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Tracking by the Smithsonian Astrophysical Observatory

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[Plate 2]

1. Introduction

A world-wide network of photographic observing stations was conceived at the Smithsonian Astrophysical Observatory (S.A.O.) more than 10 years ago to track the artificial satellites proposed for the International Geophysical Year (I.G.Y.) (Whipple & Hynek 1958). The United States planned to launch its I.G.Y. satellites from Cape Kennedy into orbits with low inclinations. Therefore the original locations of the astrophysical observing stations were selected to obtain the best practical coverage of these low-inclination orbits. Baker-Nunn cameras (see figure 1, plate 2) and Norrman time standards were installed at the familiar positions shown in figure 2, with the essential cooperation of and participation by the governments and scientific institutions of the host countries. The network operated as planned during the I.G.Y. and subsequently became an important part of the U.S. space program. The initial scientific objectives of the S.A.O. satellite-tracking program have all been realized or have surpassed expectations, as will be clear from later papers in this Discussion.

Today, the S.A.O. network and its operation differ significantly from the patterns established during the I.G.Y. Thus a review of the current status is timely. For this review, the changes have been grouped into five topics:

(1) New station locations in the network.
(2) Instrumentation and modes of operation.
(3) Interface with other networks and instruments.
(4) Selection of satellites for tracking.
(5) New scientific objectives.

These topics are discussed individually below.

2. New station locations in the network

The low-latitude network configuration optimized for I.G.Y. satellites has been modified first to recognize the existence and importance of high-inclination satellites. From low-latitude stations, obviously, a high-inclination satellite can be tracked only when it is near the equator. In this case the requirements for darkness at the station and sunlight on the satellite further restrict the possibilities for photography. Situations can easily occur in which virtually no observations are obtained; at best the observations are somewhat poorly distributed around the orbit.

On the other hand, scientific objectives emphasize the need for high-inclination satellites.

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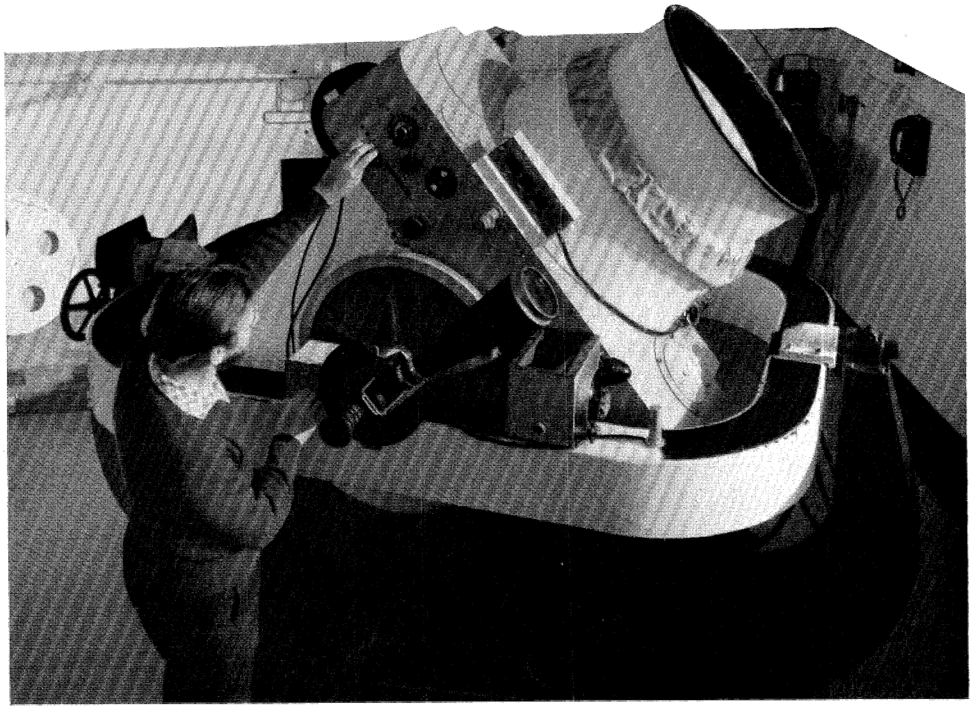

FIGURE 1. The Baker-Nunn camera.

(*a*) (*b*)

FIGURE 4. Recent widening in the Great Rift near Addis Ababa, Ethiopia (photographs taken by Robert Citron).

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To obtain information about atmospheric conditions at high latitude, a high inclination is required. Special balloon satellites in near-polar orbits have been launched for this purpose. For determination of the geopotential, the situation is similar. Detailed examination of the relative usefulness of satellites for geopotential investigations shows that a distribution of inclinations is desirable and that high inclinations have the greatest value (Kaula 1966; King-Hele 1965).

