# On the possibility of surveying krill *(Euphausia dana)* in the Southern Ocean by remote sensing

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*Euphausiid swarms are bioluminescent: low-light-level television imagery has been collected and bioluminescence radiance from swarms in the South-East Atlantic has been measured. The factors affecting a remote-sensing experiment on krill (seasonal and latitudinal daylength, ice cover, swarm distribution in space and time, patchiness, vertical distribution, density, colour and bioluminescence) indicate that both day and night techniques of remote sensing could be successful. It is suggested that the aerial/acoustic method of stock size estimation developed for pilchards may be partially applicable to* Euphausia superba, *and it is recommended that a pilot remote-sensing project on krill swarms be started in the South Georgia area or Bransfield Strait during middle to late austral summer to determine their bioluminescence emission parameters at night, spectroradiometric parameters by day, and swarm size frequency by day and night. Successful completion of the pilot project could provide specifications for sensor systems to be used in a future, multidisciplinary, remote-sensing acoustic research survey programme.*

*Die bioluminessensie van Euphausia-swerms is bekend. Laeligvlaktelevisiebeelde is verkry en die bioluminessensie van swerms in die Suidoostelike Atlantiese Oseaan is gemeet. Die faktore wat 'n eksperiment in verband met die afstandswaarneming van kril beïnvloed (breedtegraads- en seisoensverskille in daglengte, ysbedekking, distribusie van swerms in ruimte en tyd, vertikale distribusie, digtheid, kleur en bioluminessensie) dui daarop dat afstandswaarneming bedags en snags moontlik behoort te wees. Daar word voorgestel dat die akoestiese/lugopnametegniek van stapelgroottebepaling wat vir die sardyn ontwikkel is gedeeltelik van toepassing kan wees op* Euphausia superba. *Daar word aanbeveel dat 'n loodsprojek vir die afstandswaarneming van kril-swerms gedurende middel tot laat suidelike somer aangepak word in die gebied by Suid-Georgië of die Bransfieldstraat om die bioluminessensieparameters snags en spektroradiometriese parameters bedags, asook swermgroottefrekwensie snags en bedags vas te stel. Die suksesvolle voltooiing van die loodsprojek kan die spesifikasies oplewer vir sensorsisteme vir 'n toekomstige multidissiplinêre akoestiese afstandswaarnemingopnameprogram.*

## Introduction

Since 1970, the Sea Fisheries Branch of the Department of Industries has had an active programme for aircraft-borne remote sensing as part of an investigation into the South-East Atlantic pilchard population (*Sardinops ocellata* Pappé). The airborne radiation thermometers were used to measure sea surface temperature and the night-viewing devices were used as tools in the development of a method for estimating abundance of pilchards. This method involved semi-quantitative measurements of individual pilchard shoal sizes from a low-altitude, night-flying aircraft. The method was not entirely satisfactory, principally owing to an inability to acquire imagery of the shoals for more precise measurement. Consequently, a low-light-level television system ($L^3TV$) was purchased to obtain video images of shoals for manual or computer-assisted shoal measurement for the area (Cram, 1972, 1974). Reasonably satisfactory video images are obtained from the present system, although the Branch, in cooperation with the National Physical Research Laboratory of the CSIR, is involved in the development of a more sophisticated system specifically designed for the collection and processing of shoal images.

A euphausiid swarm has been observed from the research aircraft at night and identified by a research purse-seiner as *Nyctiphanes capensis* (Cram & Schülein, 1974), but the $L^3TV$ was not available for image collection. Later, when the $L^3TV$ was in use, video images of luminescent areas were obtained and identified as euphausiids on the basis of previous experience. In a parallel programme of $L^3TV$ research in the United States, euphausiid swarms identified by a research vessel have been detected and successfully recorded on videotape (Roithmayr & Wittmann, 1972).

