Introduction by Editor

Kotelnikov has been well known for many years as the author of the monograph Theory of Optimum Noise Immunity. *Those of us teaching communication theory many years ago savored our copies of the book, and often used it to augment textbook material covering the subject. What was less known was who this man was, and with what other activities he was involved. It is therefore a particular pleasure for me personally to see Vladimir*

Kotelnikov both as a human being and as an outstanding engineer/scientist portrayed so effectively in Prof. Bissell's article that follows. It is especially interesting to learn that Dr. Kotelnikov was probably the first person to demonstrate the by now well-known sampling theorem in the time domain. I commend the article to your attention.

—Mischa Schwarz

Vladimir Aleksandrovich Kotelnikov: Pioneer of the Sampling Theorem, Cryptography, Optimal Detection, Planetary Mapping...

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Abstract

In 1933 the young Russian communications engineer Vladimir Aleksandrovich Kotelnikov published a paper in which he formulated, for the first time in an engineering context, the sampling theorem for lowpass and bandpass signals. He also considered the bandwidth requirements of discrete signal transmission for telegraphy and images. Kotelnikov subsequently worked on scrambling, cryptography, optimal detection, and planetary radar (including the radar-assisted cartography of Venus). He was awarded numerous Soviet and international prizes, and played a major role in Soviet academic and professional life in the field of radio engineering. Yet his achievements are still comparatively little known outside Russia.

Introduction

Vladimir Aleksandrovich Kotelnikov was born in 1908 in Kazan into a family with a long academic tradition. His father was a university professor of mathematics, his aunt also taught mathematics at a university, and his grandfather had been Dean of Physics and Mathematics at the University of Kazan as well as assistant to Nikolai Lobachevskii, one of the pioneers of non-Euclidian geometry.

The first few years of the young Vladimir's life were happy, but in 1914 the family attempted to move to Kiev, arriving on the day when the German Army broke through the Russian lines. Great upheavals and family tragedy occurred as a result of a dreadful sequence of events: not only the First World War, but then the Russian Revolution, and finally a typhus outbreak in 1921 that killed both his mother and his aunt.

The family moved to Moscow in 1924. Shortly afterward Vladimir Aleksandrovich began to study radio engineering as an undergraduate at what subsequently became the Moscow Power Engineering Institute (MEI), and he remained there to do postgraduate work — although his ambition had been to join the Central Radio Laboratory. While still a postgraduate student he wrote the classic paper in which he derived, for the first time in an engineering context, the sampling theorem for band limited signals. At MEI he also met his future wife, Anna Ivanovna Bogatskaya; they married in 1938 and had three children.

Following wartime research and development work in Ufa (one of the temporary locations of scientific institutions evacuated from Moscow), he returned to Moscow in 1944, where he became professor and then Dean of the Radioengineering Faculty at MEI and finally, in 1954, Director of the new Institute of Radioengineering and Electronics of the USSR Academy of Sciences. He was one of the founder members (1945) and later long-term President of the Popov Society for Radio Engineering, Electronics and Telecommunications. He gained his Doctorate of Sciences[1] in 1947 on the topic of optimal detection and became a full Academician in 1953 — unusually, without the intervening stage of "corresponding member." His book *The Theory of Optimum Noise Immunity*, a translation of the 1956

Russian monograph (essentially the author's 1947 dissertation), appeared in the United States in 1959. Kotelnikov's distinguished later career included a leading role in the Soviet space program, directing work on planetary observation and mapping, for which he was awarded the prestigious Lenin Prize in 1964. He was Vice President of the Soviet Academy of Sciences from 1969 to 1988. Other awards include the German Eduard Rhein Prize in 1999 and the IEEE Alexander Graham Bell Medal in 2000. In 2003 Kotelnikov celebrated his 95th birthday; greetings from Vladimir Putin, President of the Russian Federation, and congratulatory remarks from the IEEE can be found in [1]. He died in February 2005. Most of the biographical details in this article derive from [2].

