Geophysics. — *"Registration of earth-currents at Batavia for the investigation of the connection between earth-current and force of earth-magnetism."* By Dr. W. VAN BEMMELEN at Batavia. (Communicated by Mr. J. P. VAN DER STOK).

(Communicated in the meeting of December 28, 1907.)

Notwithstanding the great progress in our knowledge of the phenomena of earth-magnetism, the desired improvement has not yet been noticed in the explanation of these phenomena.

That the different variations to which the magnetic needle is liable are the consequence of the changes of electric currents has become highly probable and the place, too, where in that case the currents are to be found is no longer entirely unknown to us.

So SCHUSTER [1]) has proved that the daily variation is in general caused by extra-terrestrial currents, whilst I myself have indicated [2]) that this is likewise the case for that part of the magnetic disturbances which shows a regular daily variation.

Suchlike electric currents have, however, not been shown experimentally and their indication in those unapproachable regions is for the present not to be expected.

Only *one* part of the earth is accessible to us, viz. the outer crust and numerous are the investigations on the electric currents circuiting in that crust.

However, all these investigations have but poorly advanced our knowledge about the connection between those currents and the magnetic variations.

The reason is not only to be found in the great experimental obstacles and the lack of cooperation in the various investigations, but especially in the complicated relations of the system of currents in those zones of the earth where those investigations have been made, viz. between 40° and 70° latitude.

My supposition that in the equatorial zone, just as for other geophysical phenomena, simpler relations must exist, has been proved to be right by the investigations which I wish to communicate here.

The annotations of the earth-current executed by me these last three years at the observatory of Batavia can be divided into two series.

During the first period, March—November 1905, I registered the

1) Phil. Trans. Vol. 180, p. 667.

2) Natuurk. Tijdschrift voor N. I. Dl. 63, p. 227.

earth-current between Cheribon and Batavia, with the aid of the intercommunal telephone-line. The variations were written down photographically, the velocity of the registering strip amounted to the usual 15 mm. an hour.

The important results obtained by this method incited me to go on and in the period now come to a close I could at night make use, by the kind cooperation of the officials of the Telegraph Service, of different telegraph-lines (to Anjer, Buitenzorg, Soekaboemi, Billiton, Poerwakarta, Cheribon, Samarang, Soerabaja and Makassar); greater velocity of registration was applied too (60 and 240 mm. an hour).

Besides continuing the different registrations of the earth-current during longer or shorter time to obtain statistic results, I also made experiments. When the registration pointed to a new connection between earth-current and magnetic variation, other registrations of the earth-current were organised to get a closer investigation of that connection. When questions on the influence of wire or groundplate cropped up, it was tried to answer them by experimentation.

The instrumental arrangement was contrived in such a way, that on a strip 20 cm. wide beside the variations of two earth-current circuits those of the corresponding magnetic components were noted down. Corresponding means here: the component normal to the direction of the earth-current circuit.

The sensibility was chosen in such a way, that the corresponding variations of earth-current and magnetic force did not differ too much in magnitude. To this end great sensibility of the magnetic variation instruments (up to 0.1 γ an mm.) was necessary; as however only the relative position during one night was considered it was easy to arrange those variation instruments quite simply.

I intend to give a more extensive communication about this at some other time.

The daily variation.

The obstacles met with in investigating the daily variation were very great. For the most important part of that variation takes place about noon, but during the day time the electric field of Batavia is disturbed by the electric tram and moreover I was allowed the use of the lines only at night.

If still I succeeded in coming to useful results, this is due to the kindness of the Superintendent of the Intercommunal Telephone Company, Mr. S. W. BAINTS, who allowed hourly readings of the amount of the earth-current to be done at the office of the Company at Batavia. The hours were 8^h45^m A. M., 9^h45^m A. M. etc. until

4^h45^m P. M.; an ordinary galvanometer with pointer was used.

I have chosen from these readings those falling on magnetically very calm days and evincing moreover not to have suffered from disturbances on the line or from other irregularities. For those same days I have used the observatory-notation during the hours of the night (6 P. M.—5 A. M.).

Two unknown quantities remained, viz. the ratio of the values of the scale division and the difference of the central position.

The former I determined one evening during a magnetic storm at the office of the Company by alternately reading the galvanometer and allowing the Observatory to register. The reduction to a same central position I got to a plausible result by using the Sunday notations. For, on those days I could use the line already after 12 at noon and from a score of magnetically fairly calm Sundays I deduced the difference between the hours $4^3/_4$ and 6 p.m.

Graphically I then interpolated the 24 values of the hours of the day.

For the employed magnetically calm days finally was calculated the daily variation of the magnetic component normal to the direction Cheribon-Batavia from the Buitenzorg magnetograms.

Daily variation of the earth-current Cheribon-Batavia and of the magnetic horizontal component normal to that direction.

