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Optical Tracking of Artificial Earth Satellites

The Moonwatch program and the precision photographic program supply much of the raw orbit data.

Fred L. Whipple

Mankind's curiosity in exploring the unknown and his ability to use the accumulated experience and knowledge of the race have resulted in his creation of nine astronomical bodies in the course of the past seven months. Five artificial satellites have been put into orbit about the earth, and three of these involved additional pieces of equipment that have constituted independent satellites. The fact that the life-times of these various artificial satellites are relatively short compared to the life-times of natural satellites does not detract from their astronomical significance or from the intellectual and technological achievement that they represent. All satellites, whether natural or artificial, are temporary in nature, if one chooses a sufficiently long time scale. Man-made satellites have now become so numerous that the people most intimately connected with the programs are beginning to have difficulty in segregating and recalling the individual characteristics of each one. Hence, for the convenience of both the writer and the reader, G. F. Schilling has kindly prepared Table 1, listing the major basic information concerning the identification, nature, initial orbit, and survival characteristics of these various satellites. Identification is by year, in the order of launching according to the Greek alphabet. When more than one component of a launching is optically detectable, the components are identified by Arabic numerals following the Greek letter, in order of decreasing optical brightness. Other entries of Table 1 are self-explanatory or are described in the legend.

The orbital elements of artificial satellites are subject to fairly rapid and major changes arising from the earth's deviation from sphericity and from the effect of atmospheric drag. The major effect of the earth's equatorial bulge is to produce a regression of the orbital nodes—the intersection of the equatorial and orbital planes—in a westerly direction for eastward-moving satellites such as now are aloft. The rate depends upon the orbital inclination and physical dimensions. The direction from the center of the earth to minimum distance (peri-

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Table 1. Artificial satellite parameters. Parentheses denote estimated value; "equals" sign denotes value expected to be equal to that for the component from the same launching given in preceding column. Experiments: (*a*) satellite temperatures; (*b*) meteors; (*c*) cosmic rays; (*d*) solar radiation; and (*e*) biological. [Prepared by G. F. Schilling]

Parameters	1957 α1 (Carrier rocket)	1957 α2 (Sputnik I)	1957 α3 (Nose-cone?)	1957 β1 (Sputnik II)	1957 β2 (Nose-cone?)	1958 α (Explorer I)	1958 β1 (Carrier rocket)	1958 β2 (Vanguard I)	1958 γ (Explorer III)
Launching date (U.T.)	4 Oct.	4 Oct.	4 Oct.	3 Nov.	3 Nov.	1 Feb.	17 Mar.	17 Mar.	26 Mar.
Launching time (U.T)	?	=	=	04 40?	=	03 48	12 16	=	17 38
Injection time (U.T.)	?	?	?	?	?	03 55	12 26	=	17 45
Initial period (min)	96.2	96.2	=	103.7	=	114.95*	134.29*	134.29*	115.91*
Initial apogee (km)	950	950	=	1670	=	2540	3965	3965	2800
Initial perigee (km)	225	225	=	240	=	368	652	652	188
Inclination (°)	65.3°	65.3°	=	65.4°		33.14°	34.30°	34.30°	33.5°
Eccentricity	0.051	0.051	=	0.0876	=	0.139	0.191	0.191	0.166
Length (cm)	?	58	?	?	?	200	145	16.4	200
Diameter (cm)	?	58	?	?	?	15.3	46	16.4	15.3
Weight (kg)	(2690)?	83.6	?	(3200)?	?	14	23	1.47	14.1
Payload weight (kg)		?		508.3		5	None	(1.0)	5?
Radio transmission (Mcy/sec)		40.002		40.002		108.00 FM	None	108.00	108.00
Radio transmission (mw)		1000		?		10		10	10
Radio transmission (Mcy/sec)		40.005		40.005		108.03 AM	None	108.03	108.03
Radio transmission (mw)		1000		?		50		5	50
Battery life-time (day)		21		7		60 and 11		?	60
Satellite life-time (day)	58	92	?	161	?	(3–5 yr)	(Many yr)	(Many yr)	(Months)
Effective mass-area ratio (g/cm^2)	(14.5)?	(24.1)†	?	(17.2)?	?	5.5†	3.8	3.96†	5.6 Geophysical
Instrumentation for scientific experiments	None	*a, b*	None	*a, b, c, d, e*	None	*a, b, c*	None	*a*	*a, b, c*

* Anomalistic period. † Antenna drag effects taken into account.

gee), moves forward (eastwardly) for inclinations below about 63° and retrograde (westerly) for greater inclinations. The nature of these motions is indicated in Fig. 1. Various periodic effects are superimposed upon these secular changes, but the equatorial bulge produces no secular terms in the semimajor axis or eccentricity of a satellite orbit.

