Invited Paper

IRST and its Perspective

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ABSTRACT

This paper starts with a review of the status of presently available IRST sensors and continues with the problems that they are facing, even after more than 25 years of development. The problems arise from uncertainty in target signatures, atmospheric effects, background clutter and different types of hardware and processing shortcomings. Yet IRST has a promising future thanks to increase in knowledge on target/background signatures, improved optics and electronics sensor fusion and algorithm development. Furthermore IRST has good perspective due to the increased number of applications for various platforms and scenarios. The perspective grows with the increased performance for lower price. It is important to consider here IRST as part of the platform system and to endeavour for close integration with other system components.

1. INTRODUCTION

Infrared Search and Track (IRST) systems have been introduced on a modest scale into air defence applications after a very slow start, taking more than 20 years of research and development. The reason for the slow start is partly the lack of integration in broader system sense (e.g. weapon system), partly the persistency of some technical problems and partly the cost of one IRST unit.

Potential users continued in comparing the performances of IRST and alternative warning receivers. The advantages of the passive character are encountered by the lack of range compared to radar. On the other hand radar sensors suffer from jamming sources and are vulnerable to anti-radiation missiles.

Besides the military use, IRST did not yet find until now distinct civil applications. As will be shown in this paper however, this position is expected to change due to two major factors: new technical advances, leading to higher performance for lower cost, and increase in need for all kinds of surveillance devices. This fact illustrates the difference in character of a military and civil IRST sensor. As military sensor it is acting as a situational awareness sensor, being part of a weapon system, carried by a military platform, either acting solitary or in formation with other platforms. As civil sensor the primary use will be for surveillance on land, at sea and in the air. IRST's may warn for intruders, may inspect harbours, survey danger areas where disasters (e.g. forest fires) may occur, alert in traffic applications and so on.

In order to guide the growth potential and to demonstrate IRST and its promise we have to clearly analyse the shortcomings of present day technology and make a synthesis of IRST with alternative and complementary sensors in synergy with command, control, communication and intelligence (C^3I) systems, governing the decision process.

In the following chapters the outline will be:

- State of the art of present day IRST sensors, basic performance limits
- Analysis of technical problem areas; alternatives
- Technological advancements; optics, detectors, processing
- System aspects, survivability, C^3I, new challenges and perspectives, military and civil
- Conclusions, recommendations.

2. STATE OF THE ART OF PRESENT-DAY IRST SENSORS

Around the world several so-called first generation IRST sensors have come into operational use. They generally scan a scene with a linear or staggered array of detectors in the way as shown in figure 1. The most important sensor parameters are:

- Total Field of View, determined by the length of the detector array, the focal length and the number of scanned bands per frame
- Instantaneous Field of View, determined by the size of the individual detector elements and the focal length
- Frame Rate, determining together with both previously mentioned parameters the electronic (and noise) bandwidth.
- Spectral Response, determining the target-background contrast given their conditions

0-8194-1911-7/95/$6.00

- Sensitivity, determined by the detectivity of the detector, size of the entrance pupil, optical transmission and the previously mentioned parameters
- Processing, determining the required signal to noise ratio for a given detection probability/false alarm requirement.

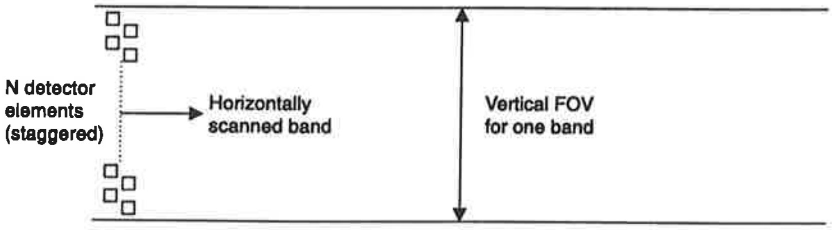

Fig. 1. Basic principle for classical first generation IRST.

These basic parameters are strongly related to the requirements of the user, the implementation into a larger system and the scenarios and missions where the IRST sensor is used. Present day operational systems can be found on ships, in aircraft and on land, mostly for air defence applications.

