Terahertz Pioneer: Erik L. Kollberg

"Instrument Maker to the Stars"

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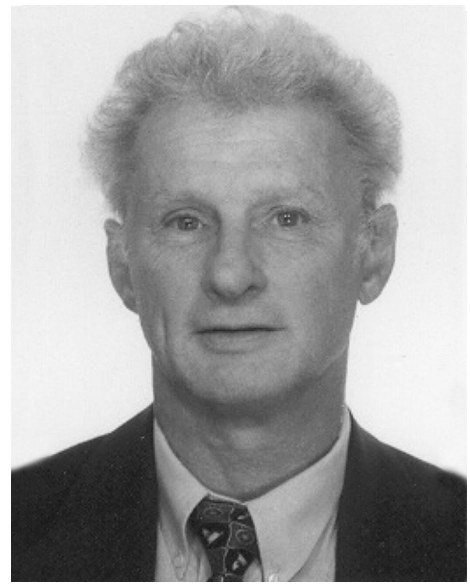

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PERHAPS, it is not surprising that a young man of 16 on his first adventure away from home aboard, an oil tanker bound for Venezuela,[1] in the middle of the Atlantic Ocean, might be transfixed and transformed by the night sky. Whether or not this experience influenced Erik Kollberg[2] to choose a lifelong career in astronomy is not for this observer to say, but this son of a trading magnate from Halmstad, Sweden, with a family history in the shipping industry, certainly strayed far from the nest when he entered Chalmers University of Technology, Gothenberg, Sweden, in 1956, to study electrical engineering.

Chalmers was host to Olof Rydbeck,[3] founder and colorful director of the Onsala Space Observatory. Olof was a noted radio astronomer, who took Kollberg and three other students under his wing in 1961, as doctoral degree candidates working on radio telescope receivers. One of these was Kollberg's lifelong collaborator and friend, Sigfrid Yngvesson,[4] who has gone on to his own very distinguished career in high frequency circuits, devices, and systems. It is an interesting and touching coincidence, that Kollberg's first refereed publication in 1965 [1] on his new chromium-doped rutile maser, and his last publication to date in 2011 [2] on modern-day hot electron bolometers, were both collaborations with Yngvesson.

In 1961, Onsala Space Observatory consisted of a 7.5 m diameter German-built Würzburg gun radar dish that had been shipped over from Norway after World War II. Rydbeck was in the process of building a 25.6 m (84 ft) diameter replacement, which could work up to 8 GHz. After graduating college, Kollberg remembers approaching Rydbeck to ask for a position. He was subsequently handed a detailed paper on electron beam devices and told to come back for a test after he had digested the material. Fortunately, he passed the exam, and after completing his military service, he joined the Rydbeck group, developing ultrasensitive masers for the new telescope.

Kollberg was so successful at this task (Kollberg and Yngvesson together developed a new maser gain medium based on chromium-doped rutile [1], [3], [4]) that by 1967, the 84 foot could boast of being the world's most sensitive telescope of its kind. The masers covered 0.8–6.4 GHz in 10 bands and were used to make a number of state-of-the-art measurements on stellar emission lines, specifically OH at 1665 MHz in a popular star forming region of Cassiopeia [5].

It is worth taking a couple of paragraphs to very briefly review how and why these masers were so useful in early radio astronomy receivers. They were, and in fact, still are, the device of choice when ultra-low noise amplification is required, even

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[1]He had a job as a cabin boy working through the summer months.

[2]Despite a long battle with Parkinson's, Erik Kollberg sat with me in his former Ph.D. student, now Professor Jan Stake's office, at Chalmers University of Technology, Gothenberg, Sweden, for the interview that resulted in this article. The loyalty and true admiration of Erik's colleagues and former students, spanning a career of more than 50 years, was palpable. Although Erik started out his radio astronomy receiver development at 900 MHz, his final major project, the delivery of the 1.4–1.7 THz hot electron bolometer mixer for the Herschel Space Observatory, secures him a lasting position as one of the Pioneer's of THz instrumentation.

[3]Olof Rydbeck (1911–1999) was educated at Harvard University and served as a professor at Chalmers University of Technology for almost 40 years. He is best known for his early work on radio wave propagation, and later for his observational work with maser receivers. He is credited with founding the Onsala Space Observatory in 1949, and the completion of the 20 m diameter millimeter-wave telescope at Onsala in 1975, the largest such telescope of its kind at the time.

