

ACCOMPANYING NOTES

CALIBRATION DATA-SET OF A SIX COMPONENT INTERNAL STRAIN- GAUGE BALANCE, B667

Test number: NA

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1 INTRODUCTION

This report is an accompanying note to a data-set. This data-set provided to AIAA Balance Workgroup by DNW contains data on the calibration of a six component internal strain gauge balance designated b667. This data set shall only be used to study balance calibration and uncertainty methodologies. Eventual negative or positive conclusions on methodologies, equipment, etc. shall be divulged to AIAA Balance Workgroup participants only. Publication of the results obtained with this data-set shall only be done after mutual agreement between the AIAA Workgroup members and DNW.

The notes comprise of a description of the balance design requirements, the QinetiQ Balance Calibration Machine (BCM), the load tables and the pre-processed data.

Note that the specification of the balance was done before the update of the uncertainty definition of DNW as presented in reference [3]. This data was also used for the publications of reference [4], [5] and [6].

2 BALANCE B667

To complement its range of internal balances DNW uses a new internal balance that is especially suited for propulsion simulation testing for Mach numbers up to about 0.4. The six component internal strain gauge balance is a moment type of balance, see Figure 1 and Figure 2. The balance has a diameter of 135 mm inclusive the heat shield and has a length of 520 mm. The balance centre is in defined at 260 mm downstream of the metric flange. The moment sections are 160 mm up- and down stream of the balance centre.

2.1 Requirements B667

The main requirements for the new balance that are of interest for this study are briefly presented below:

- Load Range is the Maximum Calibrated Load Range given in table 1. For all components the maximum single load should at least be equal to the maximum calibrated loads as listed in table 1. At 90% of the maximum calibrated load range all loads may occur simultaneously.
- Requested accuracy: The accuracy of the DNW-LLF internal strain-gauge balances is defined by the following formula (Reference [1], Reference [2]):

$$\delta_i \leq \frac{1}{1000} \cdot |F_i| \cdot \left[a_i + \sum_{\substack{n=1 \\ n \neq i}}^6 \left| \frac{F_n}{F_{n,max}} \right| \right]$$

The accuracy coefficients and the maximum load range are defined according to tables 1 and 2. These accuracy criteria must be fulfilled at room temperature. Change in the balance output due to temperature drift or temperature gradients must be correctable in order to maintain the above mentioned accuracy criteria.

a_i	Accuracy coefficient of component 'i'	[-]
F_i	Maximum load of a specific load component 'i'	[N, Nm]
F_n	Actual load acting on component 'n'	[N, Nm]
$F_{n,max}$	Maximum load of load component 'n'	[N, Nm]
δ_i	Tolerated root mean square averaged error of component 'i'	[N, Nm]

- The repeatability of the balance should be about 1/3 of its accuracy.
- Model and sting adapters should have the same size as those of DNW-LLF internal balance W608 or W616. These adapters will make it possible to calibrate the balance in the QinetiQ Balance Calibration Machine (BCM). So no further calibration tools are necessary.
- The balance deflections must be less than the values specified in table 3.
- The balance temperature operating range is between 263 and 343 K.

- The balance will have 18 Pt 100 temperature sensors on locations agreed upon by DNW.
- The dynamic load range is 1.8 x the static load range at max 5 Hz.
- Concerning the dynamic loads it should be clear that the occurrence of these loads shall not lead to any change in the calibrated characteristics of the balance.
- The balance will have heat insulation.
- The internal balance shall be designed with a safety factor of 4 on static loads (based on yield strength).
- The minimum sensitivity of any of the balance output signals shall be 0.5 mV per Volt DC excitation at full loads, with excitation voltage up to 10 Volts DC. Preferably the sensitivity of any of the balance output signals shall not exceed 1.0 mV per Volt DC excitation at full loads.
- Special provisions shall be made as to limit the total zero drift of the balance including heat shield to a minimum.

3 THE QINETIQ BALANCE CALIBRATION MACHINE

The following description of the QinetiQ Balance Calibration Machine (BCM) is in origin a text provided to DNW by QinetiQ (and therefore proprietary data). The text has been edited to account for special items concerning DNW balance calibrations.

