Considerations Regarding Instrumentation Commitments to the Photogrammetric Derivation of Rocket Flight Parameters[*]

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ABSTRACT: *The nature of the data requirements placed on the Eastern Test Range by rocket testing agencies leads to the integration of photo-optical and metric electronic systems in a mutually complementary manner designed to exploit their differing mensurative capabilities throughout various portions of the flight path.*

Comprehensive instrumentation plans are elaborated by an operations planning group whose responsibilities allow the marshalling of extensive Range resources to the complex task of tailoring a metric solution to the test objectives and the launch mode of each vehicle.

The main photogrammetric systems are described and their limitations given. Typically, they are assigned overlapping zones of coverage. Throughout the Range, all instrumentation is time-resolved to a common base. Rocket design purpose, size, configuration, propellant chemistry, on-board equipment, launch time and azimuth, roll and pitch maneuvers, coupled with variously stringent accuracy requirements, strongly affect instrumentation selection, site geometry, and vertical deployment. An idealized photogrammetric plan, applicable to a hypothetical launch operation, is presented.

Data reduction is increasingly automated. End-product is a numerically expressed model of the flight sequence, delivered to the test agency in the form of computer-printed tabulations of position, and the time derivatives of velocity and acceleration. Separate computations cover vehicle attitude vs. time, and other parameters.

Special applications of photogrammetry to pre-launch operations and to the calibration of electronic measurement systems are briefly given. The serious role of "chronogrammetry" is pointed out as an effective means of deriving metric photo-interpretation values from an intended surveillance function.

The recent trend of the telemensuration problems faced by the Range has led to the concepts of shaft-digital encoding, electronification of the photo-receptor, optical ranging, servo-tracking sensors, and to the selective integration of such or similar principles into the space-oriented, real-time instrumentation systems of the near future.

INTRODUCTION

THE Air Force Eastern Test Range (ETR) is one of the national test ranges over which the Air Force has executive management responsibility. Its well-instrumented island and ship-borne stations spread out 14,000 km. from the launch area of Station 1, Cape Canaveral, through the South Atlantic, to longitude 90° East in the South Indian Ocean. Its purpose is to obtain and to evaluate innumerable measurements to insure a maximum return on an enormous rocket flight-testing and spacecraft launching investment.

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America (RCA) operates the Range instrumentation systems. Through its Missile Test Project, RCA provides engineering support and operating services for the acquisition, transmission, processing, and analysis of the essential data. Range stations and instrumentation ships are variously operated so that data acquisition systems may be exploited to their fullest potential. Geometrical deficiencies of station distribution and spacing are offset by the mobility of the Range ships. Continuous measurement of flight parameters is sought from the launch point to ballistic impact, through orbital injection for satellite launches, or through the orbital transfer point of a lunar or interplanetary probe. Beyond the limits of the ETR, other U. S. range stations may provide orbital or interplanetary data to the Range Users, who are the various scientific or technical teams assigned by industry or government to complete, through actual flight, the long process of research and development of each program.

Data Requirements Documentation

Well-organized test requirements documentation in standard format is the channel through which a Range User's launch operations agency communicates to the Range the details of the services deemed necessary to satisfy a test program. The center of interest of this documentation lies in the often voluminous metric data required of the Range, the details of which are beyond the scope of this presentation.

The data requirements format allows no decision by the Range User with regard to the instrumentation systems to be employed. Selection, deployment, and operating times of the various systems are the prerogative of an operations planning group, whose responsibility lies in disposing of the extensive Range resources to satisfy the execution of a test program by marshalling full support in the areas of radar, optics, telemetry, communications, timing, command-control, radiation frequency control, data translation, and of the required materiel and services.

A thorough study of the test requirements documentation, many months before the inception of a launch program, is the first move in the direction of the elaboration of an integrated instrumentation plan. If the requirements exceed the existing instrumentation capabilities, a recommendation is made to a long-range planning group for the installation of new facilities, or the procurement of more sophisticated equipment. If Range capability suffices, a plan is produced for publication by a given deadline. This often voluminous plan is known as the Operations Directive (OD), which becomes the action document for a test series, down to the smallest detail. Immediately apparent from its organization is the close interlinkage of optical and electronic instrumentation systems.

Metric Optics vs. Metric Electronics

The role, the scale, and the mode of the photogrammetric effort can only be shown in context, however brief, of the characteristics of the metric electronic systems which predominate in bulk, in cost, and in the greater proportion of the trajectory which they serve to measure. Amongst ETR's impressive array of such devices several basic types stand out:

1. *Pulse radars* which range by means of electromagnetic energy at wavelengths of 3–70 cm. radiated from parabolic dishes of various configurations and sizes. Slant-range determination is by time elapsed from transmitted pulse to receipt of the corresponding echo amplified by a vehicle-borne radar beacon. A one-station solution yields azimuth and elevation angles, and range vs. time.
2. *Continuous-wave (CW) systems,* which operate as microwave interferometers. An outgoing signal, returned by a vehicle-borne transponder at a different frequency, and received by two or more suitably spaced antennas, yields, through phase differencing, continuous angular data. Antenna spacing may be as long as 50 km. Dividing the measurement of phase difference yields a number equal to the cosine of the angle between the baseline and the line joining the antenna and the source. The directional cosine of a line to the transponder in space is thereby derived. The slant-range is obtained by making instantaneous phase-difference measurements between modulated signals transmitted and received by the station.
3. *A hybrid system* which integrates both pulse and CW signals is employed to form continent-wide baselines of highest accuracy for use on space vehicles at orbital altitudes. Self-sufficient air-transportable trailer-mounted stations are designed to provide global mobility.

4. *An ultra high frequency CW doppler system* measures the total doppler shift in the frequency of a signal transmitted from the ground, received by a vehicle-borne transponder, doubled by it, retransmitted and received back at various ground stations. Measurements of accumulated cycle counts are converted to range sums from transmitter to vehicle to receiver. The range sum data from three or more sites are reduced by means of a least-squares adjustment to obtain spatial position.

Some of these techniques are of more than passing interest to photo-optical workers in the mensuration field: the advent of the laser, in either pulse or CW mode, has rendered similar procedures feasible optically.

The assorted capabilities of the cited radio frequency systems (and of others left unmentioned) are channelled in many modes of presentation to serve tasks other than metric ones: Range clearance information; Range safety analog plotting board presentation for real-time flight observation and impact prediction; digital-data computer input for "quick-look," near-real-time readouts; acquisition information for other stations still below the radar horizon; and, of relevance to the optical systems, the feeding of target acquisition servo-signals to the large tracking telescopes, properly parallaxed by on-station coordinate converters.

Finally, it is the function of vehicle-borne telemetry to transmit to the ground stations the parameters of the internal and ambient physical conditions recorded by complex on-board instrumentation. Some of these recordings indirectly serve metric purposes: transmitted values from integrating accelerometers, and of pitch, yaw, and roll sensors, permit a post-flight verification of propulsion and guidance anomalies recorded by the ground metric systems.

