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On the evaporation problem over the Adriatic Sea

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Measurements of evaporation in open sea conditions are relatively rare, so instead, evaporation is calculated using different parametrisations of bulk formulas. Although the bulk method was widely used to compute air-sea fluxes, the use of different bulk parametrisations can result with different rate of evaporation. This paper discusses the various uses of bulk-method-determined evaporation. Since direct measurements of evaporation was not yet performed above the Adriatic Sea, the evaporation measured at the coastal station (Trieste, northern Adriatic) was compared to the results obtained using three different bulk equations (by JACOBS, LAEVASTU and SMITH). Sensitivity error analysis was estimated including errors of each of the measured variables. The equation according to LAEVASTU resulted in the smallest relative error. The important source of errors in all equations was the wind measurement and LAEVASTU equation was the least sensitive to this factor.

INTRODUCTION

Latent heat flux exchange at the sea surface is important for knowledge of the energetic and dynamic properties of the sea. It plays a major role in a process of exchange of heat and mass between the sea and atmosphere. The latent heat flux, that is the heat flux due to evaporation, is an important component of the net surface heat flux. According to GARRETT, *et al.* (1993) interannual variations of the total heat flux are determined mostly by latent heat flux. Variability in the heat flux due to evaporation is associated largely with the difference between specific saturation humidity at the sea surface and the ambient atmospheric specific humidity. Evaporation over the sea may have importance in the studies of salinity, which, besides river inflows, precipitation, advection and mixing depend on evaporation as well.

Evaporation may be obtained from measurements of bulk variables by several methods such as eddy correlation, the profile and the dissipation methods (BUSCH, 1971; POND *et al.*, 1971; FAIRALL *et al.*, 1996) using different transfer coefficient schemes (GARRATT, 1977; WU, 1980; BLANC, 1985). Direct measurements of air-sea humidity fluxes have been made for more than 20 years during several experiments; for example, HEXOS (Humidity exchange over the Sea) experiment over the North Sea, TOGA (Tropical Ocean Global Atmosphere) experiment over the tropical Pacific, BOMEX (Barbados Oceanographic and Meteorological Experiment), permanent measurements at Ocean Weather Station PAPA (JACOBS, 1978; FAIRALL *et al.*, 1977). These experiments have yielded sufficient data to test the bulk aerodynamic algorithms. These algorithms were found to work quite well for wind speeds between 3-15 ms^{-1}. At wind speeds less than about 4 ms^{-1} the bulk transfer coefficients (drag coefficient C_D and latent heat transfer coefficient C_E) increase rapidly with decreasing wind speed (GREENHUT and KHALSA, 1995). The behavior of the transfer coefficient is dependent upon the surface stability (SMITH, 1980), while neglecting this effect can result in poor estimation of the evaporation rate.

Such measurements over the Adriatic Sea do not exist at all. Evaporation was rather calculated with different bulk equations, taking into account sea and water temperature, wind speed, relative humidity and air pressure over the sea. Evaporation in the Adriatic Sea was calculated in several papers (ZORE-ARMANDA, 1969; BONACCI, 1985; STRAVISI and CRISCIANI, 1986; PICCO, 1991; SUPIĆ, 1993). Their results agree for mean annual evaporation value but differ for the seasonal cycle because for example, ZORE-ARMANDA used heat balance equation while BONACCI used empirical evaporation formula.

In this paper, three historic bulk aerodynamic equations for evaporation over the sea from JACOBS (1942), LAEVASTU (1960) and SMITH (1980) were analyzed and the results were compared to the evaporation measurements for the station Trieste, situated near the sea. The sensitivity error analysis (BLANC, 1983) of the bulk equations was also performed. It was based on expected uncertainties in the measured bulk variables used in the equations. This procedure is already well know, but has not been applied yet to the Adriatic Sea. We intend to start soon with measurement of bulk variables with adequate technique which will unable calculating heat and moisture fluxes.

MATERIALS AND METHODS

Evaporation and other data originate from the meteorological station Trieste in the northern Adriatic from the period 1961-1968. Evaporation measurements are performed using an evaporigraph, where evaporation of distilled water was registered by weighting evaporated water from a metal container of 250 cm^2 surface. The results are controlled with the WILD evaporimeter. These experimental data were compared to those obtained by bulk equations using air temperature, relative humidity, wind speed and air pressure from the meteorological station Trieste, and sea temperature from the harbor of Trieste.

