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Thermal infrared detection of cavities in trees

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Abstract

The authors present a Remote Sensing System for detecting internal cavities in trees, using a thermal infrared apparatus which combines the benefit of instant data with the additional advantages of not requiring scaffolding or crews and (above all) of not entailing any injury or damage to the tree.

Introduction

The detection of internal cavities in trees has become of major interest today to plant pathologists, curators of historic gardens and even municipalities, since weakened trees constitute a public safety hazard.

On the basis of experience gained during fifteen years of remote sensing research, we decided to use a thermal scanner for the detection of internal cavities which create a discontinuity in the internal structure of a tree and, consequently, a surface thermal discontinuity.

To date, various methods have been employed for detecting the presence of internal cavities in trees. Two are based on the practice of boring into the trunk, using either a Pressler auger and examining the extracted core or a drill and measuring the variations of electric resistance across the tissues with a Shigometer[1] (Shigo 1969) or a Conditiometer[1] (Bollman Elektronik-system, Germany); a third method consists in tapping the trunk with a hammer and listening to the tone of the sound produced. The first two methods risk damaging or injuring the tree, while all three are time-consuming and require the presence of ground crews and often the use of scaffolding, ladders, etc. as well.

Compared with the three methods cited above, thermal scanning offers two outstanding advantages: (i) the examination is carried out from a distance, without the need for assistant personnel and without direct intervention on the tree; (ii) the time required for the examination can be reduced to a marked degree, since one complete scan is sufficient to reveal any cavity present in trunk or branches and the final result can be obtained and documented almost instantaneously.

Materials and methods

A number of trial scans were carried out at the Botanical Gardens of "La Sapienza" University, Rome in order to test the validity of the method. The results were most encouraging and the thermograms obtained from the scans displayed the existence of internal cavities by means of surface thermal discontinuities, in the same way as is already practiced in the field of medicine (Brünner 1984), in building and in the mechanical industry (Sayers 1984), etc., thereby confirming the utility of continuing studies on the infrared wavelengths range.

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or recommendation by the authors.

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The infrared range of electromagnetic radiation extends from 0.7 microns (the long-wavelength limit of visible red light) to 1000 microns. For convenience, this wavelength range has been devided into two bands (photographic and thermal infrared) depending on the system used for detecting the radiation, i. e.: special infrared black & white and colour (false colour) films, actinic up to 1 micron, and thermal scanners fitted with sensing elements capable of measuring infrared radiations above 2 microns (at present, up to 30 microns).

The sensing element must be kept at a very low temperature by means of an appropriate cooling system (liquid nitrogen, liquid helium, expansion of compressed gases or thermoelectric effect, depending on the apparatus) so as to reduce noise due to thermal agitation; in addition, at very low temperatures, the sensitivity of the elements increases to its maximum value and their response to input variations is almost instantaneous.

There is, however, a substantial difference between the two bands; in fact, below 2.0 microns the radiation detected is chiefly infrared radiation reflected by the object under examination and received from an external source (for example, the sun), while above 2.0 microns the radiation detected is mainly infrared radiation emitted by the object under examination. All bodies radiate energy in a continuous manner and in the form of electromagnetic radiation, provided that their temperature is above absolute zero (0°K). At ambient temperature (~300°K), all bodies have their maximum emission in the infrared range (~10 microns); hence the importance of investigating the environment with equipment capable of detecting this particular type of radiation, which is invisible to the human eye.

To date, applications in the field of botany have dealt mainly with the use of infrared photography. From the earliest experiments on black and white infrared plate (Wood 1910) to the investigations of Bawden (1933) and to more recent studies, plentiful information has been available on the capacity of infrared photographic emulsions to (a) promptly reveal the presence of centres of infection or of attack by bacteria or by insects (Ciesla 1974; Murtha 1978), often before the differences between healthy and non-healthy vegetation can be detected by the human eye, and (b) distinguish between the various species (Sayn-Wittgenstein 1978; Delbard and Jouannet 1982).

The foliage of a healthy plant, in fact, reflects the infrared radiation emanating from the sun. When the reflected radiation falls on infrared colour film (the most widely used type of film for these studies), it forms a red-coloured image; in a healthy condition, however, each species is characterized by a distinctly different shade of red owing to the different texture, pigmentation and turgor of its leaves. Any change in the shade of red typical of a given species evidences the existence of a situation (disease, severe environmental pollution, parasite attack, or other cause) which has modified the capacity of the leaves to reflect infrared radiation and, consequently, to produce the correct shade of red on the film.

