

**NPL REPORT
DEPC-TH 008**

**NMS Programme for Thermal
Metrology 2004-2007:
Survey of Applications for
LART (Th 3.1.1.01)**

**Marc Broussely, Andrew
Levick and Gordon Edwards**

JANUARY 2005



The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

The National Physical Laboratory is operated on behalf of the DTI by NPL Management Limited, a wholly owned subsidiary of Serco Group plc

Survey of Applications for LART (Th 3.1.1.01)

Marc Broussely, Andrew Levick and Gordon Edwards
Engineering and Process Control Division

ABSTRACT

Non-contact surface temperature measurement remains a problem that no commercially available technique can fully satisfy. Unknown or changing emissivity of the surface, unwanted radiation coming from the environment or multiple reflection from the target as well as transmission properties of gas or windows are the always obstacles for traditional radiometry. The LART technique developed by NPL gives an answer to this problem but its cost has always prevented it becoming a new industrial option. As new low cost high power diode lasers are introduced on the market, industrial demand for LART is rising. This report presents an overview of real world application where LART could be a solution and lists all the associated technical and theoretical issues. Some partial solutions are proposed and a last section discusses technicalities of an Infrared LART sensitive to temperatures as low as room temperature.

© Crown copyright 2005
Reproduced with the permission of the Controller of HMSO
and Queen's Printer for Scotland

ISSN 1744-0289

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

This document has been produced for the Department of Trade and Industry's National Measurement System Policy Unit under the Term Contract for Research and Development.

Approved on behalf of the Managing Director, NPL
by Peter Quested, Knowledge Leader, Thermal Measurement Team, Engineering and Process
Control Division

Content

1. INTRODUCTION	5
2. Possible industrial applications for LART	5
2.1. Gas turbine blades with thermal barrier coatings (TBC)	5
2.2. Steel billets in reheat furnace	6
2.3. Softening and descaling process in stainless steel production	7
2.4. Coal fired furnaces in electricity generation	7
2.5. Frozen/ refrigerated foodstuffs.....	7
2.6. Epitaxial growth of germanium on silicon wafers	8
2.7. Plasma / Electron Beam cold hearth refining.....	9
2.8. Reformer Furnaces	9
2.9. Cooking of food	10
2.10. Vacuum arc re-melting.....	10
2.11. Study of structure and stability of high-temperature ceramics	11
2.12. Glass making process	11
3. The LART assumptions and discussion	12
3.1. Assumptions to the theory of lart	12
3.1.1. Physical assumptions.....	12
3.1.2. Technical assumptions	13
3.2. Discussion on the application issues	13
3.2.1. Semi-transparency of the target.....	13
3.2.2. Changing emissivity	14
3.2.3. High temperature gradients	14
3.2.4. Material inhomogeneity and sub-surface defects.....	15
3.2.5. Thin layer, surface roughness and target shape.....	15
3.2.6. Moving target	15
3.2.7. Hostility of environment	16
3.2.8. Low emissivity	16
3.2.9. Invasiveness	16
3.2.10. Latent energy.....	16
3.2.11. Noise sources.....	17
3.2.12. Low temperature	17
3.2.13. Small scale.....	17
4. development of lart for low temperature targets	17
4.1. potential applications.....	17
4.2. Technical solutions.....	18
4.2.1. Light sources.	19
4.2.2. Detectors.....	19
4.2.3. Optics	19
4.2.3.1. Materials.....	19
4.2.3.2. Fibre optics	20
4.3. Comments.....	20
References	20

1. INTRODUCTION

Thermal radiation emitted from matter is highly sensitive to its temperature. This property makes radiation thermometry an accurate tool for non-invasive temperature measurement of surfaces. However two important factors must be taken into account when performing such measurements:

- Surface emissivity
- Radiation reflected on the observed object's surface from other sources of comparable but generally higher temperature.

Approximations often have to be made concerning the emissivity or the absorbing gases and a model evaluates the correction needed due to the background radiation.

Laser Absorption Radiation Thermometry (LART) enables, in principle, to measure temperature independently of target emissivity, reflected radiation from the surroundings and gaseous absorptions. It is the only general purpose infrared thermometer that is emissivity-free and that addresses the measurement of bright metals while solving the problem of background reflection. The LART technique can also offer a way to measure temperature and thermal properties of surfaces without a priori sample preparation.

The technique has a great potential for *in-situ* application for industrial targets, especially in 'difficult' environments like reformer furnaces, combustion chambers or steel making industry. The purpose of this survey is to analyse, for a number of various possible LART temperature measurement applications, the different issues that the implementer would have to deal with. Some of these issues are just a matter of being sure that the set-up is designed to overcome them, some issues present a real limit of the application of the method at present. It also shows that further development of the technique for longer wavelength can extend the range of applications possible, reaching fields in developments nowadays like processes at low to moderate temperature, as well as bio and medical research or food industry.

The second section of this report presents a number of applications, briefly listing the main problems associated with them. Each of these issues is then discussed in the third section. The fourth section deals with an aspect that could be developed to extend the domain of LART: working at far infrared for the measurement of temperature of the order of 300K.