The Sampling Theorem

Different societies quite naturally associate seminal work with pioneers from their own history, particularly when such work is carried out independently within a few years in various geographical locations. The sampling theorem is thus associated with Claude Shannon [3, 4] (and, somewhat erroneously, with Harry Nyquist [5]) in the West, and with Vladimir Kotelnikov in Russia [6]. (Nyquist's classic 1928 paper considered the maximum signaling rate over a band limited channel. He also noted the necessary and sufficient conditions on the number of coefficients of a Fourier series representing a band limited signal. Because of this, and because the Nyquist rate is equal numerically to the minimum sampling rate for a band limited signal, the contributions of Nyquist and Shannon to the notion of sampling have often become confused. Nyquist

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[1] *The Russian Doktor Nauk degree is a higher research degree awarded to distinguished researchers on the basis of a thesis, not to be confused with the kandidat degree more akin to a Western Ph.D. or equivalent, which Kotelnikov was awarded in 1938 without a formal dissertation or viva voce examination.*

(Continued from page 24)

did not consider explicitly the question of sampling a signal in the time domain.)

Kotelnikov's work is much less well known globally than that of the American engineers; one of the aims of this paper is to contribute to an understanding of the international context of information engineering from the 1930s onward.

Kotelnikov's publication *On the Capacity of the "Ether" and Cables in Electrical Communication* was intended for a conference that never took place. Papers were, however, published in 1933. English translations have appeared as Chapter 2 of [7], in [2], and as [8]. Note, however, that [2] and [7] appear to have been translated by non-native English speakers, and contain some minor stylistic and/or terminological inadequacies as indicated below.

SETTING THE SCENE

Kotelnikov begins his 1933 paper by stating the problem, which had gained in importance as a result of technological developments in telecommunications in the 1920s and 1930s:

In both wired and wireless engineering, any transmission requires the use of not simply a single frequency, but a whole range of frequencies. As a result, only a limited number of radio stations (broadcasting different programs) can operate simultaneously. Neither is it possible to convey more than a given number of channels at any one time over a pair of wires, since the frequency band of one channel must not overlap that of another: such an overlap would lead to mutual interference.

In order to extend the capacity of the "airwaves" or a cable (something that would be of enormous practical importance, particularly in connection with rapid developments in radio engineering, television transmission, etc.), it is necessary either to reduce in some way the range of frequencies needed for a given transmission (without adversely affecting its quality), or to devise some way of separating channels whose frequencies overlap — perhaps even employing a method based not on frequency, as has been the case until now, but by some other means.

At the present time no technique along these lines permits, even theoretically, the capacity of the "airwaves" or a cable to be increased any further than that corresponding to "single side-band" transmission. So the question arises: is it possible, in general, to do this? Or will all attempts be tantamount to efforts to build a perpetual motion machine?

Figure 1. *Kotelnikov as a young man.*

THEORY

The next eight pages of the paper derive theoretical results relating to lowpass and bandpass signals and their transmission. Most significant, Kotelnikov shows that any lowpass band limited function can be represented by a sequence of appropriate sin x/x waveforms; thus, a lowpass signal with bandwidth f can be reconstructed from a sequence of samples spaced at $1/2f$ intervals used to weight sin x/x waveforms. Kotelnikov's paper includes plots of the sin x/x function and the sine integral Si (x), and thereby approximations to an ideal band limited spectrum, with reference to what we know as the Gibbs phenomenon. For further details readers are referred to the original paper or to the summary in [9].

At this point it is worth noting Shannon's remarks, published 16 years later, about the origin of the sampling theorem: "This is a fact which is common knowledge in the communication art. […] but in spite of its evident importance [it] seems not to have appeared explicitly in the literature of communication theory" [4]. Indeed, mathematicians had studied the problem from a function-theoretic point of view from the mid-19th century or even earlier [7, 9].

