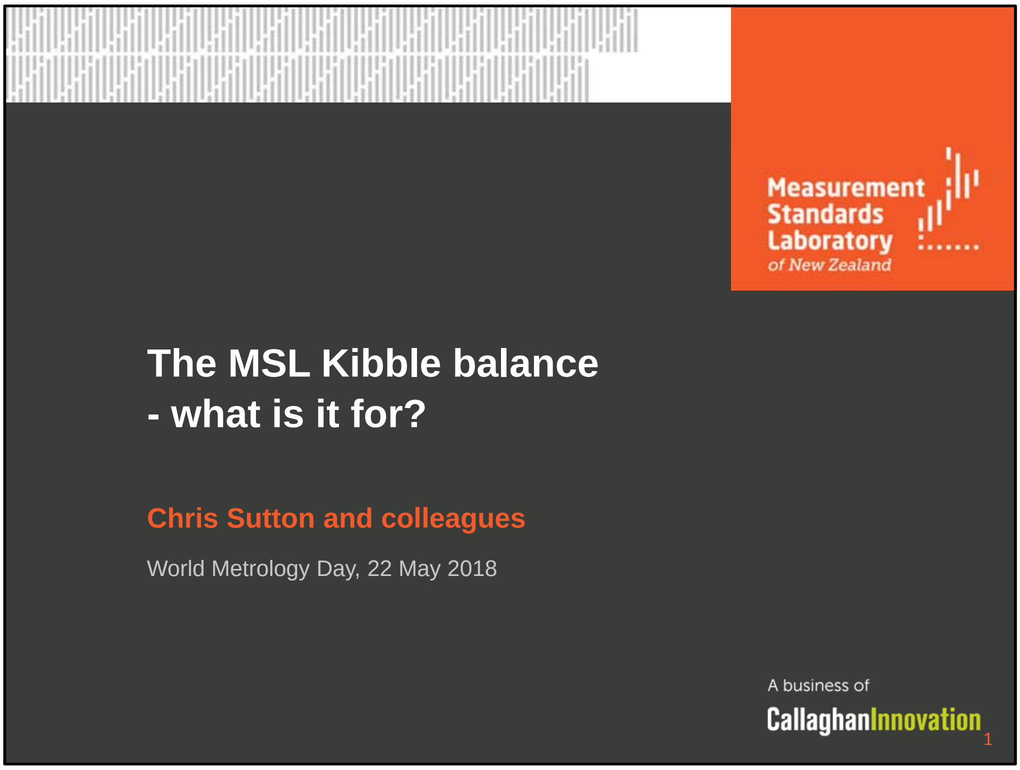

Nau mai, haere mai, whakatau mai rā, tenā koutou katoa.
Welcome and warm greetings to everyone here today.
My name is Fung and I’m a research scientist here in MSL.
Actually I’m being called to step in at the eleventh hour to deliver this talk on behalf of Chris Sutton. Chris is at an important appointment at the moment, but he should be around during lunch time.
I apologize in advance if I seem a bit disorganized and if I’m mumbling because I’m nervous. But I will try my best to deliver this talk as how it was intended to be.
So the topic today is MSL Kibble Balance – what is it for?
Before I start, I have to make an acknowledgement that the MSL Kibble Balance is a joint effort from members across different sections of MSL and you will see why in the talk.

Measurement Standards Laboratory of New Zealand

Items of this presentation

- Kilogram
- Redefinition of kilogram
- What is a Kibble balance?
- MSL Kibble balance

Firstly, we are going to talk about the current kilogram and what are the issues.
And why we have to redefine the kilogram and how are we going to do it.
There are two main methods, but we are focussing on the Kibble balance approach. We will explain what is it and how does it work.
Of course, we will present the MSL Kibble balance, how it is different from other Kibble balances around the world, its features and its potentials.

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Kilogram

International Prototype Kilogram (IPK) – definition of kilogram since 1889.

Mass standards are traceable to the IPK, comparison at BIPM.

What you are seeing here is the IPK (left picture) – the International prototype kilogram, which is a lump of Platinum-iridium metal cylinder sitting inside a triple bell jar located in a vault underground in a building in Paris. The IPK has been the definition of kilogram since 1889. To open the vault to check if the IPK is still there, three keyholders have to be present at the same time.

When I think of a vault for something that important, I think of something like this (centre picture). Actually this is only a random stock image of a vault that I used to illustrate my imagination.

But the IPK vault looks something like this (right picture), where you can see the IPK is in the middle, and there are 6 official copies of it kept under the same conditions as the IPK.

There are other copies and mass standards around the world too, they are traceable to the IPK, and are being sent for mass comparisons once every 5 years to BIPM in Paris, who is the keeper of IPK.

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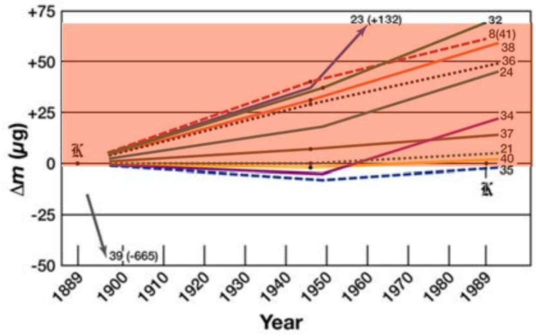
The problem



Careful mass comparisons with other copies show mass divergences of up to 70 microgram.

