Laser-Cooled and Trapped Atoms, (Proceedings of the Workshop on Spectroscopic Applications of Slow Atomic Beams, held at NBS, Gaithersburg, MD, 14-15 April 1983) Ed. by W. D. Phillips, Natl. Bur. Stand. (U.S.) Spec. Publ. 653 (1983).

THE DESIGN OF ATOMIC FREQUENCY STANDARDS AND THEIR PERFORMANCE IN SPECIFIC APPLICATIONS

S. R. Stein

National Bureau of Standards
Boulder, Colorado 80303

ABSTRACT

The reduction of timing errors in atomic clocks is shown to be important for secure communications and navigation. An approach based upon control of all systematic frequency shifts and a reduction in both the first order Doppler shift and confinement effects is recommended. Ion storage is a promising technique because of its ability to achieve extremely long observation times, negligible confinement perturbations, and laser cooling. The applicability of atom cooling should be evaluated.

Key Words: Atomic Clocks, Frequency Standards, Navigation, Secure Communications

Introduction

The development of frequency standards and clocks has been one of the most visible applications of atomic and molecular spectroscopy. For this reason, it is natural for a workshop on slow beams to consider some of the requirements for improved frequency standards and what conclusions may be drawn about the scientific research necessary for their development. At least half the applications of atomic frequency standards are in high technology defense systems whose development now requires approximately a decade from planning to implementation. Although the role of atomic clocks is often critical, the clock is such a small part of such systems that plans rarely take into account required improvements in clock performance. The subject of this workshop directs our attention towards issues of timekeeping over long periods of time since much simpler techniques are adequate for short times.

There are three general types of atomic frequency standards which are commercially available today: the rubidium gas cell frequency standard, the cesium beam frequency standard, and the hydrogen maser. These three are only a small fraction of the instruments which have been demonstrated in the laboratory. Devices not developed commercially include active rubidium masers, cesium gas cell frequency standards, thallium atomic beam frequency standards, superconducting cavity stabilized oscillators, ammonia absorption frequency standards, calcium atomic beam frequency standards, methane stabilized lasers and many others. This paper will examine the ultimate performance limitations of today's state-of-the-art atomic frequency standards and the projected requirements for improvement. It will attempt to clarify the most likely direction for research if we are to achieve these ends. Through analysis of these questions we hope to maximize the likelihood of producing additional important atomic frequency standards. Other performance characteristics such as acceleration sensitivity, size, weight and power are not considered.

The Role of Clocks in Navigation, Communications and Data Acquisition

For the sake of non-practitioners in the clock field, it may be worthwhile to start from the beginning and ask what essential function clocks serve. The answer is that they provide a uniform scale of the time coordinate between synchronization experiments. Without periodic resynchronizations, two independent clocks would necessarily differ from one and other by an amount which grows without any bound. Thus, for purposes of science and general commerce, the world would require only a single clock in a large communications network to disseminate the time of that clock. In fact, we are all quite used to operating in this fashion. Nearly every wall clock in the entire country is loosely locked to the time scale of the National Bureau of Standards by the actions of electrical utilities. Our wall clocks are only displays that register the number of cycles of the voltage delivered by the local power company.

But practically everyone wears a wristwatch in order to provide a memory of the last synchronization to Universal Time. Thus it is possible to have time information in locations not served by electric power or other means of resynchronization. Of course, depending upon his requirements, one will resynchronize his watch with the wall clock at appropriate intervals. Similarly, behind every application of an atomic frequency standard, one can discern some benefit for extending the interval of independent operation before resynchronization is required.

At first, this example may seem facetious, but it illustrates important aspects of the utilization of atomic frequency standards. In fact, the best wristwatches which are sold today are comparable in quality to the national time standards of only 150 years ago. Atomic frequency standards are employed when the application cannot or chooses not to provide frequent resynchronizations. Military systems often utilize atomic clocks to prevent jamming or increase the security. VLBI systems use remote clocks for time tagging the data acquisition process since the timing requirements are more stringent than any known means of remote time synchronization. NASA uses atomic clocks for deep space navigation for the same reasons. Commercial broadcasts and communications systems use atomic frequency standards to enhance system reliability. The benefits of using clocks - improved security, freedom from interference and redundancy - are intangibles but have great importance to modern society.