2. POSSIBLE INDUSTRIAL APPLICATIONS FOR LART

2.1. Gas turbine blades with thermal barrier coatings (TBC)

Contacts on previous survey:

Colin Bird, Measurement Specialist, Rolls Royce plc.
Dave Rickerby, Turbine Surfaces Technology (TST) Ltd

Interest:

Accurate control of the turbine blades surface temperature would mean the ability to optimise the regime of the engine, by operating at higher temperatures, leading to significant fuel savings. Moreover, such a control could detect engine faults before a breakdown.

Problem description:

The turbine blades are made from nickel superalloy and coated with a thermal barrier coating (TBC), typically a 300 μm thick layer of zirconia ceramic, allowing operation at temperatures higher than the melting point of nickel, up to 1450°C. The important background radiations (mainly from kerosene combustion) of higher temperature than the target itself and absorptions due to the combustion products render standard pyrometry measurement almost impossible on this target, thus making LART a potential solution.

Technical points leading to measurement issues:

1. Moving target

30-50 turbine blades are moving at anything up to 100,000 rpm.

2. Semi-transparency

Zirconia ceramic, the TBC, is semi-transparent at short wavelength (below 5 μ m).

3. Target accessibility – hostility of environment

Such an engine poses the problem of optical accessibility, as the optical head must be thermally protected from the high temperature environment of the engine while having a sufficient aperture for a good signal-noise ratio. A hostile environment caused by the combustion can lead to contamination of the window, causing a significant loss in signal level and is an issue regarding calibration.

4. Thin layer

The TBC has to be taken into account in the exploitation of the LART signal, leading to requirements in spot size and modulation frequency.

5. Noise sources

Very high background radiation and mechanical vibrations from the engine can lead to high noise level in the detected signals.

6. High temperature gradients

Very high gradients of temperature within the coating make it difficult to be sure what depth we are measuring. This problem is closely linked to the thickness and optical properties of the TBC.

2.2. Steel billets in reheat furnace

Contacts on previous survey:

Dr Bill Pritchard, Corus

Graham Andrews, Senior Technologist - Product Modelling & Control, Corus

Interest:

In the reheating process, steel billets are heated to around 1200°C to ensure an appropriate softness before being rolled into sheet or beam product. Knowledge of the billet temperature would help optimise the process, increasing energy savings, productivity and limiting products defects.

Problem description:

The billets pass through a reheat furnace, functioning with natural gas combustion. Ideally knowledge of the complete temperature profile in the billets is sought after. Realistically a few surface temperature points could lead to internal gradients through modelling. As for now, thermocouples are used in the furnace roof to evaluate the steel temperature with a thermal model. The high background radiations from the combustion are an obstacle for standard radiometry.

Technical points leading to measurement issues:

1. Moving target

Slow translation through the furnace. Targeting a billet can be a problem.

2. Hostile environment.

Combustion products are likely to affect the LART optical path.

3. Target shape.

Irregular target shape (or distance to optical system) can affect the accuracy of the calibration coefficient, hence of the measured temperature.

4. Strong background radiation.

Background radiation is not a problem for LART in principle; however, high temperature background can be a source of noise decreasing the signal to noise ratio.

2.3. Softening and descaling process in stainless steel production

Contacts on previous survey:

Graham Andrews, Senior Technologist - Product Modelling & Control, Corus
Stephen Marcroft, Avesta Steel

Interest:

Very temperature critical process needing accurate non-contact thermometry.

Problem description:

Stainless steel strip is going through the process of softening and scale removal in a furnace heated by combustion of natural gas. The purpose is to obtain the desired metallurgical properties. The line is continuous, as each new coil of strip is welded to the end of the last one (with tail pieces between). An accumulator system provides a buffer so that the line can be kept running while the welding takes place.

Technical points leading to measurement issues:

1. Moving target

Constant passing of the strip under the probe.

2. Hostile environment

Combustion products are likely to affect the LART optical path, which is an issue regarding calibration.

3. Surface roughness

The surface can be, or not, covered with scale at the location of measurement. This has to be taken into account so the calibration coefficient is insensitive to the surface condition. The strips to be measured are at about 1050-1100°C.

4. Low emissivity

Signals are small.

2.4. Coal fired furnaces in electricity generation

Contacts on previous survey:

Dr Rudi Rooth, Kema and Amer Power Generation Station, Netherlands

Interest:

Temperature monitoring of the furnace wall would allow a better control of the process, leading to an improvement in efficiency and lower fuel consumption. There is also an interest in monitoring the temperature of the coal flame.

Problem description:

Water is converted from liquid to superheated steam in the coal furnace heat exchanger. The chamber contains the pulverised coal, air and combusts. We seek to know the temperature of the furnace walls, which are at about 800°C.

Technical points leading to measurement issues:

1. Hostile environment

Here again, the chamber is filled with combustion products but also pulverised coal and the transmission through the space between the optical head and the surface targeted might not be constant in time. There is also the problem of contamination on the window.

2. Noise

The coal combustion is very noisy and sooty. This results in very noisy and intense background radiation intensity.

2.5. Frozen/ refrigerated foodstuffs

Contacts on previous survey:

Dr. Paul Nesvadba, head of the Food Physics Group at Robert Gordon University, chair of the Food focus interest group of T2PAC
Dr David Land, Glasgow University

Interest:

There is a necessity to monitor accurately the temperature of stored food products for obvious health and safety reasons and to comply with regulations. Aims also include improving the efficiency of cooling, thus reducing energy consumption, as well as limiting spoiled food wastage.