Refinements in electronics continue to make giant strides.(1) Yet, from the metric standpoint, basic systematic uncertainties are inherent: inaccuracy at short ranges, ineffectiveness at low elevation angles due to propagational anomalies such as ground-clutter, multipath energy returns, spurious signals and "ghosts" from atmospheric inhomogeneities, etc.(2) Furthermore, at angles which make it necessary for the radio frequency energy to pass through the engine flame to reach the vehicle antenna, the phenomenon of flame attenuation prevents usable tracking energy returns.

It follows that the most sophisticated electronic metric systems cannot be committed below a limit which fluctuates with local conditions, with various vehicle characteristics, and with the accuracies desired.

To insure continuity of measurement, the photogrammetric effort is nearly inversely geared to these variables, not just as a support for radars, but because photo-optics coincidentally also happen to be weak where radars excel. The resulting interrelationship of optics with electronics exemplifies the present state of the science of telemensuration: an all-electronic solution is as unattainable as is an all-photogrammetric one. This working interdependence is further consolidated by a central timing system which provides a common, rangewide 17-bit binary time basis for all instrumentation, a circumstance essential to "Best Estimate of Trajectory" (BET) data reduction, wherein all systems contribute to the computation of a single "most-likely-to-have-been-traversed" flight path.

At ETR, photo-optical instrumentation is applied to the tasks enumerated below (not necessarily in the order of importance):

1. Determination of absolute time-space coordinates of points on ballistic trajectories, and the derivation of velocity and acceleration.
2. Direct determination of linear acceleration at high accuracies for short intervals of time.
3. Derivation of flight attitude from goniometric measurements.
4. High-accuracy relative position for short intervals.
5. Deceleration measurements of bodies re-entering the atmosphere.
6. Miscellaneous measurements of ancillary components's performance.
7. Measurement of rocket sway under wind loads prior to launch.
8. Determination of bending moments during tanking operations.
9. Windshear moment calculation through rocket smoke-trail deformation analysis.
10. Metric photo-interpretation.
11. Prime-standard calibration of radio frequency metric systems.

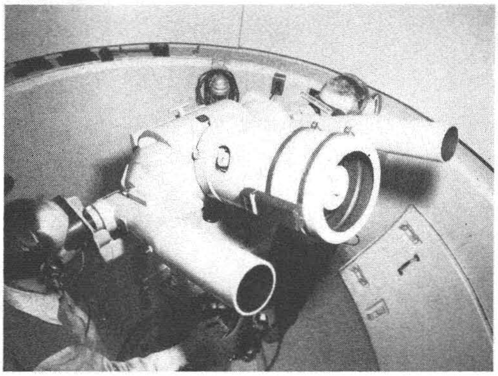

FIG. 1. Askaina Kth cinetheodolite with 1 meter focal length optics used on ends of maximum baseline.

12. Rocket geodesy.
13. Satellite geodesy.
14. Orbital data.
15. Positioning of Range Instrumentation ships with gyrostabilized phototheodolites (under study).
16. Radiation measurements which do not fall within the scope of this paper.

The modes of instrumentation commitments in each area will be discussed in turn.

THE PHOTOGRAMMETRY* OF FLIGHT

1. LAUNCH PHASE (lift-off to burnout)

a. *Cinetheodolites*

Optical instrumentation deployment for the launch phase of flight broadly hinges on the radar minimum-altitude commitment. On the basis of the missile's radar beacons and transponder parameters, antenna gain and location before and after flight-program maneuvers, the variables of ground transmitter-to-missile antenna aspect geometry, atmospheric refraction and attenuation values and other factors, a radio frequency (RF) energy balance sheet is established which serves to calculate the net signal return gain vs. time after lift-off expected for each ground station receiver. The minimum optical coverage must reach a point along the trajectory at which the ascending radar accuracy curve equates commitable values. An additional overlap zone must be sought to facilitate smoothing between systems.

The only photogrammetric system capable of adequately overlapping radar low limits is the cinetheodolite network. Determination of the space-time coordinates of a trajectory point is through triangulation of the corresponding rays originating from multiple stations. Rigorous synchronization of event-recording vs. instrumentation direction and elevation angles against time and frame count is assured throughout the system. Except for a few updating remarks, reference is made to previous descriptions.(3,4,5)

Stretched over a baseline of some 58 kilometers along the Florida East Coast eight Askania Kt-cinetheodolites (Figure 1) are now housed in astrodomed towers with an average instrument height above ground of some 8 m. Instruments are on piers resting on separate foundations and isolated from the rest of the building. Dome area and the electronics control room are thermally stabilized. Color film is used for better separation of values during the readout step. Trading off resolution for readability has proven advantageous.

Lens focal-length is generally 40 cm., but for the ends of the baseline focal-lengths of 100 cm. and 220 cm. are preferred.

Cinetheodolite commitments are governed by factors of which the more salient are the following:

1. A ratio of 2:1 slant range-to-baseline is required to stay within the usual accuracy limits. This may be stretched to perhaps 4:1 if accuracy is to be sacrificed for range.
2. For some launch azimuths, one or the other baseline end-station cannot be used effectively. The shortened baseline consequently affects committable range within a given accuracy, or accuracy within a given range.
3. A pronounced pitch programming maneuver removes the vehicle nose from view from some stations, necessitating the choice of the flame as a common reading point for data reduction.
4. For solid propellant missiles, the flaring out of the dense smoke trail eclipses both the vehicle and the flame edge reading point for some stations relatively early in flight. This cuts off the station from further usefulness.
5. With some newer hypergolic (self-igniting) propellants, the flame is nearly invisible, and may not record at all during some portions of the flight. Shift to another tracking point must be made and compensated for mathematically,

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* I.e. intersection photogrammetry. Stereo photogrammetry is not employed at ETR.

which adds undesirable complexity to the reduction step.

6. No manned station may be operated within a danger zone defined by the nature of the propellants used, and by the relatively untested behavior of a new vehicle. Any station so located is therefore subtracted from the photogrammetric net.
7. No station is committed at angles below 10° instrument elevation, a constraint imposed by the magnitude of the local atmospheric refraction for which mathematical compensation can no longer be made. Consequently, this limitation defines the low end of cinetheodolite effectiveness.
8. The system's velocity and acceleration data is limited to the values imposed by the 5/sec. sampling rate. (Upgrading to 10/sec. capability is imminent, but still inadequate in some cases.)

b. *Ribbon Frame (CZR Type) Camera System*

This system, designed to operate in a fixed mode of orientation, is intended to cover the interval from vehicle lift-off to the cinetheodolite lower limit of about 1,600 m. Space-orientation is by means of a three-axis gimbal mount locked in azimuth, elevation, and roll angles pre-computed for each site with relation to the theoretical trajectory. The vehicle traverses the long dimension of the narrow ribbon format. It is recorded against "ground-control" points provided by target arrays, whose surveyed positions provide independent orientation for each camera of the triangulation net and permit the photogrammetric determination of the most probable spatial intersection of the directed rays from each site. Dial orientations may sometimes be used, mostly in combination with targets located in "offset" position, i.e. out of the field of view of the trajectory. Time correlation is to one millisecond. Sampling rate is 30 to 180 per sec. Earlier developments of the system have previously been described (3,4,5).

