X-641-69-221
PREPRINT

NASA TM X-63578

ARTIFICIAL AURORA EXPERIMENT: POSITION MEASUREMENTS OF AURORAL RAYS AND COMPARISON WITH PREDICTIONS

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JUNE 1969

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-641-69-221

ARTIFICIAL AURORA EXPERIMENT: POSITION MEASUREMENTS OF AURORAL RAYS AND COMPARISON WITH PREDICTIONS

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ABSTRACT

An electron accelerator was launched aboard an Aerobee 350 rocket on 26 January 1969 and produced four auroral rays which were detected with image-orthicon television systems at two ground stations. The rays were neither bright enough nor of sufficient duration either to be detected visually or to be photographed directly. The purpose of the experiment was to test the feasibility of generating artificial auroras by injecting electrons into the upper atmosphere from a rocket-borne accelerator. This report describes the optical observations, the techniques employed to determine the position of the observed rays, the method used to predict the location of the rays from knowledge of the rocket orbit and the local geomagnetic field, and a comparison of the predicted and observed positions. It is found that the lower ends of the observed rays were located at altitudes of approximately 104-106 km; the upper ends were less well defined, ranging from around 120 to 130 km. The predicted positions were separated from the observed ones by less than 0.1° of arc, or about 400 meters.

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ARTIFICIAL AURORA EXPERIMENT: POSITION MEASUREMENTS OF AURORAL RAYS AND COMPARISON WITH PREDICTIONS

I. INTRODUCTION

On January 26, 1969, at 0945 UT (4:45 a.m. EST), an electron accelerator was launched aboard an Aerobee 350 rocket (17.03 GE) from Wallops Island, Va. This was a first feasibility test of the concept of using a rocket-borne accelerator to create an artificial aurora by sending an electron beam down the local field line into the atmosphere. Ultimately this technique might be developed into an experimental tool to map conjugate points, determine the length and configuration of field lines in the magnetosphere, and measure electric fields parallel to and perpendicular to the magnetic field. This experiment was under the overall scientific direction of W. N. Hess of the NASA Manned Spacecraft Center, who has written a preliminary report.[1] Numerous institutions cooperated in making optical, VLF, and radar observations of the effects of the accelerated electron beam.

The experiment succeeded in producing several artificial auroral rays in the upper atmosphere. Four of these rays were observed with image-orthicon television camera systems from two stations having adequate separation to enable the spatial coordinates of the rays to be determined by triangulation. This report describes the techniques used to measure the position of the observed rays against the star background, the results of the triangulation, the method used to predict the positions of the rays, and a comparison between the predicted and observed positions.

The electron accelerator, built by the Ion Physics Corporation, was programmed to produce a sequence of pulses of different voltages and currents. Approximately every thirty seconds a pulse of full power (nominally 500 ma at 10 kev) having a one-second duration was emitted. The first four of these "signature pulses" were detected and are analyzed herein.

Look-angle tables for the various observing stations, covering a wide variety of possible rocket trajectories, were prepared in advance by E.G. Stassinopoulos (GSFC). The nominal flight plan called for a trajectory with a peak altitude of 295 km, and an impact point 98 km from the launch pad at an azimuth of 162°. Due to a deviation in the performance of one of the rocket engines, however, the actual trajectory was well outside the limits which had been expected, and the rocket achieved a peak altitude of 269 km with an impact point only 50.4 km from the launch pad at an azimuth of 97°. Due to the unexpected orbit, no accurate look-angle tables were available to any of the observing stations. The first four signature pulses, however, were detected despite this handicap.

Figure 1 is a map of the lower Delmarva peninsula, showing the location of the launch pad and the observing sites at Franklin City, Arbuckle Neck, Igor and Eastville. Also shown is the rocket trajectory as projected onto the earth's surface and the projection of the earth's magnetic field lines (which have an inclination of approximately 69° in this region) from the rocket to the 100-km altitude for the first four signature pulses. The observed rays were located approximately midway between Salisbury and Ocean City, Maryland, at altitudes between 104 and 130 km, although the nominal rocket trajectory would have placed them much further south. Table 1 gives the geodetic latitude and longitude of the launch pad and the various observing stations.

Table 1
Positions of Launch Pad and Observing Stations

Site	Geodetic Latitude	West Longitude
Wallops Island, Launch Pad No. 1	37.8350° 37° 50'06"	75.4869° 75° 29'13"
Franklin City	38.0067° 38° 00'24"	75.3825° 75° 22'57"
Wallops Island, North Camera Site	37.8672° 37° 52'02"	75.4508° 75° 27'03"
Arbuckle Neck	37.8565° 37° 51'23"	75.5113° 75° 30'41"
Igor	37.6781° 37° 40'41"	75.6294° 75° 37'46"
Eastville	37.3462° 37° 20'46"	75.9032° 75° 54'11"

A computer program, described in Section V, was used to compute the apparent positions of the rays against the background stars as they would be seen from each observer's site. Figure 2 shows the predicted positions of the rays from the eight signature pulses for altitudes of 100-120 km for the Franklin City, Arbuckle Neck and Igor locations, plotted on a star chart.

