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White paper

Mounting encoder scales for optimum thermal performance

When the temperature of a machine changes, many parts of the machine will change length due to thermal expansion. All encoder scales obey the same thermal laws as any other component of a machine: as the temperature changes, so the length of the scale will change. It may be possible to accept the errors that arise, or to control the environment that the machine operates in, but even a single degree Celsius temperature change could lead to measurement errors of more than ten parts per million (10 µm/m). This white paper discusses how the thermal expansion of the scale can be managed. It includes options on how to calculate and compensate for thermally induced strains. It also explains how an expansion mismatch between the scale and the substrate can impact on the overall performance of the encoder system.

1 Thermal mounting methods

It is possible to calculate and compensate for thermally induced strains in scale. This is typically achieved by using measurements of the temperature and knowledge of the coefficients of thermal expansion (CTE) to calculate the length change of the scale and substrate. This can then be compensated. The thermal strain in the scale depends on the mounting method as explained below. It is important to ensure that the temperature of the relevant part of the machine and, if relevant, the workpiece is measured accurately, as errors in either can affect the thermal compensation.

Example 1: Consider a machine made of aluminium with a linear axis 1 m long which operates in a temperature range of 15 to 25 °C. Aluminium has a relatively high CTE of around 23 ppm/°C. The 1 m axis will expand and contract by ±115 µm ($1 \times 23 \times 10^{-6} \times 5 = 115 \times 10^{-6}$ m) over the temperature range (±5 °C).

Most linear encoder scales are made of materials, such as stainless steel, which exhibit different thermal behaviour than aluminium. If such an encoder were installed on this axis at 20 °C, neglecting thermal effects entirely could cause significant positional uncertainty. Our example 1 m aluminium axis could see a 115 µm positional error with a 5 °C temperature change depending on the scale mounting method.

We now need to consider whether the scale should be firmly mastered to the substrate or allowed to float independently above it.

1.1 Substrate mastered

If a machine grows by 115 µm as it heats up, it may still be desirable to travel to the same physical location on the machine at all temperatures – for example if the workpiece is fixed to specific locations on the machine. In this case, the scale should be elastic and able to stretch and compress with the machine.

This mounting method is called ‘substrate mastered’ because the substrate dominates the scale and the scale expands at the same rate as the substrate.

1.1.1 Selecting mastered scale

There are a number of applications where mastered scales excel. These include:

- When the co-ordinate system of the machine rather than absolute position is desired, such as when moving to a workpiece that is located at a fixed position on the bed of the machine.
- When the CTE of the workpiece closely matches the CTE of the machine substrate and the two are kept at the same temperature, the expansions of the scale and workpiece are closely matched. Therefore, any length change of the substrate, at a given temperature, is automatically compensated by an equivalent length change of the scale.
- When the machine axis is long, the uncertainties associated with mastered scale do not increase with length but with floating scale they do significantly increase with length.
- If the substrate has low thermal conductivity and a high thermal mass (for example, a thick piece of granite), short-term fluctuations in air temperature will cause minimal substrate temperature change and low expansion of the substrate and therefore it may be acceptable to ignore these short-term temperature changes. However, it is important to note that longer-term changes in temperature must still be considered. These may be harder to measure appropriately as it is the average substrate temperature which is important. Therefore, more direct length measurements, such as periodically comparing against a known standard, may be more appropriate.

1.2 Floating scales

Scale can be mounted so that it is free to expand or contract largely independently of the substrate: this is referred to as a 'floating' scale. The expansion of a floating scale is thus dominated by the CTE and temperature of the scale itself. In Example 1, the machine is made of aluminium which has a high thermal expansion coefficient of ~23 ppm/°C. A steel scale will have a lower expansion coefficient of around 10.1 ppm/°C which reduces the expansion to 50.5 µm per 5 °C compared to the 115 µm per 5 °C of the aluminium substrate. Performance can be further improved by using a low expansion scale and through thermal compensation.

The expansion of a floating scale is controlled by the scale's temperature. Floating scales tend to be thin (<1.5 mm) and have a relatively high thermal conductivity. Thus it is possible to assume that the temperature of the scale, as a function of depth, is uniform. This makes measuring the relevant temperature (and hence accurate thermal compensation) easier. As a floating scale is largely independent of the substrate, it is not essential to accurately know the expansion of the substrate.

