COOMET Supplementary Comparison on Fiber Optic Power Responsivity

COOMET.PR-S6.2012

Final Report

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Abstract

PTB, BelGIM and VNIIOFI conducted a supplementary comparison on the fiber optic power responsivity at 1308.9 nm and 1548.8 nm. The aim of this comparison is to examine the equivalence of the fiber optic power responsivity among participating laboratories and to provide supporting evidence for associated CMC claims in BIPM KCDB.
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1. Introduction

The present report concerns the supplementary comparison COOMET.PR-S6, international comparison of fiber optic power responsivity measurements at the wavelength of 1308.9 nm and 1548.8 nm, piloted by VNIIOFI. The technical protocol was prepared by VNIIOFI and agreed by all the other participants. The comparison was carried out through the calibration of a fiber optic power meter chosen as the comparison artifact. The comparison was organized in a star format as [pilot]-[participant]-[pilot].

The comparison measurement began in October, 2012 with three participants.

More details can be found in the Technical Protocol of the COOMET.PR-S6 comparison [1].
2. Organization of the comparison

2.1. Participants

VNIIOFI is the pilot laboratory in the supplementary comparison among the participants. The name of the participants in the order of measurement: PTB (Germany), BelGIM (Belarus). All the participants were able to demonstrate traceability to an independent realization of the quantity or make clear the route of traceability to the quantity via another named laboratory at the time of comparison measurements.

2.2. Participants’ details

Table 2-2-1. Contact list of participants.

<table>
<thead>
<tr>
<th>NMI Name (Country)</th>
<th>Personnel</th>
<th>Contact information</th>
</tr>
</thead>
</table>
| **PTB** (Germany)  | Stefan Kück | Physikalisch-Technische Bundesanstalt  
AG 4.5 Optische Technologien  
FB 4.5 Laserradiometrie  
Bundesallee 100, 38116 Braunschweig  
Telefon: +49 531 592-4100  
Telefax: +49 531 592-694100  
E-mail: stefan.kueck@ptb.de |
| **BelGIM** (Belarus) | Alexander Galygo | Republican Unitary Enterprise  
“Belarussian State Institute of Metrology”  
93, Starovilensky trakt, Minsk, 220053  
Republic of Belarus  
Telefon: +375 17 233-62-73  
Telefax: +375 17 288-09-38  
E-mail: galygo@belgim.by |
| **VNIIOFI** (Russia) | Alexey Svetlichny Vladimir Kravtsov | Laboratory of low-intensity laser radiation and fiber-optical systems metrology  
All Russian Research Institute for Optical and Physical Measurements (VNIIOFI)  
46 Ozernaya street, Moscow 119361, Russia  
Tel.: +7 495 7814587, 7814586  
Fax.: +7 495 7814587, 4373147  
E-mail: Svetlichny@vniofi.ru; Kravtsov-f3@vniofi.ru |
2.3. Form of the comparison

The comparison was carried out through the calibration of a fiber optic power meter prepared by VNIIOFI. A detailed description of the fiber optic power meter used in this comparison is given in section 3. The fiber optic power meter consists of an optical head, a unit for control and display, and an electrical cable connecting them. The participants used one and the same FC/PC type fiber optic patch cord prepared by VNIIOFI to reduce the uncertainty from using different kinds of fiber optic connector.

The comparison was organized in a star type format. VNIIOFI calibrated the artifact first and then sent it to a participant. The participant calibrated it and returned the artifact to VNIIOFI. VNIIOFI re-calibrate it to check the drift during the period of transportation and measurements in a different country. The process was repeated until all the participants finished their calibration.

It was agreed that each participant should report its correction factor at 1308.9 nm and 1548.8 nm at the radiant power level which is more then 0.3 mW and less then 1 mW.

In addition, it was agreed that each participant should specify the type of the optical source used, center wavelength with uncertainty defined in the technical protocol.

Finally, it was agreed that it is the participants’ responsibility to report the actual wavelengths used, corrections to be made to the measurement results for the center wavelength offsets and uncertainties associated with such corrections. The participants should make corrections based on the spectral responsivity data of the transfer power meter.
2.4. Timetable

Timetable of the original plan of the comparison in the technical protocol is as shown in the following table.

Table 2-4-1. Scheduled timetable of the comparison in the beginning

<table>
<thead>
<tr>
<th>Activity</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation of technical protocol and invitation of participants to members</td>
<td>October 2012</td>
<td>October 2012</td>
</tr>
<tr>
<td>Confirmation of participation by member labs and revision of protocol</td>
<td>October 2012</td>
<td>October 2012</td>
</tr>
<tr>
<td>Submission of technical protocol to COOMET TCPR for approval</td>
<td>October 2012</td>
<td>November 2012</td>
</tr>
<tr>
<td>Measurements at VNIIOFI</td>
<td>November 2012</td>
<td>November 2012</td>
</tr>
<tr>
<td>Measurements at PTB</td>
<td>November 2012</td>
<td>November 2012</td>
</tr>
<tr>
<td>Measurements at VNIIOFI</td>
<td>November 2012</td>
<td>December 2012</td>
</tr>
<tr>
<td>Measurements at BelGIM</td>
<td>December 2012</td>
<td>December 2012</td>
</tr>
<tr>
<td>Measurements at VNIIOFI</td>
<td>December 2012</td>
<td>December 2012</td>
</tr>
<tr>
<td>Materials submission to VNIIOFI</td>
<td>December 2012</td>
<td>January 2013</td>
</tr>
<tr>
<td>Draft A report preparation</td>
<td>February 2013</td>
<td>June 2013</td>
</tr>
</tbody>
</table>

However, the actual measurements were delayed from the above plan due to each laboratory’s specific circumstance, the customs clearance and so on. The following table shows the summary of history.

Table 2-4-2. History of the comparison measurements

<table>
<thead>
<tr>
<th>Activity</th>
<th>Occupied period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements at VNIIOFI</td>
<td>01 November 2012 - 10 November 2012</td>
</tr>
<tr>
<td>Measurements at PTB</td>
<td>21 November 2012 - 30 November 2012</td>
</tr>
<tr>
<td>Measurements at VNIIOFI</td>
<td>10 December 2012 - 20 December 2012</td>
</tr>
<tr>
<td>Measurements at BelGIM</td>
<td>25 December 2012 - 20 January 2013</td>
</tr>
<tr>
<td>Measurements at VNIIOFI</td>
<td>01 February 2013 - 10 February 2013</td>
</tr>
</tbody>
</table>

All the comparison reports from participants arrived to VNIIOFI by the end of May, 2013.
3. Description of the artifact

The VNIIOFI measurement artifact (transfer standard) is a fiber optic power meter consisting of a control unit and an optical head to accept light from the FC type fiber optic connector end. The control unit and the optical head are linked with an electrical cable. The control unit is Keithley 2502 picoammeter. It provides with an LCD display panel indicating the photocurrent level in amperes. The optical head is an integrating sphere with InGaAs photodiode. The sphere is included in metallic cylindrical box which is placed on metallic plate (removable). Two triaxial cables with the length of 1,2 m each go out of this box. The controller box is provided for thermostatic control of photodiode inside the optical head. Fiber optic patch cords are included in the artifact.

![Fig. 3-1. Photographs of the artifact](image)

Fig. 3-1 shows the artifact and the case to transport from one country to another. The control unit, the optical head and the thermal control unit were put into Peli case (lower write quarter of the photo) each into special housing.
4. Measurement Capability and Results of Pilot Laboratory

4.1. Description of measurement facility

The VNIIOFI primary standard is a compact laboratory calorimeter with registration and calibration system operating at room temperature and capable of electrical calibration. It incorporates two sensitive cavity-type absorbers (receiving and compensating) with a substitution heater for electrical calibration. Calibration is accomplished by direct substitution of electrically injected power using techniques to reduce drift in ambient conditions. A high fraction of the incident power is absorbed by the cavity with small spectral dependence. Equivalence of optical and electrically injected power is high with nonequivalence coefficient of 1.0018. Input to the detector is achieved through an optical-fiber adapter. The detector exhibits the responsivity of 0.27 V/W.