Ampere, mole, candela are currently dependent on kilogram – limiting the improvement to SI.

Other measurement units: newton, pascal, joule

What is the problem?

The graph that you see here is the mass difference between the IPK and other identical copies, measured through mass comparisons. Over the past 150 years, there have been a few comparisons, but what this shows is that the mass differences diverges with time. And the divergences value can be up to 70 microgram.

This could be either the IPK is losing mass, or the copies are gaining mass, or vice versa. We don’t know. In other words, it is impossible to define the IPK mass stability with any accuracy.

So having a standard of mass that changes over time is unacceptable.

If you think about it, as far as human and science is concerned, if we are the only creature in the universe to define kg and it is tied to the IPK, a physical artefact, then the mass of the universe “changes” according to the mass change of the IPK. It is a bit absurd when I think about it.

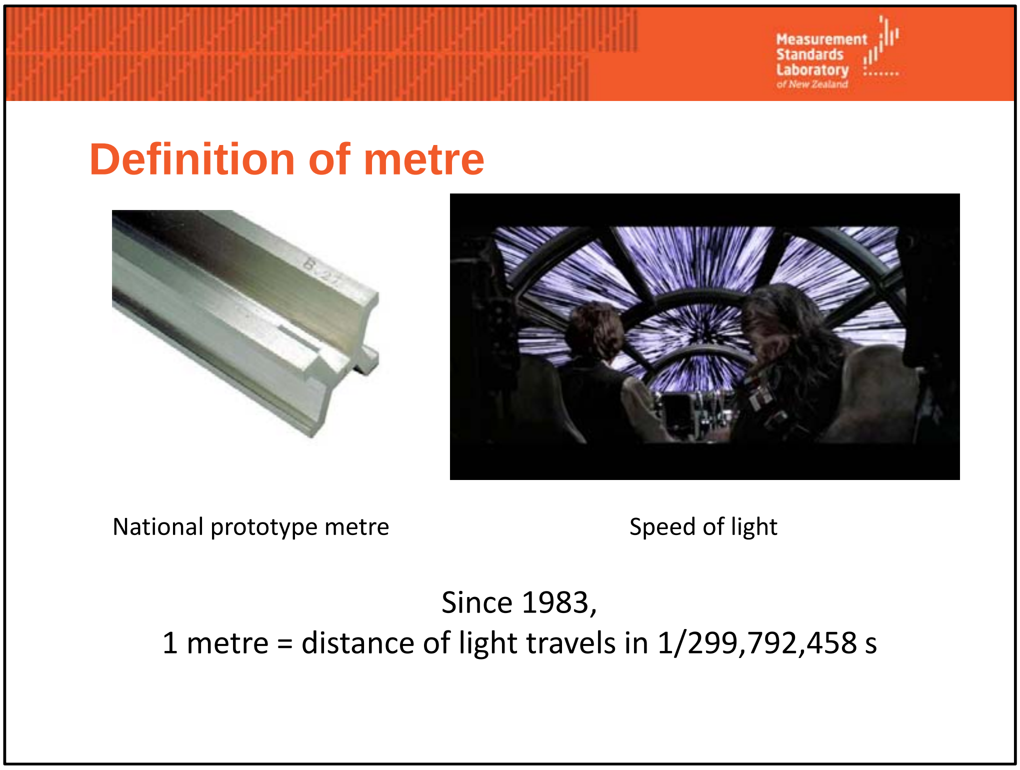
Kilogram is also the last remaining SI unit still be defined by a physical artefact. And it is actually limiting the improvements to other SIs like ampere, mole and candela, which are currently dependent on the kg other measurement units like newton, pascal and joule. We (the kilogram) certainly don’t want to be the bad apple in family, so we have to step up.

Need a new definition of kilogram based on a fundamental constant

Planck's constant (h)= 6.626 069 … x 10^{-34} Js

A physical constant that relates the photon energy to its frequency.

So we need a new definition for kilogram that is based on a fundamental constant that is invariant over time.
The constant is Planck's constant: a number that relates a photon's energy to its energy. It is usually denoted with the chracter h.



Changing a definition of a SI unit from a physical artefact to fundamental constant had been done before. One example is the metre. It used to be a platinum bar, 1 metre long, the national prototype metre, again, kept in somewhere in Paris.

But since 1983, the metre is defined in terms of the speed of light, which is 1 metre is the distance of light travels in 1 over 299,792,458 seconds. 299,792,458 metre per second is the speed of light, which is fixed.

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Linking kg to Planck's constant

1. Avogadro's project

- Counting atoms in an isotopically pure silicon-28 sphere that weighs the same as the reference kilogram and obtain Avogadro's constant and convert to Planck's constant.
- Sphere costs about 1 million Euro each, plus measurement capabilities.