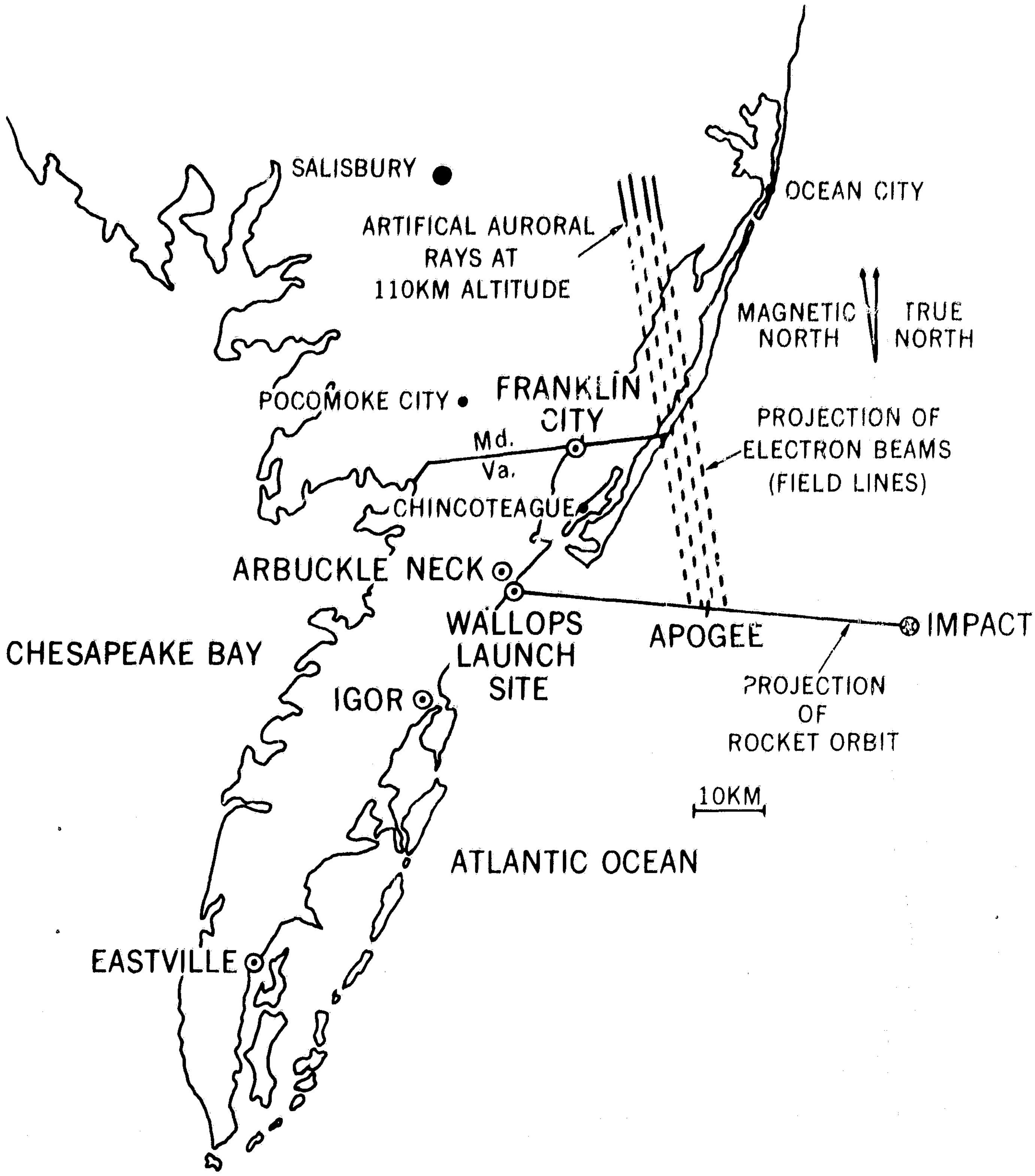

Figure 1. Map of Lower Delmarva Peninsula Showing Locations of Launch Site, Four Observing Stations, and the Projection of the Rocket Trajectory and Earth's Magnetic Field Lines for the First Four Signature Pulses