For the calibration of the transfer standard the following procedure was used. Fiber-optic patch cord was attached to the fiber adapter of primary calorimeter, the other connector of the patch cord remained unconnected. The laser source operating at 1308.9 nm and 1548.8 nm (Ando AQ-2140) was switched on. The electrical calibration of the calorimeter was performed. Then free connector of the patch cord was attached to the output of the laser source at required wavelength. Five minutes later the readings of the registration system were transferred to the optical power using the electrical calibration results. Then the patch cord was disconnected from the calorimeter input and attached to the optical input of the transfer standard and the corresponding readings were registered.

The description of VNIIOFI primary calorimeter is given in [1].

4.2. Laboratory conditions

The laboratory temperature was controlled to be (23 ± 1) °C and the humidity (45 ± 15) % throughout the calibration and measurements.

4.3. Measurement results

Table 4-3-1 to Table 4-3-3 summarize the measurement results of VNIIOFI.
Table 4-3-1. Comparison data at 1308.9 nm – first measurements, before PTB

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, ( P_{\text{VNIIOFI}} ), mW</th>
<th>Transfer standard output, ( I_{\text{TRS}} ), ( \mu \text{A} )</th>
<th>Transfer standard responsivity, ( \frac{I_{\text{TRS}}}{P_{\text{VNIIOFI}}} ), mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84750</td>
<td>0.79865</td>
<td>0.94236</td>
</tr>
<tr>
<td>2</td>
<td>0.64508</td>
<td>0.60765</td>
<td>0.94198</td>
</tr>
<tr>
<td>3</td>
<td>0.82563</td>
<td>0.77850</td>
<td>0.94292</td>
</tr>
<tr>
<td>4</td>
<td>0.88867</td>
<td>0.83812</td>
<td>0.94312</td>
</tr>
<tr>
<td>5</td>
<td>0.86585</td>
<td>0.81615</td>
<td>0.94260</td>
</tr>
<tr>
<td>6</td>
<td>0.86250</td>
<td>0.81342</td>
<td>0.94310</td>
</tr>
<tr>
<td>7</td>
<td>0.67315</td>
<td>0.63520</td>
<td>0.94362</td>
</tr>
<tr>
<td>8</td>
<td>0.87797</td>
<td>0.82766</td>
<td>0.94270</td>
</tr>
<tr>
<td>9</td>
<td>0.83858</td>
<td>0.79096</td>
<td>0.94321</td>
</tr>
<tr>
<td>10</td>
<td>0.79923</td>
<td>0.75382</td>
<td>0.94318</td>
</tr>
</tbody>
</table>

Mean value 0.94288

Standard deviation of the mean, % 0.016

Table 4-3-2. Comparison data at 1548.8 nm – first measurements, before PTB

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, ( P_{\text{VNIIOFI}} ), mW</th>
<th>Transfer standard output, ( I_{\text{TRS}} ), ( \mu \text{A} )</th>
<th>Transfer standard responsivity, ( \frac{I_{\text{TRS}}}{P_{\text{VNIIOFI}}} ), mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84182</td>
<td>0.55935</td>
<td>0.66445</td>
</tr>
<tr>
<td>2</td>
<td>0.86319</td>
<td>0.57320</td>
<td>0.66405</td>
</tr>
<tr>
<td>3</td>
<td>0.81824</td>
<td>0.54335</td>
<td>0.66405</td>
</tr>
<tr>
<td>4</td>
<td>0.81689</td>
<td>0.54350</td>
<td>0.66533</td>
</tr>
<tr>
<td>5</td>
<td>0.76029</td>
<td>0.50505</td>
<td>0.66429</td>
</tr>
<tr>
<td>6</td>
<td>0.76928</td>
<td>0.51045</td>
<td>0.66354</td>
</tr>
<tr>
<td>7</td>
<td>0.69648</td>
<td>0.46244</td>
<td>0.66397</td>
</tr>
<tr>
<td>8</td>
<td>0.86574</td>
<td>0.57570</td>
<td>0.66498</td>
</tr>
<tr>
<td>9</td>
<td>0.75807</td>
<td>0.50439</td>
<td>0.66536</td>
</tr>
<tr>
<td>10</td>
<td>0.66889</td>
<td>0.44442</td>
<td>0.66441</td>
</tr>
</tbody>
</table>

Mean value 0.66444

Standard deviation of the mean, % 0.029

Table 4-3-3. Summary results – before PTB

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Standard uncertainty, %</th>
<th>Expanded uncertainty, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9</td>
<td>0.9429</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>1548.8</td>
<td>0.6644</td>
<td>0.23</td>
<td>0.46</td>
</tr>
</tbody>
</table>
### Table 4-3-4. Comparison data at 1308.9 nm – after PTB

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, ( P_{\text{VNIIOFI}} ), mW</th>
<th>Transfer standard output, ( I_{\text{TRS}} ), ( \mu )A</th>
<th>Transfer standard responsivity, ( I_{\text{TRS}} / P_{\text{VNIIOFI}} ), mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75275</td>
<td>0.70820</td>
<td>0.94081</td>
</tr>
<tr>
<td>2</td>
<td>0.74016</td>
<td>0.69540</td>
<td>0.93953</td>
</tr>
<tr>
<td>3</td>
<td>0.70771</td>
<td>0.66500</td>
<td>0.93965</td>
</tr>
<tr>
<td>4</td>
<td>0.72123</td>
<td>0.67775</td>
<td>0.93971</td>
</tr>
<tr>
<td>5</td>
<td>0.73310</td>
<td>0.68850</td>
<td>0.93917</td>
</tr>
<tr>
<td>6</td>
<td>0.74722</td>
<td>0.70119</td>
<td>0.93840</td>
</tr>
<tr>
<td>7</td>
<td>0.60937</td>
<td>0.57209</td>
<td>0.93882</td>
</tr>
<tr>
<td>8</td>
<td>0.75876</td>
<td>0.71269</td>
<td>0.93928</td>
</tr>
<tr>
<td>9</td>
<td>0.75468</td>
<td>0.70858</td>
<td>0.93891</td>
</tr>
<tr>
<td>10</td>
<td>0.73561</td>
<td>0.69031</td>
<td>0.93842</td>
</tr>
</tbody>
</table>

Mean value: 0.93927

Standard deviation of the mean, %: 0.024

### Table 4-3-5. Comparison data at 1548.8 nm – after PTB

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, ( P_{\text{VNIIOFI}} ), mW</th>
<th>Transfer standard output, ( I_{\text{TRS}} ), ( \mu )A</th>
<th>Transfer standard responsivity, ( I_{\text{TRS}} / P_{\text{VNIIOFI}} ), mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72669</td>
<td>0.48124</td>
<td>0.66224</td>
</tr>
<tr>
<td>2</td>
<td>0.64898</td>
<td>0.42934</td>
<td>0.66157</td>
</tr>
<tr>
<td>3</td>
<td>0.67122</td>
<td>0.44428</td>
<td>0.66190</td>
</tr>
<tr>
<td>4</td>
<td>0.79603</td>
<td>0.52707</td>
<td>0.66212</td>
</tr>
<tr>
<td>5</td>
<td>0.83210</td>
<td>0.55056</td>
<td>0.66165</td>
</tr>
<tr>
<td>6</td>
<td>0.83341</td>
<td>0.55212</td>
<td>0.66248</td>
</tr>
<tr>
<td>7</td>
<td>0.73925</td>
<td>0.48940</td>
<td>0.66202</td>
</tr>
<tr>
<td>8</td>
<td>0.69772</td>
<td>0.46182</td>
<td>0.66190</td>
</tr>
<tr>
<td>9</td>
<td>0.83312</td>
<td>0.55100</td>
<td>0.66137</td>
</tr>
<tr>
<td>10</td>
<td>0.82231</td>
<td>0.54410</td>
<td>0.66167</td>
</tr>
</tbody>
</table>