Of the eleven genera of Euphausiacea all, except one, possess photophores and are luminescent. *Euphausia superba* is self-luminescent and it is therefore proposed that the night-time aerial acoustic method of abundance estimation developed for pilchards (Cram & Hampton, 1976) may be applicable to the krill population occurring in ice-free areas where it is sufficiently dark.

Alternatively, if the luminescence of shoals is inadequate, the numerous daylight photographic and spectroradiometric techniques reviewed by Benigno (1970) may be suitable. The laboratories in the United States which accomplished the above-mentioned night and day-time remote sensing work have evaluated the suitability of lasers to detect fish shoals. A mathematical simulation model and tank-testing showed that a laser system suitable for fish detection could be specified (Murphree *et al.* 1974). Such a system would be applicable to krill.

This paper is derived from a document first submitted to the SCAR group of experts on the living resources of the Southern Ocean at Cambridge in October 1975, and later, at a meeting of the same group at Woods Hole, it was used as the basis for the planning of a feasibility study on krill remote sensing. The feasibility study is described in the first volume (Research Proposals) of the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) prepared for SCAR and SCOR in August 1977.

## Behaviour and properties of krill

### Abundance

Current estimates of stock size and yield vary considerably. Some estimates are listed in Table 1. Nevertheless, a fairly reliable consensus value of potential yield of $100 \times 10^6$ tons (FAO, 1975) can be accepted. This quantity represents a considerable resource of protein with an important economic potential. The present catch does not exceed a few thousand