Problem description:

Monitoring the temperature of food products by contact probes poses the problems of invasiveness and accessibility. On the other hand infrared techniques are limited by the unknown emissivity and the surrounding radiations at ambient temperature, usually higher than the target.

Technical points leading to measurement issues:

1. Wavelengths used

Such an application of LART means the use of IR wavelengths (between 3 and 12 μm) to be able to detect signal at low temperatures. At these wavelengths, care has to be taken not to lie on the absorption bands of the atmosphere.

2. Layers and roughness

The targets here are not polished metallic surfaces but could present layers of different thermal and optical properties (skin, oil, ice...) as well as a variable roughness of surface.

3. Latent energy (modulating around a phase transtion)

Most of the food products have a high water content. In the case of products near 0°C or covered with a thin layer of ice, part or all of the light energy could be absorbed by the state change of water and thus not causing modulation of temperature.

2.6. Epitaxial growth of germanium on silicon wafers

Contacts on previous survey:

Dr David Robbins and John Glasper, QuintetiQ, Malvern, UK

Interest:

Accurate knowledge of the surface temperature of silicon is required during the process of Chemical Vapour Deposition (CVD). An accurate control of the process leads to producing integrated circuits with higher specifications.

Problem description:

In the CVD apparatus for growing epitaxial layers of germanium on silicon wafers, silicon wafers are on a heating meander, and have to be kept at a constant known temperature (typically 850°C). A non-contact temperature measurement technique is preferable because silicon is vulnerable to damage and good thermal contact is difficult to achieve.

Technical points leading to measurement issues:

1. Layers

The physics have to be well understood to be sure that the changing thickness of the germanium layer doesn't affect the LART measurement.

2. Changing emissivity

During germanium growth, the emissivity changes, and the LART measurement has to be fast enough for emissivity change to be small when the 2 channels are scanned.

3. Invasiveness

The small temperature modulation caused by the laser heating must not have any effect on the growth of the germanium itself.

4. Semi-transparency

Silicon is semi-transparent in infrared.

2.7. Plasma / Electron Beam cold hearth refining

Contacts on previous survey:

Dr Mark Ward, IRC (Inter disciplinary Research Center, Birmingham University).

Interest:

The process of Cold Hearth Refining (CHR) needs a continuous control of the alloy's surface temperature for the quality and economics of production.

Problem description:

CHR is used in the casting of titanium superalloys. Feed material is melted and refined in one or more hearths before solidifying in a crucible. Water-cooling is used on all surfaces, which will contact the material being processed, to force the formation of a 'skull' of solid material; this prevents contamination of the melt by the hearths and crucible and also aids some refining processes. The targeted surfaces can be from 1500 to 3200°C.

Technical points leading to measurement issues:

1. Hostile environment

The evaporation of elements causes an absorbing atmosphere and would pollute the optical window with time.

2. Low emissivity material

The emissivity of the materials (Titanium, Zirconium, Tantalum, Niobium) is low, causing a low signal drowned in the noise of the reflection of the very high temperature background.

3. Changing emissivity

The emissivity of the alloys is changing during the process, involving a possible difficulty in the LART measurement.

4. Electromagnetic noise

Strong EM fields are to be taken into account to avoid interferences with the measurement device electronics.

5. Background radiation

There is huge background radiation coming from the arc.

2.8. Reformer Furnaces

Contacts on previous survey:

Dr Pieter Bloembergen

Dr Geoff Beynon, Land Infrared.

Interest:

The reaction rates involved in the reformer process are temperature-sensitive, and the wall temperature of the reformer tube (typically 800°C) is a significant indicator of reaction efficiency. Continuous monitoring and control of the temperature of the reformer tubes can help maximise this efficiency, leading to lower energy consumption.

Problem description:

A mixture of gases is passed over a nickel catalyst held within narrow "reformer" tubes heated to 800°C where a chemical reaction occurs thus generating the final product. A parallel array of tubes passes through the reformer furnace, typically fired with natural gas. In hydrogen production, so-called steam reforming, steam is reacted with a hydrocarbon over a catalyst to form hydrogen and carbon oxides.

Technical points leading to measurement issues:

1. Limited aperture

The target (furnace walls) has usually to be quite far from the instrument, causing a small aperture that results in a very small signal.

2. Noise

There is a lot of background radiation caused by the combustion, thus creating a lot of noise in the signal.

2.9. Cooking of food

Contacts on previous survey:

Rob Rolston, United Biscuits

Also: Dr. Paul Nesvadba, head of the Food Physics Group at Robert Gordon University, chair of the Food focus interest group of the TMAN club (former T²PAC).

Interest:

Accurate temperature control during the cooking of biscuits can help the control of oven leading to lower fuel consumption as well as improving the product quality.

Problem description:

Biscuits are cooked on a continuous production line, in an oven at about 200°C. The temperature ideally should be measured continuously and non-invasively during the cooking process.

Technical points leading to measurement issues:

1. Emissivity change.

The cooking causes a continuous change in emissivity mainly due to the diminution of the target's water content, thus imposing a time constraint in LART measurement.

