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C-BAND STATION COORDINATE DETERMINATION FOR THE GEOS-C ALTIMETER CALIBRATION AREA

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16. Abstract

Dynamical orbital techniques were employed to estimate the center-of-mass station coordinates of six C-band radars located in the designated primary GEOS-C radar altimeter calibration area. This work was performed in support of the planned GEOS-C mission (December, 1974 launch). The sites included Bermuda, Grand Turk, Antigua, Wallops Island (Virginia), and Merritt Island (Florida). Two sites were estimated independently at Wallops Island yielding better than 40 cm relative height recovery, with better than 10 cm and 1 m (relative) recovery for ϕ and λ respectively. Error analysis and comparisons with other investigators indicate that better than 2 m (1 σ) relative recovery has been achieved at all sites. The data used were exclusively that from the estimated sites and included 18 orbital arcs which were less than two orbital revolutions in length, having successive tracks over the area. The techniques employed here, given their independence of global tracking support, can be effectively employed to improve various geodetic datums by providing very long and accurate baselines. C-band data taken on GEOS-C should be employed to improve such geodetic datums as the European-1950 using similar techniques.

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SUMMARY

Dynamical orbital techniques were employed to estimate the center-of-mass station coordinates of six C-Band radars located in the designated primary GEOS-C radar altimeter calibration area. This work was performed in support of the planned GEOS-C mission (December, 1974 launch). The sites included Bermuda, Grand Turk, Antigua, Wallops Island (Virginia), and Merritt Island (Florida). Two sites were estimated independently at Wallops Island yielding better than 40 cm relative height recovery, with better than 10 cm and 1m (relative) recovery for ϕ and λ respectively.

The tracking data used in this analysis were taken during 1969 when the radars tracked the GEOS-II transponder. The data used were exclusively that from the estimated sites and included 18 orbital arcs which were less than two orbital revolutions in length, having successive tracks over the area. In all, over 120 passes of data were used. Range biases were estimated. Error analysis and comparisons with other investigators indicate that better than 2m ($1\ \sigma$) relative recovery has been achieved at all sites.

The techniques employed here, given their independence of global tracking support, can be effectively employed to improve various geodetic datums by providing very long and accurate baselines. C-Band data taken on GEOS-C should be employed to improve such geodetic datums as the European-1950 using similar techniques.

INTRODUCTION

The advent of artificial satellites permitted the science of geodesy to make measurements directly on a global scale. By studying satellite tracking data our knowledge of the Earth's geopotential has been increased enormously. In ever increasing numbers more and more precise tracking instruments are being deployed throughout the world in support of various planned satellite missions. Seemingly, the future continues to hold great promise for the science of satellite geodesy and geodynamics.

The geodetic satellite missions planned for the remainder of this decade will have the anticipated impact of greatly improving our knowledge of the Earth's size and geopotential while making valuable contributions to the fields of oceanography and geophysics. The most immediate of these geodetic satellite missions is the Geodynamics Experimental Ocean Satellite: C (GEOS-C) with a planned December 1974 launch. The GEOS-C satellite will be extensively tracked by various metric systems including C-Band and S-Band radars, lasers and various doppler instruments. An on-board radar altimeter will provide a means for measuring geoidal undulations represented by the sea surface's conformance to an equipotential surface. A global geoid of better than 1°x1° resolution seems almost inevitable with this wealth of expected GEOS-C altimetry data. The SKYLAB altimeter data have already produced some important results.

An important phase of the GEOS-C mission involves calibration of the altimeter system. This end will be partially achieved by studying the altimeter data compared to a portion of the better known geoid. The western North Atlantic area has been selected for this purpose. A vast array of tracking instrumentation will be deployed at the tracking sites surrounding this calibration area for GEOS-C. Nevertheless in order to achieve satisfactory orbit determination over the calibration area, relative station positioning at the <2m level has become critical. Orbital error resulting from station positioning error even at this level will make the altimeter calibration difficult. This report presents results which we believe satisfies the accuracy requirements for station positioning around the GEOS-C calibration area. Figure 1 presents a map indicating the tracking sites of concern in this study and their location with respect to the calibration area.

