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COMMENTARIES
In Colorado Springs' Memorial Park, near site of Tesla's experimental station, an historic marker notes the operation.
1 June

Tesla mentioned a similar application of a magnet for extinction of the arc in rarefied gas in his lecture to the IEE in London 1892\(^{(5)}\). The initial idea for this type of detector may date from the time when he was intensively studying phenomena associated with currents in vacuum.

3 June

During the year 1899 Tesla filed applications for four patents\(^{(8-11)}\) which made use of the principle of "accumulating energy of feeble impulses". It may be seen from these patents that the function of the capacitor was to store energy from the commutated (in fact rectified) HF current. The condenser is connected to the receiver (a relay) which periodically makes contact\(^{(6,10)}\) when the condenser charges up enough. Both these patents were filed 24th June 1899\(^{(8,10)}\). The other two\(^{(9,11)}\) were filed 1st August 1899. They also refer to a method of accumulating energy but the way the incoming signal controls the charging of the condenser is different: here it causes variations in the resistance of a "sensitive device" which controls the current charging the condenser from a battery. The condenser discharges periodically through the receiver as in the previous case.

Tesla developed the magnet method while he was in Colorado Springs.

5 June

Tesla does not state the origin of the formula he uses to calculate \(M\), the power induced in the secondary, receiving coil, by the primary fed with a power of 4 kW (or \(4\times10^{10}\) erg/sec, not ergs). Although he himself expresses doubts about the calculation, the conclusion he draws is correct, i.e. that these mode of transmission is greatly inferior to that which he calls the method of "disturbed charge of ground and air", in fact that of electromagnetic radiation.

6 June

Working with a darkened Crooke's tube, on the 8th of November 1895 Röntgen noted the luminescence of barium platino-cyanide crystals and discovered that it was due to some unknown radiation which he termed X-rays. Towards the end of that year he held a lecture on his discovery, and in an amazingly short time the whole world knew about
Tesla spent some time in intensive research on X-rays, publishing his results in ten articles in the period 11th March 1896 to 11th August 1897. On the 6th of April 1897 he also gave a lecture on his X-ray studies and presented designs of a number of devices for generating powerful rays. During this lecture he reported interesting data from his earlier experiments with Crooke's tubes in 1894. He had then observed that some tubes which produced only feeble visible light had more effect on photographic plates than tubes which were brighter to the eye. The goal of his research was to obtain true phosphorescence ("cold light"), so that he postponed further investigation of this phenomenon, and of the cause of various spots and hazing on photographic plates which had been kept in the laboratory for a time before use. When he finally did get around to it a fire broke out in the laboratory, destroying practically everything (13th March 1895). It was several months before he could resume his work, and in the meantime Röntgen made his discovery. When Tesla heard about it, it was immediately plain what had been happening in his laboratory. He repeated Röntgen's experiments, which were rather cryptically described, and realized that he had been mistaken in not following up certain chance observations during his work with Crooke's tubes.

During 1896 and 1897 Tesla carried out many experiments with X-rays, also speculating about their nature. He thought "that the effects on the sensitive plate are due to projected particles, or else to vibration far beyond any frequency which we are able to obtain by means of condenser discharges" (Lit. 1, p. A-30). He immediately realized the importance of high voltages for producing powerful rays and suggested using his single-terminal tubes connected to the secondary of the disruptive discharge coil. It is interesting to note that Röntgen too, in a lecture to the Physical Medical Society of Würzburg the same month as Tesla published his first article, also pointed out the great advantage of using Tesla's high-frequency oscillator in generating X-rays.

Tesla measured the reflection and transmission of X-rays for several metals, lead glass, mica and ebonite. It is not clear, however, whether what he measured was true reflected radiation or secondary radiation. He also tried to detect refraction but did not succeed, for reasons which are today obvious. In papers and in a lecture before the New York Academy of Science he described a number of tubes for producing powerful X-rays, most of them resembling Lenard tubes (which he often mentions) but without the anode terminal.

7 June

Descriptions of the high-frequency transformer are to be found in Tesla's publications and patents from 1891 onwards, but he did not patent it until 1897. The invention protected by this patent is "A transformer for developing or converting currents of high potential, comprising a primary and secondary coil, one terminal of the secondary being electrically connected with the primary, and with earth when the transformer is in use, as set forth". It in particular protects the spiral form of the secondary, and a conical form is also mentioned. For ordinary uses a cylindrical secondary divided into two parts is proposed. A new feature is the specification that the length of the secondary should be "approximately one quarter of the wavelength of the electrical disturbance in the secondary", and the velocity of propagation of the electrical disturbance through
9–12 June

In his efforts to construct a sensitive detector for small signals Tesla worked out several designs making use of the thermal effect of high-frequency current. Since the energies involved are very small (according to Tesla of the order of 1 erg), receivers based on this principle would be extremely delicate.

In the archives of the Nikola Tesla Museum, Belgrade, a slide has been found which evidences that Tesla was probably preparing to file a patent on a receiver similar to that which he described in the diary the 9th of June (see drawing on p. 399). The entry for 11th June is stamped on the back "U.S. Patent Office, Nov. 15, 1902."

The basic principle of these detectors is of an earlier date. According to Fleming (33), Gregory carried out measurements of radiation intensity by the extension of a thin wire in 1889, and Rubens and Ritter in 1890 using a bolometer.

13 and 14 June

From the very start of his work on wireless transmission of signals in 1892–1893 Tesla advocated the use of continuous HF current, while other experimenters were working with damped impulses. The advantage of continuous currents is particularly great in the transmission of continuous signals, such as speech. The entries for the 13th and 14th of June describe two modifications of the HF oscillator which could be used for amplitude modulation. These two circuits were probably in fact the first modulators in the history of radio. It is not known whether Tesla carried out any experiments with this apparatus, but similar ideas were implemented later (19).

Tesla's notes illustrate how carefully he studied the design, from the power supply to theoretical aspects such as the ratio of the maximum modulation frequency to the carrier frequency.

The transmitter using "controlled arc" modulation of the oscillator power described in the entry of June 14th produces amplitude modulated wave by varying the carrier power about a mean value. The modulating signal can be of low power, so that the device as a whole can also be considered a frequency-shifting amplifier.

15 June

This trial run of the new oscillator was Tesla's first step towards the implementation of his high-power generator. The secondary of the HF transformer was made conical in order to reduce the voltage between turns at the top of the coil. This feature is described as one of the alternatives in his "Electrical Transformer" patent (26). Tesla was the first to suggest using braided insulated wires instead of solid conductors in HF circuits in order to reduce eddy currents (see e.g. ref. 46, p. 60).

16 June

In these experiments Tesla investigated the influence of grounding* on the HF oscillator. The main point of interest for him was the propagation of electrical waves

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* At this time there was relatively little experience with grounding. He explains in this entry that
through the Earth. He had already put forward the hypothesis that the Earth could be used as one of the conductors in transmission of energy from a transmitting to a receiving aerial in 1893\(^6\). He further developed this hypothesis in his patent application “Apparatus for transmission of electrical energy” filed in 1897\(^{13}\).

18 June

The secondary circuit was modified by the addition of another coil, altering its response to the primary and the spectrum of the oscillations. Tesla had already found in experiments in New York that this “extra coil” had a good effect. This coil was not inductively coupled to the transformer (some coupling probably existed, though weak).

19 June

Continuing his study of the receiver components referred to between 9th and 11th June, Tesla describes a sensitive detector using the attractive force between the plates of a charged condenser. Descriptions of allied devices are to be found in several of Tesla’s patents. In patents\(^8\) and \(^9\) this effect is used to periodically make the receiver circuit when main condenser charges up sufficiently (there is no preexcitation nor quenching, since the circuit quenches itself when all the stored energy gets discharged). A fuller description, where it is noted that the performance of the device is improved under reduced air pressure, may be found in patents\(^{70}\).

20 June

Tesla did not make a strict theoretical analysis of the mode of operation of his oscillator, but determined all the main parameters by tests on a simplified representation of the oscillator circuit. For example, he estimated the power supply drain from the energy in the primary circuit capacity multiplied by the rate of discharge. This involves the assumption that the condenser charges up by the same amount before each discharge (which cannot be the case when it is charged from an AC supply) and that all the energy gets dissipated before the next charging.

The “vibration”, i.e. the resonant frequency of the primary circuit is calculated from the measured inductivity of the primary with two turns (see June 17th) and its capacity. Since he was now using one turn, the inductance is divided by 4. The capacitance was somewhat greater than that measured on June 18th with the old jars. Using these \(L\) and \(C\) values he calculates the resonance period of the primary using Thomson’s formula for a lossless circuit.

He then finds the wavelength of the primary oscillations, and hence works out the number of turns the secondary must have so that its length is one quarter of a wavelength (see the commentary to 7th June). It is not surprising that he went astray in trying to set up a representation of the secondary circuit as an oscillatory system since the distributed

\(^{12}\) without wires\(^{16}\) where the alternating current source is connected “with one of its terminals to earth (conveniently to the water mains) and with the other to a body of large surface \(P\)”. Popov’s receiver of 1895 also used \(\tau\) rounding via a water pipe\(^{12}\). Around 1895 Marconi did some experiments with a Hertz apparatus grounding one terminal of the inductor and leaving the other connected to an elevated conductor.
 capacitance was not determined. Tesla's own doubts about this way of determining the secondary in terms of length of wire are best revealed when he refers to checking its resonant frequency treating it as an oscillatory circuit.