Mean value: 0.66189

Standard deviation of the mean, %: 0.016

### Table 4-3-6. Summary results – after PTB / before BelGIM

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Standard uncertainty, %</th>
<th>Expanded uncertainty, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9</td>
<td>0.93927</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>1548.8</td>
<td>0.66189</td>
<td>0.23</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Table 4-3-7. Comparison data at 1308.9 nm – after BelGIM

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, $P_{\text{VNIIOFI}}$, mW</th>
<th>Transfer standard output, $I_{\text{TRS}}$, μA</th>
<th>Transfer standard responsivity, $I_{\text{TRS}}/P_{\text{VNIIOFI}}$, mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.658014</td>
<td>0.61918</td>
<td>0.940983</td>
</tr>
<tr>
<td>2</td>
<td>0.853762</td>
<td>0.80155</td>
<td>0.938845</td>
</tr>
<tr>
<td>3</td>
<td>0.846373</td>
<td>0.79528</td>
<td>0.939633</td>
</tr>
<tr>
<td>4</td>
<td>0.740012</td>
<td>0.69508</td>
<td>0.939282</td>
</tr>
<tr>
<td>5</td>
<td>0.735848</td>
<td>0.69064</td>
<td>0.938564</td>
</tr>
<tr>
<td>6</td>
<td>0.700809</td>
<td>0.65808</td>
<td>0.939029</td>
</tr>
<tr>
<td>7</td>
<td>0.603082</td>
<td>0.5665</td>
<td>0.939341</td>
</tr>
<tr>
<td>8</td>
<td>0.799162</td>
<td>0.75</td>
<td>0.938483</td>
</tr>
<tr>
<td>9</td>
<td>0.700256</td>
<td>0.65704</td>
<td>0.938286</td>
</tr>
<tr>
<td>10</td>
<td>0.703175</td>
<td>0.65998</td>
<td>0.938571</td>
</tr>
</tbody>
</table>

Mean value: 0.93910

Standard deviation of the mean, %: 0.027

Table 4-3-8. Comparison data at 1548.8 nm – after BelGIM

<table>
<thead>
<tr>
<th>Number</th>
<th>VNIIOFI standard power, $P_{\text{VNIIOFI}}$, mW</th>
<th>Transfer standard output, $I_{\text{TRS}}$, μA</th>
<th>Transfer standard responsivity, $I_{\text{TRS}}/P_{\text{VNIIOFI}}$, mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.695586</td>
<td>0.46237</td>
<td>0.66472</td>
</tr>
<tr>
<td>2</td>
<td>0.833312</td>
<td>0.55366</td>
<td>0.664762</td>
</tr>
<tr>
<td>3</td>
<td>0.812892</td>
<td>0.54038</td>
<td>0.664762</td>
</tr>
<tr>
<td>4</td>
<td>0.791489</td>
<td>0.52631</td>
<td>0.664962</td>
</tr>
<tr>
<td>5</td>
<td>0.697897</td>
<td>0.46398</td>
<td>0.664826</td>
</tr>
<tr>
<td>6</td>
<td>0.664773</td>
<td>0.44163</td>
<td>0.664332</td>
</tr>
<tr>
<td>7</td>
<td>0.708388</td>
<td>0.47071</td>
<td>0.664481</td>
</tr>
<tr>
<td>8</td>
<td>0.724214</td>
<td>0.48121</td>
<td>0.664458</td>
</tr>
<tr>
<td>9</td>
<td>0.796778</td>
<td>0.52942</td>
<td>0.664451</td>
</tr>
<tr>
<td>10</td>
<td>0.796272</td>
<td>0.52907</td>
<td>0.664434</td>
</tr>
</tbody>
</table>

Mean value: 0.66458

Standard deviation of the mean, %: 0.010

Table 4-3-9. Summary results – after BelGIM

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Standard uncertainty, %</th>
<th>Expanded uncertainty, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9</td>
<td>0.93910</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>1548.8</td>
<td>0.66458</td>
<td>0.23</td>
<td>0.46</td>
</tr>
</tbody>
</table>
4.4. Uncertainty budget

The uncertainty budget of VNIIOFI measurements is shown in Table 4-4-1.

Table 4-4-1. Uncertainty budget

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainty component, % (k=1)</th>
<th>Uncertainty type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1308.9 nm</td>
<td>0.027</td>
<td>A</td>
</tr>
<tr>
<td>1548.8 nm</td>
<td>0.029</td>
<td></td>
</tr>
<tr>
<td>Source stability</td>
<td>0.15</td>
<td>B</td>
</tr>
<tr>
<td>Connector</td>
<td>0.12</td>
<td>B</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>0.1</td>
<td>B</td>
</tr>
<tr>
<td>Primary calorimeter</td>
<td>0.06</td>
<td>B</td>
</tr>
<tr>
<td><strong>Total standard uncertainty</strong></td>
<td><strong>0.23</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Expanded uncertainty (k=2)</strong></td>
<td><strong>0.46</strong></td>
<td></td>
</tr>
</tbody>
</table>

Expanded uncertainty is derived by multiplying the overall standard uncertainty by coverage factor $k=2$, that corresponds to the confidence level $P$ approximately equal 95 % with assuming normal distribution.

5. Measurement Capabilities and Results of Participants

5.1. PTB

5.1.1. Introduction

This report contains PTB results for comparison COOMET.PR-S6 of Fiber Optic Power Responsivity. The measurements at PTB were performed over the period 21 to 30 November 2012.

5.1.2. Reference Standards, Equipment and Experimental Set-up & Method

PTB primary standard for measurement of optical power in the range of optical telecommunication is a thermopile detector 14BT. It operates at room temperature and can be equipped with a fiber-optical adapter (FC/PC).

The calibration chain for the 14BT thermopile detector is depicted in Figure 5-1-1.

![Figure 5-1-1: The calibration chain for the 14BT thermopile detector.](image)

For the calibration of the VNIIOFI transfer standard (Optical head based on integrating sphere with InGaAs photodiode and Keithley 2502 picoammeter) the following procedure was used, see also Figure 5-1-2. The radiation from a stabilized fiber-coupled diode laser operating at 1308.9 nm (Agilent 81600B-132) and 1548.8 nm (Agilent 81600B-200), respectively, the same wavelengths as VNIIOFI used, is split by an optical fiber splitter. In a first run of measurements, the fiber output A is connected to the standard detector, the fiber output B is connected to the
The output signals, i.e. $V_{\text{STD},1}$ and $V_{\text{TRA},1}$ are measured. Afterwards, in the second run of measurement, the fibers are interchanged, i.e. fiber A is connected to the transfer standard and fiber B is connected to the standard detector and the output signals are measured, i.e. $V_{\text{STD},2}$ and $V_{\text{TRA},2}$.

