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Some Neglected Possibilities of Communication

For some kinds of messages the skin offers a valuable supplement to ears and eyes.

Frank A. Geldard

The great informers of events in the outside world seem obviously to be the visual and auditory channels. Depending somewhat on how the information is to be used, what chains of responses it will set off, we cast messages in visual or auditory form. Not exceptionally but more commonly than not, we code them auditorily:

1) If rapidly successive data are to be resolved. Audition is more useful than vision as a means of making temporal discriminations. Also, auditory reaction times are typically faster.

2) Where the recipient is preoccupied with other tasks or in a condition of reduced alertness and we wish to "break in" with unexpected messages or warnings.

3) Listening habits being what they are, where relatively brief, easy, highly meaningful materials are to be apprehended and remembered.

4) Where flexibility of message transmission is important. The voice spontaneously gives inflectional shadings and emphases.

5) Where, out of a larger mass of data, we wish to present information germane to an issue at hand—where we can, in advance of message transmission, be highly selective. The trouble with books, maps, and tables (all of them visual devices) is that you have to find what you are looking for.

6) Where visual reception is less available, whether by reason of environmental conditions that interfere with visibility, unfavorable orientation of the observer (a common visual difficulty), overloading of the visual channel, or outright sensory defect.

Visual coding seems to be indicated:

1) Where messages involve spatial orientation or guidance. Vision is the great spatial sense, just as audition is the great temporal one. Pictorial representation is often a boon.

2) Where fine discrimination is needed. Vernier visual acuity is the best the sense organs have to offer; we put our trust in needles on scales whenever we can arrange to do so in measurement operations.

3) Where complex, unfamiliar material is to be comprehended; the material is there, to be looked at again and again if need be.

4) Where reference data have to be immediately available or where simultaneous (or nearly simultaneous) relational comparisons have to be made.

5) Where a recipient of information has to make relatively prompt selection of data from larger stocks of information.

6) Where auditory reception is hampered by unfavorable environmental conditions, overloading of the auditory channel, actual auditory defect, or previously acquired attentional habits favoring vision.

These comparisons—or some like them—have been made many times and in a variety of ways, and I am indebted to my colleagues Henneman and Long for their review of this question a few years back, in which they placed just the right accent, it seems to me, on the contention that "the choice between the eyes and ears as sense channels for the presentation of information to the human operator rests upon the specific demands of various operational situations." In addition to having shown some of the relative virtues and defects of seeing and hearing, they were able to specify some message-processing situations in which two senses are better than one and some in which either sense will do (*1*).

The Skin as Informer

In all this debate about eyes and ears there has been scarcely a voice raised about other possibilities. Yet the human integument, housing several modalities, rivaling the ear as a temporal discriminator and greatly excelling the eye in this respect, sharing with the retina the property of somewhat orderly spatial extension, has many of the message-transmitting features commonly extolled in the eye and the ear. Let us glance back at our list. The skin can make both temporal and spatial discriminations, albeit not superlatively good ones in either case. It is a good "break-in" sense; cutaneous sensations, especially if aroused in unusual patterns, are highly attention-demanding. It is possible, therefore, that the simplest and most straightforward of all messages—emergency

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warnings and alerts—should be delivered cutaneously. Because of the relatively large areas available on the body surface, there are a great many sites of potential stimulation, provided only that the transduction problem be suitably engineered. Moreover, these vast expanses are practically unused, except for regulation of the water and heat economies of the organism. If we add the clear superiority of touch (when vision and hearing are lacking or impaired) to the remaining modalities, the chemical senses, smell and taste, we have a formidable set of properties to utilize in cutaneous message processing—a list that ought to challenge us to find ways to capitalize on it.