Performance of Atomic Frequency Standards

Since clocks are used to mark off uniform increments of time (phase), their performance is analyzed in terms of frequency variability. The generally accepted measure of this variability is the Allan variance, $\sigma_y^2(\tau)$, defined in reference [1]. This variance is a measure of the changes between successive frequency determinations. Figure 1 is the performance of the clocks in the NBS atomic time scale. It shows that there are two regions of averaging time for frequency measurements in which the performance of atomic frequency standard is qualitatively very different. The

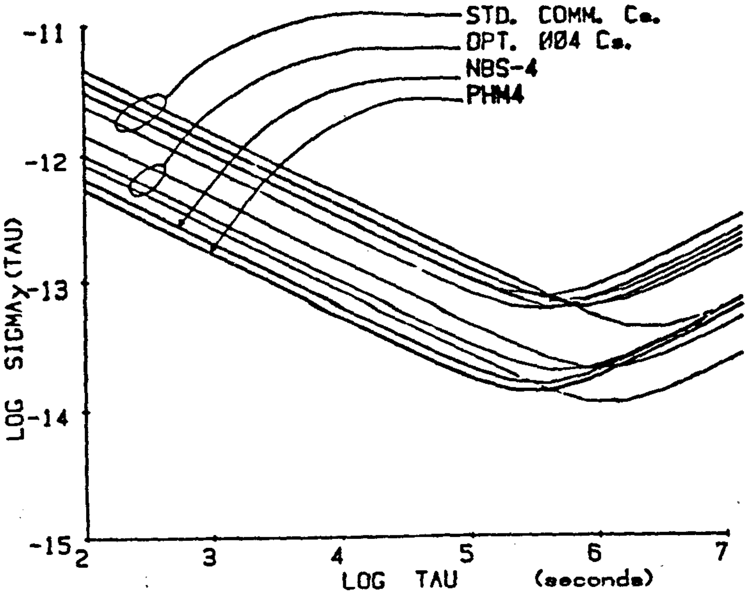

Figure 1: The estimated stability of the clocks in the NBS atomic time scale. NBS-4 is a laboratory cesium standard. PHM4 is a laboratory passive hydrogen standard. STD. COMM. Cs refers to the standard performance cesium standards from commercial manufacturers. OPT. 004 Cs is a high performance commercial option.

first performance region, called the short-term, is characterized by improving stability. In the second, long-term region, the performance ceases to improve and begins to get worse. Examination of the performance of passive and active frequency standards will illustrate the features of these two regions.

A passive frequency standard is one in which an external oscillator is used to probe an atomic absorption. Appropriate signal processing allows the formation of a discriminator signal and permits the probe oscillator to be locked to the atomic feature. In the short-term region, the frequency deviations are well understood and may be calculated quite accurately. The error between the frequency of the probe oscillator and the atomic resonance results from noise. For example, in the case of the cesium beam frequency standard the noise is due to a combination of the statistical fluctuations in the number of atoms that make the transition and shot noise of the detected signal. The result is white frequency noise which is described by [2]

$$\sigma_y(\tau) = \frac{0.2}{Q\,(S/N)^{1/2}\,\tau^{1/2}}$$

where Q is the atomic quality factor, $(S/N)^{\frac{1}{2}}$ is the voltage signal to noise ratio in a 1Hz BW and τ is the averaging time.

The short-term performance of a hydrogen maser is qualitatively different because the feedback to the atoms is high enough to permit power at the atomic transition frequency to be obtained from the ensemble of atoms. There is coherence between the individual atomic emitters so that white noise within the atomic linewidth perturbs the phase but not the frequency of the oscillation. Since the phase fluctuations are bounded, the frequency stability improves inversely with the averaging time [3].

$$\sigma_y(\tau) = \text{constant}/\tau$$

This feature of the hydrogen maser makes it the most stable atomic frequency standard in the region from approximately ten-seconds to a few hours. In the short-term, the frequency stability improves with the averaging time. Although such behavior should continue indefinitely, the standard eventually enters the long-term region in which the frequency stability begins to degrade due to imperfections in the control electronics. The atomic resonance frequency itself is subject to change resulting from variations in parameters such as magnetic field. In addition, there is always a difference between the frequency of the standard and the atomic line center and this differential is subject to change. As a result, the frequency of the standard displays an approximate random walk behavior and the frequency stability is given by the approximate formula

$$\sigma_y(\tau) \sim k\tau^{1/2}$$

where the value of k cannot be predicted from the design, but must be obtained emperically.

