A Two-Dimensional Histogram Procedure to Analyze Cloud Cover from NOAA Satellite High-Resolution Imagery

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ABSTRACT

A two-dimensional histogram method for cloud analysis from NOAA satellite high-resolution imagery is presented. The algorithm, using one visible or near-infrared channel and one infrared channel of the Advanced Very High Resolution Radiometer (AVHRR), applies to arrays segmented according to the temperature sounder (TOVS) grid; up to five cloud levels are identified in addition to the surface. A comparison with visual nephanelysis has been carried out for various cloud situations: the use of near-infrared radiance appears to give consistently better results than the visible radiance, leading to an agreement in about 87% of the cases for total cloud cover. Possible further improvements are discussed.

1. Introduction

The multichannel TOVS (Tiros Operational Vertical Sounder) radiometer on board the recent NOAA satellite series, such as NOAA-7, offers considerable perspective for initialization and validation of numerical forecasting models. Indeed, the TOVS ground resolution (30–40 km on the average) seems quite adequate to be used in short term, high space resolution models, such as the one currently under development in France (the “PERIDOT” project: Prévision à Echéance Rapprochée Intégrant des Données Observées et Télédéetectées).

One of the major problems encountered in retrieving temperature profiles from satellite sounders concerns the identification of cloud free zones, as well as the way to process data obtained in cloudy areas. Thus, it is important to obtain as much information as possible on cloud presence, extent and nature in the TOVS pixels.

In this context, it seems logical to investigate the potential of high-resolution imagery supplied by the AVHRR (Advanced Very High Resolution Radiometer) instrument, also on board NOAA-7. Since this imagery for the western Atlantic and European zones is received by the Lannion (Brittany, France) satellite acquisition station, cloud information retrieved from AVHRR might be readily integrated into the TOVS processing in the future.

In this paper, we first recall the main characteristics of AVHRR data and comment on some images (Section 2); although single-channel imagery does supply information about clouds, the necessity for using complementary information from at least two channels becomes clearly apparent.

To this effect, a two-dimensional (2-D) algorithm has been developed. On the AVHRR several couples of channels may potentially be used. The processing scheme is the same for all of them; a general description of this procedure is given in Section 3. While 2-D methods for cloud analysis are being applied to geostationary satellite data, this does not seem to be the case of polar satellite imagery so far. Thanks to very good space resolution, the AVHRR imagery allows the procedure to be carried out on smaller areas, which then stand a better chance of exhibiting homogeneous cloud cover and structure. Note that the study has been restricted to the case of the sea (excluding sunglint areas). Indeed, due to high reflectivity of ground surfaces, the recognition of clouds over continental areas requires further investigation which is beyond the scope of the present work.

We report in Section 4 the results of a comparison between the automated procedure and a visual nephanelysis. The comparison allows us to validate the method and, in addition, to select the most efficient among two channels combinations.

Finally the results are summarized (Section 5), and possible further improvements are discussed.

2. Potential use of AVHRR data for cloud discrimination

a. Main features of AVHRR data

These features are summarized on Table 1 together with the objectives assigned to each channel. The AVHRR instrument provides imagery with very good space resolution (1 km on foot track) and radiance resolution (10 bits digital range, low radiometric noise). Small size objects such as islands or fair weather cumulus clouds can thus largely be identified.
The table lists wavelength and main objectives of the five channels of the AVHRR instrument on board NOAA-7. Additional information about the radiometer may be found in Schwalb (1978). The satellite follows a polar sun-synchronous orbit with a daytime pass at about 1500 local solar time.

Data used in this study have been collected at the Centre de Météorologie Spatiale (CMS) in Lannion (France); the CMS data acquisition zone is shown in Fig. 1.

**b. Clouds as seen on AVHRR images**

Since the channel 5 spectral response is very similar to the one of channel 4, channel 5 images will not be presented here. An example of radiance maps for channels 1–4 is shown in Fig. 2. The Mauritanian Coast and Portugal appear in the lower right hand corner. Delineation of the shore is clearer on the near-Infrared channel 2 (NIR) than on the visible band in channel 1 (VIS). In the upper part of the image one recognizes (channel 4, IR) the snow cover of Greenland.