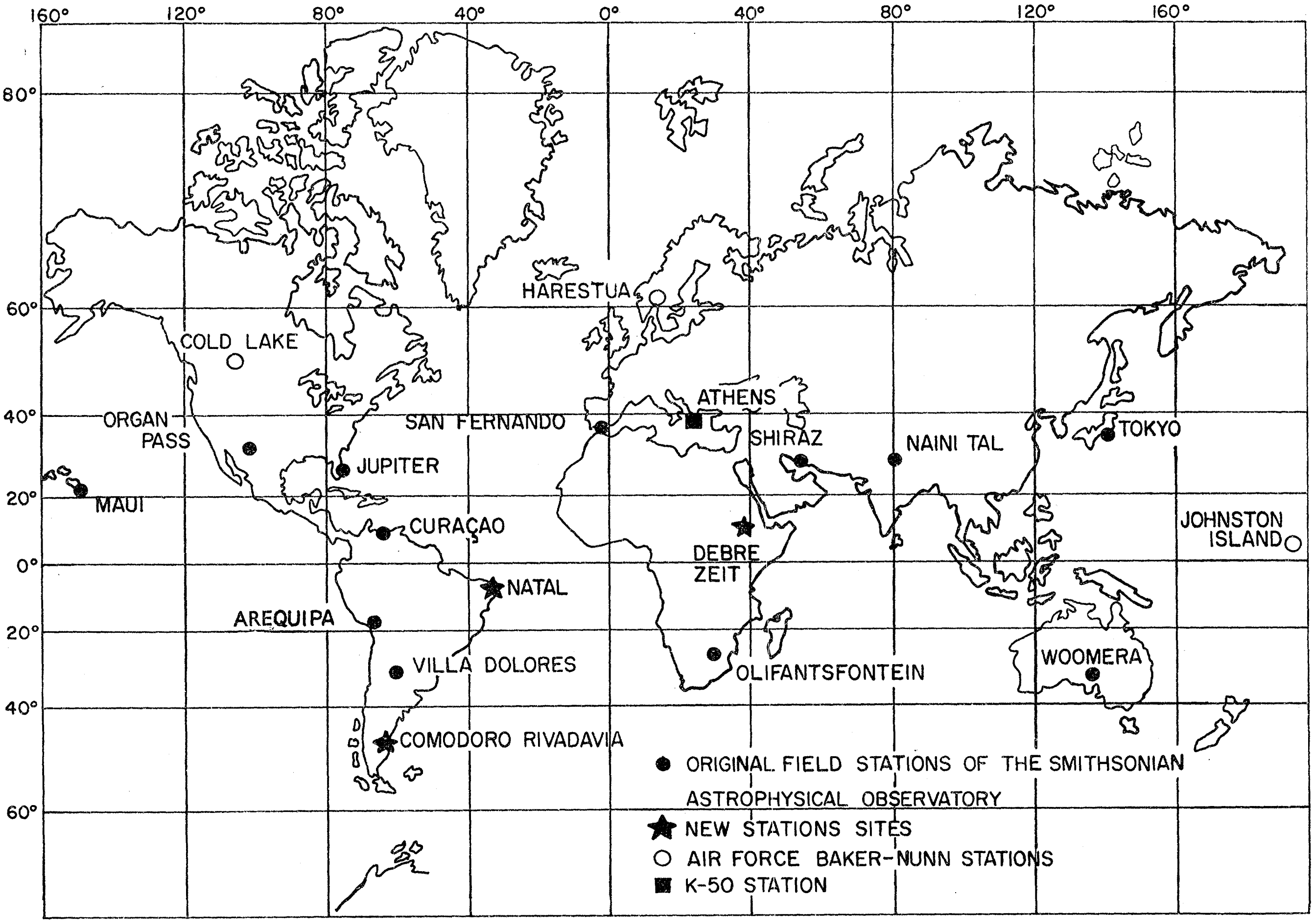

FIGURE 2. Astrophysical observing stations and cooperating stations.

Two specific actions were taken to improve the capability of tracking these satellites. First, the astrophysical observing station in Argentina has been moved from Villa Dolores to Comodoro Rivadavia. The new latitude is S 45° 55′. Secondly, an agreement was made to obtain Baker-Nunn data from the station operated by the Canadian Royal Air Force at Cold Lake, Canada, and from the station at Harestua, Norway, operated by the Oslo Observatory with U.S. Air Force sponsorship. These have latitudes 54° 44′ N and 60° 12′ N, respectively, at locations shown in figure 2.

The requirement for accurately determined station coordinates has engendered other changes in the network. Accurate coordinates are needed for dynamical analyses of satellite orbits and to satisfy geodetic objectives. One method of coordinate determination

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employs simultaneous observations of a satellite from two or more stations. Such observations are used to determine accurately the direction of the line between pairs of stations (Aardoom, Girnius & Veis 1965). This information is even more useful if the station positions form vertices of well-proportioned triangles so that the trigonometric relations of usual geodetic practice can be applied.

To improve the geometric configuration of the network, two stations have been moved. First, the Baker-Nunn from Curaçao was moved to a new site near Natal, Brazil. The three Baker-Nunn stations in South America now form a well-proportioned triangle with vertices near extremities of the continent. Secondly, the Baker-Nunn from Shiraz, Iran, was moved to Debre Zeit, Ethiopia. In this new position, the station is about equidistant from the stations in India, Spain and South Africa. In the previous configuration, the South African station was so far from any of the other stations that only an occasional simultaneous observation was obtained. Experience shows that simultaneous observations between Baker-Nunn cameras become impractical for chord distances greater than about 6000 km.

Because the distance from Maui, Hawaii, to Tokyo, Japan, is at this limit, arrangements were made to obtain supplemental observations between Tokyo and the Baker-Nunn station on Johnston Island operated by the U.S. Air Force. The chord distance from Tokyo to Johnston Island is 5275 km.

For the relocated Baker-Nunn cameras, it is most desirable to obtain simultaneous observations between the new and old sites. This can be accomplished if a second camera occupies the old site for a period after the move. This second camera need not have the sensitivity of the Baker-Nunn, but it must have comparable accuracy for the bright satellites it is able to photograph. This objective was a motivation for the development of a modified K-50 camera for satellite tracking. This instrument is described in some detail later. S.A.O. produced three modified K-50 cameras, two of which were initially deployed at Curaçao and Shiraz, primarily to obtain simultaneous observations with Natal and Debre Zeit, respectively. One of these cameras is subsequently scheduled for redeployment at Villa Dolores, Argentina.