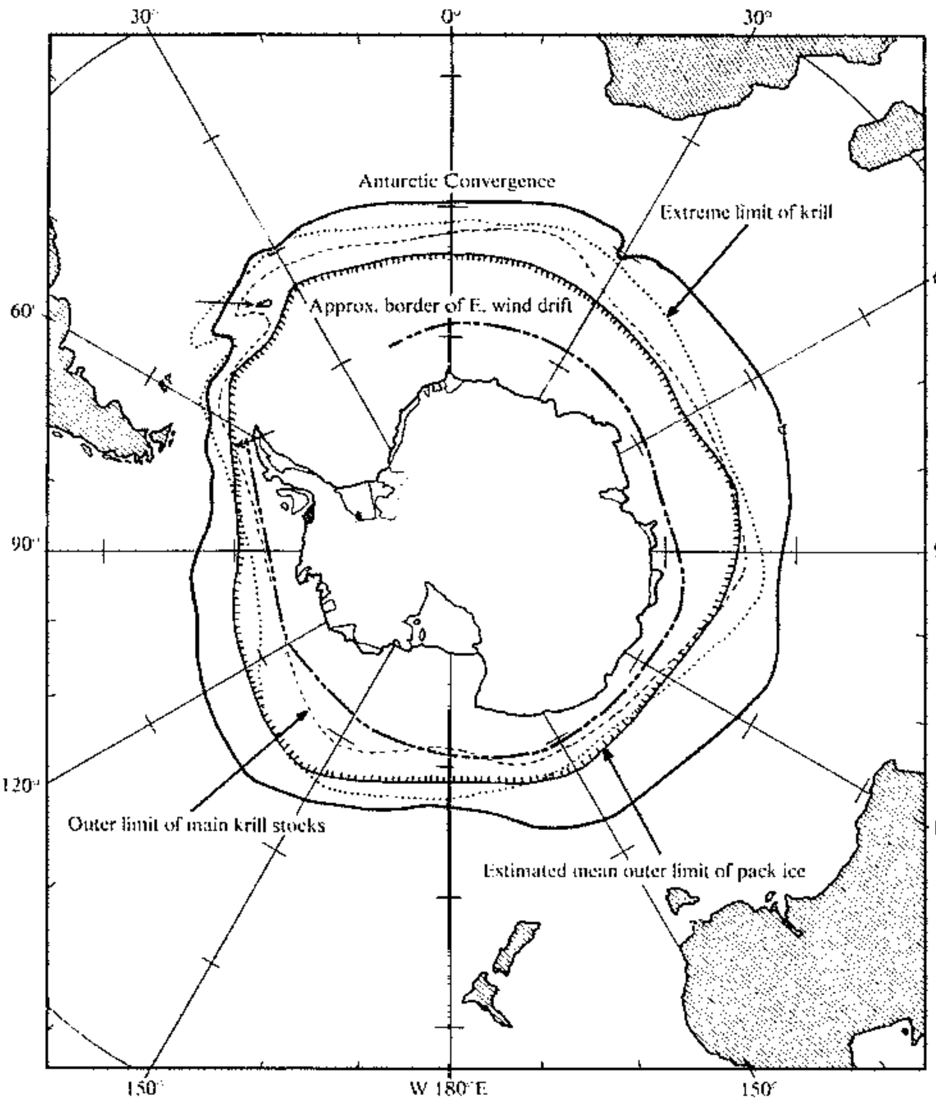


Fig. 1. Geographical distribution of krill population. From Marr (1962) and Mackintosh (1972).

tons — less than 0,01 per cent on the potential yield — and the population can be regarded as undisturbed by human intervention.

**Distribution in space and time**

Mackintosh (1972) reports that the krill zone covers an area of 20 × 10⁶ km² in total circumpolar distribution. The "krill zone" is seasonally covered with ice: the maximum cover in late winter is 60 per cent of the krill zone and the minimum, in late summer, is 11 per cent. The approximate percentage of the krill zone covered by oceanographic features are: West Wind Drift 56 per cent, Weddell Drift 16 per cent, and East Wind Drift 22 per cent (Fig. 1). According to Marr (1962) krill are not found in great abundance except in the East Wind Drift

**Table 1**

Some estimates of stock size and yield of krill.

| Source of data | Estimate type | Numerical value (× 10⁶ tons) | Reference |
|---|---|---|---|
| Krill "surplus" due to reduced whale population | Yield | 33–330 | Mackintosh (1970) |
| Krill "surplus" (as above) provisional only | Yield | 100 | Moiseev (1970b) |
| Primary production | Stock size | 500 | Gulland (1970) |
| Zooplankton standing crop | Stock size | 75 | Gulland (1970) |
| Krill "surplus" | Stock size | 50 | Gulland (1970) |
| Krill "surplus" | Yield | 153 | Macintosh (1973) |
| ? | Stock size | 800–5000 | Lyubimova *et al.* (1973)* |
| ? | Yield | 100 | Lagunov *et al.* (1973)* |
| ? | Yield | 100–200 | Omura (1973)* |

*From FAO Fisheries Report No. 153, 1975.