[4]After finishing his Ph.D. with Rydbeck, Yngvesson went on to study under Charles Townes at University of California Berkeley (who had just won his 1964 Nobel Prize in Physics for his Maser work), and then took up a faculty position at University of Massachusetts, Amherst, MA, USA, where he still works on, and teaches about THz devices and technology.

though most masers have since been replaced by cooled transistor amplifiers, which offer obvious cost, size, bandwidth and circuit flexibility advantages.

One of the most important figures of merit for a radio telescope is the system noise temperature, $\mathrm{T_{sys}}$, the sum of all the contributions to the recorded signal that derive from the hardware, the receiver electronics, and the thermal background (both sky and ground pick up). At THz frequencies the largest contribution to the system noise is almost always the front-end amplifier (if one is available) or the front-end downconverter or mixer (generally still employed at 200 GHz and above). These can add many hundreds, or even thousands of degrees to $\mathrm{T_{sys}}$. Since the integration time required to pull out a desired coherent signal from the noise background increases as $\mathrm{T^2_{sys}}$, this has a dramatic effect on one's ability to observe (record) the weak RF energy we intercept from distant sources in outer space.

At microwave frequencies, masers offer the possibility of significant amplification of the incoming signal in a direct photon-to-photon process, without adding any excess shot (current derived) noise from the amplification process itself. In fact, masers can obtain quantum limited noise thresholds while realizing substantial gain (30 dB or even much more).

The first masers were based on low pressure gases flowing through high-Q resonant cavities (e.g., ammonia or hydrogen). By the late 1950s, solid-state gain media had been discovered [6], [7, Ch. 3] which were more stable and could readily be cooled to very low temperatures (4 K or less typically) to greatly reduce thermal noise. The Rydbeck masers that were developed by Kollberg and his colleagues at Chalmers and used at Onsala, contained a new gain media based on doped rutile, instead of the more common ruby-based systems, and they used a traveling wave or slow wave coupling structure for propagating the incoming signal along the crystal.

The chromium doped rutile (titanium dioxide), or more commonly these days, chromium doped Al_2O_3 (Ruby), is paramagnetic. In the presence of a strong magnetic field the chromium ions present a system with four energy levels. With a powerful RF pump at a frequency corresponding to the energy difference between levels (1) and (4), the top level (4) and level (1) can be made equally populated, yielding an inverted energy population between (4) and (3), i.e., level (4) is more populated than (3). This situation means gain instead of absorption. The cooled system also keeps the added thermal noise extremely low, approximately equal to the bath temperature [8, Ch. 10].

For the chromium doped rutile maser at Onsala, the pump frequency was supplied by a reflex klystron operating between 47 and 50 GHz, coupled into the slow wave structure (SWS). A 10%–20% frequency tuning range could be achieved by using a variable magnetic field (electromagnet) and by changing the pump frequency. Kollberg also implemented a modulation scheme on the reflector voltage of the klystron which more efficiently coupled the pump to the transition lines and resulted in a gain increase of some 2–3 dB on all their masers. The maser amplifier was followed by a mixer, a square law detector and a spectrometer to map out the observed spectral features from the stellar sources [5].

[5]*N.B.:* Ch. 10 was replaced in later editions by "Solid-state amplifiers", and no description of masers exist in these later releases of this classic textbook!

Even though most of the maser receivers have now been replaced with cooled transistor amplifiers, they still hold the record for lowest achievable amplifier noise temperature. For comparison purposes the Onsala telescope full system noise temperature with the cooled rutile maser receiver was 37 K. Careful noise measurements using a Dicke switched radiometer and a calibrated noise source, showed the maser and mixer noise contribution was only 3 K. The rest of the noise was due to the efficiency of the room temperature antenna (added ground and sky noise), and the horn, waveguide and coaxial line losses [5].

Kollberg worked on the maser receivers throughout his thesis years, and he officially graduated in 1970 [9]. He also participated with several other research groups in using the Onsala telescope, very successfully, for Very Long Baseline Interferometry [10], [11], and he did several observational astronomy runs with Rydbeck and other collaborators [12]–[14].

After graduating, Kollberg took a permanent faculty position at Chalmers and was responsible for all the receiver front end development at Onsala. He continued to develop maser receivers throughout the available 8 GHz frequency range of the 84 foot telescope [15]–[17] until the mid-1970s and then Rydbeck and he began seriously thinking about the next generation facility instrument.

The push in the radio astronomy community was to higher frequencies, and several groups were already targeting the millimeter-wave bands above 100 GHz. This interest had been spurred by the discovery of CO (115 GHz) in interstellar space by Wilson, Jefferts and Penzias [18], [19] at Kitt Peak National Radio Astronomy Observatory in 1970.