The effect of the earth's atmosphere is to reduce the angular momentum of a satellite, the physical resistance occurring mostly in the neighborhood of the perigee because of the exponential-type decrease of atmosphere with altitude. As a consequence, the maximum, or apogee, distance of the satellite decreases more rapidly than the perigee, which remains fairly constant until the eccentricity has become rather small. Typical changes of apogee and perigee (*1*) are illustrated in Fig. 2 for an arbitrary time scale. Hence, measurements of the orbital elements of satellites can give direct information concerning the distribution of air density at high altitudes and the dynamical flattening of the earth, or the extent of equatorial bulge.

Optical and Radio Tracking

The artificial earth satellites have been put into orbit as a part of the program of the International Geophysical Year. Both radio and optical tracking have been conducted on an international basis. The U.S. National Committee of the International Geophysical Year, as a committee of the National Academy of Sciences and with the financial assistance of the National Science Foundation, has assigned to the Smithsonian Astrophysical Observatory the task of optically tracking the artificial earth satellites. The optical tracking program is under the immediate supervision of J. Allen Hynek. The program was started in 1956 and is divided into two major sections: (i) the Volunteer Moonwatch Program and (ii) the Precision Photographic Program.

The Moonwatch observers utilize small monocular telescopes, usually of aperture of 50 millimeters with a magnifying power of 6, so aligned as to form an optical fence along the local meridian or, in some cases, at other angles for best observations of satellites of high inclinations (Fig. 3). The precision photo-

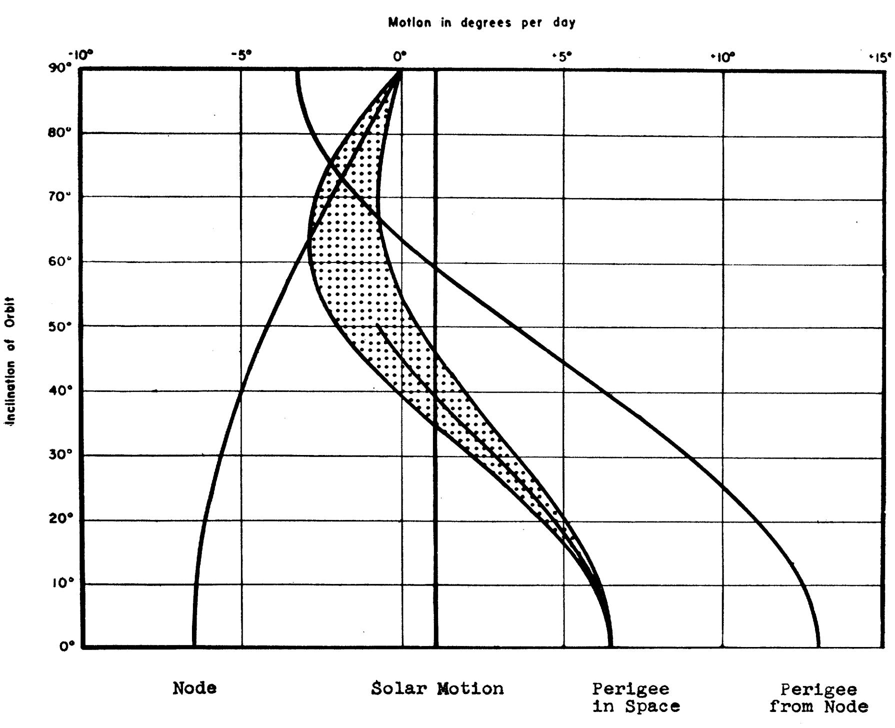

Fig. 1. Secular changes in the orbits of near-earth satellites. [Based upon calculations by L. E. Cunningham, from "The motion of a nearby satellite with highly inclined orbit," presented before the meeting of the American Astronomical Society, Berkeley, California, August 1956]

graphic system uses astronomical cameras of 20-inch aperture and 20-inch focal length, which utilize strip film of 5° by 30°. Twelve stations are planned, to be distributed around the earth between latitudes 37°N and 32°S; these were scheduled to be in full operation by June 1958. Karl G. Henize supervises the photographic program.