From combined dynamical and geometrical techniques of satellite geodesy, station coordinates are obtained in a fundamental geocentric cartesian system (Veis 1963). At present the coordinates are accurate to some 10 to 20 m (Köhnlein 1967; Lundquist 1966). Some improvement is expected with the use of data collected after the station moves. Accurate station coordinates can be used to relate the major world-survey datums to the fundamental geocentric cartesian system. If no additional information is used, this requires a minimum of three stations well distributed in a particular datum. This was a prime reason for the establishment of a K-50 station in Athens. The San Fernando, Harestua, and Athens sites form a well-proportioned triangle in the European datum.

As a final remark on the geometry of the network, perhaps it is worth noting that even after a site has been abandoned, much of the data previously collected can still be used in scientific analyses along with data from current stations. For investigations that require data from a greater diversity of sites, an added benefit is derived from the network relocations that have been made. Figure 2 shows the 19 past and present locations of Baker-Nunn and K-50 stations that have produced the basic observations used at S.A.O.

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3. Instrumentation and modes of operation

The Baker-Nunn camera has remained basic to the S.A.O. network, with only minor adaptations. The camera has *f*/1 Schmidt optics with a 20 in. focal length. Present operations employ the camera routinely in three modes.

In the most simple mode, the camera is held stationary while images of the satellite and stars are allowed to trail along the film. The images are chopped by a precisely timed shutter. Satellites brighter than 7 magnitude are customarily tracked in this mode. The standard film now used is Kodak Royal-X pan recording 2475 (extended red) emulsion on a 4 mm estar base.

In the second mode, the camera moves along a great circle approximating closely the apparent motion of the satellite. Thus the satellite builds up a 'point image' and the stars are trailed at the satellite rate. Satellites as dim as about 12 magnitude can be recorded in this mode, with a 3·2 s exposure. With present emulsion sensitivities, enough stars are photographed to permit accurate reduction. The mode in which the camera can alternate between the satellite and stationary rates is never used now because its only purpose was to ensure that enough stars would be photographed.

The Echo satellites and similarly bright objects pose a special problem for which a third mode of operation is used. The I.A.G. Western European Subcommission of the Permanent Commission for Geodetic Uses of Artificial Satellites has selected the Echo satellites as the primary objects for its purposes; hence a satisfactory Baker-Nunn mode is required for cooperation with this program. These satellites are so bright that even with a stationary camera their trailed photographic images are too large for accurate measurements. To solve this problem, each station has been equipped with a series of diaphragms to reduce the aperture of the camera. This device, however, also reduces the number of stars on the film. Consequently, the observers at a station must select the right diaphragm for the circumstances of the pass such that enough stars are obtained and yet the images of Echo are not excessively large.

The Norrman time standards originally installed at the stations had an accuracy of about 1 ms. During 1965 and 1966 these were all replaced with EECo clocks, which are able to give an accuracy of 0·1 ms. At the same time, v.l.f. receivers were installed at the stations to monitor continuously an accurate frequency tone transmitted by v.l.f. stations. The received signal is compared with the frequency of the crystal oscillator in the clock. As a further aid to more accurate time keeping, a portable clock is carried from station to station to measure the relative settings of the clocks. Timing to 0·1 ms virtually eliminates time as a source of error in Baker-Nunn observations, if proper calibration procedures are followed. This accuracy or better is essential with laser observations.

The modified K-50 camera is an *f*/4 system with a 9 in. aperture, and is based on optics fabricated for the K-50 aerial photography camera, also originally designed by James Baker. A new back for 4 in. by 5 in. photographic plates was produced and fitted with a chopping shutter. Timing is provided by a clock driven by a Sulzer oscillator.

The version of the camera installed in Shiraz and Curaçao depends on a stationary operating mode. An automatic programmer first makes a series of star exposures with timed breaks produced by a gross shutter. An exposure is then made with the satellite

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trail interrupted by a chopping shutter. Finally, another sequence of broken star images is recorded. This mode is used primarily with the Echo and Pageos satellites. The mode for Geos is similar except that the satellite images are dots produced by the flashing lights on the satellite.

At the Athens station, tests are being conducted with a moving back on the modified K-50. The motion of the photographic plate is matched to the motion of the satellite image in the focal plane, and this permits photography of dimmer satellites. This sophistication is not needed to meet the specific objectives of the Curaçao and Shiraz sites—namely, simultaneous observations with Natal and Debre Zeit.

The most promising new instrumentation in the S.A.O. network is a laser system at the Las Cruces station. Although the present equipment, assembled by S.A.O. and using a General Electric Co. laser configuration, is an experimental system, it is nevertheless operated routinely to obtain range measurements to the satellites with retroreflectors (Beacon Explorer B, 1964–64A; Beacon Explorer C, 1965–32A; Geos, 1965–89A) (Lehr, Maestre & Anderson 1967). This system should soon be replaced by the prototype of a system for eventual network-wide deployment, which is planned for 1968.

The present system and the planned prototype instrument employ a ruby laser operating in a Q-switched mode. Other characteristics of the two systems are shown in table 1. Their basic operation is quite simple. First, the laser is pointed toward the satellite, either by visual tracking during twilight or by accurate predictions and setting circles on the mount. The required pointing accuracy is determined by the projected beamwidth. A signal from the EECo clock fires the laser at the proper time, and a photomultiplier triggers a time-interval counter from the leading edge of the light pulse. Another photomultiplier at the focus of the detector optics stops the counter upon arrival of the reflected signal from the satellite.