![Figure 5-1-2: Scheme of the calibration procedure.](image)

The output signal of the standard detector is given by:

$$V_{\text{STD},1} = s_{\text{STD}} A_{\text{STD}} \beta_{A,1} \Phi_1$$
$$V_{\text{TRA},1} = s_{\text{TRA}} A_{\text{STD}} \beta_{B,1} \Phi_1$$
$$V_{\text{STD},2} = s_{\text{STD}} A_{\text{STD}} \beta_{B,2} \Phi_2$$
$$V_{\text{TRA},2} = s_{\text{TRA}} A_{\text{STD}} \beta_{A,2} \Phi_2$$

Here $s_{\text{STD}}$ ($s_{\text{TRA}}$) is the spectral responsivity of the standard detector (transfer detector), $A_{\text{STD}}$ is the amplification factor of the applied amplifier, $\Phi_1$ ($\Phi_2$) is the optical laser power in the first (second) run of measurements and $\beta_{A,i}$ ($\beta_{B,i}$) is the fraction of laser optical power which reaches the end of fiber A (fiber B) in the first respectively second run. Thus, it holds:

$$\frac{V_{\text{STD},1}}{V_{\text{TRA},1}} \frac{V_{\text{STD},2}}{V_{\text{TRA},2}} = \frac{s_{\text{STD}} A_{\text{STD}} \beta_{A,1} \Phi_1}{s_{\text{TRA}} A_{\text{STD}} \beta_{B,1} \Phi_1} \frac{s_{\text{STD}} A_{\text{STD}} \beta_{B,2} \Phi_2}{s_{\text{TRA}} A_{\text{STD}} \beta_{A,2} \Phi_2}$$

$$s_{\text{TRA}} = \sqrt{\frac{\beta_{A,1} \beta_{B,2} \Phi_1 \Phi_2}{\beta_{A,2} \beta_{B,1} \Phi_1 \Phi_2} \frac{V_{\text{TRA},1} V_{\text{TRA},2}}{V_{\text{STD},1} V_{\text{STD},2}}}$$

This simplifies to:

$$s_{\text{TRA}} = \sqrt{\frac{s_{\text{STD}}^2 A_{\text{STD}}^2 F_C Q}{s_{\text{STD}}^2}}$$

with $F_C = \frac{\beta_{A,1} \beta_{B,2}}{\beta_{A,2} \beta_{B,1}}$ (coupling coefficient), which takes into account the change in the splitting ratios during the measurement as well as the reproducibility of the fiber interchange. In principle, this factor should be 1, because ideally $\beta_{A,1} = \beta_{A,2}$ and $\beta_{B,1} = \beta_{B,2}$. Furthermore, $Q = \frac{V_{\text{TRA},1} V_{\text{TRA},2}}{V_{\text{STD},1} V_{\text{STD},2}}$ is the ratio of the output signals and $\frac{\Phi_1 \Phi_2}{\Phi_1 \Phi_2} = 1$, because the measurements with the standard and the transfer standard are performed simultaneously.

5.1.3. Results

The results are expressed as the responsivity, as defined by the protocol, i.e. the “The measurand is the responsivity defined as a ratio of the reading displayed by the artifact to the
optical power determined by the participating laboratory at the wavelengths of 1310 nm and 1550 nm (Ampere per Watt)”. The results are given in Table 5-1-1 and Table 5-1-2. The summary is given in Table 5-1-3.

Table 5-1-1. Measurement results at 1308.9 nm

<table>
<thead>
<tr>
<th>Measurement numbers</th>
<th>$V_{TRA1}$</th>
<th>$V_{TRA2}$</th>
<th>$V_{STD1}$</th>
<th>$V_{STD2}$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>4.28960E-07</td>
<td>3.74625E-07</td>
<td>0.36927</td>
<td>0.42036</td>
<td>1.03524E-12</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>3.74265E-07</td>
<td>4.29103E-07</td>
<td>0.41961</td>
<td>0.36972</td>
<td>1.03519E-12</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>4.28144E-07</td>
<td>3.75465E-07</td>
<td>0.36819</td>
<td>0.41963</td>
<td>1.04045E-12</td>
</tr>
<tr>
<td>7 &amp; 8</td>
<td>3.76318E-07</td>
<td>4.28759E-07</td>
<td>0.41810</td>
<td>0.37050</td>
<td>1.04158E-12</td>
</tr>
<tr>
<td>9 &amp; 10</td>
<td>4.28372E-07</td>
<td>3.74036E-07</td>
<td>0.36859</td>
<td>0.41833</td>
<td>1.03913E-12</td>
</tr>
<tr>
<td>11 &amp; 12</td>
<td>3.75413E-07</td>
<td>4.28623E-07</td>
<td>0.42198</td>
<td>0.37021</td>
<td>1.03002E-12</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.03694E-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.29950E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.75526E-15</td>
</tr>
</tbody>
</table>

Table 5-1-2. Measurement results at 1548.8 nm

<table>
<thead>
<tr>
<th>Measurement numbers</th>
<th>$V_{TRA1}$</th>
<th>$V_{TRA2}$</th>
<th>$V_{STD1}$</th>
<th>$V_{STD2}$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>2.43997E-07</td>
<td>2.56144E-07</td>
<td>0.35780</td>
<td>0.34086</td>
<td>5.12450E-13</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>2.57089E-07</td>
<td>2.46011E-07</td>
<td>0.34289</td>
<td>0.35985</td>
<td>5.12580E-13</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>2.46245E-07</td>
<td>2.57778E-07</td>
<td>0.35822</td>
<td>0.34233</td>
<td>5.18051E-13</td>
</tr>
<tr>
<td>7 &amp; 8</td>
<td>2.57348E-07</td>
<td>2.46501E-07</td>
<td>0.34027</td>
<td>0.35992</td>
<td>5.17975E-13</td>
</tr>
<tr>
<td>9 &amp; 10</td>
<td>2.46784E-07</td>
<td>2.57711E-07</td>
<td>0.36024</td>
<td>0.34779</td>
<td>5.07628E-13</td>
</tr>
<tr>
<td>11 &amp; 12</td>
<td>2.57975E-07</td>
<td>2.47044E-07</td>
<td>0.34409</td>
<td>0.36106</td>
<td>5.12972E-13</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.13610E-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.93374E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.60594E-15</td>
</tr>
</tbody>
</table>

Table 5-1-3. Summary results

In the following table the responsivity for the VNIIOFI transfer standard at the specific wavelengths are given together with the standard and the expanded uncertainties. The given expanded uncertainties $U(K)$ were calculated from the standard uncertainty by multiplication with the expansion factor $k = 2$. It was calculated according to the "Guide to the Expression of Uncertainty in Measurement" (ISO, 1995). The value of the measurand is with a probability of approx. 95 % within the interval $s_{TRA} ± U(s_{TRA})$.

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Responsivity $s_{TRA}$, mA/W</th>
<th>Standard uncertainty $u(s_{TRA})$, %</th>
<th>Expanded uncertainty $U(s_{TRA})$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9</td>
<td>0.9458</td>
<td>0.22</td>
<td>0.43</td>
</tr>
<tr>
<td>1548.8</td>
<td>0.6654</td>
<td>0.26</td>
<td>0.52</td>
</tr>
</tbody>
</table>
5.1.4. Uncertainties

The uncertainty budgets are given in Table 5-1-4 and Table 5-1-5.

