概　　報

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On the Analysis of Time-distance Curves Utilizing Refraction Method——Comparison between the Graphical Method and Hagiwara's Method using a Model and Field Example——

By

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Chapter I　Introduction

The general theoretical background of seismic prospecting has much in common with earthquake seismology. But, the nature of seismic waves is somewhat different in some cases. This difference is principally in period or frequency. The earthquake waves have periods ranging from a few seconds to as long as several minutes, but the waves used in seismic prospecting are of very much shorter wave length with periods of the order of 0.01 to 0.1 sec. The exploration seismics is based upon the seismic waves transmission through the underground formations. Whenever the waves encounter a discontinuity where there is a change in the physical properties of the wave transmitting medium, some part of the waves is reflected back to the surface and the rest is refracted. We also come across the phenomenon of diffraction, in case of subsurface structural discontinuities like fold, faults etc, namely the waves striking the crest of folds or edges of the faults are diffracted at various angles.

Here we will only be concerned with refraction seismic analysis. For such analysis one model and one field example of Toki area, Gifu prefecture was considered.

There are various methods of interpreting the refraction seismic data, but here we would like to take only two representative ones and they are the direct calculation graphical method and the Hagiwara's method of differences. Hagiwara's method is a simple method of analysis of the time-distance curves in case of shallow depth. It is necessary, in order to obtain more accurate profile, that the values should be correct in both the velocity and thickness of the surface layer.

Though it is difficult to obtain a unique solution by using refraction data,

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with the help of reflection and gravity, magnetic or geological evidence assumptions as to the underground structure can be made.

During this study we come across many interesting phenomena such as the diffraction of the seismic wave at the edge of the fault in case of the model study and the gap in the theoretical time-distance curve due to the presence of the fault.

It is very interesting to interpret the same data utilizing two different techniques and compare the two independently obtained results. This gives us a chance of judging the reliability and accuracy of a particular interpretation technique in a particular situation and the success or failure of a technique for interpreting that data.

Chapter II Hagiwara's method theoretical background

The time-distance curve for the case of uniform inclination of the bedrock surface can be easily analysed by simple calculation. But when the inclination is not uniform the process of analysis is not so simple. The method hitherto used was a graphic one (in which the travelling time of the refracted wave is calculated with the aid of a model of the underground structure assumed and then compared with the observed value.) The model is gradually altered until both values, calculated and observed, are identical.

Hagiwara's method : We used a method by which the depth of the bedrock at each point and the propagating velocity in the bedrock could be independently obtained.

In Fig. 1 A and B are the observation points. The explosion point is S.

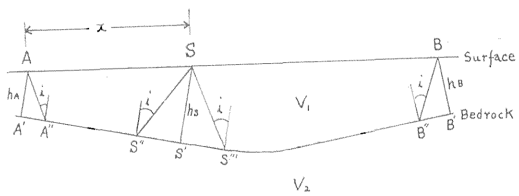

Fig. 1

The propagating velocity in the surface soil and in the bedrock, the critical refraction angle are respectively denoted by V_1, V_2 and i whence

$$\sin i = V_1/V_2 \cdots\cdots\cdots\cdots (1)$$

In the Fig. 1, SS'', $A'A''$ is the path of the refracted wave from S to A and SS''', $B'B''$ that of the refracted wave from S to B. h_A, h_S and h_B are respectively the lengths of the perpendiculars to the bedrock surface from A, S and B. The quantities that we require are the values of h_A, h_B and a series of h_S.

By drawing a perpendicular $S'R$ from S' to SS''

$$RS''/V_1 = Ro''/V_2 \sin i = S'S''/V_2 \cdots\cdots\cdots (2)$$

Where the vinculums signify the distance between R and S'', and we get

$$\overline{SS''}/V_1 = \overline{SR}/V_1 + \overline{RS''}/V_1 = hs \cos i/V_1 + \overline{S'S''}/V_2 \cdots\cdots\cdots (3)$$

