An interior view of an ammonia-maser clock being developed for NASA by its inventor, Harold Lyons, at Hughes Research Laboratory. The clock will weigh about 30 lb.

Atomic clocks for space experiments

Possible uses suggested range from an experimental check of the General Theory of Relativity to various communication and tracking applications

By Peter L. Bender

NATIONAL BUREAU OF STANDARDS, WASHINGTON, D.C.

Peter L. Bender, a physicist of the NBS Atomic Physics Section, was graduated from Rutgers Univ. in 1951, and, after spending a year at Leiden Univ. on a Fulbright grant, studied at Princeton Univ., where he received a Ph.D. in physics and an M.A. in mathematics. In 1956, he came to the Bureau of Standards as a National Research Council postdoctoral fellow. Dr. Bender received an Exceptional Service Award from the Department of Commerce in 1959 for work on the proton gyromagnetic ratio and on hyperfine spectroscopy.

Recently a number of possible uses of atomic frequency standards in satellite and space-probe vehicles have been suggested. They range from an experimental check of the General Theory of Relativity to communications and tracking applications. Of immediate interest are the capabilities of present atomic standards and of quartz-crystal oscillators for some of these purposes. In some cases what is needed is actually a clock rather than a frequency standard, but this can be easily obtained by feeding the frequency standard output into a counter.

The varieties of atomic frequency standards which have been suggested for space-vehicle use are the cesium-beam, rubidium-vapor, and ammonia-maser types. In each type, the clock rate is determined by a quartz-crystal oscillator whose frequency is servoed to the chosen atomic or molecular transition. In the first two types the oscillator frequency is continuously adjusted so that an even multiple of it will cause internal transitions in the atoms being used as a reference. For the cesium beam, these transitions cause small deflections of the paths of the atoms, while for rubidium vapor the internal transitions cause changes in the optical absorption coefficient of the sample. The ammonia maser differs from the other two types in that the ammonia molecules emit radiation which is used directly to control the oscillator frequency.

The cesium-beam frequency standard is at present the most advanced of the three types. Such standards are now available commercially with an accuracy of about 2 parts in 10^{10} and a day-to-day stability of a few parts in 10^{11}. An improved version of the apparatus is expected to be available soon. However, this apparatus is about 6 ft long and is not particularly suitable for space-vehicle use. Shorter versions, which will be less than half as long, are under development, with an expected stability of about 1 part in 10^{10}.

Commercial television utilizes a band-

(CONTINUED ON PAGE 80)

Observation Satellites

(CONTINUED FROM PAGE 29)

width of about 4.25 mc/sec. A communication link of the same bandwidth in a satellite is a reasonable technical and engineering goal. A simple equivalence from which other calculations are easily made can now be constructed.

Considering the approximate nature of the formulas already noted, the underlying assumptions, and the fact that not all the channel width can be devoted to handling this information (effective bandwidth is always less than the nominal value because of control, sequencing, and other operating information which must be transmitted), it is entirely appropriate to round off the results of this calculation into an easily remembered statement: *Transmission of the information contained in one 9 x 9-in. photograph, at 100 lines/mm resolution, on a channel of 4.25 mc/sec bandwidth, requires about 30 min.*

Another and highly instructive way of looking at the limits or constraints on the amount of information which a satellite can send to earth is to calculate what can be transmitted if this channel width is used for 24 hr—thus ignoring the very real and dominant factor that a given site can receive from a 300-mile satellite for a period of only 10 min per pass, and that this pass must be directly over the ground station. This assumption is equivalent to imagining that the satellite, at all times, in all orbits, is communicating with some ground station. Transmitting for 24 hr, the satellite can send back the equivalent of 48 high-resolution 9 x 9-in. photographs as described previously. These numbers may be used to make estimates for different film sizes and resolution numbers.

For example, suppose one wishes to compare the information capacity of two systems, A and B, where A produces 15 ft of $2^1/_4$-in.-wide (70-mm) film at 100 lines/mm and B produces 500 ft of $4^1/_2$-in.-wide film at but 40 lines/mm. We would have

$$\frac{A}{B} = \frac{(15)\ (2^1/_4)\ (100)^2}{500 \times (4^1/_2)\ (40)^2} = \frac{1}{10.7}$$

Thus system B would contain more than 10 times as much information as system A. Of course, consideration of ground resolution and real content, from the photo-interpreter's view, are excluded here.

