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# FACTORS INFLUENCING UNCERTAINTY EVALUATION FOR SURFACE ROUGHNESS MEASUREMENTS

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**Abstract** – The nominal conditions for measuring surface roughness when using stylus instruments are specified in ISO 3274. Deviations from these nominal conditions lead to significant deviations of the measured roughness parameters. An uncertainty evaluation has been made on five roughness parameters for three calibration standards. The methods and procedures for uncertainty evaluation are to i) calibrate and evaluate the uncertainty in the condition for the measuring instrument, ii) evaluate the influence of each individual deviation on the results of measurement, and iii) combine the effect of these individual uncertainties on the final result of measurement. A study has been carried out on the influence of different contributors on the combined uncertainty associated with the assessment of roughness parameters. From the results the major contributors affecting the uncertainty of measurement on different roughness parameters are given.

**Keywords**: Stylus Instrument, Surface Metrology, Uncertainty.

## 1. INTRODUCTION

Results for calibration of the roughness parameters of Roughness Calibration Standard are incomplete without a statement of the corresponding measurement uncertainty. To be able to evaluate this uncertainty, a study on the major deviations in conditions of the measuring system and their influence on the roughness parameter measured has been carried out [1].

Accurate stylus instruments are used to calibrate these calibration standards. The nominal measurement conditions of stylus instrument are prescribed in ISO 3274[2]. Possible deviations in any of these conditions may exist and will affect the value of roughness parameters measured. The procedure used is that a roughness parameter is calculated according to the nominal conditions, then re-calculated according to the nominal instrument conditions plus the deviation in the actual conditions and the difference is taken as a measure of the error in the parameter.

## 2. MAIN UNCERTAINTY CONTRIBUTORS

The procedure of evaluating the associated uncertainty conforms to the law of propagation of uncertainty as given in the Guide to the Expression of Uncertainty in Measurement (GUM). The combined standard uncertainty is given in "(1),":

$$u_c^2(y) = \sum_{i=1}^{N} \left[c_i \cdot u(x_i)\right]^2 . \tag{1}$$

where: $c_i$ is the sensitivity coefficients

and $u(x_i)$ is the uncertainty value for the (i) contributor

The main sources contributing to the uncertainty in roughness measurement by stylus method [3] are considered to be due to :-

a- uncertainty in Z-axis calibration: $c_{ZC} \cdot u_{ZC}$
b- uncertainty in X-axis calibration: $c_{XC} \cdot u_{XC}$
c- uncertainty in straightness in the external guide: $c_{sg} \cdot u_{sg}$
d- noise: $c_{no} \cdot u_{no}$
e- uncertainty in stylus geometry: $c_{st} \cdot u_{st}$
f- uncertainty in measuring force: $c_{mf} \cdot u_{mf}$
g- uncertainty in filter characteristic: $c_{f\lambda} \cdot u_{f\lambda}$
 $g_1$ - uncertainty in short cut-off: $c_{f\lambda s} \cdot u_{f\lambda s}$
 $g_2$ - uncertainty in long cut-off: $c_{f\lambda c} \cdot u_{f\lambda c}$
h- uncertainty in sampling interval: $c_{si} \cdot u_{si}$
i- repeatability: $c_{rpt} \cdot u_{rpt}$
j- homogeneity: $c_{hg} \cdot u_{hg}$

Equation "(1)" could be written as:

$$\begin{aligned} u_c^2(Rp) = {} & \left[c_{zc} \cdot u_{zc}\right]^2 + \left[c_{xc} \cdot u_{xc}\right]^2 + \left[c_{sg} \cdot u_{sg}\right]^2 \\ & + \left[c_{no} \cdot u_{no}\right]^2 + \left[c_{st} \cdot u_{st}\right]^2 + \left[c_{mf} \cdot u_{mf}\right]^2 \\ & + \left[c_{f\lambda} \cdot u_{f\lambda}\right]^2 + \left[c_{si} \cdot u_{si}\right]^2 + \left[c_{rpt} \cdot u_{rpt}\right]^2 \\ & + \left[c_{hg} \cdot u_{hg}\right]^2 \end{aligned} \tag{2}$$

