REPORT ITU-R M.739-1

INTERFERENCE DUE TO INTERMODULATION PRODUCTS IN THE LAND MOBILE SERVICE BETWEEN 25 AND 1000 MHz

(Study Programme ITU-R 7C/8)

(1978-1986)

1. Introduction

Intermodulation causes a degradation to radio services when:

- unwanted emissions are generated in transmitters;
- unwanted emissions are generated in non-linear elements external to the transmitters;

or

- in-band intermodulation products are generated in the radio-frequency stages of receivers.

These cases occur with varying probability and varying severity. They may be reduced by equipment design or careful choice of channels, but solutions of the latter type to one case of intermodulation may increase another.

2. Transmitters

The last active stage of a transmitter is usually an amplifier. The current in this stage will be repeatedly swept from zero amplitude to a maximum and the impedance of the output active device is liable to contain a small amount of non-linearity.

If any other signal from another emission is also present at the output of this stage, the non-linearity will give rise to a number of products having frequencies with specific frequency relationships to the frequency of both the wanted and unwanted signals. These products are called intermodulation products, and their frequencies may be expressed as

$$f_i = C_1 \cdot f_1 + C_2 \cdot f_2 + \dots + C_n \cdot f_n \tag{1}$$

where the sum $|C_1| + |C_2| + \dots + |C_n|$ is the order of the product.

The odd-order intermodulation products may be relatively close in frequency to the wanted signal frequency and thus coupled via the output circuit to the antenna with minimal attenuation.

In order to be able to calculate the effects of these products, it is necessary to establish certain terms.

2.1 *Coupling loss, A_c*

The coupling loss, A_c, in dB, is the ratio of the power emitted from one transmitter to the power level of that emission at the output of another transmitter which may produce the unwanted intermodulation product.

Typical values for the coupling loss on a common site are of the order of 30 dB.

2.2 *Intermodulation conversion loss, A_I*

The intermodulation conversion loss A_I, in dB, is the ratio of power levels of the interfering signal from an external source and the intermodulation product, both measured at the output of the transmitter.

Without any special precautions, typical values for semi-conductor transmitters are to be found in the range of 5 to 20 dB and for valve transmitters, in the range of 10 to 30 dB, in respect of the 3rd order product $(2f_1 - f_2)$.

The overall loss between a transmitter providing the unwanted emission giving rise to the intermodulation product and a receiver operating at the frequency of the product is:

$$A = A_c + A_I + A_p \tag{2}$$

where A_p, in dB, is the propagation loss of the intermodulation product between the relevant transmitter output and the receiver input.

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* This Report should be brought to the attention of Study Group 1.

Note that the power level of the transmitter in which the intermodulation is produced is not included in the formula but this level may have an effect on the value of the intermodulation conversion loss A_I.

Example

Signal frequency of transmitter producing intermodulation product:	f_1
Signal frequency of transmitter whose emission is coupled into transmitter (f_1):	f_2
Power level of transmitter (f_2):	+ 10 dBW
Assumed coupling loss A_c:	30 dB
Assumed conversion loss A_I:	15 dB
Assumed receiver threshold signal level:	– 150 dBW

Overall path loss is equal to 10 dBW – (– 150 dBW) = 160 dB.

If $A_c + A_I = 45$ dB, then the required value of A_p is 115 dB.

Figure 1 gives an example of propagation path losses at 100 MHz and, under free space conditions, a very large distance is required between the "product producing" transmitter and the receiver. If the receiver is a mobile station, this distance is considerably reduced. It may be concluded therefore that 2-frequency operation provides better conditions for the reduction of the effects of inter-transmitter intermodulation if the base receive frequency band is remote from the transmit frequency band.