The BCM was designed mainly for the calibration of the large internal 'sting' balances used at the 5m tunnel (QinetiQ, Farnborough). It was developed from an earlier smaller machine, and has been used successfully for 40 years with both sting balances and under-floor balances; see Figure 3 and Figure 5. A feature of the BCM is that the correct geometry of the calibration load system relative to the balance is maintained throughout the calibration, by automatic repositioning of the load system to follow balance deflection under load. So the loading tree moves along with the metric part of the balance.

The calibration loads (forces and moments) are produced by the controlled action of 6 special bi-directional pneumatic piston/cylinder assemblies called force generators (FGs), driven by Ruska pressure controllers. The FGs are mounted on a load reaction box, and they apply calibration loads to a 3 dimensional cruciform loading tree, through push/pull arms and flexures. The model end of the balance is fixed to the loading tree, such that this calibration load system is in geometrically correct alignment (i.e. calibration load paths normal to the limbs of the loading tree) with the balance at zero load; the ground end of the balance is mounted on a support sting which is fixed to the BCM frame. The load reaction box is suspended from the BCM frame on 6 restoration jacks, which form a 6 degree-of-freedom precision positioning system that is set to the relative position of the load reaction box and the loading tree at zero load. As a calibration load is progressively applied the balance starts to deflect elastically, progressively changing the position of the loading tree relative to the load reaction box. The restoration positioning system starts to cancel this change in relative position by moving the load reaction box such that, when the calibration load has settled at its final value, the load reaction box settles without overshoot to the original (zero load) position relative to the loading tree. Thus, at every calibration point, the correct geometrical alignment of the calibration loads has been restored. The weight of the loading tree is compensated by an adjustable counterbalance lever and weight system; when the balance deflects other small associated compensations are automatically made by data processing from pitch and roll sensors, see section 6.1.1.

The nominal maximum capacity of the BCM is presented in Table 4

To allow good results over various calibration ranges FGs are available in 4 sizes, nominally 10, 20, 50 and 100 kN full scale. This also helps to prevent overloading. The load range for this calibration is also presented in Table 4.

The geometry of the calibration load system is very accurate; the load reaction box and loading tree were made to an accuracy of 0.04mm, and the restoration system positioning accuracy is 0.01 mm. The machine is very rigid; it weighs 40 tonnes.

Calibration accuracy is strongly dependent on the performance of the FGs. Other calibration machines use pneumatic generation of calibration forces, but measure these forces either with load cells or a reference balance. The Farnborough BCM does not measure the forces; it relies on the accuracy of forces generated by the FGs. Therefore both the applied pressure and their mechanical behaviour must be accurately controlled.

The applied pressure is controlled by Ruska pressure controllers; these are regularly calibrated at a NAMAS certified standards laboratory to an uncertainty of 0.005%, and seem accurate in use to 0.01% of reading. Corrections are made for the relative height of each FG and changes of piston area with temperature, and for any non-linearity in the calibrated characteristic of the controllers.

Accurate control of the FG mechanical behaviour is achieved in the following way. When using the BCM, for each balance calibration point pressure is smoothly applied to the FGs till the calibration load settles at the required value. As described earlier, the restoration positioning system smoothly maintains the directions of the loads normal to the loading tree throughout this. However, the length of the push/pull arms and flexures allows them to deflect along the direction of the load, according to the magnitude of the load. This allows each FG piston and its low friction 'rolling-sock' pressure seal to travel a distance equal to the deflection of the push/pull arms and flexures at this load. Therefore, for every load, the piston and seal will travel a corresponding distance. The maximum seal travel in this way is approx 0.4mm; the seal behaviour is essentially elastic in this range.

The FGs themselves are calibrated at the 5m tunnel on a dedicated machine, the weigh beam calibration rig (WCR). This calibrates individual FGs at pressures certified by a deadweight pressure standard against certified masses, using a certified local value of 'g'. Essentially, the WCR is a single channel equivalent of the BCM; for each load it gives approximately the same seal travel as the BCM. Therefore the mechanical behaviour of the FGs is standardised for both their use and their calibration; thus inaccuracies due to seal effects are largely eliminated. Calibrations of the FGs show that they are accurate in converting applied pressures into values of calibration force, typically to within 0.003% of full scale.