Use of Existing Devices

Now, two radically opposed approaches may be made in assessing the possibilities of cutaneous communication. If one is interested in trying to utilize, in novel ways, the world's current collection of hardware, the "things" our culture has surrounded us with as elements in conventional communication systems, one asks, for example, what the skin's capacity is for feeling the disturbances present in a telephone receiver or other electromechanical transducer and interpreting such movements. This is, in fact, what was asked years ago by those who became interested in "hearing through the skin." Their approach was reasonable, given as a starting point the considerations that the skin is quite capable of apprehending mechanical vibrations and that the world contains vast quantities of hardware capable of transducing speech and music into mechanical vibrations of an intensity that can be felt by the skin.

The argument was an evolutionary one: the eardrum, which does so well at picking up and transmitting the fine dance of the air molecules present in speech, is a descendant of a cruder but not dissimilar tissue also capable of behaving with some efficiency in acoustic systems. Why not simply train the skin to do substantially what the tympanic membrane does? There were many patient experiments, and enough came out of them to stimulate persistent effort. Human speech, suitably amplified, was applied to the fingers. After a sequence of 28 half-hour training periods, in one experiment (*2*) the feeler could learn to judge, with about 75-percent accuracy, which one of ten short sentences had been delivered to the skin. In another (*3*), after some 30 hours of practice, single words, presented without context, could be recognized about half the time. Even these poor levels of performance were not maintained if the talker changed his rate of presentation or if another person sat in for him. The efforts at getting the skin to master a language not natural to it eventually petered out; the approach of adapting existing hardware had, for all practical purposes, failed.

Building Blocks for Coding

If one attack is to force a receptor system to perform in an unnatural way by trying to adjust it to the world's existing communication devices, the other involves asking how the world's properties and materials might be utilized to get the most out of the senses.

What discriminations are possible for the skin? What is the stuff out of which a cutaneous language has to be built if it is to be optimally utilizable by the skin? Having ascertained what sensory dimensions there are, one is in a position to catalog the possible discriminations, relative and absolute, that might be made along such continua. Such a procedure should yield building blocks, collocations of stimulus properties, for coding. One would, indeed, be in possession of the stuff out of which all possible cutaneous communication systems could be constructed, provided only that the dimensional analysis was exhaustive and systematic. Then, what stimulus arrays were selected for coding and use would depend mainly on what had to be communicated—whether the "message" was a warning, directional or rate information, a more sophisticated and elaborate formal "language," or what not.

Dimensions of Mechanical Vibration

If one begins with repetitive mechanical impacts, vibration, there are available but a few stimulus dimensions of the first order. They are easily listed: locus, intensity, duration, and frequency. Mechanical motion is not the only possibility, to be sure—the skin responds to thermal, chemical, and electrical stimuli as well—but vibration is the most promising one if continuous signaling is contemplated. There are also some derived dimensions, and we shall come to them later. What of the first-order ones? This is not the place to review in detail all the psychophysical data. They are the joint products of a succession of workers in the University of Virginia laboratory, and most of them have been published (*4*).

Locus

Locus has never been systematically investigated, though a good deal is known about it through the studies of Spector (*5*) and Howell (*6*). The question of how many places on the skin can be utilized is not settled by extrapolation of the results of two-point esthesiometer measurements. Unlike static pressure, mechanical vibration applied to the skin does not stay "within bounds" unless special steps are taken to prevent its spread, though Békésy, with characteristic ingenuity, has devised a coaxial vibrator that will take the special steps (*7*). This means that, under ordinary conditions of stimulation, the two-point limen for vibration is many times greater than the static one for a given region. Howell, working in our laboratory, found that seven vibrators could be spaced on the ventral rib cage with 100-percent identifiability of locus, under his conditions. This is perhaps the limit for a practical cutaneous communication system. The chest accommodates five conveniently, and it is tempting—until one finds that it won't work—to consider the combinations of vibrators (31 signals for five contactors) that might be coded. The difficulty is that two or more simultaneously acting vibrators feel no different from one, once the static pressure of each has adapted out and provided the vibratory pattern is set up in all of them with the same onset. A split-second temporal differential is all that is needed to restore two local impressions, but this leads to the further complication that such a manipulation also provides the essential conditions for synthetic movement, tactual "phi." This, in turn, could be coded, of course, and we shall encounter it again later as belonging in the family of "derived" phenomena.