Where: $u_c$ is the combined standard uncertainty of the estimated roughness parameter *Rp*

## 3. STANDARDS AND PARAMETERS INVESTIGATED

### 3.1 *Roughness Calibration Standard*

The calibration standards have different types and classification according to ISO 5436-1 [4]. Three types of calibration standards have been selected for investigation. These standards are as follow: i) type B2: having an isosceles triangular roughness profile and is produced by

Rubert, the calibration standard studied has nominal roughness parameters of Ra=0.4 µm, and RSm=15 µm, ii) type C1: having a sinusoidal roughness profile and is produced by National Institute for Standards and Technology (NIST) AND IS KNOW AS standard Reference Material (SRM-2073), with nominal Ra=3.05 µm and RSm=100 µm, and iii) type C3: have a truncated triangular roughness profile, as an example Rank Taylor Hobson (RTH) standard which has rectangular profile pattern is investigated, it has Ra=0.80 µm and RSm=80 µm.

### *3.2 Roughness Parameters under Investigation*

The roughness parameters investigated are as specified in ISO 4287 [5]. The selected parameters to be under study are: the arithmetical mean deviation of the assessed profile, Ra; the maximum height of profile, Rz, total height of profile, Rt, the mean width of the profile elements, RSm, the root-mean-square slope of the assessed profile, RΔq.

## 4. SENSITIVITY COEFFICIENTS

A theoretical study has been carried out using simulating signals to determine the sensitivity coefficients ($c_i$) used in evaluating uncertainty budged. These signals are chosen to simulate the roughness profiles patterns of the calibration standard under investigation. Three different signals were generated theoretically having isosceles triangular, sinusoidal and rectangular patterns that have same heights and space wavelength as those of the calibration standards. These signals have been evaluated when applying the nominal conditions specified for the instrument. A small change in each one of the conditions is artificially made, keeping other condition constant and the corresponding change in the roughness parameters is re-calculated. The sensitivity coefficients are the percentage of the change in parameter with respect to the percentage change in condition. Tables I to V show the sensitivity coefficients for some measuring conditions influencing Ra, Rz, Rt, RSm and RΔq values respectively. Note that; i) the uncertainties in the Z-axis directly affect any amplitude parameter, but not spacing parameters, so that the $c_{zc}$ is taken as unity for all amplitude parameters, ii) the sensitivity coefficients for the repeatability and homogeneity also directly affect any parameter it is considered to be unity. The effect of stylus geometry (tip radius and cone angle) on the roughness parameter using probes with different styli had been studied theoretically and experimentally. Kruger-Sehm and Krystek [6] studied this effect using simulation method. Styli with different radii were moved over the same surface profile for three different surfaces (coarse, medium and fine surface). They found that Rz is varied -20nm per 1µm tip radius. Also, Haitjiema [3] studied the effect of stylus geometry (tip radius "Stip" and cone angle "Stca") on the roughness parameters experimentally. He calculated the percentage error in the measured parameter per the percentage change in stylus geometry. The results have been taken in the calculation of the uncertainty budged.

TABLE I. The sensitivity coefficients for Ra

| Calibration Standard | $c_{sg}$ %/nm | $c_{no}$ %/nm | $c_{mf}$ %/% | $c_{si}$ %/% | $c_{xc}$ %/% | $c_{f\lambda c}$ %/% | $c_{f\lambda s}$ %/% |
|---|---|---|---|---|---|---|---|
| TypeC1 | 0.0001 | 0.0003 | 0.00004 | 0.0002 | 0.2705 | 0.0208 | 0.0009 |
| Type C3 | 0.0000 | 0.0006 | 0.00027 | 0.0044 | 0.0088 | 0.0183 | 0.0154 |
| Type B2 | 0.0003 | 0.0007 | 0.00013 | 0.0030 | 0.0353 | 0.0052 | 0.0279 |