The mobile instruments have been provided with astrodomes of white fiberglass, air conditioned to the ambient level anticipated for the launch operation. (Figure 2) Use of stable-base cronar film provides, to all intents and purposes, a "flexible ballistic camera plate." Tower-housed fixed instruments have been equipped with an improved mount, and in some cases with 360° astrodomes demanded by the proliferation of launch facilities. Electronic driver-racks provide voice communications, automatic camera starts and stops, and Range timing.

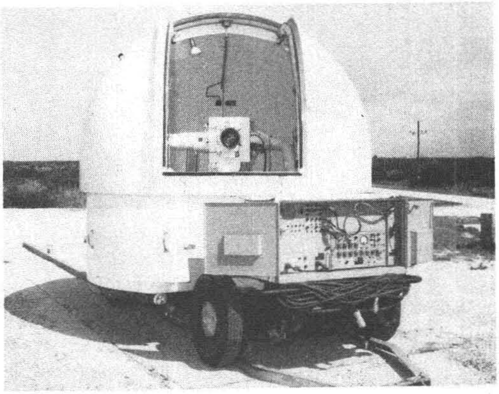

FIG. 2. Ribbon frame sequential recorder under astrodomed mobile shelter. Electronic control unit in foreground.

Overall, target pole height has been increased to a desirable new norm of some 30 m. They have been stabilized with concrete foundation blocks and more rigid guying. The four targets per pole are internally illuminated, and yield high contrast minimum size center points on film. The trajectory is as much as possible bracketed between the two target rows.

It is appropriate to allay here some classical apprehensions which prevail with regards to dynamic photogrammetric recorders. The concept of a camera designed for intersection photogrammetry at sampling rates of 180 per second is considerably at odds with the ideal of a static instrument machined from a solid block of invar. Lens interchangeability alone, not to speak of the dynamic components of the film transport mechanism, could only multiply the disturbance factors hostile to rigorous collinearity. Adding the circumstance of a curved film plane on which photographic exposure takes place during film travel at 0.8 m./sec., and the vision of the compounded perturbations acting on the ideal geometrical model is enough to send experienced photogrammetrists into despair.

Fortunately, the great potential of high-speed computer flexibility readily copes with the satisfactory mathematical restitution of the "sins" committed in image space. In addition to the classical calibration values expressing the elements of internal orientation and distortion, appropriate algebraic expressions are introduced to correct film-plane curvature and film motion during the shutter open period. Mechanical runout (wobble) of the film transport drum is kept to values worthy of watchmaking. Missile displacement in object-space is minimized in image-space by recording it across the film width, i.e. at right-angles to the film travel. The minute image elongation is consequently across the missile diameter, and little affects the reading point quality, i.e. the nose, the point-source of the optical beacon, or the flame front. A narrow slit focal-plane shutter travels opposite the film displacement, and freezes the image within the span of 3×10^{-4} sec. The film coordinates are defined by three fiducial crosses which are exposed on each frame through a secondary optical train by an ultrashort pulse of a flashing source.

Through the refinement of spatial-orientation techniques and computer programming, combined with what was originally conceived as a linear acceleration camera, the instrument represents a successful attempt at lessening the void which exists in the area of high-speed metric instrumentation.

The weaving of a photogrammetric net of fixed cameras is considerably more complex than the elaboration of a cinetheodolite triangulation scheme. Of the many factors which enter into play, the following are prominent:

1. *Prime goal* lies in reaching the cinetheodolite low limit plus a smoothing overlap. An unsymmetrical four-camera solution is sought, to permit retention of good three-camera geometry under possible loss of one instrument. Random camera-to-launch-point distances must be compensated for with focal lengths from 12.5 to 25 cm. to cover identical altitude intervals from all sites. The originally employed frame synchronization of the system has been dropped to simplify the electrical power problem. The reduction routine permits mathematical interpolation of between-frame values.[7]
2. The *altitude interval of coverage* from fixed cameras must sometimes be stretched when cinetheodolite sampling rate is insufficient relative to velocity and acceleration demands. To reach higher than the usual 600 to 800 m., the fixed cameras must be "stacked," i.e. elevation-overlapped in triangulation nets of three to four cameras to each level of coverage. A twelve-camera reduction routine permits computer derivation of a continuous trajectory from such multiple stacks. The system set-up angles are hand-calculated for simple trajectories, but require electronic computing for the secure framing of the trajectory within the narrow format throughout the "stacks."
3. *High-accuracy, short interval position requirements* are met through a 2–3 station solution with instrumentation located at distances varying from 125–350 meters. Target arrays must be installed within each field of view for absolute position determination. (For relative position, the launcher structure and the vehicle at rest, both suitably targeted, are acceptable for a pre-launch orientation.) Point-source optical beacons must be carried by the vehicle, and fed either from internal power, or through external cabling designed to break contact after an allowed slack is taken up which corresponds to the commitment upper limit. A survey of 1:15,000 is made of the beacon lamp filament as closely as possible to lift-off time. The reading points afforded by beacons in the restitution of the photogrammetric model exceed by a factor of two those of painted targets. Besides, the latter are not usable at night, nor do they permit more than a two-station solution. (A self-powered expendable beacon package is under development to eliminate the wiring problem.)
4. On the assumption of a faultless 90° liftoff, *high accuracy linear acceleration data* may be obtained from a one-station solution at ranges as close as 40 meters. No targeting needs to be recorded outside the beacon, and this is usually done at the maximum sampling rate of 180/sec. and exposures of 3×10^{-4} sec.
5. No danger-zone limitations exist for the system, since cameras in possible blast areas need not be manned. Pre-orientation exposures are made before the crews must leave the area. Synchronous or staggered automatic camera starts are provided throughout the Cape Canaveral territory by a suitably preprogrammed sequencer system. Camera stop before film depletion permits a post-orientation exposure upon the re-opening of the area to personnel.

c. *Attitude Tracking Camera System*

The rocket guidance systems' performance is quantitatively monitored through photogoniometrically derived values of deviation from normal flight attitude, i.e. with the longitudinal vehicle axis tangent to the trajectory. Deviations in pitch are those which occur in the plane of the trajectory. Yaw deviations occur at an angle to the trajectory plane. Roll is the rotation about the vehicle longitudinal axis. Attitude changes also result from purposely programmed maneuvers necessary to maintain the attitude reference plane on the required trajectory azimuth. It is therefore pertinent to measure all angular changes vs. time to extricate malfunction from function. To enable proper readout on the microcomparator used in the reduction step, the vehicle must be provided with a standard paint pattern which of necessity must reconcile high recordability with distance and fineness of markings for accuracy of readings. Eight black and white stripes, occupying alternating sections of 45° each, have been found to represent the best compromise. Black stripes of stepped lengths allow positive quadrant identification for absolute roll determination.