Now, how do we link the kilogram to Planck's constant?
There are two main approaches. The first is called the Avogadro's project.
To do this, you need to have a pure silicon-28 sphere that has been polished really well. It is known as the world's roundest object. Scientists can use x-ray crystallography and optical interferometry to determine the structure of the sphere and spacing pattern and widths with great precision. From this, we can count the number of atoms in the sphere that weighs the same as the reference kilogram and obtain Avogadro's constant and then convert it to Planck's constant with low uncertainty.
The sphere costs about 1 million Euro each, and there are only 2 available in the world at the moment, it usually comes in the form of international collaborations because you need expertise in advanced measurements from different countries.

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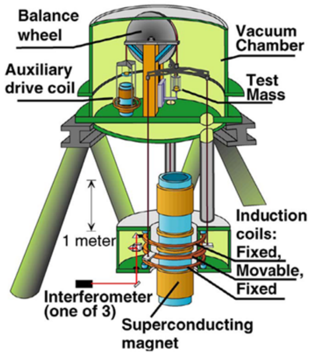
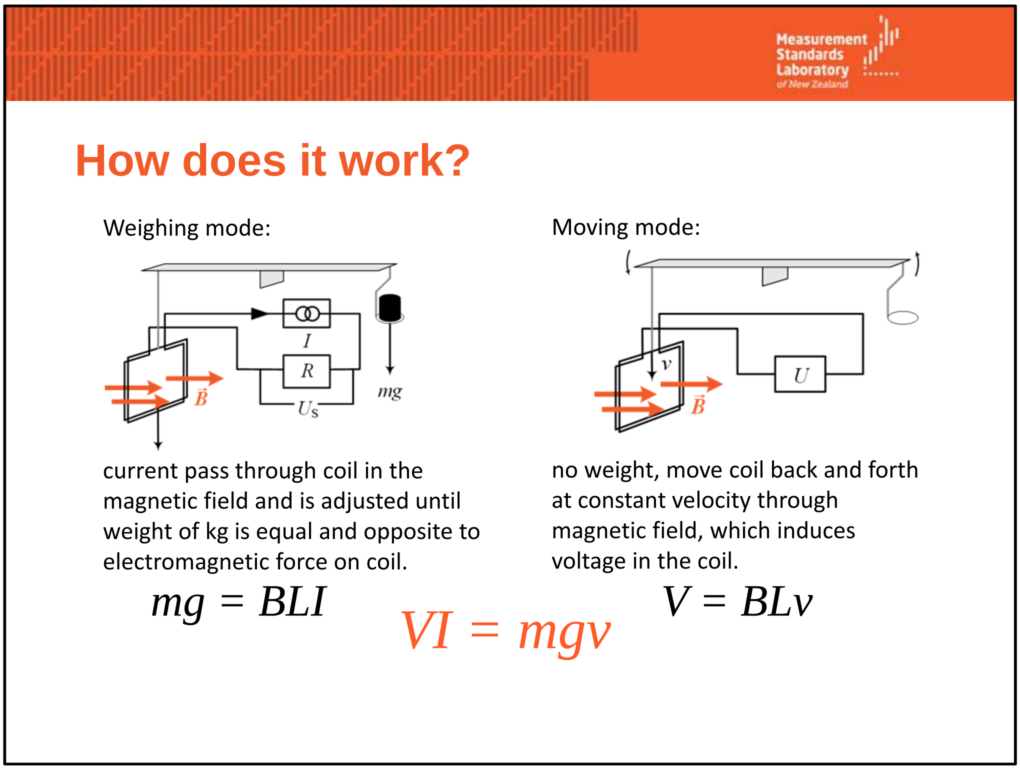
Linking kg to Planck's constant

2. Kibble balance

- Determine Planck's constant by comparing gravitational force on a reference mass with the electromagnetic force on a coil carrying current in a magnetic field.
- UK, USA, Canada, France, Switzerland
- Most practical option for NZ



The second approach is the Kibble balance approach.
Kibble balance is an apparatus that can determine the Planck's constant by comparing gravitational force on a reference mass with the electromagnetic force on a coil carrying current in a magnetic field.
There are several Kibble balances around the world at the moment: in USA, UK, Canada, France, Switzerland, China, Korea.
And the Kibble balance approach is the most practical option for NZ because we do not have to fork out 1 million Euro just to make a sphere and that would be an expensive project.
Now, when you have two methods: measuring the Avogadro number, which is a chemistry quantity and making a Kibble balance, which is a physics method, both agree on the value of Planck's constant, then that is a pretty good sign!



How does a Kibble balance work? Murray Early the previous speaker has explained it briefly before, but please allow me to go through this again to help with my thought process. Please bear with me.

Kibble balance can work in two modes.

The first mode is the weighing mode. Here, we run current through the coil in the magnetic field and we adjust the current until the weight of the weight of kilogram is equal and opposite to the electromagnetic force on the coil. This can be described in the following equation, m, the mass times g, the acceleration due to gravity is equal to B, the magnetic field strength, times L the length of the wire in the coil, and I the current that we apply on the coil. But, to measure B and L exactly is very very difficult, so we want to avoid measuring those if possible.

That’s why we have the second mode, the moving mode.

Here, we take away the weight, and then we move the coil back and forth at constant velocity through the magnetic field, by maybe using a motor, and this induces voltage in the coil, V is equal to B times L times little v, the velocity of the moving coil.