After lots of ground breaking effort on the part of Rydbeck and colleagues, a new 20 m diameter Cassegrain telescope, constructed by Essco Corporation, Concord, MA, USA, was inaugurated at Onsala in 1976 by Sweden's King Carl Gustaf XVI. This largest diameter millimeter-wave telescope facility at the time, boasted operation from 8 to 120 GHz and was easily recognizable (sometimes affectionately referred to as the golf ball[6]) by its unique 30 m diameter geodesic radome composed of thin (0.8 mm thick) translucent white panels with excellent radio transparency down to at least 3 mm wavelength [20].[7]

Kollberg had been developing both maser, and new low-noise Schottky diode-based receivers for the new telescope for several years. He took the masers up to 40 GHz [21], [22], but switched over to Schottky diode mixers above this frequency range.

Low noise millimeter- and sub-millimeter-wave Schottky diodes based on patterned gold-on-GaAs with spring loaded tungsten "whisker" contacts were in development at both Bell Laboratories [23] and the University of Virginia.[8] These diodes were generally mounted up in waveguide circuits [24] and, despite their mechanical fragility, cryogenically cooled to

[6]For a particularly apropos image see: http://www.panoramio.com/photo_explorer#user=5452867&with_photo_id=51100677&order=date_desc

[7]As an interesting anecdote to this story, Kollberg recalled that, years after Rydbeck retired in 1981, visitors to the new Onsala facility were as interested in meeting Olof as they were in seeing the new state-of-the-art radio telescope.

[8]The high frequency Schottky diode design and fabrication effort was led by noted Univ. of Virginia Professor Robert J. Mattauch, whose lab was the precursor to Virginia Diodes Inc., Charlottesville, VA, USA, founded and led by Mattauch's former graduate student, and later colleague, at University of Virginia, Dr. Tom Crowe.

reduce the thermal noise contribution [25]. In one recollected story, Kollberg had just finished cold cycling one of his new 35–100 GHz mixer designs, which was hung at the bottom of a glass tube immersed in liquid nitrogen during the noise measurements. After some very successful results, he had left the dripping tube and attached electronics in a laboratory trash can to collect the condensation, and went home for the evening. In the morning he found the trash had been emptied, and along with it, his new receiver. He chased the trash truck all the way to the main university campus garbage bin before he was able to retrieve the mixer—miraculously undamaged!

During the period between the mid-1960s and early-1970s, a lot of millimeter-wave receiver development was going on at radio observatories around the world, and especially in the US. Kollberg felt it was very important to get to know these successful radio astronomy groups and he made his first visit to the US in 1969. He stopped at Harvard's Smithsonian Astrophysical Observatory, Cambridge, MA, Caltech and JPL's Goldstone telescope facility in southern California, UC Berkeley, National Radio Astronomy Observatory in Greenbank, West Virginia and several other places. He tried to keep up these visits on a yearly basis. He recalls a particularly extensive U.S. trip around 1974, in conjunction with initial work on the Onsala millimeter-wave telescope, in which he spent time at the University of Massachusetts Five College Radio Astronomy Observatory (FCRAO), during construction of its new 14 m radio dish, and with colleague Sigfrid Yngvesson. He also stopped at Bell Laboratories, Holmdel, NJ, to see collaborator Martin Schneider [26], and at National Radio Astronomy Observatory and University of Virginia in Charlottesville (Sandy Weinreb and Robert Mattauch). I met Erik for the first time in 1975, on one of his trips to Goddard Institute for Space Studies, NYC, where I was working while an undergraduate for noted radio-engineer, Tony Kerr. Tony was developing and fielding receivers for the Columbia University 1.2 m diameter millimeter-wave carbon monoxide survey telescope, led by astronomer Patrick Thaddeus. The telescope would later go to Cerro Tololo in Chile for the first southern sky surveys of CO. With a large network of specialized colleagues, Kollberg continued to work on Schottky diode-based receivers throughout the 1980s [27]–[31], focusing on theory as well as practical components and circuits.

The mid-1970s was also a period in millimeter-wave astronomy where new ultra-low-noise quantum-based devices were being rapidly developed and fielded. This began with the Josephson junction mixer [32], and then the extremely successful superconductor–insulator–superconductor tunnel junction mixer [33]–[35]. Kollberg's proximity to Ph.D. student Staffan Rudner and his supervisor, Tord Claeson, both developing superconducting devices in the physics department at Chalmers, and his interest in practical radio astronomy receiver development, was a match made in Heaven.