TABLE II. The sensitivity coefficients for Rz

| Calibration Standard | $c_{sg}$ %/nm | $c_{no}$ %/nm | $c_{mf}$ %/% | $c_{si}$ %/% | $c_{xc}$ %/% | $c_{f\lambda c}$ %/% | $c_{f\lambda s}$ %/% |
|---|---|---|---|---|---|---|---|
| TypeC1 | 0.0002 | 0.0160 | 0.00001 | 0.0004 | 0.00 | 0.0208 | 0.0008 |
| Type C3 | 0.0013 | 0.1257 | 0.00005 | 0.0004 | 0.00 | 0.0183 | 0.0005 |
| Type B2 | 0.0015 | 0.1257 | 0.00011 | 0.0226 | 0.00 | 0.0052 | 0.1152 |

TABLE III. The sensitivity coefficients for Rt

| Calibration Standard | $c_{sg}$ %/nm | $c_{no}$ %/nm | $c_{mf}$ %/% | $c_{si}$ %/% | $c_{xc}$ %/% | $c_{f\lambda c}$ %/% | $c_{f\lambda s}$ %/% |
|---|---|---|---|---|---|---|---|
| TypeC1 | 0.0006 | 0.0288 | 0.00003 | 0.0004 | 0.00 | 0.0208 | 0.0008 |
| Type C3 | 0.0037 | 0.1495 | 0.00018 | 0.0010 | 0.00 | 0.0183 | 0.0005 |
| Type B2 | 0.0039 | 0.1269 | 0.00018 | 0.0226 | 0.00 | 0.0052 | 0.1152 |

TABLE IV. The sensitivity coefficients for RSm

| Calibration Standard | $c_{sg}$ %/nm | $c_{no}$ %/nm | $c_{mf}$ %/% | $c_{si}$ %/% | $c_{xc}$ %/% | $c_{f\lambda c}$ %/% | $c_{f\lambda s}$ %/% |
|---|---|---|---|---|---|---|---|
| TypeC1 | 0.00 | 0.0001 | 0.00004 | 0.00 | 1 | 0.00 | 0.00 |
| Type C3 | 0.00 | 0.0000 | 0.00012 | 0.00 | 1 | 0.00 | 0.00 |
| Type B2 | 0.00 | 0.0002 | 0.00001 | 0.00 | 1 | 0.00 | 0.00 |

TABLE V. The sensitivity coefficients for RΔq

| Calibration Standard | $c_{sg}$ %/nm | $c_{no}$ %/nm | $c_{mf}$ %/% | $c_{si}$ %/% | $c_{xc}$ %/% | $c_{f\lambda c}$ %/% | $c_{f\lambda s}$ %/% |
|---|---|---|---|---|---|---|---|
| TypeC1 | 0.00 | 0.0101 | 0.00020 | 0.0001 | 0.2387 | 0.0208 | 0.0008 |
| Type C3 | 0.00 | 0.0118 | 0.00045 | 0.0015 | 0.5078 | 0.0018 | 0.5102 |
| Type B2 | 0.00 | 0.0102 | 0.00020 | 0.0102 | 0.0037 | 0.0054 | 0.0816 |

## 5. NOMINAL AND ACTUAL CONDITIONS

A stylus measuring instrument has been used in the calibration of these standards. The primary profile is nominally measured as unfiltered signal using skidless mode of operation using a straight guide. The profile should be leveled then filtered using a Gaussian filter of a short and long cut-offs λs= 2.5 µm and λc = 0.8 mm respectively. The traverse length should be equal to seven long cut-offs, after filtering one cut-off length is neglected at each end of the two ends of the roughness profile; i.e. the evaluation length (ln) is equal to five long cut-offs (4mm). The nominal conditions of the probe are:- stylus tip radius = 2 µm; stylus cone angle= $90^o$ , measuring force = o.75 mN and nominal sampling interval = 0.5 µm. The instrument was calibrated to account for the deviations in the instrument condition from the nominal condition specified. The Z-axis, X-axis, the straightness in the external guide, the noise, the stylus geometry, the measuring force and the filter characteristic were calibrated, and uncertainties in their values were determined. Their uncertainty values are shown within Table VI to VIII.