21 June

Returning once more to the problem of the conversion of mains power into HF power Tesla calculates the energy in each charging cycle of the condenser (see comments for June 20th). Taking it that all the energy in the charge condenser will at some instant be found in the condenser of the secondary circuit, he in fact works out the peak voltage on the secondary condenser. The energy equation for lossless coupled circuits has the general form

$$\frac{1}{2} C_p U_p^2 = \frac{1}{2} C_s U_s^2$$

where $p$ refers to the primary, $s$ to the secondary circuit, $U$ is peak voltage. It should be noted that Oberbeck's theory yields the same ratio between the voltage on the primary condenser just before discharge begins and the peak voltage on the secondary condenser.

22 June

The circuit with two condensers, one being charged from the power supply and the second via a spark from the first represents a modification of Tesla's classic oscillator*. Theory shows that protraction of the oscillation in the primary circuit lowers the efficiency of the oscillator because energy pulses back and forth between the primary and secondary. However, in this circuit protraction of the spark does not have the same effect because while it lasts the primary capacitance is $C+C_1$, but when it stops the capacitance is only $C_1$. Why the sparks in the secondary were stronger with $C=aC_1$, $a$ a whole number, is hard to say without a more exhaustive analysis.

The note at the end of the entry indicates his satisfaction with the results and that he felt it necessary to continue research in the same direction.

23 June

The two formulae are in fact identical if the thickness of the wire is neglected, because then

$$S = (2\pi r N)^2 = 4\pi SN^2$$

24 June

Rarefied gases had long interested Tesla, and his work on their conducting properties, especially at high frequencies, is well known, e.g. the patents on an electric lighting system and an incandescent lamp. He presented detailed analyses of the same problems in his famous lectures. Rarefied gas as a conductor is also referred to in his patent application "System of transmission of electrical energy".
25 June

The device shown in the drawing was intended to amplify the vibrations, in the following way: some of the power driving cylinder A is converted by friction of brush b against A into vibrations of b. Since the friction is a function of the current in the electromagnet, the vibrations of b have a time variation similar to the time variations of the current. If the circuit of the electromagnet includes a microphone and a battery, then the device should amplify the speech signal, brush b vibrating in synchronization with the speech pressure but with much more energy. This amplified signal could be used in a modulator (see June 13th and 14th). The drawing shown on p. 405 (from Tesla’s slide in Nikola Tesla Museum, Belgrade) illustrates how Tesla thought of implementing some of these ideas.

26 June

The principle of this device using high voltages to separate gases would be that the molecules (in fact ions) of the different gases would behave differently because of their different mass:charge ratios. It is not known whether Tesla tried to verify this idea experimentally. In a later article (28) on electrical oscillators he mentions among the possible applications “formation of chemical compounds through fusion and combination; synthesis of gases; manufacture of ozone . . .” but does not mention separation of gases, so that it may be he never went any further than the initial idea.

27 June

The transmitter (Figs. 1 and 2) and receiver (Fig. 3) having several tuned circuits, the transmitter generating several signals at different frequencies and the receiver responding only when all these signals act at the same time, were the subject of two patent applications filed 16 July 1900 (subsequently granted) (18).

This method allows much more selective reception than a single-frequency channel, and is much less sensitive to interference, and the signal can only be decoded by a special receiver. In his patent applications Tesla likens it to a lock which can only be opened when one knows the combination.

The entry of June 27th was subsequently brought in evidence in a dispute before the U.S. Patent Office about priority to the idea of a multi-frequency system (68). The back of the page bears the stamp “U.S. Patent Office, Nov. 1902.”

28 June

Tesla considered that the self-capacity of the secondary winding was proportional to the number of turns and inversely proportional to the spacing between turns, so that the ratio of the distributed capacities of the new and the old coil is \( N_2/ d/N_1 d_1 \) (\( N \) — number of turns, \( d \) — spacing between turns).

The ratio of the inductance of the secondaries with different numbers of turns he finds from the relation

\[
\left( \frac{N_2}{d} \right)^2 = \left( \frac{N_1}{d_1} \right)^2 \frac{Nd}{N_1 d_1}
\]
derived from the expression for an infinitely long coil, and yielding the same ratio as in the case of capacitance.

The numerical value for the capacitance of the old coil appears here for the first time, without explanation.

The receiver experiments were probably done in preparation for a patent application. Leonard E. Curtis appears a number of times as a witness to Tesla's patents (see for example refs. 8, 10), or as one of the attorneys (on many patents from 1896 on).

30 June

Description of electric circuits in terms of mechanical analogies was at one time very popular. The resonance of an electrical circuit was likened to the swinging of a pendulum, and coupled resonant circuits to two pendulums linked together. Maxwell and his followers even tried for a long time to describe the electromagnetic field in terms of a mechanical model. Tesla's comparison of his "additional coil" to a pendulum is not precisely formulated but rather intuitive. He correctly discriminates between the excitation (initial conditions) and the Q-factor. He does not fully explain how he imagined that the vibrations of the three systems, the primary, the secondary and the "combined system", would be the same. By "freeing" the additional coil he means a weakening of the coupling between it and the secondary exciting it. He obviously had a clear understanding that a circuit can oscillate at its own resonant frequency if the coupling with an excitation circuit is loose.

2 July

Here Tesla gives the calculation of values for the spark gap oscillator in the fullest detail so far. However, the analysis does not include all the magnitudes relevant to the functioning of the oscillator, e.g. the primary/secondary coupling of the transformer and the distributed capacitance of the secondary. The power equation is also not fully explained and justified. However, by means of this approximate calculation Tesla did get a valuable rough guide relatively quickly and easily.

3 July

The distributed capacitance of the secondary windings is difficult to determine. It depends on the coil diameter, the dimensions of the wire and the insulation and the winding pattern. In a single-layer coil it is due mostly to the capacity between neighboring turns, and this is the way Tesla calculated it. He considers a greatly simplified model in which it is taken that the parasitic capacity per turn is equal to $A/4\pi d$, where $A=\pi d$, half the surface area of the wire in one turn, and $d$ is the distance between turns. The capacitance is calculated as that of a plate condenser of area $A$ and gap $d$ with air between the plates. This model is open to a good many criticisms, but it must not be forgotten that Tesla had to find some solution, whatever its shortcomings. It is also not correct that the total inductance and capacitance of the secondary circuit with the "additional coil" are additive. but Tesla was himself aware that this was guesswork, and often mentions the words "rough-
from the resonant frequency of the secondary circuit and the known primary inductance (one turn) he finds the required capacity of the primary circuit. He then checks whether this capacity can be used with an LF transformer of the given power. The formula is approximate, but gives a good rough guide for the power in the mains transformer. The peak power rating of the transformer must be even greater than the value found because the condenser is not charging all the time but only in short pulses.

5 July

It is possible that Tesla was planning to construct a balloon to take an antenna to great height\(^{(13, 14)}\), and was therefore interested in the generation of hydrogen. He does not give any indication, however, of whether he actually carried out any experiments in this direction, or of the grounds he had for expecting the desired decomposition to take place.

7 July

For the “resonance method” Tesla envisaged two possible types of resonant transformer: one with loose coupling between the primary and secondary, and the other with tight coupling but only with part of the secondary inductance\(^*\). This latter type he protected under the patent “Apparatus for transmitting electrical energy”, for which he applied on 18 January 1902\(^{44}\); a good deal of his time at Colorado Springs was spent in developing it.

His conclusions about various parameters of the oscillator indicate that he had by then gained sufficient experience to be able to design such devices with improved performance in the parameters he wanted. As the experiments proceeded he gradually increased the voltage of the LF power supply. On June 20th he had calculated with an excitation voltage of 20 kV, but he had assumed a much higher rate of charging of the condenser, so that he obtained then a greater power than now with 40 kV. The difference in the number of chargings per second is nowhere explained, nor had he ever previously described how it was calculated. The first time he had probably taken it as being equal to the number of breaks on the rotary discharger, and the second time as double the mains frequency. In this light the accuracy of “the capacity of condenser which the transformer will be able to charge” is dubious. However, Tesla did not take the value he calculated as limiting the capacitance in the primary, noting that it did not take into account resonance and other factors which might enable the transformer to charge a much larger condenser.

8 July

From observing the behavior of his oscillator Tesla came to an interesting conclusion concerning the shape of the conductor of the primary winding, i.e. that a strip conductor was better than a wire of circular cross section because all other conditions being the same it did not get so hot. He believed that there was a special reason for this “not yet satisfactorily explained”. Since the dimensions of the strip conductor are not known we cannot work out the reduction in resistance relative to a circular section conductor due to the

\(^*\) It is easily demonstrated that these two methods are similar. If in the second case a part \(L_2\) of the secondary capacitance is coupled to the primary with a coupling coefficient of \(k_2\), while in the first case the entire capacity of \(L_2\) is coupled to the primary, then the exposure of the secondary
skin effect. The surface area of a strip will always be greater than that of a round conductor, the more so the flatter the strip: for a width to thickness ratio of 10 : 1 a strip will have about 1.8 times more surface area; this could effect a considerable reduction in resistance, which would explain, at least in part, the phenomenon which Tesla discovered.