Earth-current in Volt per Kilometer $\times 10^{-5}$ (Direction Ch.-Bat. = +)		Magnetic Component in 10^{-5} C. G. S. (NE = +)	Earth-current in Volt per Kilometer $\times 10^{-5}$ (Direction Ch.-Bat. = +)		Magnetic Component in 10^{-5} C. G. S. (NE = +)
1 a. m.	— 38	—11.1	1 p. m.	+ 33	22.2
2	— 36	— 9.6	2	— 6	13.9
3	— 40	— 9.3	3	— 33	3.3
4	— 33	— 7.9	4	— 40	— 4.5
5	— 32	— 6.5	5	— 32	— 9.4
6	— 22	— 3.0	6	— 23	—10.2
7	11	3.4	7	— 51	—11.0
8	81	8.8	8	— 60	—13.1
9	153	15.9	9	— 51	—13.6
10	154	24.2	10	— 47	—14.6
11	117	29.5	11	— 46	—13.7
12	84	28.5	12	— 39	—12.9

Out of the curves, indicating according to the above numbers the daily vibration of earth-current and magnetic component, is evident:

that this vibration for them corresponds;

that the direction of the earth-current is such that it can be regarded as causing the variations of the magnetic component;

further: *that the magnetic component is retarded with respect to the earth-current* and finally;

that the ratio of the amplitudes of corresponding vibrations decreases with the duration of that vibration, so that those of the earth-current are relatively larger with a shorter duration.

The chief maximum in the afternoon is reached by the earth-current about an hour and a half earlier, the chief maximum at night about two hours earlier.

The secondary vibration in the evening-hours is for the earth-current much stronger.

It is an indication to apply here the harmonic analysis and to employ for it the formula

$$A = A_n \sin n\,(t + c_n).$$

The results of the harmonic analysis confirm in full what the mere observation taught us.

Especially the increase of the earth-current as the duration of the corresponding variation of the earth-magnetism becomes shorter is very distinctly expressed.

This dependence can be pretty accurately expressed by the following formula.

Let the amplitude of the magnetic component be M; the duration expressed in days T, and the amplitude of the earth-current A, then

$$A = 0.8 \sqrt[4]{\frac{1}{TM}}.$$

The values in the above column "calc" (on the next page) have been computed with the aid of this formula.

Yet not much value must be attached to that correspondence, as the higher terms of the harmonic analysis are very untrustworthy on account of the inaccuracy of the hourvalues employed.

The difference of phase increases regularly as far as the 5th term, and then drops again to the value it had for the 3rd term; but the phase differences found for the higher terms deserve little confidence.

I have been successful in obtaining a confirmation of a part of these results with the aid of the cable Batavia—Billiton. The four months March—June 1906 gave for the nightly course proper results.

	AMPLITUDE					PHASE.			
	Earth-current Volt. p. K.M. × 10−5	Magn. Comp. C.G.S. × 10−5	Earth-current / Magn. Comp. Observ.	Earth-current / Magn. Comp. Calc.	Δ C—O		Earth-current	Magn. Comp.	Earth-current − Magn. Comp.
A_1	75	18.6	4.0	3.9	−0.1	C_1	299°	286°	13°
A_2	44	7.6	5.7	5.9	0.2	C_2	73	53	20
A_3	28	3.0	9.4	8.0	−1.4	C_3	122	98	24
A_4	9	0.9	10.0	10.8	0.8	C_4	53	15	38
A_5	7	0.5	13.1	13.6	0.5	C_5	103	56	47
A_6	6	0.4	15.7	15.9	0.2	C_6	57	34	23

The variation of the corresponding magnetic component changed its nature pretty much (as was to be expected) during these months.

The earth-current really followed this variation whilst the maxima and the minima kept preceding those of the magnetic component.

Out of the average for the 4 months this is obvious.

	7	8	9	10	11	Midnight	1	2	3	4	5
Earth-current Volt. p. KM. × 10−5	0	−27	−25	−29	−17	12	20	28	26	0	−14

Magnet. comp. 0 —2.1 —3.7 —5.3 —**5.5** —4.9 —4.1 —**3.3** —3.4 —4.5 —5.4 10^{-5} C. G. S.

For the earth-current the maximum comes one hour, the minimum about half an hour earlier. Let us suppose this minimum to belong to the preceding vibration of $3^h\ 30^m$ duration, then the difference in phase is 26°.

The ratio of the amplitude is 26°.0, whilst I deduced roughly out of the Sunday notation for the great vibration 16.0 when the cable was at my disposal from 0^h till 4^h p.m.

So we meet here too with decrease of the ratio between earth-current and corresponding magnetic component together with increase of the duration of the vibration, but by the side of it a much stronger earth-current than for the line Cheribon—Batavia.

Annual inequality in the daily vibration.

At Batavia the amplitude of the daily vibration of the magnetic force is liable to a single- and a double-yearly inequality, where the maxima are attained in March and September, the minima in January and in June. The two maxima and the two minima are of the same magnitude.

From the continued measurements at the office of the Intercommunal Telephone Company I could deduce that the variations of the earth-current show the same annual inequality.

This series of measurements shows two breaks.

First in January '06 the lines were permanently disturbed and secondly in August '06 errors seem to have slipped into the observations, on account of which repeatedly improbably large values were read. After my having pointed this out, the readings in December next were again serviceable.

Out of each month I have taken those days which were in the first place magnetically calm and for which in the second place as much as possible complete and useful readings of earth-currents were at hand.

Of the mean hourvalues for each month was then taken the difference of the smallest and the greatest value.

The maximum generally fell in with the $8^3/_4$ a.m. or $9^3/_4$ a.m. observation, the minimum with that of $3^3/_4$ p.m. or $4^3/_4$ p.m.