Table 5-1-4. Uncertainty budget at 1308.9 nm

\[ s_{STD} = 0.278917 \text{ V/W} \pm 0.15 \% \]
\[ A = (3329.92 \pm 0.33) \text{ V/V} \]
\[ F_c = 1.0000 \pm 0.13 \% \]
\[ Q = (1.03694 \times 10^{-12} \pm 1.75526 \times 10^{-15}) A^2/V^2 \]

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Value</th>
<th>Standard uncertainty</th>
<th>Distribution</th>
<th>Sensitivity coefficient</th>
<th>Fraction of Uncertainty</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_{STD})</td>
<td>0.278917 V/W</td>
<td>418\times10^{-6} V/W</td>
<td>Normal</td>
<td>3.4\times10^{-3}</td>
<td>1.4\times10^{-6} A/W</td>
<td>48.3 %</td>
</tr>
<tr>
<td>(A)</td>
<td>3329.920 V/V</td>
<td>0.191 V/V</td>
<td>Rechteck</td>
<td>280\times10^{-9}</td>
<td>54\times10^{-9} A/W</td>
<td>0.0 %</td>
</tr>
<tr>
<td>(Q)</td>
<td>1.03694\times10^{-12} A^2/V^2</td>
<td>1.76\times10^{-15} A^2/V^2</td>
<td>Normal</td>
<td>460\times10^{-6}</td>
<td>800\times10^{-9} A/W</td>
<td>15.4 %</td>
</tr>
<tr>
<td>(F_c)</td>
<td>1.00000</td>
<td>1.30\times10^{-3}</td>
<td>Normal</td>
<td>950\times10^{-6}</td>
<td>1.2\times10^{-6} A/W</td>
<td>36.3 %</td>
</tr>
<tr>
<td>(s_{meas})</td>
<td>945.77\times10^{-6} A/W</td>
<td>2.04\times10^{-6} A/W</td>
<td>Rechteck</td>
<td>280\times10^{-9}</td>
<td>54\times10^{-9} A/W</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>

Table 5-1-5. Uncertainty budget at 1548.8 nm

\[ s_{STD} = 0.278844 \text{ V/W} \pm 0.15 \% \]
\[ A = (3329.92 \pm 0.33) \text{ V/V} \]
\[ F_c = 1.0000 \pm 0.14 \% \]
\[ Q = (5.13610 \times 10^{-13} \pm 1.60594 \times 10^{-15}) A^2/V^2 \]

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Value</th>
<th>Standard uncertainty</th>
<th>Distribution</th>
<th>Sensitivity coefficient</th>
<th>Fraction of Uncertainty</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_{STD})</td>
<td>0.278844 V/W</td>
<td>418\times10^{-6} V/W</td>
<td>Normal</td>
<td>2.4\times10^{-3}</td>
<td>1.0\times10^{-6} A/W</td>
<td>33.8 %</td>
</tr>
<tr>
<td>(A)</td>
<td>3329.920 V/V</td>
<td>0.191 V/V</td>
<td>Rechteck</td>
<td>200\times10^{-9}</td>
<td>38\times10^{-9} A/W</td>
<td>0.0 %</td>
</tr>
<tr>
<td>(Q)</td>
<td>513.61\times10^{-15} A^2/V^2</td>
<td>1.61\times10^{-15} A^2/V^2</td>
<td>Normal</td>
<td>650\times10^{-6}</td>
<td>1.0\times10^{-6} A/W</td>
<td>36.7 %</td>
</tr>
<tr>
<td>(F_c)</td>
<td>1.00000</td>
<td>1.40\times10^{-3}</td>
<td>Normal</td>
<td>670\times10^{-6}</td>
<td>930\times10^{-9} A/W</td>
<td>29.4 %</td>
</tr>
<tr>
<td>(s_{meas})</td>
<td>665.44\times10^{-6} A/W</td>
<td>1.72\times10^{-6} A/W</td>
<td>Rechteck</td>
<td>280\times10^{-9}</td>
<td>54\times10^{-9} A/W</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>
5.2. BelGIM

5.2.1. Introduction

This report contains BelGIM results for comparison COOMET.PR-S6 of Fiber Optic Power Responsivity. The measurements at BelGIM were performed over the period 25 December 2012 to 20 January 2013.

5.2.2. Reference Standards, Equipment and Experimental Set-up & Method

BelGIM primary standard for measurement of optical power in the range of optical telecommunication is the standard calorimetric system reproducing average power unit (SCSRAP).

SCSRAP is intended to reproduce and storage of the average power unit during its operation as a part of national primary standard of this unit. By its function SCSRAP comprises calorimetric transducer PSM.PM, system of registration and calibration of the calorimetric transducer, meteoscope to measure ambient temperature and computer to operate SCSRAP and measurement results processing.

SCSRAP operation principle is based on PSM.PM electrical calibration using electrical calibration system. Consequent transformation takes place that transforms the electrical current power that is discharged in electrical heater into thermal flow and then in thermal battery into analogue output electrical signal of measuring information that is proportional to average power of the created thermal power. After electrical calibration in PSM.PM the signal is transmitted from the optical radiation source. Transducer receiving element absorbs this radiation and transforms it into thermal flow, average power of which is proportional to the average radiation power. As the result the thermal battery of PSM.PM reacts to thermal power and produces electrical signal of measuring information that is proportional to the exposure power and, consequently, to the optical radiation average power. This allows to perform (with the use of SCSRAP) indirect measurements of average power of optical radiation and to reproduce this unit.

5.2.3. Results

The results are expressed as the responsivity, as defined by the protocol, i.e. “The measurand is the responsivity defined as a ratio of the reading displayed by the artifact to the optical power determined by the participating laboratory at the wavelengths of 1310 nm and 1550 nm (Ampere per Watt)”. The results are given in Table 5-2-1 and Table 5-2-2. The summary is given in Table 5-2-4.
Table 5-2-1. Measurement results at 1308.6 nm

<table>
<thead>
<tr>
<th>Meas. number</th>
<th>Optical power, mW</th>
<th>Picoammeter indications, μA</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Average value for transfer standard responsivity, mA/W</th>
<th>Standard deviation of the mean, mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.83668</td>
<td>0.78550</td>
<td>0.93883</td>
<td>0.93787</td>
<td>0.00058</td>
</tr>
<tr>
<td>2</td>
<td>0.79948</td>
<td>0.74839</td>
<td>0.93610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.79633</td>
<td>0.74433</td>
<td>0.93470</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.83797</td>
<td>0.78747</td>
<td>0.93974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.83063</td>
<td>0.78020</td>
<td>0.93929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.78849</td>
<td>0.73820</td>
<td>0.93622</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.78633</td>
<td>0.73660</td>
<td>0.93676</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.79248</td>
<td>0.74310</td>
<td>0.93769</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.79325</td>
<td>0.74533</td>
<td>0.93959</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.79159</td>
<td>0.74390</td>
<td>0.93975</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-2-2. Measurement results at 1546.8 nm

<table>
<thead>
<tr>
<th>Meas. number</th>
<th>Optical power, mW</th>
<th>Picoammeter indications, μA</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Average value for transfer standard responsivity, mA/W</th>
<th>Standard deviation of the mean, mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.74743</td>
<td>0.49428</td>
<td>0.66131</td>
<td>0.66070</td>
<td>0.00015</td>
</tr>
<tr>
<td>2</td>
<td>0.79521</td>
<td>0.52534</td>
<td>0.66063</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.79126</td>
<td>0.52316</td>
<td>0.66117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.74841</td>
<td>0.49422</td>
<td>0.66036</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.63731</td>
<td>0.42105</td>
<td>0.66067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.74644</td>
<td>0.49315</td>
<td>0.66067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.80253</td>
<td>0.53082</td>
<td>0.66143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.74809</td>
<td>0.49424</td>
<td>0.66067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.74188</td>
<td>0.48970</td>
<td>0.66008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.74411</td>
<td>0.49115</td>
<td>0.66005</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.4. Wavelength Correction

Central wavelengths of BelGIM sources: 1308.6 nm and 1546.8 nm.

Table 5-2-3. Spectral responsivity of the transfer standard

<table>
<thead>
<tr>
<th>λ, nm</th>
<th>Sλ, %</th>
<th>λ, nm</th>
<th>Sλ, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1290</td>
<td>100.00</td>
<td>1530</td>
<td>94.40</td>
</tr>
<tr>
<td>1300</td>
<td>99.62</td>
<td>1540</td>
<td>95.45</td>
</tr>
<tr>
<td>1310</td>
<td>99.22</td>
<td>1550</td>
<td>96.57</td>
</tr>
<tr>
<td>1320</td>
<td>98.52</td>
<td>1560</td>
<td>98.46</td>
</tr>
<tr>
<td>1330</td>
<td>96.92</td>
<td>1570</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Correction factor at 1308.9 nm: \( S(1308.9\text{nm}) / S(1308.6\text{nm}) = 0.99988 \)
Correction factor at 1548.8 nm: \( S(1548.8\text{nm}) / S(1546.8\text{nm}) = 1.00233 \)
5.2.5. Summary results

The results after wavelength correction are given in Table 5-2-4.