In connection with coils, a problem to which Tesla often returned was that of the velocity of propagation of phenomena through the circuit. In order to achieve the maximum voltage across the secondary terminals without the addition of capacitance Tesla considered that the length of the windings should be equal to a quarter of the wavelength. This would be perfectly correct in the case of a straight conductor with one end grounded. Such a system, when excited, would certainly have the maximum voltage at the free end, but its magnitude would depend greatly on whether the conductor were horizontal (when radiation is small, so that the Q-factor of the resonant system is high) or vertical (when radiation is efficient so that the damping is high). With a helical conductor as in Tesla’s oscillator, radiation is low as with a horizontal conductor, so that high resonant voltages are possible unless they are reduced by parasitic capacity. In fact, helical winding increases the distributed inductance and capacitance so that the velocity of propagation of current through the coil is reduced, which means that the wire must be made shorter to achieve maximum voltage across the terminals. If the secondary is terminated with a capacitive load (e.g. a metal sphere) the winding length must be still further reduced in order to maintain the same resonance conditions. Tesla took both these effects into account in designing the secondary.

Figures 1—8 illustrate several ways of reducing the distributed capacitance of the secondary. The solution of placing the turns far apart (Fig. 6) is still used today when it is necessary to reduce parasitic capacitance.

9 July

In calculating D (the ratio of the turn spacing of the old and new secondary) Tesla accidentally took the frequency instead of the period, so that he got \( D = 83 \) instead of \( D = 2.45 \). A second numerical error occurred in the formula relating \( D \) and \( C \) (38 omitted from under the square root) so that \( C \) came out to be 10,000 cm instead of 227 cm. Since he never made use of these results, Tesla naturally never discovered his mistakes.

Tesla’s method of measuring the oscillator frequency by means of an auxiliary coil is interesting. This coil, with its own distributed capacity, in fact constituted an absorptive resonator. The size of the spark across its terminals provided an indication of the amount of power it absorbed. (In some respects it resembled Hertz’s resonator). Tesla adjusted its resonance by varying the number of turns for the biggest spark. He then calculated the wavelength on the assumption that at resonance the length of the coil winding was one quarter of a wavelength. The wire length he determined by measuring the coil resistance, the resistivity per unit length of the wire being known. This method embodies a systematic error due to neglecting the reduction in speed of propagation through the coil, and it is applicable for oscillators of high power. However, it was the most reliable method Tesla had used to determine oscillation frequency up to that time.

For theoretical calculation of the oscillation period Tesla used two formulae: one
the secondary short-circuited. How far this is justified it is difficult to say because an oscillator which discharges heavily does not satisfy the simple theory of the resonant transformer oscillator; the secondary is then heavily damped and free oscillations in it decay rapidly, so one would have to apply a theoretical treatment for heavily damped oscillators.

10–11 July

In order to try and increase the secondary voltage of the HF transformer by keeping down the distributed capacity of the secondary Tesla added a third oscillatory circuit, thus obtaining an oscillator with three resonant circuits of which two are tightly coupled*. The third circuit will not necessarily be most strongly excited when its resonant frequency coincides with that of the primary and secondary (assuming these are the same) and the primary and secondary are tightly coupled. If the spark in the primary circuit lasts long, then the tightly coupled primary-secondary system will produce two distinct oscillations, and the third circuit will be most strongly excited if it is tuned to one (strictly speaking to near one) of these two frequencies. On the other hand, if the spark is of short duration the tightly coupled system may oscillate strongest at the resonant frequency of the secondary, and then the third circuit will be excited the strongest when all three have the same resonant frequency. Tesla believed that his system of coupled circuits was producing a single vibration, which under certain conditions is in fact feasible.

12 July

Early on in the diary Tesla mentioned a method using a condenser to store energy from weak impulses arriving at a receiver. In the circuit drawn here, the condenser is charged by a battery via a self-inductance coil and a coherer shunted by the secondary of an oscillation transformer. In the absence of an external signal the resistance of the coherer is large so that the charging current is small. The circuit breaker periodically discharges the condenser through the primary of the transformer generating alternating current in the secondary which biases the coherer. When an external signal is received the resistance of the coherer is reduced and the charging current rises rapidly, which in turn increases the AC bias on the coherer which therefore soon gets to full conductivity (in fact there is a feedback loop).

14 July

He had tried out the devices shown in these drawings earlier on, some of them for wireless remote control of a boat. Patent No. 613809, “Method of and apparatus for controlling mechanism of moving vessels or vehicles” of 8 November 1898 (application field 1 July 1898) mentions the possibility of using electromagnetic resonance but does not give the circuit diagram of the transmitter referred to here.

15 July

Earlier on (see the entry for June 3rd) Tesla presents a general scheme in which the ‘dynamo principle’ is referred to as one of the ways of accumulating energy from weak

* Similar systems were analyzed in 1906 and 1907 by M. Wien, in 1907 by C. Fischer, and in 1909 by J. Kaiser(46). From their papers it may be seen that the effective value of the current in the loosely
signals. The circuits given here illustrate how he implemented this principle. The "sensitive device" has a resistance which varies as a function of the antenna signal, and is connected so as to alter the excitation of a DC (Figs. 1, 2, 3) or AC (Fig. 4) dynamo.

Although he says that apparatus using this principle had already worked well in New York, none of these receivers, nor the principle they embody, appeared in any of his patents.

17 and 18 July

This is a continuation of the work described in the entry of June 12th, with different combinations of the same components plus relay R for registering the signals received. In all the circuits the sensitive device has an accumulating function. He experimented with different modifications trying to optimize sensitivity and reliability. The circuit in Fig. 1 of July 18th has two batteries, and that Fig. 5 an autotransformer instead of the usual transformer with a primary and secondary.

19 July

This is the first mention of a device which functions either as a transmitter or, with certain modifications of the power supply and antenna circuits, as a receiver. The transmitter is powered from the mains, the receiver from two batteries, $B_1$ biasing the sensitive device $a$ with AC pulses obtained by discharge of condenser $C$ through the primary of an HF transformer when the mercury switch closes.

The modification in Fig. 2, in which the relay is the secondary of the oscillator transformer, is simpler, but cannot be used as a transmitter.

21 July

In this setup a small excitation of one sensitive device is rapidly amplified by a feedback loop which acts via a transformer on the other sensitive device. Figure 10 shows how the receiver was excited by aerial (elevated metal ball $C$ or $C_1$) — earth system.

22 July

Figure 8 shows the circuit of a receiver obtained by modification of the transmitter Tesla was then experimenting with. When functioning as a transmitter it is powered from the mains and is in fact a standard Tesla oscillator with a mercury interrupter between the condenser $C$ and the primary $P$. The relay, sensitive device $a_1$ and battery $B_1$ are omitted and the secondary is connected to the antenna and ground. It may be noted that Tesla did not use the best receiver modification (as in Fig. 6), probably to simplify reconnection as a transmitter.

23 July

The "sensitive device" Tesla used for detecting electrical waves is usually known as a coherer\(^{(47)}\). It consists of a tube of some insulator with contacts at either end and metal powder (chips) inside. Its resistance is normally high, but drops rapidly when a large
electrical discharges. A major advance was Branly's observation in 1890 that a spark changed the conductivity of a metal powder at a distance. He carried out many experiments with various metal powders, determining their change in resistance by connecting them in series with a galvanometer and battery. In 1894 Lodge* showed that the conductivity of a metal powder could be altered by an electromagnetic wave; this was the final step which preceded the widespread introduction of coherers for the detection of radio waves. From the period 1895—1896 the coherers used by Popov and Marconi are well known.  

Once activated, a coherer remains in the conducting state. To reestablish the high-resistance state it has to be shaken. The strength and timing of the shaking have to be properly adjusted. A novel method of decoherence of powders was invented by Popov, and used by him in his receiver and later by others.(43) In 1898 Rupp(48) found that constant slow rotation of the coherer keeps it sensitive. The decohering effect of rotation had been discovered earlier, in 1884, by Calzecchi-Onesti(49).

Tesla mentions that he had worked with a rotating coherer in the New York laboratory, so it is possible that he used decoherence by rotation before Rupp. He finds it superior to other methods of decoherence because then the sensitive device behaves like a selenium cell, conducting only when radiation acts upon it. Also its sensitivity can be controlled by changing the rate of rotation.

24 July

From the pagination of the manuscript it may be seen that the entry for this day was divided into three parts (the previous day two parts). The first part, three pages, refers to experiments with a 35-turn secondary on the oscillator, the second part, five pages, to a resumption of these experiments, and the third, three pages, to the determination of the capacity of the 35-turn secondary.

Tesla adjusted the regulating coil in the primary to obtain the maximum secondary voltage, judged by the size of streamers. He connected an "extra coil" to the free terminal of the secondary. He investigated the operation of the transformer at harmonic frequencies by doubling the primary capacity** and making fine adjustments of the primary frequency by varying the inductance in order to get maximum response of the secondary to the harmonic of the primary.