These differences expressed in Volt pro kilometer $\times\ 10^{-6}$ follow here.

	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.
1905		**266**	194	208	190	129	**127**	**127**	170	**173**	167	131
1906		171	**177**	127	125	**109**	135	233 (?)				122
1907	**81**	**118**	113	90	88.							

Notwithstanding the imperfection in these measurements, the double annual period and its correspondence with that of the magnetic component is so distinctly expressed that doubt is not possible.

Variations of short duration.

The second period of registration, November 1905—October 1907, was chiefly devoted to the study of the connection of the vibrations of short duration in earth-current and magnetic component.

The usual velocity of registration was here 1 mm. a minute, which with sharp photographic lines allows the measurement of variations with the duration of half a vibration of 0.2 to 0.3 minute, but in numerous nights the velocity was enlarged to 4 mm. a minute, when it was possible to measure accurately differences of time of 0.1 minute.

By the continued registration of the earth-current along different lines, each one accompanied by that of the corresponding magnetic component, an extensive material of curves was collected, from which in general the following could be gathered.

For the earth-current along about east-west lines [1]) to each vibration answers a similar one of the magnetic component. For that of the nearly north-south lines that correspondence seems also to exist in part, but it is greatly disturbed by the circumstance that the earth-current keeps following more or less the vibrations of the east-west line.

So also near the equator we find complicated phenomena, but only in part, for as far as the east-west current is concerned we meet with such a striking correspondence that it is possible to deduce simple laws; the two same laws, which were found for the daily variation:

1. *the vibration in the earth-current precedes that of the magnetic component with a certain difference in phase;*

2. *the ratio of amplitude of earth-current and magnetic component decreases when the duration of the vibration increases;*

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1) The east-west lines were:

	Direction	Distance
Bat. — Anjer	W 6° N	106 K.m.
„ — Poerwakarta	E 40 S	78 „
„ — Cheribon	E 18 S	200 „
„ — Semarang	E 12 S	406 „
„ — Soerabaja	E 10 S	665 „
„ — Makassar	E 5 N	1486 „

The north-south lines were:

	Direction	Distance
Bat. — Billiton	N 13° E	392 K.m.
„ — Buitenzorg	S 5 E	46 „
„ — Soekaboemi	S 9 E	84 „

appear distinctly from this material of registering curves with its thousands and thousands of shorter and slower vibrations.

To deduce the real amplitudes and phases of those variations we should have to execute for each separate case an immensely extensive harmonic analysis and, this being quite impossible, corresponding variations had to be chosen and measured discriminately. Therefore all the measurements have been done by me personally.

The precedence of the earth-current.

This precedence was rule; it was quite exceptional if it was not met with. When choosing cases for measurement I always avoided those where by a superposed oscillation of greater length and amplitude the time of the turning point was made to appear much earlier or later.

The difference of phase proved to vary from case to case but to be already constant in the mean of a small number.

For the lines Batavia—Soerabaja and Batavia—Poerwakarta the difference in phase was determined with respect to that of Batavia—Cheribon and not with respect to the magnetic component.

For the lines Batavia—Buitenzorg and Batavia—Billiton the deduction was accompanied by great difficulties, as perfectly corresponding cases between earth-current and the magnetic component seldom made their appearance on account of the interference of the east-west component.

For Batavia—Soekaboemi I have therefore desisted from making a calculation and the difference in phase for the two first lines must be mentioned with reserve.

Difference in phase.

Batavia—Poerwakarta	22°	Batavia—Buitenzorg	23° (?)
„ —Anjer	14	„ —Billiton	28 (?)
„ —Cheribon	22		
„ —Semarang	36		
„ —Soerabaja	32		

The difference in phase found here for Cheribon and Billiton shows a striking resemblance to that found for the daily variation.

Cheribon.	
Variations of short duration.	Average of 6 terms of the daily variation.
22°	27°

Billiton

Variations of short duration. Nightly variation.

28° 26° (?)

Ratio of amplitude.

The accurate indication of the moment of maximum or minimum of a vibration is sooner impossible than the measurement of an amplitude on account of the interference of smaller superposed variations.

I have therefore been able to select a much greater number — 346 — of cases for measurement; the results are as follows:

Batavia—Cheribon.

Amplitude Earth-current in Volt p. Kilom.
Amplitude magnetic component in C.G.S.

Duration of half vibration.	Magnetic Component in 10^{-5} C. G. S.							
	0 23	0 37—0 40	0 50—0 79	0.90—1.50	1 7—1.8	2 8—3 2	5 5—7 6	15.1—18.6
0.3 m.	23 3	22.1	22 4					
0 5	24 3	23 8	21 4	22 8				
0 8		23.6	22 3	19 4				
1.2		22 4	21.1		22 5			
3 7			19.2	21.1		19.1		
7 6			18 3		16.9	17 8	15.6	
15 2				14 8		14.3	14 0	
29 0						15.9		
36 3							12.1	
39.6								10.8
120 —		15 7						
144.—			13 1					
180.—				10.0				
240 —						9.4		
360.—							5 7	
720 —								4.0

According to this table the increase of the amplitude when the duration of the vibration diminishes seems to reach a maximum value at 0.5 min. and moreover the ratio of amplitudes seems to be dependent on the amplitude itself and in such a way that with equal duration it increases with the diminishing of the amplitude.