TABLE 1. LASER SYSTEMS

		present laser system	prototype laser system
transmitter	pulse length (ns)	60	10
	power output (MW)	8	500
	beamwidth (arc min)	3	2
	wavelength (Å)	6943	6943
receiver	effective aperture (m)	0·5	0·5
	bandwidth (Å)	70	6
	beamwidth (arc min)	20	2
	quantum efficiency (%)	3	3

The range to the satellite is simply computed from the elapsed time interval, corrections being made for system delays and other known effects. One of these corrections is for the reduced velocity with which the light travels through the atmosphere. At zenith, for a sea-level station, this is equivalent to about 3·3 m range correction. The accuracy with which the correction for the atmosphere can be made seems to be the principal limit to the accuracy of the laser-ranging method. This has been estimated as a few decimetres. The present experimental system has only ±1·5 m resolution limited by the 10 ns least count for the particular time-interval counter used.

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In summary, experience with laser systems at S.A.O. and elsewhere (Plotkin 1965) indicates that 1 m range accuracy is a present possibility and that with further development the method can probably be pushed to even greater accuracy. The 1 m figure is already an order-of-magnitude improvement over Baker-Nunn data.

4. Interface with other networks and instruments

An outstanding challenge today is the utilization of diverse tracking data in precise scientific investigations. Several groups of investigators have analytical procedures approaching the basic accuracy of their individual tracking systems, yet no one has published comparably accurate results from a blend of data from different systems. Investigators at S.A.O. and elsewhere are working toward this goal.

As a specific step in this direction, several other instruments were collocated at S.A.O. stations during the past two years. One or more selected satellites were tracked simultaneously by the Baker-Nunn and the collocated system. The same satellites were added to the tracking list for the whole S.A.O. network. Collocation eliminates several variables in a comparison of techniques, since the satellite position, observation time, and station position are essentially identical. Any difference in results must be attributed to the differences in tracking and reduction techniques. This is a powerful way to isolate and identify the problems that may arise in efforts to use mixed data.

At S.A.O. the greatest progress so far made has been the combined utilization of range from laser measurements and directions from Baker-Nunn photographs (Lehr *et al.* 1967). Geos orbits have been determined from a mixture of these data. The residuals between the determined orbit and observation are comparable for the two data types, with the use of the range of the satellite to express the residuals in comparable units. The combined standard deviation is about 2×10^{-5}, or 4″, which is typical of a well-determined orbit by means of Baker-Nunn data alone. This is all that can be expected for the present because range was available only from one station; thus the orbit is primarily dependent upon Baker-Nunn observations.

The present S.A.O. computer programs for orbit determination have a precision adequate for Baker-Nunn observations but inadequate for a full utilization of ranges an order of magnitude more accurate. Hence more precise programs are in preparation for later use with laser data. Meanwhile laser ranges can be combined with Baker-Nunn photographs for investigations where the accuracy of the latter is adequate. Presumably the same is true for other ranging systems when observations from them become available.

Data for a comparison of Doppler and optical tracking were taken in 1965 while a station operated by the U.S. Navy was collocated at the S.A.O. New Mexico site.

In another collocation experiment, the N.A.S.A. Goddard Space Flight Center arranged for many different cameras to be set up at the S.A.O. station in Florida between December 1965 and May 1966. The cameras used are listed in table 2. The investigation was based primarily on photographs of the flashing lights on Geos. Optimum relative weighting of data from various camera types is one of the expected results.

Of course collocation is not the only tool to explore methods for combining various tracking data. The Geos satellite affords a valuable opportunity because it was designed specifically to carry the on-board equipment for all of the major United States tracking

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systems (Rosenberg 1964). These are listed in table 3. At the time of this writing the satellite is still operating and analysis of data from it has barely begun.

Many comparisons of results from these systems are under way. For example, the Goddard Space Flight Center is conducting an intercomparison experiment by means of an extensive array of tracking instruments centred on Eastern North America (Berbert 1966). Very accurate short arcs for Geos across this region of dense tracking will be determined. The fit to these arcs for data from each tracking system will be examined.

Table 2. Cameras in Jupiter, Florida, collocation experiment

cameras	aperture (mm)	focal length (mm)	field	remarks
1. Baker-Nunn (S.A.O.)	500	500	5° × 30°	super-Schmidt
2. K-50 (S.A.O.)	229	914	6·5° × 8·5°	modified aerial camera, sidereal drive, fixed camera back
3. BC-4 (N.A.S.A.–Langley)	117	305	33° × 33°	ballistic camera, aerial camera lens on theodolite base
4. M.O.T.S.-24 (N.A.S.A.)	102	610	—	equatorially mounted camera
5. M.O.T.S.-40 (N.A.S.A.)	203	1016	11° × 14°	equatorially mounted camera
6. PTH-100 (SSL on lease to N.A.S.A.)	203	1016	10° × 10°	ballistic camera, similar to PC-1000
7. PC-1000 (U.S.A.F.)	203	1016	10° × 10°	ballistic camera

Table 3. Tracking systems on Geos

1. Secor radio ranging
2. Flashing light (4 lamps)
3. Doppler system
4. Range-and-range-rate (N.A.S.A.)
5. Corner reflectors, for laser (334 1 in. cubes)

On the other hand, S.A.O. is using long arcs for another comparison. Orbits determined from Baker-Nunn data and parameters determined for the Smithsonian Standard Earth (Whipple 1967) are the basis of comparison because they are the material with which S.A.O. is most familiar. Intervals from 2 to 4 weeks are used for this purpose. The laser calculation mentioned previously is an early step in this investigation. As they become available, data from other networks will be used.