It is essentially simple and straightforward to sketch out the characteristics of satellite systems that would collect in one day many times more data than could be transmitted by video link. One example will suffice. Consider a 36-in. focal-length system (a median example, since, for mapping, much shorter lenses could be used; for extremely detailed observation, much longer lenses) which covers, either through single-lens panoramic techniques or through a conventional multiple-camera installation, an angle of about 90 deg from about 150-mile altitude.

It may be readily calculated that such a system could cover about 6,000,000 sq mi per day, and consume at least 3000 ft of 9-in.-wide film. If a resolution level of 100 lines/mm is obtained, this amount of information would require about three months to transmit, transmitting 24 hr per day! The system described would seem to be within the state of the art. Systems of much larger capacity are conceivable and may prove desirable.

Video Can't Keep Up

There are important cases, then, where a video link cannot transmit information as fast as it can acquire it. Small improvements in transmission systems, such as increasing the number of ground stations, are minuscule attempts to cope with an inherent impotence which misses requirements by factors which could be as high as a thousand or more. This is one of the main reasons for physical recovery of the film payload, and furnishes further evidence that extreme precision in the formulation of the information transmission problem is not warranted. Arguments about factors of 30 percent or so in the formula for bits or in the formula for channel capacity are microscopic in a situation where an alternative system has a capacity 1000 times greater.

An observer aboard a satellite could, in principle, study a large amount of data and transmit selected portions of the data, or, perhaps, selected remarks about the data. This form of data processing would greatly reduce the complexity of communication facilities (from the satellite to earth), but obviously raises new problems concerned with providing an environment for the man. The weight of the man and the much greater weight of his environment must be deducted from the total payload. Hence, the oversimplified comparison, for a given weight on orbit, is between a man plus a small camera, and a much larger, unmanned camera.

It is not the intention of this paper to argue either the advantages or the disadvantages of the manned observation satellite. It seems fairly clear, however, leaving a discussion of usefulness aside, that manned observation satellites will not be available as early as unmanned observation satellites.

Physical recovery of a film payload

such as that described in the last example—3000 ft of 9-in.-wide film—produces a given amount of information faster than it can be delivered by video link.

This last remark is deliberately provocative, for it exposes the nature of some potentially fallacious comparisons between recovery and video transmission systems. Consider the last example. It is clear that if a film recovery satellite and a video talkback satellite were launched together, the first data to be returned would come from the talkback satellite. However, the delivery rate would be small.

None of the data from the satellite utilizing physical recovery can be in hand until all of it is recovered. The delay to the first data is therefore large, but the production rate after this is tremendous. These remarks do not suggest dominance of either system. What is suggested is that the two systems can, and likely should, perform different kinds of tasks.

Twenty-Four Hour Satellite

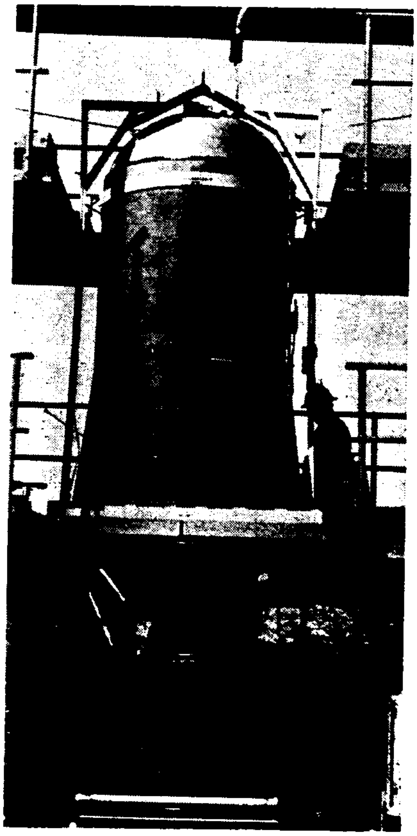
The satellite whose period is exactly that of the earth—commonly called the 24-hr satellite—is a topic of wide interest and speculation, and is of special interest in any discussion of observation satellites.

This vehicle would appear to remain at the same point in space, and from it huge areas of the earth could be put under constant surveillance, limited to some extent, with respect to the satellite's visual sensors, only by darkness and clouds. The observation potential seems enormously attractive.

Several points need to be made. The actual period of the satellite would be equal to the sidereal, and not the solar, day. This is 23^h, 56^m, 4091^s, and not 24 hr, and is the same as the earth's rotation period. The 24-hr day differs from this because of the earth's advance in its orbit and the consequent extra rotation necessary to bring the sun back into the meridian plane. Further, the satellite must be moving in an easterly direction as the earth does, at a height of some 22,240 miles above the earth (5.61 earth radii) in an orbital plane coincident with the earth's equatorial plane.