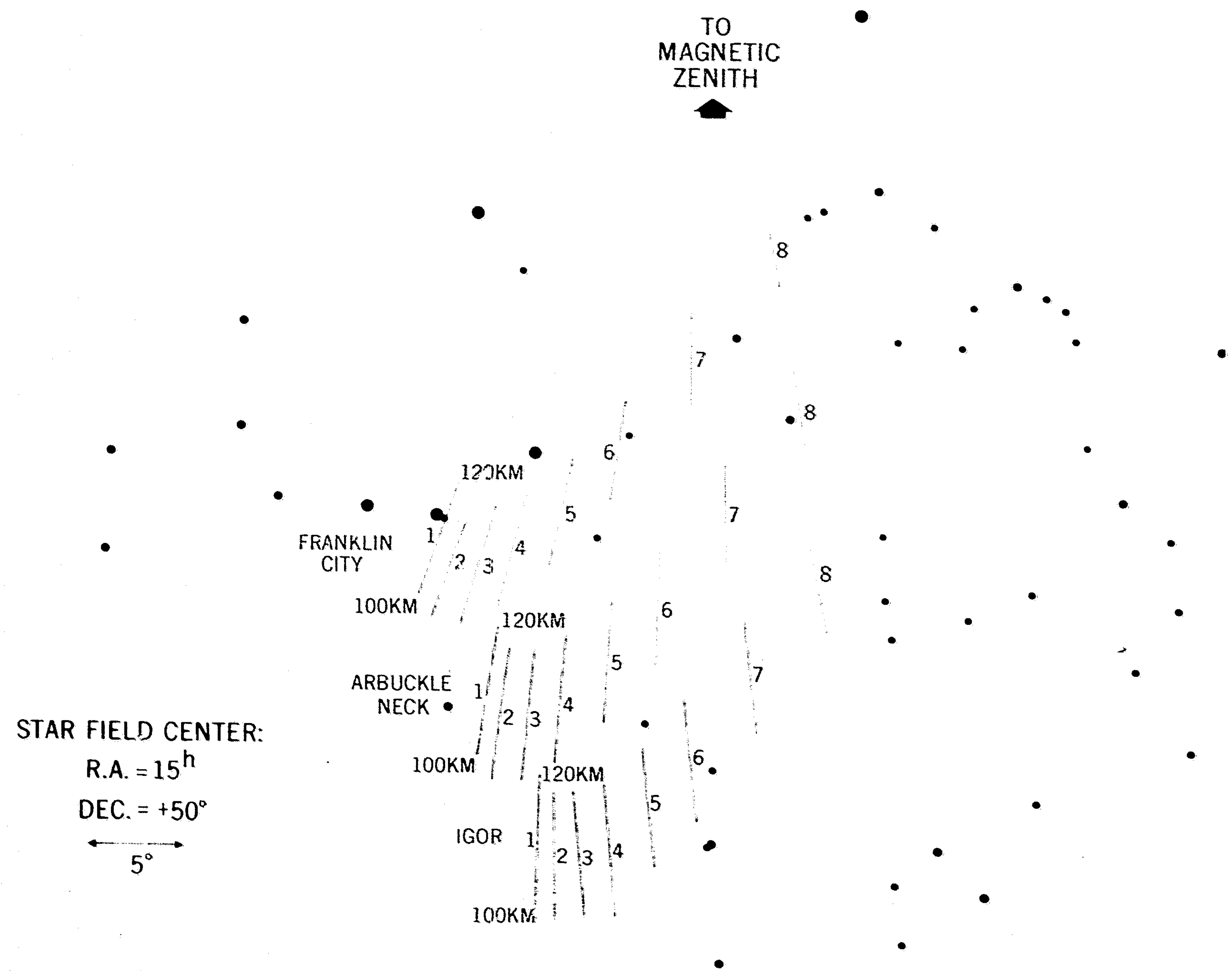

Figure 2. Predicted Positions of Auroral Rays from Signature Pulses 1–8 as Seen from Franklin City, Arbuckle Neck and Igor, Plotted on a Star Chart. Note the Big Dipper stars at left.

II. OPTICAL OBSERVATIONS WITH IMAGE-ORTHICON TELEVISION SYSTEMS

Image-orthicon television systems were operated at Franklin City, Igor, and Eastville by the University of Alaska group; at Greenbelt, Md., by E. N. Wescott (GSFC); at Accokeek, Md., by Grady Hicks of the Naval Research Laboratory; and at Arbuckle Neck by J. T. Williams of the Smithsonian Astrophysical Observatory. Rays from the first four signature pulses were observed by the University of Alaska systems at both Franklin City and Igor. No other observations of any of the rays have been recorded. In most cases this was due to inadequate look-angle information caused by the unexpected rocket trajectory, resulting in improperly-aimed cameras.

Figures 3 and 4 show the auroral rays observed at Igor and Franklin City. Each figure is a montage of 4 photographs of the television monitoring screens, placed together so that the star backgrounds overlap each other. Rays 1 through 4 are indicated by the arrows. The Igor TV camera viewed the sky through an Oude Delfte f0.75/105 mm lens which resulted in a field of view 12x16°. The wide-field, 16x20°, TV camera at Franklin City was fitted with a Super-Farrand f0.87/76 mm lens. The Franklin City system was not as sensitive as the Igor system, and therefore the rays are not as easily seen. In fact, ray No. 3 is almost unobservable from Franklin City.

III. MEASURING THE RIGHT ASCENSION AND DECLINATION OF THE OBSERVED AURORAL RAYS

The first step in measuring the positions of the rays observed by the image-orthicon systems at Igor and Franklin City was to identify the background stars. Bečvář's Atlas of the Heavens, Atlas Coeli 1950.0,[2] Norton's Star Atlas and Reference Handbook,[3] the Lick Observatory Sky Atlas, the Palomar Observatory Sky Survey, and the Smithsonian Astrophysical Observatory Star Catalog[4] were the principal sources used to aid in the identification of over 200 stars shown in the photographs. This includes a large number of the fainter stars, in some cases down to $9^m_.5$, near the rays themselves. The right ascension (α), declination (δ) and visual magnitude (m_V) for each star was stored in a computer star catalog. Because equatorial coordinates (α, δ) near the celestial pole are not rectangular, a program was written to convert the star coordinates to a set of x-y coordinates on a rectangular grid. A "plate center" in the vicinity of the observed rays was chosen. The α - δ coordinates of each star were first precessed to their 1969.0 values. Appropriate formulas applicable to spherical triangles were used to compute the distance and azimuth of each star relative to the plate center. This distance, in degrees of arc, was then converted to a linear distance in inches, using an appropriate scale factor. This linear distance was combined with the azimuth to compute x and y.

The scale factor was chosen so as to obtain a star chart which would most accurately match the scale of the 8 x 10 glossy photographs of the image-orthicon television screens. This was rather difficult, as numerous distortions in the television system, camera, enlarger, etc., gave rise to a wide variation (as much as 25 percent) in the scale over various portions of a given photograph. The scales found to be most satisfactory for overlay work were 1° = 0.635 inch for the Igor photographs and 1° = 0.465 inch for the Franklin City photographs.

The rectangular coordinates obtained from the computer program were plotted on transparent overlays which could then be placed over the photographic prints for tracing the observed rays. Due to the local variations in the scale on the photographs, the overlays had to be moved around constantly so as to match up stars in the immediate vicinity of the rays being traced. This very tedious and painstaking step was carried out by two of us independently; the results were compared, discussed, and modified until a single final set of ray positions was obtained. These rays, plotted against a background of the brighter stars in the star catalog, appear in Figure 5. Ray 3 was barely visible on the Franklin City photograph and is therefore shown as a dashed line. In a few cases a ray seemed to extend up to or beyond the plate edge. Such cases have been marked by an (*).

Next the x-y coordinates of the end points for each ray were read from these plots. Another program converted these x-y values to right ascension and declination for use in the triangulation calculations.

IV. TRIANGULATION TO OBTAIN SPATIAL COORDINATES OF THE AURORAL RAYS

The procedures described so far for determining the positions of the auroral rays have been in only two dimensions. In order to obtain the spatial coordinates, or three-dimensional position, of the rays, it is necessary to employ triangulation techniques.

A computer method for determining the position in space of a luminous vapor trail has been described by F. J. Smith.[5] M. Miller, working with E. Wescott (GSFC), has programmed this method for the IBM-360 computer at Goddard and kindly provided us with her program for use in triangulating the data from Igor and Franklin City.