A complete confirmation of these results was found in 312 cases for the Anjer-line.

Batavia-Anjer.

$$\frac{\text{Amplitude Earth-current in Volt p. K.m.}}{\text{Amplitude Magnetic Component in C. G. S.}}$$

Duration of half vibration.	Magnetic Component in 10^{-5} C. G S.				
	0 19—3.0	0.53—0.68	1.36—1.83	2 30—3.89	5.20—5.48
0.4 min.	96	95	97		
0.6	97	104	95		
0.9	86	90	89		
1.8	92	84			
2.3			64		
5.3		86	74		
6.3				68	
7.7	83				
9.2			68		
9.7					60
10.8		68			
12.3			73		
13.6		58			
19.9				75	
22.0					63

Here too with a short duration a maximum is found, viz. with 0.6 min.

Beside this correspondence we find the unexpected result, *that the Batavio—Anjer current is about four times stronger than the Batavia —Cheribon current.*

That ratio is constant for different duration of vibration, as was proved by the arrangement according to groups of mean equal duration.

Duration of half a vibration	Batavia-Anjer / Batavia-Cheribon
0.33 min.	4.28
0.54	3.94
0.66	4.36
0.76	4.21
0.96	4.21
1.67	3.79
5.6	4.25
7.6	3.84
15.1	5.21
Mean	4.23

When we wish to compare the values for the ratio of amplitudes of magnetic force and earth-current of vibrations of shorter duration with those of the six terms of the daily variation, it is best to inscribe all values in one diagram with abscis $\sqrt[4]{M}$ and ordinate $\sqrt[4]{1/T}$. When now the formula $A = 0.8 \sqrt[4]{\frac{1}{TM}}$ found above for the 6 terms of the daily variation will still hold, then the values which lie on the same radius-vector through the origin must be the same.

It is evident that this is only the case for the middle part of the diagram, namely for the radius-vector where $0.8 \sqrt[4]{\frac{1}{TM}} = 150$.

The ratio $\sqrt[4]{1/T}$ and $\sqrt[4]{M}$ is therefore $= 2$.

If the amplitude of the magnetic component is relatively larger, then the radii with equal values are bent gradually to the axis of abscissae, and if $\frac{1}{T}$ is relatively larger, then they are bent to the axis of ordinates.

For a great $\frac{1}{T}$; i. e. for a duration of vibration of about one minute, they turn again to the axis of ordinates and a maximum seems to be formed.

It will be possible to force these curves in a formula, but we

must not expect that that formula will give the real formula, as it must be very complicated on account of the nature of the phenomenon.

What according to me is clear from the diagram is that the ratio of amplitudes for the vibrations of shorter duration will gradually pass into those of longer duration (the six terms of the daily variation) and so that between these two phenomena there is also a gradual transition.

The results for the earth-current Buitenzorg-Batavia and Billiton-Batavia are again uncertain on account of the lack of agreement with the magnetic component. I found:

Buitenzorg-Batavia.

Duration of half a vibration	Amplitude Magn. Comp.	Amplit. earth-current in V. p Km. / Amplit. magn. Comp. in C. G. S.	Number of cases
1.1 min	0.38 J.	75	20
3.7	0 96	79	20
7.6	1.20	71	28
			68

Billiton—Batavia.

0.7	0.39	63	14
1.3	0.29	74	14
3.5	0.49	66	14
7.0	0.50	58	23
22.4	1.44	41	5
			70

If indeed these figures are trustworthy then the ratio of amplitudes of the earth-current with respect to the magnetic component decreases here too when the duration increases.

The increase at the outset with very small duration is also found in the above figures, even in much greater ratio than for the Anjer- and Cheribon-current.

The numbers for Buitenzorg are a little smaller and for Billiton smaller than for Anjer, but still larger than for the Cheribon-current.

The line to Poerwakarta I had but for two nights at my disposal.

I have then allowed the Poerwakarta-current to be registered at the same time as the Cheribon-current and I have found a complete correspondence between them for vibrations of a duration from 0.8 to 15.5 minutes.

Not before the last months of the registering-period have I extended the investigations to the lines to Semarang and Soerabaja and to my surprise I found a pretty great deviation from the circumstances which appear on the lines Cheribon and Anjer.

Semarang—Anjer.

Duration of half a vibration	Amplitude Anjer-current 10^{-6} V. p Km.	Amplitude Anjer / Amplitude Semarang	Number of cases
0.33 min.	38	1.70	20
0.69	74	2.06	20
1.04	61	2.16	20
1.71	57	2 32	20
7.43	160	3.96	20
20.81	290	4.61	16
			116

Soerabaja—Anjer.

0.37	43	2.17	20
0 93	92	2.87	20
2.65	110	3.27	20
11.85	326	4.71	20
34.28	739	7.16	7
			87

So the influence of the duration on the amplitude of the earth-current is here much greater for the Semarang- and Soerabaja-current than for the Anjer-current.

It is remarkable that here too the increase of the influence with the duration takes place about according to $V^{1}/_{T}$.