2. Surface conditions

In such products, the surface conditions are unpredictably variable, quite rough and porous; the thermal diffusion physics is rendered difficult by the non-homogeneity of the matter and the varying absorption coefficient. However, LART should be able to cope if modulation frequencies are the same.

3. Wavelengths used

Such an application of LART means the use of long IR wavelengths (between 3 and 12 μm) to be able to detect signal at low temperatures with the related complications.

4. Latent energy

Water is constantly evaporated from the targets; part of the light energy used for the photothermal effect could be absorbed by the latent energy of the state change.

5. Sub-surface defects

The bulk of foodstuffs is usually not homogeneous and contains 'bubbles' especially appearing during the cooking while the water evaporates. Such bubble just under the probed surface can have a strong effect on the photothermal signal. Here again, the use of same modulation frequencies for both channels should make LART immune to the problem.

2.10. Vacuum arc re-melting

Interest:

Temperature measurement by contact is not possible if the purity of the alloys produced is to be maintained. Radiation thermometry must overcome the problems of extraneous radiations from the background and the arc as well as unknown and varying emissivity. Accurate temperature measurement would allow the validation of the process modelling as well as provide on-line information for both traceability and feeding closed-loop control systems.

Problem description:

Vacuum arc re-melting is used to make ingots of high quality alloys (titanium alloys or nickel superalloys for instance). The melting is achieved by the heat generated by an electric arc between the mould where the metal drops and the bottom of the feedstock, held above. To understand and better control the process, involving complex coupling between electromagnetic, thermal and mechanical effects, models are developed as well as closed-loop control systems to improve the reproducibility and traceability of production.

Technical points leading to measurement issues:

1. Changing emissivity

During both melting and solidification, the metals surface properties change, thus provoking possible strong changes in emissivity and reflectivity.

2. Noise

The radiations coming from the arc and reflected on the observed area is likely to cause high levels of shot noise in the detected signal.

3. Low emissivity

Such melted alloys have very low emissivities, so the signals detected would be weak.

2.11. Study of structure and stability of high-temperature ceramics

Contacts

Dr. Rudi Winter, Institute of Mathematical and Physical Sciences, University of Wales, Aberystwyth.

Interest:

It is not possible to apply contact thermometry during such experiments and pyrometry is rendered difficult by unknown emissivity. Temperature is a parameter of great importance when studying the structure of such materials and LART would provide a robust temperature measurement technique.

Problem description:

Ceramics constitute a material class suitable for applications at severe thermal, chemical or mechanical conditions. Their inhomogeneous medium-range structure allows tuning their thermal and mechanical properties to fit the particularities of various technical environments. Relevant structural features include size, shape, distribution and orientation of grains, the atomic structure of intergranular material and crack surfaces, and their influence on crack propagation and the effectiveness of structural reinforcements. A recently started project exploits aerodynamic levitation (a spherical sample suspended by a gas flow and held in place due to the turbulences occurring above the sphere) to heat containerless ceramic and glass samples up to 2500K using an infrared laser. This technique is applied to NMR spectroscopy and various diffraction experiments to gain high-temperature data under *in-situ* conditions.

Technical points leading to measurement issues:

1. Semi-transparency

Some ceramics are semi-transparent at high temperature, which can be a problem for applying LART.

2. High temperature gradients

The technique of heating by CO₂ laser coupled with aerodynamic levitation can cause significant temperature gradients within the samples.

2.12. Glass making process

Interest:

Good temperature control in the different stages of glass production results in improving efficiency, energy saving, quality and repeatability of the glass production.

Problem description:

Glass making involves melting, float process and cooling where temperature plays an important role. The raw material is composed of grains having different melting points. Then the floating process has to be monitored for obtaining the required quality of glass. Eventually the annealing process, or controlled cooling, produces glass ribbons where considerable stresses can be developed. These stresses, weakening the end product, have to be released through heat treatment with a close temperature control.

Technical points leading to measurement issues:

1. Semi-transparency

Glass is semi-transparent or transparent for large bands of wavelength. The wavelengths used for LART have to be adapted to the application.

2. Moving target

In liquid state in the float bath, the glass is submitted to convection flows, which can be an issue if the glass flow at the temperature control point is not known. During the cooling process, ribbons of cooled glass are streamed at a limited speed; the movement of the material has to be taken into account in the measurement.

3. Noise

High background radiation during the melting process can lead to high levels of shot noise.

3. THE LART ASSUMPTIONS AND DISCUSSION

In this section, we describe the LART theory, emphasizing the different assumptions that are made. We then discuss the possible effect of the issues arising in the applications and discuss possible solutions.

3.1. Assumptions to the theory of lart

3.1.1. Physical assumptions

- We only consider the first derivative of $L(T, \lambda)$

This means we assume that the δT induced by the laser heating is small enough.

- We assume that the emissivity variation with T within the δT modulation is negligible.

- We assume that the modulation frequency is above a value, often referred to as the cut-off frequency, where thermal diffusion physics can be considered monodimensional.

This allows simplifying the expression of the modulated temperature $T(\omega)$ and allows expressing linearly the signal ratio in function of the Planck function.

- The targeted object needs to be semi-infinite.