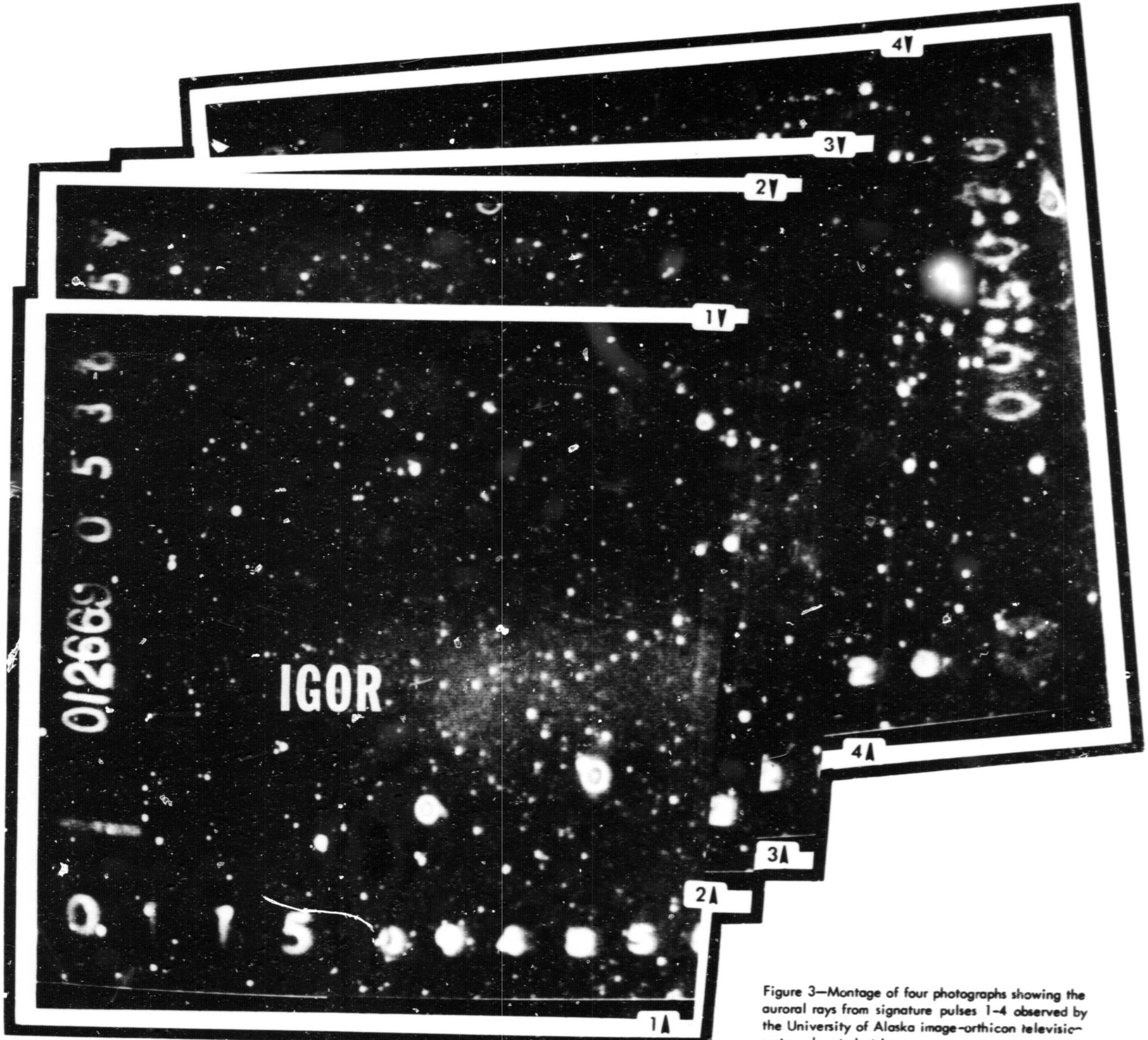

Figure 3—Montage of four photographs showing the auroral rays from signature pulses 1–4 observed by the University of Alaska image-orthicon televisio- systems located at Igor.

Figure 4—Auroral rays as observed from Franklin City.