The magnitude of measurement errors of meteorological parameters used for calculation of error in evaporation equations were those given in the ANNUARIO 1975. In addition, sea water temperature measured in Trieste refers to the 2 m depth. Since the knowledge of surface temperature is indispensable for evaporation calculation, data for station Trieste were corrected to surface temperature using simultaneous measurements at surface and at 2 m depth in 1988 (CATERINI *et al.*, 1988; GRBEC and KOVAČEVIĆ, 1993).

Bulk equations, often used in oceanography to estimate evaporation over the sea surface by flow method, can be cast in a form (PICKARD and EMERY, 1982):

$$E = K(e_w - e_a)v \qquad (1)$$

where E is the rate of evaporation, K is the selected function or constant, e_w and e_a saturated vapor pressure at the sea surface and vapor pressure at the anemometer level, respectively and v is the wind speed.

In this paper, a comparison of the following equations is presented:

$$E1 = 0.143(e_w - e_a)v \rightarrow \text{JACOBS, } \mathit{1942} \qquad (2)$$

$$E2 = (0.26+0.077v)(0.98e_w - e_a) \rightarrow \text{LAEVASTU, } \mathit{1960} \qquad (3)$$

$$E3 = C_E \rho v(q_w - q_a) \rightarrow \text{SMITH, } \mathit{1980} \qquad (4)$$

In the equation by SMITH, ρ is the air density, approximated by the constant of the magnitude 1.25 kg m^{-3}, C_E is the transfer coefficient which is, because of the lack of data, set to be a constant of the magnitude 1.15×10^{-3}, q_w is the specific humidity of air saturated by water vapor at sea surface and q_a is the specific air humidity. Equation (3) takes into account the dependence of evaporation on the same parameters as equation (2), but has a different form that better represent the conditions over the sea. When the wind speed is zero, equations (2) and (4) result in zero evaporation, while according to equation (3) there is still some evaporation. The effect of salinity on vapor pressure is also considered in the equation (3) by the introduction of the coefficient 0.98 with e_w. Equation (4) is similar to equation (2), distinguished only by the fact that the effect of nonconstant atmospheric pressure is included.

Considering the mean monthly values, evaporation was calculated first for the station Trieste for the period 1961-1968 using three different bulk equations. Calculated values from three equations were compared to measured evaporation data over the land in order to evaluate differences obtained with different equations. Correlation coefficients between measured parameters and evaporation calculated with equations (2), (3) and (4) were also obtained.

Sensitivity error analysis was performed including errors in the measured bulk variables used in the equations. Brief background of this analysis is noted.

Let u be a value of a function of three measured variables:

$$u = f(x,y,z), \tag{5}$$

$$u + \Delta u = f(x+ \Delta x, y + \Delta y, z + \Delta z)\,. \tag{6}$$

The value of a function u is a correct value, within the limits of the accuracy (errors) of measurements. If the error of measurement of each variable is known it is possible to calculate the error of a function:

$$\Delta u = f(x+ \Delta x, y + \Delta y, z + \Delta z) - f(x,y,z)\,. \tag{7}$$

If the errors of measurements are small relative to the measured values it is possible to express the relation with a differential:

$$\delta u = f(x+ \delta x, y + \delta y, z + \delta z) - f(x,y,z)\,. \tag{8}$$

The total differential is:

$$\delta f = f_x \delta x + f_y \delta y + f_z \delta z\,. \tag{9}$$

The sum of partial differentials is the total differential for each equation. Partial differentials could have positive or negative terms and the resulting error could be small or zero, although errors itself could be considerable. Since we are looking for maximum error, only absolute errors of each of the variables are taken into account.

Evaporation value is :

$$E = E' \pm \Delta E\,, \tag{10}$$

where the differentials are as follows:

$$\Delta E1 = \partial E1 = 0.143(e_w + e_a)\partial v + 0.143(\partial e_w - \partial e_a)v\,, \tag{11}$$

$$\Delta E2 = \partial E2 = 0.077(0.98e_w - e_a)\partial v + (0.26 + 0.077v)(0.98\partial e_w - \partial e_a)\,, \tag{12}$$

$$\Delta E3 = \partial E3 = C_E \rho \partial v(q_w - q_a) + \frac{C_E \rho v}{p^2}(\partial e_w - \partial e_a) \tag{13}$$

Each equation takes into account errors for each measured variable: sea and air temperature, wind speed, relative humidity and air pressure.