Table 5-2-4. Summary results

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Transfer standard responsivity, mA/W</th>
<th>Standard uncertainty, %</th>
<th>Expanded uncertainty, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9</td>
<td>0.9378</td>
<td>0.19</td>
<td>0.38</td>
</tr>
<tr>
<td>1548.8</td>
<td>0.6622</td>
<td>0.18</td>
<td>0.36</td>
</tr>
</tbody>
</table>

5.2.6. Uncertainties

Expanded uncertainty is derived by multiplying the overall standard uncertainty by coverage factor $k=2$, that corresponds to the confidence level $P$ approximately equal 95 % with assuming normal distribution.

### Table 5-2-5. Input quantities analysis at 1308.6 nm

<table>
<thead>
<tr>
<th>Input quantity</th>
<th>Uncertainty type</th>
<th>Distribution type</th>
<th>Estimation value</th>
<th>Standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{pf}$ - transfer standard sensitivity, $\mu$A/mW</td>
<td>A</td>
<td>Normal</td>
<td>0,93787, $\mu$A/mW</td>
<td>0,062 %</td>
</tr>
<tr>
<td>$\Delta_{a1}$ - correction for random constituent of the error of measurement of optical radiation average power SCSRAP, %</td>
<td>A</td>
<td>Normal</td>
<td>0 %</td>
<td>0,07 %</td>
</tr>
<tr>
<td>$\Delta_{a2}$ - correction for systematic constituent of the error of reproduction and storage of the unit optical radiation average power SCSRAP, %</td>
<td>B</td>
<td>Normal</td>
<td>±0,09 %</td>
<td>0,052 %</td>
</tr>
<tr>
<td>$\Delta_{non-stability}$ - correction for non-stability of the radiation source output power, %</td>
<td>B</td>
<td>Normal</td>
<td>±0,34 %</td>
<td>0,1 %</td>
</tr>
<tr>
<td>$\Delta_{connector}$ - correction for attenuation induced by fiber-optic connector, %</td>
<td>B</td>
<td>Normal</td>
<td>±0,4 %</td>
<td>0,12 %</td>
</tr>
<tr>
<td>$\Delta_{4}$ - update for correction for wave length, %</td>
<td>B</td>
<td>Normal</td>
<td>±0,01 %</td>
<td>0,01 %</td>
</tr>
</tbody>
</table>

### Table 5-2-6. Uncertainty budget at 1308.6 nm

<table>
<thead>
<tr>
<th>Quantity $x_i$</th>
<th>Measurement unit</th>
<th>Value $x_i$</th>
<th>Interval $\pm$</th>
<th>Uncertainty type</th>
<th>Probability distribution</th>
<th>$u(x)$</th>
<th>Sensitivity factor $c_i$</th>
<th>Uncertainty constituent</th>
<th>Percent constituent, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{pf}$</td>
<td>$\mu$A/mW</td>
<td>0,93787</td>
<td>-</td>
<td>A</td>
<td>Normal</td>
<td>0,062</td>
<td>1</td>
<td>0,062</td>
<td>11,04</td>
</tr>
<tr>
<td>$\Delta_{a1}$</td>
<td>%</td>
<td>0</td>
<td>-</td>
<td>A</td>
<td>Normal</td>
<td>0,070</td>
<td>1</td>
<td>0,070</td>
<td>14,22</td>
</tr>
<tr>
<td>$\Delta_{a2}$</td>
<td>%</td>
<td>0,09</td>
<td>B</td>
<td>Normal</td>
<td>0,052</td>
<td>1</td>
<td>0,052</td>
<td>7,84</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{non-stability}$</td>
<td>%</td>
<td>0,170</td>
<td>B</td>
<td>Normal</td>
<td>0,100</td>
<td>1</td>
<td>0,100</td>
<td>28,11</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{connector}$</td>
<td>%</td>
<td>0,200</td>
<td>B</td>
<td>Normal</td>
<td>0,12</td>
<td>1</td>
<td>0,12</td>
<td>38,69</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{4}$</td>
<td>%</td>
<td>0,010</td>
<td>B</td>
<td>Normal</td>
<td>0,006</td>
<td>1</td>
<td>0,006</td>
<td>0,10</td>
<td></td>
</tr>
<tr>
<td>$C_{1310}$</td>
<td>$\mu$A/mW</td>
<td>0,93787</td>
<td>Overall standard uncertainty, %</td>
<td>0,19</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overall standard uncertainty, % = 0,19
Extended uncertainty, % = 0,38
Table 5-2-7. Input quantities analysis at 1546.8 nm

<table>
<thead>
<tr>
<th>Input quantity</th>
<th>Uncertainty type</th>
<th>Distribution type</th>
<th>Estimation value</th>
<th>Standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{pr}$ - transfer standard sensitivity, $\mu A/mW$</td>
<td>A</td>
<td>normal</td>
<td>0.66070, $\mu A/mW$</td>
<td>0.023 %</td>
</tr>
<tr>
<td>$\Delta_{nl}$ - correction for random constituent of the error of measurement of optical radiation average power SCSRAP, %</td>
<td>A</td>
<td>normal</td>
<td>0 %</td>
<td>0.070 %</td>
</tr>
<tr>
<td>$\Delta_{n2}$ - correction for systematic constituent of the error of reproduction and storage of the unit optical radiation average power SCSRAP, %</td>
<td>B</td>
<td>normal</td>
<td>0 %</td>
<td>$\pm 0.09$ %</td>
</tr>
<tr>
<td>$\Delta_{non-stability}$ - correction for non-stability of the radiation source output power, %</td>
<td>B</td>
<td>normal</td>
<td>0 %</td>
<td>0.052 %</td>
</tr>
<tr>
<td>$\Delta_{connector}$ - correction for attenuation induced by fiber-optic connector, %</td>
<td>B</td>
<td>normal</td>
<td>0 %</td>
<td>0.12 %</td>
</tr>
<tr>
<td>$\Delta_{\lambda}$ - update for correction for wave length, %</td>
<td>B</td>
<td>normal</td>
<td>0 %</td>
<td>$\pm 0.01$ %</td>
</tr>
</tbody>
</table>