On resuming the experiments Tesla sought an explanation for the occurrence of the largest streamers from the secondary when the regulating inductance was practically cut out. He found that the highest voltage at the free terminal of the extra coil (connected to the secondary like in Fig. 2 of July 11th) was not obtained when the frequency of the excitation was equal to the natural resonant frequency of the coil. After an extensive analysis he came to the correct conclusion (unlike that of June 30th, which was valid only for a special case), that when free oscillation of the secondary becomes influential, the parameters of the primary have to be adjusted to get maximum voltage across

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* The term "coherer" is due to Lodge, and denotes a device containing particles of metal such that its resistance is normally high, but is reduced under the influence of electromagnetic radiation.

** For the primary to oscillate at half the frequency the capacity would have to be quadrupled. It is possible that instead of connecting the banks of 8-9 iars in series, equivalent to the capacitance of
the secondary, and resonant frequency of the extra coil has to be equal to the resonant frequency of the coupled primary-secondary system. It seems that it did not occur to Tesla that when the coupling was tight the combined system produced different spectra during and after the spark. It would seem therefore, all the more significant that he was able to reach this correct conclusion, through a combination of empirical results, simple theory and intuition.

Tesla notes that during discharge in the secondary sparks went across the lightning arresters. Since the arresters were connected to the power line, Tesla thought that the HF voltage came from a wave propagating through the earth and getting into the line somewhere else. We have no evidence which would support this statement or establish whether it was not due to coupling between the oscillator and the mains via the power transformer.

The third part of this entry refers to measurement of the capacity to ground of the secondary coil as a whole. Tesla does not explain how he performed the comparison with a standard capacitor nor at what frequency.

26 July

This entry is concerned with much the same topics as that of June 30th. He investigated the influence of the HF transformer primary-secondary coupling on the 8th of July.

27 July

In his first condenser discharge oscillation transformer for generating high frequencies in 1891(4, 13) Tesla used a simple air gap for regulating the charging and discharging of the condenser. However, a year later he had already described several improvements on simple spark gaps using a magnetic field or an air current for rapid extinction of the arc thereby reducing the period of the charge-discharge cycle. He also described the advantages of a splitted arc across several smaller air gaps: with the same total gap length the breakdown voltage is higher, so that smaller gaps can be used and the losses are less*. A fourth form of improvement which he invented was the use of various rotary interrupters(5).

In the period from 1893 through 1898 Tesla patented several types of interrupter, or "electric circuit controllers". It is interesting that all these patents refer to various types of rotary interrupter, with or without an air gap. Some rotary interrupters were protected within patents for high-frequency generators, including the following:

- the combination with discharge points immersed in oil. The turbine whose blades make and break the condenser circuit is driven by oil under pressure(50)
- mechanical make-break controllers for DC(51)
- synchronous controllers with and without regulation of the interrupt timing, for use with AC sources(52)
- commutators for alternate switching between two condensers in the primary circuit of a Tesla oscillator(53).

In 1897 and 1898 Tesla was granted a number of patents for "electric circuit controllers". The principle requirement was that they should make and break a circuit at the rate of from a large number of operations per unit
time. In eight patents(27) Tesla gives designs for rotary interrupters with conducting or conducting and insulating fluids, usually mercury and oil, respectively. In some designs the interruption takes place in an inert gas under pressure. He gives ingenious designs for using a mercury jet playing on a toothed metal rotor, and for producing two mercury jets (fluid contact).

The rotary interrupter with two auxiliary air gaps shown in the figure was a new idea. One of the reasons Tesla added these air gaps was probably the high voltages with which he was working, since they allowed him to regulate the excitation. That this could be done may be seen from the statement that by adjusting these gaps the period of charging from the secondary of the mains transformer could be shortened. At the end of the entry he records that the best results were obtained with two rotary interrupters (with toothed disks) rotating in opposite directions. He does not explain how he chose the tooth ratio so that the number of interruptions was equal to the product of the number of teeth.

28 July

This entry provides one of the most detailed descriptions of the receiver with two rotating coherers and a condenser for accumulating the energy from weak signals. At point b the circuit C—P is periodically made and broken and the resulting AC pulses bias sensitive device A' in the secondary. Sensitive device A is still poorly conducting so the charging current of C via damping coil L is small. When an arriving electromagnetic wave reduces the resistance of A, C charges much faster and the voltage induced in secondary S also rises rapidly. The resistance of A' drops rapidly and current from battery B' activates relay R. Judging by Tesla's report, the receiver was very sensitive to distant electrical discharges.

29 July

To check out his theoretical conclusions about the free oscillation of the "extra coil" (see 30 June and 26 July) Tesla made a new coil with a higher inductance. As this was his first experiment with the new coil, he had to adjust the circuit parameters by trial and error.

Tesla's ingenuity found full expression in the way in which he developed condensers for high voltages. He filed a patent application on his design for a fluid electrolyte condenser on June 17th, 1896(67).

30 July

To try and verify his hypothesis about the rejection of harmonics with appropriate coils, Tesla changed the connection of his "extra coil" as shown in Figs. 4 and 5. To understand his way of proceeding one must take into account his ideas from 1893(6) concerning the induction of earth currents via an aerial-earth system. However, the standing waves in terms of which he tried to explain the arcing over the lightning arresters cannot be significant at these frequencies.

31 July

Tesla made the condensers for the primary circuit out of mineral water bottles filled with a neutral solution of each salt, and standing them in a metal tank of the same
electrolyte in the bottles) could be connected in parallel as desired. The smallest capacity adjustment possible was equal to the capacity of one bottle.

After various tests of what voltage the glass dielectric of the bottles could stand, Tesla returned his attention to the secondary of the oscillator, in which rightly way the limiting factor for obtaining higher voltages. His analysis of the distributed capacity of the secondary is a good illustration of his inventiveness in a little known field and how he sought to reduce problems to a simple but mathematically and physically sufficiently accurate model. It must not be forgotten that these are Tesla's working notes, which is sufficient justification in itself for some of the hypotheses which the reader might otherwise rightly object to.

2 August

A receiver of this type is mentioned in the entries of July 12th (the principle), July 28th (circuit diagram with two sensitive devices and relay), July 30th (in connection with earth waves). The transformer here has a frame similar to that of July 28th but with somewhat more turns. The sensitive device was described on July 21st.

Tesla often worked on several problems in parallel. Here for example we have entries concerning the receivers, the development of condensers for the primary of the big oscillator, and the power equation for a new configuration of the oscillator primary circuit. The condenser $C_1$ in Fig. 2 protects the mains transformer against overload but has the drawback that it reduces the initial voltage on $C_2$. Tesla's analysis refers to the case of two condensers in series, neglecting all transient phenomena. It may be that he was induced to think about protecting the mains transformer because of his doubts about the ability of the dielectric to stand the voltages which he intended to use.

3—14 August

These experiments are a continuation of some earlier research. Here Tesla investigates various modifications of his "condenser method of magnifying effects". All the circuit diagrams of receivers, over 50, include at least one battery, sensitive device, condenser, rotary interrupter and HF transformer. Some of them show a relay for registering the signal received, while in others its presence is understood. Likewise, in all except one case (5 August, Fig. 1) the plates which brings the excitation to the sensitive device are not shown. Tesla says that these plates can be in one or two media, meaning that both can be in the air, both in the ground, or one in the air and the other in the ground, preferably elevated. In the patent\(^8\), referring to these plates, he also says: "... they may be connected to conductors extending to some distance or to the terminals of any kind of apparatus supplying electrical energy which is obtained from the energy of impulses or disturbance through the natural media."

As regards mode of operation, the various receivers have in common that the sensitive device is biased by a battery. They also include a Tesla oscillator (clockwork rotary interrupter) which creates an added bias on the sensitive device (or devices). This AC pulse bias acts as positive feedback, avalanching the sensitive device into conduction as soon as an arriving signal starts to cause some change. In the receivers with two sensitive devices
the one which receives the external signal is usually in the primary side and the other, which activates the relay, on the secondary side. When there is only sensitive device it usually shunts the transformer secondary (which has a high impedance so as not to reduce the performance of the device), thus creating an efficient feedback loop.

A general feature of all Tesla's receivers is their delicacy. Very careful adjustment was necessary to get the sensitive device at the threshold of avalanching. Most of the sensitive devices were rotated (see June 23rd) so that they were only good conductors during the action of a signal. In some cases, however, this did not achieve satisfactory deactivation of the coherer. Then he used an electromagnetic buzzer to periodically interrupt the excitation of the sensitive device (see Fig. 2 of August 8th). Probably the circuit in Fig. 2 gave him the idea for that in Fig. 3, where the rotary interrupter is replaced by a buzzer as an electromagnetic interrupter. He then used a buzzer in various other configurations (Figs. 5 and 6 of August 8th), with the aim of reliably biasing the condenser, and hence also the sensitive device, to threshold.

Tesla did not measure the sensitivity of his receivers by any definite method, but there is no doubt that he did compare them in some way. From his notes very little can be deduced about their sensitivity, i.e. the power required to activate them. A rough idea is given by data from July 4th, when he used similar receivers to register electrical discharges. He estimated that he registered waves produced by lightning at least 200 miles away, and continued to receive signals (at periodic intervals) later when the weather had already cleared. He records that with the receiver shown in the figure of July 28th he was in one instance able to register lightning discharges at a distance of 500 miles. He estimated the distance from the periodicity of the signals as the storm moved away.