Many clouds are easily identified on the infrared image because their temperature is lower when compared to the sea in the background; such is the case of light cirrus clouds which are almost invisible in channels 1 and 2. Conversely, some low clouds with temperatures close to the sea surface temperature (SST) are best identified in those channels; this is illustrated by the stratiform cloud band along the African coast. Similarly, the cold area south of Greenland is actually a sea zone, as evidenced by channel 1 or 2 images. Thus it appears that channels 1 (or 2) and 4 offer complementary information in order to detect and classify most of the clouds.

Difficulties are likely to occur for certain kinds of cloud, such as very small cloud cells (e.g., cumulus) which are not resolved by the radiometer, or tenuous, stratiform layers (e.g., mist, edges of stratus clouds). In such cases, the infrared radiation from the ground combines with the radiation from cloud top to produce a grey level indistinguishable from the surface (Brigham, 1981). Furthermore, the reflectance is low and does not allow one to discriminate the cloud against the sea. Some of these clouds, however, might possibly be detected through their 3.7 \( \mu \text{m} \) signature. For example, in the lower part of the channel 3 image, most clouds may be discerned, including objects undetected by any other channel (e.g., the small elements south of the Canary Islands). The sunglint area is also clearly apparent. Nevertheless, channel 3 data obviously present a difficult problem for an automated procedure: clouds may appear warmer than the sea or alternatively colder, depending on their size and depth as well as the sun elevation.

**c. Single channel procedures**

In many cases, clouds can be recognized from their reflectance in the visible band only; depending on the value of reflectance with respect to a predetermined level, the scene is classified as cloudy or cloud free. This method assumes a very good relation between brightness and cloudiness and excludes consideration of sunglint. Furthermore, in the presence of aerosols, the sea reflectance may increase and eventually exceed the threshold; the discrimination then becomes unreliable.

The histogram of infrared radiances above a cloud free, clear air, homogeneous sea area is quite narrow since its broadening is only due to principle to instrumental noise. Whenever clouds partially obscure the field of view, the histogram spreads towards cold values, keeping a sharp cut-off on the warm side nevertheless. A SST value can then be retrieved by fitting a standard Gaussian curve to the warm tail of the histogram.
histogram, and the cloudiness can be derived next (Smith et al., 1970; Harris, 1981). This method encounters problems in cases where SST gradients occur in the field of view or in the presence of low clouds with temperature close to the SST.

Two-channel methods have been implemented in order to process data from geostationary satellites GOES (Maul, 1981) and METEOSAT (Simmer et al., 1982; Desbois et al., 1982). These techniques are based on a common principle: a 2-D (VIS–IR) histogram is constructed in which the sea is associated to a warm, dull cluster, and cloud layers to cold, bright clusters. Processing methods may differ somewhat. The algorithm to be described next is an improved version of the one proposed by Pastre and Tournier (1974), a development which has later been implemented for processing METEOSAT images.

### 3. The two-dimensional histogram procedure

The main steps of the procedure currently in use in CMS are summarized by the diagram of Fig. 3. First, AVHRR data are segmented according to the TOVS grid and stored for a given TOVS pixel. Next, orbital information is used to compute geographical coordinates as well as solar elevation. The nature of the surface is found from a geographical atlas, and the reflectance maximum value is estimated in the sunglint area.

**Fig. 2.** Raw radiance fields observed in AVHRR channels 1–4. Low reflectance zones (channels 1–2) and warmer zones (channels 3–4) appear with darker shades. The sunglint area is easily seen as a warm area in the lower left hand corner of the channel 3 image.

**Fig. 3.** Schematic diagram of the two-dimensional procedure.
The next step begins with calibration of each channel; VIS and NIR reflectances are normalized, taking into account the solar elevation. Radiometric data are then compacted to 4 bits for channels 1 and 2 and 8 bits for IR data (on the 220–310 K interval). Thus one digital count now corresponds to 6.25% of the reflectance range (for channels 1 and 2) and 0.3 K on the average (for the IR channel), respectively. VIS and 2-D histograms are then constructed for each array.

**Fig. 4.** Shape of a two-dimensional cloud histogram for three typical cases: (a) stratocumulus layer, (b) cirriform cloud layer and (c) cumuliform clusters in a rear zone. The $X$, $Y$, and $Z$ axes correspond to VIS, IR counts, and frequency, respectively. For better clarity, the histogram for case (a) is also explicitly shown as a table.