More specific examples of applications are:

- Short range IRST for use on board of ships for defence against incoming threats; coupling with a fire control system.
- Air Defence Alerting Device, with multiband scan for larger vertical Field of View; coupling to short range ground to air missile system.
- High altitude IRST, mounted in aircraft at 10 km or more altitude; target detection at long range; no atmospheric problems, coupling to alerting system and long range missile defence systems.

For a general discussion on IRST performance and theoretical aspects, reference is made to Vol. 4 of the Infrared and Electro-Optics Handbook[1]. More popular presentations on IRST can be found in consumer oriented journals like IDR[2]. More recent publications/presentations are for example found on SPIE conferences from 1993, as well as on Design Criteria[3], demonstrators[4], experiments[5], and target contrast effects[6]. They show that IRST is a high priority subject in many nations and also that many problems have to be solved in order to achieve the ultimate ranges that the sensors intrinsically contain.

3. TECHNICAL PROBLEM-AREAS

The generally used most simple range formula for point target detection systems like IRST is:

$$R = \sqrt{\frac{\Delta W * \tau(R)}{NEI * K}} \qquad (1)$$

in which R is the range, $\tau(R)$ the atmospheric transmission over the range R, ΔW the target radiant intensity contrast, NEI the Noise Equivalent Irradiance of the sensor and K the required signal to noise ratio for a given detection/false alarm probability. Even from this simple formula we can determine directly a variety of problems, resulting in range uncertainty on sensor limitations:

3.1. Target contrast

The value of ΔW is not just a simple number, but the outcome of complex, time consuming computations, or the result of measurements with lack of accuracy. A number of subproblems can be mentioned:

- target aspect angle
- contribution of selective plume radiator (if present), partly shielded by the target body
- target surface (specular) reflection: cold-sky reflectance or hot earth reflectance on both
- background radiance around the target; here also background solar scattering has to be considered[6]
- due to the trajectories of target and sensor the aspect angle is ever changing as well as the range; thus the signal changes with time.

Concerning the selective plume radiance it is recalled that the atmosphere acts as a selective absorber, which causes a different extinction coefficient for plume- than for solid body radiation.

3.2. Background (clutter)

Mentioned before was the static homogeneous background surrounding the target. Of key importance are also the fluctuations in background radiance. Background radiance generally has not the same spectral distribution as the target, but the variations in the background (e.g. wave reflections) in themselves also may vary spectrally. Another physical phenomenon which may differ between target and background is the degree of polarization and the variations in polarization within one picture element. Finally we have temporal and spatial fluctuations. Temporal fluctuations can be everything between slow and fast. A number of examples is the following:

- sunglints on wave facets; these may rapidly vanish and appear rather randomly, depending on the position of sun and observer; in the tropics they can be all around.
- white caps on waves; these clutter sources generally are much slower, slow enough to see them in 2 or more consecutive frames.
- clouds; these sources change in position and shape in a rather slow pattern compared to the 1 Hz frame rate.
- land clutter; this clutter source is even more static, although cloud shadows passing by may cause instantaneous reflection and radiance (temperature) changes.
- bird clutter; this source may rapidly change position; also bird-wing reflection may cause intensity fluctuations with high frequency or low frequency when the birds make a turn.
- coastal clutter; this is rather static, unless some human activity causes fluctuations (factory chimneys).
- battle effects; in this situation fires, explosions and obscurants have to be considered.

Spatial fluctuations may also vary from small to large and everything in between; also the shape and strength can be of all kinds where within one area of "homogeneous" signals the spectral content can vary as well as the temporal distribution. Examples are:

- clouds; edges apparently differ from the cloud centers; spectral effects occur due to the wavelength dependence of scattering.
- waves; observed from near horizontal directions spatial extension dominates horitontally; here waves may partly be obscured by nearer waves[14].
- land background; here the spatial fluctuations differ by the way how people have cultivated the land and how the climate affects the areas of homogeneity: soil, vegetation, water, roads, buildings, dikes etc.