The frequency stability of an atomic clock will not deteriorate indefinitely as $\tau^{1/2}$ because frequency excursions beyond a certain size are exceedingly unlikely. For example, it would be unreasonable for the frequency to change by as much as a linewidth. In actuality, one knows with a fair degree of confidence that the frequency will change by much less than that over the life of the standard. Today, a manufacturer of cesium beam standards may specify a maximum lifetime frequency change of 3×10^{-12}. Thus the Allan variance is bounded by the limit

$$\sigma_y(\tau) \lesssim 3 \times 10^{-12} \quad \text{for} \quad \tau \gtrsim 100 \text{ s.}$$

Although there is no reason to expect that $\sigma_y(\tau)$ would remain constant at lower levels than implied by the above argument, such a model (flicker noise) has been improperly used for the long-term frequency stability of atomic frequency standards. New techniques of statistical analysis indicate that a random walk of frequency model is more conservative. Primary standards utilize techniques which quantitatively relate the frequency to the unperturbed atomic frequency. They are therefore said to have the property called accuracy, which is the ability to reproduce a specified frequency. NBS-6, the NBS primary frequency standard is estimated to be accurate to 8×10^{-14}. Thus NBS-6 could be used to assure that

$$\sigma_y(\tau) \lesssim 8 \times 10^{-14} \quad \text{for} \quad \tau \gtrsim 100 \text{ s.}$$

Time Dispersion: The Bottom Line

To compare the timekeeping capability of various clocks one must compute the rms error $x(\tau)$ which a clock accumulates in time τ. In order to simplify this very complicated problem we assume that the behavior of the clock is known and the frequency variations are described by

$$\sigma_y(\tau) \sim \left[b^2\tau^{-1} + c^2 + d^2\tau \right]^{1/2}$$

where b, c and d are the 1 second intercepts of the three dominant noise types - white frequency, "flicker" frequency, and random walk frequency. In practice, one must also take into account the uncertainties in clock parameters such as drift so this approach will yield slightly optimistic results. The time error of the clock has been shown to be [4]

$$X(\tau) \sim \left[b^2\tau + 1.4c^2\tau^2 + d^2\tau^3 \right]^{1/2}$$

Table 1 shows the time errors of two clocks. The performance of clock A is dominated by random walk frequency noise such that $\sigma_y(10^5 s) = 10^{-14}$. Clock B has an accuracy of 10^{-14} and the noise is conservatively estimated as $\sigma_y(\tau) = 10^{-14}$.

TABLE 1: Time Error in Nanoseconds

	Clock A	Clock B
τ	$x(\tau)$	$x(\tau)$
10^5s	1	1
10^6s	32	12
10^7s	1000	120

Some Applications of Atomic Frequency Standards

Let us consider two applications which now or in the near future need improved frequency standards: secure diplomatic and military communications and military navigational systems. First, we consider the direct benefits of decreased time dispersion and extended update intervals. Later we will examine other important benefits of improving clock technology.

Secure communications are generally provided through the use of data encryption and steganography. (Encryption is the generation of a cypher text from a plain text message while steganography consists of techniques which hide the transmission of a message.) The encryption process is accomplished by a device called a crypto which uses an algorithm similar to the Data Encryption Standard published by the National Bureau of Standards and an encryption key. Decryption is accomplished by a second crypto using a decryption algorithm and key. Such systems require that the receiving crypto be synchronized to the transmitting crypto and this function is usually provided by the communication system itself.

The level of security provided by such a system is generally sufficient for even the most sensitive commercial information. However, further levels of security are required for diplomatic and military communications. For these applications, it may also be desirable to employ some technique to hide the signal in order to protect against jamming or so that the signal may not be detected and decryption attempted. In fact, in some cases knowledge that a signal has been sent at all is more than one is willing to reveal. The most common methods of hiding communications signals are frequency hopping and pseudorandom noise spread spectrum modulation. Spread spectrum techniques hide the signal beneath a high level of simulated noise. For example, an audio voice channel may be mixed with an rf pseudorandom noise signal before transmission from the secure facility. Alternatively information at a rate of a few bits per minute may be phase modulated on a carrier in a band near 76