Kollberg, Rudner, Claeson, and visiting post-doctorate Mark Feldman (out of Ray Chiao's group at UC Berkeley), put together an SIS receiver based on the available lead–alloy tunnel junctions [36][9] that became one of the first to be deployed on a radio telescope. Their paper [37], on a 73 GHz SIS array-junction receiver followed immediately after the Tom Phillip's led Caltech group's somewhat more highly cited result at 115 GHz [38].[10]

Kollberg and his colleagues continued to develop SIS receiver technology and devices for frequencies used on the Onsala 20 m dish throughout the 1980s [39]–[43], and then moved to additional applications [44], [45]. Kollberg's involvement in SIS devices culminated in some novel work with Valery Koshelets' team at the Institute of Radio Engineering in Moscow, Russia, on fully integrated superconducting receivers at 500 GHz [46]–[48].

In 1982, Kollberg again joined up with colleague Sigfrid Yngvesson, to look at developing planar millimeter-wave antennas that might be used for building integrated receiver focal plane arrays. This was a topic under much discussion within the radio astronomy community as a means of improving signal throughput for large area mapping. By simultaneously receiving contiguous or near contiguous beams distributed across a large astrophysical source (much larger than the telescope beam area) observation times could be dramatically reduced.

Kollberg and Yngvesson came upon a conference paper by Peter Gibson of Philips Research lab, UK describing a new type of planar endfire antenna with high gain and broad frequency bandwidth in the microwave regime, which Gibson termed a Vivaldi Aerial [49].[11] After first proposing its use at millimeter-wave frequencies [50], Kollberg and students at Chalmers, along with Yngvesson and Dan Schaubert and students at University of Massachusetts, analyzed and enhanced the concept, introducing the constant width slot antenna and several variants [51]–[53].

The constant width and tapered slot antennas developed by Kollberg and colleagues would prove to be extremely useful for array applications in both the millimeter [54] and submillimeter-wave bands [55]. They could be integrated onto a wide variety of dielectric substrates, and stacked so that diffraction limited imaging was achievable in at least one plane. The antenna was employed in the first large scale demonstration of a passive millimeter-wave imaging array camera by a team from TRW, Redondo, CA, USA (now Northrop Grumman) in the early-1990s [56], and has been proposed (and utilized) for a wide variety of array receivers and transceivers ever since.

The history of THz applications closely follows the development of THz power sources. For the radio astronomy community this meant having low noise, stable, very narrow linewidth millimeter and submillimeter-wave sources of modest power (mW levels) to serve as local oscillators in the heterodyne receiver downconversion process. Although high frequency, high voltage vacuum electron beam devices existed up to 1 THz

[9]These lead–lead oxide–lead devices were inherently short lived and were later replaced by more robust superconducting niobium and niobium nitride devices with various oxide layers.

[10]For some additional historic background on Josephson and SIS mixers, in relationship to THz developments, see:

P. H. Siegel, "THz pioneer: Paul L. Richards—Working at the edge—Transition edge sensors and the edge of the universe," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 2, pp. 341–348, Nov. 2011.

P. H. Siegel, "Terahertz pioneer: Thomas G. Phillips—The sky above, the mountain below," *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 5, pp. 477–485, Sep. 2012.

[11]Note that contrary to popular gossip, Kollberg related that Gibson did not name the antenna because of its French-horn-like edge contour, but rather because he thought of the concept while he was listening to Vivaldi on the phonograph.

(klystrons, carcinotrons and backward wave tubes),[12] solid state sources, if available, were preferred. Many types of solid-state oscillators and coherent upconverters were proposed and tested throughout the 1980s and 1990s, but none proved to be as successful as the point-contact Schottky barrier diode used as a harmonic multiplier [57] (a driver oscillator at the starting frequency had to be employed, but this was possible up to about 150 GHz using phase locked Gunn devices or klystrons). The Schottky diode multiplier was based on the generation of harmonic power through the non-linear capacitance variation induced by changes in the thickness of the diode depletion layer by the applied RF pumping (varactor mode). If significant forward current flowed through the diode, additional harmonic conversion was generated by the nonlinear resistance across the barrier (varistor mode) [58].