Similarly, $\overline{SS'''}/V_1 = hs \cos i/V_1 + \overline{S'S''}/V_2$

$$\overline{AA''}/V_1 = h_A \cos i/V_1 + \overline{A'A''}/V_2 \quad (4)$$

$$\overline{BB''}/V_1 = h_B \cos i/V_1 + \overline{B'B''}/V_2$$

We denote the travel time of the refracted wave t for example, t_{SA} is the time of the refracted wave travelling from S to A. t_{SB} and t_{AB} have also the same meaning. Then

$$t_{SA} = \overline{SS''}/V_1 + \overline{S''A''}/V_2 + \overline{A''A}/V_1 \quad (5)$$

$$t_{SB} = \overline{SS'''}/V_1 + \overline{S'''B''}/V_2 + \overline{BB''}/V_1 \quad (6)$$

$$t_{AB} = t_{BA} \quad (7)$$

$$= \overline{AA''}/V_1 + A''S'' + S''S' + S'S''' + S'''B''/V_2 + \overline{BB''}/V_1 \quad (8)$$

Referring to the equations from (3) to (8)

$$t_{SA} + t_{SB} = 2hs \cos i/V_1 + t_{AB} \quad (9)$$

Consequently,

$$hs = V_1 \ (t_{SA} + t_{SB} - t_{AB}) \ /2 \cos i \quad (10)$$

In the equation (10) V_1 is known from the time-distance curves for the direct surface wave, and t_{SA}, t_{SB}, and t_{AB} are also known quantities directly obtained by observation, whereas cos i alone is unknown, because V_2 is general unknown. If we know V_2 the value of hs can be obtained by the equation (10). Next we shall consider the method for obtaining V_2.

From (3), (4), (5), we get

$$t_{SA} = h_A \cos i/V_1 + A'A''/V_2 + A''S''/V_2 + S''S''/V_2 + hs \cos i/V_1 \quad (11)$$

We consider a quantity t_{SA} that is expressed by the equation

$$t'_{SA} = t_{SA} - (t_{SA} + t_{SB} - t_{AB})/2 \quad (12)$$

We can obtain t_{SA} from the observed values. From (9), (11), (12)

$$t'_{SA} = h_A \cos i/V_1 + A'S'/V_2 \quad (13)$$

The equation is a linear one with respect to $A'S''$. We measure the distance x towards B, taking A as origin. If the angle of the seismic ray in the bedrock to the horizontal line (which is equal to the inclination angle of the bedrock surface when the latter has a curvature concave upwards) is denoted by ω then

$$A'S'' = \int_A^S dx/\cos \omega \quad (14)$$

Actually, since the value of ω is not very large, we may put $\cos \omega = 1$, approximately, this approximation will be dealt with later, consequently

$$A'S' = x \qquad \text{approx.} \qquad \text{Hence}$$

$$t'_{SA} = h_A \cos i/V_1 + x/V_2 \quad (15)$$

the equation (15) is linear for x, if we take x as abscissa and t'_{SA} as ordinate and plot the corresponding points as shown is Fig. 2 a sort of time-distance curve is obtained, the inclination angle of which give us velocity in the bedrock, and the point where the straight line cuts the ordinate is $h_A \cos i/V_1$ and the same process is repeated for t'_{SB}. Thus by using this value of V_2 the value of hs,

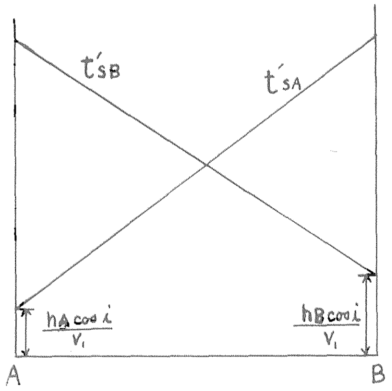

Fig. 2

that is the depth of the bedrock at S can be obtained from the equation (10). Such calculation can be extended to every detector point and as a result thereof we are able to calculate the depth of the bedrock below each detector position which can be plotted below them at a suitable scale by arcing and so the subsurface structure can be obtained. The calculation tables in both cases of the model and field example are given.