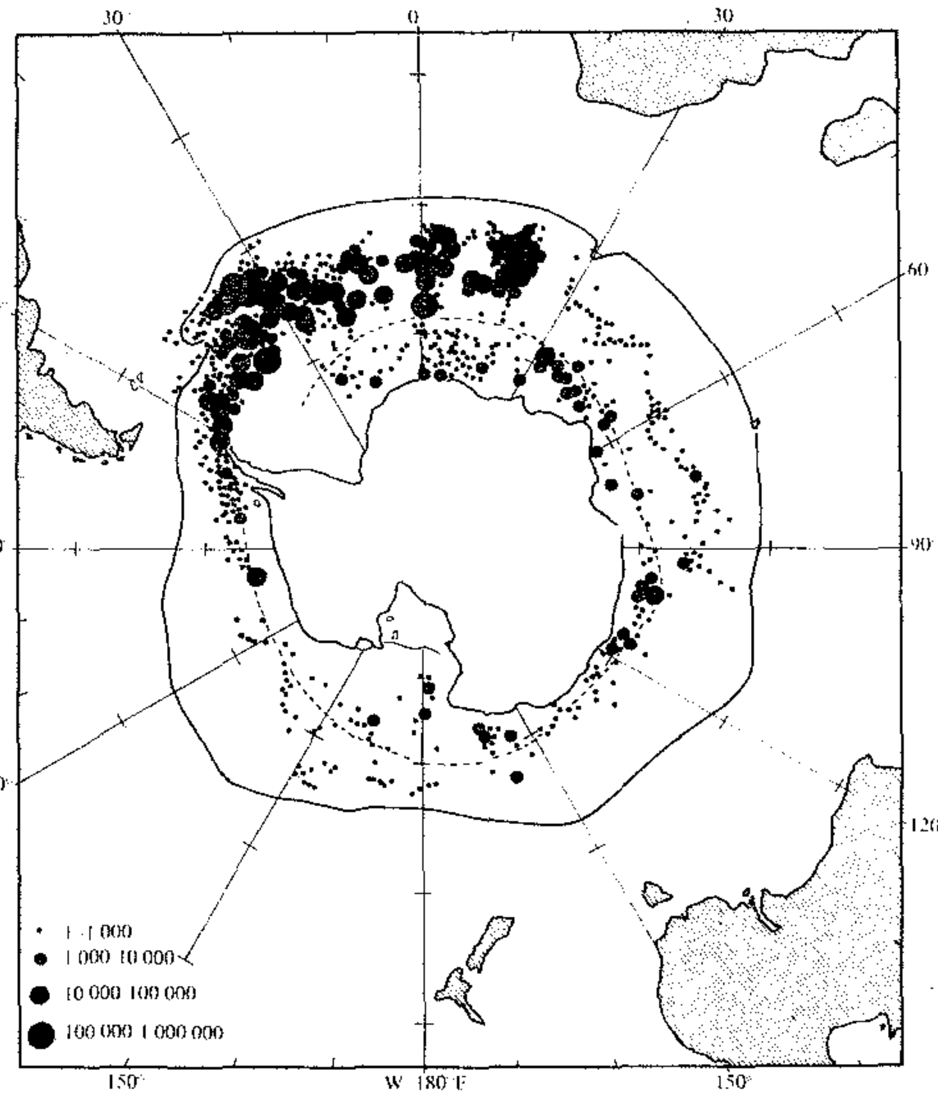


Fig. 2. Distribution of total krill population biomass in numbers per net haul. From Marr (1962).

and the Weddell Drift and the main concentrations are found in the Bransfield Strait and near South Georgia (Fig. 2).

There is a marked seasonal variation in the composition of the near-surface population: in spring larval, adolescent and adult krill are spread throughout the feeding grounds; in summer larvae predominate in the Weddell Sea; in autumn larvae outnumber the older stages, whereas in winter larvae and early adolescents are abundant. However, few krill swarms are seen before December, after which they become extremely abundant in the Bransfield Strait and near South Georgia. Krill swarms, in all stages of development, are conspicuous all year on the north-east side of South Georgia. The peak swarming seems to occur between March and May in the western part of the Weddell Drift. Swarms may also be abundant in the East Wind Drift (Marr, 1962). Moiseev (1970a) observed that krill swarms occur every year in the Scotia Sea (observations since 1962), but their behaviour, location and population composition vary apparently in response to hydrometeorological conditions.

**Patchiness**

There are a number of observations on the size of patches indicating that they are generally small but may infrequently be very large. An area of the Weddell Sea was observed to be covered with swarms of variable shape separated by gaps of 450–600 m. The largest was 150 × 20 m² but the usual size was 60 × 40 m². On another occasion a colour patch suspected to be krill extended as far as the eye could see (Hardy & Gunther 1935). Ozawa *et al.* (1968) measured shoals on two occasions, the mean sizes being 23 ± 10 × 16 ± 5 and 24 ± 13 × 17 ± 8 m. The swarms were egg-shaped or belt-shaped (Fig. 3), similar to those drawn by Gunther and reproduced by Marr.