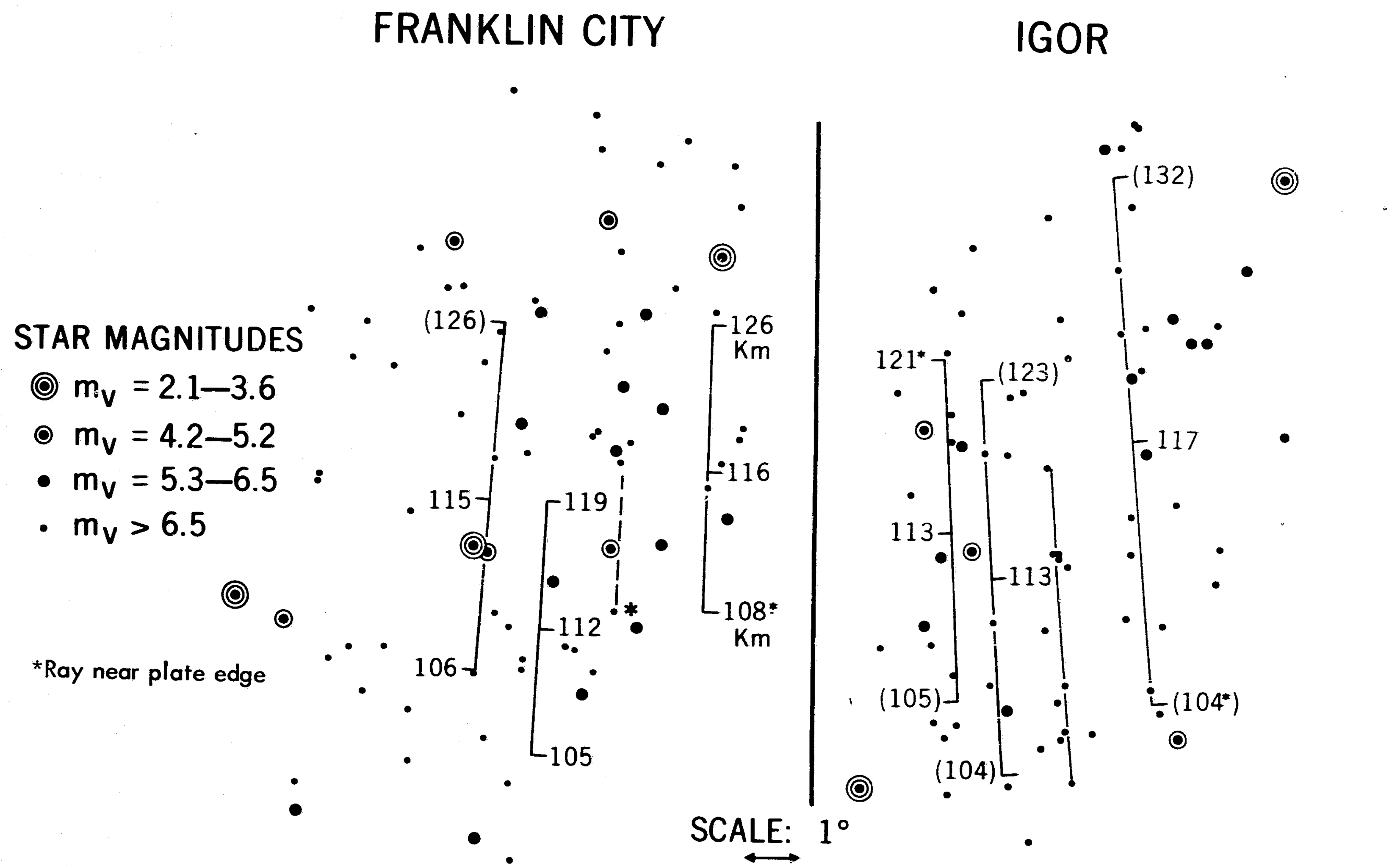

Figure 5. Positions of Observed Rays, and Altitudes Obtained from Triangulation Between Igor and Franklin City Photographs

Figure 6 is a schematic representation of the triangulation technique used. The basic data is two photographs of the same auroral ray MN from each of two observing sites, A and B. Because of the separation of A and B, this ray appears in projection against different star backgrounds. The problem is to find a point on the first projected ray which "corresponds" to a given point on the second projected ray so that the apparent coordinates from the two different ground observing sites actually refer to the same point on the true ray.

The two projected rays were divided into ten equal segments and the α, δ coordinates of the eleven points along each ray were determined. The radius vector AG'G joins station A with a point G on its projected ray. Minimum perpendiculars, $\vec{P}_1$, $\vec{P}_2$, $\vec{P}_3$, ..., were computed between AG'G and the radius vectors, BD'D, BE'E, BF'F, ..., joining station B and successive points, D, E, F, ..., on its projected ray. The point G on the first ray does not necessarily correspond to any of the successive points, D, E, F, ..., along the second ray. In order to find a corresponding point, successive minimum perpendiculars are examined for a change in direction, i.e., sign. If there is no change in sign, then all the points D', E', ..., on the true ray lie on the same side of point G'. There is then no point on the visible portion which corresponds to point G on the first photograph. It is then necessary to extrapolate beyond the visible portion to obtain a point of correspondence.

If, on the other hand, there is a change in sign between two successive minimum perpendicular distances, as between $\vec{P}_2$ and $\vec{P}_3$ in Figure 6, there does exist a point "g" on the visible portion of the ray in the second photograph which corresponds to point G on the first photograph; this point is found by interpolation.

Having found a pair of corresponding points on two photographs of the ray, the triangulation can be performed. The formulas used to determine the spatial coordinates of this point are given in the article by Smith. The calculations are performed in a cartesian coordinate system with its origin at the mid-point between the two observing sites. It is thus necessary to be able to convert latitude, longitude, and altitude into x, y, and z, and vice versa, for an oblate earth. These transformations are contained in the program.

Using the procedures described above, each point along a given ray as observed from Igor was triangulated with the same ray observed from Franklin City. Then the procedure was reversed, and the Franklin City observations were triangulated against the Igor data. In each case the spatial coordinates were found either by interpolation, if the corresponding point was on the visible portion of the second ray, or by extrapolation, if the corresponding point was outside the visible portion. This triangulation was performed for the auroral rays produced by signature pulses 1, 2, and 4. Ray 3 was not triangulated since its celestial coordinates could not be accurately determined from the Franklin City photograph.

The results of the triangulation are given in Table 2 for the midpoint and end points of each ray. If the spatial coordinates were obtained by extrapolation from the second photograph, the coordinates are enclosed by parentheses. An asterisk (*) indicates that the end point of the observed ray was near the plate edge. The altitudes are also shown beside the observed rays in Figure 5.