Table 5-2-8. Uncertainty budget at 1546.8 nm

<table>
<thead>
<tr>
<th>Quantity $x_i$</th>
<th>Measurement unit</th>
<th>Value $x_i$</th>
<th>Interval $\Delta x_i$</th>
<th>Uncertainty type</th>
<th>Probability distribution</th>
<th>Standard uncertainty $u(x_i)$, %</th>
<th>Sensitivity factor $c_i$</th>
<th>Uncertainty constituent %</th>
<th>Percent constituent, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{pr}$</td>
<td>$\mu A/mW$</td>
<td>0.66070</td>
<td>-</td>
<td>A</td>
<td>Normal</td>
<td>0.023</td>
<td>1</td>
<td>0.023</td>
<td>1.68</td>
</tr>
<tr>
<td>$\Delta_{nl}$</td>
<td>%</td>
<td>0</td>
<td>-</td>
<td>A</td>
<td>Normal</td>
<td>0.070</td>
<td>1</td>
<td>0.070</td>
<td>15.72</td>
</tr>
<tr>
<td>$\Delta_{n2}$</td>
<td>%</td>
<td>0</td>
<td>0.09</td>
<td>B</td>
<td>Normal</td>
<td>0.052</td>
<td>1</td>
<td>0.052</td>
<td>8.66</td>
</tr>
<tr>
<td>$\Delta_{non-stability}$</td>
<td>%</td>
<td>0</td>
<td>0.170</td>
<td>B</td>
<td>Normal</td>
<td>0.10</td>
<td>1</td>
<td>0.10</td>
<td>31.07</td>
</tr>
<tr>
<td>$\Delta_{connector}$</td>
<td>%</td>
<td>0</td>
<td>0.200</td>
<td>B</td>
<td>Normal</td>
<td>0.12</td>
<td>1</td>
<td>0.12</td>
<td>42.77</td>
</tr>
<tr>
<td>$\Delta_{\lambda}$</td>
<td>%</td>
<td>0</td>
<td>0.010</td>
<td>B</td>
<td>Normal</td>
<td>0.006</td>
<td>1</td>
<td>0.006</td>
<td>0.11</td>
</tr>
<tr>
<td>$C_{1550}$</td>
<td>$\mu A/mW$</td>
<td>0.66070</td>
<td></td>
<td>Overall standard uncertainty, %</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extended uncertainty, %</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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6. Results and Discussions

6.1. Artifact Stability

The artifact stability was additionally checked by the pilot after the artifact had been returned to the pilot from PTB and then from BelGIM. Therefore, there were 2 data sets (as compared to initial values) on the deviation of transfer standard responsivity for both 1308.9 nm and 1548.8 nm with respect to the reference detector of the pilot.

Table 6-1-1 shows the accumulative deviation of transfer standard responsivity.

<table>
<thead>
<tr>
<th>Date</th>
<th>Deviation of transfer standard responsivity (%)</th>
<th>Remark (checked after this NMI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 November 2012</td>
<td>0.00 0.00</td>
<td>VNIIOFI</td>
</tr>
<tr>
<td>20 December 2012</td>
<td>-0.38 -0.38</td>
<td>after PTB</td>
</tr>
<tr>
<td>10 February 2013</td>
<td>-0.40 +0.03</td>
<td>after BelGIM</td>
</tr>
</tbody>
</table>

Table 6-1-1. Artifact drift check results

From Table 6-1-1 we see some changes in the responsivity of the artifact after PTB and after BelGIM. The changes for two wavelengths are not correlated with each other, but the relative change is about the same on its absolute value. It looks like if there are two stable conditions for the artifact and its responsivity that may be caused by non-ideal characteristics of the artifact, for example, some mechanical instability of a small part of the integrating sphere. The difference of the last data for 1548.8 nm from previous one may occur as a result of the artifact BaSO₄ covering ageing. Therefore, the artifact instability had a character of not monotonic drift, but a time-unpredictable step change. The value of this change ($\Delta_{\text{ins}}$, where “ins” means instability) can be estimated as about 0.4 % for both wavelength.

In principle to improve the results additional studies of the artifact responsivity and design is necessary but, first, this requires time and, second, the study of the design will lead to the disassembling of the artifact, and even if we find the cause of such a bistability, the responsivity after assembling will inevitably change and new comparison cycle will be required. As far as the drift deviations are comparable with the presented participant’s uncertainties values, we’ll estimate the results for received drift deviations.

6.2. Difference from Pilot

For each value of the artifact responsivity measured by a participant ($C_i$) there are two corresponding values measured by the pilot before and after the participant measurement.
Taking into account the fact that the artifact instability was not a monotonic drift, but had a character of random step change (see the section 6.1), we have decided to not average the “before” and “after” pilot values, but we have decided to use that pilot value which is closer to the corresponding participant value. Thus in the case of PTB we used the VNIIOFI values obtained before PTB measurements. It means that we assumed the artefact responsivity changed in between the PTB measurements and the “after PTB” VNIIOFI measurements. Comparing the “before BelGIM” and “after BelGIM” pilot values one can see the 0.4% change at 1548.8 nm and no change at 1308.9 nm. It is tempting to think that the responsivity change happened during the “after BelGIM” measurement, and there was change between the “before BelGIM” and BelGIM measurements. The corresponding values are presented in Table 6-2-1.

The relative difference $\Delta_i$ of transfer standard responsivity between the participant $i$ and the pilot is then calculated by

$$\Delta_i = \frac{C_i}{C_i^\prime} - 1$$  \hspace{1cm} (6-2-1)

and its uncertainty $u(\Delta_i)$ by

$$u(\Delta_i) = \sqrt{u^2_r(C_i) + u^2_{r,ad}(C_i)}$$  \hspace{1cm} (6-2-2)

where $u_{r,ad}(C_i)$ denotes the additional uncertainty of the transfer standard responsivity by the participant $i$ due to non-ideal characteristics of the artifact. This uncertainty is defined as:

$$u_{r,ad}(C_i) = \frac{|\Delta_{\text{ins}}|}{2\sqrt{3}}$$  \hspace{1cm} (6-2-3)

Using the typical change in artifact responsivity $\Delta_{\text{ins}}$ equal to about 0.4% (table 6-1-1) we have

$$u_{r,ad}(C_i) = 0.12\%$$  \hspace{1cm} (6-2-4)

We ignored the uncorrelated components of the pilot in Eq. (6-2-2) because they were negligible for all participants.

For the pilot lab ($i=0$), $\Delta_0 = 0$ and the uncertainty $u(\Delta_0)$ is also calculated by (6-2-2).

The calculated results are summarized in Table 6-2-1, Table 6-2-2 and Fig. 6-2-1.

Table 6-2-1. Difference of transfer standard responsivity of participants from the pilot (%) and its uncertainty (1308.9 nm)

<table>
<thead>
<tr>
<th>Participant</th>
<th>$C_i$, mA/W</th>
<th>$C_i^\prime$, mA/W</th>
<th>$u_r(C_i)$, %</th>
<th>$u_{r,ad}(C_i)$, %</th>
<th>$\Delta_i$, %</th>
<th>$u(\Delta_i)$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>0.9429</td>
<td>0.9429</td>
<td>0.23</td>
<td>0.12</td>
<td>0.00</td>
<td>0.26</td>
</tr>
<tr>
<td>PTB</td>
<td>0.9458</td>
<td>0.9429</td>
<td>0.22</td>
<td>0.12</td>
<td>0.31</td>
<td>0.25</td>
</tr>
<tr>
<td>BelGIM</td>
<td>0.9378</td>
<td>0.9392</td>
<td>0.19</td>
<td>0.12</td>
<td>-0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Table 6-2-2. Difference of transfer standard responsivity of participants from the pilot (%) and its uncertainty (1548.8 nm)

<table>
<thead>
<tr>
<th>Participant</th>
<th>$C_i$, mA/W</th>
<th>$C_{i_0}^P$, mA/W</th>
<th>$u_r(C_i)$, %</th>
<th>$u_{r,\text{rad}}(C_i)$, %</th>
<th>$\Delta_i$, %</th>
<th>$u(\Delta_i)$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>0.6644</td>
<td>0.6644</td>
<td>0.23</td>
<td>0.12</td>
<td>0.00</td>
<td>0.26</td>
</tr>
<tr>
<td>PTB</td>
<td>0.6654</td>
<td>0.6644</td>
<td>0.26</td>
<td>0.12</td>
<td>0.15</td>
<td>0.29</td>
</tr>
<tr>
<td>BelGIM</td>
<td>0.6622</td>
<td>0.6619</td>
<td>0.18</td>
<td>0.12</td>
<td>0.05</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Fig. 6-2-1. Difference of transfer standard responsivity of participants from the pilot (%) and its uncertainty

### 6.3. Comparison Reference Values

The comparison Reference Value (RV) was calculated according to the Guidelines for CCPR Key Comparison Report Preparation (CCPR-G2, Rev.3, July 1, 2013) [4].