The failure to explore the entire body for locus as a codable cue is not the result of neglect, nor yet of lack of interest in the outcome. In this electronic age so many things have to await technological advance. We simply have not had a transducer with the right properties to make the experiment feasible. When Howell had an array of eight vibrators on his subject's chest he was literally trapped in a forest of concrete-rooted supports, flexible goosenecks, and long, flat springs necessary, with the vibrators then in use, to insure independence of vibratory generation and preservation of uniform static background pressure. It is, therefore, a considerable satisfaction to report a technological "breakthrough" in the summer of 1959, whereby my colleague R. C. Bice succeeded in modifying radically a transducer of the hearing-aid variety to provide strong, low-frequency vibrations which are not readily damped by the skin. He also found an ingenious way of utilizing fabric fasteners to couple the vibrator firmly to any chosen site of stimulation. The instruments are sufficiently small and light, and their electrical properties are such as to yield high powers without undue heating. For the first time the systematic exploration of the dimension of locus seems to be in sight.

Why is it so important that it be explored? There are several reasons, but the chief one has to do with the bearing the result may have on communication theory. It is not inconceivable that nothing other than variation in absolute cutaneous locus, suitably coded, is necessary to provide as complex a communication system as may be needed for many purposes. Thus far, in exploiting locality as a dimension, we have confined all stimuli to the rib cage. This has not been an entirely arbitrary matter. The ventral thorax is a relatively traffic-free area of somewhat uniform sensitivity in the males of college age who served as subjects in our experiments. We also had in mind the possibility that applications of any cutaneous communication system we devised might be to vehicular situations in which all other major areas of the body surface would be ruled out as otherwise occupied, either by reason of their motility or their favorable relation to the body's center of gravity. Cosmetic considerations could not be entirely ignored, either.

However, these are accidental restrictions that need not be permanent, especially if we are getting at principles. It seems probable that the integument has a sufficient range of local "tags"—call them, with Lotze, "local signs," but don't trouble yourself, at the moment, with the perplexity they generated for a century—to yield a very considerable set of differentiable and absolutely recognizable signals which might be coded to provide a satisfactorily complete language. We have a hunch that the "magical number seven" may not be controlling, because the body schema calls for a fair number of named and familiar parts. The skin surface is "multidimensional," in Miller's meaning of the term (*8*), and channel capacity should increase accordingly. If this turns out to be the case then the problem may be that of ascertaining whether rapid attentional leaps may be made from one bodily region to another—from the forehead to the left calf to the right shoulder-blade, say—without benefit of psychoneurosis in any form. Well, there is not too much point in further speculation along these lines. The laboratory will provide the only acceptable answer.

Intensity

What of intensity? There have to be some limits. Each part of the integument has its own absolute threshold, and each part has its susceptibility to discomfort and to damage by the trip-hammer action of powerful vibrators. In the chest region a useful range of stimulus amplitudes is that limited by the values 50 and 400 microns; the former value is safely above the 100-percent absolute threshold, the latter falls well below the threshold of discomfort. Between these limits the average observer, under laboratory conditions and with the use of a careful psychophysical procedure, can detect about 15 steps of intensity. On an absolute recognition basis, unless one were to select subjects for the purpose or train them, it would be unsafe to include more than three steps, widely spaced over this range. Intensity is, in fact, the least exploitable of all the first-order dimensions. An analysis of errors in a communication system which coded locus, intensity, and duration shows nearly all the mistakes to have been made along the intensity dimension (*6*). There appear to be two chief reasons for this: (i) a fixed amplitude applied to different loci varies considerably in its "feel," perhaps owing to accidents of local innervation, perhaps to reinforcing or damping variations in underlying tissue; (ii) it is not easy, in view of breathing motions and disturbances coming from circulatory events, to maintain a strictly invariant relation between a mechanical vibrator and the skin surface on which it rests.