3.3. Atmosphere

Atmospheric effects on the target detectability are the next topic of concern. The longer the atmospheric path, the more concern and this is a non-linear relation. Certainly EO/IR is not an all-weather medium: for long ranges, molecules and particles may severely diminuate the signal received by the sensor. Knowledge on the atmospheric effects is alternatively built up by modelling and experiment[7]. The most important phenomena are mentioned below:

- extinction by CO_2 and H_2O molecules; their concentration depends on temperature and humidity, causing dependence on geographic location (subarctic - tropic); the problem is that these data are generally insufficiently known; furthermore propagation models presently tend to disagree with real data; one aspect is the non-homogeneity over the pathlength.
- extinction and scattering by aerosols; aerosols can originate from various sources but tend to have a variety of particle size distribution, furhtermore dependent upon the height; extinction is strongly wavelength dependent as well as scayttering is; scattering causes the before mentioned background or foreground radiance.
- turbulence effects; temporal variations in temperature; humidity and pressure in space cause optical beam deviations, resulting in blurring (point spread function of the atmosphere) and scintillations; the phenomena are modelled as well as measured at several locations (see e.g. ref [9] and ref [12]); the scintillations may give severe peak signal variations for ranges greater than 10 km; peaks may vary a factor 5 or more and in some cases atmospheric "transmission" values > 1 are observed.
- refraction; static gradients in temperature in the vertical direction cause static beam deviations, resulting in subrefraction (cold air over warm water) or superrefraction (warm air over cold water)[15]; in some cases double images may appear (mirages) which may influence the performance of the point target processing algorithm.

3.4. Hardware

Some hardware problems are inherent to the system like the limited field of view or the frame rate. Limitations in data handling capability (and cost) reduce the speed and so the frame rate. Low frame rate might exclude high speed targets. Small field of view provides limited protection. In formula (1) the NEI term dominates the sensitivity, again in a simple way determined by the sensor parameters: A_p (pupil area), τ_{opt} (optical transmission), D* (detectivity of detectors), T (frame time), N (number of detector elements), *l* (length of the array), f (focal length):

$$NEI = \frac{1}{A_p * \tau_{opt} * D^*} \sqrt{\frac{\pi * l * f}{T * N}} \tag{2}$$

Hardware imperfections can be listed in the following way:

- optical blur; considered as MTF (modulation transfer function) or energy received by each detector sensitive area; this may vary over the field of view; keep an eye on chromatic aberrations and on flatness of the field.
- detector inhomogeneity; generally this is compensated by NUC (non-uniformity correction); due to variations in spectral response NUC's are not 100% perfect; in this category fall dead pixels.
- mechanical imperfections; to be mentioned are platform instability and inaccuracy of the synchronization signals, resulting in errors from the target discrimination algorithms.
- noise behaviour; here we have to separate the various noise sources: background "clutter" noise, photon noise and electronic noise; the electronic noise consists in itself of a number of contributions (analog, digital etc.) and may show a strong non-Gaussian behaviour; background noise has been mentioned in the background paragraph and is difficult to take into account due to its variability.
- optical transmission; here we have to take into account the target spectral emission, atmospheric spectral transmission as well as the spectral response of the sensor and its pointspread function.

In general, system noise is measured as RMS in the NEI definition; letter is to take the noise statistics of the complete sensor.

3.5. Processing

Although processing power has been improved orders of magnitude, present day systems still suffer a lot of false alarms in a number of occasions. Many of the reasons are directly coupled to the previously mentioned problems. One result of the processing until now is especially inadequate: range information. Several methods have been introduced to obtain range:

- signal growth; this method suffers from the scintillations and from the aliasing between detectors; with a low frame rate it takes a lot of time before a reliable fit can be made with the $\tau(R)/R^2$ law; even image restoration algorithms as discussed in ref [13] do not provide a complete solution.
- stereoscopic imaging; this is a classical method, which leads to more bulky sensors, but with reasonable result; however, it has to be realized that even at short distance (0.5-1.0 m) the signals from distant targets may be decorrelated completely.
- kinematic ranging; this method takes into account the platform motion and changes in observed target direction with time[11].
- laser ranging; the addition of a laser for ranging (or jamming) is not popular for the whole user community; directing the laser beam is the biggest problem; uncertainty exists on the laser cross section of small targets and the 2-way beam propagation aspects.

Other processing problems arise from the spatial discrimination and the limited geometrical resolution. Much effort is spent on new algorithms, as has been published recently (e.g. ref [10] and ref [21]). Some of the recent IRST models[8,9] contain sophisticated processing algorithms. Processors, discriminating birds, have not shown until now to be strong enough to reach a sufficiently low enough false alarm rate (< 1/hour). Especially in coastal areas this remains a problem. Also the processing against the sea background clutter just below the horizon in higher sea state conditions is a difficult problem which needs to be solved.