Hz [5]. In order to receive the signal it is necessary to integrate for substantial periods of time to synchronize the receiving crypto with the transmitting crypto and to extract the signal from the background noise. To make signal interception as difficult as possible, information required to synchronize the receiving crypto to the transmitting crypto is generally not transmitted with the message. The receiver contains a clock which maintains an imperfect memory of the original synchronization. After a period of time the synchronization degrades due to time dispersion between the two cryptos and the receiver must search over a larger and larger time interval for indication of successful signal decryption. A 20 MHz communications channel must be searched with tens of nanoseconds resolution. A 75 Hz channel requires only milliseconds resolution but long integration intervals are required to separate signal from noise. Once decryption commences, the crypto machines may be locked together. Thus the most difficult operational requirements for the frequency standard is the need to permit receivers which have been out of communication for substantial periods of time to quickly regain entry into the communications net. Communications systems now in the planning and development phases need frequency stability in the range of $\sigma_y(\tau) \sim 10^{-14}$ over long time intervals [6].

Satellite based military navigation systems place comparably stringent requirements on the satellite atomic frequency standards. For example, the desired performance of GPS satellite clocks is $\sigma_y(\tau) \leq 10^{-13}$ for time intervals between 1 and 10 days. This performance would result in a clock contribution to the navigation error of approximately 3 meters at one-day and 30-meters at 10-days. Today, it appears to be acceptable for the GPS system to operate for 10 days without updates from the ground. This policy may be based more on what is practical given today's technology than what is desirable for system operation. Longer periods of autonomous operation would serve to increase the security and survivability of the GPS system. It is important to bear in mind that the clock performance in the GPS system cannot be treated as an independent issue. The performance of the system during periods of autonomous operation is also degraded by the absence of updated ephemeris information. Improvements in both areas are necessary to extend the autonomous operation period at a given performance level. The availability of improved clocks would allow the study of the ephemeris in greater detail, thus speeding the solution of this overall problem. Improvement of clocks to the $\sigma_y(\tau) \leq 10^{-14}$ level would extend the autonomous operation period for the GPS system to 100 days with no degradation in current performance levels.

In addition to the actual timekeeping performance of atomic clocks, there are other aspects of performance which could be improved at the same time. There is considerable interest in reducing the turn-on time, and the sensitivity to radiation effects. The reliability and the lifetime of clocks need to be increased. Many or all of these are amenable to improvement.

Factors Limiting the Long-term Timekeeping Performance of Atomic Clocks

We have seen that for times of a day and longer, the performance of atomic frequency standards is limited by systematic offsets of the frequency from the ideal. By far the largest of the systematic offsets result from Doppler effects. In general, we may write the absorption frequency of an atom initially moving at velocity v with respect to a source at rest as

$$\omega \sim \omega_0 + \underset{\sim}{k} \cdot \underset{\sim}{v} - \frac{1}{2}\omega_0 \left(\frac{v}{c}\right)^2 + \frac{\hbar \omega_0^2}{2Mc^2}$$

The measured frequency ω is equal to the nominal frequency ω_0 with three corrections. The second term in the equation is an offset proportional to the velocity difference, $\mathbf{v}$, between an atom and observer called the first order Doppler effect; $\mathbf{k}$ is the radiation wave vector. The third term is due to time dilation. Because of its quadratic behavior, this term is usually called second order Doppler effect. $\mathbf{c}$ is the speed of light. The fourth term takes into account the recoil of the atom. It will be neglected here since it is generally small except in the optical case.

The first order Doppler effect is generally the largest of all the systematic errors in the atomic frequency standard. A cesium atom from the vapor at 350K has a most probable velocity of approximately 200 meters per second. Thus the first order Doppler shift is approximately one part per million. Although at the present time there is little agreement on what limits the long-term performance of commercial atomic frequency standards, the situation is more clear in the case of laboratory standards which perform roughly a factor of 10 better than their commercial counterparts. It is fair to say that these devices are limited in performance either by residual first order Doppler shift or by whatever technique is used to cancel this shift.