The boundary conditions applied to derive the expression of $T(\omega)$ assumes the semi-infinity of the object. Then it means that the target must be thermally thick (thickness large compared to the thermal diffusion length $\sqrt{2D/\omega}$). It also includes the fact that there must not be cavities under the surface within a distance comparable to the thermal diffusion length. However, the technique remains correct when the same modulation frequency is used for both channels.

- The target must be opaque

The laser radiation must be absorbed within a small skin-depth on the target. This assumption is necessary to justify some simplifications of the temperature modulation on the surface.

- The Kirchhoff law needs to be verified on the target.

The spectral emissivity must equal the spectral absorbance. This is not true anymore if the target is semi-transparent and sufficiently thick. We will see in the next section that LART can still work under certain conditions.

- The temperature of the target shall not vary too much within the volume concerned.

The temperature modulation on the surface due to the laser heating depends on the properties of the material probed inside the volume where the heat diffusion is taking place, defined by the heat diffusion length. A high gradient would cause thermal properties gradients leading to non-linearities not taken into account in the theory developments. Here again, effects of these non linearities are discarded if the modulation frequencies are the same.

- The detected area must cover the modulated region.

3.1.2. Technical assumptions

- The optical transmission must be reciprocal

The LART calibration coefficient only contains information about the instrument itself. The transmission coefficients (gaze, lens, window...) does not affect the LART result, by definition. However this is not true if the transmission and reflection coefficient are different for laser emission and radiation detection. This can occur if the optical path for the laser and the detection are not identical.

- The signal must be strong enough compared to the noise

A strong enough signal is compulsory, especially if the noise is high. That means both noisy environment and small detected radiations are issues.

The first says that noise has to be avoided as much as possible, including ground loops (electronic noise), vibrations that might affect the detector's response (mechanical noise), high background radiations (thermal noise), temperature variations around the electronics (ambient temperature issue), detected backscattered or reflected laser light (laser spectral purity issue).

On the other hand the signal detected needs to be high enough. That concerns: lasers power, viewing angle, detectors responsivity and transmission of the optical path between detection and target. It is also to be noted that the lower the target emissivity or the higher the thermal diffusivity, the weaker the detected signal.

3.2. Discussion on the application issues

3.2.1. Semi-transparency of the target

One solution is the coating of the surface. The main disadvantage is that it discards the non-invasive characteristic of the technique. Moreover we then meet a new problem: having to deal with a thin layer, including a possible thermal resistance between that layer and the substrate.

An important example of a semi-transparent target is silicon. Referring to some studies [1] and to the LART measurements done at NPL on silicon wafers in 1997, the configuration has to take into account the optical properties of silicon. For a given temperature, silicon is opaque to wavelength below the material's band-gap. At that stage the emissivity varies with the wavelength due to variations of the reflectivity. Past a critical wavelength the material starts to be semi-transparent. Consequences are both an absorption taking place in a layer of material, possibly even after multiple reflection between the two surfaces of the sample. The emissivity is also changing rapidly. It is shown that for 1320 nm, the wavelength used for one of the channel of our LART instrument, the temperature has to be above 600°C to be able to consider the silicon as opaque. And the emissivity is also varying quite strongly with temperature.

If the temperature is above about 600°C, the silicon is opaque for both wavelengths. If the silicon is semi-transparent for one channel it has been demonstrated that the LART technique can still result in the correct temperature as long as we use the same modulation frequency for both channels, 840 nm and 1320 nm. The problem arising then is the strong variation of emissivity and reflectivity with temperature; it is discussed later in this section.

3.2.2. Changing emissivity

To derive the LART principles the surface emissivity is considered to be independent of temperature within the amplitude of the modulation. This is because the temperature modulation created by the laser heating is assumed to be small and the emissivity (and reflectivity) changes considered negligible.

The variation ΔS of the photothermal signal for a temperature change of ΔT due to a change in radiative properties of the targeted surface can be expressed using:

$$\begin{aligned} \frac{dS}{dT} &= \frac{d}{dT}(\varepsilon L(T, \lambda)) + \frac{d}{dT}(RL_B(T_B, \lambda)) \\ &= \varepsilon \frac{dL}{dT} + L \frac{d\varepsilon}{dT} + R \frac{dL_B}{dT} + L_B \frac{dR}{dT} \end{aligned} \quad (0.1)$$

The first term here is the only one assumed in the LART theory. Now we can see that the second term, especially for a temperature and wavelength resulting in a high Planck function value $L(T, \lambda)$, the modulation of emissivity due to the modulation of the temperature will add a component to the modulated signal detected at the frequency used. The emissivity variation being very small it is usually negligible but for an application with a low emissivity target and significant emissivity change with temperature that can lead to an error, as it happens with silicon under certain conditions of temperature and wavelength used. The third term can be considered negligible, as the emitted radiation from the background has no reason to be correlated with the modulation of the target temperature. However, if the reflectivity of our target changes at the used modulation frequency (fourth term) then a signal proportional to the emission from the background will be detected, thus causing a possible error. Again, this is an issue with silicon if certain conditions are not met.

In addition to that, the variation in emissivity will also affect the temperature modulation itself as it affects the energy absorbed by the target from the laser light.