For each of the equations (2), (3) and (4), absolute errors were determined from equations (11), (12) and (13), respectively. Total relative errors (the ratio between the error and evaporation magnitude) and contribution of each measured parameter to the total relative error was also determined.

Relative errors of each variable were calculated, keeping other variables constant. The constant values for bulk variables are set to be: v = 3.0 ms^{-1} for wind speed, $t_w = t_a$ = 15.0 °C for sea and air temperatures, RH=50% for relative humidity and p=1000.0 hPa for air pressure.

RESULTS AND DISCUSSION

The evaporation was calculated by equations (2), (3) and (4) for the period 1961-1968 from the available data for Trieste station. The results of the application of these equations, compared to evaporation measured over the land, are presented in Fig. 1. Mean annual evaporation value for the whole period is 2.85 mm day^{-1}, 3.42 mm day^{-1} and 1.99 mm day^{-1} for the equations (2), (3) and (4), respectively (Table 1). The difference in the evaporation values at a annual scale is generally accepted as the accuracy of the bulk formulae, due to the limited accuracy of the meteorological data. The differences between equations (3) and (4) are the largest. Equation (4) gives the lowest values but these values are comparable to evaporation above the land.

Table 1. Monthly mean evaporation calculated by equations (2), (3), (4) and evaporation measured over the land

MONTH	Eq. (2) (mm day^{-1})	Eq. (3) (mm day^{-1})	Eq. (4) (mm day^{-1})	Evap. over land (mm day^{-1})
1	2.34	2.73	1.63	0.99
2	1.59	1.90	1.10	1.12
3	1.58	1.85	1.11	1.40
4	1.47	1.91	1.03	1.60
5	2.16	2.71	1.52	1.83
6	2.52	3.30	1.77	1.86
7	3.81	4.68	2.66	2.16
8	4.21	5.11	2.94	2.00
9	3.73	4.66	2.61	1.50
10	4.02	4.61	2.79	1.28
11	3.38	3.86	2.36	0.91
12	3.40	3.67	2.37	1.15
ANN. MEAN	2.85	3.42	1.99	1.48