Only one application of the thermal infrared scanner to the botanic field has been reported so far: that is, for measuring the temperature of tree crowns by air reconnaissance. In fact, in an area infested by pathogens (for example, *Poria weirii*) which attack the roots of trees, with a consequent reduction in the absorption of liquids from the ground and minor transpiration through the leaves, the crowns of ailing trees have a higher temperature than the crowns of healthy trees (Neubert 1969; Andrieu 1983), at times even more than 4°C; these trees are commonly referred to as being "feverish".

Transpiration through the leaves is also reduced when a plantation (of trees or crops) is irrigated insufficiently and, as a result, the foliage temperature of the tree crowns is higher than that of the same plantation properly irrigated (Millard et al. 1978; Andrieu 1983). Nevertheless, it is possible to distinguish between the two situations. In an area infected by pathogens, in fact, only a limited number of plants will be in an unhealthy condition (unless the disease has become so rampant for the effects to be plainly visible to the naked eye), while in an insufficiently irrigated plantation all the plants will be at a higher temperature than that of a similar properly irrigated plantation in the neighbourhood, adopted as a reference for observing the phenomenon (which otherwise would obviously not be detectable). Furthermore, while in the first case it is necessary to examine each crown of foliage almost one by one (with high resolution photographic equipment and low altitude flying) (NEUBERT 1969), in the second case the survey can be carried out at a higher altitude using photographic equipment with a wider field of view and lower resolving power.

An infrared thermal scanner was used for the preliminary trials, fitted with an indium antimonide sensing element cooled with liquid nitrogen and capable of measuring infrared radiations in the band between 2 and 5.6 microns.

The equipment used consisted of two main components, that is: (i) a telecamera containing the infrared sensing element; (ii) a control and display unit. The optical lens system within the telecamera (comprising two motor-driven revolving prisms set at right angles to one another) resolves the image into an array of dots, which are then picked up by the sensing element and converted into electrical signals. At each instant, therefore, only a very small portion of the object (Instantaneous Field of View) is examined by the detector and systematic sweeping is realized mechanically by the rotation of the two prisms. The time required for producing a single image is one-sixteenth of a second.

Table 1. **I.F.O.V. and F.O.V. of the lenses of the thermal scanner used**

Lens	I.F.O.V.*	F.O.V.**
10°×10°	1.3 cm	1.75 m
25°×25°	2.5 cm	4.45 m
45°×45°	3.5 cm	8.16 m

(for objects located at a distance of 10 m from the telecamera)

* I.F.O.V. = Instantaneous Field of View of sensing element: the scanner will not detect surface areas smaller than a square with side as indicated in the Table.
** F.O.V. = Field of View of telecamera: a square with side as indicated in the Table.

Three different optical lens systems were used for varying the field of view, i.e. 10°×10°, 25°×25° and 45°×45°. All three lenses were of specially treated silicon, since glass does not let through infrared radiations with wavelengths in the range above ~2.0 microns. In photographic terminology, it can be said that the first system can be defined as a "telephoto" lens, the second as a standard lens and the third as a "wide-angle" lens; as with the normal photographic camera, the resolving power of the lens decrease with the increase of the field of view and vice versa.

The infrared radiation strikes the detector which then generates an electrical voltage signal across its terminals; the amplitude of the signal varies with the temperature variations detected on the surface of the object under examination. The signal is amplified and used to modulate the intensity of the electron beam of a TV-monitor tube in the display unit. The image is displayed in black and white and consists of a pattern of different shades, ranging from black through grey to saturated white; a reference scale at the base of the image permits an immediate evaluation of thermal variations of the different regions of the object scanned, since the lighter the shade, the higher the temperature of the emitting surface.

The scanner was used in conjunction with auxiliary equipment (Colour Slave Monitor) which quantizes the reference range of grey shades into a set of ten different colours. The ten colours can be arranged in any order in the set, as desired, and the selected sequence is then displayed beneath the image on the screen. Therefore, an item reproduced in a given colour is at a higher temperature than the item reproduced in the colour located to the left of that colour in the set. In this way, the recorded temperature differentials were displayed more distinctly and were easier to discern[2].