It is to be noted that in a case of LART application where that kind of problem exists, a correction can be applied to the resulting LART through an evaluation of the background radiation as well as knowledge of the target behaviour for given temperature and wavelengths.

3.2.3. High temperature gradients

Standard radiation thermometry methods detect the emitted radiation from the target. As it was already noted, it is then only accurate when having a good knowledge of the emissivity and reflectivity of the surface as well as the surrounding radiations. It is also sensitive to the optical absorption depth of the target and the material observed is usually assumed to be optically thin and only emit from its surface. The LART technique is in principle not sensitive to emissivity or background radiation as they are respectively discarded by the use of two wavelengths and the use of modulation. We have seen in a previous section that it can be sensitive to the absorption properties of the material but one main difference with standard radiometry is that the signal is related to the thermal diffusion occurring in a small volume near the surface observed. The depth to which the absorbed laser heat diffuses is characterised

by the thermal diffusion length $\delta_T = \sqrt{\frac{2D}{\omega}}$. This means that the temperature derived from the

photothermal signal will in effect depend on thermal properties depending themselves on the temperature inside that volume. A strong temperature gradient adds non-linear terms to the heat diffusion equation and complicates the solution of the temperature modulation at the

surface. However, this only poses a problem if the modulation frequency used is different for the two wavelengths. If they are identical the effect on the signal ratio should be minute.

In the case of the turbine blades, the Zirconia coating is a thermal barrier and a gradient of about 300°C exists through about 300 μm , causing non-linearities across the coating thickness. The most obvious way to limit the effect of such a gradient is to reduce the thermal diffusion length as much as possible by using small scales (reduce the spot size to a few tens of micrometers) or by increasing the modulation frequency. If the first idea is limited by the target-to-instrument distance requirements, the second is limited by signal level compared to noise as the signal drops with the frequency ω .

3.2.4. Material inhomogeneity and sub-surface defects

As explained in the previous section, the photothermal signal depends on the heat diffusion within a depth of the order of the thermal diffusion length δ_T . It is then obvious that any strong variations of the material properties within this depth will have a strong effect on the photothermal signal itself. However these effects tend to cancel out provided both channels use the same laser modulation frequency with the same laser spot geometry, and that we are detecting the whole laser spot area.

3.2.5. Thin layer, surface roughness and target shape

The presence of a thermally thin layer, or a rough surface condition, is not an issue for LART temperature measurement as the conditions are identical for both channels. However, as the thermal diffusion length is defined by the modulation frequency, the frequency used for each channel should be the same.

Concerning the shape of the target, it is important that both channels scan the same area so the geometrical parameters (especially the angle of view of the surface) are identical for the two wavelengths. Unless the zone heated by the laser has a complexity of shape of the order of the laser spot size, this does not pose a problem in principle.

3.2.6. Moving target

The two main cases are a translation and rotation. In both case we can imagine that the device could be designed to “follow” the target for a reading, so that the heated and detected spot remains the same on the material scanned, involving a moving optical head.

The LART theory developments include the case of a moving target so that if the probe stands still then the ratio of the signals will still lead to the right temperature. However, the level of the signals detected will drop with the speed of the movement until a certain limit which depends on a lot of parameters including the modulation frequency, material properties, emissivity, laser power, optical aperture, wavelengths used etc...

If the theory answers quite positively about the problem, there can be a technical breakdown if the emissive properties of the surface are uneven the two LART channels might measure over 2 spots of slightly different emissivity, inducing big errors in the signal ratio and consequently in the temperature.

In the case of a rotation at high it is unlikely that the laser spot has enough time to induce a significant temperature rise on the surface. However as the region heated is periodically back under view, the LART principle should work if the signal detected is strong enough. This becomes a very complex application for this instrument.

3.2.7. Hostility of environment

The LART is in principle immune to gaseous absorptions and the presence, between the optical head and the target, of fumes or vapour should not be a problem. It is however necessary that sufficient radiation can be transmitted from the probe to the target. The issue a hostile environment can create is more a change of conditions in time. If the amount of smokes is varying significantly during the measurement process so that it affects the signal level differently for the two wavelengths this would lead to an error in the ratio, hence in the temperature. In such conditions it is important to carry out measurements as fast as possible or alternatively to have the two wavelength simultaneously.

Moreover, there is a situation where an inhomogeneous deposition of dust or any combustion product on a window could pose a problem. The transmission factors are discarded provided the optical path is identical for laser emission and radiation detection. If these paths are different then the ratio of transmission factors might change with time and affect the measurement. An obvious solution is to make sure these paths are identical, by using a single fibre extension for instance.

Finally, the presence of parts of the LART equipment, optics or lasers, in a hostile environment can simply deteriorate it with time and that has to be taken into account when designing the instrument.

3.2.8. Low emissivity

By definition the temperature of a target can be measured by LART without a knowledge of its emissivity. However the individual signal levels are very sensitive to emissivity and the lower the emissivity, the lower the signal to noise ratio. If the configuration is already leading to low signals (high thermal effusivity of the target, long distance, small collection aperture, low laser power) or/and if the environment is noisy (background at higher temperature, presence of smoke or absorbing gas, dirty window, moving target) then a low emissivity can lead to high uncertainties in temperature (see also ‘changing emissivity’).