Metric attitude data are gathered by three types of tracking instrumentation deployed in depth from the launch point. Confined to the Cape Canaveral area proper are IFLOT (*i*ntermediate *f*ocal *l*ength *o*ptical *t*racker) (Figure 3). Medium-speed motion picture cameras are coupled to cassegrainian optics of 1 meter to 3 meters focal-length on powered mounts, one-man operated through aircraft-type servo controls. Along the Florida Coast, distributed over a baseline of 110 km., are IGOR (*i*nstrument, *g*round, *o*ptical *r*ecorder) and ROTI (*r*ecording *o*ptical *t*racking *i*nstrument) (Figures 4 & 5). These large tracking telescopes with 45 and 60 cm. mirrors respectively, allow a pre-setting of focal-length from 2.5 m. to 12.5 m. Each type is housed in astrodomed installations providing shelter also for the ancillary electronics. This includes a radar target acquisition coordinate converter, automatic focus control provided by radar signal inputs, continuous automatic exposure control, and the necessary communications and timing equipment. ROTI is one-man operated through hydraulic controls. IGOR is mechanically operated by two men. Sampling rate selected for attitude coverage is 10/sec. for 70 mm. film, and 12/sec. for 35 mm. Lighted fiducials projection is incorporated in all cameras.

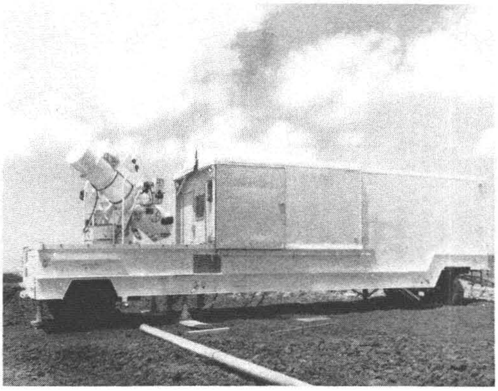

FIG. 4. Mobile IGOR in air-transportable trailer housing.

The *modes of attitude instrumentation* commitments are conditioned by the following:

1. For *pitch and yaw* the basic purpose is to record differential apparent pitch angle (the so-called "V" angle) i.e. the shifting

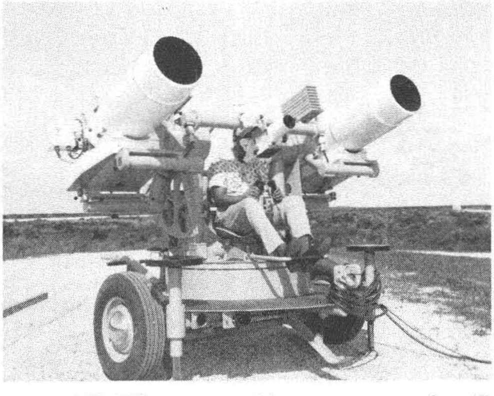

FIG. 3. IFLOT power tracking mount carrying 80 inch metric attitude cameras.

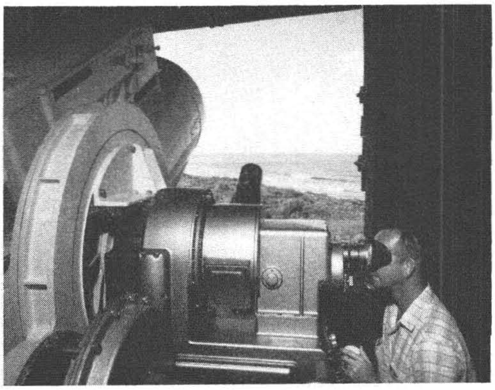

FIG. 5. ROTI in an astrodomed tower installation.

angular relationship between the film vertical fiducials and the vehicle longitudinal axis as recorded from the chosen locations. The employed reduction routine for pitch and yaw was designed to accept four cameras[7]. Instrument set-up geometry should be reasonably symmetrical about at least 120°. An unsymmetrical distribution is preferred whenever 180° can be exceeded about the launch point. Site choice is also influenced by most favorable sun position at scheduled launch time.

2. For *roll reduction*, one of the four cameras should be as nearly as possible on the reciprocal angle of the flight azimuth. This uprange location alone satisfies the holding to a minimum of the apparent vehicle pitch-angle on film, which may not exceed 12–15° to be in harmony with the roll-reduction equations[8].
3. An alternate reduction routine for *high-accuracy roll** (9) is based on an inversion of the classical Finsterwalder pyramid principle of ground control for aerial photogrammetry. In this instance, positions orthogonal to the flight line may be used, for which the only geometrical limitation lies in excessive image foreshortening encountered with high instrument elevations. Microcomparator readings of at least four rigorously premeasured points of the vehicle paint pattern are required. Drawback of the method lies in tediousness of readouts, and rapid degradation of accuracy under even midly unfavorable atmospherics.
4. *IFLOT effectiveness* is restricted to a zone defined by the hyperfocal distance, by the minimum acceptable image-size, and by a maximum tolerable instrument elevation-angle of 45°. IFLOT deployment must be calculated to reach some 2,500 m. vehicle altitude, the lower effective limit of the ROTI-IGOR system imposed by atmospherics plus magnification factor.
5. The tracking telescopes' *useful geometry* is laterally limited by the fixed baseline presented to the varying flight azimuths. As a result, a move is being made in the direction of trailer-mounting the IGORS for deployment to locations tailored to each launch direction (Figure 4).
6. The metric attitude data *obtainable with the large telescopes* cannot be firmly pre-calculated owing to the many variables encountered, especially those of visibility conditions relative to each station. However, acceptable values have been obtained to some 100 km. No attitude commitments can be made during night launches, and only pitch and yaw can be covered during twilight. Dual expendable beacons mentioned previously may remedy this limitation, except for the reduction of absolute roll.