13 August

The last experiments with the oscillator were described July 31st, with numerous comments and the remark "this to follow up". Probably he had prepared a new condenser bank in the meantime for work with higher voltages (he measured the capacitance of the new bottles on August 11th, and tried them out with the highest voltage so far from the power supply transformer.

15 - 21 August

With the new condenser bank the secondary had to be modified, and on August 15th he worked out the length of wire required. He calculated the period of the primary from the capacity of the new bottles and the inductance per turn of the primary found earlier (mentioned on June 28th as \(7 \times 10^4 \) cm, probably one quarter of the value measured for two turns on June 17th). It was also his intention to adjust the oscillator to the "extra coil".

The entries for 16, 17, 20 and 21 August give some new circuit diagrams for the oscillator which he thought would be more suitable for working at high excitation voltages. They bear witness to Tesla's constant search for improvements involving only limited changes in the apparatus which he used for lower voltages. The chief problem was overloading of the power supply. It is recorded elsewhere that Tesla's experiments with his spark oscillator (probably on some other occasion) burnt out the generator of a power
22 August

In this entry he returns once again to the receivers. He tried out two receiver circuits using one battery and one sensitive device. He changed the capacity in the primary circuit over a wide range, but it is not clear why 1 μF proved best. It remains unexplained what was the relationship between the frequency of the incoming signal and that generated by the receiver itself. Could it perhaps be, if the rotating coherer behaved as a nonlinear element, that the signal was amplified as in a heterodyne receiver? 

23 August

He now put the extra coil in the center of the primary, retaining this configuration from then on. After the usual adjustment of the oscillator he got sparks 2 m, and later 4 m long, indicating a voltage of around 2 million volts.

26 August

Tesla experimented with twice the interruption rate. The oscillator worked better and there was heavy sparking across the lightning arresters (Fig. 4). Investigating the cause of this sparking he inserted a coil in the lead of the metal sphere (Fig. 1) to reject high frequencies. In an earlier experiment (see July 30th) inserting such a choke coil in the ground line had stopped sparking across the arresters. This time it did not, so Tesla tried the circuit in Fig. 2. Still there was no marked change, the sparking across the arresters was only slightly reduced. After this experiment he began to wonder whether the grounding point of the secondary was not perhaps a peak rather than a node of the standing wave. It must be understood that Tesla thought that standing waves were set up around the transmitter (like waves on an open transmission line. With shorter waves the rate of change of amplitude with distance would be faster (i.e. maxima and minima would occur at shorter distance intervals), so he thought that a large potential difference could be obtained with a short distance between the grounding of the secondary and that of the lightning arrester.

In order to explain what happened when the sphere was not grounded (which would mean that there were no short waves) but the sparking across the arrester did not stop, Tesla found it necessary to formulate a new hypothesis: “Could the sparks be produced by static induction upon wire through the air and not chiefly by conduction through earth?”

The experiment with which he tried to verify this hypothesis did not yield any definite answer.

27 August

Although he has noted several times already that good results were obtained with various decoherence techniques (rotation, interruption of the excitation current), this reexamination of his old ideas shows that Tesla is still seeking a more reliable solution. One of the ideas he was gathering together for further investigation is illustrated by the diagram in Fig. 4, in which a rotary interrupter, condenser, choke and battery provide
28 August

Tesla's idea of the Earth as a perfectly conducting sphere lead him to a mistaken hypothesis about the general behavior of the electromagnetic field around the grounding of the transmitter. What he expected at frequencies of the order of 10 kHz in fact occurs at much lower frequencies (73), at which, as far as can be seen from his notes, he did not work in Colorado Springs. He correctly observed that the decisive factor determining whether predominantly waves of the "Hertzian type" or the waves which he thought to be propagated through the earth (in fact waves in the spherical condenser constituted by the Earth and the ionosphere) would be excited was the excitation of the "Earth". Tesla was also certainly in error when he tried to make generalizations concerning the wave frequency, and in his conviction that he needed extremely high voltages to "create" the second conductor for a system of wireless power transmission. He could not know that this conductor already existed permitting transmission at very low loss of very low frequency waves, and that it would not matter whether the energy transmitted was high or low.

29 August

Although the circuit looks simple enough, an analysis of Tesla's receiver with a "magnifying effect" is rather complicated, because transient phenomena have to be taken into account and the resistance law of the sensitive devices as a function of voltage has to be known. It was not easy to adjust a receiver like this to work properly.

Apparently there was an earphone $T$ in the secondary circuit of the transformer, but it is not mentioned in the notes. The sensitivity of an earphone would normally be much greater than that of a relay, so it would be interesting to find out how this apparatus performed. Unfortunately, earphones are practically not mentioned anywhere in the diary.

Tesla here at last makes a few remarks about how the sensitivity of receivers was estimated. To test its response he put a "small capacity" across sensitive device $a$, but of what value, and whether it was charged or not he does not say.

3 and 4 September

The aim of these experiments is not explained, but it was probably associated with the "experimental" coil with which he examined currents in the water pipe. This was a resonant coil which in the receiver played a part analogous to that of the "extra" coil in the transmitter. Its purpose was to maximize the received signal. Since Tesla connected one terminal to ground, it appears that he wanted to pick up electrical vibrations from the earth. In this case too he found that it was not sufficient just to increase the Q-factor $\frac{pL}{R}$, but also that it was necessary to keep the coil's distributed capacity as low as possible. This conclusion was consistent with what he had earlier found about the influence of distributed capacity of the coil on the length of wire needed to achieve resonance. Conclusion (5) is interesting in that it shows Tesla was aware that the secondary and the extra coil, although excited by the same primary, would each oscillate at its own resonant frequency, and if these were not the same, they would beat.
5 September

After a number of experiments, including a few outside the laboratory, Tesla once more concludes that parasitic capacity is very harmful, so he decides to try winding a coil to have minimum capacitance. Unfortunately he does not describe how this was done. In his desire to get the maximum possible voltage from the coil he went as far as thinking that it was best to have no capacity at the free terminal. From one aspect he was right (theoretically a coil gives the highest Q-factor with the least capacity in the resonant circuit), but without the "elevated" metal sphere the received signal was much weaker because the free terminal of the coil no longer had a monopole antenna. In the circuit which he in fact used he did not, however, go to such extremes. He added the "experimental" coil but left the metal sphere (aerial capacity) connected to one end of the sensitive device.

6 and 7 September

In calculating the wavelength for the cable and ball Tesla made an arithmetical error. For the calculated $T$, the wavelength ought to be about ten times less, so that his assumption that on September 7th, he got vibrations of the system consisting of a ball of capacity 38 cm and 120 feet of cable is probably false. It is more likely that the experimental coil was excited by the coupled system of primary, secondary and extra coil.

11 September

Tesla probably thought that he would more easily detect standing waves in the vicinity of the laboratory if the wavelength was shorter. He assumed that the ball-cable system would produce waves which could be registered by the receiver. However, although he measured the electromagnetic field up to a mile away, he probably did not find the expected variation, and could only conclude that electrical disturbances were registered.

13 September

From a document found in the archives of the Nikola Tesla Museum in Belgrade it may be seen that Westinghouse Comp. sent Tesla a 50 kW power transformer for a primary voltage of 200/220 V and secondary tappings of 40, 50 and 60 kV. This is probably the Westinghouse transformer which he often mentions.

15—17 September

The receivers described on September 5th, Fig. 3, and September 11th, Fig. 2, include "tuned" coils whose function is similar to that of the "synchronized" coils shown in the diagrams of September 15th. Tesla did not make a detailed analysis of these receivers, nor do any of his patents on receivers refer to similar circuits. It therefore seems that we do not have sufficient information to draw any reliable conclusions about their sensitivity or their ultimate purpose (for example it is not clear whether they are just for registering signals or for receiving intelligence).

18 and 19 September
the loading of the secondary circuit, and this alters the mode of oscillation. Also, shunting the secondary with capacitance (as in the diagrams of 18 September and 19 September Figs. 2, 3 and 4) alters the spectrum of the oscillation in comparison with that yielded by an oscillator with two oscillatory circuits. Configurations such as those shown in Figs. 5 and 6 of September 19th can be considered as typical Tesla oscillators with a loosely coupled third circuit consisting of the extra coil and capacitive load. Then the greatest voltage at the free terminal of the extra coil is obtained when the natural resonant frequency of this circuit (together with the ball antenna) is the same as that of the strongest component in the spectrum of the oscillator.

22 and 23 September

Having investigated the tapering secondary Tesla started making a new, 15 mm diameter cylindrical secondary. The criterion that the weight of copper in the primary and secondary should be the same follows from the requirement of equal losses in the two windings (losses in the copper). This way of calculating the gauge of the primary and secondary conductors is applied in designing LF transformers, but for HF transformers it only provides a rough guide, for a number of reasons, e.g.: the current ratio may differ considerably from the turns ratio, skin effect is not taken into account, etc.

25 September

As he often did earlier, before finalizing a set up Tesla measured the inductance of the primary and the regulation coil which he usually used as an added, adjustable primary inductance. The value he obtained for $L_2$, differs from that obtained earlier (see July 17th) by the same method.