Duration

Duration of a continuous vibratory "package" is judged with some precision over the entire useful range. The range, of course, has to be selected on the basis of extraneous considerations. In our experiments we have chosen not to deal with any durations of less than 0.1 second, on the ground that a "buzz" much shorter than this is likely to be mistaken for a "nudge" or a "poke." At the other end of the scale we have set 2.0 seconds as a limit beyond which we are unlikely to wish to code signals; a communication system employing units lasting more than 2 seconds is certainly a ponderous one. Between 0.1 second and 2.0 seconds, then, there is a durational continuum within which the average observer can make about 25 distinctions, the steps being of the order of 0.05 second at the low end and 0.15 second at the high end of the range. This is again the relatively precise Δt of the psychophysical experiment. Absolute identifications with 100-percent accuracy yield four or five considerably more widely dispersed levels, and if there is to be neither selection of subjects nor training of them, it is safer to use only three levels.

Frequency

It is clear from all this that we possess three sets of building blocks of cutaneous communication systems—a limited number of absolutely discriminable steps of locus, intensity, and duration. There is, of course, a fourth primary dimension. This is frequency. The story of frequency discrimination in the vibratory realm is not a simple one. There is a history, and also there are some interesting outcomes of recent experiments. We may summarize the history by saying that failure to control for differences in subjective intensity, when frequencies were being compared, and for contaminating transients at the "on" and "off" points of the stimulus envelope has invalidated all measures obtained prior to those recently obtained by Genevieve Goff in our laboratory (9). She overcame these defects by first assembling a band of equal-loudness stimuli, which differed in frequency, then measuring Δf systematically within that band throughout the obtainable frequency range. Her basic results show that, at very low frequencies, below 70 cycles, say, vibratory "rate" judgments are quite good, but it is equally clear that discriminability fades rapidly as the frequency scale is ascended. In the region that is best for speech sounds the skin does very badly indeed, and this finally explains why the "hearing through the skin" programs, alluded to earlier, yielded such disappointing results.

There is one additional difficulty where vibratory frequency is concerned; were it not for this it might conceivably be possible to transpose audible frequencies downward into the tactile range. The difficulty is this: The correspondence between vibratory frequency and perceived "pitch" is a tenuous and uncertain one. Vibratory pitch proves to be a joint function of both frequency and amplitude. To be sure, this is also true, for much of the audible range at least, in hearing as well, but intensity is only a very minor determinant of auditory pitch; the loudening and softening of pure tones can move pitch about only a little, and, if tones are as impure as they have to be to be musical, they apparently do not budge. Frequency is very nearly in absolute control. In the cutaneous sphere things are different. Increase the amplitude of a moderately loud 40-cycle sinusoidal vibration applied to the finger tip and it undergoes a marked downward shift of pitch. Decrease the amplitude and the pitch goes up perceptibly. Békésy has recorded shifts of the order of three octaves (7). It is obvious that frequency would have to be handled gingerly in a communication system, especially if intensity were simultaneously manipulated as a variable.

Language of Vibration

In our initial efforts to form a system of vibratory signals capable of being coded, only the three obviously useful dimensions of locus, intensity, and duration were employed. A simple alphabetic code was devised and applied successfully by Howell, so successfully that a subject who had invested a total of 30 hours in learning the alphabet of the "vibratese" language could, after a further training period of only 35 hours, receive sentences with 90-percent accuracy when these were transmitted at the rate of 38 five-letter words per minute.

This performance in no wise represents the optimal one. With the same rules as those of international Morse code with respect to interword and intraword spacing (0.1 and 0.05 second, respectively), the system requires only 0.79 second to transmit the "average" five-letter English word. This means that the ceiling transmission rate is 67 words per minute, a speed well over three times that of proficient Morse. To approach this rate, however, there would be required an extensive and somewhat elaborate engineering job to devise an automatic coder, perhaps of the tape variety, that would initiate signals faster than our present homemade machine, a manually operated typewriter that triggers "flip-flop" circuits (for time) and a bank of potentiometers (for intensity). The closing of the gap between 38 and 67 words per minute we leave to those interested in establishing world's records.