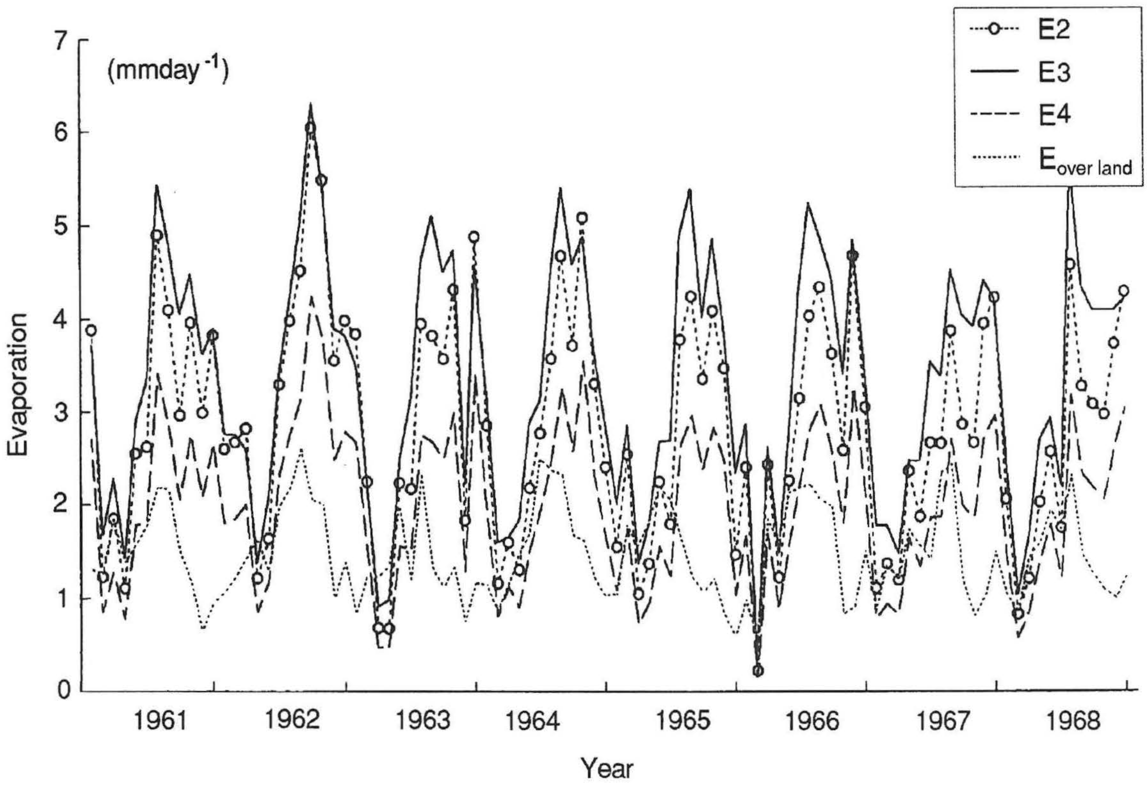

Fig. 1. Monthly mean evaporation calculated by equations (2), (3) and (4) and monthly mean evaporation measured over the land

Mean seasonal cycles obtained from equations (2), (3) and (4) are similar but absolute evaporation values are different (Fig. 2). Annual evaporation over the land differs from evaporation obtained by these equations. It is obvious that evaporation over the land follows physical processes different from those over the sea. Evaporation over the land is very well in concordance with the seasonality of the air temperature (Fig.3), while seasonality of calculated evaporation over the sea is comparable to the seasonality of the sea surface temperature (see Fig. 2). It is easy to note that seasonal extremes for evaporation over the sea and land coincide with temperature extremes.

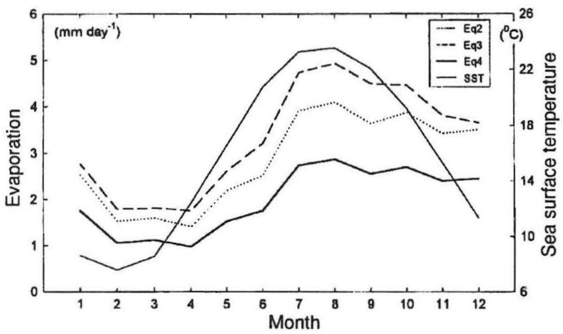

Fig. 2. Mean seasonal cycle of evaporation calculated by equations (2), (3), (4) and monthly mean sea surface temperature

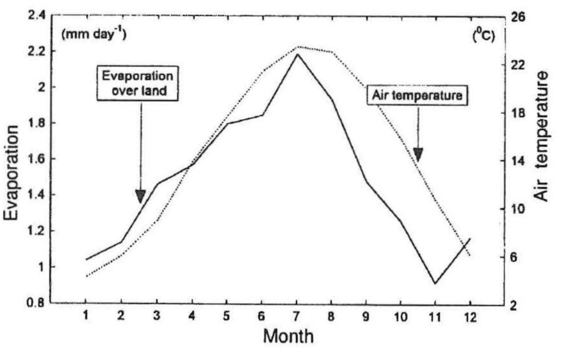

Fig. 3. Mean seasonal cycle of evaporation measured over the land and monthly mean air temperature

The greatest influence on evaporation in three equations comes from the difference (e_w-e_a), which is mainly determined by the temperature conditions of the two media. Seasonal cycles from the equations (2), (3) and (4) are similar to seasonality of the (e_w-e_a) (Fig. 4). Constants introduced in equations have only different attenuation effects.