More interfaces between the S.A.O. and other networks arise from the objectives of geometrical geodesy. In Europe, for example, S.A.O. is operating its cameras to obtain photographs of the Echos at the times selected by the European prediction centre. This will provide a link between the European geometrical ties and the coordinate system defined by S.A.O. Similarly, many European stations are photographing Geos flashes. These data will be used by investigators at the observing organizations, at S.A.O., and at other institutions participating in the Geos programme. The S.A.O. observational data and results will be published for general use by the scientific community.

Cooperation between S.A.O. and the Royal Radar Establishment station at Malvern, England, is one example of an arrangement with a single instrument. Since the Malvern camera has a capability similar to that of the Baker-Nunns, it can participate in several of the observing programmes, geometrical and dynamical.

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On a larger scale, as the United States Coast and Geodetic Survey (C.G.S.) moves its BC-4 stations around the world on its uniform geometrical pattern, S.A.O. will photograph Pageos when possible at the times selected by C.G.S. Other cameras in the areas of operation may arrange to do likewise. Similarly, when S.A.O. uses Pageos for simultaneous ties between its stations, the predicted times will be available to other stations that may wish to coordinate their photographic programme.

These instances of coordination between various networks and individual stations are only examples of the many possible arrangements. Where practical, S.A.O. will entertain cooperative observations with any serious investigators, provided data and results are freely exchanged and published.

5. Selection of satellites for tracking

During the early years of the space age it was possible and interesting to track all of the artificial satellites. On 1 October 1966, there were 1150 objects in orbit, and the Baker-Nunn network has time to track only a small fraction of these regularly. About 30 satellites are considered a reasonable complement for the S.A.O. network.

These satellites must be carefully selected. The first group of about 10 objects is specified by N.A.S.A. in response to operational requirements. For example, the Agena launched originally for Gemini 8 was tracked until Gemini 10 made a rendezvous with it.

A second group of satellites is selected for investigation of the atmospheric density and its variations. Generally, these satellites have perigee altitudes below 600 km and a significantly eccentric orbit. A body of spherical or nearly spherical shape is preferable. Several balloon satellites have been launched specifically for atmospheric measurements. The satellites now being tracked for this objective are listed in table 4.

Satellites for intervisible simultaneous photographic observations form a third group. Some of the satellites selected by S.A.O. for this purpose are at quite a high altitude, since the S.A.O. stations are widely separated. The Echo satellites also fit into this group because they are popular for cooperative observations with other networks. Pageos was launched particularly for this purpose, and is the latest addition to the list of such objects in table 4.

The most interesting selection question concerns the satellites chosen for determination of the geopotential. It has been shown that a distribution of inclinations is required for significant separation of the effects of the spherical harmonics in the expansion of the geopotential. Further, the atmospheric drag must be quite small or its separation from the gravitational effects will be difficult. Still the satellite must be as low as this limit will allow because the high-order harmonics have effects that fall off with high powers of distance from the centre of the Earth. To meet this problem, a more sophisticated treatment of drag will soon be introduced into the differential orbit improvement programme. It is hoped that this will allow lower satellites to be used for geopotential determinations.

The objects now being tracked to determine the geopotential are listed in table 4. Figure 3 shows the same list in the more graphical representation of inclination against perigee altitude. This list is frequently examined in the light of newly launched satellites. For example, there is a gap at very low inclination that should be filled if an appropriate satellite were launched for any reason.

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Another consideration in the selection of the S.A.O. list is the opportunity for intercomparison with other tracking systems as discussed in the previous section. Thus all three of the satellites with retroreflectors for laser tracking are carried in the list. For this reason also, the planned French geodetic satellites with retroreflectors will probably be added to the list if successfully launched—particularly, if they have inclinations differing from other retroreflector satellites. Other satellites are selected because they have one or more of the electronic tracking systems from which data will be available for scientific analysis.

Table 4. Satellites tracked by S.A.O. (September 1966)

satellite	N.A.S.A. requirement	atmospheric studies	geopotential studies	geometrical geodesy	laser tracking
1958 α 1	.	×	.	.	.
1959 α 1	×	×	×	.	.
1959 η 1	.	.	×	.	.
1960 η 1	.	.	×	.	.
1960 ι 1	×	.	.	×	.
1960 ι 2	×	.	×	×	.
1960 ν 1	.	.	×	.	.
1960 ξ 1	.	×	.	.	.
1961 $\alpha\delta$ 1	.	.	×	×	.
1962 $\beta\mu$ 1	.	.	×	.	.
1962 $\beta\psi$ 1	.	.	×	.	.
1962 $\beta\tau$ 2	.	×	.	.	.
1963 24A	×	.	.	.	.
1963 26A	.	.	×	.	.
1963 30A	.	.	.	×	.
1963 53A	×	×	.	.	.
1963 30D	.	.	.	×	.
1964 4A	×	.	×	.	.
1964 64A	.	.	×	.	×
1964 76A	×	×	.	.	.
1965 32A	.	.	×	.	×
1965 63A	.	.	×	.	.
1965 78A	.	.	×	.	.
1965 81A	×	.	×	.	.
1965 89A	×	.	×	×	×
1965 98A	.	×	.	.	.
1965 34C	.	.	.	×	.
1966 5A	.	.	×	.	.
1966 44A	.	×	.	.	.
1966 56A	×	.	.	×	.

Fortunately, since 30 is a rather small number, it has been possible in many cases to combine objectives for which a satellite is tracked. Wherever possible a body listed for operational reasons is also used for scientific objectives. Likewise a satellite tracked for any reason can be used for simultaneous observations if its altitude is appropriate to the station separation and if the satellite is not too large and irregular. The current list of satellites tracked by S.A.O. is available at any time to interested parties for coordination and planning purposes.