There are several different Doppler cancellation approaches in common use. In the case of the hydrogen maser and the rubidium gas cell frequency standard, the atom is confined to a region of space smaller than one-half wavelength. Under these conditions the Doppler lineshape consists of a discrete, narrow line well resolved from the broad Doppler pedestal. The linewidth of this feature is determined by other mechanisms such as finite observation time or relaxation processes. In a hydrogen maser, the atoms are confined within a teflon coated vessel, whereas, in a rubidium frequency standard they are confined by collisions with a buffer gas. In either case, the atoms experience frequency perturbations which are extremely difficult to measure and control.

In a cesium beam frequency standard, collision effects are avoided by using a low density atomic beam which passes through a microwave cavity in a region where there are no reversals of the microwave phase. In a perfect, lossless microwave cavity, the first order Doppler shift would be perfectly nulled. However, the finite conductivity of the walls results in asymmetry of the counter propagating microwave fields and a residual first order Doppler shift which is proportional to the misalignment of the atomic beam from the orthogonality with microwave Poynting vector.

The second order Doppler effect is only on the order of 10^{-12} for room temperature atomic species, but is even more difficult to characterize. Furthermore, aging effects have been observed to change the velocity distribution by a significant amount. Figure 2 shows the velocity distribution of a cesium beam tube before and after a modification. The broken line was data taken after the standard had drifted in frequency $\delta\nu/\nu \sim 2 \times 10^{-12}$ over the course of one year. Note the non-Maxwellian nature of the density of atoms at high velocity. Since detector aging was the suspected cause, changes were made in the collector potentials and a subsequent velocity distribution measurement, indicated by the solid line, was more nearly normal. The frequency returned to its original value. Data such as this indicates that if all the more serious problems in atomic beam frequency standards were eliminated, variations in the second order Doppler effect would probably limit performance at the 10^{-14} level for a 350K beam temperature.

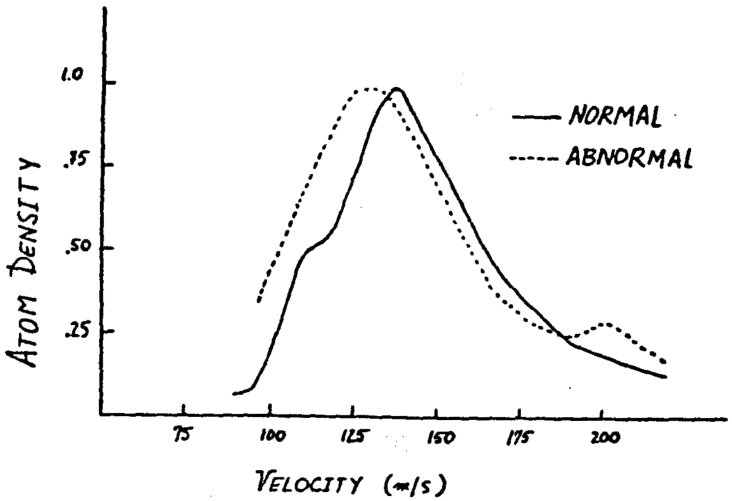

Figure 2: The change in detected atom velocity distribution due to aging of the detector in a commercial cesium beam tube. The accompanying frequency change was approximately $\Delta\nu/\nu = 2 \times 10^{-12}$.

The electronic control circuitry that determines the center of the resonance is subject to a very long list of problems that produce substantial frequency offsets. For analog control systems, the problems include harmonic distortion in the phase modulation, spurious lines in the microwave signal, variations in the mean microwave power and pulling by the microwave cavity. Digital control circuits reduce the problem associated with modulation and spurious signals but add additional difficulties related to maintaining symmetry of the squarewave modulation cycle. As a result of all of these problems, the best existing electronics has difficulty maintaining consistent operation even down to the 10^{-14} level.

Probable Direction for Breakthroughs in the Long-term Performance of Atomic Frequency Standards

The current generation of atomic frequency standards is extremely mature. Laboratory devices reach a performance floor of approximately 10^{-14} for times longer than one day. Performance deteriorates to worse than 10^{-13} for times of several months to one-year. Engineering improvements to existing commercial standards and some new commercial devices such as room temperature ion standards may very well achieve performance comparable to today's laboratory standards but significant improvements beyond what is achieved today in the laboratory are unlikely without some fundamental changes.

