely to have similar values than two data points that are far apart” (see Figure 1).

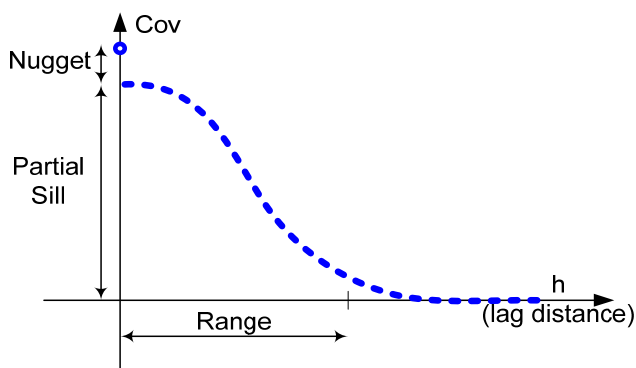


Figure 1: A typical covariance function which describes the similarity between two points, as the points get further away from each other the similarity vanishes.

By definition the covariance between two points  $s_i$  and  $s_j$  is:

$$\begin{aligned} c(z(s_i), z(s_j)) &= \text{cov}(z(s_i), z(s_j)) = E((z(s_i) - m_i) \cdot (z(s_j) - m_j)) \\ &= E(z(s_i) \cdot z(s_j)) - E(z(s_i) \cdot m_j) - E(z(s_j) \cdot m_i) + E(m_i \cdot m_j) \\ &= E(z(s_i) \cdot z(s_j)) - m_i \cdot m_j \end{aligned} \quad (5)$$

Where  $m_i$  and  $m_j$  are the mean values at point  $s_i$  and  $s_j$  and  $E$  denotes the expectation operator. Using the method of moments and the assumption of second order stationarity one can estimate the covariance (shown in Figure 1) between two points separated by a lag distance of  $h$  (i.e.,  $s_i$  and  $s_i+h$ ) by:

$$\begin{aligned} c_z(h) &= C(z(s_i+h), z(s_i)) = E(z(s_i+h) \cdot z(s_i)) - m^2 \\ \hat{c}_z(h) &= \frac{\sum_{i=1}^n (z(s_i+h) \cdot z(s_i))}{n} - \hat{m}^2 \end{aligned} \quad (6)$$

where  $\hat{m}$  is the estimated process mean given by:

$$\hat{m} = \frac{\sum z(s_i)}{n} \quad (7)$$

In the same manner, the cross-covariance is defined between  $z(s_i)$  and  $y(s_j)$  as:

$$\begin{aligned} c_{zy}(h) &= C(z(s_i+h), y(s_i)) = E(y(s_i+h) \cdot z(s_i)) - m_z \cdot m_y \\ \hat{c}_{zy}(h) &= \frac{\sum_{i=1}^n (z(s_i+h) \cdot y(s_i))}{n} - \hat{m}_z \cdot \hat{m}_y \end{aligned} \quad (8)$$

Note that the cross-covariance function can be negative at some values, this may happen when the two variables are negatively correlated. Moreover note that the cross-covariance function is not necessarily symmetric, namely:  $C_{zy}(h) \neq C_{yz}(-h)$ .

A plot of  $\hat{c}_z(h)$  or  $\hat{c}_{zy}(h)$  against  $h$  is known as the empirical covariance or Cross-covariance function respectively. The discrete values of the empirical covariance or cross-covariance function must be fitted to a continuous model that necessarily provides a (conditionally) positive-definite covariance function. Many valid mathematical models are presented in the literature; some examples include, Cressie (1993, pp. 61-64), which provides six isotropic standard models. These mathematical functions typically utilize three parameters: sill, range, and nugget (see Figure 1, where the sill is the sum of the Partial Sill and the nugget) which are determined by Weighted Least-Squares adjustment (Cressie, 1993) or Total Least-Squares (Felus and Schaffrin, 2005).

### 3. CASE STUDY, INTEGRATING GPS-BM MEASUREMENTS WITH PRELIMINARY EGM 08 DATA.

The cokriging approach was examined on fusing 72 well distributed GPS-BM data point with the preliminary version of the EGM08 in Israel. The primary dataset was a list of selected

points with ellipsoidal height measured using GPS and orthometric height measured and calculated by a set of high accuracy leveling sessions (see Figure 2). These points were selected from high density network of leveling loops so that they are uniformly distributed and have an average distance of 20 miles between each other. The 72 selected points will allow us to properly test the accuracy of the geoid model and specifically get an estimate of the accuracy in the gaps between the leveling loops.