With respect to the first value for $t = 0.33$ min., respect. 0.37 minutes duration we get:

	$\sqrt[4]{\frac{t_n}{t_0}}$	$\sqrt[4]{\frac{A_x}{A_0}}$		$\sqrt[4]{\frac{t_n}{t_0}}$	$\sqrt{\frac{A_x}{A_0}}$
Semarang	1.20	1.21	Soerabaja	1.26	1.32
	1.33	1.27		1.64	1 51
	1 51	1.36		2.38	2 17
	2.18	2.33		3.10	3.30
	2.82	2.71			

Direct comparison of the Batavia-Semarang current to the magnetic component furnished: (June 18—21, '07):

Duration of half a vibration	Amplit. of the Magnet. Comp. in 10×10^{-5} C.G.S.	Amplit. earth-current in Volt p. K.M. / Amplit. earth-current in C.G.S.	Number of cases
0.6 min.	1.3	43	14
1.0	0.9	35	15
1 4	0.9	31	13
5.0	0.7	18	10
11.5	2.2	13	9

The last two values fit in very well with the scheme of the values found for the Cheribon-current, but the first three show a much quicker increase when the duration of the vibration is shorter.

This peculiar increase immediately strikes one when regarding the registered lines. In order to investigate whether that increase of the influence of the duration was connected with the increase of the distance of the two stations between which the earth-current was measured, I asked for and obtained direct connection with Makassar. The loss by defective isolation on the line however was so great, that the real distance had not obtained any lengthening of importance.

On the trustworthiness of the results.

A certain doubt has always been left when observing earth-currents whether the results arrived at do give an idea of the real existing earth-current.

According to SCHUSTER (Terr. Magn. III, p. 130) the intensity of the current is really to be determined by switching on in the circuit a cell of known E. M. F. I have therefore always used this

simple means and connected to it often, by introducing a resistance of 100 or 1000 Ohm, a measurement, though a rough one, of the total resistance of the whole circuit.

The results generally showed a mutual correspondence, only for longer lines a distinct loss by defective isolation was often discernible.

For the earth-current this loss by defective isolation is of not much consequence; for, if two points lying at a distance L from each other with potentials P and $P + L_p$ are connected by a wire the potential will vary along that wire proportional to the distance of P to $P + L_p$ and will be in a point between the two, say at $1/a$ of the distance, $P + \frac{L_p}{a}$. But there the potential of the earth will also be $P + \frac{L_p}{a}$ if that earth potential likewise varies proportionally to the distance (which we shall suppose to be true at first computation). There will thus be no difference of potential between line and point of contact with the ground, neither loss of current.[1])

However there is loss of current, when I switch on a cell, thus when I generate a drop of potential along the wire, that does not at all run parallel to the earth potential.

This explains that the image of the earth-current rose and fell so regularly with the magnetic component, whilst so often a great loss by defective isolation took place on the line, so that the determination of the values of the scale division by means of inserting a cell gave abnormal values.

When, however, an investigation must be made of the regular or non-regular increase of the earth-potential with the distance, then this loss by defective isolation is disturbing. That is why the registering with the continuous connection Batavia—Makassar shed no light upon the subject.

Influence of the material of the line.

I could experiment accurately on the possibility of the influence of the material of the conductive wire on amplitude and phase of the earth-current by registering simultaneously the currents between Cheribon and Batavia, resp. through the copper telephone wire and the iron telegraph one.

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[1]) If we suppose the earth-current to form a closed circuit passing round the earth and our wire to have contact with it in three points viz at the two end stations and the point of contact, there is a distribution of current according to WHEATSTONE and the contact is the bridge of WHEATSTONE.

The resistance of the former circuit was generally about 10 times smaller than that of the other.

At Batavia the two circuits were on the same groundplate, at Cheribon the two groundplates hung in the same well. Moreover the wires ran for the greater part on the same telegraphpoles.

An all but perfect correspondence was now found, so that all influence of the material (especially with respect to magnetic induction) may be regarded as non-existing.

Influence of the current of polarisation.

I was more anxious about a disturbing influence of the polarisation of the ground-plates to which repeatedly from various sides attention has been drawn. For, the polarisation might be able to explain the difference in phase and the change in the ratio of amplitudes.

Let us suppose that the earth-current together with the magnetic component increases, then the resisting current of polarisation also grows. If now the increase of the earth-current and of the magnetic component passes into a decrease, the current of polarisation will for the moment keep increasing and consequently the observed current (i.e. earth-current minus current of polarisation) will sooner reach its turning-point than the magnetic component. If the vibration increases in duration the current of polarisation will also increase first faster, then slower, and therefore the observed current will always lose with respect to the magnetic component and the ratio of amplitudes — as was really found — will decrease first faster, then slower.

Though the influence to be expected of the polarisation had therefore to agree with what was found, yet we could not believe that it could be the cause of those phenomena, as for the observations made at the office of the Telephone Company the connection with the earth was made every hour only for a few moments and so there could be no question about a continual increase of the polarisation.

To find out the influence of the polarisation I have taken the following experiment. To begin with I measured the current of polarisation directly. To that end I buried a second ground plate a few meters from the old one and made a new connection: old earthplate—galvanometer—new ground-plate.

The old ground-plate I polarised strongly by switching on a cell into the line (Cheribon—Batavia). After breaking the con-

nection with Cheribon I immediately closed the new one, in consequence of which the depolarisation-current passed through the second galvanometer.

I actually found the polarisation with its characteristic qualities, but its intensity was hardly more than a few percents of the chief current and thus really too small to serve as cause of difference in phase and change in ratio of amplitudes.