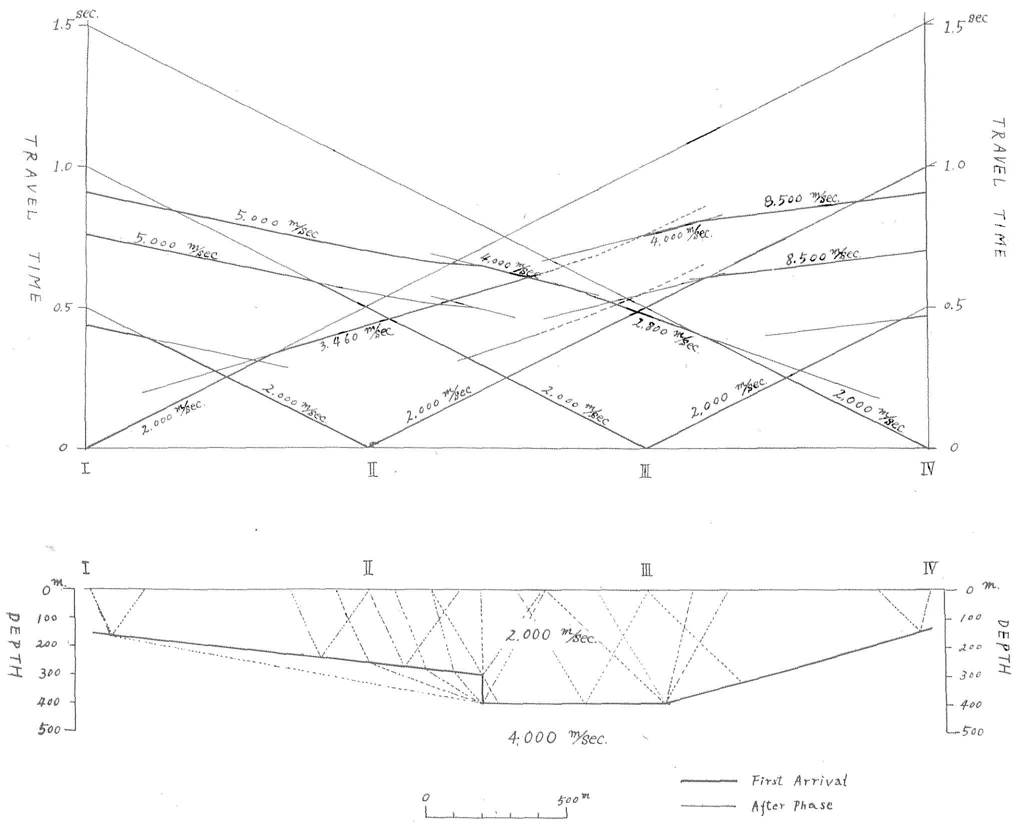

Fig. 3 Theoretical time-distance curve of model structure

Chapter III Consideration of time-distance curve by utilizing simple model structure specially double layer

The theoretical time-distance curve of the model were calculated. The model as shown in Fig. 3 with sloping surface at both ends and fault having 4 shot points was assumed having the 181 layer velocity of 2, 000 m/sec and the 2nd layer velocity 4, 000 m/sec. The wave paths were drawn and the time at each assumed detector position was calculated. In case of the shot point being on the fault upthrow side, the sloping distance between the shot point and the lower edge of the fault plane was considered to be straight whereas in the case of the shot point being on downthrow side, the refraction angle of the waves after crossing the fault plane has to be calculated and the wave path was accordingly drawn.

For taking into account the diffraction of the elastic wave at the corners and edges, many refracted wave path were drawn at each point and the time calculated. At the fault plane the diffracted wave path were drawn at different angles in different derections and minimum time path was calculated. The throw of the fault which is already known was again determined from the break in the time-distance curve utilizing the formula.