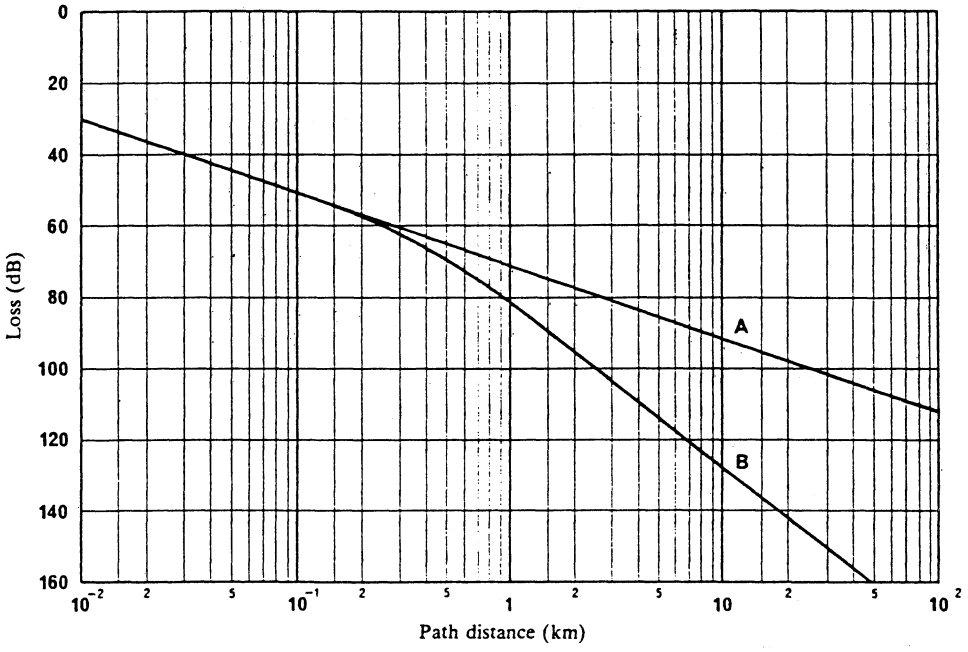

FIGURE 1 – *Short range path loss at 100 MHz ($\frac{\lambda}{2}$ dipoles assumed)*

Curves A: free space
B: Recommendation 370-3; $h_1 = 37.5$ m, $h_2 = 2$ m

The intermodulation caused by two or more mobile transmitters will be worse when the mobiles are closest together and when the desired signal originates at a mobile at the edge of the service area, an event which is associated with some (perhaps small) probability. The mobile being interfered with will be received at its base as a signal of widely varying level (due to fades and shadows) which will be independent of the IM interference. These wide and independent variations can allow the IM to reach harmful values for periods of time, even when its average value is much less than that of the signal.

3. External non-linear elements

On most sites, external non-linear elements will be at junctions in masts, feeders, and other antennas which are closely coupled to the radiating elements of nearby transmitters.

It would be useful to determine conversion losses for masts etc., of various qualities in terms of the isotropic loss between transmitters and the masts, etc. It would then be possible to establish specific values as good engineering practice.

4. Receivers

An intermodulation response is a response at the output of a receiver from an in-band signal generated in the RF stages of the receiver. This in-band signal is generated by the presence of two (or more) high-level signals in a non-linear section of the RF stages. As with transmitters, the two (or more) unwanted signals must have specific frequencies such that the intermodulation product lies within the frequency band accepted by the receiver.

This receiver characteristic is normally recorded as a single measurement with the level of the unwanted signals equal and is given as a single ratio which is:

the ratio of the level of these two equal signals

to

the apparent level of the intermodulation product at the input to the receiver.

It is possible, however, to cause a similar product level when the unwanted signals are not equal.

Figure 2 gives examples (3 theoretical and 1 measured) of the overall third order intermodulation characteristic of receivers. It shows that intermodulation may easily be a problem when one of the unwanted signals is not excessively high. Such curves can be used to calculate other intermodulation product levels when the unwanted signals do not have values equal to those plotted.

For a product with a frequency relationship of the form $(2f_1 - f_2)$, the level will be proportional to the level of the signal at frequency f_2, but will vary as the square of the level of the signal f_1; i.e. the product will have an amplitude of the form $k \cdot V_1^2 \cdot V_2$, where V_1, V_2 are the amplitudes of the signals at frequencies f_1 and f_2 respectively.

When a mobile receiver is used in a multi-channel system it will be subject to an intermodulation response due to many equally spaced high level signals. The following relationship has been suggested by the People's Republic of China to relate the maximum permissible signal level with the intermodulation response rejection ratio of the receiver [CCIR, 1982-86a]:

$$E_s + 3E_M \geqslant 3E_{I\,max} + B + k(n,p)$$

where:

E_s : wanted signal level (dB) above sensitivity;

$E_{I\,max}$: maximum interference signal level (dB) above sensitivity;

E_M : receiver's third-order intermodulation rejection ratio (dB) (for two signals);

B : RF protection ratio (dB);

$k(n,p)$: a constant dependent on the number of channels n and channel sequence p.