## 6. UNCERTANITY RESULTS

The budget of uncertainty was determined and tabulated, were the repeatability, $u_{rpt}$, has been evaluated experimentally for each specimen and the homogeneity, $u_{hg}$, has been evaluated from the scatter of measurements values over the test surface. Applying "(2)" the combined standard uncertainties for different parameters were computed. The expanded uncertainty were computed with K=2. Examples of the uncertainty budget are given for Ra parameter for the three different calibration standards used, shown in Table VI to VIII.

TABLE VI The uncertainty evaluation of Ra parameter for Type C1 calibration standard of sinusoidal pattern

| Uncertainty components | | Sensitive Coefficients | $u_i$ *$c_i$ |
|---|---|---|---|
| $u_i$ | Value | $c_i$ | % |
| $u_{zc}$ | 0.3 % | 1 | 0.3 |
| $u_{xc}$ | 0.23 % | 0.2705 % | 0.0622 |
| $u_{sg}$ | 20 nm | 0.0001 %/nm | 0.002 |
| $u_{no}$ | 10 nm | 0.0003 %/nm | 0.003 |
| $u_{stip}$ | 6.5 % | 0.0008 % | 0.0052 |
| $u_{stca}$ | 0.89 % | 0.005 % | 0.0045 |
| $u_{mf}$ | 100 % | 0.00004 % | 0.004 |
| $u_{f\lambda s}$ | 1.25 % | 0.0009 % | 0.0011 |
| $u_{f\lambda c}$ | 1.34 % | 0.0208 % | 0.0279 |
| $u_{si}$ | 0 % | 0.0002 % | 0 |
| $u_{rpt}$ | 0.0355% | 1 | 0.0355 |
| $u_{hg}$ | 0.0619% | 1 | 0.0619 |
| $u_{c\,\%}$ | | | 0.3160 % |
| $U\,\%$ | K=2 | | 0.6319 % |

Ra = 3.036±0.63% =3.036±0.019 μm

TABLE VII The uncertainty evaluation of Ra parameter for Type C3 calibration standard of rectangular pattern

| Uncertainty components | | Sensitive Coefficients | $u_i$ *$c_i$ |
|---|---|---|---|
| $u_i$ | Value | $c_i$ | % |
| $u_{zc}$ | 0.3 % | 1 | 0.3 |
| $u_{xc}$ | 0.23 % | 0.0088 % | 0.002 |
| $u_{sg}$ | 20 nm | 0 %/nm | 0 |
| $u_{no}$ | 10 nm | 0.0006 %/nm | 0.006 |
| $u_{stip}$ | 6.5 % | 0.01 % | 0.065 |
| $u_{stca}$ | 0.89 % | 0.016 % | 0.0142 |
| $u_{mf}$ | 100 % | 0.00027 % | 0.027 |
| $u_{f\lambda s}$ | 1.25 % | 0.0145 % | 0.019 |
| $u_{f\lambda c}$ | 1.34 % | 0.0183 % | 0.0245 |
| $u_{si}$ | 0 % | 0.0044 % | 0 |
| $u_{rpt}$ | 0.1268% | 1 | 0.1268 |
| $u_{hg}$ | 0.2929% | 1 | 0.2929 |
| $u_{c\,\%}$ | | | 0.4450 % |
| $U\,\%$ | K=2 | | 0.8900 % |

Ra = 0.808±0.89% =0.808±0.0072 μm

"Fig.2" to "Fig.4" show the relative effect of the different contributors on Rz, Rt, RSm and RΔq respectively, for the three calibration standards investigated.