The secondary surface was a part of the preliminary Earth Gravity/ Geoid model produced by the NGA by optimally combining gravitational information extracted from dedicated geopotential mapping satellite missions (CHAMP, GRACE), with NGAs' data from a global gravity anomaly database at a 5'x5' resolution. This new model is completed to degree and order of 2160, and the finalized model will aim at a  $\pm 15$  cm global Root Mean Square (RMS) geoid undulation error. Nevertheless direct statistical comparison of the model to the Israeli leveling network presented a bias of -0.61m and a standard deviation of 0.26m on the all set of 833 points.

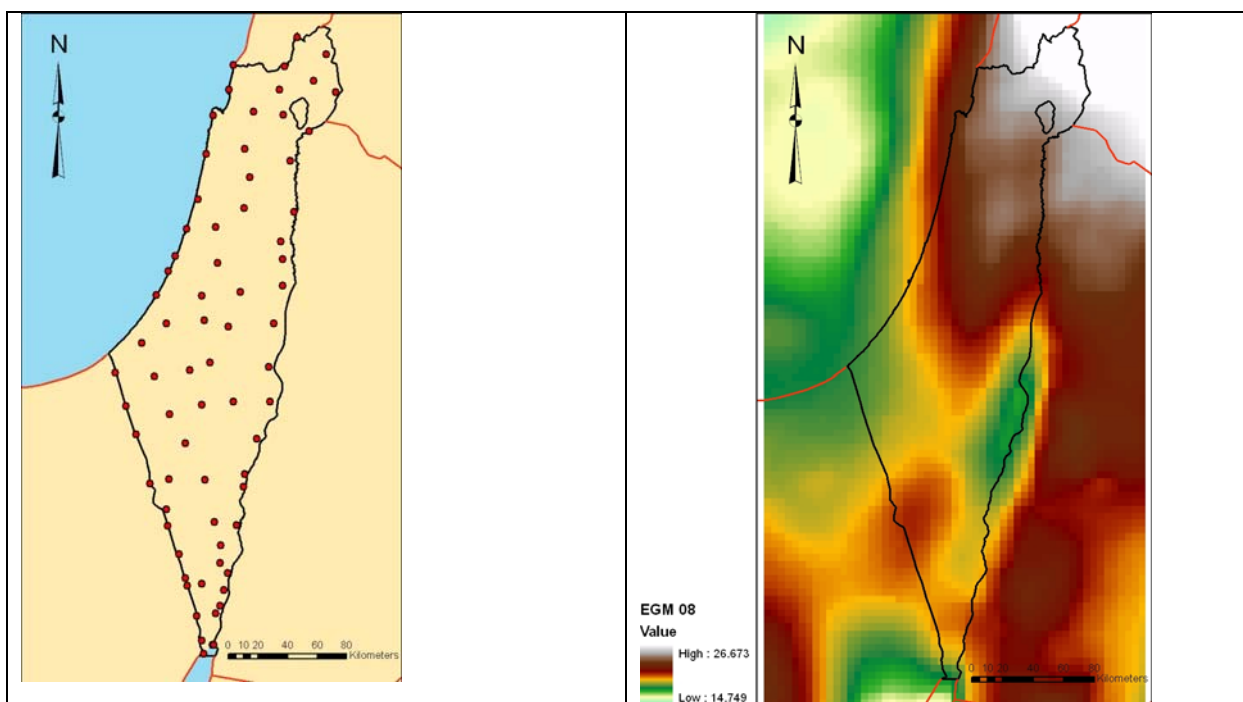


Figure 2: Left The 72 GPS-BM data points, Right the preliminary EGM08 model of NGA over the state of Israel.

Various mathematical functions to model the covariance are developed in the geodetic literature including the Gaussian (Smith and Roman 2001), exponential, and various polynomial functions. Following careful investigation of cross-validation results and models goodness of fit, the Spherical model in Equation 8 was found to be most suitable for the specific geoid undulation data.

$$\sigma_e^2 + \sigma_y^2 \left[ 1 - 1.5 \left( \frac{h}{r} \right) + 0.5 \left( \frac{h}{r} \right)^3 \right] \quad 0 \leq h \leq r \quad (8)$$

$$\sigma_e^2 \quad h > r$$

where  $h$  is the lag distance,  $\sigma_y^2 > 0$  is the partial sill,  $\sigma_e^2 < \sigma_y^2$  is the nugget,  $r > 0$  is the range. The estimated parameters are presented in Table 1. These were fitted to the empirical covariance values using Weighted Least Squared method (Cressie, 1993).