The derivation of this formula and the calculation of $k(n,p)$ are given in Annex I.

5. Reduction of intermodulation product levels in transmitters

5.1 *Intermodulation conversion loss*

It is obvious that a reduction of the non-linearity, particularly of the odd-numbered orders, will improve the overall performance and increase the value of the intermodulation conversion loss A_I.

From the example in § 2, it is evident that a considerable improvement is necessary before the relevant path loss reduces to manageable values.

5.2 *Coupling loss*

The coupling loss can obviously be increased by increasing the distance between the relevant transmitters but it may not always be possible to do so effectively at a particular site.

Ferrite isolators could be used in the output circuits of the transmitter in which the product is generated but present production units do not provide much more than 25 dB additional loss and the use of multiple units is inhibited by the inherent non-linearity of the isolators themselves. To suppress undesirable products, filters may be required after such isolators. These isolators are equally effective irrespective of the frequency spacing between f_1 and f_2.

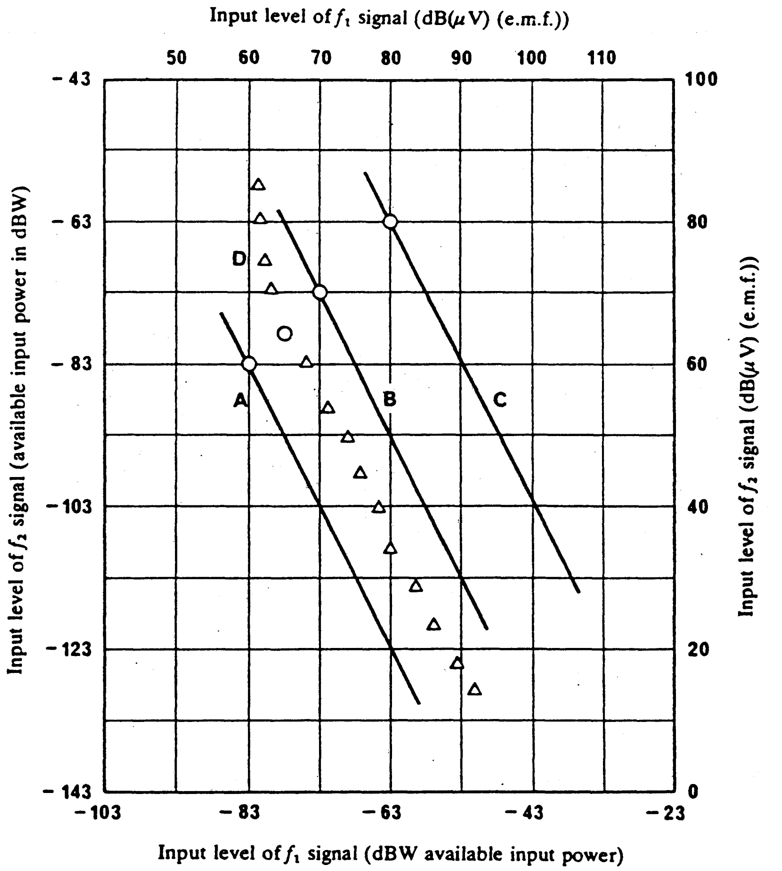

FIGURE 2 – *Receiver intermodulation characteristic*

Levels of unwanted input signals which together produce a constant product level.

Curves A, B and C: derived characteristics based on a single recorded value of the receiver's third order intermodulation characteristic, i.e. for $(2f_1-f_2)$.

Curves A: based on a single value, with both input levels at a level of 60 dB(μV) (e.m.f. to 50 ohms).

B: based on a single value, with both input levels at a level of 70 dB(μV) (e.m.f. to 50 ohms).

C: based on a single value, with both input levels at a level of 80 dB(μV) (e.m.f. to 50 ohms).

D: measured values for a receiver for which the specified criterion is achieved with equal input signal levels of 65.5 dB(μV) (e.m.f. to 50 ohms).