Meanwhile, what other building blocks are available? We have considered only the first-order dimensions of the vibratory stimulus. There are some derived dimensions, a few of which have already received some attention. It would be helpful to have additional codable cues, if only to be in a position to add redundant elements. Much has been written about purifying and simplifying languages by the reduction of redundancy. Where intelligibility is less than optimal there is much to be said for making the language more, rather than less, redundant, and the vibratese language would doubtless benefit by this kind of doctoring.

Intensity as a Function of Time

What are the candidates here? Intensity variations as a function of time present one set of possibilities. A signal may be imposed on the skin quite abruptly or more gradually, just as in music one may have variations in "attack," "hitting" a tone or "sliding into" it. Systematic manipulation of this variable has been carried out by Howell (10) for mechanical vibration, and by me for direct electrical stimulation of the skin with alternating currents. For mechanical stimulation, a growth of amplitude from zero to 480 microns—the largest that it was practicable to work with—and for rise times bracketed by the shortest transientless one for the system and the longest it would be reasonable to consider for signaling purposes (a growth requiring a full second to achieve), there prove to be six discriminable steps. As with all other similar functions, these come from the conventions of psychophysics. Absolute identifications are, of course, not spaced this closely. Indeed, if 100-percent recognizability of "attack rate" is demanded, over this range of onset slopes there are but two; the "magical number" proves to be seven minus five! There are presumably another two steps associated with offsets.

Wave-Form Variations

A second possibility, in the realm of derived dimensions, is wave form. This has not been investigated as yet, though it is clear that wave-form variations should be discriminable if the basic frequency is low enough. Still other moment-to-moment variations should be detectable. Perhaps it would be possible to introduce variations within signal envelopes other than those of onset and offset—a gradually increasing or decreasing frequency, say. This is a totally unexplored field.

Spatially Discrete Loci

Another patterning of stimuli involves space as well as time. As in vision, the successive stimulation of two separated receptive areas, provided the temporal relations are right, leads to perceived movement. Unlike vision, the critical time relation for tactual "phi" is the absolute interval between the beginnings of the two successive exposures, not the duration of the silent interval between them. Indeed, there need be no silent interval at all. They may overlap and still yield good movement if the onsets are properly spaced. Cutaneous phi has not been surveyed with a view to coding it and incorporating it into a communication system so much as it has been studied with respect to its essential conditions as a phenomenon, but clearly it offers some possibilities (11).

It is doubtful that vibratory phi should be coded into any language of the type I have already described. Indeed, in any rapid succession of signals applied to spatially discrete loci the crucial conditions for synthetic movement are already given. Movement has to be overlooked, not apprehended in this situation, of course. On the other hand, the phenomenon of cutaneous movement is an extraordinarily powerful one; it is highly attention-demanding. Place a ring of vibrators around the body (for example, three across the front and three across the back of the thorax), energize them successively with a 0.1-second temporal separation, and there is felt a vivid "swirling" motion, entirely novel in the experience of most people, because the observer seems to be at the center of it! This effect is a completely prepossessing one, and, accordingly, it is an ideal one for coding in a different fashion, as a warning signal to be infrequently used but capable of highly significant coding. It would do valiant service attached to a "panic button."

Role of Cutaneous Communication

This raises the important question of the ultimate place of the cutaneous channels in the total communication picture. Coding to letters and numerals is really a quite pedestrian way of getting meanings into tactile patterns. There are, to be sure, obvious ways of making such a system "fly" at a faster rate. One way would be to code the vibratory signals to phonemes. We have not attempted it because of the prodigious investment entailed in learning the phonemes themselves, but it ought to be tried. It is also possible that there may be developed an entirely novel cutaneous shorthand, one capitalizing on distinctively tactile properties. Serious study of basic cutaneous perceptual phenomena, an area dignified by the devotion of not more than a dozen first-rate minds in the whole of recorded history, might turn up such a linguistic development.