3.6. IRST Testing

When the IRST sensor is completed, test and evaluation has to be carried out to see if all requirements are fulfilled. Component testing can be done beforehand like spectral response, MTF, noise statistics and so on. Complete sensor test implies collimated point sources, over which the IRST beam sweeps, extended homogeneous blackbody sources (homogeneity better than 0.01 K) to test noise character and finally simulated or real background structure to test the strength of the discriminators. Non-cooperative targets like birds or sea backgrounds are difficult to manage however. Normally co-registration is done with a sensor of the same sensitivity but higher frame rate and limited field of view in order to better characterize the areas where false alarms might or might not trigger the IRST. Similarly this co-registration sensor serves as a device to characterize the atmospheric effects like scintillation, refraction and aerosol extinction. Of course the spatial resolution has to be at least the same as the IRST and also its spectral response.

4. TECHNOLOGICAL ADVANCEMENTS

Without technical progress we would stay with the 1st generation IRST systems with limited use. However, on many areas a lot of research and development work is spent to tackle the problems mentioned in the previous chapter In the following we will consider the technological advancements, resulting from these R&D efforts. A review of part of this work, as carried out in the Netherlands, is presented in [16]. Here we summarize recent international progress on signatures, atmospheric effects, opto-mechanics, detectors, sensor fusion, electronics and processing algorithms all of them leading towards improved IRST performance.

4.1. Signatures

Thanks to improvement in understanding the physical phenomena of EO/IR signatures we know better how to prepare the sensor in order to obtain the optimum contrast. This understanding originates from better measurement methodology and from improved and validated target and background models. Knowing carefully collected meteorological data and target-physical structure, we can predict its contrast. This improvement will continue for a certain time until the target constructors counteract with countermeasures, leading to more stealthy targets. Knowledge of the target-spectral and -temporal signature compared to its background allows for new discriminators. These may involve additional complexity like knowledge of spatial clutter leads to complex spatial filters. As a result the detection problem of point targets in sea clutter seems to be solvable in the near future.

4.2. Atmospheric effects

Again the knowledge of the phenomena increases rapidly as in the case of signatures. Especially the knowledge on scintillation, combined with higher frame rates, leads to increased range performance and better discrimination and false alarm reduction. The capability to predict mirages will affect the spatial discrimination algorithm. For this we need a method to measure temperature gradients in the atmosphere. One possibility is a radiometric spectrometer, another a LIDAR setup, both rather expensive methods. A cheaper, but more cumbersome method is hardware sounding (dropsonde).
Knowledge on spectral emission/transmission provides an input in TDA's (tactical decision aids) predicting how to select or combine the optimum spectral bands or polarizers. This may be dependent upon the direction of observation. Similarly, knowing the sensor height and the vertical structure in any direction, one may predict at which range a given target at given height is detectable.

4.3. Opto-mechanics

New optical designs with aspheric, off-axis mirror optics allow for multispectral data collection through one optical window and precise colocation of the pixels for different bands. These designs may come close to the diffraction limit (3 mirror systems[17]).
On the other hand mechanical scanning is a serious drawback, which is solved if we move towards staring IRST's. Multiple sensor optics will remove the need for very wide-angle fisheye type lenses. Multiple eyes will however introduce the need for appropriate fitting of the edges of the fields of view.
Full staring might involve a too high cost in the near future if we want high spatial resulution. For example 2π steradian requires $2\pi \times 10^6$ pixels of 1×1 mrad over a hemisphere. An intermediate solution is the so-called step-stare method like the scanning in classical movie projectors. The incorporation of a laser into the system is another challenge. The trick is to achieve very fast beam directors, slaved to a tracking sensor.
The stabilization problem is a serious one if the supporting platform is heavily moving like helicopters and r.p.v.'s. Fortunately, optical gyro's have become available, allowing for short term subpixel accurate electronic stabilization.

4.4. Detectors

These components have received a tremendous development during the last decades; large 2 D arrays of various kinds of materials have become available. This makes either a full staring sensor with high frame rate possible, or in the case of scanning time delay and integration (TDI). Roughly this provides a gain in sensitivity proportional to the root of the number of elements.