### a. Shape of two-dimensional histograms

In most cases, the pixels corresponding to the same kind of surface yield radiances (sea or cloud layer), the variability of which is low at the mesh scale, so that each surface appears on the 2-D histogram as a sharp cluster or peak (Fig. 4a). Because both depend on cloud thickness (Kaveney et al., 1977), the visible reflectance and the infrared radiance of cloudy pixels are correlated. As a consequence, the clusters are
elongated along an axis which is tilted with respect to the axes of the diagram (Fig. 4a). Cloud layers represented by such clusters may be characterized by averaged radiometric parameters.

There are two exceptions: cirrus clouds and cumuliform clouds to the rear of a cold front (rear zone clouds). Due to their transparency, the presence of cirrus clouds results in highly variable reflectance and luminance (Fig. 4b). Similarly, rear zone clouds yield extended clusters (Fig. 4c), because of the variability of their thicknesses and sizes. Such cloud structures cannot be characterized by averaged parameters.

The visible reflectance of the sea, excluding the sunglint zone, seldomly exceeds 6% (Bernstein, 1982). Hence, the corresponding cluster reduces to a 1-D histogram along the infrared axis. A few examples of sea histograms for cloud free, adjacent arrays are shown on Fig. 5.

Fig. 5. Examples of one-dimensional histograms for cloud free, adjacent areas in orbit 5312 (5 July 1980).
b. Fitting standard Gaussian surfaces to the clusters

1) Sea clusters

As noted above, the sea cluster normally reduces to a 1-D infrared histogram. In the procedure described by Simmer et al. (1982), this histogram is fitted by a Gaussian curve, the width of which is a free parameter. This accounts for the spread of sea IR radiances due to both radiometric noise and SST gradients present in a given array. Such a choice, however, is costly in terms of computing time and would possibly require a sampling of the data, which would in turn represent a severe handicap for discriminating small size clouds.

We have, alternatively, chosen to fit the IR sea peaks to a Gaussian curve with fixed standard deviation \( \sigma_x \). The value chosen for \( \sigma_x \) (i.e., 2.5 numerical counts) corresponds to the addition of radiometric noise to a spread typical of average SST gradients empirically observed over a 40 km distance. For further simplicity, the center of the curve is assigned to the IR integer level exhibiting the highest frequency.

2) Cloud clusters

For simplicity, we have again selected a 2-D Gaussian surface with fixed width parameters. The IR standard deviation \( \sigma_x \) is equal to the one \( \sigma_x \) chosen for the sea peak; the VIS (or NIR) standard deviation \( \sigma_y \) equals 5% which corresponds to the accuracy needed for a cloud description (see, e.g., Reynolds and Vonder Haar, 1976). The correlation between the VIS (or NIR) and IR counts has been empirically adjusted to 0.66. Finally, the cloud Gaussian surface equation is

\[
G(x, y) = G_{\text{max}} \exp[-p(x, y)],
\]

\[
p(x, y) = \frac{(x - x_0)^2}{\sigma_x^2} - \frac{(y - y_0)^2}{\sigma_y^2} + \frac{2r(x - x_0)(y - y_0)}{\sigma_x \sigma_y},
\]

with \( \sigma_x = 2.5 \) IR counts, \( \sigma_y = 0.8 \) VIS count and \( r = 0.66 \).

It has been noted that a single cluster may be made of pixels belonging to two different cloud layers. Fitting the cluster to a single standard Gaussian surface does not allow us to distinguish between several surfaces; however, the probability to meet such cases is obviously reduced when using a small array size, as is the case here. On the other hand, due to the fixed nature of the width parameters, it may happen that a single cloud layer will be split into several distinct, adjusted peaks. In order to correct for this effect, merging rules between adjacent peaks will have to be defined.

c. Cluster classification procedure

The classification procedure aims to identify well-defined, significant clusters. Such clusters should therefore include a minimum number \( M_c \) (for the sea) or \( M_c \) (for clouds) of pixels. The thresholds \( M_s \) and \( M_c \) do not have to be the same; they should be chosen in order to allow the most efficient analysis. In the present work, our purpose is limited to a comparison with visual estimation of cloud cover, the accuracy of which is estimated to be 10%. Thus, while the choice of \( M_c \) has no consequence here, an adequate value for \( M_s \) is 63, corresponding to a 5% fraction of the total pixel number (1254) per array. Actually this choice is not critical and we have taken \( M_s (= M_c) = 75 \) for practical reasons.