Kollberg had spent some time working on the analysis of quantum well (resonant tunneling) diodes [59] while developing his SIS receivers [41]. These had been proposed as potential oscillators for the submillimeter-wave bands, but had never realized significant power or stability. Several variants of the Esaki quantum well oscillator were also being tested as frequency multipliers by making use of the nonlinear capacitance variation that could be achieved with multiple barriers [57], [60]. A big advantage of these devices was the possibility of tailoring the capacitance-voltage curve to enhance output at particular harmonics. Also, the symmetric nature of the capacitance variation and antisymmetric current-voltage relationship in the device meant that they could be designed so that only odd harmonics would be generated (no power lost to intermediate or higher-order even harmonic frequencies).

Kollberg came up with a very simple variant of the multiple barrier quantum well structure that he called a quantum barrier varactor (QBV), more commonly referred to now as a heterostructure-barrier varactor (HBV). The HBV uses a single insulating barrier to suppress the diode current flow, but preserves the symmetric nonlinear capacitance-voltage variation that is used to produce odd harmonics only. He and his student Anders Rydberg (now at Uppsala University, Sweden) published the HBV concept in 1989 [61]. Significantly improved performance over existing quantum-barrier devices was realized quite rapidly [62].

Kollberg, students and colleagues at Chalmers, especially Jan Stake, and others in the millimeter-wave community have continued to develop and improve the HBV device to this day [63]–[67]. Although they have so far proven to be most useful in the millimeter-wave bands, an upcoming paper planned for this journal has record HBV quintupler ($\times 5$) results close to 500 GHz [68].

The last major topic that Kollberg worked on in his long career is perhaps the most relevant for the THz community. In 1991, he received two visitors from Moscow State Pedagogical University—Gregory N. Gol'tsman and Evgeni M. Gershenzon, who were on an exploratory trip seeking out potential technical and financial collaborators in the West as the Soviet Union began to unravel. Their now classic paper introducing the concept for the Hot Electron Bolometer (HEB) mixer based on resistive heating in superconducting niobium films [69] had just recently been published, but only in Russian. When they spoke to Kollberg about their detector work, he became very interested in the HEB as a potential low-noise THz receiver.

Gershenzon and Gol'tsman needed financial support for their research work in Moscow. They could offer Chalmers some high frequency Russian backward oscillators (rare in the West) as a sort of trade-in-kind. Kollberg began buying Russian backward wave oscillators, and a solid long term cooperative relationship between the two groups developed. Later in the same year the first niobium nitride thin-film HEBs were tested by the Moscow group [70] and they had response times in the picosecond range (intermediate frequency beyond 2 GHz). The use of superconducting HEB mixers as mainstream THz detectors[13] was assured!

Kollberg went to Moscow in December 1991, along with Errico Armadillo from the European Space Agency, Thijs de Graauw [71], and then graduate student Joakim Johansson (now at RUAG Space, Sweden), who was working at Chalmers on the planar antennas [51]–[53], [55]. According to Joakim, it was an amazing trip, falling as it did during the very week that the Soviet Union officially dissolved. "We entered the USSR and exited Russia!" On their visit they were hosted by the Russian Academy of Sciences Institute of Radio-Engineering and Electronics and they met primarily with A.N. Vystavkin and Valery Koshelets, with whom Chalmers had strong ties [45]–[48]. They also had time to meet with Gol'tsman and Gershenzon, setting in motion a collaboration that would bring NbN films to Chalmers and place HEB mixers on the Herschel Space Observatory some 18 years later.

Over the next ten years, Kollberg worked on HEB mixers with his Russian collaborators, Sigfrid Yngvesson and many students and colleagues at Chalmers [72]–[80]. A very fruitful collaboration was also initiated with Thijs de Graauw and the receiver group at the Netherlands Institute for Space Research (SRON). One of Gol'tsman's students, Boris Karasik [69], [72]–[74], made several extended trips to Chalmers in 1993 and 1994 to work with the Swedish team. Boris ended up at JPL in 1995, where he has been a respected colleague of mine, and a THz device expert, for more than 18 years.

In 2002, Kollberg reached mandatory retirement age in Sweden and had to drop to 25% time at the university. This did not diminish his enthusiasm however, and he helped ready the HEB mixers for their most challenging astrophysics application to date—as a critical part of the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory.

Kollberg was one of the original team members on the Letter of Intent to Propose the Far Infrared Space Telescope (FIRST) mission to the European Space Agency back in 1982 [71]. By the time Herschel receiver development was in full swing (starting around 2002), Kollberg was already in semi-retirement. Never-the-less his long standing expertise, pioneering

[12]Canadian made klystrons could reach 200 GHz with a few mW, French carcinotrons were made commercially at 400–500 GHz and Russian backward wave tubes could reach 1.2 THz.