2. MIDCOURSE PHASE

Past the burnout point for ballistic missiles, and during the first coast phase of spacecraft, the electronic measuring systems' accuracies may drop below the mandatory level. "Mandatory" data necessitates a degree of excellence without which the test objective cannot be met. This leads to night launches which permit the use of the extreme-accuracy, star-field oriented ballistic cameras, more properly referred to as phototheodolites (3, 10). To the early Wild 115, 210, and 300 mm. instruments, the Nortronic 600 mm., and the Instrument Corporation Florida MBC 1,000 mm. air transportable van system have been added (Figures 6, 7, & 8). A six camera solution is typical, but as many as ten or twelve have been used to cover a number of sky areas

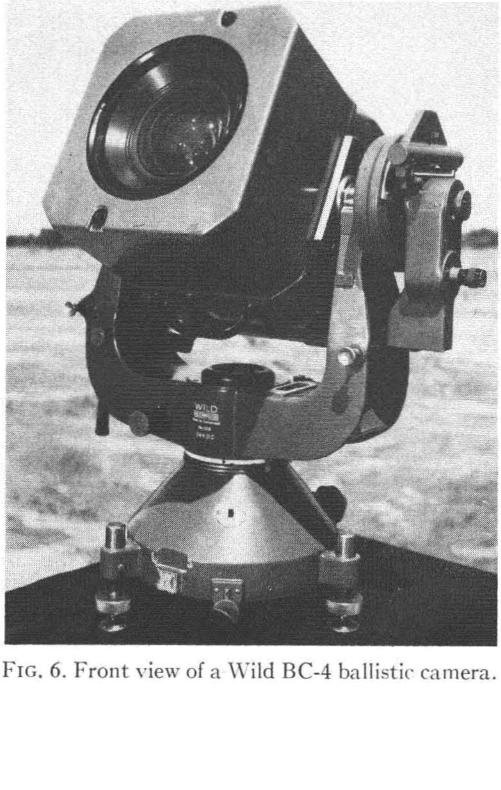

FIG. 6. Front view of a Wild BC-4 ballistic camera.

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* Defined as better than one degree.

along one trajectory. The instrumentation deployment logistics are often involved in that mainland operators and much heavy equipment must be transported and be operational on the prepared down-range sites, if possible with a regroupment capability for subsequent operations.

The Range User assumes the responsibility of providing the vehicle with a pyrotechnic flare ejection mechanism. Flare intensity must be compatible with the anticipated instrument distances. The high luminosity and light weight advantages of flares are offset by the long (3–5 millisecond) flash duration, by activation at an appreciable distance from the vehicle, and by the limited number of flashes possible. As an alternative, high-intensity gas discharge tubes have come to the fore, whose flash sequences can be programmed over longer time spans. Drawback is weight penalty and actinic energy insufficient to longer ranges (by one order of magnitude against flares). Flash intervals are programmed according to the desired sampling rate, not exceeding 2/sec. for both sources (11).

Instrumentation setup angles, computer derived from theoretical trajectory values, are teletyped to the operators of each site. Individual pre- and post-operation star calibration need not be carried out in synchronism, but shutter open periods coincide for all stations within optical range of each flare firing sequence. Orientation is by means of incremental, and subsequently decreasing time exposures serving the time-coding of the star traces. Time correlation between stations is through telemetered pulses of the response of a vehicle-borne photocell. This method lacks constancy in the incurred propagation delays, and is often uncertain with the plate-to-plate flash identification. The response of high-sensitivity photomultipliers slaved to radar dishes is preferred. For both methods, recording is on magnetic or oscillograph paper tape. A number of photomultipliers may be used for weather redundancy. While photogrammetric flare operations commitments are for positional values only, flareless coverage may be used for the determination of ignition or burnout times of upper stages.

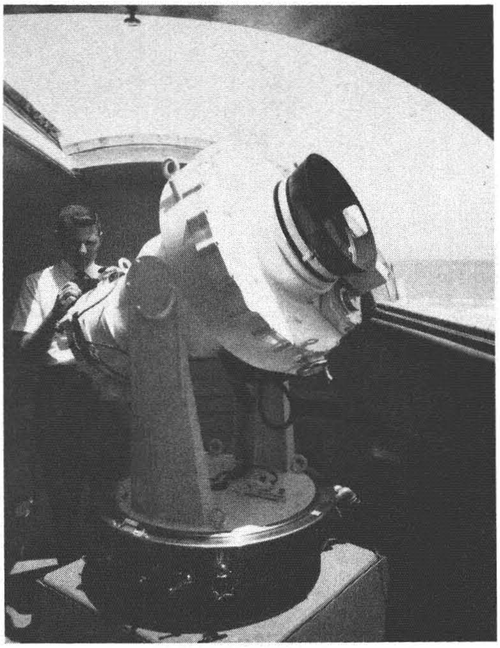

FIG. 7. Sheltered Nortronics BC 600 mm. f/2 system installation at Vero Beach.

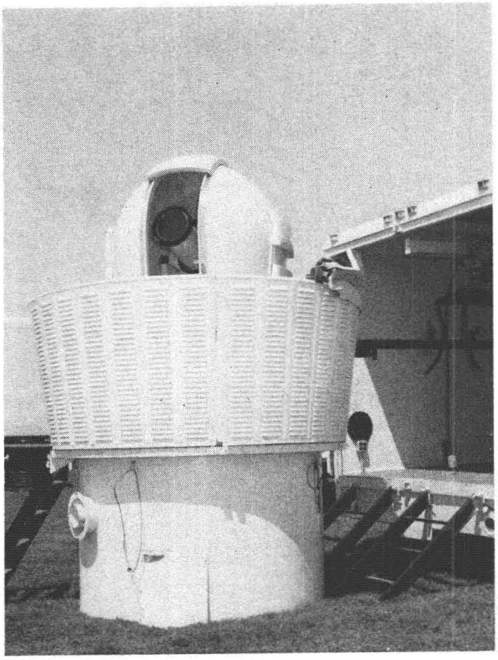

FIG. 8. ICF-MBC-1,000 mm. in air conditioned transportable folding shelter.

The exposed plates may be flown back to Station 1 by fast aircraft, ahead of the heavy equipment. Phototheodolite data reduction is fully automated to a point where star field identification is executed by computer on the basis of memory storage of a complete star catalog down to 5th magnitude objects.

3. ATMOSPHERIC RE-ENTRY PHASE

In the impact area, the operational problems differ somewhat with the mechanics of target acquisition and with the self-luminous nature of the decelerating re-entry bodies. Daytime launches from Cape Canaveral may be scheduled for night re-entry at Ascension Island by taking advantage of the 4.5 hours time differential between stations. Phototheodolite operation may be in the shutter open mode for the recording of fragmentation dispersion against a star background. More frequently, the flame-chop mode is employed with an interim synchronous system capable of 2 millisecond time correlation. Pre- and post-orientation again is by incremental and decreasing exposures of the star-field, for time correlation of the calibration which is concurrently also recorded on oscillograph paper tape or on magnetic tape.

Event timing is accomplished by programming all shutters with a 5 pps. (pips per second) and 1 pps. superposed binary code from a central control station. This results in the luminous meteor-like trace itself being recorded in a composite binary pattern. The leading and trailing ends of long and short dashes thus formed on the plate represent points in space perfectly matched on all plates. These yield position from the known external orientation of each camera. Through the precise time values coded into the trace, the derivatives of velocity and deceleration are obtained. The running tape recording of all the time parameters includes a shutter-return signal from each camera to verify proper shutter operation.