Project Vanguard, under the direction of the U.S. Naval Research Laboratory, bears the major responsibility of tracking the IGY satellites by radio signals originating in the satellites. Seven of nine Minitrack receiving stations, operated by the U.S. Army, are distributed near the 75th westward meridian to constitute a radio fence. A second system of radio tracking, the Microlock system, has been developed by the Jet Propulsion Laboratory of Pasadena and shares the responsibility for radio tracking. Various powerful radar telescopes have been successful in tracking the rocket stages of the Russian satellites and have contributed enormously by making observations of their death throes. Particularly important are the great 250-foot radio telescope at the Jodrell Bank Experimental Station in England, the 80-foot radar of Project Lincoln in Massachusetts, and the 60-foot radar of Stanford in California.

Of some 230 volunteer Moonwatch stations registered in April 1958, 126 are in the United States. The other stations are operated through their respective National Committees of the International Geophysical Year and include some 70 stations in Japan and a number in Australia and South Africa. Represented are South America, Central America, the East Indies, Canada, and other countries. In addition, the U.S.S.R. has organized some 70 Moonwatch stations,

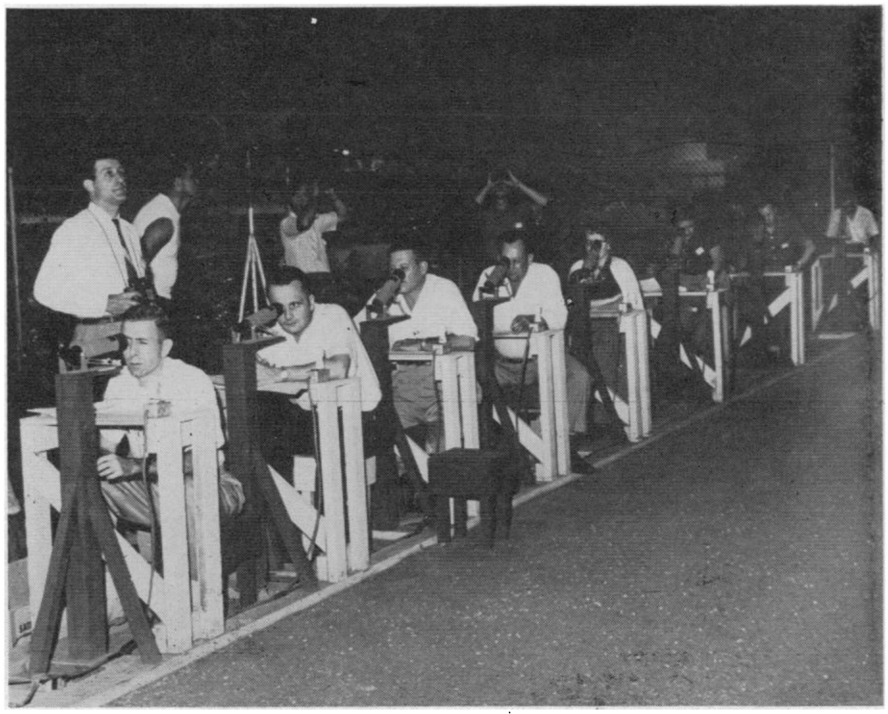

Fig. 3. Terre Haute, Indiana, Moonwatch station.

following the basic principles of operation and equipment utilized in the U.S. IGY program. Our program is under the immediate supervision of Leon Campbell, Jr., while Armand Spitz has been responsible for much of the organization.

More than 3000 observations of the various artificial satellites had been made by 179 of these volunteer Moonwatch stations by 1 April 1958. The program has thus become much more extensive and even more vital to the satellite tracking program than was originally expected. Planned as a program to "back up" the radio satellite tracking program in case of radio failure and as a system for observing the later stages of satellites as they finally plummet through the atmosphere, Moonwatch became the primary network for tracking the huge rocket stages of the U.S.S.R. satellites after the batteries of the radios were exhausted. The high inclinations of these satellite orbits reduced the observational opportunities for the photographic tracking stations located at lower latitudes, while the early firings of the Russian satellites occurred before the completion of the photographic network.