The instrumentation described above is capable of projecting images of objects at temperatures ranging from −30 to +850 °C, but it can only measure surface temperature differentials as it is not provided with an internal reference. In effect, the thermal scanner measures radiated power (i. e. the power emitted by an object) which is dependent on the nature as well as the temperature of the surface under examination. The influence of the nature of the subject is reckoned on the basis of the emissivity[3] of the object under examination; in the case of trees, the emissivity of the bark can be assumed as almost constant.

The minimum temperature differential measured by the instrumentation can be preset, for any temperature in the above-mentioned range of temperatures, to ten different values by adjusting the sensitivity control. The value of 0.5 °C was selected for this investigation.

Two Nikon F motor-driven cameras, loaded with 250-frame film magazines, were positioned in front of the screens for recording the images on black and white and on colour films.

An inverter, powered by a high-capacity alkaline battery, supplied the 220 V a. c. current required for operating the scanner and ensured a 4-hour autonomy of operation; a standard a. c. power pack can be used for investigations extending over a longer period of time. The liquid nitrogen for cooling the sensing element was stored in a lagged metal cylinder (Dewar flask).

The instrumentation, mounted on suitable supports, was installed with the ancillary equipment in an utility van, for greater freedom of movement from site to site and for reaching trees located far from the road without difficulty; the operator's control post was also installed in the van.

The photograph shown in Figure 1 was taken during a recent investigation with the thermal scanner.

During the survey, the telecamera was stationed at a distance from the tree ranging from 5 to 10 metres.

To take the higher reaches of the tree, it was sufficient to point the telecamera at the desired area by operating the drive unit. As can be seen from the attached thermograms, the variation in range in no way affected the response of the scanner nor did it alter the quality of the images. The results obtained by filming other tree species, some with rough and cracked bark (lime, pine, cedar of Lebanon, plane-tree, etc.) (Catalano et al. 1988; Catena and Palla 1987; Catena et al. 1989, 1990; Palla et al. 1988) confirmed that the distance between object and telecamera does not appear to have any effect on image quality, at least within the 15–20 m range. At greater distances, however, there is the possibility that small cavities may be very difficult to detect, owing to the reduced resolving power of the instrumentation.

When a cavity, or an inclusion of dead tissue, is present in the living tissues of a plant, the internal thermal conductivity of the plant will present a variation in the affected area. This internal discontinuity will produce a corresponding variation of the surface temperature which will appear on the black-and-white monitoring screen as a darker or lighter area, that is an area with a different temperature to that of surface tissues in its immediate surroundings.

[2] For administrative reasons, only the black and white thermograms obtained have been reproduced in this article: the corresponding colour thermograms can be examined in the article by Catalano et al. 1986.

[3] Emissivity is a characteristic quantity of the surface of a body and is defined as the ratio of the radiation emitted by a surface to the radiation emitted by a perfect blackbody radiator at the same temperature and wavelength. Its value is dependent on the nature of the body and on the condition of the surface (e. g. smooth or rough, clean or stained, bright or dull, oxidised, etc.).

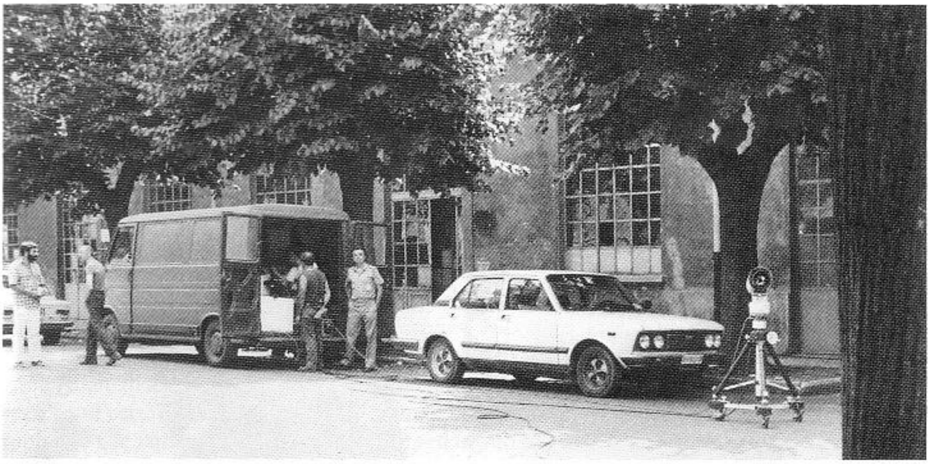


Fig. 1. Tipical field investigation with scanner: the operator and instrumentation are in the van in the background; on the right, the telecamera mounted on its tripod is scanning the tree in the foreground on the right-hand side of the photograph