The cluster classification procedure begins following the construction of the histograms. Its successive steps, summarized in Fig. 3, are described as follows and illustrated by an example (Fig. 6).

1) Sea clusters

As noted above, pixels with a VIS (or NIR) count equal to unity are a priori considered as cloud free. In order to be identified, the cluster should include a number of points larger than \( M_s \). Then, the IR coordinate of the peak is sought in the first column of the 2-D histogram (this is 84 for the selected example on Fig. 6a); this value is the most likely cloud free radiances \( R_1 \) in the array. The cloud free Gaussian curve is then adjusted to the histogram along this column. For each IR count, the number of points accounted for by fitting the curve is written against the actual frequency (Fig. 6a). This number is then removed. In cases where the number of data points remaining in column 1 exceeds \( M_s \), the procedure is repeated, yielding a second radiances \( R_2 \). Whenever the IR count difference \( |R_1 - R_2| \) is low, typically less than 10 (i.e., about 3 K), the spread is assumed to be due to a SST gradient and both clusters are merged. Conversely, when the difference is large, the colder peak is associated to a cloud.

Following this step, every remaining pixel is considered as cloudy (possibly including haze and aerosol cover). The relative number of these pixels gives the total cloudiness. For the selected example, the remaining points in the histogram are displayed in Fig. 6b; the total cloudiness equals 0.3.

2) Cloud clusters

The analysis of cloudy pixels now begins with the highest VIS counts (i.e., from right to left). As soon as the VIS (or NIR) histogram indicates a number larger than \( M_c \), a maximum is sought along the corresponding VIS column. In the example (Fig. 6b), its coordinates are \((4, 92)\) for a frequency equal to 27. Now, the coordinates of the actual peak have to be found. For this purpose, the frequency is compared to the 8 surrounding ones, and the location initially found is accepted as a maximum if no higher frequencies are detected in the neighborhood. Other-
Fig. 6. Successive steps of the two-dimensional histogram processing. The last line yields the total pixel number in each reflectance class: (a) raw histogram, (b) after the sea peak has been removed, (c) after the first cloud cluster on the right side has been removed and, (d) final step. The number of points accounted for by the fitting curve or surface is given in parentheses for each step.

wise, the procedure is repeated until an actual maximum is found. The two-dimensional Gaussian surface given by (1) is then fitted to this part of the histogram. In the example, the number of points accounted for by the fitting is displayed; these points are removed from the histogram, and their number yields a partial cloudiness (here 0.10). The procedure is then continued (Fig. 6c).
Two cloud peaks very close to each other are assumed to represent a single cloud layer and consequently merged together, following rules described below.

3) Merging rules

While fixing the widths of surfaces makes the fitting procedure simpler and faster, cases arise where the actual extent of a cluster is significantly larger than the fixed one; then several separate clusters are identified in turn and should be merged together later according to a specific criterion. Cluster peaks with a VIS count equal to 2 (i.e., reflectance value between 6.25 and 12.5%) deserve particular attention. In cases where the IR temperature is very close to that of the sea, corresponding data ought to be merged to the sea peak. On the other hand, pixels with low reflectances may either correspond to semi-transparent or small sized clouds, or indicate the existence of an aerosol layer which should not be assimilated to a cloud layer according to meteorological use. Such clusters, therefore, are not to be merged with a higher reflectance cloud cluster.

Keeping these remarks in mind, merging rules between neighboring clusters have been empirically derived. Merging thresholds have been tested on several arrays and adjusted in order that the points belonging to the same surface are merged together and that the sum of these points agree with the surface estimated by a nephanalyst. Results are given in Table 2.

In the table empirical rules are specified for deciding to merge neighboring clusters (1 and 2) according to their visible counts $C_{\text{VIS}}$ and absolute differences $\Delta C_{\text{VIS}}$ and $\Delta C_{\text{IR}}$ between visible and infrared counts. Recall that the $C_{\text{VIS}}$ unit is 6.25% reflectance, the $C_{\text{IR}}$ unit is about 0.3 K.