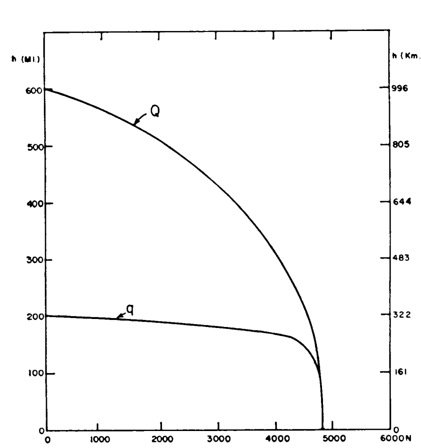

Fig. 2. Variation of perigee and apogee altitude with number of revolutions and with time.

Photographic Telescopes

Although photographic tracking of the rocket stages of the Russian satellites at distances of only a few hundred miles is relatively simple, photographic telescopes are designed to track 20-inch spheres to a distance of 2000 miles. An extremely powerful optical system (2) was designed by James G. Baker and produced by the Perkin-Elmer Corporation. The mechanical system, designed by J. Nunn and constructed by the Boller and Chivens Company, facilitates the following of rapid motions of small satellites from rough prediction data without visual acquisition. Hence, the mounting is triaxial (Fig. 4), so that the camera can be pointed at any direction in the sky and adjusted to follow at any angular velocity up to 2° per second along an arbitrarily chosen great circle. A cycling system makes it possible to

Table 2. Air densities.

Geometric height (km)	Air density (gm/cm^3)
120	6.91×10^{-11}
130	3.01×10^{-11}
140	1.49×10^{-11}
150	8.07×10^{-12}
160	4.70×10^{-12}
170	2.89×10^{-12}
180	1.87×10^{-12}
190	1.25×10^{-12}
200	8.63×10^{-13}
210	6.04×10^{-13}
220	4.47×10^{-13}
230	3.32×10^{-13}
240	2.51×10^{-13}
250	1.93×10^{-13}
260	1.51×10^{-13}
270	1.19×10^{-13}
280	9.51×10^{-14}
290	7.68×10^{-14}
300	6.27×10^{-14}
310	5.16×10^{-14}
320	4.29×10^{-14}
330	3.58×10^{-14}
340	3.02×10^{-14}
350	2.55×10^{-14}
360	2.18×10^{-14}
370	1.87×10^{-14}

photograph a moving satellite as a fixed point on a single photographic frame and, for reference, a fraction of a cycle later to photograph the star background without trailing. Time is maintained at each station by a precision crystal clock, built by the Norrman Company. As a rotating shutter periodically occults the trailing star images while the satellite is being photographed, the time of the central occultation is photographed on the film to a readable precision of 0.0001 second and a realistic precision of about 0.001 second, limited by the variations in ionospheric path of the calibrating signals from the time standard WWV of the National Bureau of Standards in Washington, D.C.

Figure 5 shows the first image of Explorer I, 1958α, photographed on 18 March 1958 by Robert Cameron at the satellite tracking station near Johannesburg, Orange Free State, Union of South Africa. The power of the photographic system is indicated by the fact that the satellite, optically a 6-inch cylinder painted white over a length of about 40 inches, was photographed at a distance of some 700 miles when it was moving at a rate of 5 miles per second. Figure 6 is a reproduction of the first photograph of Vanguard 1958β1, the rocket stage, optically equivalent to about a 20-inch perfectly reflecting sphere. This photograph was made on 19 March 1958 by E. Horine and J. Emerson at Organ Pass, New Mexico; they were using a Super-Schmidt meteor camera of the Harvard Meteor Program in New Mexico.

Major Results

The major result obtained to date from the tracking of the first three artificial earth satellites is the determination of atmospheric density at altitudes of from 120 to 204 miles, where air densities are too low for determination by sounding rockets. This result is derived from the rate of orbital shrinkage arising from air drag and indicates air densities at 120 miles some five times greater than was anticipated on the basis of previous information. The results obtained by T. E. Sterne, B. Folkart, and G. F. Schilling (*3*) are presented in Table 2 for an altitude range from 120 to 370 kilometers. At the greater altitudes given in Table 2 the extrapolation based upon the measures from the first two U.S.S.R. satellites has been confirmed by T. E. Sterne (*4*) from observations of Explorer I. The temperatures corresponding to the density measurements depend upon the unknown mean molecular weight of the atmosphere at the altitudes involved but probably will be higher than expected. Near an altitude of 390 kilometers the temperature is 3000°K, to be corrected by the ratio of the actual mean molecular weight of the atmosphere to the assumed value of 29.0 atomic units.