In using the BCM to generate a typical calibration load, these small inaccuracies in the FGs will combine with small inaccuracies in the Ruska pressure controllers, in the BCM geometry and in the weight counterbalance. Calibration loads seem typically to be accurate to 0.01% of BCM full scale. For example, the 5m under-floor mechanical (weigh beam) balance uses the full scale of the BCM; when calibrating this balance most of the calibration points are within 0.01% of full scale of a linear (first order) fit to the whole calibration data (if the BCM is correctly adjusted so that the rate of application of FG pressures matches the response of the restoration positioning system). As many of the inaccuracies are load dependent the absolute inaccuracy will reduce with smaller loads. Therefore when calibrating a balance of load capacity about 30% of BCM full scale we believe the typical error in calibration load is about 0.02% of balance full scale.

4 TEST SET-UPS

The balance is mounted in the BCM with a set of adapters. The balance centre is in the centre of the BCM. All adapters have a flange mating connection. Keys are used to prevent rotation along the x-axis.

5 TEST PROGRAMS

In total three calibrations were performed in succession. The first one can best be described as a One Factor A Time (OFAT) load table with additional independent data to check the validity of the calibration. The second and third are designated as MDOE structured and MDOE randomized.

The OFAT load table:

This load table starts off with a 1st order calibration of pure loads. For the 2nd order calibration the following calibration procedure was adopted. For all 15 combinations of two loads, combined loads were applied. First, one load component was held constant at +75% of its load range and the other load component was varied from 0 to +75% and from 0 to -75% of its load range. Then the one load component was held constant at -75% of its load range and the other load component was varied from

0 to +75% and from 0 to -75% of its load range. After this the second load component was held constant at +75% and -75% of its load range and the first load component was varied from 0 to +75% and from 0 to -75% of its load range. The number of load points are chose in such away that the 1st order calibration took about 1/3 of the total number of load points and the 2nd order calibration thus 2/3 of the total number of load points.

Overall the 1st order calibration consisted of 253 data points and the 2nd order calibration consisted out off 481 data points.

Since the BCM allows simultaneous application of 6 load components it was used to simulate a wind tunnel measurement of a typical DNW-LLF model. The simulated conditions represented a weight polar, a pitch polar, a yaw polar, the maximum load condition and a repeat of the yaw polar. The load table was finally ended with a single component 1st order calibration repeat of the axial component. The maximum load point is the maximum simultaneous load condition, 90% of the FS load range on all 6 components.

MDOE structured

This load table consists of 101 points. The load table was devised out of convenience. It is certainly not optimized. The general idea is that since we are only fitting a second order model (see Reference [2]) it should be sufficient to use only the maximum load points out the OFAT load table in order to be able to fit the math model. These points should be sufficient to support the model. In addition extra zero load points were measured to get a feel for the repeatability.

MDOE randomized

This load table is essentially the same as the MDOE structured load table only it I randomized. Unfortunately during the randomization process a number of load points were omitted and replaced with a zero load point. The -100% load points of the single components were replaced by a zero load point for all but the Fz component.

A brief resume:

DPN 0-24	(25)	First loadings of he balance. Check of the BCM
DPN 25-277	(253)	First Order calibration points pure forces and moments (34.47%)
DPN 278-758	(481)	Second order calibration (65.53%)
DPN 759-872	(114)	Check points
DPN 759-775	(17)	WT simulated weight polar
776-792	(17)	WT simulated pitch polar, with rudder deflection
793-810	(18)	WT simulated yaw polar
811	(1)	Max load point (90% FS simultaneously)
812-829	(18)	WT simulated yaw polar repeat
830-872	(43)	Repeat Fx calibration
DPN 1-101	(101)	MDOE load table structured
DPN 0-102	(103)	MDOE load table randomized

6 DATA REDUCTION

6.1 Corrections

The data-set has been pre-processed. Pre-processing is needed to apply a number of corrections. All applied pre-processing is briefly documented below.

6.1.1 Tare forces

The loads applied to the balance have to be corrected for tare-forces due to the weight of the loading tree. On the metric end of the loading tree two inclinometers are installed. These inclinometers measure the Roll and Pitch angles of the metric side of the balance. The weight tares are rotated over Roll and then Pitch to the metric axis system.

6.1.2 Signal corrections

The zero signals of the balance are recorded before the balance is mounted to the BCM. This zero represents a situation where the balance mounted to a sting and no loads are applied to the balance

(only the weighted part of the balance, the adapters, the BCM mounting block and the electronic offset is measured by the gauges).