Following the theoretical develop-

ment, Kotelnikov gives a discussion informed by practical engineering requirements.

TIME VS. BANDWIDTH

Kotelnikov recognized clearly the essential difference between analog and digital communication, and the trade-off between bandwidth and the time needed to transmit a given quantity of information (although he did not express it in quite these terms):

Speech, music, and other objects of telephone transmission are arbitrary functions of time, having a frequency spectrum whose width is completely defined and which depends on how well we wish to represent the [original] sound.

When transmitting this function by wire or radio, we convert it into another function of time, and it is the latter, strictly speaking, that we transmit. Moreover, for continuous transmission, this latter function may not … have a spectrum of frequencies narrower than that of the audible frequencies that we wish to transmit. … Such a minimum spectral width can be achieved at present by means of single sideband transmission, as is well known.

The proviso "for continuous transmission" is of great importance, since by means of transmission with interruptions any sounds — music say — can occupy less bandwidth than that of the original audible spectrum. To do this, it is sufficient first to record the music to be transmitted on gramophone records, and then to transmit from them but playing back at half the speed, say, of the recording. Then every frequency will take on half its normal value, and the transmission will require half the bandwidth. The original can similarly be recovered by gramophone. It is clear that such transmission cannot increase channel capacity, since the ether or the cable will be occupied the whole time, while communication will proceed with interruptions.

DISCRETE TRANSMISSION

In his discussion of what we would now term digital signals, Kotelnikov examined in the same 1933 paper telegraphy and the transmission of multilevel discretely coded images:

In telegraph transmission, and also in the transmission of images without half tones[2] or with a limited number of half tones specified in advance, we again have to deal with the transmission of some N elements per second, equivalent to the transmission of N numbers per second. In this case, however, the magnitudes of these elements, and thus the numbers, are not completely arbitrary, but must take on completely determined values known in advance. …

In fact, for such transmission the necessary frequency range can be reduced as much as desired and hence, at least in theory, the channel capacity can be increased indefinitely. We can proceed in the following manner. Suppose we wish to transmit, at a rate of N per second, elements that can take on the values 0 and 1 only, and to use a bandwidth of only $N/4$ rather than $N/2$ …. In order to do this we shall transmit two such elements by means of a single element or number, as given in the following table. Here column I holds the value of the first element, column II the second, and column III the value of the element by means of which we wish to transmit the other two. In this way we can transmit N elements per second, each of which can take on one of two values, by means of $N/2$ elements per second, each of which can take on four values; the latter … can be transmitted using a bandwidth $N/4$.

I	II	III
0	0	0
1	0	1
1	1	2
0	1	3

[…]

In such transmission, in view of the fact that it is necessary to distinguish between four instead of two levels in the received signal, it is obvious that the power of the transmitter has to be increased by a factor of $3^2 = 9$ in comparison with the usual transmission.

In an analogous fashion it is possible to reduce the frequency band by a factor of n, transmitting n elements, each of which can take on one of two values, by a single element taking on one of 2^n values (the number of combinations of n elements, each taking on one of two values). But for this it is necessary to increase the power by a factor of $(2^n - 1)$.[2]

For the transmission of images with a predefined number of half tones, each element will take on several values, say m (in this case $m > 2$). In order to decrease the bandwidth by n times in such a transmission, it is possible to replace n transmitted elements by one with m^n possible values (the number of possible combinations of n elements each having m possible values). Then the power must clearly be increased by a factor

$$\frac{(m^n - 1)^2}{(m - 1)^2}.$$

As can be seen, reducing the bandwidth in this way requires an enormous increase in power. Furthermore, such methods are very bad for shortwave transmission due to fading. For wired communication, however, such bandwidth reduction may be of current practical importance since the powers are necessarily small, and received strengths do not vary rapidly.