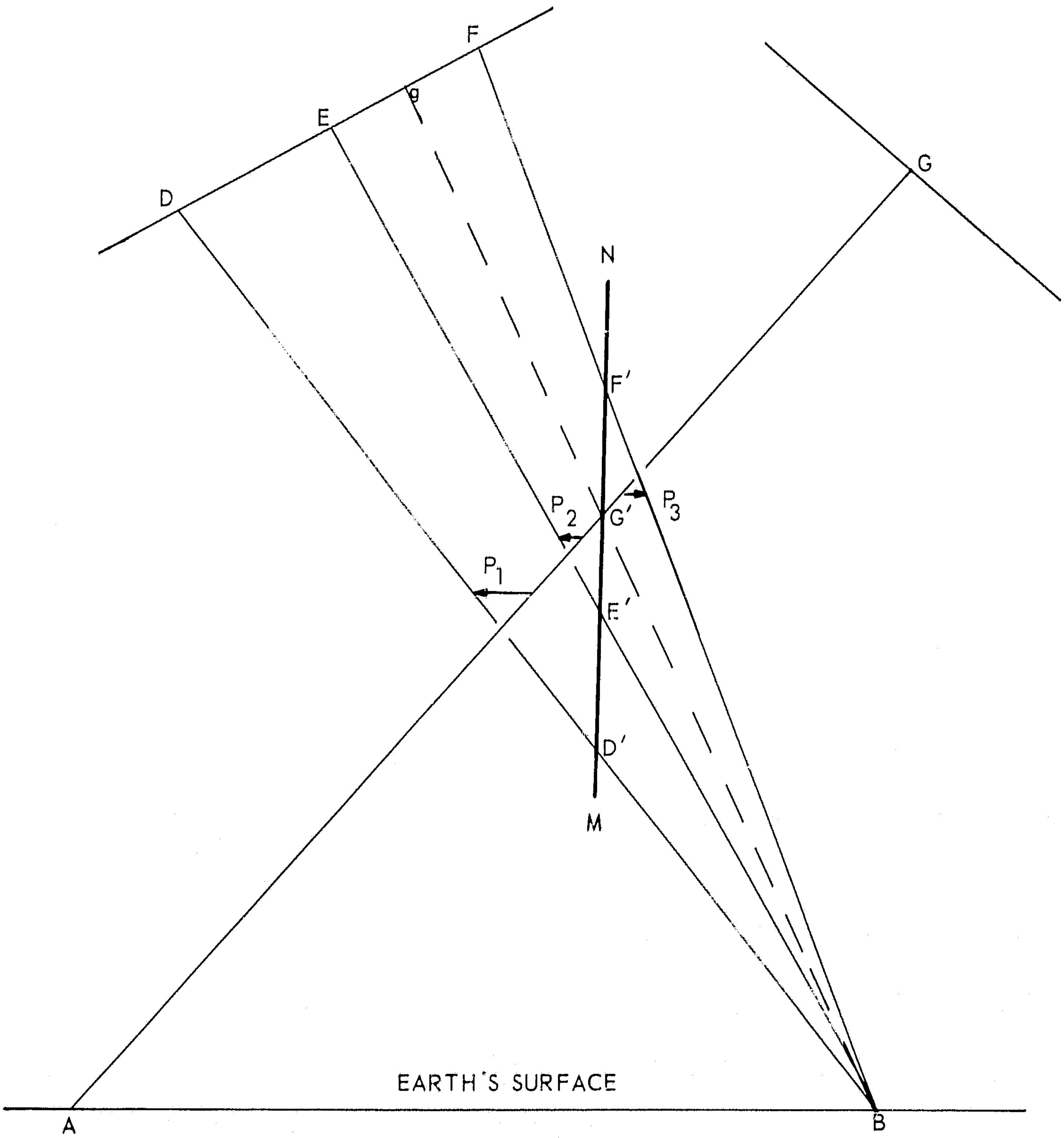

Figure 6. Schematic of Triangulation Technique for Determining Spatial-Coordinates of Auroral Rays

Table 2
Triangulation Results

2a. Igor Triangulated with Franklin City					
	Right Ascension	Declination (deg)	Geodetic Latitude	West Longitude	Altitude (km)
<u>Igor Ray 1</u>					
Upper end*	$14^h 54.2^m$	64.85	38.282*	75.329*	121.2*
Midpoint	$15^h 09.4^m$	67.40	38.312	75.334	112.8
Lower end	$15^h 28.1^m$	69.83	(38.339)	(75.338)	(105.0)
<u>Igor Ray 2</u>					
Upper end	$15^h 01.2^m$	64.82	(38.297)	(75.306)	(123.0)
Midpoint	$15^h 20.4^m$	67.69	38.332	75.311	113.1
Lower end	$15^h 44.7^m$	70.39	(38.364)	(75.316)	(103.9)
<u>Igor Ray 4</u>					
Upper end	$15^h 03.8^m$	60.64	(38.244)*	(75.235)*	(132.0)*
Midpoint	$15^h 27.4^m$	64.35	38.289	75.246	117.0
Lower end*	$15^h 58.0^m$	67.74	(38.328)	(75.256)	(103.7)

2b. Franklin City Triangulated with Igor					
	Right Ascension	Declination (deg)	Geodetic Latitude	West Longitude	Altitude (km)
<u>F.C. Ray 1</u>					
Upper end	$13^h 23.4^m$	51.15	(38.267)	(75.327)	(125.7)
Midpoint	$13^h 23.9^m$	54.19	38.303	75.333	115.2
Lower end	$13^h 24.4^m$	57.22	38.335	75.334	106.2
<u>F.C. Ray 2</u>					
Upper end	$13^h 31.0^m$	54.13	38.312	75.308	118.9
Midpoint	$13^h 32.1^m$	56.34	38.336	75.311	111.8
Lower end	$13^h 33.4^m$	58.55	38.358	75.315	105.4
<u>F.C. Ray 4</u>					
Upper end	$13^h 46.7^m$	50.67	38.264	75.239	126.1
Midpoint	$13^h 49.3^m$	53.13	38.292	75.247	116.3
Lower end*	$13^h 52.2^m$	55.58	38.316*	75.253*	107.7*

Note: ( ) means extrapolated value; * means ray near plate edge.

V. COMPARISON WITH PREDICTIONS

From a knowledge of the rocket orbit, the direction of the local magnetic field, and the geographic locations of the observing sites, it is possible to predict the look angles (elevation and azimuth) at which the auroral-ray-intersects at specific altitudes should be seen from each station. With the additional knowledge of the local sidereal time at the time of the launch, one can compute the right ascension and declination of the rays as viewed against the background stars. These predictions can then be compared with the observed ray positions. The method we used is as follows.

The geodetic latitude, longitude, and altitude of the Aerobee 350 rocket at times corresponding to the eight signature pulses were read from the computer printouts of the smoothed rocket orbit as obtained from the radar tracking installations at Wallops Island. The orbital positions obtained from two independent radar installations were compared with each other and found to agree within about 10 meters. An average of the two was taken as the basis for subsequent calculations. These rocket positions are given in Table 3.