Thermal compensation of floating scale can be improved by using a scale with a low CTE. As compensation corrections will tend to be small, any compensation errors resulting from imperfect temperature measurements will also be small. This is particularly beneficial if there is uncertainty in temperature measurements, or if there may be local temperature variations across the machine.

Expansion of the substrate will at least partially affect the net expansion of the scale for all potential mounting systems: the scale will not expand exactly as predicted by its CTE alone. The deflection of the scale away from the position which would be predicted from a perfectly floating scale is referred to as disturbance and preferentially should be minimised for a floating scale installation. It should be noted that this disturbance limits the minimum achievable effective CTE even if the scale material has very low CTE. Renishaw has two fundamental methods of mounting floating scale which are designed to minimise the disturbance of the scale under different conditions. These include the use of a self adhesive backing tape, and to physically restrain the scale from off axis movement (referred to as mechanically mounted) using clips for spar scale and *FASTRACK™* for steel tape scale. The next section discusses disturbance of scale away from perfect floating behaviour in more detail.

2 Disturbance of floating scales

2.1 Scale disturbance

Renishaw has developed and experimentally verified mathematical models of the disturbance resulting from the two mounting methods: adhesive tape mounted and mechanically mounted. The models themselves are too complex to present in full here and some of the results are non-linear: for example, the end of the scale sees the most positional error but this error cannot be simply linearly interpolated along the scale length.

The following equations predict the worst-case disturbance of the end of the scale.

2.1.1 Key terms

Disturbance is the positional error of the end of the scale caused by the mounting method partially coupling the expansion of the scale and the expansion of the substrate. It is the difference in length between a theoretical perfectly floating scale and the real scale. Disturbance is typically measured in µm and in this paper it is designated by *u.*

Relative dilation is the relative change in thermally induced expansions between the scale and the substrate due to temperature changes, as shown in Figure 1. In this paper it is designated as ρ and is measured in ppm. It is defined as:

Relative dilation = $\rho = \Delta T(CTE_{substrate} - CTE_{scale})$

Where:

ΔT is the temperature change away from some set temperature, normally the installation temperature (20 °C)

$CTE_{substrate}$ is the coefficient of thermal expansion of the substrate (ppm/°C)

CTE_{scale} is the coefficient of thermal expansion of the scale (ppm/°C)

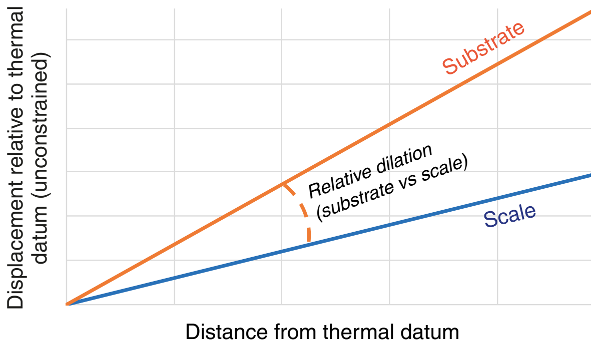

Figure 1. Relative dilation between scale and substrate

Free length is the distance between the scale's anchor to the substrate, i.e. thermal datum (see section 3.1), and the furthest free end of the scale. Typically, the thermal datum would be in the middle of the scale and the free length would be half the scale's total length. In this paper, the free length is designated as z and measured in m.

Expansion mismatch is the difference in the thermal expansion of the scale and the thermal expansion of the substrate between the thermal datum and the furthest free end: it is calculated as $z\rho$.

2.1.2 Equations

Parameters

The following parameters are used in the equations below.

E = Elastic modulus of the scale (Pa)

A = Scale cross sectional area (m^2)

L = Total length of the scale (m)

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z = Free length of the scale (m)
i.e. for scale with a central datum $z = L/2$

u = Disturbance (µm)

ρ = Relative dilation (ppm)

q = Frictional drag per unit length due to mechanical mounting (Nm^{-1})

k = Tape shear stiffness per unit length due to adhesive tape mounting (Nm^{-2})

Mechanically mounted scales:

For mechanically mounted scale (clipped and *FASTRACK*) the scale disturbance (*u)* can be estimated by using:

$$u = \frac{qz^2}{2EA}$$

This relationship is correct as long as the relative dilation is above a threshold value given by:

$$\rho \geq \frac{qz}{EA}$$

This condition is satisfied in most real conditions. An important consequence of this is that the disturbance is typically independent of the relative dilation.