KOTELNIKOV'S RECOMMENDATIONS

Kotelnikov concludes his paper with a number of recommendations, informed by his theoretical results. He states that:

- Attempts to increase capacity beyond the theoretical limit represented by single-sideband transmission should be abandoned as theoretically impossible.[3]
- The possibilities for what we now call digital techniques should be investigated further.
- Existing single-sideband technologies should be developed further, since they appear to be the theoretical "best option."
- Other areas of research should include: the use of directional antennas; the extension of the radio spectrum to ultra short wavelengths; and the improvement of

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[2] Half-tones: printing terminology for the technique of reproducing shades of gray by means of combinations of black and white. Sometimes mistranslated in English versions of Kotelnikov's paper as half-shadows, penumbra, or semitones.

[3] Only comparatively recently have techniques such as perceptual coding and spread-spectrum modulation changed our views of the limits to source coding and signal transmission.
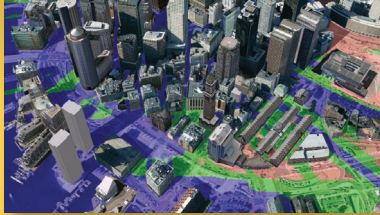
the frequency stability of radio transmitters.

Kotelnikov's result was not widely known or understood even within the Soviet Union. He attempted to publish an article in the journal *Elektrichestvo* in 1936 — his letter of rejection is shown in Fig. 2. He was awarded his kandidat (~ Ph.D.) degree in 1938 on the basis of this and other work without a formal viva voce.

KOTELNIKOV'S SUBSEQUENT WORK

Following the completion of his post-graduate studies at MEI in 1933, Kotel-nikov continued to teach there, and also worked at the NKS (People's Commissariat of Communications) Research Institute. In the late 1930s he developed single-sideband techniques, successfully launched on the Moscow-Khabarovsk link (to the far east of the Soviet Union) in 1939. But with war approaching in Europe, the overriding need was for secure communications.

SCRAMBLING AND CRYPTOGRAPHY

In the period immediately before the entry of the USSR into the Second

Figure 2. *"The editorial board of Elektrichestvo is returning your article …"*

World War, Kotelnikov worked on secure voice transmissions, including scrambling and vocoder applications. Existing techniques of transposing frequencies were not secure, and Kotelnikov proposed scrambling by rearranging time segments in addition to frequency transposition. He was aware of American work of the late

1930s on vocoders and developed a Soviet device by 1941. He produced a classified report on the fundamentals of automatic encoding in June 1941 (which seems never to have been published), just before Hitler's invasion of the Soviet Union. He is still acknowledged in the former Soviet Union as a key player in cryptography. When the German
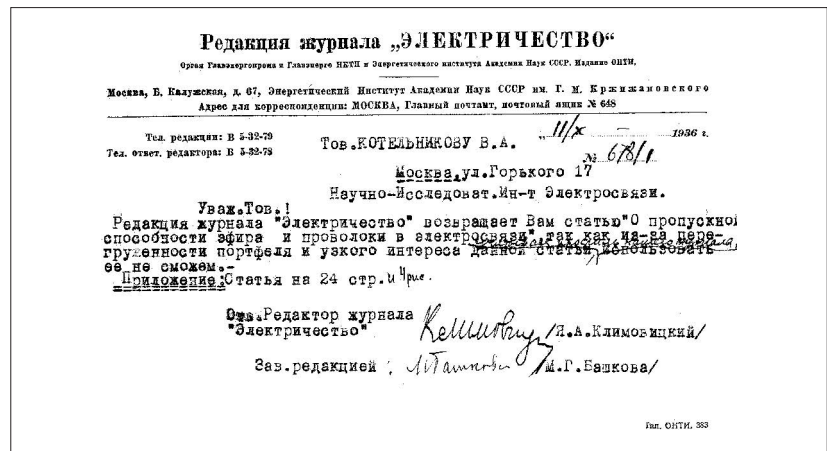
Figure 3. *Kotelnikov in later years*

army seemed likely to reach Moscow, Kotelnikov's laboratory, together with other scientific establishments, was evacuated to Ufa, around 1000 km to the east. There the laboratory continued to work on secure radio telephony, and by the beginning of 1943 such equipment was being produced on a large scale for the Red Army, having been tested the year before during the battle of Stalingrad. The encryption equipment was later used during negotiations at the Tehran, Yalta, and Potsdam Conferences.