6. New scientific objectives

The Baker-Nunn network was established with three principal scientific objectives (Whipple & Hynek 1958): to tie together the observing stations and the centre of the geoid to a precision of the order of 10 m; to add appreciably to knowledge of the density distribu-

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tion of the Earth, particularly in the crustal volumes; and to provide precise information on the density of the atmosphere and periodic cyclic effects that may occur in it. Each of these objectives has been attained, the latter two far beyond any early hopes. Thus it is appropriate now to set new objectives for the continuing programme of research based on tracking data.

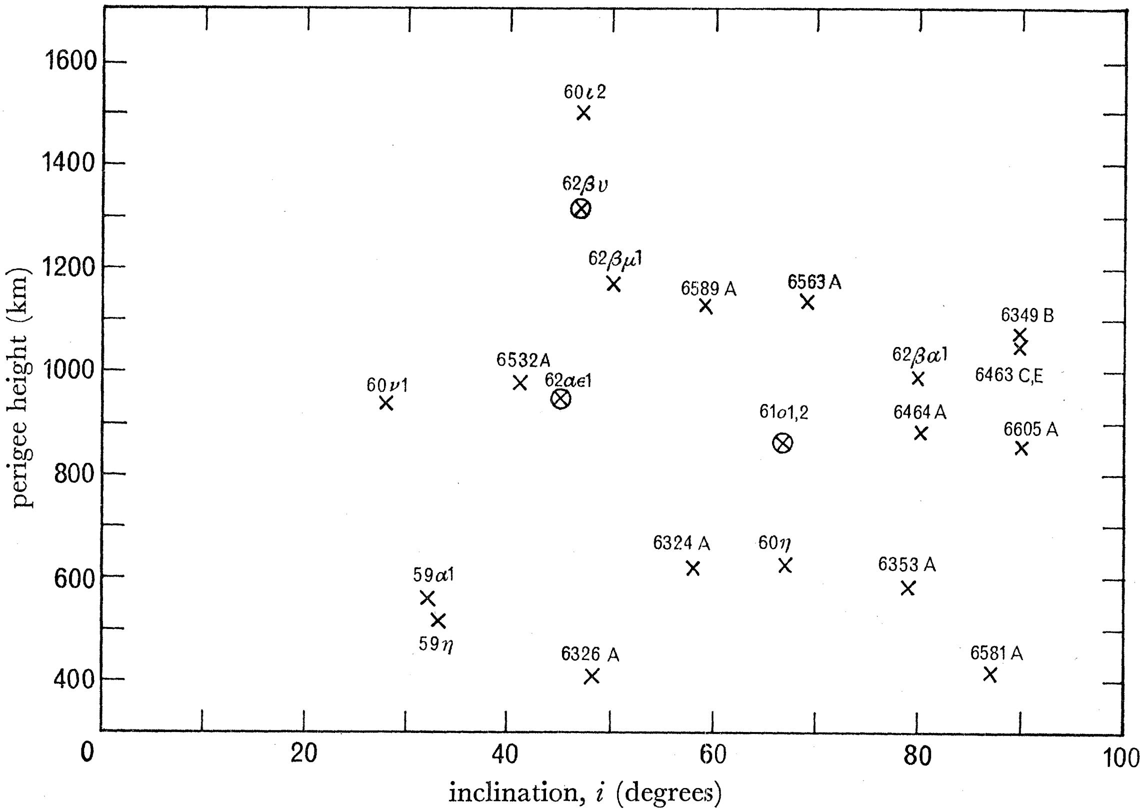

Figure 3. Graphical representation of inclination against perigee height of satellites tracked by S.A.O. (September 1966). ×, Being observed; ⊗, observed at one time.

These objectives must recognize the evolution of instrumentation discussed in §3. Particularly, the greater accuracy of the laser data may be reflected in more ambitious investigations. The diversity of data and the close relations with other networks examined in §4 have other consequences. Also it must not be overlooked that utilization of more accurate observations requires correspondingly more sophisticated analytical and numerical treatment. In the case of the Baker-Nunn camera, 8 years passed before geophysical understanding and the quality of the data treatment approached the limit from the observations. The 4·0″ accuracy of position residuals from the better arcs still does not match the 2″ accuracy expected from the cameras. Hence more results are probably contained in the currently reduced observations.

A first restated objective must embrace continuing measurement of the variation of the high atmosphere in response to solar and geophysical influences. The continuity of these measurements is essential through the coming maximum of solar activity. The quality of

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the atmospheric data will benefit in several ways from improvements in tracking technique. For temporal changes it should be possible to push the time resolution to the limit imposed by the nearly impulsive character of the drag perturbation applied near perigee once per revolution. Already the accuracy of the geopotential and station coordinates in the Smithsonian Standard Earth has made possible the identification of the short-period drag perturbations on baloon satellites. Previously this effect was submerged in orbit deviations because of uncertainties of the geodetic parameters. Atmospheric changes of smaller magnitude will be detectable with increased tracking accuracy. Better orbit determination will also permit more critical investigation of changes in inclination that may result from atmospheric motions relative to the Earth.