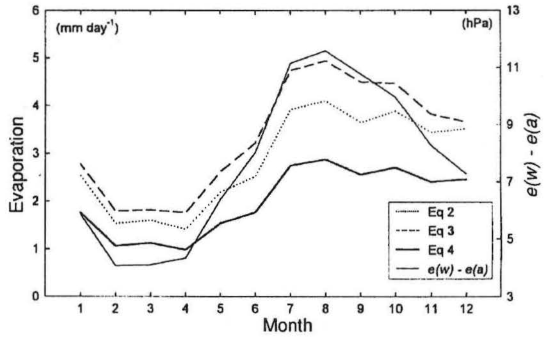

Fig. 4. Seasonal cycle of monthly mean evaporation calculated by equations (2), (3), (4) and monthly mean difference (ew-ea)

Correlation coefficients between evaporation, according to equations (2), (3) and (4) on one hand and all variables present in equations on the other, are presented in Table 2. Among all variables, sea surface temperature has the largest effect on variability in the equation (3), while it less affects equations (2) and (4). The wind also contributes to the variability of evaporation, but it influences more equations (2) and (4) than equation (3). The air pressure effect on the variability of evaporation was below the significance level, therefore it is reasonable to use equations with the constant pressure, on the monthly scale.

Table 2. Correlation coefficients between evaporation obtained by equations (2), (3) and (4), and air temperature, sea surface temperature, wind speed, relative humidity and air pressure

Eq.	Air Temp. (°C)	Sea surface temp. (°C)	Wind (m s^{-1})	Rel. Humidity (%)	Pressure (hPa)
(2)	0.31	0.55	0.58	-0.27	/
(3)	0.48	0.72	0.34	-0.20	/
(4)	0.31	0.55	0.58	-0.27	0.07

Because of different seasonal cycles of the evaporation over the sea and land, caused by different interface conditions, evaporation over the land, even for the station close to the sea, should not be used as evaporation over the sea.

Taking into account errors of measurements it is possible to determine which one of the three relations gave the smallest error or the smallest ∂E value. The ∂E is the total error as a result of the errors of measurements. Errors of measurements of anemograph (∂v), thermometer (∂t), hygrograph (∂RH) and barograph (∂p), given in the Annuario 1975 were taken as follows: $\partial v = 0.1$ ms^{-1}, $\partial t_w = \partial t_a = 0.1$ °C, $\partial RH = 2$ % and $\partial p = 0.1$ hPa.

Total relative errors are calculated from evaporation equations for the period 1961-1968 for the station Trieste. The errors from three relations were compared and the contribution of each component analyzed. Total relative errors are 0.118, 0.098 and 0.118 for eq. (2), (3) and (4), respectively. Mean values of the absolute errors of evaporation are 0.306 mm day^{-1} for equation (2), 0.302 mm day^{-1} for equation (3) and 0.212 mm day^{-1} for equation (4). From the comparison of evaporation calculated by different equations, it follows that equation (3) depends mostly on the sea temperature while equations (2) and (4) depend mostly on the wind speed.

Comparing relative error values (Fig. 5) it is possible to determine only which evaporation equation is the least sensitive to the error of each variable. Among all errors of measurement parameters, the error caused by the wind is the smallest in equation (3), since this equation resulted in the smallest total error. Since the estimated errors from these equations leades to the equation with the smallest error (equation (3)), it can not be the sufficient criteria for the proper selection of the evaporation equation over the sea.