At first, the cut-off value of the uncertainty is determined by

$$u_{\text{cut-off}} = \text{average}\{u_r(C_i)\} \quad \text{for} \quad u_r(C_i) \leq \text{median}\{u_r(C_i)\} \quad (i = 0 \text{ to } N),$$

where $N$ is the number of participants excluding the pilot ($N = 2$).

Then the reported uncertainty of each NMI is adjusted by the cut-off as

$$u_{r,\text{adj}}(C_i) = u_r(C_i) \quad \text{for} \quad u_r(C_i) \geq u_{\text{cut-off}}$$
$$u_{r,\text{adj}}(C_i) = u_{\text{cut-off}} \quad \text{for} \quad u_r(C_i) < u_{\text{cut-off}} \quad (i = 0 \text{ to } N).$$

The uncertainty of the relative difference $\Delta_i$ after cut-off is also adjusted by

$$u_{\text{adj}}(\Delta_i) = \sqrt{u_{r,\text{adj}}^2(C_i) + u_{r,\text{rad}}^2(C_i)}$$

The weights $w_j$ is then calculated by

$$w_j = \frac{u_{\text{adj}}^2(\Delta_j)}{\sum_{j=0}^{N} u_{\text{adj}}^2(\Delta_j)}.$$

Now the RV, $\Delta_{\text{RV}}$, is determined by
\[ \Delta_{RV} = \sum_{i=0}^{N} w_i \Delta_i , \quad (6-3-5) \]

and the uncertainty of the RV is given by

\[ u(\Delta_{RV}) = \sqrt{\sum_{i=0}^{N} \frac{u^2_i(\Delta_i)}{\sum_{i=0}^{N} u^2_{i,adj}(\Delta_i)}}, \quad (6-3-6) \]

and the expanded uncertainty of the RV is \( U(\Delta_{RV}) = k u(\Delta_{RV}) \) \((k=2)\).

The calculated values are summarized in Table 6-3-1 and Table 6-3-2 based on the summarized results in Table 6-2-1 and Table 6-2-2.

Table 6-3-1. RV and its uncertainty (1308.9 nm), \( u_{cut-off} = 0.21\% \)

<table>
<thead>
<tr>
<th>Participant</th>
<th>( \Delta_i ), %</th>
<th>( u(\Delta_i) ), %</th>
<th>( u_{r,adj}(C_i) ), %</th>
<th>( u_{adj}(\Delta_i) ), %</th>
<th>( w_i )</th>
<th>( \Delta_{RV}, % )</th>
<th>( U(\Delta_{RV}), % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>0.00</td>
<td>0.26</td>
<td>0.23</td>
<td>0.26</td>
<td>0.3104</td>
<td>0.05</td>
<td>0.28</td>
</tr>
<tr>
<td>PTB</td>
<td>0.31</td>
<td>0.25</td>
<td>0.22</td>
<td>0.25</td>
<td>0.3326</td>
<td>0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>BelGIM</td>
<td>-0.15</td>
<td>0.22</td>
<td>0.21</td>
<td>0.24</td>
<td>0.3570</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-3-2. RV and its uncertainty (1548.8 nm), \( u_{cut-off} = 0.22\% \)

<table>
<thead>
<tr>
<th>Participant</th>
<th>( \Delta_i ), %</th>
<th>( u(\Delta_i) ), %</th>
<th>( u_{r,adj}(C_i) ), %</th>
<th>( u_{adj}(\Delta_i) ), %</th>
<th>( w_i )</th>
<th>( \Delta_{RV}, % )</th>
<th>( U(\Delta_{RV}), % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>0.00</td>
<td>0.26</td>
<td>0.23</td>
<td>0.26</td>
<td>0.3457</td>
<td>0.05</td>
<td>0.28</td>
</tr>
<tr>
<td>PTB</td>
<td>0.15</td>
<td>0.29</td>
<td>0.26</td>
<td>0.29</td>
<td>0.2838</td>
<td>0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>BelGIM</td>
<td>0.05</td>
<td>0.22</td>
<td>0.22</td>
<td>0.25</td>
<td>0.3705</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.4. Chi-square Value

The Chi-square value \( \chi^2_{obs} \) is calculated for consistency check by

\[ \chi^2_{obs} = \sum_{i=0}^{N} \frac{(\Delta_i - \Delta_{RV})^2}{u^2_{adj}(\Delta_i)} \quad (6-4-1) \]

The calculated \( \chi^2_{obs} \) values are presented in Table 6-4-1.

Table 6-4-1. Chi-square values

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>( \chi^2_{obs} )</th>
<th>( \chi^2_{0.05} )</th>
<th>Consistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1308.9 nm</td>
<td>1.771</td>
<td>5.991</td>
<td>Satisfied</td>
</tr>
<tr>
<td>1548.8 nm</td>
<td>0.161</td>
<td>5.991</td>
<td>Satisfied</td>
</tr>
</tbody>
</table>

\( \chi^2_{0.05} \) is determined from the Table 6-4-2, \( \nu=2 \).

For this comparisons for both wavelengths \( \chi^2_{obs} \leq \chi^2_{0.05} \), so the consistency is satisfied.
6.5. Differences from Reference Values

Difference from RV of the participant \( i \) is defined by

\[
D_i = \Delta_i - \Delta_{RV} ,
\]

and the uncertainty of \( D_i \) is given by

\[
u_i = k \sqrt{u^2(\Delta_i) + u^2(\Delta_{RV}) + \sum_{i=0}^{N} u^2_{adj}(\Delta_i)} ,
\]

and

\[
U_i = ku_i ,
\]

with the coverage factor \( k=2 \) at the level of confidence of approximately 95 %.

Table 6-5-1 and 6-5-2 summarize the calculated differences from RV and uncertainties. These results are also presented in Fig. 6-5-1 and 6-5-2.

### Table 6-5-1. Differences from RV and their uncertainties at \( \lambda=1308.9 \) nm

<table>
<thead>
<tr>
<th>Participant</th>
<th>( \lambda = 1308.9 ) nm</th>
<th>( D_i ), %</th>
<th>( U_i ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>-0.05</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>PTB</td>
<td>0.26</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>BelGIM</td>
<td>-0.20</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6-5-2. Differences from RV and their uncertainties at \( \lambda=1548.8 \) nm

<table>
<thead>
<tr>
<th>Participant</th>
<th>( \lambda = 1548.8 ) nm</th>
<th>( D_i ), %</th>
<th>( U_i ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIIOFI</td>
<td>-0.06</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>PTB</td>
<td>0.09</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>BelGIM</td>
<td>-0.01</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6-5-1. Differences from RV and expanded uncertainties of each participant at the wavelength of 1308.9 nm. Red dotted lines indicate the uncertainty ($k=2$) boundaries of RV.

Fig. 6-5-2. Differences from RV and expanded uncertainties of each participant at the wavelength of 1548.8 nm. Red dotted lines indicate the uncertainty ($k=2$) boundaries of RV.
6.6. Conclusions

COOMET supplementary comparison of among PTB, BelGIM and VNIIOFI on fiber optic power responsivity at optical power level of 0.5 mW and at the wavelengths of 1308.9 nm and 1548.8 nm has been carried out.

An integrating sphere type optical head was selected as a comparison artifact in order to suppress polarization dependence and to reduce multiple reflection.

The comparison showed good agreement between all participants. Differences from the comparison Reference Values (RV) for all participants were less than the RV expanded uncertainty, which is 0.28 % and 0.30% for 1308.9 nm and 1548.8 nm, respectively.

With regard to CMC claim on the item 7.1.0 of CCPR service category that is “Responsivity, Fiber optic power meter”, this comparison report can be used to support it as an evidence.

7. Reference