Available today are 2 D arrays, manufactured from PtSi, InSb and HgCdTe for the 3-5 μm band and HgCdTe, GaAs:AlGaAs and Si:Ge Multi Quantum Well arrays for the 8-14 μm band. Each of the materials has its advantages and drawbacks: quantum efficiency, stare time, fill factor and operating temperature. For IRST applications the fill factor is the most important aspect: For point target detection, microscanning seems to be inevitable for appropriate functioning. Up to 4 × 4 microscan has been realized, providing a well restored signal.
Possibilities have been demonstrated on the development of non square large arrays of detectors (2000 × 200 elements) providing better adaptation to IRST sensors with large horizontal and small vertical field of view in one optics and high read out frame rate. In the case of a 0.5 mrad pixel size the sensor field of view becomes 60° × 6°, involving 6 sensors for full around staring.
In addition to the IR detectors, visual and near IR detectors can support the detection process in daytime conditions. Sensitivities of peltier-cooled silicon detectors have been increased in such a way that they approach the photon limit. Stare time is increased in this approach, which is a disadvantage if we want to have high frame rates.
The TDI concept with staggered arrays provides at this moment the highest sensitivity for the 8-12 μm band. Arrays of about 500 × 10 and more have been reported with reduced element sizes. One limit of importance is the charge storage capacity of each element or row of elements. The higher the storage capacity, the longer stare time can be allowed or higher speed optics. Advanced systems use both 3-5 and 8-12 μm arrays, mounted parallel and scanning synchronously. Because both are photodiode arrays, the heat load for the cooler is limited.

4.5. Sensor fusion

As in nature the combination of seeing, hearing, smelling and tasting provides a near perfect method to survive, such combinations are not easy to realize in the technical world. But combinations of seeing in terms of multispectral sensing, thermal sensing, laser sensing, passive mm wave sensing, radar sensing are more and more receiving interest. The multispectral methodology has led to imaging spectrometers with hyperspectral sensing (up to hundreds of channels between 0.2 and 1.0 μm). The enormous stream of data seems to be analyzed as close to the focal plane as possible, for which microcircuitry is becoming more and more available. Lasers allow for 3 D sensing, not only for determining range, but also for target identification. Similarly narrow field of view radiometers are capable to provide information on target identity (e.g. rotor-blade frequency of helicopters).
In the land environment acoustic detection systems allow for non line-of-sight detection of sound producing targets (vehicles, air targets). Radar sensors provide an attractive alternative. Their advantage of penetration through fog and the provision of range information are opposed by the disadvantage of lesser angular accuracy (as with the acoustic sensors).
Interesting is the complementarity of radar ducting (depending upon temperature and humidity gradients) to optical refraction in the atmosphere.

4.6. Electronics

The downsizing and speeding up in computer world has led to tremendous increase in data processing capability. Memories, storing hundreds of millions of bytes from sample points, are realized. Parts of the memory can be read out and presented in standard TV format. Dynamic ranges have been increased to more than 12 bits, which prevents saturation at high and low signal levels. This is of great importance in procedures that compare the signals in multispectral bands.
Miniaturization of preamplifiers and preprocessors reduce a number of interference problems in a harsh environment (e.g. on board of ships). Data transfer through fiber optical cables helps in a similar way. Future optical storage and processing techniques will serve further IRST developments.

4.7. Processing algorithms

In interaction with the increased knowledge on signatures and atmospheric effects, processing algorithms receive much attention, as shown at various SPIE conferences (e.g. Signal and data Processing for Small Targets). Special attention receive the spatial filters, developed for moving platforms with sensors to detect moving targets on the ground[18].
The higher the frame rate, the more power can be developed to discriminate moving targets against a dynamic background. Stereoscopic effects can be utilized as well as the method called "observational diversity", a single camera observing from various locations. The higher frame rate allows for a more detailed signal growth analysis.
Bird clutter discrimination can be carried out in various ways, but also in this case the high frame rate serves similarly.
In most systems a database with alarms is built up and comparison between consecutive frames is carried out. A certain number of detections is required to call an alarm a real detection (e.g. 3 out of 4).