More precise tracking will naturally result in better determined station positions. These are directly valuable to relate geodetic datums on Earth. Precise enough positions can perhaps provide new knowledge about crustal motions. To be meaningful for this purpose, the accuracy of location must correspond to the predicted limit for laser-range accuracy improved by the atmosphere, that is, a few decimetres. Horizontal crustal motion on opposite sides of major faults may average a few centimetres per year. If this represents a rate at which large crustal units move relative to each other, after several years, detectable changes in station positions should not be surprising. The recent widening (see figures 4(*a*) and 4(*b*)) in the Great Rift near Addis Ababa may already present motions of this order of magnitude (Mohr & Gouin 1967). At least a search for such motions should be undertaken as accuracies become significantly better than 1 m. Motions associated with really large earthquakes may even exceed 1 m, but the likelihood of a station suddenly experiencing so great a motion is fortunately small.

Higher order terms in the geopotential will be determined as more data of improved accuracy become available. However, the same general procedures yield other information that is perhaps more interesting. As a paper by Kozai (this volume, p. 135) will elaborate, it is already possible to detect the gravitational perturbations due to mass displaced by tides in the solid Earth. Also the changes in moments of inertia of the Earth associated with changes in its rotation may be found through their effect on satellite motion. Similarly, the seasonal redistribution of atmospheric mass is at the threshold of producing observable effects on the motion of a satellite, as is the Chandlerian wobble.

The above are examples of dynamical processes influencing the mass distribution of the Earth that are at the threshold of detectability with Baker-Nunn accuracy. With greater accuracy, such processes can be explored in detail. This is an exciting prospect that deserves recognition as a significant new objective of satellite tracking.

In conclusion, it is fair to say that scientific results from satellite tracking have substantially surpassed the original expectations and even hopes when S.A.O. initiated its programme some 10 years ago. It is also clear that the end is not in sight. Improved methods of analysis should provide new results from the present observations while significant improvement in tracking accuracy is also at hand. Correspondingly, more challenging problems await investigation.

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References (Whipple & Lundquist)

Aardoom, L., Girnius, A. & Veis, G. 1965 *Second int. symp. on the use of artificial satellites for geodesy* (in the Press). Amsterdam: North-Holland.

Berbert, J. 1966 *Surveying and mapping* (in the Press).

Kaula, W. M. 1966 *J. Geophys. Res.* **71**, 4377.

King-Hele, D. G. 1965 *Nature, Lond.* **207**, 575.

Köhnlein, W. J. 1967 *Space Research VII*, vol. 2 (edited by R. L. Smith-Rose), pp. 694–701. Amsterdam: North-Holland.

Lehr, C. G., Maestre, L. A. & Anderson, P. H. 1967 *Space Research VII*, vol. 2 (edited by R. L. Smith-Rose), pp. 723–734. Amsterdam: North-Holland.

Lundquist, C. A. 1966 *Surveying and mapping* (in the Press).

Mohr, P. A. & Gouin, P. 1967 (In preparation).

Plotkin, H. H. 1965 *Cospar Inf. Bull.* **29**, 18.

Rosenberg, J. D. 1964 Presented at Symposium for Establishment of a European Geodetic Network Using Artificial Satellites, Paris.

Whipple, F. L. 1967 *Space Research VII*, vol. 2 (edited by R. L. Smith-Rose), pp. 675–684. Amsterdam: North-Holland.

Whipple, F. L. & Hynek, J. A. 1958 In *Proc. VIII Int. Astronaut. Congr.*, p. 429. Vienna: Springer-Verlag.

Veis, G. 1963 In *The use of artificial satellites for geodesy*, p. 201. Amsterdam: North-Holland.

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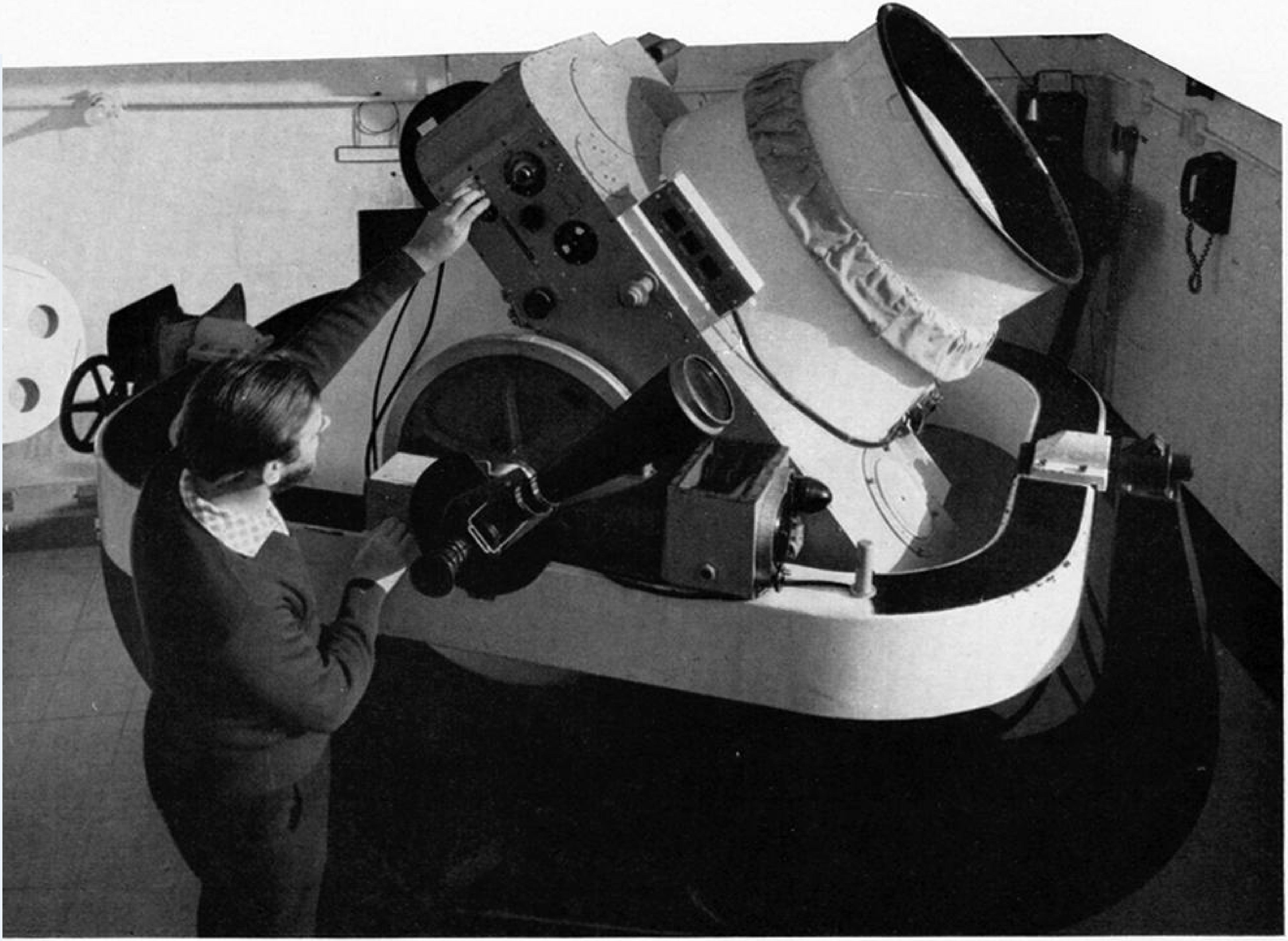