A van mounted, air-transportable IGOR telescope of 12.5 m. focal length originally tracked re-entry bodies from an elevated site of Ascension Island. Target acquisition was by a combination of computer-provided "look-angles" and by radar assist. The sampling rate of 30/sec. allowed a record to be made on color film for metric photo-interpretation supported by position information from other systems. For some re-entry coverages the IGOR aperture and sampling rate have been shown to be insufficient. Consequently, an IFLOT is now utilized with 16, 35 and 70 mm. capability, at frame rates to 200/sec. Another mobile IGOR, however, still provides optical re-entry coverage at other impact locations.

A Photo-Optical Instrumentation Deployment Plan

Assuming a launch operation of a large rocket with re-entry programmed for Ascension Island, the following plan might be committed:

No.	*Type*	*Altitude Interval*	*Coverage*	*Accuracy*
1	RF	0–1 m.	High accuracy acceleration	0.5 cm/sec/sec
2	FC	0–3 m.	Translational displacement	2 cm.
2	RF	0–60 m.	Position and derivatives	30 cm.
4	RF	60–600 m.	Position and derivatives	*
4	RF	600–1,400 m.	Position and derivatives	*
4	RF	1,400–2,500 m.	Position and derivatives	*
7	CT	2,500–30,000 m.	Position and derivatives	*
4	IFL	0–2,500 m.	Attitude (daylight only)	2°
4	TT	2,500–10,000 m.	Attitude, also ES to 120 km.	5°
4	BC	Early Midcourse	Position (night only)	15–20 microradians
4	BC	Midcourse	Position (night only)	15–20 microradians
3	BC	Re-entry	Position-deceleration (night only)	50 microradians
1	TT	Re-entry	ES and Possible PIM	

* At these altitudes it is customary to express the desired accuracies in terms of a formula based on a minimum value plus a percentage of slant range, as for example: $2+(7\times10^{-5}\times\mathrm{SR})$ where SR = slant range in feet.

RF	Fixed Ribbon Frame Camera
FC	Fixed Cine Camera
IFL	Intermediate Focal Length Telescope
CT	Cinetheodolite
TT	Tracking Telescope
BC	Ballistic Camera
ES	Engineering Surveillance
PIM	Photo Interpretation, Metric

Additionally, 25–30 time-resolved chronographs (high-speed) cameras may be deployed around the engines, the umbilical masts, the launch area, and in the tracking mode at staggered ranges.

THE REDUCTION OF METRIC DATA

The reduction, at ETR, of the data gathered by photo-optical instrumentation has been related elsewhere (3, 4, 5, 6, 7, 8, 9, 10 & 12). To touch upon this activity, even in part, would fall beyond the intent of the present paper. It is likely that updated information may see early publication, thanks to other efforts. Suffice it to say that the trend will continue to be in the direction of increasing automation of those processes which mathematically culminate the function of the Range.

The end-product of a launch operation takes the form of voluminous computer-printed tabulations. Here, the combined orderly mazes of figures represent a numerical model of the completed flight, reduced from a multitude of parameters individually recorded by instruments which, in some cases, are dispersed over a good portion of the globe. The tabulations are published for each instrumentation system, for interpretation by the Range User of the trajectory as a continuity.

On the ascendancy is another form of presentation under which a unique flight model results from the combined outputs of all metric systems. Since there are available, at most points in time, several position values from different systems, each with distinct random and systematic error characteristics, a method was devised which succeeds in combining the data from certain intersystem redundancies into a single positional value for each time point. This method is called Best Estimate of Trajectory, or BET for short. (13)

While BET is currently derived from the outputs of groups of independent tracking systems, emphasis is being shifted rather to consider an input of pure measurement parameters as such: elevation, azimuth, range, range sum, and range difference from whatever source derived. Thus, the computer routines need not be changed whenever new mensuration systems are phased into the Range metric instrumentation apparatus.

Regardless of the mode of presentation asked of the Range by the Range User, the launch operation does not end here insofar as the test agency's data groups are concerned. For them, whether the flight was a success or a failure, the task of analyzing has just begun.

Other photogrammetric data are reduced by the RCA Data Reduction group, which are of particular interest to devotees of Commission V, since the list given amplifies in a small way the ever growing roster of special (non-topographic) applications of photogrammetry.

SPECIAL PHOTOGRAMMETRY

Some pre-launch check-out operations require photogrammetrically derived parameters for the evaluation of diverse auxiliary functions. Time correlation is to one millisecond.

1. *Velocity and direction verification of electrical umbilical and fuel line disconnects or of umbilical boom retraction:* two orthogonally positioned calibrated high-speed cameras are used, usually without external targetry.
2. *Umbilical eject recoil reaction on the vehicle in X, Y, and Z*, in terms of possible disturbance effects to the guidance mechanism: same setup as above, except that micrometer-like pointers are recorded at extreme closeup range, for registering X, Y, and Z values of deflection of the entire vehicle.
3. *Windload sway effects on free-standing vehicles during preflight checkout periods:* temporary aluminum spike mounted on nose of vehicle recorded (together with an optical collimator target) at low sampling rates from two orthogonally placed 35 mm. cine cameras with 1 meter focal-length catadioptric systems. Third cine camera records anemometer and wind direction meter inside the blockhouse.
4. *Flexing, sagging, or structural twist of booster rocket under load*, as for example, during tanking operation: covered from launch complex area by two orthogonally deployed 35 or 16 mm. cameras equipped with 2 m. or 1 m. catadioptric systems respectively. High stability optical collimators are employed to project an illuminated reticle reference target on the film through the taking lens (to record possible camera motion) alongside the rocket target image. The

latter may be supplemented by a fine grid for X, Y, and Z vernier readout.

5. *Windshear-moment calculations:* in order to evaluate the shear forces to which the soon-operational super boosters will be subjected, a measurement program is based on the launching of rockets, carrying smoke generators, from the tip of Cape Canaveral. Three T-11 aerial mapping cameras were suitably converted for ground use and located some 10–15 km. north, west, and south of the launch point. Photo-coverage is the breaking up of the smoke trail to an altitude of some 25,000 m. Orientation is through the framing of the breakup zone between ribbon-frame camera-type targets mounted on 30 meter high, guyed poles. Sampling rate is 12/minute. Time correlation is through a centrally controlled synchropulse. Reduction (by the Range User) is with a computer routine based on a principle of successive approximations in the determination of the horizontal coordinates, rather than on the establishment of corresponding conjugate image points. (14)

METRIC PHOTO-INTERPRETATION THROUGH "CHRONOGRAMMETRY"

Significant metric information retrieval is obtained from time-resolved high-speed chronographs whose function is one of overall surveillance. Peeping through inch-thick windows made of quartz in heavy steel containers and weathering the cataracts of fire under the blasted launcher structures, perched atop the umbilicals' steel masts with the great mass of intercontinental missiles rising past only inches away, ringing the launch point from every aspect angle and riding behind the distant tracking telescopes, they expend great lengths of film at sampling rates up to 2,000/second and randomly freeze for deferred scrutiny elusive transient events requiring close examination. Through well-controlled time resolution, known focal values, position data obtained from other systems, and with the aid of good fiducials, techniques of measurement have been evolved worthy of more precise a designation than "high-speed photography."