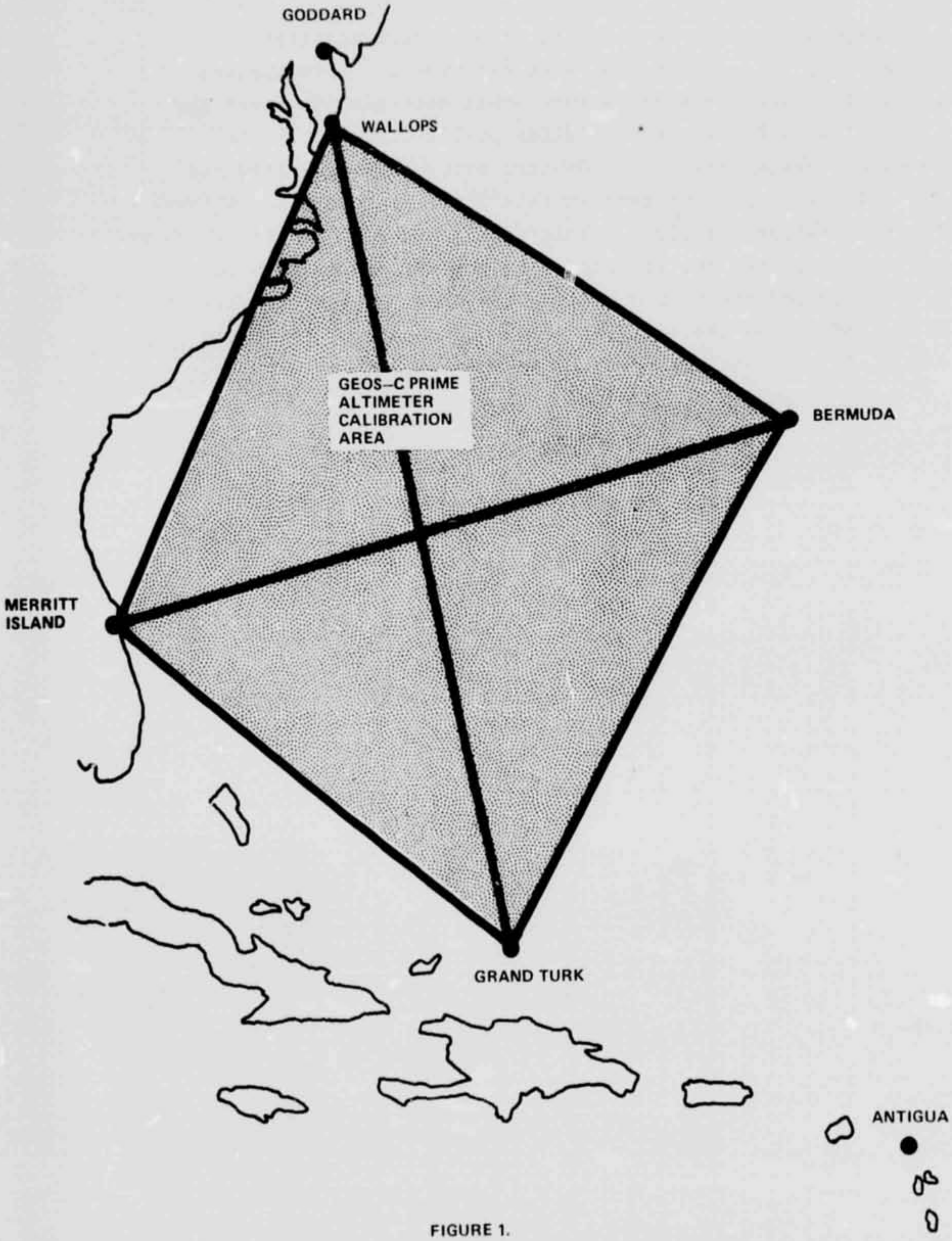

GODDARD
WALLOPS
GEOS–C PRIME
ALTIMETER
CALIBRATION
AREA
BERMUDA
MERRITT
ISLAND
GRAND TURK
ANTIGUA

FIGURE 1.

EXPERIMENTAL DESIGN

During the months of January through February and later in October of 1969, the C-Band Network extensively tracked the C-Band beacon flown on the GEOS-II satellite. Table 1 presents the nominal orbit for GEOS-II. Incidental to this extensive radar tracking was some laser data taken at Goddard Space Flight Center (Station No. 7050), Mount Hopkins (7055) and Carnarvon (7054), Australia. A large amount of this radar data was taken by the sites of interest for the GEOS-C altimeter calibration. It was this data which were used to recover the center-of-mass positions of the radars located at Wallops Island (4840,4860), Bermuda (4760), Grand Turk (4081), and Merritt Island (4082). Although Antigua (4061) has not been designated as a primary radar for the GEOS-C altimeter calibration, its geographical proximity to the calibration area caused us to select it for recovery also. Data from the Woomera (4946) C-Band site were also utilized for some related geopotential model analysis.

Various techniques were considered for station positioning. Dynamical orbital techniques were chosen primarily due to the suspected biases believed to be within the radar data.

The GEODYN orbit determination system (T. Martin, 1972) was used for the station recovery. GEODYN is a Bayesian least-squares, multiarc, multiple satellite orbit and geodetic parameter estimation system based upon Cowell type numerical integration techniques. Modeled parameters include luni-solar gravitational perturbations, solar radiation pressure, BIH polar motion and UT1 data and several geopotential models.