When the balance is mounted in the BCM the loading tree is positioned in such away that the signals of the balance correspond to the previously recorded zero.

The then recorded zero is subtracted from all further recorded signals.

The supply voltage is measured for each data point. The balance output signals are corrected for deviations to the nominal supply voltage of 10V. This is done for each output signal individually.

The output signals are made 'non-dimensional' with the nominal supply voltage of 10V.

The natural zeros of the balance have been recorded later at the DNW-LLF.

The zeros are listed in Table 5.

6.1.3 Sign convention.

The loads are according to the DNW sign convention for balance loads, see Figure 4. Note that the QinetiQ sign convention only differs for the forces. The forces in the QinetiQ sign convention are opposite to the forces according to the DNW sign convention.

6.2 BCM Data

The data have been exported to an Excel file (B667 Cal Data.xls).

All double measured data points have been omitted from the data-set. In total 8 data points have been omitted.

The data-set consists of the following variables

IDENT	[#]	Load table identification (1=OFAT, 2=MDOE structured, 3=MDOE randomized)
DPN	[#]	Load point number
SQN	[#]	Sequence number, data point number
R1	[mV/V]	1 st balance signal
R2	[mV/V]	2 nd balance signal
R3	[mV/V]	3 rd balance signal
R4	[mV/V]	4 th balance signal
R5	[mV/V]	5 th balance signal
R6	[mV/V]	6 th balance signal
X	[N]	Axial Force (load table load)
Y	[N]	Side Force (load table load)
Z	[N]	Normal Force (load table load)
L	[Nm]	Rolling Moment (load table load)
M	[Nm]	Pitching Moment (load table load)
N	[Nm]	Yawing Moment (load table load)
Fx	[N]	corrected Axial Force (calibration load)
Fy	[N]	corrected Side Force (calibration load)
Fz	[N]	corrected Normal (calibration load)
Mx	[Nm]	corrected Rolling Moment (calibration load)
My	[Nm]	corrected Pitching Moment (calibration load)
Mz	[Nm]	corrected Yawing Moment (calibration load)

6.3 Concluding remark

It should be note that this is a moment type of balance and this balance is not a direct read balance and should therefore not be treated as one. Nevertheless for clarity for this moment balance the signals respond to the following forces.

$$F_x \equiv R_1$$

$$F_y \equiv R_2 + R_5$$

$$F_z \equiv R_3 - R_6$$

$$M_x \equiv R_4$$

$M_y \equiv R_3 + R_6$
 $M_z \equiv -R_2 + R_5$

7 REFERENCES

- [1] Eckert, D. et al, *Design and Construction of Internal Balances for the German/Netherlands Wind Tunnel (DNW)*, 1st International Symposium on Strain Gauge Balance, 14 August 1997
- [2] Philipsen, I., Hoeijmakers, H., Alons, H.J., *A New Balance And Air-Return Line Bridges For DNW-LLF Models (B664 / RALD 2001)*, 4th International Symposium on Strain-Gauge Balances", San Diego, USA, 10–13 May 2004
- [3] I. Philipsen, R. Bergmann, *Some Contemplation on a Proposed Definition of Uncertainty for Balances*, AIAA 2010 4546, 27th Aerodynamic Measurement Technology and Ground Testing Conference, Chicago, Illinois, USA
- [4] I. Philipsen, J. Zhai, *Comparative Study of Strain-Gauge Balance Calibration Procedures Using the Balance Calibration Machine*, AIAA-2007-0143, 45th AIAA Aerospace Sciences Meeting & Exhibition, 8-11 January 2007, Reno Nevada, USA
- [5] R. DeLoach, I. Philipsen, *Stepwise Regression Analysis of MDOE Balance Calibration Data Required at DNW*, AIAA-2007-0144, 45th AIAA Aerospace Sciences Meeting & Exhibition, 8-11 January 2007, Reno Nevada, USA
- [6]

Tables

Table 1: Load Range B667

Load	Range
F_x	8000 [N]
F_y	8000 [N]
F_z	21000 [N]
M_x	5000 [Nm]
M_y	6000 [Nm]
M_z	4000 [Nm]