Consider what can be seen from such a satellite. It may be readily shown that from this position the maximum latitude that can be seen, with line of sight tangent at that point, is about 81.3 deg (north or south). However, atmospheric attenuation, requirements for perspective, image contrast, etc. set a practical limit of about 5 deg less than this, reducing the area capable of being observed to what lies within the latitudes 76.3 deg N and S. The 5-deg limit may be considered a minimum useful visual angle of attack. The area falling within these latitude limits, and visible from the satellite viewpoint, can be shown to constitute about 38.2 percent of the earth's surface, or approximately 75 million sq mi.

Able-Star Upper Stage



Technicians check the Able-Star upper-stage rocket that saw its first use helping to put the Transit satellite in orbit April 13. Developed by Aerojet-General for the Air Force, Able-Star features a rather precise guidance system for an upper stage and a restart engine.

Inclining the orbit plane slightly, say 10 deg, will result in the satellite's tracing a "figure eight" pattern over the ground, and will remove the blind spots north and south of 76 deg latitude. Clearly, when the satellite orbit is inclined, the satellite position will wander off the meridian, i.e., not remain directly above a given longitude. The maximum departure from the meridian, for an orbital inclination of the order of 30 deg, is about 5 deg. For a 10 deg orbital inclination, this maximum departure from the assigned meridian is 1 deg. These points are shown in the illustrations on page 29, taken from J. H. Hutcheson's paper on "Earth-Period Satellites."

Extended discussion of factors which might affect the positioning of such a satellite, especially those inevitable errors and natural perturbations which will cause departures from perfect circularity at the assigned altitude, are out of place in this necessarily brief discussion. These effects are real, and are discussed more fully in the same paper. Preliminary assessment and evaluation of these factors are necessary to determine whether there are reasons which would preclude placing a satellite in such an orbit. The answer seems to be that there are none. This is not to deny that there may be considerable engineering and technical difficulties; on the other hand, all complex projects have such problems in common.

Interest in the 24-hr satellite stems mainly from the intuitive notion that it would be useful for observation of the earth and its cloud patterns. Of course, there may be other potential uses, such as communication, listening, and the like, but observation is the most readily appreciated use of a satellite.

On the other hand, it is not altogether obvious that useful observation can be made from such a great distance. A preliminary examination of the optical and photographic problems involved should therefore be useful in thinking about the role of such satellites.

The drawing on page 28 illustrates the geometry of viewing a point on the earth at 45-deg latitude from the orbital altitude of 22,240 miles. The slant range to this point is 23,560 miles, and the angle δ (which may be called the visual angle of attack) is 38.17 deg.

Let us assume we desire to resolve 100 ft, in the x direction, on the ground (perpendicular to the line of sight, and hence perpendicular to the plane of the drawing). It may be readily calculated that 100 ft subtends an angle of only 8.04×10^{-7} radian, or approximately 0.166 sec of arc. By way of illustration, a $^1/_4$-in.-diam pencil subtends this same angle at about 5 miles! The Dawes criterion (developed under conditions of perfect optics, and entailing the visual examination of two bright point images, such as stars, and hence not entirely applicable to this problem) gives the theoretical resolution in seconds of arc as a function of lens diameter in inches as

$$\text{Resolution, in seconds of arc} = \frac{4.5}{\text{Diameter of lens, in inches}}$$

From this formula, required lens diameter for the case under discussion is about 27 in.

Because of projective effects, 100 ft in the y direction (along the line of sight, and in a direction perpendicular to the previous case) subtends a smaller angle (by a factor of 1/sin 38.17° = 1.62 times), and hence requires optics about 44 in. in diam.

Now, the required resolution called for in this example—about 0.1 sec of arc—is substantially better than that achieved routinely in astronomical observation such as those at Mt. Wilson and Mt. Palomar. Visitors to these installations cannot help being impressed with the engineering and scientific accomplishment represented there. Yet these observatories have difficulties in consistently achieving resolution better than 1 sec of arc, despite the 100- and 200-in.-diam optical systems in use.

One second of arc represents about a mile at the distance of the moon. However, the troubles that affect earthbound observatories—that is, those which limit resolution and degrade it to much less than the figures given by theoretical limits and optical performance—are, in large part, chargeable to the atmosphere. Temperature gradients, wind shears, atmospheric inhomogeneities—all degrade resolution. The optical system in the 24-hr satellite and the satellite itself will encounter many problems, but not the problem of "seeing."

Specification of lens diameter alone is insufficient to describe the required optical system. This system could be used as a telescope, if an observer were aboard, or as a camera using either photographic or television techniques.