On return to Moscow Kotelnikov's laboratory was transferred to the NKVD, the state secret security organization formally entitled the People's Commissariat of Internal Affairs (forerunner of the KGB). The NKVD ran a number of prison research and development laboratories known colloquially as sharashkas. One particular sharashka — the Marfino — had its roots in Kotelnikov's laboratory and later became famous through the novel *The First Circle* written by its most celebrated inmate, Aleksandr

Solzhenitsyn. By this time, however, Kotelnikov had been invited back to MEI to head a new group in the Fundamentals of Radio Engineering, and he appears to have been only too relieved to return to the university sector. The Rector of MEI was the wife of the then First Secretary of the Central Committee of the Communist Party, and seems to have been able to pull strings to keep Kotelnikov out of state security establishments even in 1947, when he was asked — and refused — to lead a specialized state laboratory to develop secure government communication systems.

OPTIMAL DETECTION

In 1946 Kotelnikov was encouraged to write a thesis for the higher Russian doctorate, the Doktor Nauk (Doctor of Sciences). This degree — although a significantly higher distinction than a Western Ph.D. — is more common than the even higher D.Sc. award in the United Kingdom, and is often gained by university academics in mid-career. Kotelnikov's thesis, *Theory of Potential Noise Immunity*, duly appeared the following year and was a tour de force in the application of statistical theory to the detection of signals in the presence of noise. One of the major contributions of this work is the introduction of the representation of signals in an n-dimensional vector space, the notion at the heart of modern signal constellation diagrams (although the thesis did not include any graphical representation of the idea). Kotelnikov wrote:

… every waveform of finite length and with a finite frequency spectrum can be represented as a point or radius vector in n-space. Thus, each of the m signals considered … can be represented by its own point or radius vector. If to the transmitted signal is added a noise waveform with a vector which can have an arbitrary direction and arbitrary length, then the resulting received waveform will also be characterized by a point in n-space, which most often will not coincide with any of the points corresponding to signals. Depending on the position of this point, the receiver will reproduce some message or other …

The thesis also included the now standard result that the energy of a pulse for a given noise power density is the effective determinant of error probability.

Kotelnikov's work was so novel that it proved difficult to find examiners. Furthermore, he had produced it alone,

without an advisor, and referred to no other technical literature! The distinguished mathematician Academician Papaleksi declined an invitation to examine it, but a panel was eventually constituted, and the thesis was successfully defended in January 1947. It was finally published in Russian in 1956 and translated into English in 1959. By this time much relevant work had been published outside Russia by researchers unaware of Kotelnikov's results. In an introduction to the English edition Paul Green, then of the MIT Lincoln Laboratory, wrote:

… few of us have been aware that there existed in 1947 in this dissertation a statistical analysis of communication problems using what we now call decision theory techniques and anticipating by several years much of the work of Woodward, Davies, Siegert and others, with which we are more conversant. … By no means all of Kotelnikov's results have been obtained independently by others, and thus the volume should be of much more than just historical interest. [10]

THE INSTITUTE OF RADIOENGINEERING AND ELECTRONICS AND THE SOVIET SPACE PROGRAM

Part of the work of Kotelnikov's department at MEI had been devoted to the development of aircraft telemetry, so when the Soviet Union began its missile and space program in earnest in the late 1940s Kotelnikov became a key player. He was a member of the interdepartmental Council of Chief Designers, headed by the "father of the Soviet space program," Sergei Korolev. Korolev had served time in two sharashkas (one led by the well-known aircraft designer Tupolev in Omsk) but was freed toward the end of World War II to work on rocketry, including evaluating German wartime developments, and went on to distinguish himself in Soviet space research and development.