Table 1: covariance function parameters for the two datasets

	Range	Sill	Nugget
GPS-BM data	167630	3.3108	0.01
Cross covariance	167630	3.2721	–
Preliminary EGM08	167630	4.5077	0.15

The next step in the case study was to investigate the best method to generate an accurate geoid. Three approaches were analyzed: kriging of the GPS-BM data, kriging of the preliminary EGM08 data, using cokriging of the GPS-BM data and the preliminary EGM08 data. These interpolation methods were evaluated using independently measured 33 points spread around the country and using cross-validation. During the cross-validation procedure one data point is removed and the rest of the points are used to predict the removed data. Thus an estimate of the accuracy on this point is obtained by:

$$Error = Predicted\ value\ for\ the\ point - known\ value \quad (9)$$

Table 2 presents the RMS results of the various interpolation methods. The cokriging approach outperformed the two kriging approaches in both the cross-validation and during the investigation on the independent set of points. The RMS results of independent set of points were better than the cross-validation RMS in the GPS-BM case since the 33 independent points were relatively closer to the set of 72 points than the 72 point among themselves.

Table 2: covariance function parameters for the two datasets

	Kriging of GPS-BM data	Kriging of P-EGM08 data	Cokriging GPS-BM and P-EGM08
Cross-validation (RMS)	0.28	0.04	0.21
Independent data (RMS)	0.20	0.31	0.15

Further comparison of differences between measured orthometric heights and heights that are calculated from reduced ellipsoidal measurement via the geoid model (as in Steinberg and Even-Tzur 2006) is being performed and will be described in future publication .

Following the experimental step where it was verified that the cokriging approach outperforms the kriging approach, the co-kriging approach was implemented on the complete dataset with 833 points and a surface with an average cokriging variance of 0.143 m was obtained (see Figure 3).

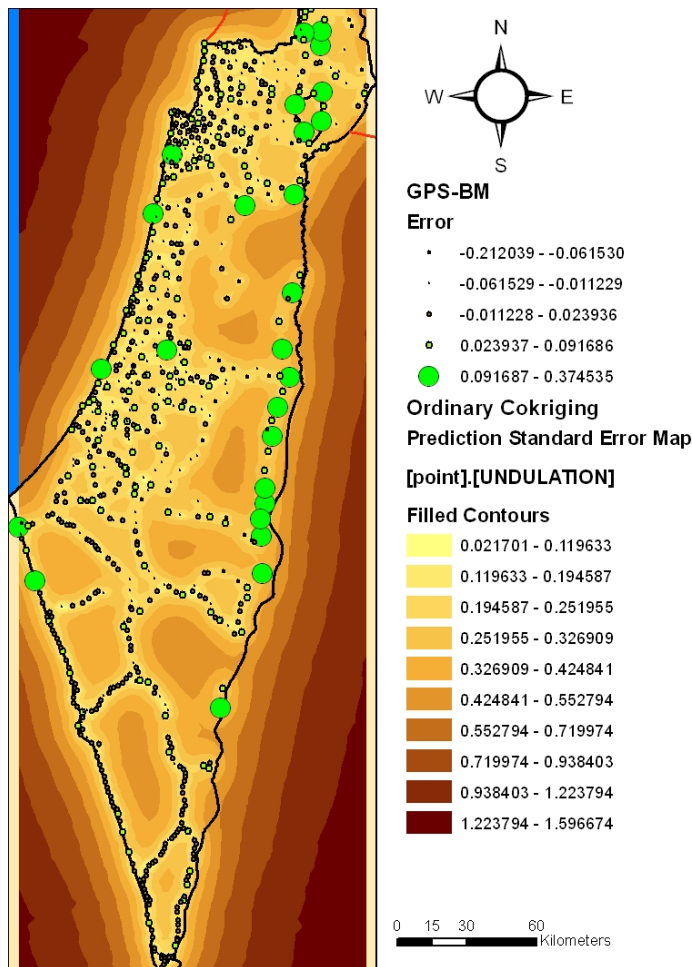


Figure 3: The cokriging variance surface map and the 833 GPS-BM points used to create the full geoid model with erroneous points drawn as large circles.

Much like the kriging variance, the cokriging variance indicator depends on estimated nugget value and may be either too optimistic or too pessimistic depending on the variance/covariance function parameters. Moreover, Figure 3 highlights the cross-validation results on the 833 point and specifically shows points with high cross-validation error as presented in Equation 9. These points include a few points on the boundary of the country where the cokriging performed extrapolation with the primary dataset (GPS-BM) and not interpolation which increase the error. Many points along the eastern border of the state have large errors. These points are located along the Syrian-East African Rift (also known as the Great Rift System) which separates the Arabian Plate from the African Plate. This rift represents a discontinuity (breakline) in the surface (i.e., the geological structure and therefore the gravity surface). The smooth cokriging interpolation and the smooth low resolution preliminary EGM08 surface are less accurate in modeling this abrupt change.