It can also be seen that the disturbance depends on the square of the free length.

Adhesive tape mounted scales:

For adhesive tape mounted scales, the disturbance of the scale is approximately:

$$u = \frac{\rho k z^3}{3EA}$$

This differs from the mechanically mounted alternative in two significant ways: the disturbance is now dependent on the relative dilation and on the cube of the free length rather than square of the length.

Boundary condition:

The two alternative mounting methods give theoretically identical disturbances when:

$$z\rho = \frac{3q}{2k}$$

When an application has smaller values of expansion mismatch (free length times relative dilation) than this critical value, adhesive tape mounting produces smaller disturbances than mechanical mounting. The reverse is true for higher expansion mismatches.

The crossover point only depends on q and k, and once these are known the crossover expansion mismatch can be evaluated for all scale configurations.

This expansion mismatch crossover point can be used to determine if adhesive tape mounted scales or mechanically mounted scales would give a lower disturbance for a given condition. The crossover expansion mismatch for RTL family tape scale is 20 µm and for REL / RSL spar is 500 µm.

Disturbance / relative dilation graphs

The following graphs provide a graphical summary of the effect of mounting methods on the displacement of the ends of scale. These can be used to predict how the metrology of a system may be affected by the chosen mounting method. In these graphs, pairs of disturbance / relative dilation curves, for adhesive tape and mechanical mounting, are plotted for various scale lengths.

The mounting method which causes the least disturbance (better performance) is highlighted through the use of solid lines.

The graphs in Figure 2 can be used to identify which mounting system will give the least disturbance for a given relative dilation.

For example, if a 1 m piece of RTL scale (*CTE* ≈ 10 ppm/°C) was mounted on an aluminium substrate (*CTE* ≈ 23 ppm/°C) with a central datum, and then heated by 5 °C, we would get a relative dilation of *(23 –10.1) x 5 ≈ 65 ppm.*

From the graph in Figure 2a, we can see that the disturbance is minimised when using *FASTRACK* mounting (~0.18 µm) compared to adhesive tape mounting (~0.28 µm).

The area on the graph to the top right, above the black line, indicates where the adhesive tape may fail due to excessive expansion mismatch between the scale and the substrate.

Please note that these graphs are based on the overall scale length, *L*, assuming that it is either centrally anchored or has no anchor at all i.e. $z = L/2$. In all other cases, where the free length z (anchor to free end) is known, simply use $L = 2z$ in these graphs.

Determining the effect of friction on mechanical mounting is somewhat uncertain: the graphs provide a good cautious design guide but should not be used to attempt specific error compensation.

2.2 Hysteresis

It is possible that the disturbance of a mechanically mounted scale will be affected by its thermal history. To understand this, imagine a mechanically mounted scale with zero CTE attached to a substrate with non-zero CTE. The system is heated. Initially, the scale is approximately mastered by the substrate, as the thermal stresses are insufficient to overcome the friction in the mounting method. The initial heating causes expansion of the scale according to the CTE of the substrate (*step 1* in Figure 3).

Eventually the stresses induced will be large enough to cause the scale to slide over the substrate and it will then expand according to its own (in this case zero) CTE (*step 2*).