26 September

By this method the frequency of an oscillator is found with a help of a resonant circuit of known parameters. When its resonant frequency is adjusted to coincide with the frequency of the oscillator, the voltage across its terminals, estimated by the strength of the spark across an “analyzing gap”, is a maximum. Tesla says that the excitation must be “convenient”. Since he introduced regulation of the excitation by means of the small gap $b$, it is clear that “convenient” excitation was obtained with loose coupling. Loose coupling between the primary and secondary circuits of a spark oscillator ensures that the two frequencies which such an oscillator normally produces are very close. Up to a certain degree of coupling, Tesla’s oscillator produces a single frequency. According to Fleming and Dyke[11], with an ordinary spark gap the maximum coupling coefficient for monochromatic oscillation is around 0.05 (certainly less than 0.1), while with a rotary break producing pulse excitation a coefficient of up to 0.2 gives good results. With higher coupling coefficients three components are obtained, even if the primary and secondary circuits by themselves have the same resonant frequency.

27 September

True to the principle that measurements should be checked by calculation, Tesla
but does not obtain agreement. Since distributed capacitance increases the effective inductance at frequencies below the natural resonance of the coil, the second possible reason which he mentions (inexactness of the coil dimensions) could have some influence, but the main reason is the poor approximation provided by the formula when applied to a coil with this length-diameter ratio.

28 September

The circuit diagrams are of great interest because they illustrate a new approach to feeding the antenna (now known as shunt feed) which obviates the problem of insulating the aerial pole. Unfortunately the explanations Tesla gives are too cryptic to be fully comprehensible. The figures do not clearly show whether the lower terminal of the antenna is grounded or insulated. Tesla's conclusions that a standing wave is set up along the antenna and that the distance between points of equal potential is half a wavelength are correct.

The frequencies he was using were not high enough for his antennas to work in the manner shown by the figures (in which case they would be much more efficient radiators than he usually had), so that this contribution to the theory of wire antennas was never properly formulated.

29 September

Tesla says that he experimented with the antennas shown in the drawings, but he does not compare them with a grounded antenna.

The shortness of the antennas relative to the wavelength made them inefficient radiators. The configuration shown in Fig. 3 was best probably because it had the greatest terminal capacity, providing the most favorable current distribution on the antenna. Lack of coil and ball dimensions makes it impossible to go into any more detailed analysis of these antennas.

3 October

The drawing of several of the coils which Tesla often used offers some interesting information about the laboratory which cannot be seen from the numerous photographs. One sees that there was a wooden floor raised 30 cm above ground level, and the drawing shows the dimensions of the coils and how the HF transformer of the oscillator was wound.

4 October

Tesla was primarily interested in the change of capacity of a ball with height, so he measured the primary capacity for two elevations of the ball. In both cases he tuned for resonance of a "special coil". In the first measurement he had \( L_p \), \( C_p = L_c \), \( C_{b1} = 1/\omega_1^2 \) and in the second \( L_p \), \( C_{p2} = L_c \), \( C_{b2} = 1/\omega_2^2 \), where \( p \) refers to the primary circuit and \( b \) to the ball. These equations neglect the effect of interaction between the primary and secondary. They readily yield Tesla's equation

\[
\frac{C_{p1}}{C_{p2}} = \frac{C_{b1}}{C_{b2}}
\]
6-8 October

From the measured inductance of the new secondary and mutual inductance of the primary and secondary, and the primary inductance measured earlier (see September 23th), it follows that the coupling coefficient was 0.58, i.e. tight coupling*. An oscillator with this much coupling will probably produce three pronounced components, even with very rapid interruption of the spark in the primary; this is indicated by the results Tesla obtained with spark oscillators with looser coupling (see the commentary on 26 September).

As before, Tesla determined the wavelength of the oscillator from the period of the primary circuit (see, e.g., June 20th). He compares one quarter wavelength with the total length of wire in the secondary, special coil and extra coil (when no other coils were used, he considered that the length of the secondary windings should be one quarter wavelength).

9 October

He made the last measurements of the change of capacity of a sphere with height on October 5th, but did not give the calculation results. He subsequently improved the apparatus as a whole, and in the present entry describes a different way of connecting the "special coil"; the chief effect of which was to loosen the coupling, which immediately proved its advantages. With weaker excitation it was easier to adjust the "special coil" to resonance because there were no streamers. Parasitic capacities were reduced, mainly to the distributed capacity of the "special coil".

Tesla first determined the distributed capacity of the "special coil". He assumed that the ball circuit resonated at \( \omega_0 \), determined by the primary circuit, so that one can write

\[
L_{p1} C_p = L_{sc} (c + C)
\]

where \( L_{p1} \) and \( C_p \) are the total inductance (including the regulating coil) and capacity of the primary circuit, \( L_{sc} \) is the inductance of the "special coil" (including connecting wires), \( C \) is the distributed or parasitic capacity of the "special coil", and \( c \) the capacity of the ball.

Subsequent changes in the height of the ball changed the capacity in the circuit of the "special coil". To bring the oscillator into resonance with this circuit again, Tesla changed the inductance in the primary circuit. When resonance is achieved, according to Tesla, one can write

\[
L_{p2} C_p = L_{sc} (c' + C)
\]

Dividing this by the preceding equation yields

\[
c' = \frac{L_{p2}}{L_{p1}} (c + C) - C
\]

which is in fact the equation Tesla uses to find \( c' \). Because of an arithmetical error in calculating \( C \), Tesla's numerical results for the ball capacity are about 10% higher than they should be, but this does not essentially affect the conclusions. To calculate the distributed capacity of the coil** he uses the relation \( L_p C_p = L_{sc} (C + c) \) for the ball at

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* The regulating coil in series with the primary reduced the coupling. The new coupling coefficient is found to be \( k' = \frac{k}{\sqrt{L_p (L_p + L_{sc})}} < k \).
a height such that he could consider its capacity close to the theoretical capacity of an isolated sphere.

11 October

Tesla obviously did not sleep much the previous night since he was photographing the oscillator in operation both late at night and early in the morning. The Nikola Tesla Museum in Belgrade possesses several photographs which date from this period, but they are too faded to be worth showing. One of the better preserved photos is shown on p. 221.

12 and 13 October

To calculate the inductance of cylindrical coils Tesla used the formula for a coil of infinite length, which always gave values too large, especially when the diameter:length ratio of the coil was not much less than unity. However, when the proper corrections are made (Russel\(^1\)), the inductances obtained differ from Tesla's values by less than one percent.

15 October

Because of the arithmetical error made on October 9th (see commentary), he mistakenly concludes that the capacities of the ball are now somewhat less than before. Had he used the correct values, his conclusion would have been just the opposite.

17 October

The 122 ft metal pole bearing the 30' ball is the antenna to be seen in the middle of the laboratory on many photographs. The bottom end of the antenna is insulated by a wooden pole. This is a single-pole antenna of small electrical length. At around the highest frequencies which Tesla used the \(h/\lambda\) ratio was about 0.015. The terminal capacity made the effective height somewhat greater than \(h\), but it still remained an electrically short antenna.

20 October

Tesla was measuring the capacity of the coil which he had used for determining the change of capacity of a sphere with height (up till October 9th he had called it a "special coil"). Considering the dimensions of the primary (coil diameter 15 m) and the coil being tested (diameter 64 cm, length 145 cm), the coupling between them was obviously loose, so that the frequency found from the parameters of the primary circuit (provided that the main secondary of the oscillator did not influence the oscillation of the primary) can now be accepted as accurate. It is not stated how resonance was determined, but it was probably from the sparks at the terminals of the test coil. Similar resonance methods are given in recent textbooks on electrical measurements\(^{56}\). It must be noted, however, that determination of the distributed capacity of a coil from the resonance of the coil
21 October

In a thorough analysis of all details of his measuring apparatus, Tesla did not omit a determination of the parasitic inductance of the connections, by an interesting method which he says he used often in the New York laboratory. Varying the primary inductance and capacitance but keeping a constant frequency of the oscillator (as determined with an auxiliary resonant circuit), one has

\[ C_{p1}(L_{p1} + L_{con}) = C_{p2}(L_{p2} + L_{con}) \]

where \( C_{p1}, L_{p1} \) are the first and \( C_{p2}, L_{p2} \) the second capacitance-inductance pair in the primary giving the same frequency. From this equation one can find the parasitic inductance of the connections \( L_{con} \), which Tesla denotes by \( x \).

23 October

In further experiments to determine change of capacity with height Tesla uses an apparatus similar to that of the previous day. As far as can be judged, the coupling between the oscillator and the measuring circuit (coil with elevated ball) was loose. The lower terminal of the latter was connected with a condenser of the oscillator circuit. Loose coupling is evidenced by the relatively weak sparks obtained across the air gap of coil I. (See figure) in comparison with the sparks obtained when a similar coil was excited by the secondary of the oscillator, tightly coupled to the primary (as for example on October 4th and 5th). Under these conditions the spark oscillator would generate a single frequency, determined by the parameters of the oscillatory circuit with the spark gap.

26 October

Tesla had already been using the 689-turn coil for several days in experiments to determine change of capacity with height of a ball. On October 18th he calculated its inductance using the formula for an infinitely long coil. Now he determines it by measuring the current and voltage at a frequency of about 140 Hz, knowing the resistance. He gives the results of two sets of measurements. He is convinced that the second set, for which he used a small dynamometer, gave low values, and this was probably so. The first set gave an inductance slightly less than calculated, but a correction of the theoretical value for the finite D/l ratio* gives a value about 6% less than that measured. Thus the calculated value ought to have been 0.023 H, while the experimental result was 0.024 H. The accuracy of the measurement method cannot now be verified but in view of the small difference between reactance and resistance it is doubtful whether it could be of the order of a few percent.