Fig. 4. A Baker-Nunn satellite tracking camera. Karl G. Henize in foreground.

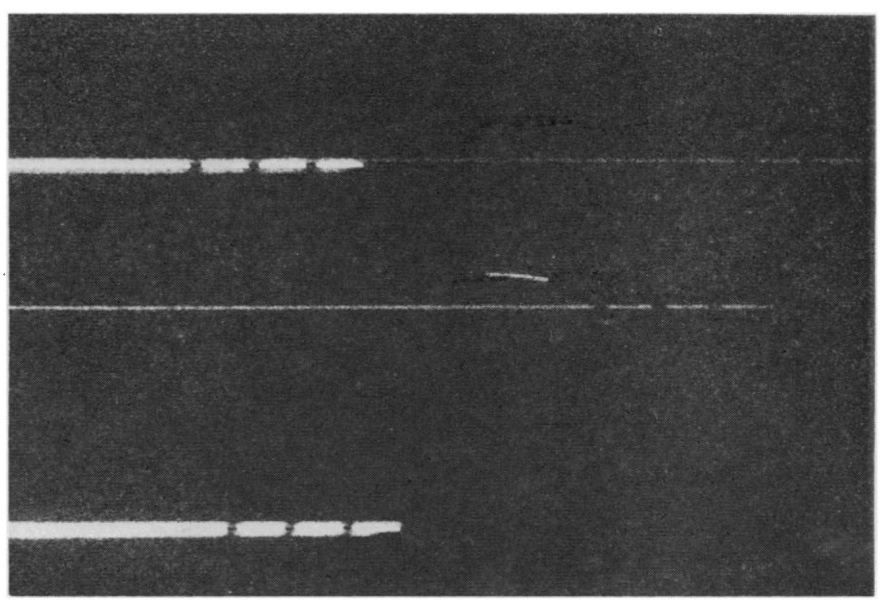

Fig. 5. Photograph of 1958α (Explorer I) taken on 18 March by Robert Cameron at the Olifantsfontein, South Africa, satellite tracking station.

Since the orbital shrinkage by atmospheric drag occurs mostly near the perigee, satellites of greater perigee distance will be required in order to extend these atmospheric density determinations to much greater heights. With its tremendous perigee height of 405 miles, 1958β2 (Vanguard) will lead to an extension of these data.

Orbital calculations have been carried out at the Smithsonian Astrophysical Observatory by the No. 704 calculator of the International Business Machines Corporation (*5*). The orbital planes of the satellites have moved in the expected sense and amount within the degree of accuracy that the analysis to date has permitted. Thus, 1957α and β showed a nodal regression of 3.1° per day and 1958α, of some 4.3° per day. Perigee motions also are consistent with theory. A definitive analysis of the optical data from the two Russian satellites should lead to an improved value for the dynamical oblateness of the earth that produces these perturbations.

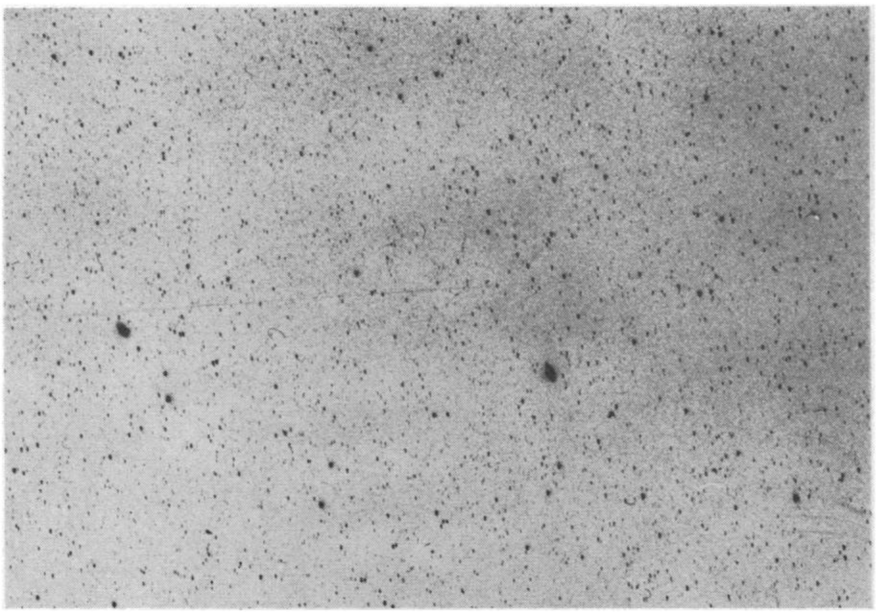

Fig. 6. The first photograph of Satellite 1958β1 (third stage rocket of Vanguard), taken on 19 March by E. Horine and J. Emerson at Organ Pass, New Mexico, with a Harvard Super-Schmidt meteor camera.