Now if we combine the two equations together, we get this (orange equation), where BL is nowhere to be seen. And what we are left with is VI, the ‘virtual’ electrical power is equal to mg times v, the mechanical power. It is used to be called as the Watt balance before, since watt is the unit for power, but has been changed to Kibble balance, in memory of the inventor of the Watt balance, Byran Kibble.

One more thing, remember some of the quantities here are actually vectors, and this is important to take note, but here I do not show the vectors for simplicity sake.

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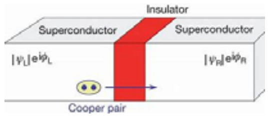
Essential measurements

$VI = mgv$

V, voltage: can accurately measure using a macroscopic quantum effect that involves Josephson junctions, apply microwave frequency f across the junctions and create a voltage across the device with stack of N junctions.



$$V = \frac{Nhf}{2e}$$

I, current: measure V on R, the resistance. R can be measured very accurately using quantum Hall effect.

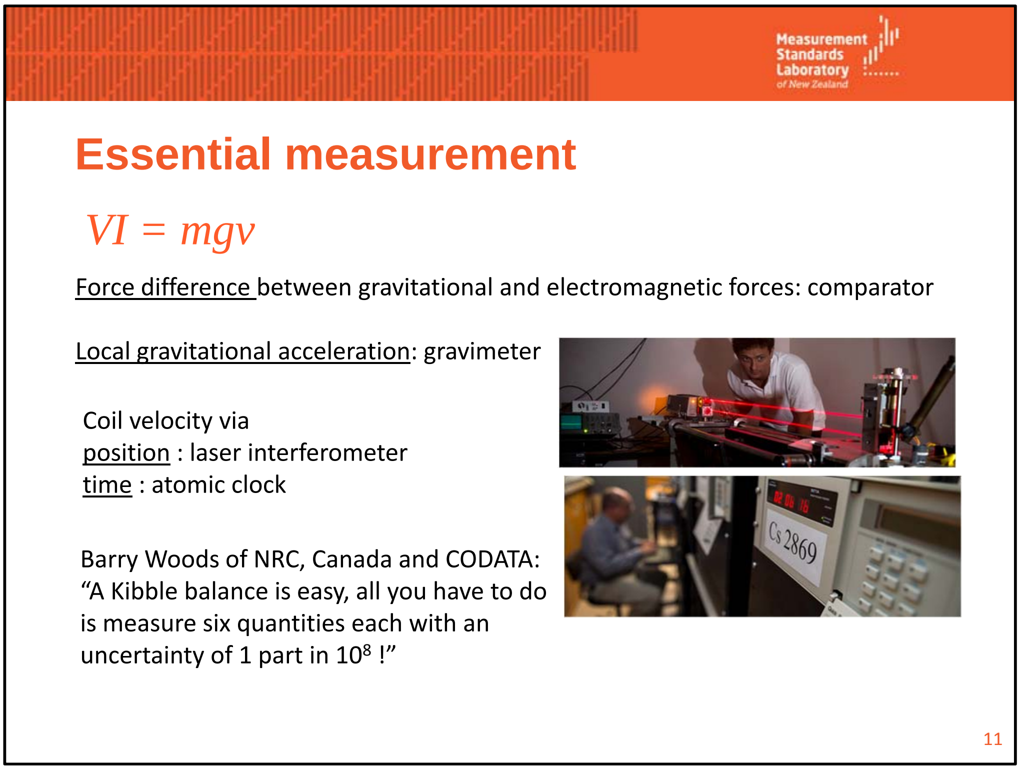
$$I = \frac{V}{R} \qquad R = \frac{h}{ne^2}$$

To make a Kibble balance work, we need to measure the quantities in this equation (orange equation) very well.

For V, we can accurately measure using a macroscopic quantum effect that involves Josephson junctions, which was mentioned by Murray before. We can apply microwave of frequency f across N junctions and this will create a voltage across the device with stack of N junctions. The voltage is given by N times h, the Planck's constant times f divided by 2 e, the electron charge.