Table 3
Radar-Determined Positions of the Aerobee 350
during Times of Signature Pulses

Signature Pulse #	UT	Time after Liftoff	Geodetic Latitude	West Longitude	Altitude (km)
1	0948:55.3	235.3	37.8283	75.2412	261.538
2	0949:22.5	262.5	37.8263	75.2134	268.364
3	0949:52.6	292.6	37.8241	75.1828	268.123
4	0950:19.9	319.9	37.8217	75.1550	260.828
5	0950:49.9	349.9	37.8190	75.1234	245.023
6	0951:17.3	377.3	37.8160	75.0941	223.453
7	0951:47.3	407.3	37.8127	75.0605	191.960
8	0952:14.7	434.7	37.8094	75.0287	155.942

Since the electron beam traveled less than 200 km before reaching the 100-km level of the atmosphere, the curvature of the field line was small. To first order, the position of the 100-km intersect can therefore be obtained quite accurately by assuming straight field lines inclined at an angle characteristic of the midpoint between the rocket and the appropriate intersect.

A number of recent field models, including the latest Cain model based on recent POGO data and the International Geomagnetic Reference Field, as adopted at the 1968 Symposium on the Earth's Magnetic Field, were used to calculate the direction of the earth's field in the vicinity of the rocket. All were reduced to the 1969.0 epoch. The direction of the field is defined by the inclination, or dip angle, and the magnetic declination angle. These angles vary by less than half a degree over the region of interest (latitude 37.8—38.4°, longitude 75.0°—75.4°, altitude 100-300 km); different recent models vary by as much as a degree between themselves. As a first approximation, an "average" value of 69.0° inclination, -8.5° declination was chosen.

The x, y, and z coordinates of the rocket vehicle at the times of the eight signature pulses were calculated from the orbital data. The cartesian coordinate system used was centered at 38.0° geodetic latitude, 75.5° west longitude. The x-y coordinates of the field-line-intersects at 100, 110, 120, and 130 km were then computed, assuming straight field lines. Next the cartesian coordinates of each of the observing sites were determined, using the longitude-latitude data from Table 1. The look angles (elevation and azimuth) were then calculated for each observing site from simple geometric formulas, with the inclusion of correction terms for the earth's curvature.

Using data from the 1969 American Ephemeris and Nautical Almanac, a formula was developed to give the local sidereal time for each station as a function of longitude and time:

$$\text{L.S.T.} = 13^h\,7^m 2.338^s + 1.003\,T - \lambda$$

where T is the time after rocket liftoff (T = 0 at 0945 UT January 26, 1969) and λ is the longitude west of the 75th meridian. Thus at the moment of launch, stars with right ascension $13^h 7^m$ were on the local celestial meridian for an observer at 75° west longitude.

A FORTRAN subroutine was developed to convert elevation and azimuth into right ascension and declination, given the local sidereal time and the geodetic latitude of the observing station. Using this subroutine, the predicted right ascension and declination of the auroral rays were calculated for each observing site.

In order to compare these predictions with the positions of the observed rays, the right ascension and declination of points along the predicted rays were converted into rectangular x-y coordinates, using the same routine used to convert star positions, as described in Section III. The same plate centers and scales were used as had been used earlier to prepare the star charts for the Igor and Franklin City regions, respectively. These predicted ray positions were then plotted on the star charts along with the observed positions.

When plotted together, the predicted rays were separated from the observed rays by less than 0.5° on the sky for each of the Igor and Franklin City regions. The field-line orientation was then varied slightly to see if a better fit could be obtained. It was found that a change of 0.5° in both inclination and declination improved the fit considerably at both sites. The final angles used were 69.5° inclination, -8.0° declination. These values are well within the variances predicted by the various field models for this region of space.

The predicted ray positions at 100, 110, 120, and 130 km altitudes are shown together with the positions as actually observed from the two sites in Figure 7. In each case the predicted rays are separated from the observed rays by less than 0.1° of arc, or about 400 meters. The orientation of the observed rays is almost exactly the same as the predicted rays.

The geodetic latitudes and longitudes of the predicted-ray-intersects, based on the final field-line orientation angles, are given in Table 4.

Table 4
Coordinates of Field-line Intersects at 100 and 130 km

Signature Pulse #	100 km		130 km	
	Latitude	Longitude	Latitude	Longitude
1	38.361	75.341	38.261	75.324
2	38.382	75.317	38.282	75.300
3	38.379	75.287	38.279	75.270
4	38.352	75.255	38.253	75.239
5	38.298	75.215	38.198	75.199
6	38.224	75.174	38.125	75.158
7	38.117	75.122	38.019	75.106
8	37.996	75.070	37.898	75.054