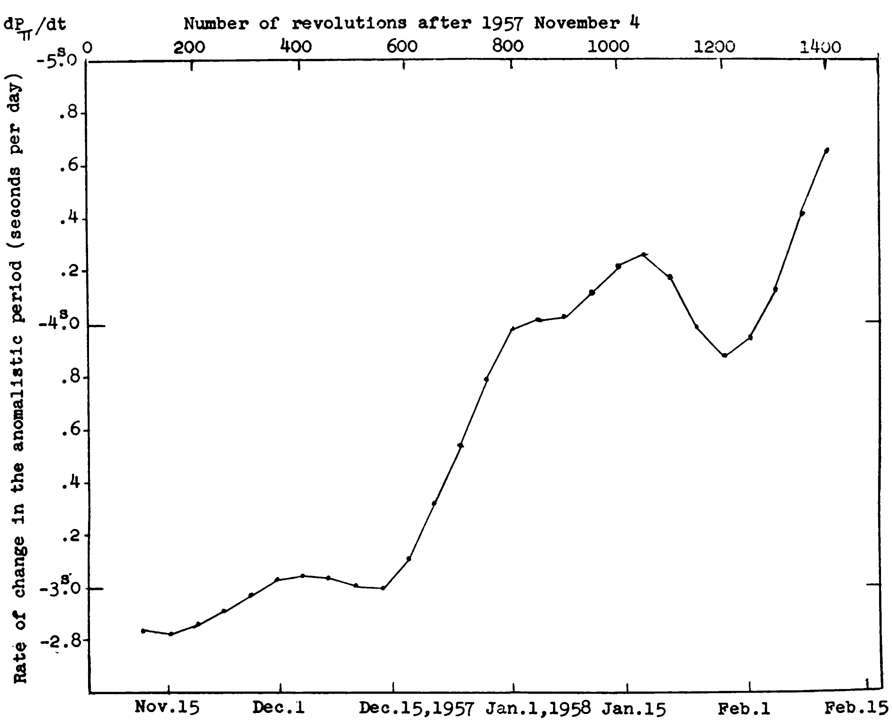

Fig. 7. Rate of change of the anomalistic period as a function of time (1957β1).

The Moonwatch observations during the demise of U.S.S.R. satellites 1957α1 and 1957β1 indicate that as these rocket stages enter the lower atmosphere they glow like meteors for about a revolution before their final disintegration and plunge to the earth's surface. The rocket stage 1957α1 appeared as a very bright object in the late afternoon sky to the Moonwatch team at Los Altos, and over San Diego, California, nearly a revolution before it appeared similarly at two stations in Siberia. Its final breakup was not certainly observed. In the case of 1957β, the rocket was seen after the end of the twilight period by Canadian and New England Moonwatch teams as a fourth-magnitude glowing object. A few minutes later it disrupted in a great meteor-type display over the Barbados Islands, but part of the rocket may have persisted beyond. Thus the heavy satellite rocket stage was in effect a meteor for an appreciable fraction of a revolution around the earth.

A detailed study of these phenomena will be of interest with regard to the interaction between metallic surfaces and the very high atmosphere, both at night and under solar illumination. Of aerodynamic interest is the fact that both rocket stages apparently stopped tumbling and oriented themselves like arrows during their last few revolutions.