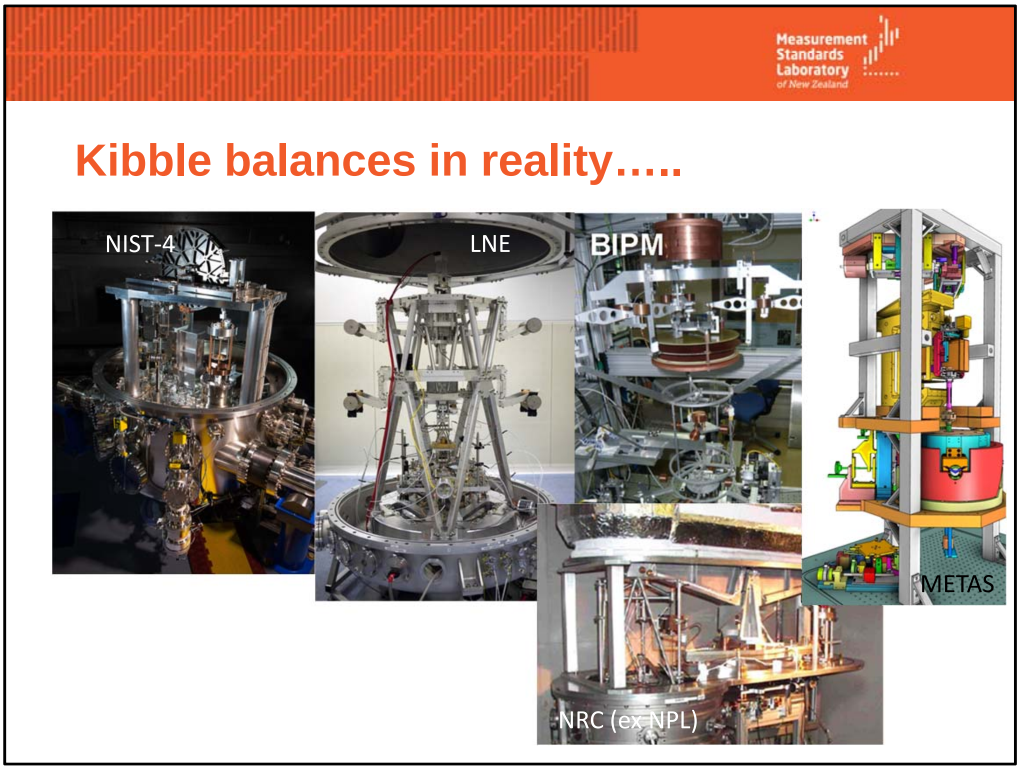
For I, we don't directly measure the current, because we can measure V very very well by using the Josephson effect and we can measure R the resistance very accurately by using another macroscopic quantum effect called the quantum Hall effect, which was again explained by Murray before. R here is equal to the Planck's constant divided by the quantum number n and electron charge squared.

Note how the Plancks' constant is in these expressions. So if we plug these into the left hand side of the orange equation and rearrange, we can basically express the Planck's constant in terms of mass, which can be a kilogram. This is how the Planck's constant comes into the picture when linking it to the kilogram.

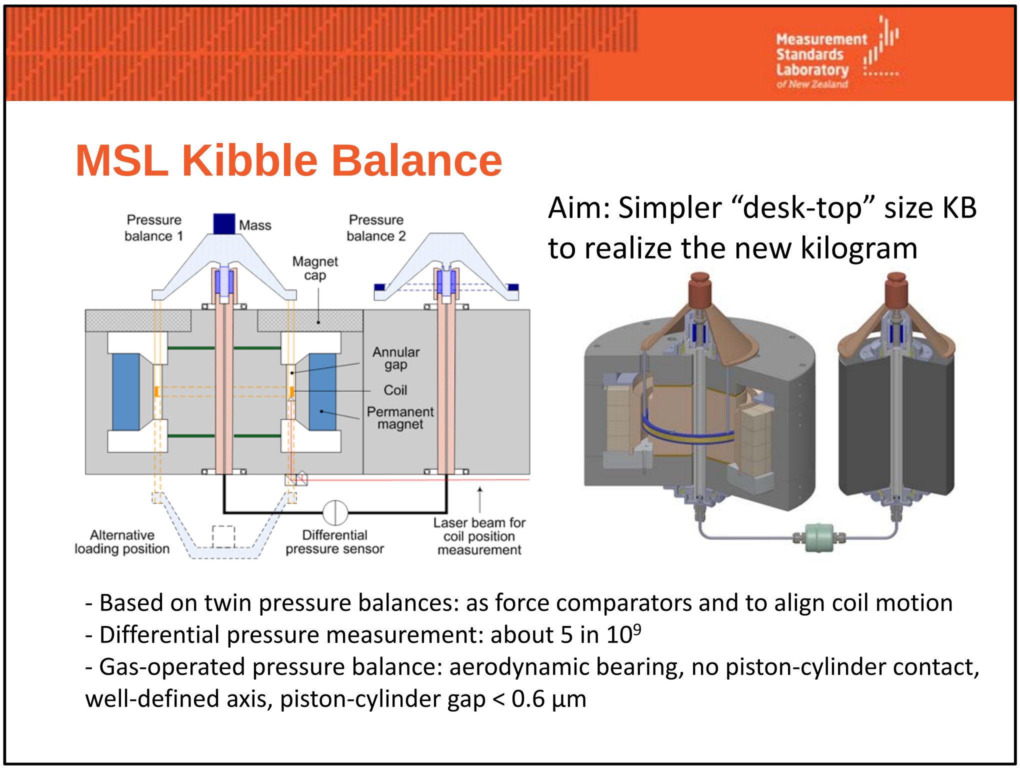


We also need to measure the force difference between the gravitational and electromagnetic forces and this can come in the form of a force comparator.
The local gravitational acceleration, the g, measured by a gravimeter.
And then the coil velocity, the v, by measuring its position using a laser interferometer and time, where we use the time reference from an atomic clock.

To put it in the words of Barry Woods: "A Kibble balance is easy, all you have to do is measure six quantities each with an uncertainty of 1 part in 10 to the 8 !" Sounds easy right?



But in reality, Kibble balances look like this. Here are some of the pictures of Kibble balances from around the world.
Typical KB usually comes in the form of beam balance, which can be complex mechanically and its hard to align the forces well. Remember the vector quantities that I mentioned before?
Some of them can be quite huge, up to two storey building high. It looks amazing!