21 October

Tesla does not explain how he made the comparison with a standard 0.5 \( \mu F \) condenser. The number of bottles used in the condenser bank is indeed impressive. He did not

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* Russell(57) gives the inductance of a coil at very low frequencies as

\[
L = \frac{(\pi D)^2}{l} \left[ 1 - 0.424 \frac{D}{l} + 0.125 \left( \frac{D}{l} \right)^2 - 0.0156 \left( \frac{D}{l} \right)^4 \right]
\]

Substituting \( \pi D^2 = 4S \) (\( D \) is the mean diameter of the coil), and \( n=N/l \) (number of turns per cm), the first term in the above equation yields the expression Tesla used. \( l \) is coil length. When all quantities are expre-
carry out measurements on individual bottles to determine what kind of tolerance they had. Since he only measured complete banks, i.e. rather large capacities, and mentions "readings with 7 cells battery", he probably made the comparison in terms of stored charges.

28 October

After several days gathering data and making further measurements of inductance and capacitance, he finally proceeds to the calculation of the unknown capacity of the sphere, using the readings of October 23rd and 26th. Consistent with his general principle, he checked the measured values by (usually approximate) calculations.

He calculates the capacitance of the vertical wire by the formula for an isolated ellipsoid of high eccentricity. It is not known whether Tesla first had the idea of using this formula, but it was used later for a similar purpose[58]. All things considered, the agreement between the calculated and measured values is very good.

Tesla then calculated the ratio of the capacities in the lowest and highest positions. In the lowest position the sphere makes little difference to the total capacity. In the highest position it increases the capacity in the coil circuit by 18.7 cm. This is less than the theoretical value for an isolated sphere of 18" diameter, which does not agree with some of his earlier measurements (see the results of October 21st for a 30" ball). However, if a comparison is to be made, it must be noted that the new results are probably better because the apparatus had been modified and the parameters checked.

29 October

His remark about eddy currents in the sphere is interesting. To prevent their formation he slit the tinfoil with a knife. Did he assume that in the vicinity of the coil the sphere would behave like a short-circuited turn? It is readily shown that if this effect is pronounced (and not taken into account) the measured capacity of the sphere will be too low. This might be an explanation for the reduction of the effective capacity of the sphere in the lowest position (see the calculation of October 28th for an 18" sphere in the lowest position).

1 and 2 November

The new extra coil was larger in diameter but shorter than the previous one (see August 23rd). The formula for an infinite coil introduces a rather large error, but with the correction referred to in the commentary to 26 October the agreement with the experimental results is good. The correction terms are significant because the ratio $D/l$ is even greater than unity, and the correction is more than 30%. The corrected value is 0.0198 H, 2—3% less than the measured values.

3 November

A repeated measurement of the capacity of the vertical wire and the 30" sphere by the method of October 29th but with a new coil $L$ (see October 31st). A new feature
5 November

Photographs of the Colorado Springs laboratory always show the pole rising from the center of the building. Its dimensions are given in the entry of 17 October. Now Tesla calculates the capacity of the pole as the sum of the capacities of its parts of different thickness, using the formula first cited on October 28th. His final remark indicates that he had thoroughly understood the physical essence of the phenomenon.

6 November

Tesla carefully measured the capacitance of the aerial pole by the resonance method, from the known inductance of the 550 turn coil (see September 8th) and known frequency of the oscillator, with two measurements, one with and the other without the capacity to be measured. He did not make use of his earlier results for the inductance of the regulating coil and connections from October 30th, although he could have done. A calculation check shows that the results of October 30th were rather high (by as much as 10% for 2 1/8 turns of the regulating coil), but Tesla probably thought that the new procedure was better and so did not use the old results. An analysis shows that if the old values had been used the final result would not have been essentially affected, so that Tesla’s conclusion that the measured capacity of the pole was less than the theoretical value of November 5th remains valid.

From the relatively lengthy discussion following the measurements it may be seen that Tesla expected just the opposite. As usual when his expectations were not fulfilled, he considers ways for getting more reliable results.

7 November

Measurement of the capacity of the structure at two frequencies was intended to demonstrate the reduction of effective capacity with increasing frequency. Tesla did in fact obtain a small difference, but it is dubious proof considering the accuracy of the measurements. The frequency difference was quite large, from 50 kHz to nearly 250 kHz (using “extra” and “experimental” coils).

8 November

The primary inductance values cited are from November 5th. The other values given in the table do not agree with those derived from the measurements of October 30th. Also, earlier data do not include values for half a turn of the regulating coil. It must therefore be concluded that the measurements from which the tabulated values were calculated are not described in the diary.

It seems that in measuring inductance from voltage, current, frequency and resistance Tesla had difficulty because of unreliability of the frequency determination. He therefore used the voltage ratio, when it is only necessary for the frequency to be constant. By this method he measured the inductance of the regulating coil plus connections, for various numbers of turns.

9 November

The measurements of mutual inductance in terms of the inductance of the primary when the secondary is open and short circuited are noteworthy. They were made at constant
To reduce the oscillator frequency, in some cases Tesla used two special coils which he refers to only by wire gauge number. He compares the calculated and measured values for these coils. The values measured by the voltage ratio method are about 2% less than those found from voltage, current and frequency. The calculated values are lower than either. Correction of the measured values as described in the commentary to 26 October does not make much difference (about —5%) because the D/I ratio is relatively small.

10 November

Had Tesla published the measuring methods he developed in New York and Colorado Springs, his name would probably be frequently encountered in earlier textbooks and handbooks on electrical measurements at high frequencies. As it is, we can only remark his exceptional ingenuity in designing measuring devices and the accuracy with which he determined the resonance of oscillatory circuits. An especially interesting feature is his method using a lamp already heated up by a supplementary power source, greatly increasing its sensitivity to small amplitude changes around the resonance peak of the oscillatory circuit.

11 November

In measuring the capacity of a sphere at different heights Tesla here uses a loosely coupled circuit containing a lamp to determine resonance. The results for a 50 ft wire differ somewhat from those of October 28th, but are within the limits of error of the method. The values for the capacity of the sphere are somewhat higher than before, but not in proportion to the diameter of the sphere.

12 November

Measurements of the pole capacity, like those of November 7th, but now using a coil with 1314 turns. Resonance was determined by means of a small lamp in series with a coil loosely coupled to the measuring circuit. The value obtained was again similar, so Tesla concludes that it is near the true value of the effective capacity.

13 November

Tesla uses an improved method for determining the resonance point, with the light bulb in a dark box for more precise detection of luminance, and determines the capacity of the iron piping once more, obtaining a value about 10% less than in earlier measurements (see November 7th and 12th).

15 November

Tesla again measures the capacity of the sphere on top of the metal pole as on November 7th and 12th, but with the secondary coil of the oscillator instead of the earlier "supplementary" coils. The results did not agree with those obtained earlier. Tesla puts this down to the large distributed capacity of this coil, but it would seem that other factors
Main entrance to Colorado Springs Laboratory in the early phase of development. Tesla is looking through the door (Tesla's own photograph now at the Nikola Tesla Museum, Belgrade)
16—20 November

Capacity measurements made during the period 16—22 November agree on the whole with those made earlier. Tesla does not explain why he repeated similar measurements, e.g. those of November 16th and 18th when he determined the distributed capacity of the supplementary coil and the vertical wire. Nor does he explain why he repeated the measurements of the change of capacity of the sphere with elevation (see November 18th and 20th). He may only have wanted to confirm the earlier results.

On November 17th and 19th he measured the capacity of a vertical wire of various lengths and gauges. From his comments on November 17th it may be seen that at greater lengths he expected some inductive effect. A check of the wavelength, however, reveals that all Tesla’s antennas were short in comparison (h/λ of the order of 0.01), so that divergence between the theoretical and measured values cannot be ascribed to an inductive effect.

21 November

For some reason which he does not explain, Tesla was interested in the capacity of the same wire when vertical and horizontal, which he measured by the usual resonance method, repeating it with a different capacitance in the primary as a check. Although the results from the two sets of measurements differ appreciably, the value obtained with the wire horizontal was somewhat higher in both cases. The formulae which Tesla used July 24th here yields 54.37 cm for the vertical wire and 58.43 cm for the horizontal. These values agree well with his measurements, especially the first set.

24—26 November

To check the values for the inductance in the primary circuit (of the oscillator) which he had earlier measured by the voltage, current and frequency method (see October 30th), Tesla repeats these measurements using the resonance method. He described the procedure on October 21st and made some measurements but did not follow them up with calculations. This time he made both measurements and calculations, but only for one \( L_0 C_p \) combination. He compares them with values derived from the table given November 8th using linear interpolation. He was probably satisfied with the agreement, and did not make further checks. He had measured the capacity of the same structure, but without the protective cap and using the “extra” and “experimental” coils, on November 7th. On November 12th he had made similar measurements using the 1314-turn coil. In the 26 November entry he refers to the result of 7 November with a new “extra” coil. There is also one more result obtained with an “extra coil”, using the best method he had developed for detecting resonance (see 13 November). This result, which differs appreciably from the others, is not mentioned November 26th.