Sea clusters 1 and 2 are merged (rule A) when the absolute difference of their IR radiance is lower than 10 counts (about 3 K), corresponding to possible values of SST gradients inside an array. A cluster with a VIS count equal to two is merged with the sea peak when the IR count difference is smaller than one (rule B). With such a threshold it has been observed that points corresponding to small cumulus or tenuous stratus edges are occasionally merged with the sea cluster; conversely, some sea points are occasionally classified as cloudy. Selecting a higher threshold would damage the SST estimation, while a lower value would lead to frequent overestimations of total cloudiness. Therefore the proposed threshold is the best compromise suggested by our tests.

Clusters with high reflectances are merged together when they exhibit small VIS and IR differences (rule D). The selected values are not very critical and correspond to the accuracy needed for cloud description.

4) END OF THE PROCEDURE FOR AN ARRAY

The program ends either when the remaining data sample becomes smaller than $M_i$ (i.e., there is no more discernible surface) or when five cloud levels have already been identified. Note that some data points may remain unsorted (Fig. 6d): this occurs when the histogram is flat (e.g. cirrus layer) or exhibits a number of scattered small peaks (rear zone clouds) or when more than five cloud clusters exist in the field under analysis.

4. Validation of the method—Choice of optimal channel combination

a. Validation procedure—Comparison sample

The only direct method to ascertain the validity of a satellite computerized cloud cover estimation seems to consist of comparing its results to those of visual analysis. Note that the analysis of enhanced images, as performed by experienced nephanalysts, allows cloud identification through both their spectral features and texture, thus reaching a substantial degree of reliability. Nephanalysts are considered to be able to estimate total cloudiness within a 10% accuracy. Nevertheless, in certain particular cases mentioned in Section 2, cloud identification may be ambiguous, leading to two possible cloud cover values. For example, stratus edges can be classified alternatively as clear or cloudy.

Two orbits displaying various kinds of typical cloud situations have been selected. Orbit 1117 (10 September, 1981), over Western Europe, exhibits several interesting areas:

- over the Mediterranean Sea, western Corsica and Sardinia (Fig. 7, zone 1), overall clear region dotted with cumuliform and cirrus clouds;
- over the Atlantic Ocean (Fig. 8, zone 2), frontal line and rear zone extending from Spain back to Scotland;
- over the North Sea (Fig. 9, zone 3), stratiform area.

Orbit 1964 (9 November 1981) displays a typical stratocumulus layer over the Atlantic Ocean, west of France and Ireland (Fig. 10, zone 4).

In order to test the procedure for critical conditions, the comparison areas (which include 702 arrays) have been selected with a bias in favor of partial cloud cover. Therefore the sample is not represen-
tative of the climatology, concerning both the fully overcast case (although a large part of the frontal band in zone 2 is included) and especially unambiguously cloud free situations.

Radiometric images are enhanced in order to ease the discrimination between various kinds of cloud, and the TOVS grid is superimposed to those images. Visual analysis and the 2-D procedure as described above, using both (1, 4) and (2, 4) channel combinations, are then carried out for each TOVS array.

The validation has been restricted to the total cloud cover \( N \), which is among the most important parameters derived from the procedure, and obviously the easiest to validate.

b. Results and discussion

Results of the comparison are presented in Figs. 11a–b which shows, for each selected zone 1–4 and both (1, 4) and (2, 4) channel sets, scatter diagrams of cloud cover \( N \) computed by the algorithm against the value \( N^* \) resulting from visual analysis.

For zone 1 (Fig. 11a–b), results for the (2, 4) set are close to the diagonal axis, although \( N \) tends to be slightly larger than \( N^* \). Points showing large discrepancies correspond to small size cumulus clouds, when they are merged into the sea peak.

On the other hand, the (1, 4) set exhibits a large scatter and a general overestimation of cloud cover by the automated procedure. This is because the reflectance criterion on channel 1 often fails to discriminate cloudy and cloud free cases properly: due to Rayleigh scattering and turbidity effects along the shorelines, the reflectance of cloud free zones may exceed 6.25%; then, corresponding pixels have a VIS count larger than 1 and are a priori considered as cloudy. The occurrence of strong SST gradients increases the chances that a spurious cloud peak will
Fig. 10. As in Fig. 7 for orbit 1964 over the eastern Atlantic (zone 4); (a) channel 2 and (b) channel 4.
persist after the merging rules have been applied. Such errors are also present in the following zones.