3.2.9. Invasiveness

A main advantage of all optical methods is non-invasiveness. The LART is not completely non invasive because heat is transferred to the target. If the temperature modulation amplitude is too high then it can have an effect on the target itself (an extreme being the deterioration of the surface, generally when the material has a low thermal diffusivity). In the epitaxial growth of germanium for instance, the temperature of the surface is of importance and the laser power and spot size have to be chosen so as not to affect the actual process.

3.2.10. Latent energy

In the case of frozen food applications near zero degrees, the material targeted is mostly composed of water. In certain conditions some of the heat could locally be absorbed by the ice as latent energy, inducing non-linearities in the heat diffusion problem. This phenomenon needs to be taken into account in the design of the experimental apparatus (especially concerning the laser power and spot size).

3.2.11. Noise sources

The LART deals with very small voltages and all sources of noise have to be closely investigated. The two main sources of noise are the NEP (noise equivalent power) of the detector itself and the noise from the hot body observed.

The noise current generated in the detector is $I_D^2 = R^2 \cdot \text{NEP}^2 \cdot \Delta\lambda$, R is the responsivity of the detector and $\Delta\lambda$ the bandwidth detected. The detector and bandwidth have both to be adapted to the application.

The noise due to the random fluctuation of the electric current, also called Shot noise, is $I_N^2 = 2q \cdot I_{dc} \Delta\lambda$ for a photodiode, I_{dc} being the diode direct current, which increases with the temperature of the body observed.

A noisy hot background, due to sooty combustion for example, can easily increase the noise from the detector. Then the design of the measurement apparatus has to take into account other sources of noise, like vibrations that can affect a fibre coupling or the detection area on the photodiode and add some fluctuations, but that can also be electro-magnetic fields or noisy power supplies.

3.2.12. Low temperature

The LART at present uses near infrared wavelengths (840 nm and 1320 nm) that only allows to measure temperature above about 500°C in principle and more realistically above 700°C for satisfactory uncertainties. Certain applications present a real need for emissivity independent thermometry technique and LART could only be a solution if the wavelengths used are carefully selected for the application temperature range. This topic is developed in **section 4**.

3.2.13. Small scale

With the rapid progress in digital electronics and its miniaturization, it becomes necessary both to control the manufacturing process of integrated circuits and to apply non-destructive evaluation of these. The use of LART technique for such purpose would require adapting it to microscope systems.

4. DEVELOPMENT OF LART FOR LOW TEMPERATURE TARGETS

4.1. potential applications

Some medical operations or food process areas need a careful control of temperature. Such applications generally require a non-invasive technique but the surfaces concerned can have their emissivity varying in time and space. Medical interventions using laser-induced heat on tissue for instance can lead to serious and sometimes irreversible damage that a temperature measurement could prevent. Freezing / thawing or cooking food can lead to the development of bacteria and a temperature monitoring allows to follow a strict procedure. Thermal radiation for the temperatures concerned here is small and only measurable in the infrared

portion of the spectrum, that is why if the LART technique is to be used it would need to be modified to wavelength of 3 μm and above.

4.2. Technical solutions

For temperatures of the order of 0°C to 100°C, the wavelength we use are not suitable. As can be seen on the Figure 1 below, representing the spectral emissive power as a function of the wavelength for different temperatures (Planck law), wavelengths should be used between about 4 μm and 25 μm . However, another important parameter is the transmission factor of the atmosphere. Figure 2 shows the main transmission windows to avoid the absorption wavelengths, mainly from CO₂ and H₂O. The grey zones correspond to the short waves (SW) and long waves (LW) IR cameras bandwidth designed to exploit the two IR windows. The best choice is then to find two lasers, together with detectors, between 8 and 12 μm .

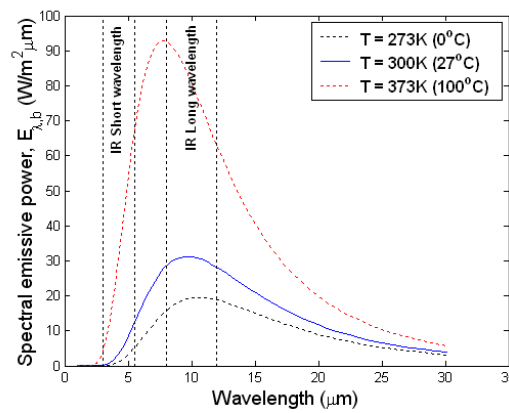


Figure 1: Spectral black body emissive power

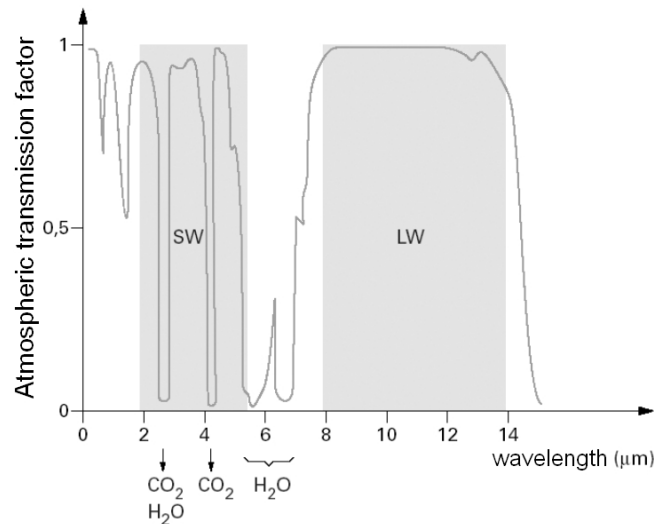


Figure 2: Atmospheric spectral transmission factor (path length 30m)

Designing a LART instrument for long wavelengths is not trivial as the possibilities for light sources, detectors and optical equipment are limited in the middle to far infrared region.