This chronographic event-correlation, when it provides the backbone for metric interpretation of those events which frequently elude the purely metric systems, is best described as "chronogrammetry." Its importance is exemplified by the following figures: of a typical number of 93 chronographs committed for engineering surveillance on a SATURN launch, 28 were used for the derivation of metric data subsequently presented in tabular form.

PHOTOGRAMMETRIC CALIBRATION OF OTHER MEASUREMENT SYSTEMS

The principle of combining the great precision of the phototheodolites with a high redundancy of "well surveyed point-source controls" at infinity, places an instrumentation system based on stellar orientations in a unique position of boasting of a bias factor substantially less than unity. As a consequence, no other system is nearly as qualified to serve as a calibration standard. For trajectory computations of actual missile tests, the ballistic camera position points are routinely used as master correction points for the bias errors of other systems.

More specifically, however, calibration tests for electronic systems are continually being carried out. These are based on two principal modes of (night) operations:

a. A helicopter carrying a fixed light source is successively made to hover at predesignated coordinate points selected from geometrical considerations. Star oriented ballistic camera plates are exposed from favorable sites by synchronous shutter action.
b. An aircraft-borne high-intensity flash source is pulsed during programmed high altitude runs throughout properly timed shutter-open periods of all cameras in the network.

In both cases, the electronic systems which are to be calibrated are tracking the air-borne transponder. Both data outputs are subsequently compared, and electronic corrections are applied in succeeding calibration runs.

ROCKET GEODESY

Refinements of the geodetic position of ETR instrumentation stations (11) and of Bermuda (15) have been possible through the secondary exploitation of photogrammetric flare data obtained from star-oriented plates. The disadvantage of the method lies in that the geodetic effort is of necessity subordinated to the primary launch mission. Pure rocket geodesy is being tested under an Operations Directive specifically designed for Range Geodetic Survey.

SATELLITE GEODESY (16, 17)

The launch of geodetic satellite ANNA in October 1962 (18) caused the deployment of ETR phototheodolite teams over a number of prepared stations in the United States, the Range Stations to Pretoria, and to Bermuda. Teams belonging to other organizations were on a world-wide deployment. A malfunction in the high-intensity flash source brought this effort to a halt. The unexpected recovery of the flashing mechanism in August 1963 reactivated the Range program of a refined adjustment of the stations' coordinates. Accuracies from simultaneous recordings of geodetic satellites are expected in the vicinity of 1 part in 150,000, with possible improvement to 1 part in 500,000, through use of the greater focal-lengths optics that are being introduced. A program for a Range Calibration Satellite is being studied at ETR whose orbital inclination would be specially calculated for both the improvement of Range surveys and for the calibration of the electronic systems (19). Data reduction techniques are being re-examined to serve the significant advances promised by satellite geodesy (20, 21, 22).

ORBITAL DATA

Metric values are obtained from orbiting objects only under circumstances especially favorable to several ends:

a. A *one-station cinetheodolite solution* is applied to update the ephemerides of satellites making high-angle passes over the Station 1 (Cape Canaveral) baseline. Corrections are subsequently employed to calibrate Range Ships' radar systems by using these same orbiting bodies for targets.
b. *Two-station solutions* are committed to position determination (or position refinement) of satellites, and of "space junk," i.e. spent boosters or upper stage rockets in low, or decaying orbits.
c. *Tracking telescopes photo-coverage* is used to determine size and tumbling rate of such objects.

MISCELLANEOUS DATA

a. *Practice airdrops* of instrumentation packages, of space capsules, and other objects, as well as the impacting of objects within optical range due to aborted launches, are covered by the cinetheodolite network with orders to track to the splash point. Instrument azimuths are then locked, and the angles are communicated by all stations to rescue-boat crews who proceed to the fix-point thus obtained.
b. *Dimensions of rocket flames* and of the gigantic ion sheath which forms at altitude are calculated from telescope film supported by other position data.
c. *Percentile distribution of clouds* over a 360° field is measured by a slow pulse "crystal ball" camera to verify cloud interference with radio frequency energy propagation of electronic measuring systems.

GEODETIC SHIP POSITIONING

Recent feasibility tests with regards to the use of star-field oriented phototheodolites for accurate positioning of Range instrumentation ships have shown the desirability for further study (22).

Under the land based test, involving the recording of an airborne flash source against a star field by five control cameras, the geodetic positions of these were held as constants, while the gyrocamera position atop a ship-motion simulator was held as a variable, subject to constraints. The computed gyrocamera position came to within 30 cm. of the previously established field survey values.

Shipborne tests, about to be begun, will use a Nortronics BC Geo on a three-axis mount (Figure 9), an airborne flash source, land-based phototheodolites for positioning that source, Lorac navigation techniques for determining the ship's course, and cinetheodolites for verifying the ship's positions by tracking a mast-mounted high-intensity continuous light.

The ultimate goal is the development of a real-time geodetic system with an accuracy gain of one order of magnitude over the existing ship-positioning devices which were essentially designed for navigational purposes.

IMMEDIATE EVOLUTION

The successive research and development phases of the aerodynamic cruise missiles, the short-range, medium-range, and intercontinental ballistic missiles, and of the early space probes were paralleled by corresponding development stages of the early rudimentary metric cameras into the present Range photo-optical instrumentation apparatus.

Throughout this short decade one trend remained consistent: the requirements placed on the Range for measurement of objects

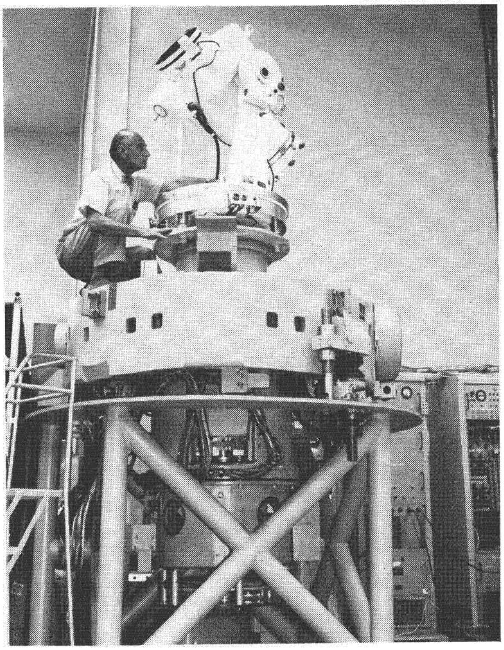

FIG. 9. Nortronics 600 mm. ballistic camera mounted on Norden three-axis gyro-stabilized platform.

more remote, geometries more transient, events more rapid, and at a steadily growing rate of accuracy, have caused the forced development of instrumentation, of reduction techniques, and of production-line data outputs without precedent. And currently, the shift of emphasis from intercontinental ballistic missiles to space vehicles is forcing the following—still evolutionary—shifts in the design concepts of tomorrow's—still photo-film dependent—metric systems.