**Vertical distribution and density**

Acoustic and trawling work led to the conclusion that the krill concentrations were located in the photic layer usually at depths less than 40 m, and seldom deeper than 70–90 m. The greatest densities occurred in subsurface waters in daylight (Makarov *et al.*, 1970). Swarms occurred at or very near the surface or 1–4 m below the surface (Marr, 1962). The patches were of uniform thickness, being 1–2 m thick. Marr's data are supported by Moiseev (1970a), who stated that the swarms are usually in the upper layer (less than 5 m) and rarely at depths over 40 m. The use of hull-mounted acoustic transducers for krill detection is rendered difficult as the swarms are usually above the transducer. Sasaki *et al.* (1968), using a 28 kHz echo-sounder, observed krill swarms as sound-scattering layers and detected vertical migration. From sunset onwards the krill swarms moved towards the surface and as it became dark, they gathered near the surface. In general, during daylight, the scattering layer was thick, extending from the surface to 30–60 m. Makarov *et al.* (1970) observed that krill patches at the surface retain their structural integrity in winds of up to force 7. Ozawa *et al.* (1968) found a diurnal variation in the occurrence of patches in that no patches were located from two hours before or until two hours after local noon. No observations were made at night.

The density of shoals has been reported as 10–16 kg/m$^3$ (Ozawa *et al.*, 1968; Moiseev, 1970a), whereas Marr (1962) calculated densities of approximately 5,2 kg/m$^3$ but believed this to be an underestimate due to avoidance of the net by the krill, the real figure being closer to 62 kg/m$^3$.

### Colour

Marr (1962) noted that swarms on the surface were a brilliant (blood) red; those at 2–3 m were a rusty red or mahogany brown, whilst those even deeper faded, becoming cloudy and indistinct. Sometimes surface shoals were ochre or yellow, possibly owing to variation in pigmentation. The circumpolar distribution of surface discoloration supposedly attributable to krill closely follows the gross distribution of the total *Euphausia superba* population as determined by net collections. Sasaki *et al.* (1968) found that the occurrence of such discoloured water was most likely between 02h00 and 06h00 and between 18h00 and 20h00.

### Euphausiid luminescence

The emission of light from krill is sufficient to make individuals clearly visible from a ship's deck (Marr, 1962). Brightly illuminated krill swarms have been reported near the South Orkney Islands and along the Antarctic Convergence (Staples, 1966). In contrast with many other luminescent organisms which emit light as a flash, the euphausiids emit a steady light (Boden & Kampa, 1957).

Although no quantitative measurements on krill bioluminescence are available, it can be assumed that emission intensity and spectral energy distribution would be comparable to other euphausiids. A single *Euphausia pacifica* caused an irradiance of $160 - 200 \times 10^{-9}$ $\mu$W cm$^2$ at 1 m, having a spectral energy distribution peaking at 476 nm and with a slight inflexion at about 520 nm. Figure 4 shows a comparison of the spectral energy distribution of *Euphausia pacifica* with the mean of four homogenates of another euphausiid, *Thysanoessa raschii* (Boden, 1959). *Meganyctiphanes norvegica* caused an irradiance of $1,2 \times 10^{-9}$ $\mu$W cm$^2$ at 1 m (recalculated from Clarke *et al.*, 1962) and a diurnal rhythm of luminescence emission intensity (Mauchline, 1960).

In the Scotia Sea and near South Georgia, Ivanov (1969) has observed luminescent krill patches possessing very clear boundaries, which retained their visibility up to wind force 3–4. The patches were both self-luminescent and outlined by mechanical stimulation of more numerous microplankton.