Relative dilation / disturbance graph for RTL family tape scale

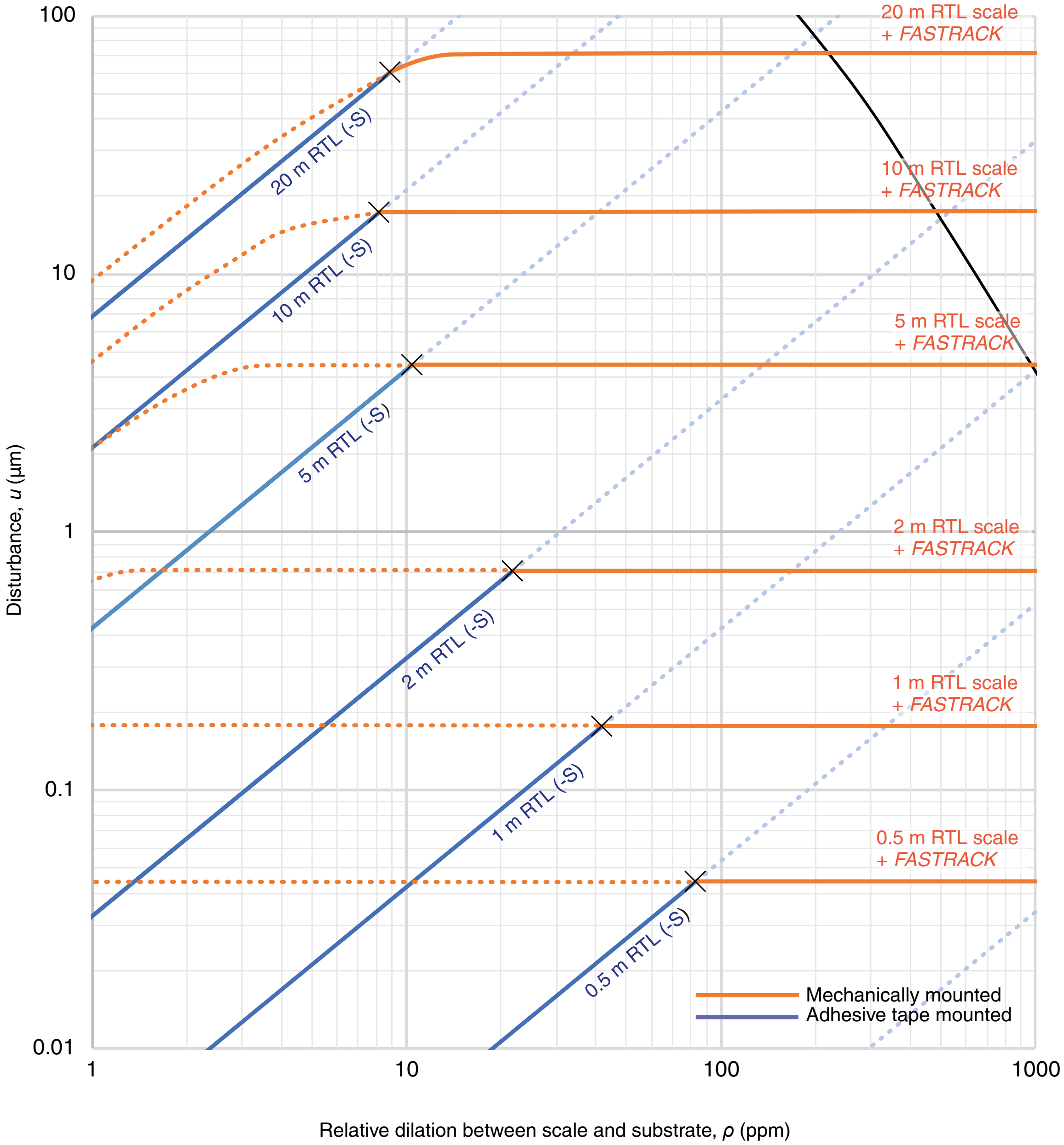


Figure 2a. The disturbance resulting from a known relative dilation, for different RTL family scale lengths and mounting methods. Please note that these graphs assume a central anchor, or no anchor at all.