Assume, for example, that photographic film will be used, and that a combined film-lens resolution level of 100 lines/mm is achieved on the film. This performance far exceeds the standards of skilled amateur or professional photographers, but is within the present state of the art, assuming new emulsions, the best optical designs, vibration-free systems, and the best camera design practice.

Because of interaction effects, this performance implies that the resolution capabilities of both the lens and the film receptor must separately be considerably greater than the required final resolution number. These capabilities are, by now, fairly well understood by workers in the field.

Lens Performance

The relation between the theoretical performance of a lens and the resolution it alone can deliver in its focal plane (no film), when examined visually, is usually given by:

$$\text{Resolution in lines/millimeter} = \frac{1500}{f/\text{number}}$$

For the case under discussion—achieving 100 lines/mm on film—we may assume the lens must have a resolution capability of its own of at least twice this amount, or 200 lines/mm.

From the simple formula above, it appears that the lens speed must be at least $f/8$. There are new film emulsions which have demonstrated a capability of resolving several hundred lines per millimeter. One of these could be used; on the other hand, there is a trade between film speed or sensitivity and resolution. Hence the use of high-resolution film will require faster optics than $f/8$, in order to permit useful short exposure times.

From the lens diameters derived in an earlier section of this series, 27 and 44 in., it might be argued that the larger number should be used. As it turns out, this number is not large enough. Suppose that a 40-in.-diam system, at $f/8$, is chosen. This yields a focal length of 320 in. The scale number, S_y, for objects lying in the y direction is found to be 7,550,000. Thus the image size of a 100-ft object is given by

$$\text{Image size} = \frac{\text{Object size}}{\text{Scale number}} = \frac{100 \text{ ft}}{7.55 \times 10^6}$$

This calculation, upon conversion to millimeters, yields an image size of 0.004 mm = 1/250 mm which is well below the obtainable resolution. The only way to take account of the loss in resolution imposed on the system by employing film (which of necessity has a finite resolution capability) is to increase lens diameter, while keeping speed or $f/$ number the same. Thus we are led to a requirement for lens diameters approaching 8 ft with focal lengths of about 64 ft. Such optics are huge even by terrestrial standards, since this is approximately the size of the Mt. Wilson telescope. It may be well to keep the result of this calculation in mind when thinking about observing the earth from the moon, which is about 10 times farther from the earth than the 24-hr satellite.

Occasionally, one hears discussions of the possibility of resolving 20 ft on earth from an observatory on the moon. Note that this requires resolution 5 times better from distances 10 times as great as those in the example just calculated. Thus, to resolve 20 ft on earth in photographs from the moon will require a camera system working at its theoretical resolution limits, with an aperture about 400 ft in diam and a focal length of at least 3200 ft!

Suppose that the much more modest camera of 8-ft aperture and 64-ft focal length were used to take photographs 4 x 5 in. (the common press camera film size) from the 24-hr position. The total field of view of the camera would be less than 0.5 deg. The area covered by this 64-ft focal-length camera, if it were pointed at the earth at 45-deg latitude, would be about 152 by 197 miles, or approximately 30,000 sq mi. This is only slightly less than the combined area of Connecticut, Massachusetts, New Hampshire, and Vermont, or of Denmark and the Netherlands.

Clearly, the achievement of ground

Far-Infrared Scanner

Designed and built by Martin-Baltimore, this new 50-lb gyroscopic Far-Infrared Scanner, adaptable for anti-ICBM missile guidance or interplanetary navigation, permits detection of objects having very low temperature, such as the outer surface of a satellite.

All the components—mirrors, detectors, and detector amplifier—can be rotated as a unit, permitting the device to remain stable during spins or turns of its carrier.

The scanner could sense heat from an attacking ICBM, distinguish this heat from bogus heat or flare decoys, and guide an anti-missile missile to target intercept by means of a sensitive electromechanical system.

In space navigation, it could be used to detect infrared rays from stars, planets, or satellites, and could help guide a space probe to its destination.

Engineer's face is reflected in the Scanner's primary mirror, surrounding the unit's detectors and preamplifiers. Secondary mirror extends on tripods in front of the Scanner.

resolution such as that calculated above would be an engineering and scientific triumph of the first magnitude. Requirements for stability of the camera system, given any reasonable exposure time, such as 1/100 sec, are severe. Angular motions which tend to blur the photograph must be kept to, say, 0.05 sec of arc during the exposure time. This is formidable indeed.

Other problems, such as communication with or from this satellite, handling of the pictorial or visual information, use of other sensors, such as infrared systems for detection of missile firings, will simply be noted.