FIGURE 1. The Baker-Nunn camera.

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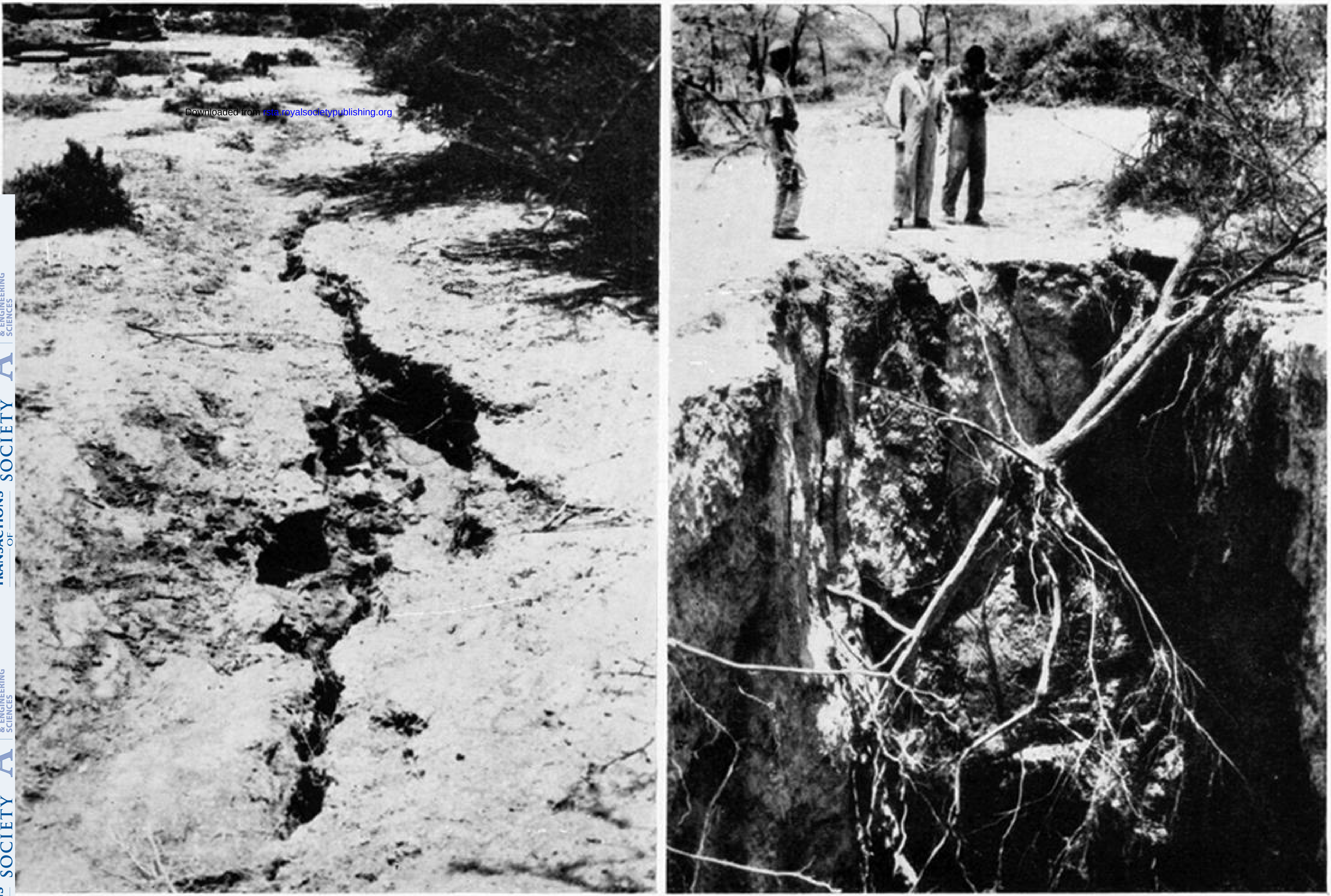

FIGURE 4. Recent widening in the Great Rift near Addis Ababa, Ethiopia (photographs taken by Robert Citron).