4.2.1. Light sources.

Lasers operating between 3 and 12 μm are diode, chemical, CO_2 and HeNe lasers, as well as quantum-cascade lasers.

The diode lasers can go up to 30 μm but the powers available at long wavelength are of the order of the milliWatt, which is far too low for LART. A particular adaptation of HeNe laser can operate at 3.9 μm but the power available is also only a few tens of mW. The chemical lasers, deuterium-fluoride (3.5 – 4.2 μm) or hydrogen-Fluoride (2.6 – 3.3 μm) are usually of very high power and complex as well as very expensive and are not appropriate for our application.

Some quantum-cascade lasers can now reach almost a Watt of peak power but are still only pulsed. Cascade technologies Ltd. (<http://www.cascade-technologies.co.uk/>) for instance are developing QC lasers but the peak power is about 500 mW so it's about 10 % of this, 50 mW, for an average power, which is not yet high enough for our purpose.

4.2.2. Detectors

At such wavelength the choice of detectors is reduced and the obvious solution is a HgCdTe photodiode. The cut-off frequency of such detectors can go up to 12 μm with a responsivity of the order of $4 \cdot 10^5$ V/W. An inconvenience is that the detector needs to be cooled.

4.2.3. Optics

4.2.3.1. Materials

Choosing the optics is not easy at this range of wavelengths where glass is opaque to light and we need to use materials like Germanium (Ge), transparent from 1.8 to 16.6 μm (refractive index of 4 at 2 μm) or Zinc Selenide (ZnSe), transparent from 0.6 to 13.9 μm (refractive index of 2.2 at 2 μm). Sapphire, commonly used for 'short wave' infrared application is not transparent in the 8-12 μm range.

Other existing materials are:

- AMTIR (Amorphous Material Transmitting IR). It is a glass, resistant to corrosion, transparent from 0.1 to 16 μm , with a refractive index of 2.5 at 2 μm .
- CdTe, also known as Irtran-6, transparent from 0.5 to 25 μm , refractive index of 2.67 at 2 μm .
- GaAs, it is a hard crystal that can be made amorphous. Transmits from 1.5 to 15.5 μm , refractive index 3.33 at 2 μm .
- Si, which is an inert crystal, can be of great interest also but its transmitting bandwidth depends on its doping (refractive index 3.4 at 2 μm).
- KBr, transmitting from 0.25 to 25 μm , is a low cost crystal but it is also soft and soluble in water.
- KRS-5 (Thallium Bromide Iodide) is transmitting from 0.5 to 40 μm but is soft and toxic.
- NaCl transmits from 0.25 to 16 μm . It is a very soft crystal soluble in water but is very low cost. Refractive index 1.52 at 2 μm .
- ZnS, also known as Cleartran, transmits from 0.6 to 12 μm and has a refractive index of 2.2 at 2 μm .
- Chalcogenide (AsSeTe glass) transmits from 2.5 to 11.1 μm and has a refractive index of 2.8 at 2 μm .

4.2.3.2. Fibre optics

Polycrystalline Infra-Red (PIR) fibres transmit high powers of light between 4 and 18 μm and can operate from -250°C to 250°C , using $\text{AgCl}:\text{AgBr}$ solid solution crystals. (source: Calphotonics Ltd., which already provides NPL with optical systems). This presents an ideal solution for the use of far IR laser lights.

Chalcogenide glass is also developed as a fibre optics material for infra-red transmission.

4.3. Comments

The technology for an IR LART to be used at temperature of the order of 300K exists although prices are still quite high, especially for the lasers. The detectors for this application need to be cooled, which is not convenient for a ruggedized LART instrument. The main concern is that the only laser opportunity are CO_2 , which can operate from about 9 to 11 μm , which would not represent a big difference between the two wavelengths. On the other hand, using a wavelength in the mid-infrared would mean about 3 μm or under, where the signals detected might be very low. The future development of quantum-cascade lasers might result in new types of cw lasers operating from about 5 to 12 μm .

REFERENCES

1. G. Sutton, A. Levick and G. Edwards, Radiation Thermometry in High Ambient Temperatures: Survey of Techniques and Current Applications and Identification of an Area for Further Study, Project TH1.6a, Deliverable for work packages 1 & 2, October 2002.
3. G. Edwards, M. Loveday, M. Ward, Study of Temperature Measurement Requirements and Technical Feasibility for Advanced Materials Processing, NMSPU PROJECT 1.7, NPL, 2000
2. P.J. Timans, Emissivity of Silicon at Elevated Temperatures, J. Appl. Phys. **74** (10), Nov. 1993.