Precision Observations

The longer range program with the precision photographic cameras will involve extremely precise tracking and computations in which the satellite is in effect a triangulation target for geodetic measures. The tracking cameras should be able to provide positions accurate to about 2 seconds of arc normal to the trail and 10 feet at 200 miles distance and, along the trail, to an accuracy of 0.001 second or approximately 25 feet. Thus, the geometrical analysis, coupled with the most precise orbital calculations, should lead to determinations of the relative positions of the stations with respect to the center of the earth to an accuracy of some 30 feet, approximately ten times the present available precision. Thus, the geodetic systems of the various continents can be interrelated with this high degree of accuracy, the oblateness of the earth derived to this accuracy, and a more exhaustive search made for lack of circular symmetry around the equator. In addition, the orbital variations will measure gravitational irregularities, or gravitational anomalies, on the earth and determine more precisely the distribution of matter within the earth. These results will derive from a great many precision observations of satellites for which atmospheric drag can be calculated with assurance—in other words, circular satellites, giving a uniform cross section for atmospheric resistance. Figure 7 shows the variations in the change of orbital period for 1957β1 as derived by L. G. Jacchia (*6*). The elongated object presented a varying frontal area with consequently great irregularities of motion. Predictions for such satellites can be made only a few days in advance, and variations in atmospheric density cannot readily be measured. The rocket stage of 1958β gives great promise of being extremely valuable for these geodetic purposes because of the great perigee distance. Even though the drag itself may not be predictable with precision, its amount is so small that good results are to be expected from precision observations of the rocket stage. The satellite itself, of course, can scarcely be the object of routine observations by any of the available photographic techniques. A more massive satellite, therefore, in an orbit with a very high perigee is the most desirable type for such geodetic investigations, and we expect such satellites to be launched in the near future.

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News of Science

Rockefeller Panel Urges Education Changes

On 22 June the Special Studies Project of the Rockefeller Brothers Fund released a report by its Panel V on "The Pursuit of Excellence: Education and the Future of America." The panel consisted of 15 educators and editors headed by John W. Gardner, president of the Carnegie Corporation of New York. Earlier reports in the Special Studies series have examined military security, economic and social matters, and foreign trade policy.

Following is the report as excerpted in the *New York Times*. The full report has been published as a Doubleday News Book.

I. The Dignity of the Individual

Ultimately the source of a nation's greatness is in the individuals who constitute the living substance of the nation. A concern for the realization of individual potentialities is deeply rooted in our moral heritage, our political philosophy, and the texture of our daily customs.

Our devotion to a free society can only be understood in terms of these values. It is the only form of society that puts at the very top of its agenda the opportunity of the individual to develop his potentialities. But in its deepest sense our concern for human excellence is a reflection of our ideal of the overriding importance of human dignity.

Our success or failure in this task is of crucial importance not for ourselves alone. All over the world peoples are striving for a new and fuller meaning of life. No challenge is more important than to give concrete meaning to the idea of human dignity.

II. The Nature of the Challenge

A. The setting of the problem: our population characteristics. Since 1950 on an average day there has been a net rise of about 7600 in the population; over the year, a rise of some 2,800,000. This may give us a population of not quite 225,000,000 by 1975.

The age composition of the population in 1975 will differ markedly from that of 1955. The recent baby boom will have resulted in an enormous increase in age groups 15 to 24; and as our present middle ages attain the later brackets, there will be a large increase in the age 65 and over.

This pattern of future population will present two vital problems. The first concerns the flood of young people who will place an immense pressure on educational institutions in the next 20 years, and on the labor market shortly thereafter. The second problem involves the social and individual problems posed by a rapidly expanding older group.

B. *The changing demands of society and the pressure on the supply of talent.* One of the striking features of contemporary life is the growing range and complexity of the tasks on which our social organization depends. This is dramatically apparent in science but is no less a reality in nearly every field of endeavor.

The demand for highly trained talent is not a sudden development. It has been coming for a long time. The increase in skill and training needed by our labor force can be expected to accelerate in the years ahead. Automation will reduce the number of routine jobs and will replace them by more demanding tasks of supervision, maintenance and regulation in addition to the production of the machines themselves.

There is a constant pressure by an ever more complex society against the total creative capacity of its people. Our most critical need a decade hence may be unknown today. Rather we must prepare ourselves for a constant and growing demand for talents of all varieties, and must attempt to meet the specific needs of the future by elevating the quality and quantity of talented individuals of all kinds.

One of our great strengths as a people has been our flexibility and adaptability under the successive waves of change that have marked our history. Never have we needed the trait more than today. It is for this reason that we should educate our young people to meet an unknown need rather than to prepare them for needs already identified.

C. The problem of change. One of the characteristics of a dynamic society is that its frontiers are constantly changing. The frontier of today becomes the familiar territory of tomorrow.

A dynamic society requires above all receptivity to change.

D. The social ceilings on individual