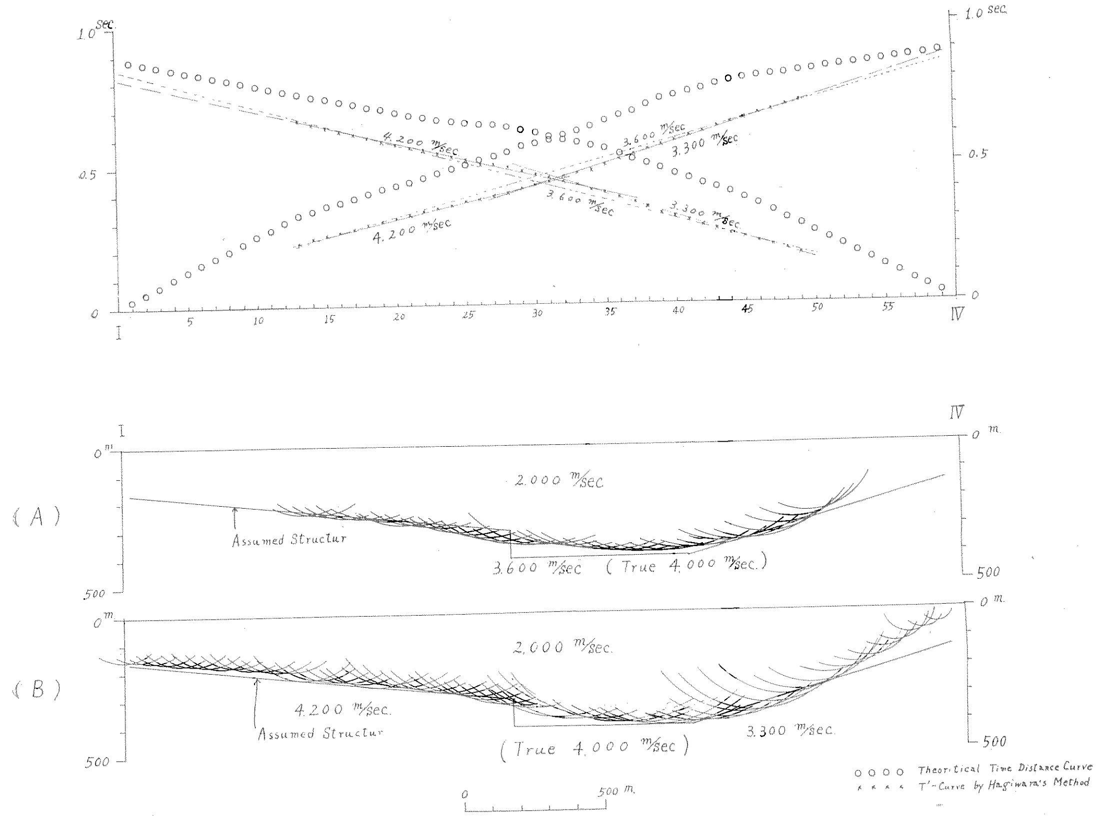

Fig. 4 Analysis on the theoretical time-distance curve by Hagiwara's method

$\Delta t = Z_2 \cos i / V_1$

Where, Z_2 is fault throw, Δt, the time break, i the incident angle of the waves and V_1 the surface wave velocity, which amount to the actual fault throw. (Nettleton, 1940)

The theoretical time-distance curves for each shot point location along with the assumed model structure are shown in Fig. 4.

The theoretical time-distance curves obtained as result of direct calculation were interpreted by Hagiwara's method. The details about the calculation procedure are referred to the early part of this report. The interpretation is given one, assuming the average second layer velocity of 3,600 m/sec and the second with a lateral variation from 4,200 m/sec to 3,300 m/sec. The sections are shown in Fig. 4 (A) and (B). The sections as a result of this calculation were compared with original model structure and it was found that there is no indication as to the presence of the fault in the Hagiwara's interpretation.

Chapter IV Refraction analysis of the Toki field data

Refraction seismic survey was carried out in Toki area, Gifu prefecture in order to obtain the information about the basement granite channel structure. The uranium deposits as explored in Ningyo-toge area, Okayama prefecture are thought to be associated with granite channel structure. The area consists of a thin layer of alluvium overlying the Mizunami group (middle Eocene) and granite basement. This geologic sequence is proved by two test wells (No.1 & No.2) near the site (shown in Fig. 5).

Refraction seismograms of line No. 2 oriented N 12° E having a total spread of 1,360 meters with 2 shot points. Nos. III & V at a distance 1,200 meters apart, were obtained for analysis.