Here in MSL, we come up with a way simpler design for a Kibble balance that is based on a twin pressure balance. It is the only Kibble balance to be based on a twin pressure balances that acts as force comparators and to align the coil motion.

This (left picture) is the schematics of it and this (right picture) is the 3D drawing of it. Here we can see the two pressure balances connected, with the differential pressure sensor in between, the coil, the permanent magnet, and the laser measurement beams for interferometry.

Differential pressure measurement have shown the average difference in pressure between the two pressure balances has a short-term stability of about 0.5 millipascal or 5 parts in 10 to the 9 of the 100 kilopascal line pressure. So they can act as a force comparator with good repeatability.

The pressure balance is gas-operated, there is no contact between the piston and cylinder, it has a well-defined axis, and the piston-cylinder gap is about 0.6 micrometre. This will make the vertical alignment of our Kibble balance much simpler.

The aim is to have a simpler and “desk-top” size Kibble balance to realize the new kilogram here in New Zealand.

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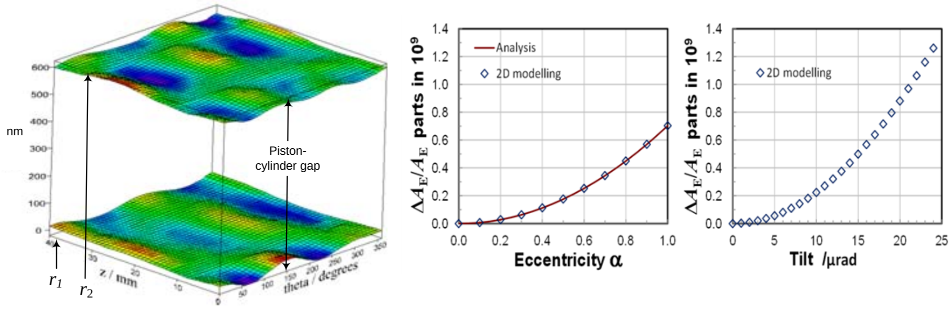
Pressure balance modelling

- Pressure balance effective area A_E must remain constant
- Investigated using 2D finite difference modelling
  - Effect of changes in piston tilt & eccentricity in cylinder on A_E : < 2 parts in 10^9
  - Effect of geometric imperfections in piston & cylinder: insignificant change vs modelling results
  - Results consistent with 5 parts in 10^9 differential pressure performance.



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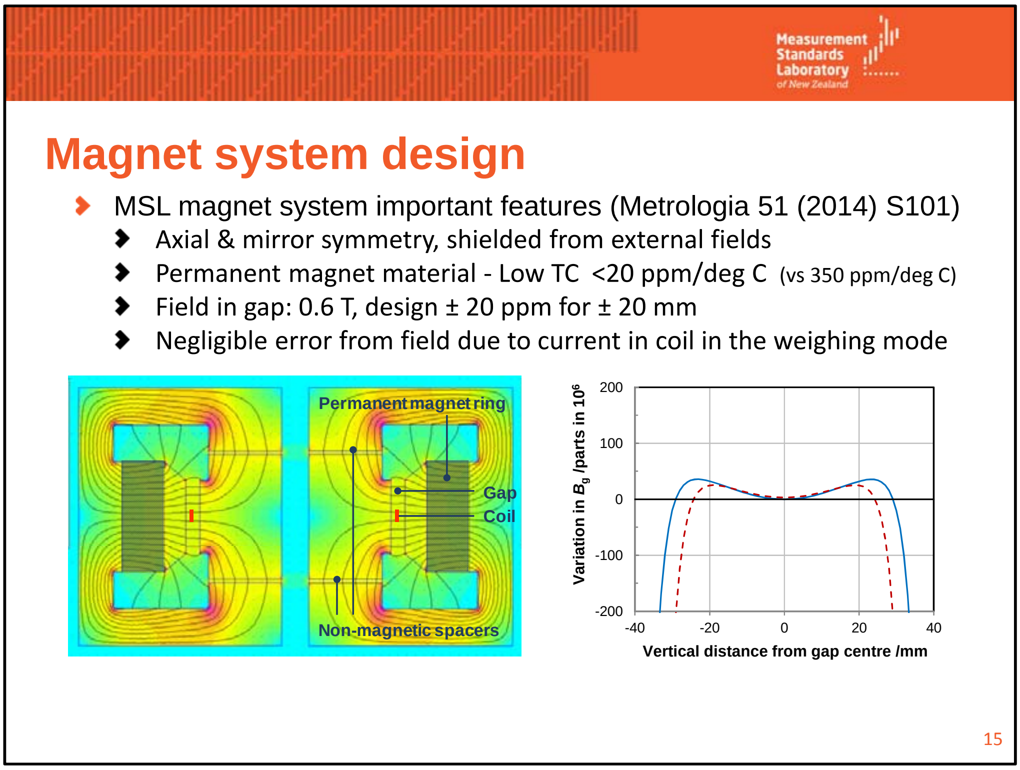
To make sure that we can use pressure balances in our Kibble balance, we need to characterize them. So we have done 2D Modelling of the behaviour of the two pressure balances, these are Chris' and Mark's work mainly.
We have to ensure that the effective area remains constant. The effect of changes in piston tilt and eccentricity in cylinder on the effective area is very small, about 2 parts in 10 to the 9. The effect of geometric imperfections in piston-cylinder are also insignificant.
These results are also consistent with the 5 parts in 10 to the 9 differential pressure performance as a mass comparator.