After this investigation I have placed a set of non-polarising ground-plates (amalgamated zinc plates immersed in a solution of $Zn\,SO_4$ in porous pots) [1]) on the garden of the Observatory, and repaired to Cheribon to place a corresponding set there. The repetition of the experiment described above showed really the non-appearance of polarisation.

After this I connected one of the two telephonewires between Batavia and Cheribon with the old polarising ground-plates, the other with the new non-polarising ones, and allowed the two earth-currents to register simultaneously on the same strip with the same sensibility and a velocity of registration of 24 cm. an hour together with the magnetic component. The experiment could hardly have been taken more accurately.

As I expected the result for the difference in phase was a very slight influence in the sense mentioned above; for the ratio of amplitude I found for *one* night also a very small influence in the expected direction, but during two other nights a somewhat greater difference in opposite sense. I think I must attribute those last influences to the unavoidable inaccuracy of the determination of the values of the scale division (by switching on a cell of known E. M. F.).

At any rate I had proved sufficiently that the current of polarisation was not the cause of the found phenomena, so I can take those phenomena to be real.

Connection between earth-current and magnetic force.

If we wish to investigate more closely the connection between the variation of earth-current and magnetic component it is necessary to regard the variations of the latter quite by themselves.

The general rule holds at Batavia that the two horizontal components change simultaneously, i. e. that generally between the turning-points of X and Y only a small difference in time exists and that on the other hand Z generally has a difference of phase of 90° with X and Y.

AD. SCHMIDT (Met. Zeitschrift 1899) has pointed out, that the

[1]) C. A. BRANDER. Inaugural Dissertation, Helsingfors, 1888.

variations of the magnetic component might be explained by the passage of electric current vortices.

Following this explanation we should have to conclude for Batavia to the passing of vortices whose centre remains far from Batavia, so that only the outside slightly bent pieces of current pass by.

So as a first approximation we may assume that the extra-terrestrial current is almost rectilinear at Batavia and when varying in intensity has but slight oscillations in direction.

The average direction must be $WSW - ENE$ for almost without exception an increase of the N-component is accompanied by a weakening of the E-component and so $\Delta X > \Delta Y$.

That current we really find back in the diagram of the equipotential lines of the daily variation according to SCHUSTER-VON BEZOLD, [1]) which equipotential lines follow at first approximation the current-lines.

Also for the explanation of the phenomenon found by me of the *earthmagnetic after-disturbance*, it was a matter of fact to take a current encircling the earth and this current too had to have a suchlike direction as was mentioned above, but the angle with the equator was at Batavia much smaller than is found now.

Each varying extra-terrestrial current will induct an intra-terrestrial one and the magnetic variation observed at the surface is the sum of the influence of the two. LAMB (see the paper quoted above of SCHUSTER on the daily variation) proves that the ratio of the potential of the primary and the secondary field is complex and that therefore difference in phase exists. The horizontal component caused by the extra-terrestrial current is in advance compared to the one generated by the inducted currents; so the resulting component will be in retardation compared to the extra terrestrial current.

By SCHUSTER however no difference of phase is found for the vertical force and LAMB has pointed to the fact that this can be the consequence of increasing electric conductivity of the earthstrata towards the depth. The results of the new seismological observations point to an iron nucleus of the earth and therefore to a very great increase.

We may therefore probably assume that the difference in phase is very little, at any rate that difference in phase is slight for variations of short duration.

The magnetic force observed consisted of a primary and of a secondary part, which have the same sign as far as the horizontal component is concerned,

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[1]) Sitz. Ber. der Berliner Akademie für 1895.

The ratio c' between the secondary and primary part increases with the frequency of the vibrations of the current.

Let us call the magnetic force X, then

$$X = \text{primary} + \text{secondary}$$
$$X = \text{primary}\ (1 + c'),$$

so the primary part of $X_0 = \frac{X}{1 + c'}$.

The extra-terrestrial current which we can put $S = s \sin 2\pi \frac{t}{T}$ will induct in the upper earthstrata a current S':

$$S' = \varrho f(ST) \frac{2\pi}{T} \cos 2\pi \frac{t}{T}.$$

The induction will depend on the distance and the latter possibly on intensity and duration of the vibration of the current, moreover on the conductivity ϱ of the upper earthstrata.

The primary magnetic force will at first approximation (the distance being about the same) depend in the same manner on the extra-terrestrial current. So:

$$X_0 = f(sT) \sin 2\pi \frac{t}{T}$$

and

$$X = (1 + c') f(sT) \sin 2\pi \frac{t}{T}.$$

The existence of a vertical conducting current having been proved we must also take for granted that part of the extra-terrestrial current is closed by the earth and that a current is generated equally directed as the current of induction.

Already the properties of the conductivity of the atmosphere point to a dependence of magnitude and duration of the extra-terrestrial current, also on the conductivity of the upper earthstrata.