Table 2: Requested Accuracy Coefficients B667

Accuracy coefficients	B667 [1=0.1%]
a_{F_x}	1.0
a_{F_y}	1.0
a_{F_z}	1.0
a_{M_x}	1.0
a_{M_y}	1.0
a_{M_z}	1.0

Table 3: Required Deflection Coefficients B667

Balance Load	Deflection coefficient [°/Nm]
M_x	75 E-06
M_y	75 E-06
M_z	75 E-06

Table 4: BCM Load Range

Load	Maximum Range	Current Range
F_x	22 [kN]	20 [kN]
F_y	127 [kN]	20 [kN]
F_z	90 [kN]	90 [kN]
M_x	140 [kNm]	12.3 [kNm]
M_y	15 [kNm]	15 [kNm]
M_z	40 [kNm]	12.3 [kNm]

Table 5: Zeros of B667

Signal	QinetiQ Zero [mV/V]	Natural Zero [mV/V]
R1	-0.0206	-0.0204
R2	-0.0161	-0.0054
R3	-0.0441	0.0143
R4	-0.0248	-0.0101
R5	0.0248	0.0148
R6	0.0002	0.0030

Figures

Figure 1: Balance B667

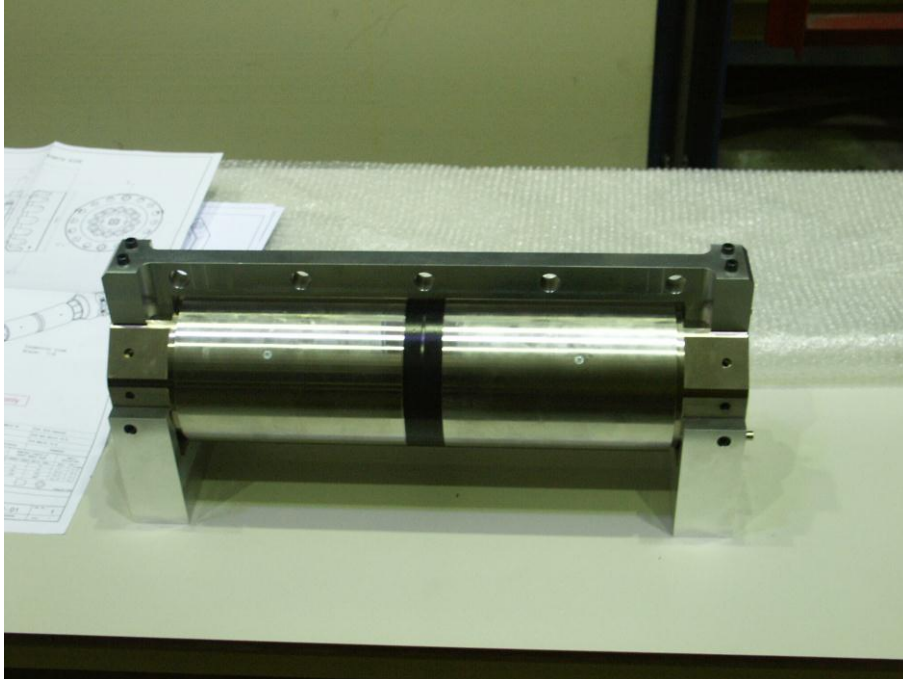


Figure 2: Balance B667



Figure 3: Loading Tree of the BCM

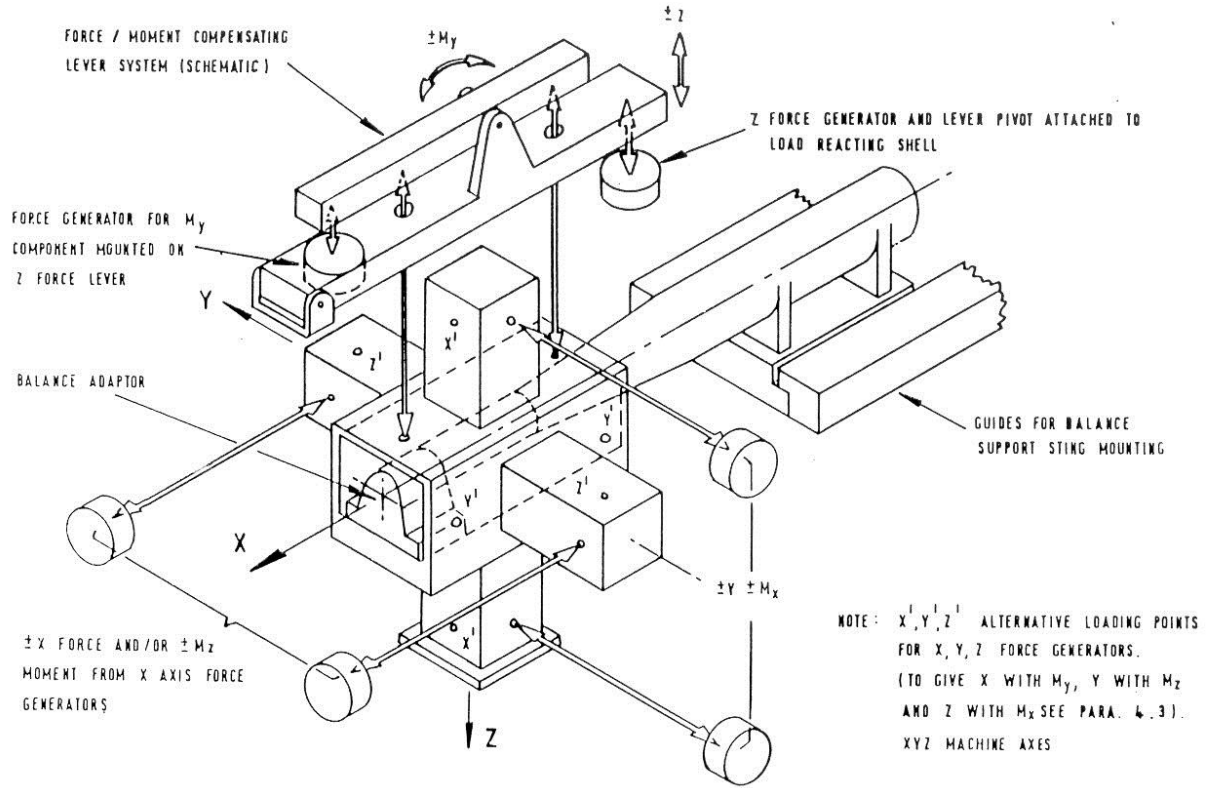


Figure 4: Balance B667, sign convention

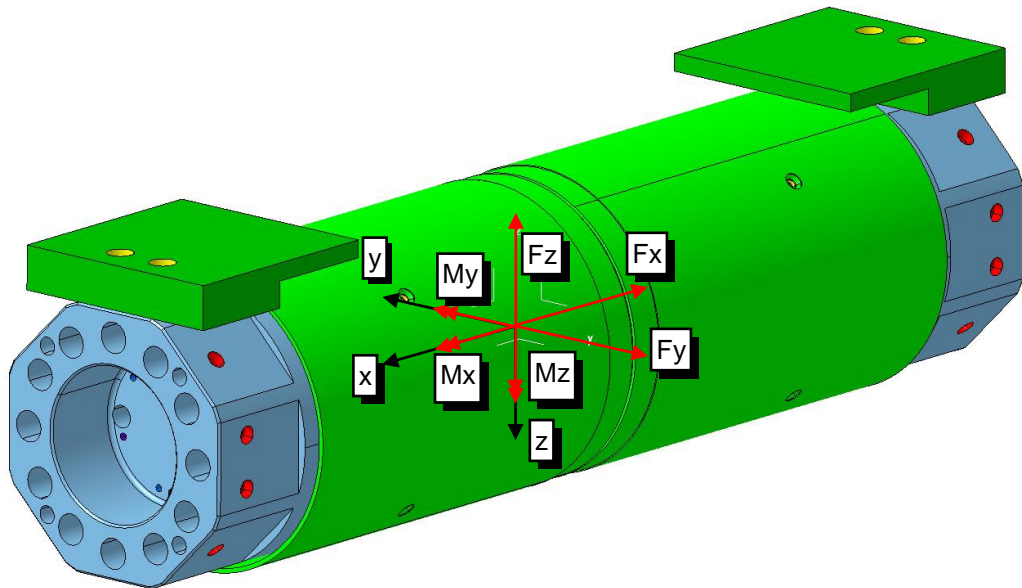


Figure 5: Sketch of the BCM