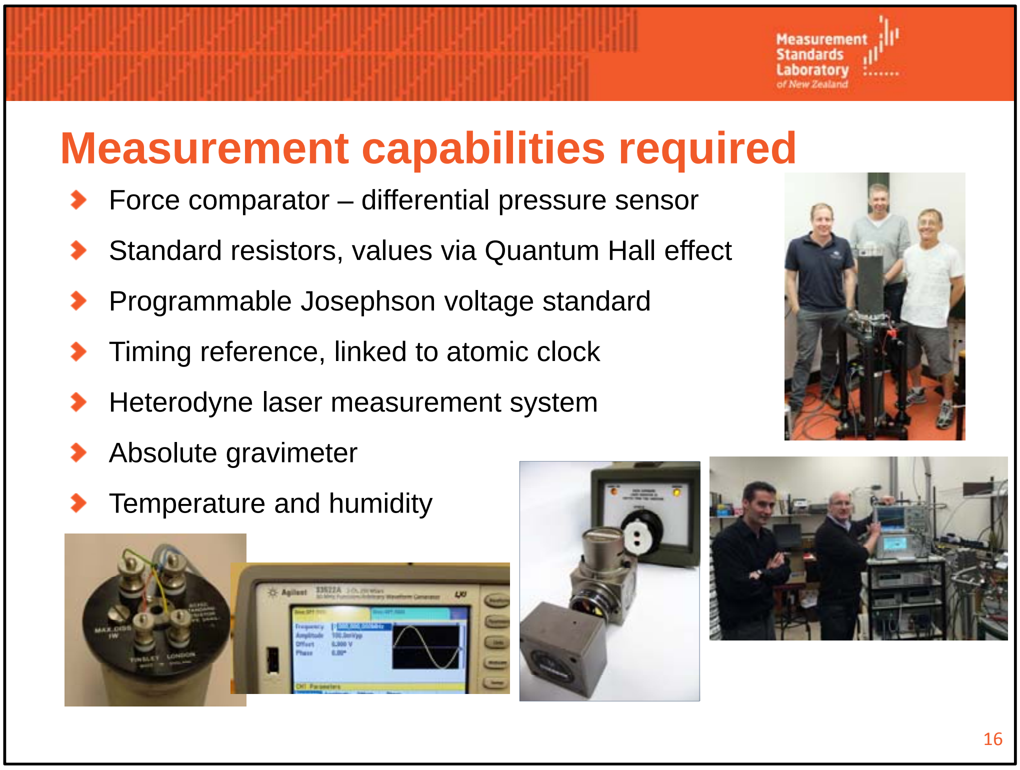


Other than that, the a novel magnet system for MSL Kibble balance was carefully designed and it has some important features. Again, these are Chris' and Mark's work and was published in Metrologia in 2014.

The magnet system has axial and mirror symmetry and is shielded from external fields. The permanent magnet material used has a low thermal coefficient, about 20 ppm per degree celcius, this is as opposed to other magnet material, which has thermal coefficient of about 350 ppm per degree celcius.

The magnetic field strength in the gap, where the coil is moving, is about 0.6 Tesla, and it is fairly constant, which changes of about 20 ppm for the 20mm coil moving region.

It also has negligible error from the field due to the current running in the coil in the weighing mode. This error can be a major source of uncertainty if not taken care of. This feature will allow the Kibble balance to be used in several operating modes.



The measurement capabilities required for the MSL Kibble balance are as follows.
First, the force comparator, which comes in the form of differential pressure sensor in our case, and we have that capability already.
Standard resistors, values obtained from quantum Hall effect and programmable Josephson voltage standard, these are the electrical standards.
Timing reference, we can get that from our beloved atomic clock and “Time Lord” here in MSL, so that’s not a problem.
Heterodyne laser measurement system, this is a length measurement, we have the expertise in this and are developing the system for the Kibble balance.
We need to measure the local gravity, for this we ask GNS Science to do local gravity mapping at MSL and Geoscience Australia to do absolute g measurement.
Of course, we need temperature and humidity measurements too, which MSL already have, to make sure that we have the ideal ambient conditions.
As you can see here, to make a Kibble balance, we need capabilities from different sections and measurement units. It is not enough to be just good in mass measurements, as this project involves electrical, pressure, length, time, temperature and so forth, and MSL happens to have good capabilities in all these. That’s why I said before, this is actually a joint effort from different measurement units to make this happen.

Measurement Standards Laboratory of New Zealand

Current status - activity on many elements

- Current source – design & construction (6, 12, 24) mA
  - MSL modified METAS design
- Modification to triggering board in 3458 voltmeter with NIST
- Assembler/splitter for magnet system with HTS-110
- Temperature controlled resistance network
- Heterodyne laser non-linearity length errors
- Kibble balance laboratory being prepared
- DHI pressure balance characteristics
  - Particularly piston righting moment
- Weight loading mechanism
- Adjustable cylinder base
- Chamber design
- Initial loading masses

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A lot of activities that have been going on for the MSL Kibble balance. I won't elaborate too much here because I'm running out of time, but if you are interested, you are most welcomed to come have a look at our new Kibble balance lab afterwards to see yourself the current status of it. We can talk about it later.