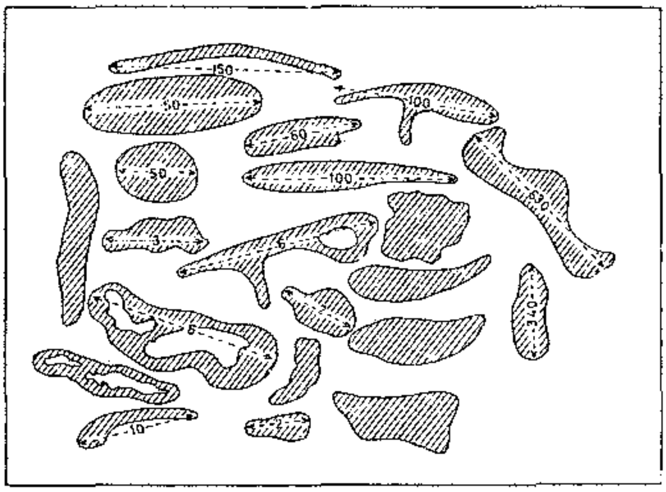

Fig. 3. Krill swarm shapes and sizes. Dimensions in metres (not to scale). Drawn by Gunther. From Marr (1962).

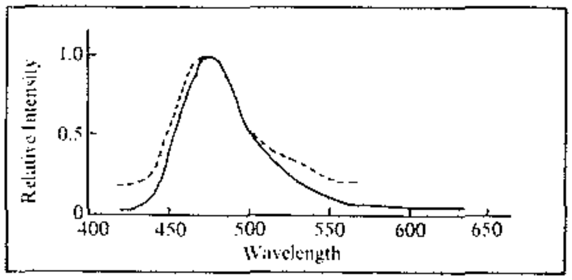


Fig. 4. Spectral distribution of luminescence of *T. raschii* (solid line) and *E. pacifica* (dashed line). From Boden (1954).

### Avoidance of vessels

If a remote-sensing/acoustic technique is to be employed in a study of krill, the effect of krill avoidance of research vessels, acoustic devices or nets must be considered. Marr (1962) reported that krill swarms avoided vessels and kept 1–2 m away from the ship's side. When a lead-line was thrown across a swarm, an "instantaneous" reaction of avoidance of the line was provoked. Sasaki *et al.* (1968) refer to extreme avoidance habits. Other sources mention that avoidance of nets presents no problem.

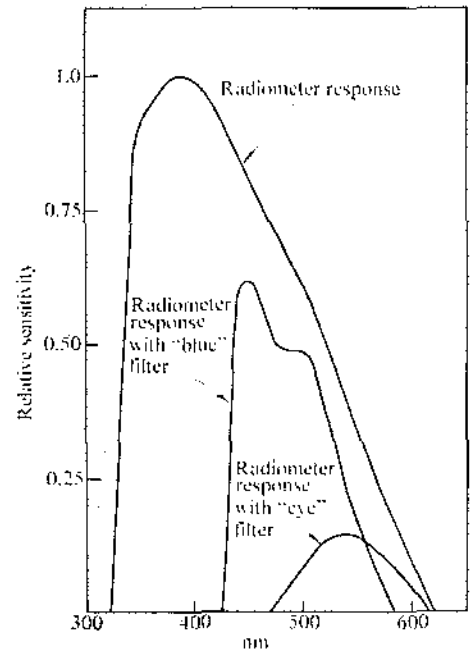


Fig. 5. Approximate spectral sensitivity of radiometer with alternative filters.

## Feasibility of detection by remote sensing

Since krill are widely distributed in the Southern Ocean, there will be a high probability of locating a sizeable population for a pilot study by means of either a suitably equipped helicopter operating from Antarctic supply ships or from fixed-winged aircraft operating from South African, South American, Antarctic or sub-Antarctic bases.

The large average size of krill patches places no severe restrictions on the spatial resolution of airborne (or even spaceborne) sensor systems, with the result that the other parameters of such systems could be conveniently optimized. Furthermore, krill usually gather near the surface, particularly at night, and should thus be detectable by remote sensing.

The property of krill most amenable to remote sensing seems to be their luminescence. For the luminescence of the swarm to be visible at the sea surface, the intensity will have to be sufficient to give a signal-to-background ratio of at least 2.