Table IX shows a summary of the uncertainty value in determining different roughness parameters with its main contributor affecting its value.

"Fig.1" shows the relative effect of the different contributors on Ra value for the three calibration standards investigated.

TABLE VIII The uncertainty evaluation of Ra parameter for Type B2 calibration standard of triangular pattern

| Uncertainty components | | Sensitive Coefficients | $u_i$ *$c_i$ |
|---|---|---|---|
| $u_i$ | Value | $c_i$ | % |
| $u_{zc}$ | 0.3 % | 1 | 0.3 |
| $u_{xc}$ | 0.23 % | 0.0353 % | 0.0081 |
| $u_{sg}$ | 20 nm | 0.0003 %/nm | 0.006 |
| $u_{no}$ | 10 nm | 0.0007 %/nm | 0.007 |
| $u_{stip}$ | 6.5 % | 0.04 % | 0.26 |
| $u_{stca}$ | 0.89 % | 0.007 % | 0.0062 |
| $u_{mf}$ | 100 % | 0.00013 % | 0.013 |
| $u_{f\lambda s}$ | 1.25 % | 0.0279 % | 0.0349 |
| $u_{f\lambda c}$ | 1.34 % | 0.0052 % | 0.0070 |
| $u_{si}$ | 0 % | 0.003 % | 0 |
| $u_{rpt}$ | 0.1867% | 1 | 0.1867 |
| $u_{hg}$ | 0.2643% | 1 | 0.2643 |
| $u_{c\,\%}$ | | | 0.5137 % |
| $U\,\%$ | K=2 | | 1.0275 % |

Ra = 0.399±1.03% = 0.399±0.0041μm

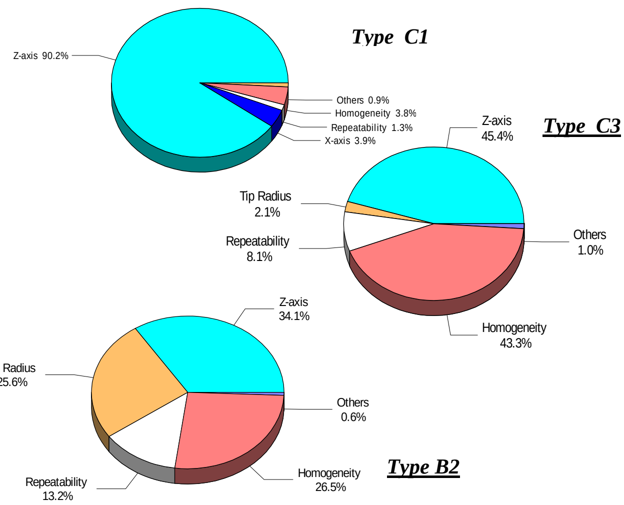


Fig. 1 :PI chart for Ra

TABLE IX. The percentage of expanded uncertainty for different parameters with its main contributor

| Calibration Standards | Expanded uncertainty (%); (main factor) | | | | |
|---|---|---|---|---|---|
| | Ra % | Rz % | Rt % | RSm % | RΔq % |
| Type C1 | 0.63;(a) | 0.73;(a) | 0.87;(a) | 0.49;(b) | 0.74;(j) |
| Type C3 | 0.89;(a) | 2.61;(d) | 1.59;(d) | 0.66;(b) | 1.84;($g_1$) |
| Type B2 | 1.03;(a) | 3.45;(d) | 4.94;(j) | 0.61;(b) | 0.99;($g_1$) |

## 7. CONCLUSIONS

1-The major contributor(s) affecting the values of the parameters are as follows: for Ra is the uncertainty due to the calibration of the Z-axis; for Rz and Rt is the noise of the measuring system; for RSm is the uncertainty in the calibration of the X-axis; for RΔq is the uuncertainties due to homogeneity and repeatability.