So we put for the current

$$\varrho\psi(sT) \sin 2\pi \frac{t}{T}.$$

And for the total current we find:

$$A = \varrho \left[\frac{2\pi}{T} f(sT) \cos 2\pi \frac{t}{T} + \psi(sT) \sin 2\pi \frac{t}{T} \right]$$

or

$$A = \varrho \left[\psi^2(sT) + \frac{4\pi^2}{T^2} f^2(sT) \right]^{1/2} \sin \frac{2\pi}{T} \left(k + \frac{T}{2\pi} Bg\ tg \frac{f(sT)}{\psi(sT)} \frac{?\pi}{T} \right),$$

whilst we found above

$$X = (1 + c') f(sT) \sin 2\pi \frac{t}{T}.$$

For the difference in phase we found a constant part of T or

$$\frac{T}{2\pi} Bg\, tg \frac{f(sT)}{\psi(sT)} \frac{2\pi}{T} = \frac{T}{K}.$$

For angles of $\pm 23°$, found for Cheribon for a shorter duration of the vibration, we may write here approximately

$$\frac{f(s\,T)}{\psi\,(s\,T)} = \frac{T}{K}.$$

So the ratio of amplitudes becomes

$$\frac{A}{X} = \frac{\varrho}{1 + c'} \frac{\psi\,(s\,T)}{f(s\,T)} \left[1 + \frac{4\pi^2}{K^2}\right]^{1/2},$$

$$\frac{A}{X} = \frac{\varrho}{1 + c'} \frac{1}{T} \frac{1}{\sqrt{K^2 + 4\pi^2}} = C \frac{\varrho}{1 + c'} \frac{1}{T}.$$

For $1 + c'$ we find according to LAMB-SCHUSTER for that part of the potential which is to be expanded in terms of a spherical function of order 2 (for that part which is to be expanded in terms of spherical functions of a higher order, the increase is quicker).

$\sigma = \frac{constant}{T}$	$1 + c'$
10	1.172
20	1.278
30	1.337
40	1.374
50	1.399
100	1.466
900	1.605
6400	1.643

So for higher frequency (for duration of half a vibration = 1 minute σ is 7200) $\frac{1}{1 + c'}$ is about constant.

So we get $\frac{A}{X}$ proportional to $\frac{1}{T}$.

The observations, however, give for Cheribon and Anjer proportionality with $\sqrt[8]{\frac{1}{T}}$ (for still smaller T, even inversion, and for Semarang and Soerabaja proportionality to $\sqrt[4]{\frac{1}{T}}$.

AD. SCHMIDT (Met. Zeitsch. 1902 p. 94) brings the supposition forward that the current can be generated in the wire by induction only, thereby supposing the wire to be closed by the earth.

Then putting the case very simply we arrive by application of the rule of AMPÈRE at :

$$A_{E-W} = -\gamma \frac{dX}{dt} + \delta \frac{d^2Z}{d\varphi\, dt}.$$

This gives the difference with respect to the above that the variation Z makes its appearance.

The Z, however, changes but little in equatorial regions, so it cannot make the theory correspond to the observations.

The slow increase of the earth-current when the frequency increases does *not* point to induction, but rather to direct connection with the primary current.

The quantity $\frac{1}{1+c'}$ has indeed, compared to $\frac{1}{T}$, rather a slow course.

That difference in phase is according to SCHUSTER-LAMB rather decreasing for quicker vibration whilst for the earth-current it proves to be constant.

But whence the difference in phase?

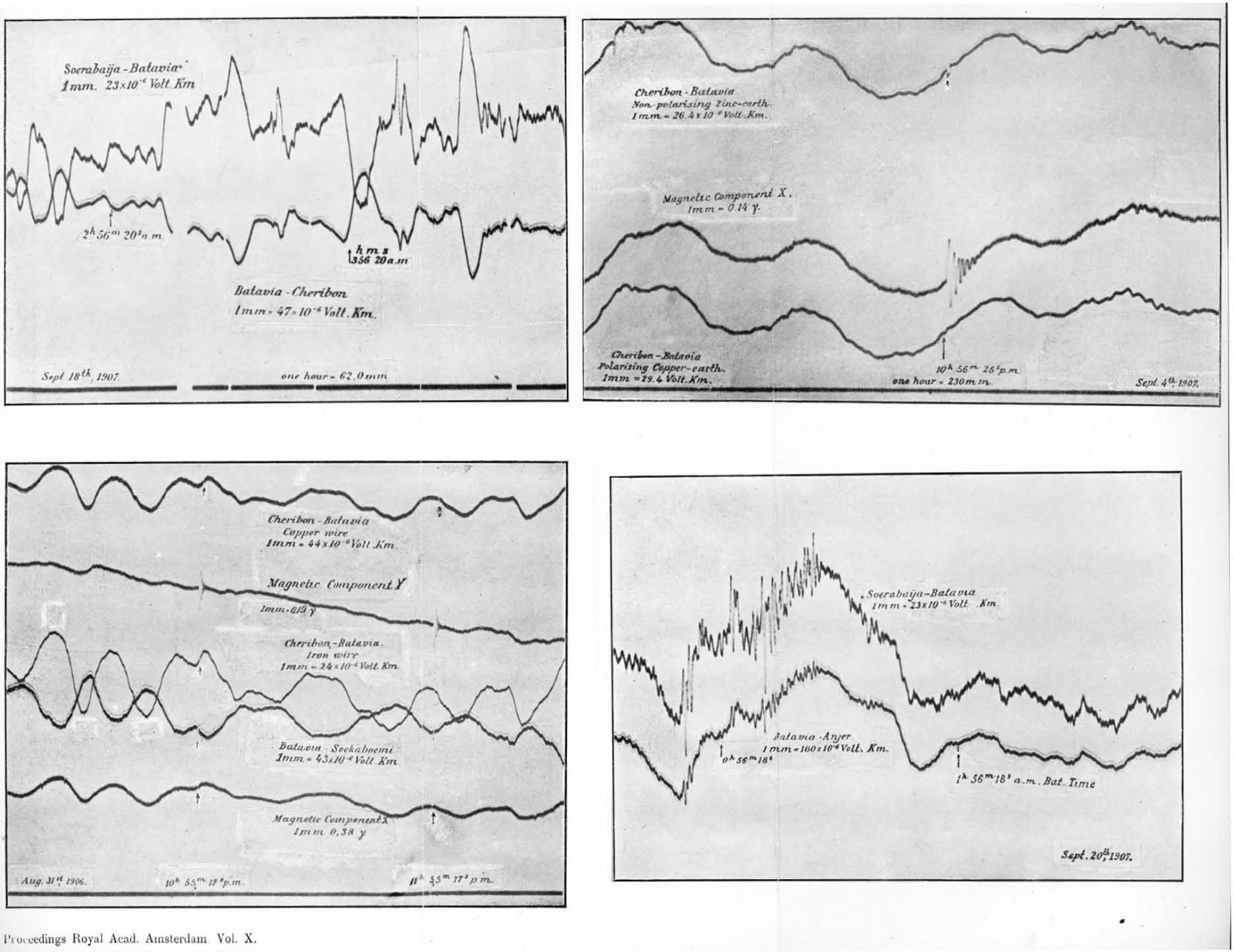
The differences in the intensity and the difference in phase of the earth-current for the lines to Anjer, Cheribon, Billiton and Buitenzorg can be explained also by the difference in conductivity of the ground between those places and Batavia.