Relative dilation / disturbance graph for REL and RSL spar scales

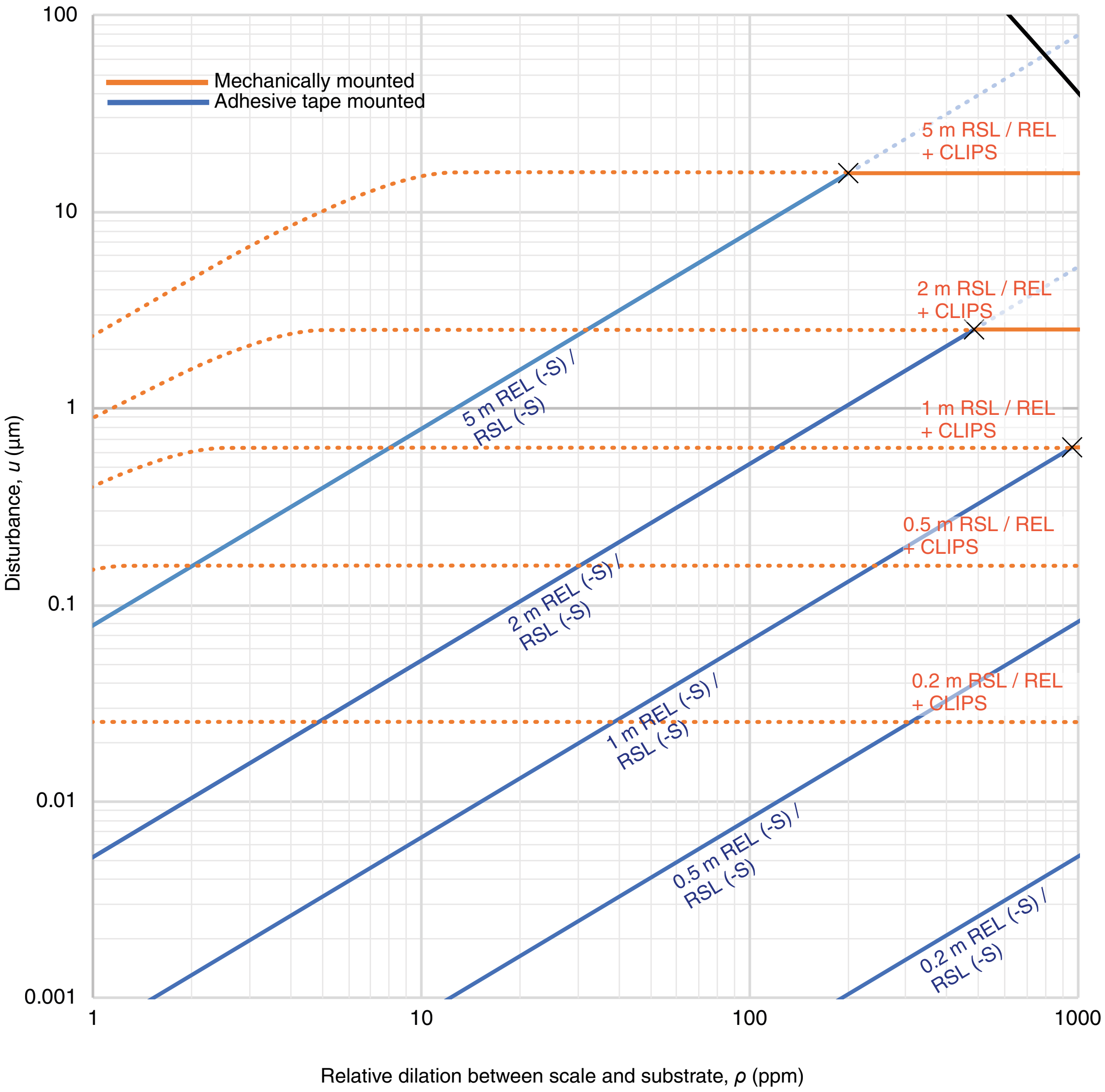


Figure 2b. The disturbance resulting from a known relative dilation, for different RSL / REL scale lengths and mounting methods. Please note that these graphs assume a central anchor, or no anchor at all.

When the temperature is then reduced, the reverse will happen with some cooling required before the scale is able to overcome the mounting friction and slide over the substrate (*steps 3 and 4*). It can therefore be seen that the position of the scale depends on the history of the system: this is referred to as mounting hysteresis. Mounting hysteresis gives rise to some uncertainty in the expansion of the scale. The magnitude of this effect equals the maximum disturbance seen for mechanically mounted scales. Typically, adhesive tape mounted scales do not experience mounting hysteresis because mechanical friction is absent.

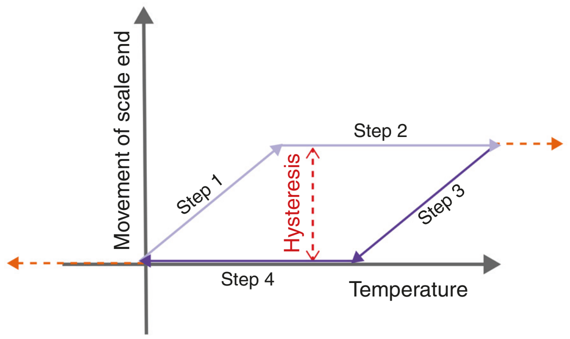


Figure 3. The movement of the end of a piece of scale as the temperature is changed. It assumes that the scale is mechanically mounted, has zero CTE and the substrate has a positive CTE.