2- Type C1 calibration standard gives smallest values of uncertainty with all parameters, so it could be used for calibrating purposes also it was less sensitive to tip radius except for the mean slop parameter RΔq.

3-The uncertainties associated with Type B2 calibration standard are much higher than other standards especially for amplitude parameters (Ra, Rz and Rt). The effect of uncertainty of stylus tip radius is more pronounced when assigning Ra value.

4-Type C3 calibration standard gives relatively small value of uncertainty with Ra parameter, so it could be used for calibration purposes of Ra meter. This Type gives the highest uncertainty in the mean slop parameter RΔq and it is recommended not to use this type for the calibration of the mean slop parameter RΔq.

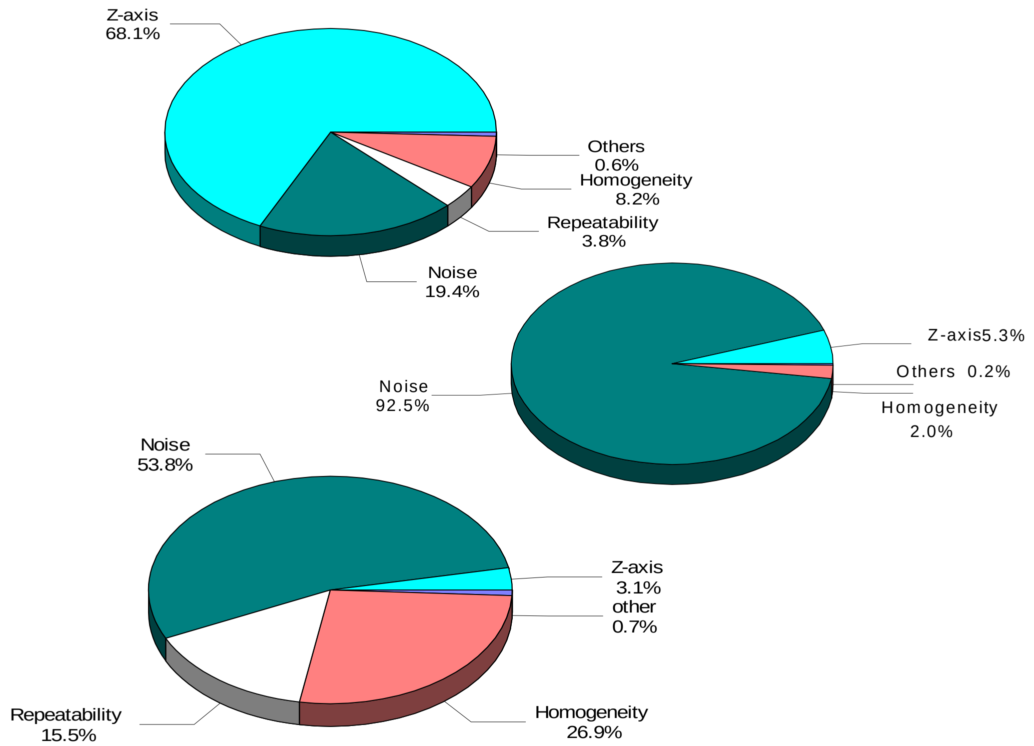


Fig. 2 :PI chart for Rz

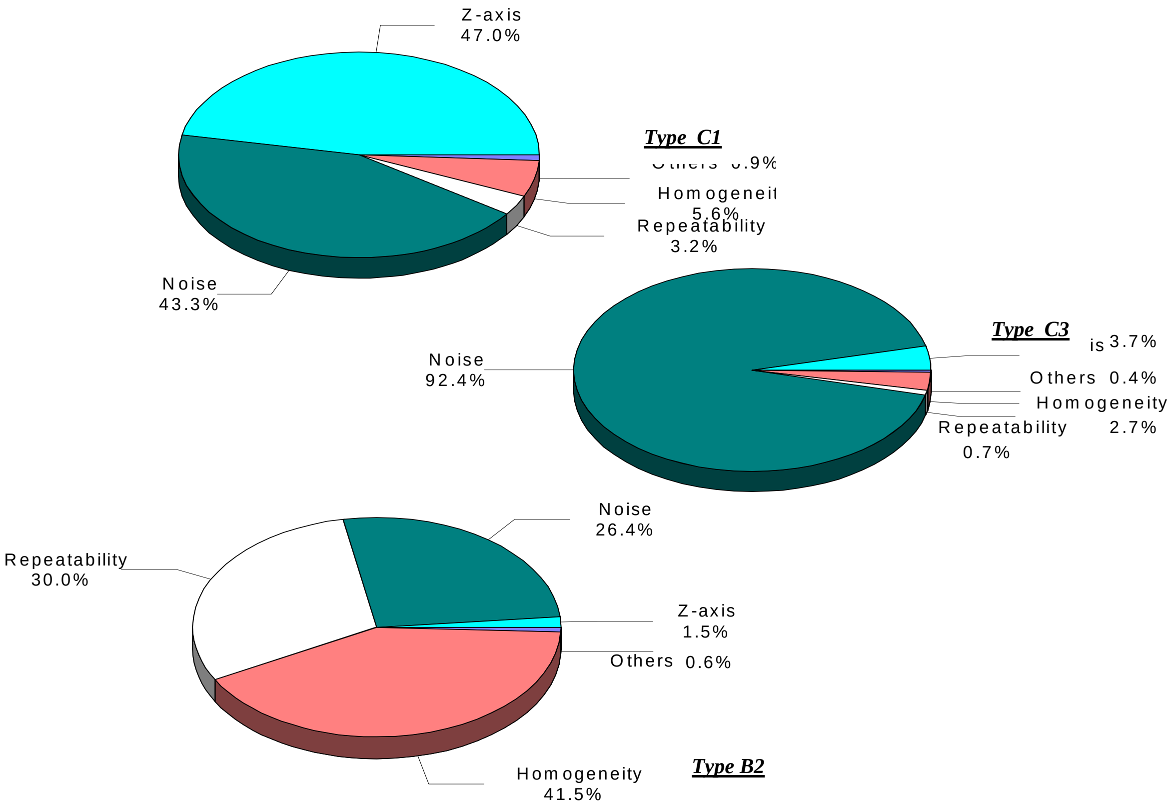


Fig. 3 :PI chart for Rt

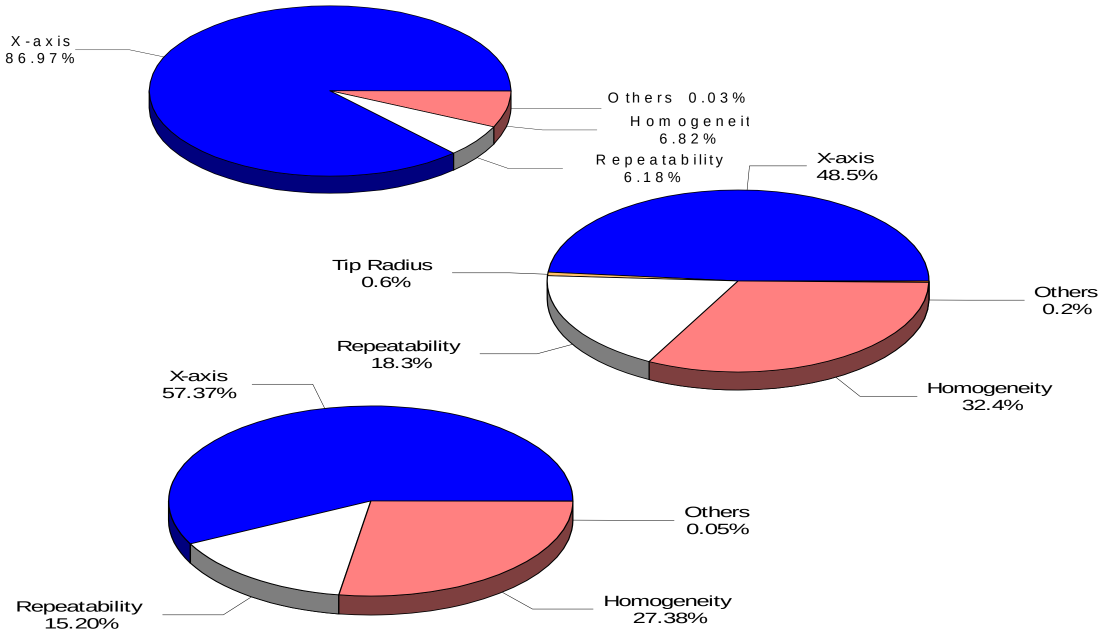


Fig. 4 :PI chart for RSm

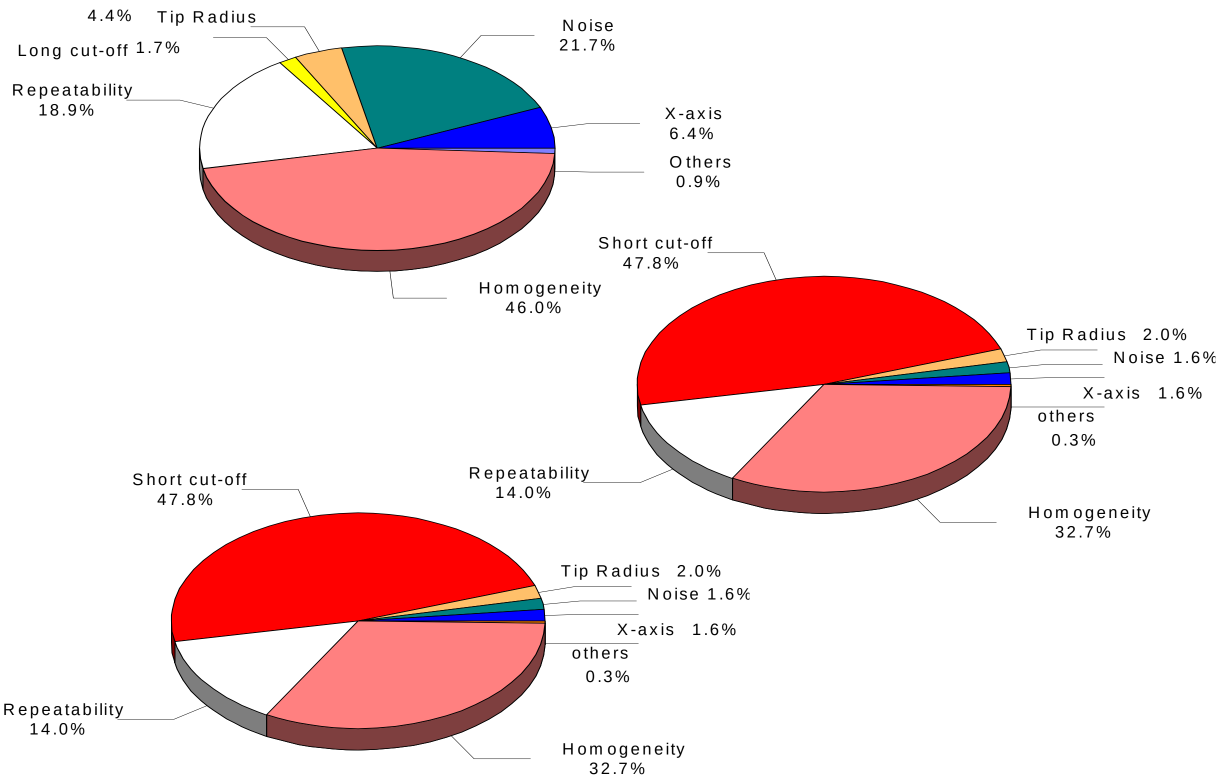


Fig. 5 :PI chart for RΔq

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