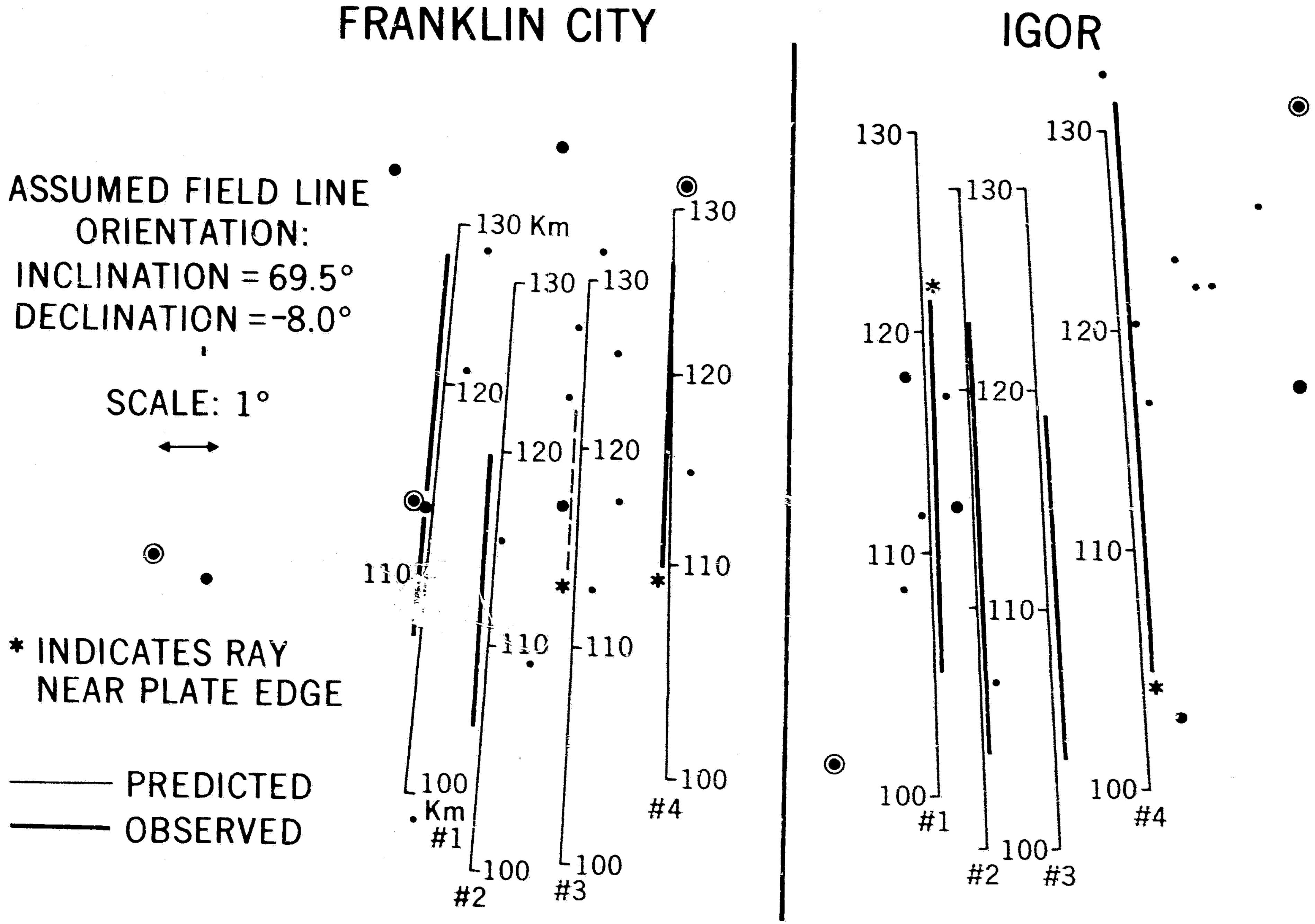

Figure 7. Positions of Observed vs Predicted Rays for Igor and Franklin City

VI. ANALYSIS OF OTHER PHOTOGRAPHIC DATA

Photographs of the sky during times of signature pulses were taken by the Super Schmidt meteor cameras operated by the Smithsonian Astrophysical Observatory group at Arbuckle Neck and Eastville, and by J. S. Maksimik at the North Camera Site, Wallops Island. These records were searched for the presence or absence of visible artificial auroral rays.

Analysis of the SAO photography was hampered by the poor positioning of the cameras due to inadequate look-angle information caused by the bad trajectory. Three exposures, averaging approximately 39 seconds, were taken from each site; the camera shutters were open during signature pulses 2, 5 and 8, respectively. The star fields covered by each photograph were compared with the predicted positions of the rays for each site. It was established that rays 2 and 8 were out of the field of view of the first and third Eastville photograph, but that rays 2, 5, and 8 from Arbuckle Neck and ray 5 from Eastville were partially within the field of view. These photographs were examined by SAO personnel and by us, and there were no observable rays in the vicinity of the predicted positions.

Since ray 2 had been observed by the image-orthicon systems at two sites, we concentrated special attention on the first photograph from Arbuckle Neck. The predictions indicated that about 80% of the ray should have been within the field of view. An x-y chart was made of the stars in the vicinity of ray 2 as would be observed from Arbuckle Neck, and the position of the predicted ray carefully drawn in. The film was analyzed by identifying the stars near the position of the predicted rays and by scanning under 50X, 10X, and 4X magnification. No indication of a ray, or portion thereof, was visible. Maksimik's plate was examined in a similar manner, but also without success in detecting the rays.

VII. SUMMARY AND CONCLUSIONS

Two methods have been used to determine the spatial coordinates of the artificial auroral rays. The first is a direct triangulation based on measurements of the apparent right ascension and declination of points along a ray as observed from two locations. The second is by comparison of the positions observed against the background stars with predictions based on knowledge of the rocket orbit and the local geomagnetic field.

A comparison of Figures 5 and 7 indicates that the results of the two methods compare very well with each other. The lower end of the visible rays are located at an altitude of approximately 104 - 106 km on those rays for which this end is not cut off by the edge of the plate. The upper end is less well defined, but seems to be around 120 to 130 km. This is in accord with previous calculations of auroral ray brightness, which show a much sharper cutoff at the lower end, due to the large gradients in atmospheric density.

The fact that the rays were not detected by photographic techniques, even with high-sensitivity film, indicates that accelerator pulses of greater intensity and/or longer duration are needed for future programs if the auroral rays are to be recorded directly on photographic film. In any case, it would be essential to devise means whereby the shutter is open only for the duration of the strong pulses to cut down on background brightness and thus improve the signal-to-noise ratio.

REFERENCES

1. Hess, Wilmot N., "Generation of an Artificial Aurora," in press, Science, 1969.

2. Bečvář, Antonín., Atlas of the Heavens, Atlas Coeli 1950.0, Sky Publishing Corp., Cambridge, Mass., 1962.

3. Norton, Arthur P., A Star Atlas and Reference Handbook, Sky Publishing Corp., Cambridge, Mass., 1938.

4. Smithsonian Astrophysical Observatory Star Catalog, Smithsonian Institution, Washington, D. C., 1966.

5. Smith, F. J., "The Measurement of High Altitude Wind Velocities from Vapour Releases-II," Planet. Space Sci., 11, 1311-1317, 1963.