*In situ* radiometric measurements were obtained of a euphausiid swarm made from an altitude of 500 m off South-West Africa on 16 April 1975. For the purposes of the experiment, different filters were used in front of the objective lens of the radiometer in order to alter its spectral response. These were, respectively, an "eye" filter providing the response of the photopic eye, and a "blue" filter providing the response given in Fig. 5. The background irradiance caused by the sea surface at the radiometer without filter was between $0,9 \times 10^{-8}$ and $1,2 \times 10^{-8}$ Wm$^{-2}$ ster$^{-1}$ nm$^{-1}$.

As indicated in Fig. 6 the luminescent intensities associated with fish shoals and euphausiids are comparable. Where luminescent areas associated with fish or euphausiids were present, the irradiance measured at the radiometer using the "blue" filter was up to $4,7 \times 10^{-8}$ Wm$^{-2}$ ster$^{-1}$ nm$^{-1}$, implying a maximum signal-to-background ratio of about 4,5. By using the "eye" filter, a signal-to-background ratio of maximum 2 could be obtained, indicating rejection of the background radiation by the "blue" filter in those spectral regions where no luminescence occurs.

Video recordings of a euphausiid swarm were also obtained during the same flights by means of the Sea Fisheries Branch Low Light Level Television System which is sensitive to about $10^{-8}$ Wm$^{-2}$ (Fig. 7).

These results, compared with calculations by El Sayed (1968), indicate that with similar equipment krill swarms in the Weddell Sea and Bransfield Strait should be visible to a depth of about 5,5–17 m from a flying altitude of 250 m, which is the arbitrary lower altitude safety limit for this type of operation.

## Proposed pilot project

In view of the success of abundance estimates of pilchards by a night-time aerial acoustic method, and with our knowledge of the behaviour and properties of krill, it is suggested that a pilot project be undertaken to determine the feasibility of using a similar method for krill. Simultaneously the possibility of using a passive remote sensing method during daytime or a laser detection system should be investigated.

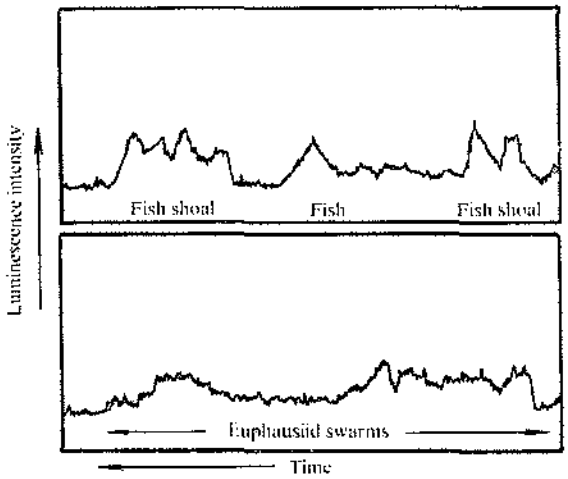


Fig. 6. Radiometer recorder output. Top, fish shoals. Bottom, euphausiid swarm. (Recorded with same filter and sensitivity setting.)

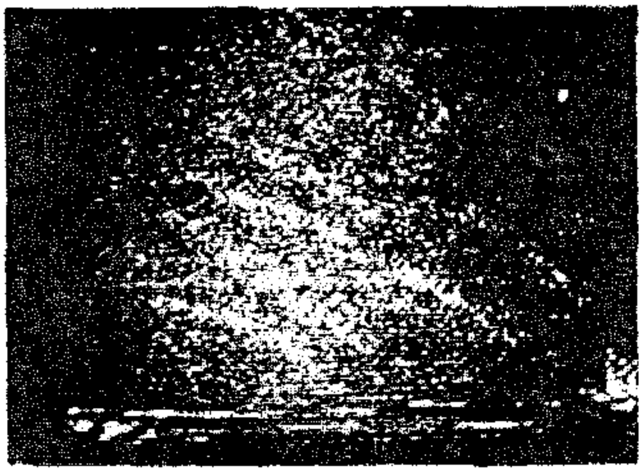

Fig. 7. Photograph of video monitor display of euphausiid swarm obtained by L$^3$TV.