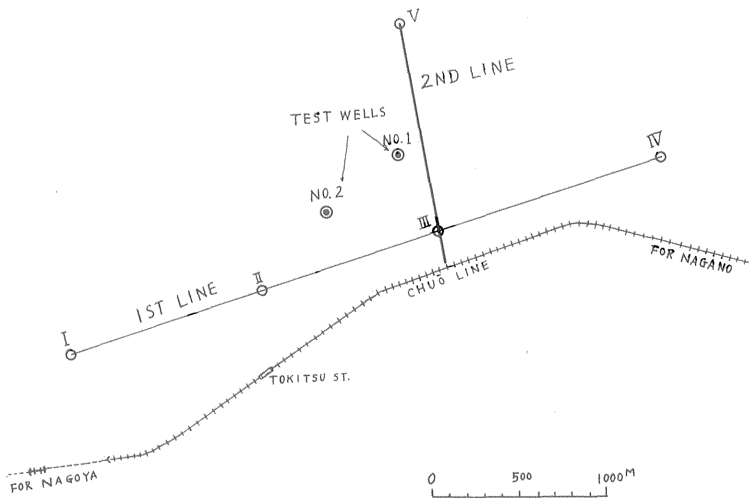

Fig. 5 Traverse line of seismic prospecting and test boring station in Toki field

Graphical analysis : The time-distance curves of the refraction line No. 2 shows the first layer velocity of 2, 200 m/sec and second layer apparent velocities of 3, 700 m/sec and 5, 500 m/sec. The true 2nd layer velocity was tentatively decided to be 4, 500 m/sec. The observed time were corrected to the weathering layer by assuming a velocity of 750 m/sec. After the velocity analysis of weathering layer core sample by ultra sonic method, the thickness of the weathering layer was graphically determined. The approximate depth to the basement below the shot points can be easily determined by using the convenient formula.

$$Z = \frac{x_c}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$$

Where Z is the depth. x_c is critical distance. V_1 and V_2, the velocities of the 1st and 2nd layer respectively. For the first approximation both depth point were joined and from this structure the time-distance curves were calculated following the wave paths and compared with the observed curve. The presumed structure was altered and by such trial and error method we can obtain the most probable monoclinal shaped structure dipping about 8°, the theoretical time-distance curve due to which gives a very close fit to the observed curve. (Fig. 6)

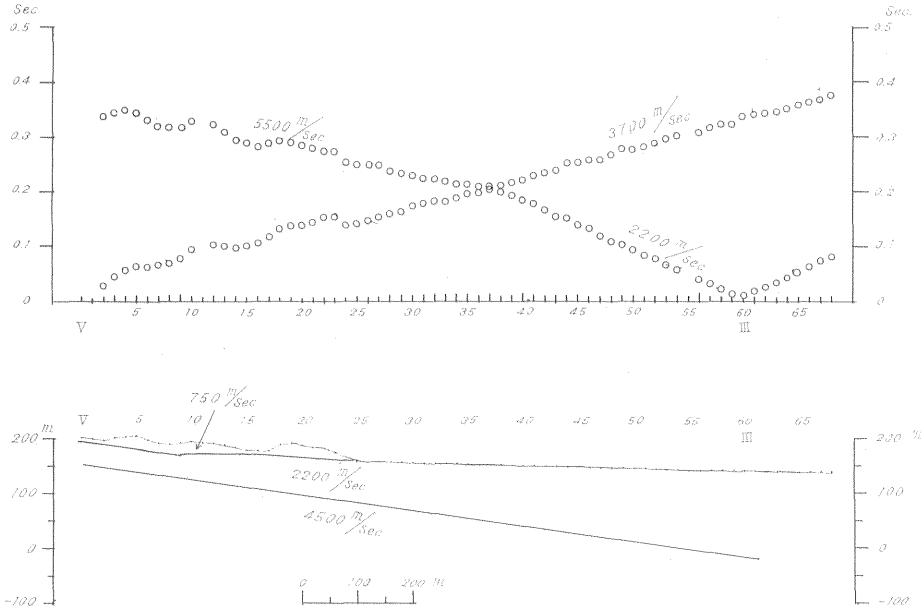

Fig. 6 Time-distance curve and velocity distribution by graphical method in the Toki area, Gifu prefecture

Hagiwara's method : Some travel time curves after weathering correction were utilized for this interpretation. The true 2nd layer wave velocity as determined by Hagiwara's technique was found to be 4, 600 m/sec which was utilized for computing the depth to the basement below every detector position.