[13]Note that cryogenically cooled hot electron bolometers composed of InSb had been operated as sensitive low noise THz mixers for many years (see referenced articles in [10]Footnote 10, for example). However the response time of these bolometers was extremely slow (microseconds) compared to the new superconducting HEBs, and so the intermediate frequencies at which these devices were able to respond as mixers only reached MHz frequencies. The Russian NbN devices could respond well above 2 GHz—a significant advantage for astronomical spectral line coverage.

development work, and connections to the Moscow University bolometer group, served Chalmers very well. The Chalmers receiver team, in collaboration with Gol'tsman's group, JPL and Caltech developed and delivered the critical, and successful, 1.4–1.9 THz HEB mixer for HIFI in 2009 [81]–[84].

In 2006, once again, teaming up with his old friend and colleague, Sigfrid Yngvesson, and the SRON team (J. R. Gao in particular), Kollberg extended his work on HEBs to include an important contribution to the understanding of the quantum noise contributions in THz devices [85]–[87], and on arraying applications [88]. He also worked on direct detection contributions to HEB mixer noise [89]. In his most recent, but hopefully not his final contribution to radio astronomy instrumentation, Kollberg joined up with Yngvesson and several longstanding colleagues for a recent (2011) paper in this journal on understanding and calculating the input matching of HEB devices to connected antennas [2].

Before we completed our discussion, Kollberg wanted to especially mention the many excellent students he has worked with over the years, as well as a particularly capable and loyal engineer, Carl-Olaf Lindstrom [39]. Erik has now dropped down to a very minimal technical role at Chalmers, but after so many years, and so many valuable contributions to radio astronomy devices and instrumentation, he and his papers will remain on the *receiving* screen of many researchers' reprint folders, including my own.

Acknowledgment

The author is grateful to more than a few former students and colleagues of Professor Kollberg for suggesting him as a candidate for this series. He also personally thanks Dr. J. Stake for hosting his visit to Chalmers and Dr. J. Johansson for one of the stories relayed in this article.

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Erik L. Kollberg (M’83–SM’83–F’91–LF’11) was born in Stockholm 1937. In 1970 he received the Ph.D. degree from Chalmers University of Technology, Göteborg, Sweden.

In 1979, he was appointed a full professor at Chalmers. From 1967 to 1987, he headed a group which developed radio astronomy receivers for frequencies from a few GHz up to 150 GHz for the Onsala Space Observatory telescopes. He was acting Dean of Electrical and Computer Engineering between 1987 and 1990. He founded the NUTEK and Chalmers center for high speed electronics (CHACH), and led it from 1995 to 1997. Until 2001, he was Head of the Department of Microelectronics in Electrical and Computer Engineering ($\approx$100 people), and of the Microwave Electronics group ($\approx$35 persons). Between 1963 and 1976, he performed research on low-noise maser amplifiers. Several masers working in the frequency range 1–35 GHz were developed for the Onsala Space Observatory, which became well known for having the best receivers for radio astronomy in the world. In 1972 he initiated research on low-noise millimeter-wave Schottky diode mixers, and in 1981, he expanded this to superconducting quasiparticle (SIS) mixers. This research covers device properties as well as mixer development for frequencies from about 30 to 750 GHz. Research work also included GaAs millimeter-wave Schottky diodes (since 1980), and since 1986, resonant tunneling devices and three terminal devices such as FET’s and HBT’s.

Kollberg pointed out the limitation in performance of varactor multipliers due to current saturation effects and he is the inventor of the heterostructure barrier varactor (HBV) diode for multiplier applications. He was one of the pioneers in superconducting hot electron mixer research and his group has achieved world record results with these devices for frequencies up to 2.5 THz. He published more than 300 scientific papers and has edited and authored chapters in several books. He also holds 9 patents.

Dr. Kollberg received the 1982 Microwave Prize given at the 12th European Microwave Conference in Helsinki, Finland, and he was presented with the Gustaf Dahlén gold medal in 1986. He was invited as a guest professor at Ecole Normal Superieure, Paris, France, in the summers of 1983, 1984, and 1987. Between September 1990 and March 1991, he served as a Distinguished Fairchild Scholar at the California Institute of Technology, Pasadena. In 2000, he was awarded an Honorable Doctorate at the Helsinki University of Technology. He is a member of the Royal Swedish Academy of Science and the Royal Swedish Academy of Engineering Sciences, and has been a Fellow of the IEEE since 1991, and Life Fellow since 2011.