Because of the increased accuracy on platform angles corrections can be made, providing better track accuracy. For larger size targets shape determination and changes in shape serve as predictors with higher accuracy for the target trajectory. More recently, superresolution algorithms have been developed[19] to overcome the limits, set by the center to center distance of the elements of focal plane arrays, by using microscanning techniques.

5. SYSTEM ASPECTS; NEW PERSPECTIVES

In a broader sense the user is more interested in the survival of his platform(s) and the people operating it than just an IRST. IRST is only one of the components that have to be integrated into the complete package of C^3I (Command, Control, Communication, Information) system on board. The key issue is situational awareness and the interaction with fire control, countermeasure system, mobility and sustainability.

In situational awareness of a platform or group of platforms knowledge is considered about the presence of a potential enemy, the possibility for the enemy to detect my platform, knowledge about the direction and at what range he is located, what kind of weapons he has, if he is firing at me and if the weapon is on its way. The turn on of countermeasures or weapons is a matter of fire control and the knowledge if my counteraction was successful is again a matter of situational awareness: kill assessment.

Because of the complexity in various threats, target identification and so false alarm identification needs to be done to a high degree of accuracy. In this way appropriate communication with the other platforms is of great importance.

Another general item of importance is of course the mission that the platform is undertaking. Examples of such missions are: transfer from one area to another area over a relatively long distance, with or without air protection and so on, protection and or guarding of an area, such as is occurring in peace keeping operations, defence or attack of an area.

In each of these missions IRST plays a different role and different types of threat may be expected. They can be considered as a special case of warning receivers like laser warning and radar warning sensors, flash detectors and Battlefield IFF (BIFF) sensors.

If properly designed, IRST sensors could serve all these tasks including a general navigation or driving aid and for rescue operations. For maritime operations, a high frame rate sensor could serve the fire control system directly as well as the detection/identification of surface targets from 100 m to 10.000 m. On airfields IRST could provide high-angular resolution detection of aircraft, not only as part of an air defence system but as part of a landing aid in cases of radar silence. If cost permits, each vehicle could be provided with an IRST for nearby situational awareness. Here the advantage has to be mentioned of having wide angle automatic detection in favour of the narrow FOV FLIR's, operated by human observers. Their searching speed is highly limited. This short range IRST could exist of a number of uncooled, cheap focal plane arrays staring around. For example 12 sensors, each of them with an FOV of $15° \times 30°$ using a 128×256 detector array (e.g. that of GEC) provides 2 mrad resolution, enough for target detection (vehicle) at 1000 m and people at 300 m, at the same time adequate for driving in the dark.

On the civil market, wide area survey systems seem to have a great future. Here we think of survey of harbours, air fields and objects of value with buildings, stores etc., where intruders may penetrate day and/or night. Combination of IR sensors with visual and/or low light TV sensors, eventually supported by additional light sources (near IR). The advantage of this type of survey over TV search is evident, because of the higher resolution and the lack of need for scanning. Automatic processing removes the need for human operators. Survey of forest areas from high towers is becoming more and more popular, in view of the increased number of fire disasters, occurring over the world. Multispectral survey, including near IR (InGaAs) arrays, just becoming more widely available, provides a promising solution. At TNO-FEL experience has been obtained in the detection of smokes from "early stage" forest fires.[20]

6. DISCUSSION, CONCLUSIONS, RECOMMENDATIONS

In this introductory paper a brief review has been given of present day IRST sensors and summary of the technical problems that they are facing. There are two reasons providing hope for future IRST: one is a vast amount of technological advancements, to be applied in 2nd generation IRST, the second is the increased market leading to reduced cost due to integration of IRST into the platform concepts and civil applications. This promising perspective is in more detail based upon a number of technical recommendations:

- increase of the frame rate, which will result in strongly improved processing algorithms.
- introduction of multiple staring FPA's with microscan and superresolution; processing preferably in sectors.
- use of multispectral sensors on a pixel by pixel basis (preferably through the same pupil, multispectral optics); provision for target identification.
- integration of IRST as part of the C^3I system on board of a variety of platforms; the use is dependent on missions.
- use of multiple, spatially separated "eyes" providing stereo view or making use of sensor displacement for ranging.

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9–13 July 1995
San Diego, California

Sponsored and Published by
SPIE—The International Society for Optical Engineering

Volume 2552
Part One of Two Parts

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