The properties of noncircular 24-hr orbits are not easily visualized. The general effect is to distort the lobes of the "figure-eight" pattern shown on page 29. The Hutcheson paper provides an analysis of the effects of eccentric orbits and an appreciation of their usefulness. Clearly, it should be possible, by proper shaping of the orbit, variously to apportion and weigh the positions and dwell-time of the satellite's subpoint. For various problems involving communication, observation, or both, it might be desirable to have the satellite spend most of its time over a given area of interest. Use of properly chosen orbits, i.e., considering varying eccentricity, orbital inclination, and apogee position, can produce quite a broad spectrum of satellite observational-communication characteristics. The Hutcheson article includes a detailed analysis of these orbits.

Meteorological Observation

One application of the 24-hr satellite will not require the huge optical systems described above. The possibility of conducting meteorological observation from the 24-hr satellite is especially intriguing because of the relatively low definition or ground resolution required and the enormous view afforded from the position of this satellite. As will be noted later in this series, no one in the U.S. has examined enough extreme (rocket or satellite) altitude cloud photographs, taken under enough different circumstances and times, to permit building a firm photo-interpretation system, with its keys, libraries, and techniques.

Study of the history and development of aerial photographic interpretation seems to demonstrate that as the art has developed, the skilled interpreter tends to use photographs at scale numbers which would have been rejected in the past. This simple and important fact makes discussion of satellite observation, of whatever kind, a reasonable and viable topic. Photo-interpreters active during World War II have been known to exhibit shock and incredulity at (and therefore to dismiss) the notion that photographs taken from altitudes of hundreds of miles might ever be useful.

The Largest Forged

These H-11 tool-steel blanks for solid rocket end-closures were closed-die forged by the Wyman-Gordon Co. by a single squeeze of a 50,000-ton press. The largest ever forged of H-11 steel, the blanks measure 40 in. in diam and weigh about 840 lb each.

It may therefore be expected, with considerable confidence, that as photo interpreters become accustomed to looking at cloud photographs, their resolution requirements for *a given level of recognizability will be relaxed.*

This is not to remove the sensible requirement for occasional small-area, high-definition photography, to verify or to identify larger cloud areas of the same texture and composition. Further, other special meteorological phenomena might well demand closer and more detailed looks than those demanded by routine weather observation.

For the following illustrative example, let us assume that a ground resolution of 2500 ft will satisfy the resolution requirement for cloud photography. Taking account of the curvature of the earth and proceeding from the calculations performed earlier in this section, it may be shown that, based on achieving 100 lines/mm on film, an optical system of say 2- or 3-ft focal length will do. Significant improvements in obtainable resolution would permit reduction of the required camera size.

Because the satellite is so far from the earth, a 2-ft-focal-length camera, taking standard 9 x 9-in. format photographs, will cover all the earth visible from that position. It seems reasonable that several properly spaced 24-hr satellites could cover the entire earth. If no more than four photographs per day are taken from one of these satellites, and then processed and transmitted to earth by video link, it can be shown that this requires a bandwidth of 6 mc/sec for a total time of 90 min to send back all four photos. If transmission can be increased to 2 hr per photo—which seems reasonable and proper, trading bandwidths for time—it could take somewhat under 1-mc/sec bandwidth.

Transmission would be greatly simplified by having ground stations within line of sight of the satellite continuously, thus eliminating the difficulties encountered with low-altitude (e.g., 300-mile) satellites—finding the satellite, locking on to it, and reading for no more than, say, 10 min.

The low rate of film consumption—say, four photographs per day—yields a year's operation on somewhat more than 1000 ft of film, which for the $9^{1}/_{2}$-in. width required, and use of available thin-base film, would weigh less than 25 lb.

If progress in the film and camera art arrives at the point where resolutions of 200 lines/mm are available for use in this satellite, the film size needed would be about the same as the 4 x 5-in. film used by news photographers, with the camera focal length going to 12 in. In this case, film widths would be cut in half over the example calculated previously, film length for a year's operation would decrease to 500 ft, and film weight for a year's operation would be about 6 lb!

In principle, television systems could be used for meteorological or weather observation from the 24-hr satellite position. There are obvious, fundamental, and attractive advantages to TV systems when compared with photographic systems which consume non-reusable film. On the other hand, TV-tube image format areas and their resolution are both much less than in the photographic example given above, requiring both scanning mechanisms and focal lengths perhaps 10 times greater than what would be required for very-high-resolution film systems.

—Amrom H. Kantz

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Part 4 in this series, to appear next month, will cover the application of observation satellites to scientific problems and the use of such satellites in mapping and geodesy.