Cavity filters can also be used and examples of their theoretical responses are given in Fig. 3. They may be used in cascade or in more complex series-parallel combinations but in all cases, their performance is dependent on the frequency spacing between f_1 and f_2. They have the advantage that they will also attenuate the product level at the input to the antenna or transmission line and thus increase A_I.

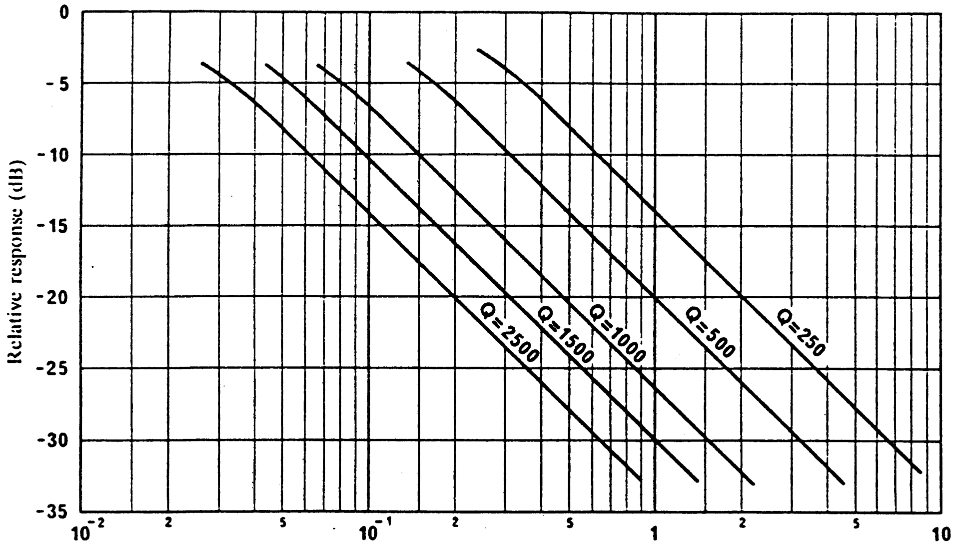

FIGURE 3 – *Theoretical response of cavity band-pass filters*

For values of loaded Q of 250-2500.

Note. — The unloaded Q should be at least 5 times the loaded Q and preferably 10 times.

An economic and efficient filter is the coaxial cavity resonator, either in its pure quarter-wavelength form or with varying degrees of modification to reduce the overall length and improve the value of the loaded Q. The resonator should be robust, simple to tune, highly efficient in terms of transmission loss, and provide a high degree of isolation at the required frequencies. Resonators for use with transmitters should have a low temperature coefficient and good thermal conductivity, so that their performance is not affected by changes in ambient temperature or through being heated by transmission losses. Temperature compensation can be employed to maintain the length of the centre conductors. Physical robustness is necessary to avoid changes in technical parameters from being caused by mechanical shock or deformation. The physical and mechanical design should also prevent the formation of electrical discharges or corona. Adjustable telescopic centre conductor assemblies permit a variation of resonant frequency of, typically, ± 15% of the centre frequency.

Reliable and economical resonators can be manufactured from high-conductivity aluminium for the larger units, and silver-plated copper or brass for smaller units. Practical limitations of mechanical engineering govern the upper limits of Q obtainable with a cavity resonator. As the diameter is increased, the value of the unloaded Q is increased, but the sensitivity of tuning and the temperature coefficient become more critical. Practical and satisfactory resonators with a power handling capacity of up to 250 W can, however, be made for the band 150-170 MHz, for example, having an unloaded Q as large as 18 000, with a diameter of 0.58 m, and length 0.63 m, giving 35 dB discrimination at a frequency 1% removed from the resonant frequency.

It is not usual to employ cavity resonators for values of Q_0 below about 1000, since there are more satisfactory techniques, e.g. helical resonators, which can be coupled together to form smaller but relatively efficient filter units. Tables I and II give the choice of types of filter and their relative costs.