Major advances are likely to come through research and development focused in three directions. First, low velocity ions or atoms should be used in order to reduce the magnitude of the Doppler effects. Second, significantly higher atomic line-Q and longer observation times must be obtained. This would improve the ability to cancel the first order Doppler shift. Frequency offsets due to the electronic control circuitry would also be reduced at least in proportion to the increase in the Q. Finally, all variables which affect the operating frequency of the standard should be referenced directly back to the atomic frequency itself including such things as the Zeeman shift due to the finite magnetic field.

A reasonable objective for the next generation of advanced atomic frequency standards will be to achieve routine 10^{-15} performance for very long times. To accomplish this goal, the first order Doppler effect either needs to be reduced in absolute magnitude by a factor of 100 or nulling techniques must be improved by this same factor. The second order Doppler effect needs to be reduced to below the 10^{-15} level. For a trapped ion device, the first order Doppler effect is reduced to negligible proportions by confinement. Reduction of the second order effect requires a temperature of 300 mK. As explained earlier, traditional attempts to exploit this technique have resulted in significant frequency shifts due to the confinement mechanism. But the dc electric and magnetic fields used to confine ions result in uncertainties less than 10^{-15}, three orders of magnitude smaller than the best prior state-of-the-art. In the case of a neutral atomic beam, cooling to approximately 30 mK is needed to null the first order Doppler effect.

The ability to confine ions with negligible perturbations allows enormous enhancement of the atomic line-Q. Experiments performed on magnesium have demonstrated 10 millihertz linewidths at a transition frequency of 300 MHz or an atomic line-Q of 3×10^{10} [7]. Other experiments have demonstrated Q's as high as 2×10^{11} [8]. This is a factor of 10 to 100 improvement over the hydrogen maser, and a factor of 100 to 1000 improvement over the highest Q cesium atomic beams. Assuming that the same linewidth can be obtained using ^{201}Hg which has a hyperfine frequency of 26 GHz, the Q would be 10^{12}. Improvement in Q may also be obtained in a cold atomic beam. However, the effect of gravity on the beam inhibits obtaining very long interaction times and trapping is indicated. It is not known whether confinement effects can be made sufficiently small.

Frequency standards have reached the point where many of the parameters must be controlled to extremely high levels of precision. State-of-the-art control is required for temperature, the influences of external magnetic fields, and certain parameters of the electronic circuitry. In the past, this has been accomplished using a variety of sensors and references. In the future, it will be increasingly necessary to reference all critical variables directly to invariant atomic properties. For example, Zeeman frequency shifts can be measured by observing the magnetic field sensitive transitions. This philosophy may sound very much like the design principles of a primary frequency standard such as NBS-6. This is because the ability to guarantee from first principles that the frequency of a standard is within 10^{-15} of some arbitrary value assures that long term frequency stability must be better than 10^{-15} forever. Once such a standard is constructed, examination of the control signals over a long period of time will make it possible to design simpler devices which, although they have lost the property of frequency accuracy, retain adequate long term frequency stability for many applications. This design philosophy is exactly the one which led to the cesium beam standard and can probably be employed again to achieve dramatic results.

Building an accurate standard in order to achieve long term frequency stability can have significant additional advantages. Such a device should have greatly increased reliability due to its self-monitoring and correction capabilities. It would also have enhanced capability to withstand adverse environments such as extremes of temperature, radiation or EMP, since the atomic resonance itself is relatively unperturbed by these effects. The accuracy approach would also improve the speed with which the standard could be brought into operation. Present day frequency standards suffer from retrace error. That is, the frequency after start up differs from the previous operating frequency. Sometimes the operating environment prevents the rapid evaluation of this new frequency. For example, when a cesium standard is started up on a GPS satellite, its frequency can be predicted to only 10^{-11}. The perturbations due to the atmospheric delays permit the new frequency to be measured to ~5 x 10^{-13} in 1 day and 1 x 10^{-13} after 5 days. An accurate frequency standard would evaluate its own frequency without the need to reference a standard on the ground. Its frequency would be known to 1 x 10^{-13} in hours.

In conclusion, we believe that it is now possible to make major improvements in the timekeeping ability of atomic clocks. Three approaches are recommended: The use of narrower atomic features, the reduction of Doppler effects and the evaluation of all systematic frequency offsets in terms of atomic properties. Laser cooling of stored ions is an extremely promising technique which should make it possible to achieve frequency accuracy and stability at the 10^{-15} level. Secure diplomatic and military communications, space and military navigation, and scientific investigations will be the prime beneficiaries.

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