Possibilities for cutaneous communication are by no means confined to conventional language, of course. Other kinds of information may be imparted tactilely. Rates, amounts, directions—anything falling on unidimensional or bidimensional continua—could presumably be communicated to the skin by way of suitably patterned mechanical impacts or sequences of them. One of these possibilities has already been exploited in our experiments. Vibratory tracking of the compensatory-pursuit variety has been carried out by lining up three vibrators across the chest, letting them be successively energized to give the impression of continuous movement in one direction or the other (through utilization of phi), such that the "arrowhead" always "points to" the target, and with the vibratory sequences temporally spaced to indicate degrees of urgency in getting back "on target." The subjects manipulated a steering wheel and attempted to eliminate all cutaneous signals by promptly neutralizing all off-target indications.

Ten subjects performed in response to these tactile signals. Ten others were presented the visual analog, lights being substituted directly for the vibrators. Both groups learned rapidly, and the vibratory performance was in no wise inferior to the visual. Whereas the visual situation is not the optimal one for this sense, of course—the target was traveling only at the rate of 3.5 degrees per second, and the eye can handle speeds many times as great—the tracking task imposed on the subjects was one that would keep all but the speediest vehicles comfortably on course, and the skin was handling the assignment fully as well as the eye.

Subsequently, this experiment was simplified. Synthetic movement was taken out of the display, the three vibrators were reduced to two, and even the "urgency" feature was eliminated. Now there occurred only a simple "nudge," a brief burst of 60-cycle vibration, to indicate direction off the target to the right or left. Performance showed no significant deterioration with this removal of redundancy in the signal. Only a meager display is needed to give directional information of a kind that is adequate for fairly complex performance.

Currently, there is being tested a bidimensional vibratory display designed to signal both "right-left" and "up-down" deviations from the target, such as occur in following a glide path or keeping a missile on course, and there is every indication that the system will do what is expected of it. The value for situations in which vision and hearing are pre-empted, for one reason or another, is obvious.

Electrical Stimulation

Another whole domain of possibilities opens up when we consider that only one form of energy, the mechanical, has thus far entered our calculations. Whereas not much is to be hoped for from the chemical and thermal forms of stimuli—they are both too ponderous in their operation to be of much use in communication; at best they could only provide the analogs of smoke signals—there is the whole important realm of electrical stimulation. The skin responds with lively patterns to both direct and alternating current. Indeed, the heart of the problem is that the patterns are, in general, somewhat too lively for comfort. We have devoted several years of intensive effort to finding the conditions of electrical stimulation that will yield codable vibratory patterns unaccompanied by pain and that can be reproduced on demand. The problem has turned out to be a slippery one. Electricity is the great "nonadequate" stimulus; it triggers everything, as physiologists well know. However, the important stimulus parameters are few in number and my colleague John F. Hahn has been able to isolate the really significant one in skin stimulation (*12*). Where square waves are employed and are systematically varied in frequency and duration, thus obviating any influence of the change in rate of current increase such as occurs with alternating current of variable frequency, it turns out that absolute threshold is related not at all to frequency but only to duration. This fundamental discovery permits us to narrow our search for the basic medium of reception in electrical sensitivity of the skin. The great stumbling block thus far is the omnipresent pain. While, under some reproducible conditions, pain tends to adapt out in continuous signaling, leaving behind a not too unpleasant tingle, it is doubtless asking too much, in practical communication situations, to expect anyone to tolerate from a transducer even transient discomfort.