The remark closing this entry suggests the possibility of a systematic error in the determination of resonance, and Tesla emphasizes that it has to be checked.

5 December

In this, as in earlier measurements, he found a “reduced inductance of the primary,
the oscillator starts to produce oscillations of two frequencies, and when the spark is broken it gives a third frequency which is determined by the secondary oscillatory circuit. With a third circuit ("extra coil") the oscillation of the system becomes even more complicated, the oscillations during break being determined by the secondary circuit and the "extra coil." Neglecting for the moment the "extra coil," the three frequencies which a Tesla oscillator with tight inductive coupling and equal natural resonant frequencies of the coupled circuits can be expected to produce are

\[
\omega_0 = \frac{1}{\sqrt{LC}} \quad \omega_1 = \frac{1}{\sqrt{LC(1-k)}} \quad \omega_2 = \frac{1}{\sqrt{LC(1+k)}},
\]

where \(k\) is the coupling coefficient. Thus \(\omega_1\) can be interpreted as the natural frequency of a circuit with capacity \(C\) and inductance \(L(1-k)\). For the primary inductance of Tesla's oscillator (see 9 November) one obtains the "reduced" \(L\), i.e. \(L(1-k)=23,094\) cm; Tesla measured \(L=24,063\) cm.

6 December

The photographs of the inside of the laboratory show the 100-turn "extra coil" raised above the floor in the center. With this coil Tesla again got similar results for the "reduced" inductance of the primary. However, aware of the indeterminacy of this "reduction," and hence also of the oscillation frequency, he notes that the secondary should be broken at more points when the primary is used as a measuring inductance. This would ensure monochromatic oscillation of the oscillator by reducing the coupling of the primary and secondary (i.e. the circuit of the "extra coil"). The measurements with the secondary eliminated are more reliable, and the accuracy with which the values sought are determined depends mainly on the accuracy to which the inductance and capacitance in the exciting circuit of the oscillator are known.

1 January

Photograph XVII shows lamps connected into a resonant circuit consisting of one square turn. According to the data Tesla gives, one side of the square was about 1.3 m from the secondary coil of the oscillator. The capacity of the oscillatory circuit consisted of two condensers in parallel. The lamps are paralleled.

Tesla calculates the inductance of the square turn from the formula for the inductance of two parallel conductors, as if there were two such pairs connected in series. The formula for a square coil (Fleming, p. 155),

\[ L = 8I \left( \ln \frac{d}{r} - 0.774 \right) \]

yields a value 12.6% less than Tesla found. The calculated resonant frequency is therefore somewhat higher than it should be, so that the inductance of the oscillator primary, as Tesla calculates it, is still less. In fact, because of the tight coupling of the secondary the oscillator must have been producing a complex spectrum, probably with its strongest component at the resonant frequency of the oscillatory circuit of the square coil.

In connection with photographs XVIII—XXI showing the secondary producing localized effects, Tesla made the interesting remark about signalling over great distances.
Interior of Colorado Springs Laboratory
one could expect signals to be picked up at distances of a thousand miles or more, even on the Earth's surface. The diary does not mention any measurements at great distances, but in an article\(^{(41)}\) he published soon after finishing work at Colorado Springs he states that he observed effects at a distance of about 600 miles.

\[2 \text{ January}\]

In this entry of 21 pages (the longest in the Notes) Tesla describes 11 photographs.

The explanation to Photograph XXII concerning the transmission of power from the excited primary circuit to the "extra coil" via the earth is similar to that he gave in 1893\(^{(6)}\). The experiment to which the photograph refers was made with the aim of estimating the power of the oscillator from the thermal effect of the HF current. What Tesla calls the "total energy set in movement" would correspond to the total energy transferred to condenser in the secondary (i.e. the power) if an energy of \(\frac{1}{2}CV^2\) is transferred in each half-cycle. It can be shown that the active power dissipated in the circuit is much less than this and is inversely proportional to the \(Q\)-factor of the oscillating circuit.

The next few photographs show a movable coil which powers light bulbs by means of the high-frequency power which it picks up. One end of the coil is grounded, the other free or just connected to a short piece of wire. The bulbs are inductively coupled to the resonant coil via the auxiliary secondary. Tesla gives no data about the distance of the resonant coil from the oscillator coil.

Tesla's commentary on photograph XXVIII illustrates that he still retained a lively interest in the problem of electric lighting, even after a period of over ten years. His earlier discovery of the luminescence of the gas and not only the filament with HF currents was here again confirmed\(^{(5)}\).

In photograph XXVIII the bulb is connected in series with the terminal capacitive load. In the calculation Tesla does not use the "total energy set in movement" but assumes that \(\frac{1}{2}CV^2\) of electrostatic energy is consumed in the bulb in each half-cycle. A similar comment applies to photograph XXIV.

Several times Tesla remarks that the principle energy transfer from the oscillating to the receiving coil takes place via the earth. He finds confirmation for this in the experiment described on p. 363 (photograph XXX). He found that the voltage induced in the receiving coil was greatly reduced if the ground connection was broken. It may be that such experiments led him to the conclusion that "transmission" through the earth was a more efficient method of wireless transmission of power than the "inductive method".

Photograph XXXI is an X-ray picture of a finger. Tesla's comments on this experiment illustrate his interest in this type of radiation, already referred to (see the commentary to 6 June 1899).

\[3 \text{ January}\]

After describing some photographs of the laboratory, in the commentary to photograph XLI Tesla explains some transformations of the streamers. He mentions the splitting of streamers near the floor, splitting and reuniting, the phenomenon of luminous parts on the streamers (which he then refers to as sparks), and the burning of sparks.
larly noteworthy. This phenomenon has been a source of interest since ancient times. Some references to it can be found on Etruscan monuments, in the works of Aristotle, Lucretius and other old sources. Fireballs are considered to be a form of electrical discharge generated during thunderstorms. They are rare in nature, but a fair-sized body of observations has nevertheless been assembled upon which several theories of their origin have been founded. Some hypotheses maintain that fireballs are an optical illusion (an opinion shared by Tesla until he produced them himself), others that they are the traces of meteors. The first genuine scientific approach to the problem was Arago's analysis of some twenty reports of fireballs in 1838. After the publication of his work they became a legitimate subject of scientific interest, but to this day have remained something of an enigma.

A fireball is a luminous sphere occurring during a thunderstorm. Fireballs are usually red, but other colors have also been observed: yellow, green, white and blue. Their dimensions vary, a mean diameter being about 25 cm. Unlike ordinary lightning, fireballs move slowly, almost parallel to the ground. They sometimes stop and change their direction of motion. They can last for up to 5 seconds. Their properties vary greatly from case to case, so that it is believed that there are various types. According to Singer it can be stated that as yet no single theory can explain the occurrence of fireballs in nature.

Despite numerous attempts, only a few types of fireball have been created, and not entirely successfully, in the laboratory. These include the weakly luminescent fireballs generated when ordinary lightning strikes some object. Tesla mentions phenomena of this type several times as the result of sparks or streamers striking wooden objects (see e.g. photograph XL). According to recent theories, fireballs consist of a plasma zone created by electrical discharge. The latest research and calculations by Kapitsa show that the lifetime of a fireball cannot be explained by the energy it receives at the time of genesis, but that it must receive energy from its surroundings. Kapitsa theorizes that this external energy is produced by a naturally created electromagnetic field. The small zone of ionized gas created by the initial lightning or other electrical phenomenon during the storm subsequently expands at the expense of the external electromagnetic field. The diameter of the plasma sphere is determined by the frequency of the external field, so that a resonance occurs. The usual dimensions of fireballs would require that the electromagnetic field have a wavelength of between 35 and 100 cm. According to this theory standing waves created by the reflection of natural electromagnetic waves from the earth would play a certain role. The theory has obtained partial experimental confirmation, but there are still many points on which it is unable to give a satisfactory explanation. It has been found that to maintain a lump of plasma in air requires a power of the electromagnetic field of about 500 W, which is much less than power which can be produced by an electrical discharge. However, too little is known about natural electromagnetic waves to allow any reliable conclusions to be drawn.

Tesla's hypothesis on the origin and maintenance of fireballs includes some points which are also to be found in the most recent theories, but it also bears the stamp of the time. For instance, like Kapitsa, Tesla considers that the initial energy of the nucleus is not sufficient to maintain the fireball, but that there must be an external source of energy. According to Tesla this energy comes from other lightnings passing through the nucleus, and the concentration of energy occurs because of the resistance of the nucleus, i.e. the
the nucleus of a fireball is small, so Kapitsa's hypothesis that act via electromagnetic
standing waves is more logical. It is possible that in Tesla's experiments the "passage"
of a number of later discharges through the same nucleus was more frequent.

7 January

This is the last entry in the diary. Apart from the usual description of photographs,
Tesla writes about experiments he intends to carry out on his return (where?). He qualifies
the experiments to date as satisfactory, considering that his aim was "to perfect the ap-
paratus and make general observations". The apparatus which he was then envisaging
for future experiments was to be an improved oscillator which would enable better results
than any he had so far obtained.