For instance between Anjer and Batavia lies the volcano Karang and therefore the conductivity is probably greater than between Batavia and Cheribon, and the fact that the earth-current is four times as strong can be attributed to it.

The great intensity of the earth current for Buitenzorg—Batavia may be partly attributed to the same reason and moreover to the difference in height (280 M), that between Batavia and Billiton to the well conducting seawater.

For the lines Semarang—Batavia and Soerabaja—Batavia we find however for the ratio of amplitude a distinct difference for vibrations of short duration. Each attempt at explanation of the connection between earth-current and magnetic variation will be in vain as long as this has not been confirmed and expounded.

To explain it out of the loss by isolation is impossible, as the difference would have to appear less for the lines Anjer-Batavia (106 K. M.) and Cheribon-Batavia (200 K. M.) which is not the case.


Soerabaija - Batavia
1 mm. 23×10⁻⁶ Volt. Km
2h 56m 20s a.m.
h. m. s
356 20 a.m
Batavia - Cheribon
1 mm = 47×10⁻⁶ Volt. Km.
Sept 18th. 1907.
one hour = 62.0 mm
Cheribon - Batavia
Non-polarising Zinc-earth.
1 mm = 26.4 x 10⁻⁶ Volt. Km.
Magnetic Component X.
1 mm = 0.14 γ.
Cheribon - Batavia
Polarising Copper-earth.
1 mm = 29.4 Volt. Km.
10h 56m 25s p.m.
one hour = 230 m.m.
Sept. 4th. 1907.
Cheribon - Batavia
Copper wire
1 mm = 44×10⁻⁶ Volt. Km.
Magnetic Component Y
1 mm. 0.19 γ
Cheribon - Batavia.
Iron wire
1 mm = 24×10⁻⁶ Volt. Km.
Batavia - Soekaboemi
1 mm = 43×10⁻⁶ Volt. Km.
Magnetic Component X
1 mm 0,38 γ
Aug. 31st. 1906.
10h 55m 17s p.m.
11h 55m 17s p.m.
Soerabaija - Batavia
1 mm = 23×10⁻⁶ Volt. Km.
Batavia - Anjer
1 mm = 160×10⁻⁶ Volt. Km.
0h 56m 18s
1h 56m 18s a.m. Bat. Time
Sept. 20th, 1907.

Neither can it be explained by mutual induction of the two lines, passing partly along the same telegraphpoles, as that influence would just work inversely.

There is a circumstance which causes the lines to Anjer and Cheribon to differ greatly from those to Semarang and Soerabaja; that is the greatest depth below the surface of the earth which the chord reaches between those places and Batavia.

It is for Batavia—Anjer 1 K. M.
Batavia—Cheribon 3 „
Batavia—Semarang 14 „
Batavia—Soerabaja 37 „

When thus the variations of short duration cause a current chiefly at a greater depth, where the conductivity is very different from than at the surface, a distinct difference might appear. The opposite however is more to be expected.

To conform that difference it will be necessary to register at Semarang the current between Cheribon-Semarang and Soerabaja-Semarang.

If we find for that the same as for Batavia-Cheribon and Batavia-Anjer, then indeed we must attribute the greater increase of amplitude with short duration for the lines Batavia-Semarang and Batavia-Soerabaja to the greater distance.

ERRATUM.

In the Proceedings of the Meeting of March 30, 1907:

p. 770 l. 3 from the bottom: for 46.419 read 46.491.
p. 779 l. 10 from the top: for VII H_2 1 read VII H_2 2.

(February 20, 1908).