Conclusion

I have indicated some of the kinds of things it would be important to know for further investigation of the cutaneous communication problem. There are others, many others. Indeed, almost any certain fact about somesthetic functioning is likely to prove valuable here. When one is working so close to the foundations of an edifice there is high probability that anything accomplished will turn out to be important for the superstructure ultimately to be erected. Though we address ourselves to the practical problem of getting messages transmitted over the cutaneous channel, we find ourselves asking about very basic matters—about the perception of time and tactual space, about intensity discrimination, and about topographic variations in sensitivity. There is not the slightest doubt that a host of other observable cutaneous phenomena—adaptation, masking, reaction latencies, spatial interactions, temporal summations, "loudness" and "pitch" functions, recruitment effects, and so on—are more than peripherally related to the central problem. We have not yet really begun to look carefully into the communication possibilities offered by the human integument or even into the bare facts that provide the possibilities (*13*).

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The Mössbauer Radiation

Low-energy gamma rays provide the most precisely defined electromagnetic frequency yet discovered.

Winston E. Kock

One of the latest discoveries in physics which is now intriguing scientists in many fields remained relatively unknown for a year after its publication. Early in 1958 Rudolph L. Mössbauer published in the *Zeitschrift für Physik* (*1*) his first report concerning an emission and absorption process for low-energy gamma rays. Between that time and September 1959 there was no published evidence of any related work going on at other laboratories, yet today there is extensive activity at many institutions, including Harvard, Los Alamos, Illinois, and the Argonne Laboratory in America, and Harwell, Birmingham, Cambridge, and Manchester in England.

What is it about this new effect that suddenly has brought it such attention from the scientific community? Most spectacular is the revelation that the gamma-ray radiation involved has a frequency which is more stable by many orders of magnitude than the best atomic clocks available today. Because the electromagnetic waves involved have frequencies of the order of 10^{18} cycles per second, ordinary radio techniques for observing their amazing frequency stability are not usable. For his detector, Mössbauer employed an absorber which was similar to his radiator in that its absorption effect exists over the extremely small frequency range of the radiator.

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Experimental Techniques

Figure 1 shows how the narrowness of the frequency (or line width) of the radiator and absorber are measured. When the radiator is stationary relative to the absorber, the frequency of the radiated gamma ray and that of the absorber are identical and the counter reads a relatively low value. If, now, the radiator is set in motion relative to the absorber, a Doppler shift is imparted to the radiated electromagnetic wave and the two frequencies differ. The "stop band" of the absorber "filter" is no longer effective at the Doppler shifted frequency, and the counter reads a higher value than before.

From the velocity of the radiator as measured experimentally, the amount of Doppler frequency shift is known, and the frequency characteristics of the source and absorber can be ascertained. Figure 2 shows a plot of the measured line width of the gamma ray of the isotope of iron-57, as measured by R. V. Pound and G. A. Rebka, Jr., of Harvard University (*2*). As shown in the figures, the half-width point corresponds to a source velocity of 0.017 cm/sec. When one considers that the velocity of light is 3×10^{10} cm/sec, the remarkable frequency stability of the gamma ray is evident. A velocity of one million millionth that of light has shifted the radiating frequency an appreciable amount from the absorber "filter" band. The center frequency of the line is 10^{12} times the line width; if a regulation capability of one thousandth of the line width (the capability normally achieved in present atomic clocks) is assumed, "the 'least count' in the Pound and Rebka experiment is about 3 parts in 10^{16}" (*3*).

Applications

To what use has this remarkable discovery been put? One of the applications contemplated earlier for precise atomic clocks was that of checking, from satellites, the gravitational red shift predicted by relativity theory. Relativity maintains that two identical clocks would run at different rates if one were kept on earth and the other were removed to a point of lower gravitational potential (for example, by means of a satellite). This gravitational effect is quite small; thus it would cause a clock at 2000 miles above the earth to differ from an identical earth clock by one second in 500 years.

The discovery of the Mössbauer effect changed the picture dramatically. Pound and Rebka (*4*) first published the suggestion that Mössbauer's findings would eliminate the need for the great height difference demanded by the con-