3 Further scale mounting considerations

3.1 Datums

When using floating scale, it is recommended that a thermal datum is used. This is a single point where the scale is rigidly attached to the substrate so they cannot move relative to each other.

It is generally recommended that the thermal datum is in the middle of the scale length as this minimises the free length and therefore the total disturbance of the scale.

As seen previously in section 2.1.2, the disturbance at the end of the scale depends on the free length squared for mechanically mounted scale, and on the free length cubed for adhesive tape mounted scale.

It is possible to mount Renishaw scale without a datum. However, not using a datum is inadvisable for a number of reasons. Without using a datum, it is not possible to know the point where the scale does not move relative to the substrate. Symmetry based arguments might suggest that this point is in the middle of the scale length but this will not be the case if there are thermal gradients, or variation in the mounting or substrate properties down the length of the scale. In addition, having a thermal datum helps to prevent scale movement if the axis is subject to acceleration.

3.1.1 Confirming installation performance: *FASTRACK* and clip mounting

When using mechanically mounted scales the quality of the installation can affect the frictional drag and therefore the disturbance which may occur. It is important that care is taken to ensure that the substrate is clean before installation, that the installation is straight, no liquids which leave a residue behind are spilt onto the installation and that repeated wiping of the surface with a cloth which can fray is minimised.

When using *FASTRACK* or clip mounted scale it is important to check the sliding force of the axis before applying the datum to the scale. Comparing the sliding force to that expected for the installation (≤0.3 Nm^{-1} for RTL and ≤25 Nm^{-1} for spar) will inform whether the calculated disturbance will be achieved. Sometimes installation errors are made but not detected because the sliding force is not checked and this can significantly increase the disturbance of scale. The friction, and therefore maximum disturbance, of clipped spars can be lowered by reducing the number of clips used to hold the scale in place as advised by the scale installation guide.

3.1.2 Adhesive tape mounted scale: maximum expansion mismatch

The maximum expansion mismatch of adhesive tape mounted scales should not exceed 1 mm even during transit, as shown by the black lines in the top right of Figures 2a and 2b. Beyond this point the mechanical performance of the adhesive tape cannot be guaranteed.

3.1.3 Substrate mastered scale: RKL and RGS

When using a substrate mastered RKL or RGS scale, it is important to apply epoxy end clamps to form two points where the scale is rigidly attached to the substrate. These ensure that the scale is properly mastered, as adhesive tape alone is not stiff enough to achieve mastering.

4 Scale selection guidance

The following process can be used to help to determine the most appropriate scale and mounting option for a given application.

Scale types:

RTL is a floating steel tape scale

RKL is a mastered steel tape scale

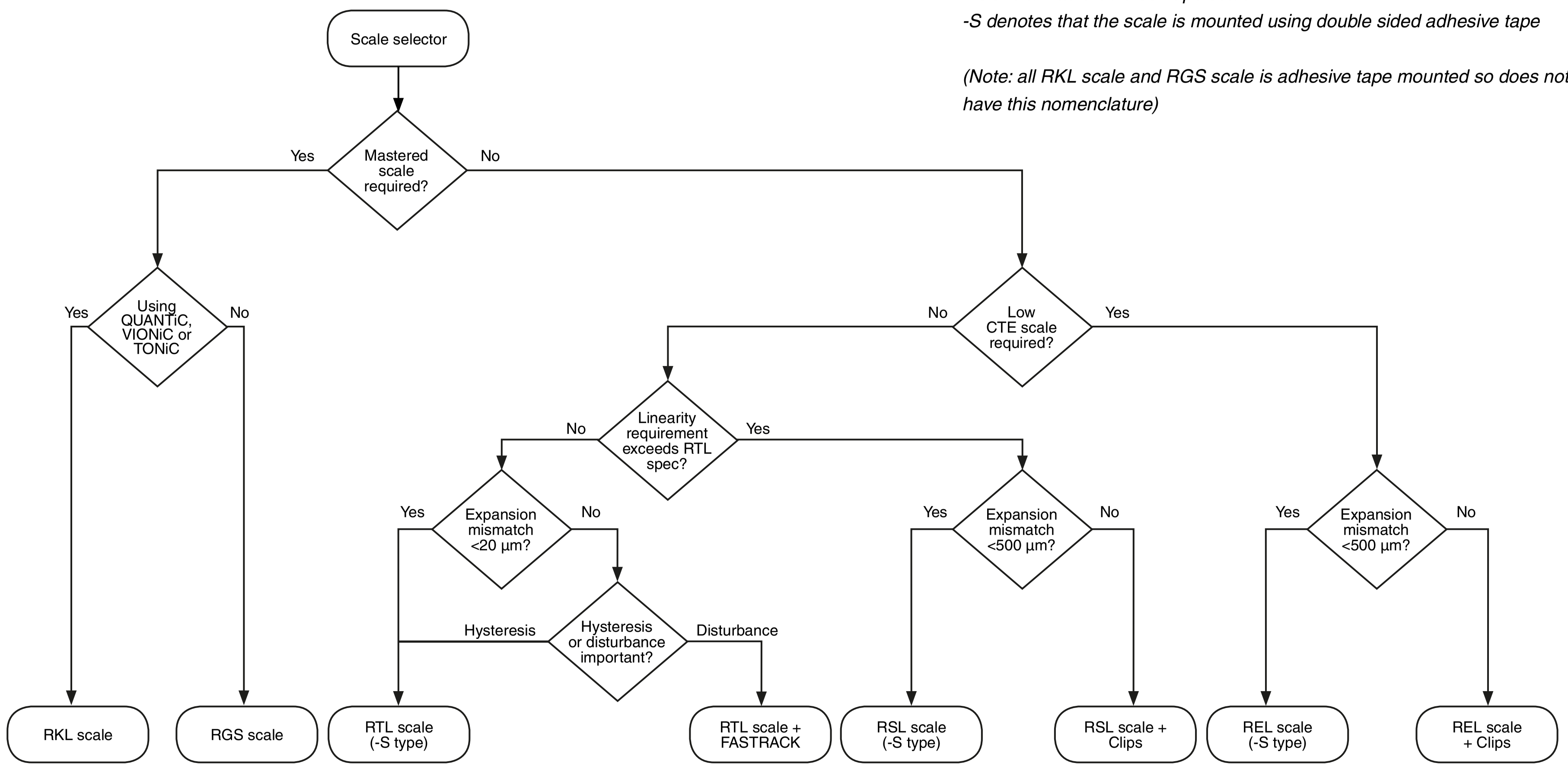
REL is a floating low-expansion steel spar scale

RSL is a floating steel spar scale

RGS is a mastered steel tape scale

-S denotes that the scale is mounted using double sided adhesive tape

(Note: all RKL scale and RGS scale is adhesive tape mounted so does not have this nomenclature)



To understand if mastered or low CTE scales are required, please refer to sections 2.2 and 2.3.
Sometimes it is beneficial to use adhesive tape mounting rather than mechanical mounting even though the latter has less disturbance. This is because tape mounting does not have hysteresis, which can be important for some applications.

5 Glossary

Terminology	Definition
Adhesive tape mounted	Scale that is held in position using double sided tape applied along its length.
CTE	Coefficient of thermal expansion (CTE), the amount an object changes size with temperature. Typically quoted in parts per million per degree Celsius, or ppm/°C.
Dilation	The change in length of a component divided by its original length.
Relative dilation	The difference in dilation between a substrate and the scale mounted on it.
Disturbance	The positional error of the end of the scale caused by the mounting method. It is the difference in length between the ideal perfect floating scale and the actual position of the end of the scale.
Expansion mismatch	The difference between the thermal expansion of the scale and the thermal expansion of the substrate between the thermal datum and the furthest free end.
Floating	A system where the thermal expansion of the scale is controlled by the scale's properties, and should be largely independent of the substrate.
Free length	The distance between a floating scale's thermal datum and the end of the scale furthest from this point. If no thermal datum is used, it should be assumed that the thermal datum is in the middle of the axis.
Mounting hysteresis	The difference in net expansion of scale, at a single temperature, when approaching that temperature from a higher or lower temperature.
Mastered	A system where the thermal expansion of the scale is controlled by the expansion of the substrate.
Mechanically mounted	When scale is held in position through mechanical guides. These are either *FASTRACK* for tape scale, or clips and clamps for spar scale.
Thermal datum	A point where floating scale is firmly attached to the substrate. No movement of one over the other is possible, so all expansion of the scale relative to the substrate is centred around this point.