The generating pressures are fourfold:

a. Increase of launch area from 6,000 hectares to 40,000 ha. demands greater flexibility of instrumentation deployment.
b. Manned flights require greater accuracies to greater ranges.
c. Larger vehicles and exotic fuels demand greater safety zones denied to manned instrumentation, and
d. shorter data delivery times must be had to lessen the analysis time-lag.

The grappling with data commitment problems will, however, be somewhat eased in a number of directions through the following adjuncts:

Cinetheodolites: Sampling rate of 10/sec. (with 30/sec. ultimate), instruments rendered mobile, increased focal-lengths, encoding on film of angular values vs. time for automatic readout in near-real-time, and servo-track capability for danger-zone emplacements.

Fixed (Ribbon Frame) System: Reduction in number of tower stations and mobilizing of their instruments, refinement in targeting, of other means of orientation, and of reduction, including speedup of film reading time.

Attitude System: Adaptation of video image-intensification to the large tracking telescopes for increase of effective aperture and image-contrast, mobilization of all IGORS, and addition of an Airborne-Lightweight Optics Tracking System (ALOTS) of about 5,000 mm. focal-length, providing automatic track through an electro-optical tracking sensor.

Ballistic Camera System: Improvement and extension of the system synchronization to 100–200 microseconds correlation between stations. More rigorous controls applied further to reduce random error. Servo-controlled mounts for long focus photo-multipliers.

Optical Beacons: Self-contained expendable units with sufficient intensity for recording by outlying fixed cameras and by cinetheodolites.

THE SURGE TOWARD REAL-TIME

The gathering of many metric values at many dispersed stations by latent deformation of a crystal structure, the necessity for means to unload the cameras and to transport the image carriers to a laboratory—hours and sometimes days away—to modify the latent information for visual analog retrieval through treatments in unstable liquids (of subsequently undesired wetness), to dry and to transport these records in great lengths, and orderly arrangement to preview, edit, and prepare for careful frame-by-frame examination, so that the analog coordinates may be converted to digitally encoded form, and then, the preparation of a punchcard run for digital computers that have been idle all that time. These complex manipulations between event and measurement thereof are stretching out for days what might be done in minutes, if only signals could be transmitted from the instruments in use straight to the computer.

The pressures of the constant tardiness of photo-data have generated conceptual shifts which place electro-optical and other techniques into a status of early adaptation to Range needs:

1. *Tangential motion discriminator. Purpose:* measurement of windload and tanking stresses as a real-time capability. *Principle:* image of black and white target is focused by 2 m. catadioptric lens on a photocathode. Target motion image on aperture at rear of image dissector tube causes feedback circuit to hold the electron image at the aperture. Feedback signal is an analog of the target displacement. Presentation is by meter, oscilloscope or paper tape. Vibration proof mount is concrete truncated pyramid. *Status:* on hand. *Name:* Optron.
2. *Optical Direction and Ranging (OPDAR) Purpose:* to provide one order of magnitude better accuracy than ribbon-frame camera system and cinetheodolite-system to 16,000 meters slant-range, to provide simultaneous computer input for real-time exploitation together with magnetic tape record for postflight near-real-time analysis. *Principle:* ranging data by continuous-wave (CW) laser 10 mw. modulated carrier, retro-reflector on rocket. Infrared servo tracker for coarse track, error signal compensation for fine track, loss-of-count ambiguities (clouds, etc.) resolved by method of quick approximation. *Angular data:* shaft digital encoders. *Deployment:* 3 one-station solutions from location 300 m. (unmanned servo-tracking) 2,300 m. and 23,000 m. (manned) for proportional overlapping coverage. *Status:* prototype under assembly. (Other approaches are based on a one-station solution for the same interval.)
3. *Liftoff Measurement System. Purpose:* The penetration of dense smoke and cascades of frost immediately after liftoff, when the physical tracking points, optical beacons, or retro-reflectors are obscured. (Premise: an optically opaque zone could be penetrated by radar. However, to achieve one second of arc accuracy, a pulse radar operating at 250 KMC would require an antenna dish of 200 meters in diameter. CW radar could not resolve its ambiguities.) *Principle:* radioactive source carried by rocket, scintillation counters at surveyed ground positions; scintillation count decreases with range of source by known amount. Position calculations by trilateration. The principle, (in reverse) is old with anti-aircraft miss-distance indicators, where target drone carries scintillation counter, the projectile carries the source. A later approach, based on an aspect of the Mössbauer effect, employs phase count of coherent Gamma radiation. *Status:* under study.
4. *Attitude laser system. Principle:* Polarized laser beam receives further angular modulation by polarizing retro-reflector to provide "V" angle data at ground-station receivers. Readouts from several stations are computer reduced in near-real time. *Status:* under study. (23)

Other approaches, under consideration by those whose task it is to visualize the missions of ETR a decade hence, have been described (24). Whether each one will be translated into usable hardware is still the subject of debate. One thing, however, appears quite clear: *electronification*—as it has to many other fields—must come. Not only to such ancillaries as timing pulse generators or digital encoders (25), but to the photosensor itself. Concepts one hears and reads about contain such sounds as this: . . . "gated circuit video system" . . . "image centroid detectors" . . . "error signals for servo-track correction" . . . "$X-Y$ calibrated grid photosensors" . . . "thermoplastic tape recording" . . . "real-time playback-and-erasure" . . . "solid state mosaics" . . . "digitized video" . . . "multi-million fiber matrix" . . . "real-time ballistic camera," and so on in that same vein. And if the latter appears most infeasible of all, let us remember the intriguing stellar-navigational devices and their mutational potential as remoted computer input modules of one of the real-time metric optical systems of the near future.

Also advancing on a convergent course with photogrammetry are the astronertial systems, whose astonishing measurement potential from dynamic platforms will make itself heard in due time.

CONCLUSIONS

Charged with the measurement of objects more remote, geometries more transient, events even more rapid, and at accuracies more stringent, photogrammetry as applied to rocketry must face a quantum jump in the evolution of its tools. The scope of the oncoming change cannot leave much unaffected: from mensuration methods and data sampling rates, through information storage and transmission, to a time-compressed data reduction step. These changes, added to similar trends elsewhere in photogrammetry, may well affect the definition of our entire discipline.

A new perspective is unfolded by a staggering wealth of unprecedented advances in the realm of mensurative instrumentation. (26) Their predictable impact on photogrammetry leads to the proposition that, preferably sooner than later, we break what is becoming an increasingly restrictive allegiance to one single sensor, and officially concern ourselves with *all* measurements achieved by means of photon action, with a major emphasis placed on electro-optical methods.

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