Results

Scans carried out at the Botanical Gardens fully confirmed the hypothesis that an internal discontinuity produces a variation of the surface temperature distribution. No discontinuities were observed in the thermograms obtained for a number of specimens of *Cedrus libani* A. Richard, *Cedrus deodara* (D. Don) G. Don Fil., *Abies alba* Miller, *Pinus pinaster* Aiton and *Pinus pinea* L.; on the contrary, a specimen of *Celtis australis* L. which had a very extensive external cavity in the distal portion of the trunk, caused by the loss of a main branch (Fig. 2), gave a thermogram (Fig. 4) showing a "colder" darker patch in the area marked "A" in Figure 2.

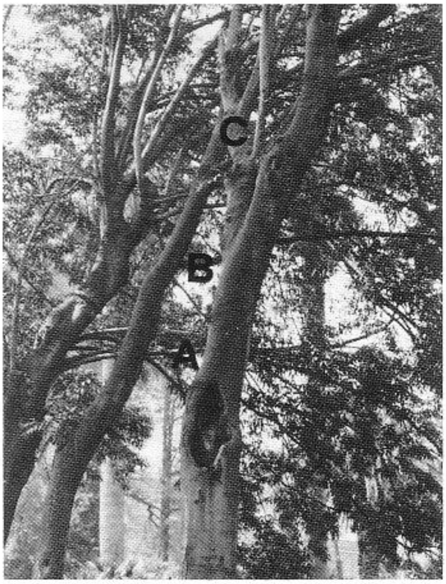
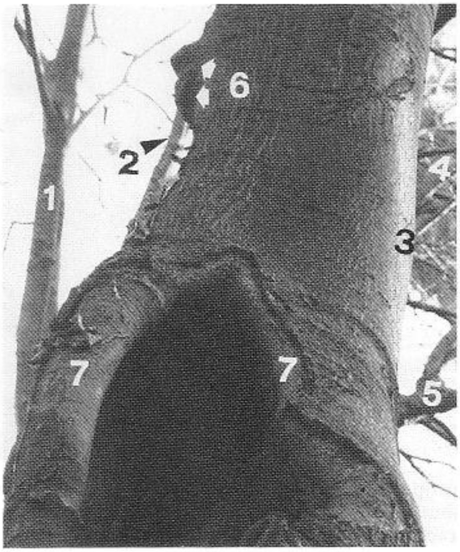


Fig. 2. The *Celtis australis* of the Botanical Gardens which was investigated with the scanner. The letters A, B and C indicate the areas corresponding to the thermograms reproduced in the Figures that follow. The extensive cavity caused by the loss of a main branch is visible immediately below A



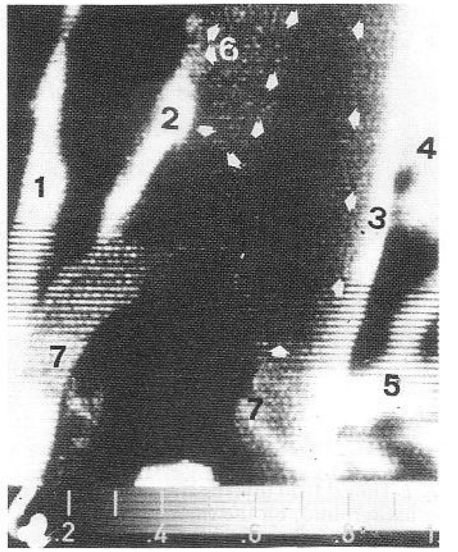


Fig. 3 (left). Close-up of the area marked A in Fig. 2. Reference nos. 1, 2 and 5 indicate limbs of trees in the immediate background. Reference no. 4 indicates the crown of the palm in the far background, no. 3 the portion of tree-trunk on which the sun was shining, no. 6 the scars left on the trunk by the cutting of twigs and no. 7 the scar tissue around the external border of the cavity – *Fig. 4.* Thermogram of the area shown in Fig. 3. An extensive portion of the trunk is displayed in a darker shade than the adjacent parts, indicating the upwards extension of the cavity (evidentiated with white arrows and confirmed by a subsequent direct on-the-spot examination). All areas illuminated by the sun (reference nos. 1, 2, 3, 4 and 5) are displayed as saturated white; scar tissue (reference nos. 6 and 7) is displayed in a lighter shade than the surrounding healthy tissue

A direct on-the-spot examination was made to confirm the presence of the internal cavity, or at least of some kind of discontinuity in the wood, using a ladder and introducing a hand in the hollow in the tree-trunk. The cavity was found to extend upwards, as shown in the thermogram, but the presence of dead and decaying tissues prevented exploring fully its extension up to the boundaries of the dark patch (indicated by white arrows).