NB: Any queries, you may contact us at chris.sutton@measurement.govt.nz and yinhsien.fung@measurement.govt.nz

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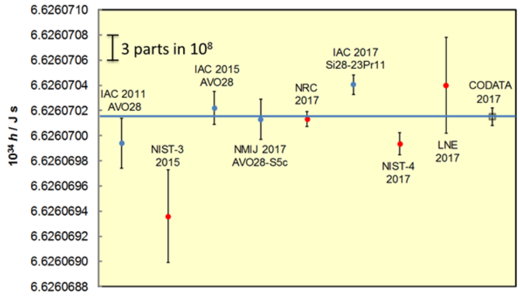
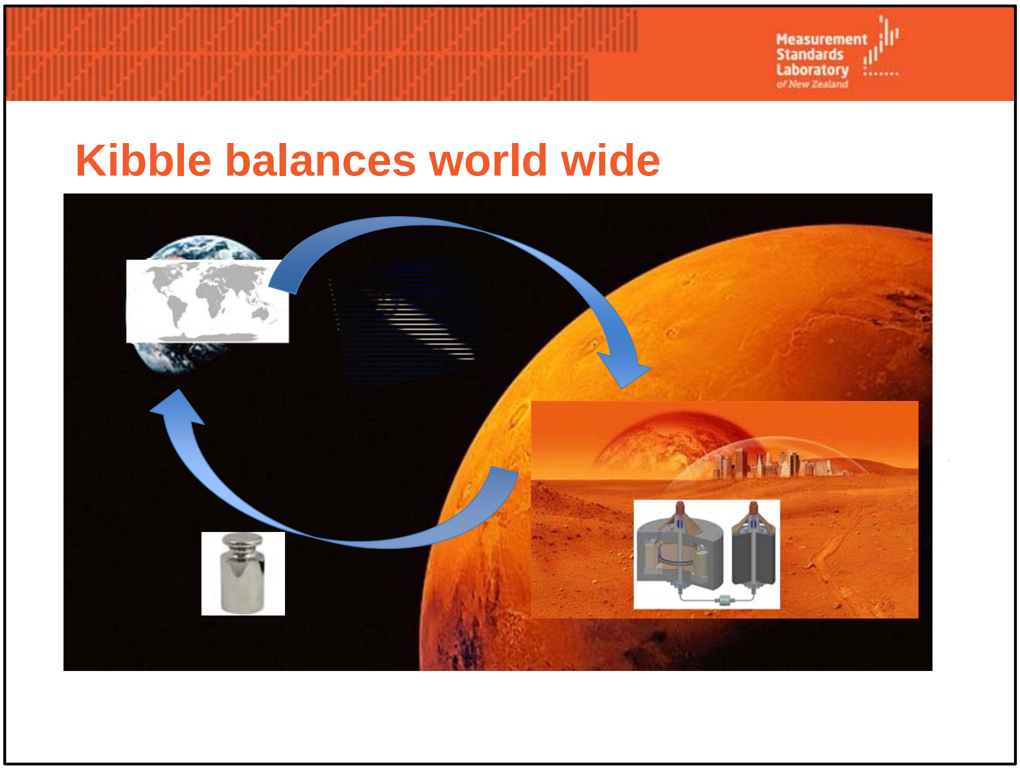
Global status



- Agreement between current primary kg realizations is not good enough
- CCM/CIPM proposing an interim consensus value
  - Via BIPM ensemble of reference mass standards (and selected primary realizations?)
  - Key comparison of primary kilogram realizations to start after the kilogram is redefined 20 May 2019? Anticipate that MSL will be a participant.
  - CCM *Task Group* established to manage the consensus value.

Global status, I won't be able to talk about this too much since I don't really understand the whole thing, but then you can ask Chris when he is here later.

NB: Any queries, you may contact us at chris.sutton@measurement.govt.nz



(Showing world map with several Kibble balances location) With the new definition of kilogram, other than making the kilogram more stable, we can basically realize the kilogram in any corner of the earth, without having to rely on an artefact stored in a particular location. There are several Kibble balances around the world. And of course, in New Zealand, we will have one too, right here in Gracefield. As you can see, we will be the first Kibble balance in the region. We are in a good position to make this happen because we have the advantages of being a tight knit national metrology institute with lots of know-how, experience and capabilities across different sections.

(Showing the earth and mars picture) To end this talk, allow me to indulge in my fascination with space explorations. One day, we will colonize Mars, and then we will perhaps move to Mars. And then you might want to set up a calibration lab in Mars. At that time, are you going to send your mass standards set back to Earth, Paris once every 5 years to be compared with the physical mass standards on Earth? No right? Because you can build a Kibble balance, and hopefully that will be an MSL designed Kibble balance.

Thank you for your attention.

NB: Feel free to contact us if you have any questions.
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