### Objectives

The objective of the pilot study should be to determine resolution and radiance parameters for the specification of sensor systems to study krill from satellite or aircraft platforms (whichever is most practical). The objective can be achieved through three avenues of research: (i) To determine the bioluminescence emission parameters of swarms; (ii) to determine the spectral reflectance characteristics of swarms in daylight; and (iii) to determine size frequency of krill swarms during night and day.

### Experimental approach

The pilot study should concentrate on either the Bransfield Strait or the South Georgia area in middle to late summer. Krill patches are probably detectable with all sensors which have proved to be suitable for the detection of fish shoals from low-altitude aircraft. The characteristic red-brown colour of patches is favourable for sensing in reflected sunlight but the diurnal vertical migration may remove the swarms from the visible zone around local noon. Bioluminescence may prove to be spectrally characteristic of euphausiid species.

The Sea Fisheries Branch with the assistance of the National Physical Research Laboratory developed the sensors required for the bioluminescence work (L$^3$TV, radiometer and spectrophotometer) to an operational state, and has access to long-range aircraft. No experiments have yet been undertaken in daylight remote sensing techniques.

There are at least three approaches to the execution of the experiment:

(i) To equip a long-range aircraft with all sensors and fly to the survey area from a suitable airport. Unless a synchronous survey is planned, no ground truth would be possible. Weather satellites would be able to provide advance notification of clear sky in the survey area.

(ii) To equip a suitable helicopter with all sensors and fly from a suitable research vessel in the survey area. A ship servicing Antarctic or sub-Antarctic bases would be convenient. The advantages of this mode would be the opportunity for collecting ground-truth data and the possibility of repetitive surveying.

(iii) To equip a suitable aircraft with all sensors and fly from an airstrip at an existing Antarctic or sub-Antarctic base. The southern tip of South America is an alternative site. Conditions of item (i) apply. Existing transport aircraft may be suitable.

Satisfactory completion of the pilot study would provide basic data upon which a large scale remote sensing programme of research into krill abundance could be based.

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# Some observations on the former sea levels of Marion Island

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*Investigation of raised beaches together with mathematical extrapolation from a river long profile suggest two definite former sea levels with the possibility of a third. True raised beaches were found at* c. *+3 m and* c. *+6 m with extrapolated levels of +5,9 m and +10,8 m. Stone roundness and flatness indices were used as additional aids to differentiation of various levels. Comparison is made with former sea levels found on other sub-Antarctic islands.*

*'n Ondersoek van strandterrasse met behulp van wiskundige ekstrapolering van 'n rivierlangse profiel af dui op twee besliste vroeëre seevlakke, met die moontlikheid van 'n derde. Egte strandterrasse is by* c. *+3 m en* c. *+6 m gevind met geëkstrapoleerde vlakke van +5,9 m en +10,8 m. Klippe se rondheids- en platheidsindekse is as verdere hulpmiddels by die onderskeiding van die verskillende vlakke aangewend. 'n Vergelyking word getrek met vroeëre seevlakke wat op ander sub-Antarktiese eilande gevind is.*

## Introduction

As part of the study of the Quaternary history of Marion Island (46°54'S, 38°45'E) an investigation of former sea levels was undertaken. Observations by Verwoerd (1971) had shown no evidence for former levels and he suggested that this may be due to the "differential tectonic settling of the volcano . . . so that they were drowned". The volcanic nature of Marion is such that many of the recent black lava flows, which line the coast, could be morphologically mistaken for a former marine level owing to their bench-like form. However, despite the problems of possible tectonic disturbance and the extensive lava flows a number of distinct raised beaches could be recognised at several locations around the island.

Two main methods were used to determine the former marine levels, namely direct observation (and subsequent survey) and mathematical extrapolation from the long profile of a river. As an aid to direct observation use was made of stone roundness and flatness indices to help differentiate the