Subsequent investigation of the dead tissue with the help of metal stylets showed that this tissue occupied the entire cavity revealed by the thermogram.

To facilitate interpretation of the thermograms, the branches and other particulars of interest are identified with the same reference number both in the thermograms and in the ordinary black and white photographs.

Comparison of Figure 4 with Figure 3[4] shows that reference nos. 1 and 2 indicate limbs of background trees, while reference no. 3 indicates part of the tree-trunk under examination with the sun shining on it from the right. Reference nos. 4 and 5 indicate, respectively, the crown of the palm (*Jubaea chilensis* = *J. spectabilis*) and the small limb, both of which are visible in the background on the right-hand side of the photographs.

Examination of the thermogram shows that neither at the level of the small branch nor at that of the crown of the palm is it possible to distinguish the trunk under examination from the branch or from the palm, since all three were in full sunshine and at a temperature

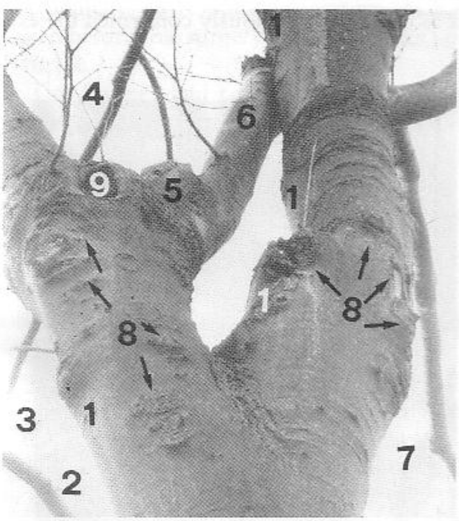
[4] Unfortunately, the photographs taken at the same time as the scan were accidentally destroyed; the photographs reproduced in this article were taken at a later date. For the record, the photographs of Figs. 2 and 7 were taken before tree surgery (pruning of dead and damaged branches) was carried out (as a result of the thermal examination); those of Figs. 3, 5 and 8, instead, were taken a year later when the tree was again leafless (the original thermograms were recorded in February), taking all possible care to take the photographs from the same angles.

outside the range selected for studying the trunk (5 °C). In this connection, it should be mentioned that objects at temperature above or below the preselected range are displayed, respectively, as white or black patches.

Reference no. 6 indicates a cluster of small scars (the result of twig pruning) which appear as patches of a lighter shade than the surrounding healthy tissue; scar tissue differs from ordinary tree tissue and may possibly therefore have a different emissivity. The scar tissue is displayed in the thermograms in a lighter shade of grey than the original bark of the tree. This is confirmed by examination of the border of the cavity indicated by reference no. 7: the corresponding point on the ordinary photograph shows that the tissue in this zone differs from the surrounding bark.

Comparison of the two images also upholds the previously made statement regarding the resolving power of the lenses of the scanner. All object points which cannot be resolved by the lens will not appear in the thermogram, even though their temperature is higher (or lower) than that of adjacent object points. In fact, only sufficiently large twigs can be "seen" and certainly not the numerous small twigs which are visible in the ordinary photograph and the same situation can be observed in subsequent thermograms. The small branches in front of the crown of the palm, on the contrary, cannot be distinguished from the crown itself because they too have a temperature higher than the selected range and therefore are displayed as white patches like the crown; the black patches correspond to the "empty" spaces between the branches.

The darker band across the centre of the thermogram in Figure 4 is a recording defect caused by imperfect matching of the scanning rate (1/16 sec.) with the camera exposure (1/15 sec.).