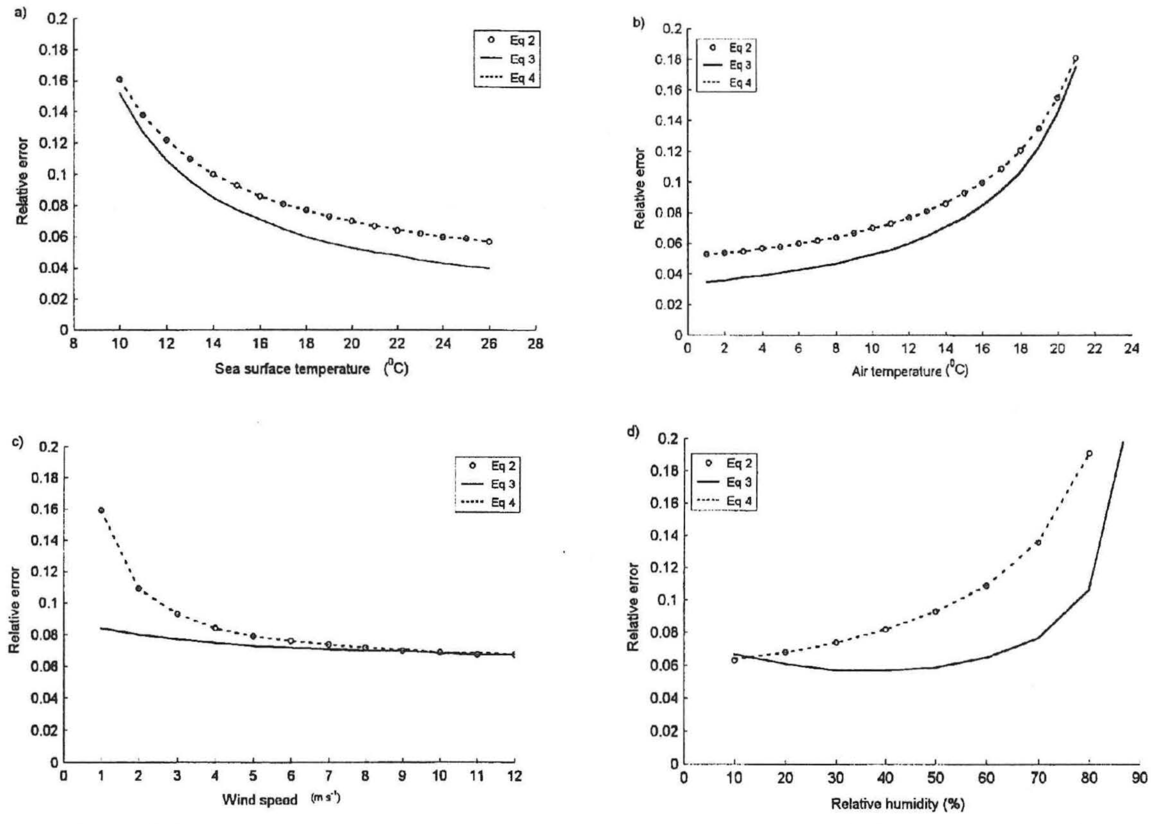

Fig. 5. Total relative error of measurements versus air temperature, sea temperature, wind speed and relative humidity

CONCLUSIONS

The differences in mean seasonal cycles of evaporation, obtained from bulk equations and evaporation measured over the land point to the fact that the evaporation over the sea and over the land is governed by different physical processes. Therefore, in determination of the most suitable equation for evaporation over the sea, evaporation over the land should not be used. The direct measurements of evaporation over the land may be relevant for the process over the sea when winds are blowing towards the shore. The most frequent wind in northern Adriatic is bora which blows from the land, so evaporation over the land and over the sea follows different regimes for most of the year. For proper estimation of evaporation over the sea, meteorological parameters used in the bulk equations should be measured over the sea and not over the land. The pan-water temperature from coastal station and thus saturation vapor pressure are not the same as those at the sea, responding more closely to overland air temperature than to the sea surface temperature. Similarly, wind speed is generally substantially lower over coast than at sea.

The comparison of errors showed that the smallest error resulted from equation (3), which should be recommended as the most suitable of all three equations, but only from the aspect of measurement's error. The best accuracy in equation (3) comes from its smallest sensitivity to wind measurement error. Therefore improving wind measurements accuracy will improve accuracy of other two equations.

Further studies should deal with the direct evaporation measurements above the sea through the eddy covariance technique, which would allow testing of bulk equations for the evaporation over the Adriatic under actual conditions.

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O problemu isparavanja nad Jadranskim morem

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SAŽETAK

Direktna su mjerenja isparavanja na otvorenom moru vrlo rijetka, te se za određivanje isparavanja često koriste različite parametrizacije empirijskih jednadžbi što rezultira različitim iznosima količine isparavanja. Kako direktna mjerenja isparavanja nad Jadranom ne postoje, za usporedbu s rezultatima triju polu-empirijskih jednadžbi korištena su mjerenja isparavanja na priobalnoj postaji (Trst, sjeverni Jadran). Pripadajuće pogreške, za svaku od polu-empirijskih jednadžbi, određene su na osnovi pogrešaka mjerenih varijabli koje se koriste u jednadžbama isparavanja. Značajan izvor pogrešaka u svim jednadžbama je pogreška pri mjerenju vjetra. Izneseni postupak određivanja ukupne relativne pogreške, čiji je uzrok pogreška u mjerenju, pogodan je samo kao postupak odabira jednadžbe koja je najmanje osjetljiva na pogreške mjerenja.