TABLE I – *Relative sizes and costs of resonators (150-174 MHz)*

1	2	3	4	5	6
Reference	Q_0	Q_L	Attenuation at 1% F_0 (dB)	Diameter (m)	Relative cost of practical resonators
A	920	100	7	0.03	1.0
B	2 300	250	14	0.07	1.7
C	4 600	500	20	0.14	2.8
D	6 900	750	24	0.21	3.3
E	9 200	1000	26	0.29	3.9
F	11 700	1250	28	0.37	4.6
G	13 800	1500	30	0.46	5.3
H	16 100	1750	32	0.53	6.8
I	18 400	2000	35	0.58	7.1

TABLE II – *Relative costs of practical resonators for other frequencies*

Resonant frequency (MHz)	Cavity height (m)	Unloaded Q					
		920	2300	4600	6900	9200	13 800
50- 60	1.55	*	*	8.7	12.0	14.7	+
60- 80	1.15	*	*	5.5	7.3	10.6	14.9
95-110	0.85	*	3.3	4.1	5.2	6.4	10.7
120-150	0.68	*	2.6	3.3	4.2	5.0	8.9
150-174	0.63	1.0	1.7	2.8	3.3	3.9	5.3
160-180	0.52	0.9	1.5	2.4	2.9	3.4	4.6
400-500	0.24	0.8	1.0	1.5	2.0	2.2	3.0

Note. – Items not tabulated are identified as follows:
* Helical resonator superior
\+ Single cavity large and somewhat uneconomic.

Compared with the total cost of the radio equipment at a base station, cavity resonator filters are an economical and efficient means of reducing spurious emissions and preventing or minimizing interference.

5.3 *Identification of the source of an intermodulation product*

The frequency of the third order intermodulation resulting from the interaction of two transmitters may be expressed as either $2f_1 - f_2$ or $2f_2 - f_1$.

If the product is $2f_1 - f_2$, the mixing is occurring within or close to the transmitter operating on f_1.

Conversely, if the product is $2f_2 - f_1$, the mixing is occurring within or close to the transmitter operating on f_2.

In the case of FM or PM emissions, the deviation caused by modulation is doubled when a second harmonic is generated. So if the modulation on one of the intermodulation products appears to be excessive, this modulation is probably transferred from the f_1 signal of a $2f_1 - f_2$ mixing.

6. Reduction of intermodulation products in receivers

As with transmitters, a reduction in the non-linearity of a receiver will improve the performance.

Attenuation at the input of the receiver may be used to reduce the level of an intermodulation product. The levels of these products are related to the levels of the signals that produce them, in such a way that the attenuation (in dB) of each "n^{th}" order product will, in most cases, be n times the attenuation (in dB) of the wanted signal.

For example, a 3 dB attenuator will reduce a third order product by 9 dB while reducing the wanted signal by 3 dB. This may also be used as a test device to prove that the intermodulation product is being generated in the receiver.

Cavity filters can be used, either as rejection filters to f_1 and/or f_2, or as band-pass filters to the wanted signal. Again the effectiveness of these filters depends on the frequency spacings involved.

7. Reduction of intermodulation interference by frequency arrangements

The frequencies to be used can be arranged so that no receiver on the product frequency is required to operate in an area where the unwanted signals may produce an intermodulation product of sufficient level to disturb the service. If this level is at the maximum sensitivity level of the receiver; it will mean receivers cannot be used for distances up to 2 km from the sites of the base station operating at f_1 and f_2. This applies even when the f_1 and f_2 stations are separated by several kilometres and thus implies that the base station on the product channel must be sited outside the service area of stations operating on f_1 and f_2. This leads to very poor use of the frequency spectrum.

In systems that operate a number of frequency channels, most cases of harmful base transmitter and mobile receiver intermodulation within the system can be alleviated by the choice of even channel sets at the base stations. This means that the channels of each base station are evenly distributed at a constant frequency separation. In a service area the intermodulation products within the band used will in that case coincide with channels of the set, and the ratio of the desired signal to the intermodulation product in a mobile receiver is independent of the distance and propagation characteristics.

8. Reduction of intermodulation interference by other arrangements

If continuous tone signalling is used, the receiver will operate only in the presence of this signalling tone and it is then necessary only to ensure that the wanted signal on the product channel exceeds the level of an unwanted product of f_1 and f_2 by an amount in excess of the required protection ratio. This can be best assured by siting the product channel base transmitter at the same, or near to, the site of stations operating on f_1 and f_2. Under these conditions, the need for filters or other devices in the transmitter or receiver is reduced.

REFERENCES

CCIR Documents

[1982-86]: a. 8/3 China (People's Republic of).