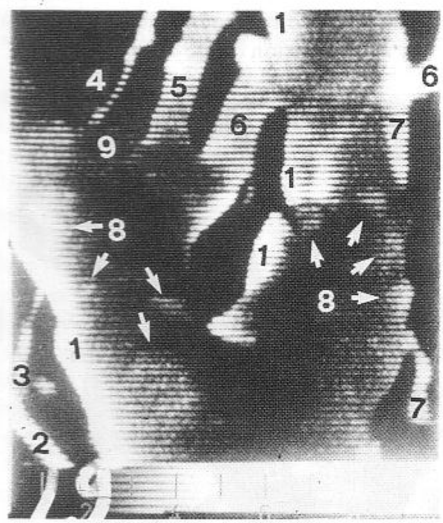
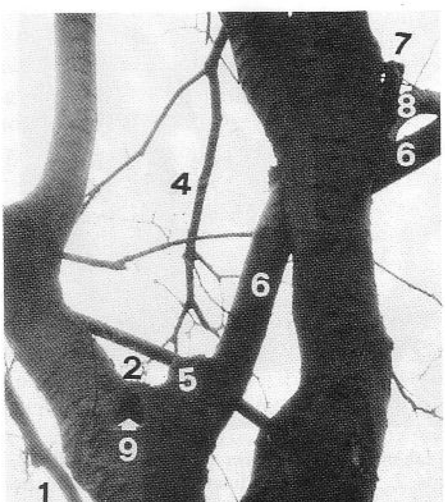


Fig. 5 (left). Close-up of the area marked B in Fig. 2, taken from a different angle to that of Fig. 2, i. e. 90° to the left of the earlier shot. Reference nos. 2, 3, 4 and 7 indicate small limbs in the background. All areas illuminated by the sun are indicated with reference no. 1, while reference nos. 5 and 6 indicate branches of the tree under examination. Reference no. 8 indicates the numerous scars left by small cut-off branches, no. 9 a cavity due to a loss of a branch (for reference no. 5, refer to Fig. 7) – *Fig. 6.* Thermogram of area shown in Fig. 5. In this case, too, a large dark patch was recorded involving both branches and extending downwards, due to the presence of a large internal cavity (as confirmed by subsequent direct investigation). Reference no. 9 indicates that, while the cavity is displayed as a dark blotch, the scar tissue surrounding it is displayed in a shade of grey lighter than that of the adjacent original bark, in the same way as with the other scars indicated by reference no. 8

Fig. 7. Photograph taken before tree surgery was carried out and a number of dead branches removed (e. g. those indicated by reference no. 5 in Figs. 4 and 5 and by reference no. 7 in the upper right-hand corner of Figs. 8 and 9

Cavities were also detected higher up the same tree in the area above "B" in Figure 2. The exposures reproduced in Figures 5–9 were taken from a different angle to that of Figure 2, i. e. 90° to the left of the previous shot. The very dark patch in the thermogram recorded at the height of the first bifurcation (Fig. 6) reveals the existence of a cavity of considerable depth (judging by the shade of grey) and extending into both branches. In this case, too, direct examination carried out as described previously confirmed the existence and extension of the cavity.



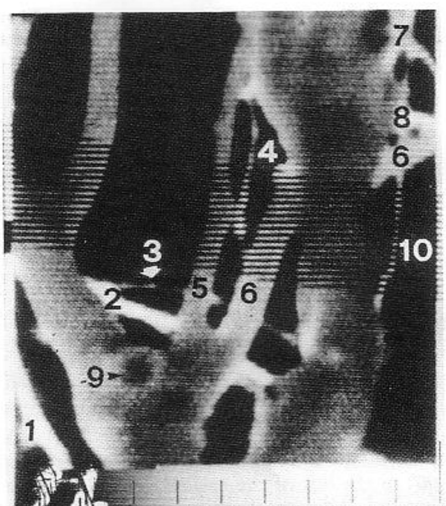


Fig. 8 (left). Close-up of area marked C in Fig. 2. Reference nos. 1, 2 and 4 indicate small branches in the near background, nos. 5, 6, 7 and 8 branches of the tree under examination (for reference no. 5, refer to Fig. 7), no. 9 a cavity due to the loss of a branch as seen in Figs. 5 and 6 – *Fig. 9.* This thermogram also shows a large blotch indicating the presence of an internal cavity which extends, in the right-hand branch, up to the level of reference no. 7. Reference nos. 3, 5, 7 and 10 are the thermal traces of small branches cut off during pruning of the tree. For the remaining references, see comments on other thermograms