The results obtained by both the techniques independently very closely agree with each other. (Fig. 7)

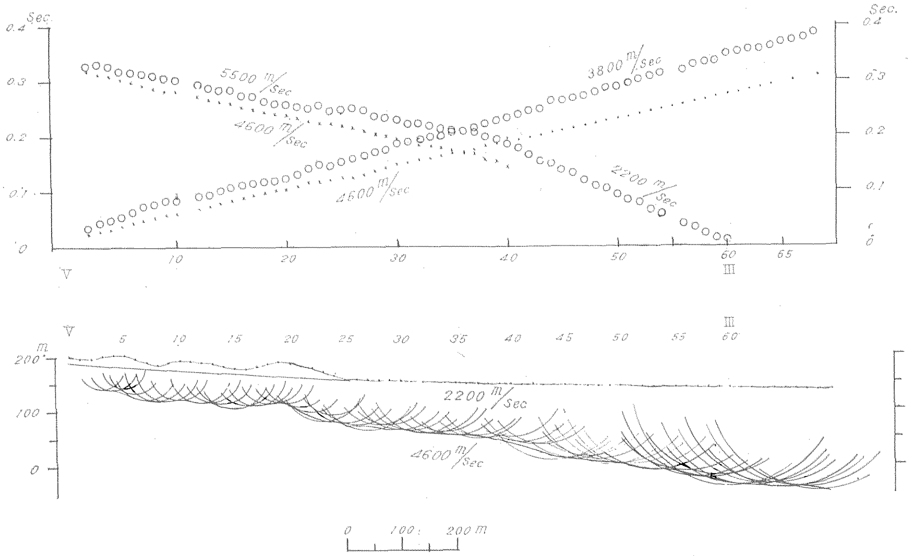

Fig. 7 Time-distance curve and velocity distribution by Hagiwara's method in the Toki area, Gifu prefecture

Chapter V Comparison, Conclusion and Remarks

Graphical method

This method gives us quite accurate results, because the calculation are based upon the actual wave path and by making proper alterations in the presumed structure it is possible to give the closet interpretation to the observed time distance curve. The true wave velocity determination for each layer, in case of multiple layers is very important.

Hagiwara's method

In some cases it might become difficult to assume a structure just by the observation of time-distance curves. This method though applicable to only simple 2 layer case and in this respect inferior to the graphical method, utilizes independent techniques of the true wave velocity determination and the depth calculation below every detector position with no prior structural assumptions and hence gives us a picture about the subsurface which can be tested for higher

Graphical method	Hagiwara's method
1. Higher accuracy	1. Accuracy not as high
2. Subsurface structural presumption necessary	2. Not necessary
3. No independent method of true wave velocity determination	3. Independent method of true wave velocity determination
4. Can be extended to multiple layer cases, steeply dipping and discontinuous structure	4. Only available for 2 layer case, and continuous structure

accuracy by graphical method.

Here after utilizing both the techniques for the same data we would like to compare the reliability of both the techniques in interpretation.

Acknowledgement

The help and guidance provided by Dr. M. Hayakawa of the Geological Survey of Japan is highly acknowledged.

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屈折法走時曲線の解析について

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要　旨

ユネスコの地震工学研修のため来日したパキスタン国地質調査所 Syed 氏は，併せて地震探査法における屈折法走時曲線の解析技術についても研修，研究するため，昭和39年5月下旬から8月中旬まで，週1～2日の割で地質調査所物理探査部へ来所研修した。本所では早川および平沢が指導に当つた。

屈折法の解析は比較的繁雑な作図作業が多く，短時間にこれを履修することは困難ではあるが，幸いわが国には萩原博士の考案による簡便な計算法が広く用いられており，最近は同法を基礎として発展改良された多くの研究もある。そこでこの方法および本所物理探査部が従来実施してきた図式解析法を用いて，次のような内容の研究を行なつた。

1) 萩原の方法について
2) 2層構造模型による走時曲線の考察
3) 岐阜県土岐地区地震探査資料による実際の解析作業
4) 図式解析法と萩原の方法との比較検討

以上の英文報告は上記の主旨による研究報告であり，特に目新しい研究ではないが，模型地下構造による走時曲線を解析して，原模型と比較検討することは屈折法解析精度上に興味ある問題と思うので，ここに公表する次第である。

なお，計算表などは割愛した。