In zone 2 (Figs. 11c–d), the (2, 4) results agree rather well with nephanalysis. Some overestimations for cover values in the (0.3–0.6) $N$ range occur in the rear zone (top, left side of Fig. 8). In this region the background shade is slightly lighter than in other parts of the image, both for VIS and IR channels, and is thus interpreted by the algorithm as cloudy, while the nephanalyst assumes that breaks through the higher cloud layer are cloud free. There may actually well exist small cumulus clouds in such regions, not mentioning the possible presence of a cirrus cover. Note however that such cases occur only when the background is cold: whenever it is warm (for example in the middle of Fig. 8), $N$ and $N^*$ agree.

In zone 3 (Figs. 11e–f), the bulk of the data show good agreement; however about 20% of the data
points are far removed from the diagonal axis. This mostly corresponds to stratus edges when the histogram does not include samples with VIS counts equal to 1, and thus the algorithm classifies the whole array as overcast. Note that the contrast around stratus edges is quite low so that the visual analysis is highly dependent on the choice of enhancement scale. We shall consider as dubious those cases where the nephanalysis yields diverging results for (1, 4) and (2, 4) sets, one of them being in agreement with the algorithm.

In zone 4, the overall agreement is good; some dubious cases are encountered when small cumulus clouds are erroneously merged into the sea peak, or conversely when visual analysis likely underestimates cloud coverage, as described for zone 2.

The results are summarized in Fig. 12 which shows the histograms of cloud cover differences \( \Delta N = N - N^* \) for both channel sets. The mean values and standard deviations are +1 and 21%, and +3 and 13%, for (1, 4) and (2, 4) sets, respectively, confirming the superiority of the (2, 4) combination. When dubious cases as defined above are removed from the sample, for the (2, 4) set the values become a +1%
5. Conclusion

A two-dimensional histogram procedure has been developed in order to analyze cloud layers and estimate SST and fractional cloud covers over the ocean, from the NOAA-7 AVHRR imagery. This procedure has been tested against visual nephanalysis for total cloud cover and shown to yield results of comparable quality in about 87% of the cases. Also, the channel 2 radiance (near infrared band) appears to be significantly better suited to cloud analysis than the visible band channel. Probable explanations for such a result are:

1) a better delineation of shorelines and
2) a lower reflectance of the sea, allowing a better resolution of cloud free areas. Channel 2 reflectances in clear areas are lower mainly because Rayleigh scattering is reduced and turbidity effects along the shores are nearly absent. While cloud reflectances in the NIR band also appear to be generally lower than in the VIS band, this does not seem a major drawback for detecting low clouds, as evidenced by the results obtained in a stratiform area (zone 3) when using channel 2. This is in agreement with remarks by Maul (1981) with respect to GOES imagery, even though still better results should be expected when using a channel near 1 μm such as the AVHRR channel 2.

Some deficiencies have been noted along the way, particularly concerning the discrimination between small size clouds (cumuliform cells...) or tenuous cloud veils, and the sea surface. While a linear compacting scale has been adopted both for reflectance and radiance, this may not be the optimal choice; it might, for example, be useful to enhance the resolution for low visible counts. Also the 3.7 μm (channel 3) information is obviously relevant for cloud analysis; in spite of the complexity of dealing with daytime 3.7 μm images, further attempts along this direction need to be undertaken.

Furthermore, arrays where total cloudiness is underestimated may be filtered by comparing SST values yielded by the procedure to climatological data, or better to neighboring values.

We plan to test the impact of such improvements by repeating a comparison with visual nephanalysis and including the validation of partial cloudiness description as well. Finally, it will be necessary to develop a similar method to analyze cloud cover over the continental areas.

Such developments now require a large data base. During the year 1982, the 2-D algorithm, as it stands, has been applied on a routine basis to daytime AVHRR data collected at CMS. The resulting cloud analysis will then be used in a climatological study of low level nebulosity (the NEPHOS project); in the course of this research, comparisons will be carried out with nebulosity fields deduced from ECMWF (European Center for Medium Range Weather Forecasts) products, in the hope to improve both methods.
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