By comparing Figures 5 and 6, it can be seen that these shots were taken from a different angle (i. e. 90° to the left) to that of Figures 3 and 4 and while the sun was shining on the left-hand side of the tree-trunk. The areas of the trunk illuminated by the sun are all marked with reference no. 1; reference nos. 2, 3, 4 and 7 indicate small background branches which are displayed as white patches (like the areas marked by no. 1) since they too were in the sunlight. The areas marked with nos. 5 and 6 correspond to two secondary branches of the tree; these branches appear as patches of a darker shade of grey, since they are bigger than the background limbs and therefore possess a higher thermic inertia; in other words, the smaller the object the faster it heats up when exposed to the sun. Reference no. 5 corresponds to the dead branch which was subsequently removed during tree surgery operations; it can also be seen, in Figure 7, marked with the same reference number. The lighter grey patches (no. 8) are scars left by small cut-off limbs, the roundish dark blotch (no. 9) on the left-hand branch is a pruning scar, the lighter shaded area encircling the blotch is scar tissue and the black central portion is dead tissue.

In the thermogram, the darker band caused by imperfect matching of the scanning rate with the camera exposure has moved to the upper part of the image.

The thermogram of Figure 9 refers to the branches above the bifurcation, marked "C" in Figure 2, and reveals the existence of other cavities (darker patches) in both left-hand and right-hand branches which were also confirmed by direct examination, carried out as described previously. The roundish dark blotch (no. 9 here and in Figs. 5 and 6) stands out vividly in this thermogram. While the cavity does not extend beyond the bifurcation in the left-hand branch, it reaches instead up to the secondary bifurcation in the right-hand branch and affects the bases of the two vertical limbs in the foreground.

In this case, too, the small branches in the background are displayed as white patches. The branches corresponding to thermal traces 3, 5, 7 and 10 which are visible in Figure 7 (taken before tree surgery was carried out) are no longer visible in the later photograph of Figure 8.

The darker band corresponding to the recording defect mentioned above this time stretches across the centre of the thermogram.

Conclusions

Even on the basis of these preliminary results it is possible to conclude that the thermal scanner is a reliable system for detecting internal cavities or dead tissues in the trunk, provided that these latter produce a discontinuity in the surface temperature of the tree. In addition, it is a fairly uncomplicated method and one that, with a little practice, is accessible to almost everyone, easy to use and it gives results quickly without having to resort to practices that can be detrimental to the plant. If a polaroid camera is included in the system, suitable documentary evidence can be made immediately available to the experts and interested technicians for the necessary remedial action.

Numerous questions, however, still remain unanswered to which it is hoped the ongoing studies will provide a solution. For example:

– why does the presence of a cavity or of dead tissue lower the surface temperature in that area?

– it would appear that the colour shade of scar tissue in the thermograms is invariably lighter than that of the surrounding tissue; is this due to the fact that scar tissue is meristematic and therefore different from the surrounding tissue both in nature and in emissivity or is the scar at a higher temperature than its surroundings because the tree has suffered an injury in that area?

– the empty spaces between branches invariably appear as black patches; if this is due to the fact that the temperature of the air is lower than the surface temperature of the trees (the latter are always displayed in a lighter shade of grey than the surrounding air), could it be that trees have a temperature of their own and can vary this temperature (even if within narrow limits)?

These and other questions, open up new fields of research and highlight aspects which have possibly been neglected by botanists, but which instead deserve to be investigated.

Résumé

Détection thermique infrarouge des cavités dans les arbres

Les auteurs présentent un système de Remote Sensing pour la détection des cavités dans les arbres, par recours à un appareil thermique à infrarouges. Cet appareil présente l'avantage de mesures instantanées, sans recours à un échaffaudage ni à une équipe et surtout sans provoquer de dégâts aux arbres.

Zusammenfassung

Eine Temperatur-Infrarot-Methode zum Auffinden von Hohlräumen in Bäumen

Es wird eine Methode vorgestellt, mit der aus der Entfernung Hohlräume in Bäumen gefunden werden können. Das verwendete Temperatur-Infrarot-Gerät verbindet den Vorteil unmittelbar erfaßbarer Ergebnisse mit den Vorteilen, daß weder Gerüste noch großer personeller Aufwand erforderlich sind, und vor allem dem, daß die Methode völlig zerstörungsfrei arbeitet.

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