By 1953 Kotelnikov had been elected a full member of the Soviet Academy of Sciences and appointed Deputy Director of a new Institute of Radioengineering and Electronics (he became Director the following year). He

appears to have been a charismatic leader, even allowing for an element of hyperbole in Russian biographical writing about eminent scientists! Yu V Gulaev writes, in [2]:

[His Directorship] started a new phase in which his talents as an outstanding scientist, science organizer, and science manager of a large research body could manifest their brilliance. He directed all his energy and talent at searching for interesting and promising approaches to solving various scientific problems and to formulating and advancing fundamental research … [p. 726]

Vladimir Aleksandrovich was a quiet, even tempered man, who treated everyone, from a factory worker to an academician, a general or a government minister, with equal kind-hearted attention … He created in the IRE a rather specific, very friendly atmosphere. We practically never suffered from squabbles among the staff. [p. 727]

Among the research fostered by Kotelnikov at the IRE were tropospheric propagation of ultrashort radio waves; extraction of weak signals in the

presence of noise; waveguide propagation; statistical radio physics; and so on. The Institute thus played an important role in interplanetary research, particularly the measurement and mapping of planets by radar. During the early 1960s successful missions took place to Venus, Mercury, Mars, and Jupiter, and in the early 1980s the surface of Venus was mapped by a team including the Institute and a number of other academic and industrial organizations. The project achieved a spatial resolution of 1 or 2 km and an altitude resolution of about 250 m.

CONCLUSION

There is little doubt that Kotelnikov's 1933 paper was the first to address the problem of sampling a continuous band limited signal in an engineering context, even though the mathematical basis of sampling had been considered earlier by a number of mathematicians. The first mathematician to use what we would now recognize as the full approach to sampling appears to be Whittaker [11, 12], as a result of which the sampling theorem is sometimes referred to as the WKS (Whittaker-Kotelnikov-Shannon) theorem.

In addition, Kotelnikov's discussion of what we now call *M*-ary signaling — again something that had been examined by others — pointed the way to his later examination of the optimal detection of signals in the presence of noise.

Russian work in the 1930s and 1940s was not known at the time in the West; indeed, only after the Second World War, and in the context of the Cold War, did translations of public domain Russian scientific and engineering research become widely available. Before, and just after, the Russian Revolution, scientists often published their work in French and German journals in addition to Russian periodicals. By the mid-1930s this was discouraged by the Soviet state, unless for officially sanctioned purposes. Because of this (and also because of the tendency under Stalin for spurious claims to be made for Russian priority in science and technology) English-language histories of 20th century technology do not always recognize the significance of Russian contributions.

In addition to making significant technological advances through his personal research, Kotelnikov was also an excellent organizer and manager of research and development projects at a time when this was not an easy task under the Soviet regime. Like a number of other Russian academics, he was drawn into politics (one did not refuse such invitations, whatever one's personal inclinations). Indeed, he acted as Chairman of the Russian Supreme Soviet from 1973 to 1980. In an interview with an Izvestiya journalist in 2003 he commented on this:

I was curious at the beginning. How does the system work? Then I got it. It was as simple as can be. Those who took the floor were handpicked by the Central Committee, draft speeches were approved beforehand. They reportedly did so not for the sake of control, but to avoid parallelism. It must have been the easiest job in my life. The most noticeable, though. An irony of fate.

(http://www.inauka.ru/english/article35674.html, accessed 7 December 2008)

Over the last 15 years or so it has become much easier to trace the development of technology during the Soviet era. Yet even in recent publications the socio-political aspects of Russian science and engineering are still often played down. From the available literature we gain a picture of Kotelnikov as a man of great intellectual stature and integrity who achieved an enormous amount under an extraordinarily difficult state system.

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