#### 4. DISCUSSION AND CONCLUSIONS:

Cokriging was tested as a unique approach to improve the accuracy of a state wide geoid model derived from GPS-BM data set. The preliminary EGM08 data has less sample points and it is less accurate but it is uniformly distributed around the project area (heterotopic case) and fills-in the gaps in the GPS-BM collected data. Substantial improvement of the state geoid was obtained using this procedure. An even better improvement would be obtained with the final version EGM08 geoid where some corrections and modifications have been added.

Like in many other countries the orthometric system in Israel has biases and local distortions, the ordinary cokriging approach maintain the local bias while strengthening and improving the relative geometry of the surface with low frequency data.

A key aspect in geoid modeling and its applications is the fidelity or accuracy of the slope (e.g., value of vertical deflection). In other words, the change of the geoid undulation is often more important for surveying and engineering applications than the absolute value of the geoid undulation. Measurements of the slope can be performed with good accuracy using short leveling segments integrated with GPS ellipsoidal height measurements as described in Melzer et al. (1996). Further research should be done for improving geoid models using measurements of geoid slopes. Those are easy to survey as they can be independently performed with no ties to existing BM.

Cokriging should not be used if the two datasets have equal accuracy. In this case, simple addition of the datasets may yield more accurate results. Research should be performed to investigate more efficient algorithms such as the Collocated Cokriging which is preferred when the secondary data are available at every location being estimated. The Collocated Cokriging algorithm reduces the size of the equation systems and can be computed faster.

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## **BIOGRAPHICAL NOTES**

### **Dr. Yaron A. FELUS**

is an Associate Professor in the Surveying Engineering Department at the Ferris State University. He holds a BS from Ben-Gurion University, Israel (Electrical and Computer Engineering), a M.S. from the International Institute for Geo-Information Science and Earth Observation, Netherlands (Geomatics), and both M.S. and Ph.D. from the Ohio State University (geodetic science). He is a Professional Surveyor in Michigan, USA and a Licensed Surveyor in Israel.

### **Dr. Gershon STEINBERG**

Since 09/2003: Chief Scientist and Chief Geodesist of the Survey of Israel.

1995- 2003: Deputy Director General for Geodesy and Cadastral Surveys.

1993 - 1995: Head, division of Cadastral Surveys and Geodetic Computations.

1988 - 1993: Head, division of Cadastral Surveys.

1972 - 1988: Head, division of Horizontal and Vertical Geodetic Field Control.

Since 2006: Adjunct senior teaching fellow (equivalent to associate professor) in the Technion, Israel Institute of Technology, Haifa, Israel.

Since 1993: Adjunct senior lecturer in the Technion, Israel Institute of Technology, Haifa, Israel.

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### **Societies**

Israel's delegate to commission 5 of FIG.

Rotary International, Ramat- Hasharon, Israel.

### **Dr. Yakov TUCHIN**

Is responsible for the maintenance and development of geodetic infrastructure in the Calculations Department of the Survey of Israel .His academic experience includes a MSc in Applied mathematics from Novosibirsk State University, and a PhD in Geodesy from the Novosibirsk Institute of Surveying and Mapping .He worked as an Associate Professor in the Novosibirsk Institute of Surveying and Mapping, USSR (now SGGa, Russia), as an Engineer

in a Photogrammetric Company Ltd, Tel Aviv, Israel (1991 - 1998), and with the Survey of Israel (since 1998). Practical experience include: geodetic network calculations, GPS computations, mapping, programming, and lecturing in applied mathematics and geodetic calculations.

## CONTACTS

Yaron A. Felus  
Surveying Engineering Department  
Ferris State University  
Big Rapids, MI, USA 49307,  
Tel: 231 5912221  
E-mails: [felusy@ferris.edu](mailto:felusy@ferris.edu)

Gershon Steinberg  
Survey of Israel  
1 Lincoln St.  
Tel Aviv 65220, Israel  
Tel. + 972 3 5615708  
Fax + 972 3 6231806  
E-mail: [gershon8@mapi.gov.il](mailto:gershon8@mapi.gov.il)

Yakov Tuchin  
Survey of Israel  
1, Lincoln St.  
Tel Aviv 65220, Israel  
Tel. + 972 3 6231819  
Fax + 972 3 6231820  
E-mail: [yakov.tuchin@gmail.com](mailto:yakov.tuchin@gmail.com)