ANNEX 1

RECEIVER INTERMODULATION RESPONSE IN A MULTI-CHANNEL SYSTEM

1. Number of third-order intermodulation products in a multi-channel system

When a system consists of n channels with equal intervals and n is an even number ($n \geqslant 4$). the number of third-order intermodulation products S_r falling into each channel is shown in Fig. 4 [Morinaga, 1972] including types $2A - B$ and $A + B - C$, designated as type III-1 and type III-2 respectively. From channel 1 to channel n, each channel has $\left(\frac{n}{2} - 1\right)$ type III-1 products and the rest are type III-2 products. The type III-2 products are 6 dB above type III-1's. Since there are three unwanted signals involved. it is valid only when $n \geqslant 4$.

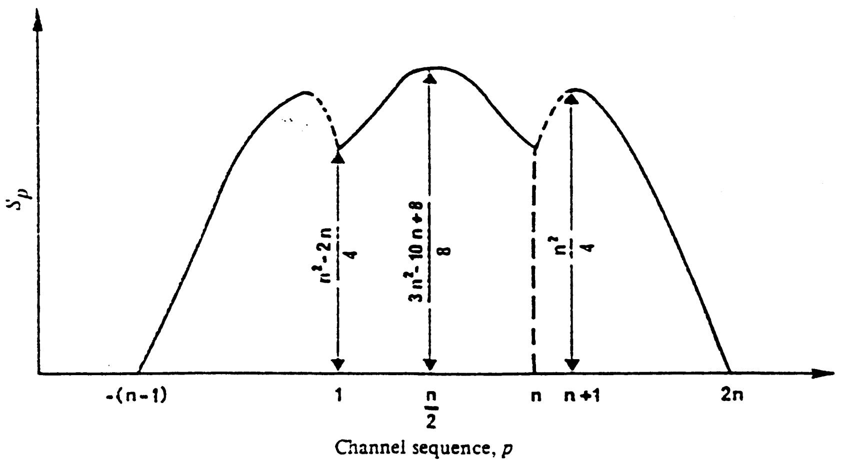

FIGURE 4

Due to the fact that $S_{p\,max}$ with an odd number of n is still equal to or less than that with an even number of n, n can be taken as an even number for the following analysis.

2. Intermodulation products in a multi-channel system

As the third-order intermodulation products are random in phase, the intermodulation product level in each channel will be $k(n,p)$ dB higher than the value of sensitivity.

For mid-channels:

$$k(n,p)_{max} = 20 \log \sqrt{\left[\frac{3n^2 - 10n + 8}{8} - \left(\frac{n}{2} - 1\right)\right] \times 2^2 + \left(\frac{n}{2} - 1\right) \times 1^2}$$

$$= 10 \log \frac{1}{2} (3n - 7)(n - 2)$$

For channels on the edge:

$$k(n,p)_{min} = 20 \log \sqrt{\left[\frac{n^2 - 2n}{4} - \left(\frac{n}{2} - 1\right)\right] \times 2^2 + \left(\frac{n}{2} - 1\right) \times 1^2}$$

$$= 10 \log \frac{1}{2} (2n - 3)(n - 2)$$

3. Influence on systems with adjacent channels

Due to the presence of the third-order intermodulation, the frequency spectrum is extended three times, so a system with n channels would influence the bandwidth for $3n$ channels.

Similarly:

$$k'(n,p)_{max} = 20 \log \sqrt{\left(\frac{n^2}{4} - \frac{n}{2}\right) \times 2^2 + \frac{n}{2} \times 1^2}$$

$$= 10 \log \frac{1}{2}\, n (2n - 3)$$

$$k'(n,p)_{min} = 0$$

4. If $E_{I\,max} > E_M$ (i.e. the maximum interference signal level exceeds the intermodulation rejection ratio), the third-order intermodulation products level (in dB) will increase by $3\,(E_{I\,max} - E_M)$. So the level of the intermodulation product (E_I) will be:

$$E_I = k(n,p) + 3\,(E_{I\,max} - E_M)$$

For satisfactory system operation:

$$E_s - E_I \geqslant B$$

So:

$$E_s + 3\,E_M \geqslant 3\,E_{I\,max} + B + k(n,p)$$

REFERENCES

MORINAGA, T. [March, 1972] Mobile Communication – Theory and Design. Electronic Communication Academy of Japan. 85-91.