TABLE 1. GEOS–II

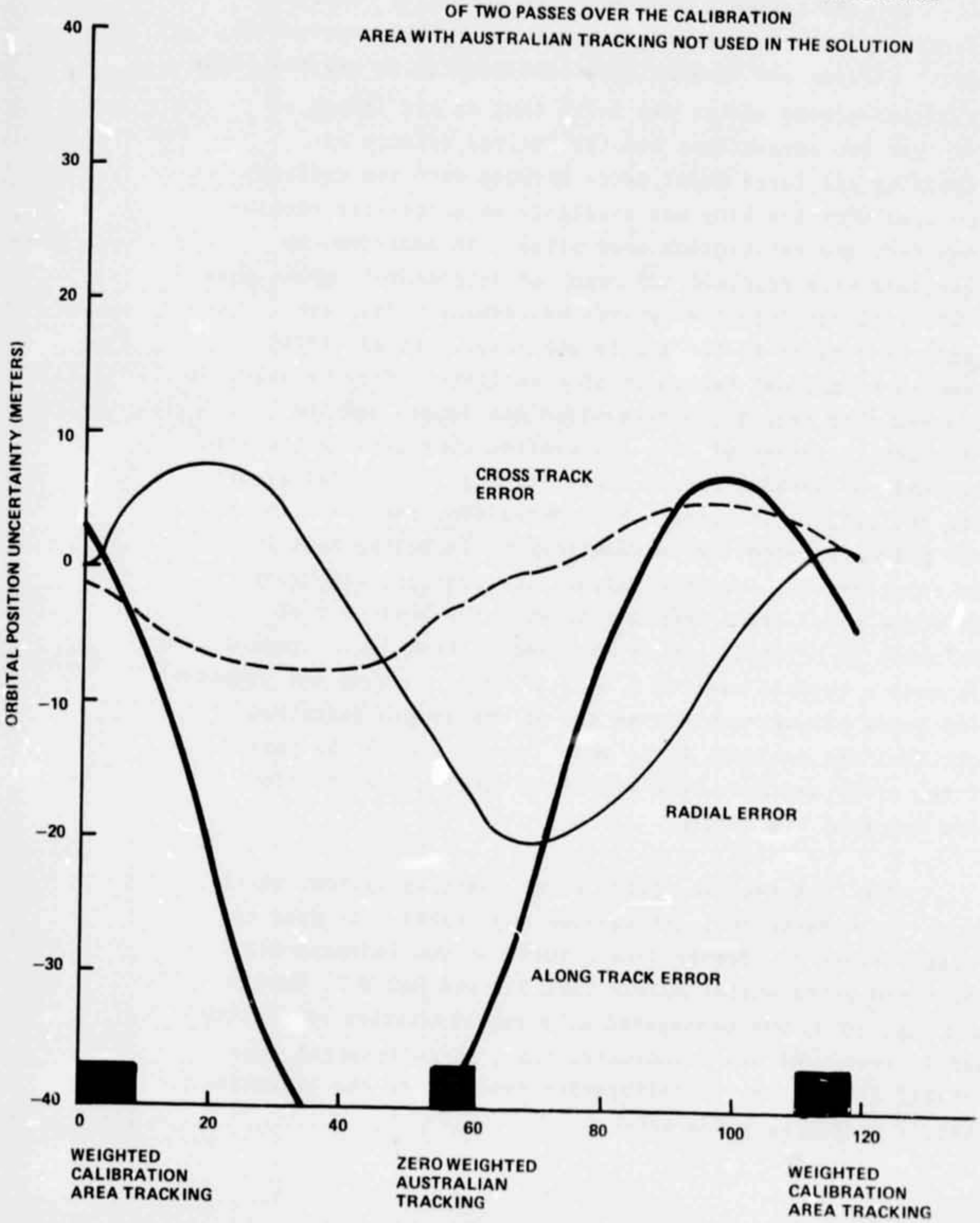
EPOCH	APRIL 28, 1968
Apogee Height	1569 km
Perigee Height	1077 km
Eccentricity	0.03
Inclination	105.8
Anomalistic Period	112.1 min.

Initial analysis centered upon two major concerns; selection of arc length and the best available geopotential model. Various arc lengths were simulated in an orbital error estimation scheme and it was found that an arc length of less than two revolutions had the desired effects of minimizing the force model error effects over the calibration area when tracking was available on successive revolutions from the calibration area sites. In addition, no other data were required and even had detrimental impact when it was included into the orbital adjustment. This arc length is similar to the arc length Schutz, et al (1974) found to be optimal for their BE-C analysis. Very briefly, we found that this 1 1/3 revolution arc length and the selective inclusion of only calibration area data in the solution had the desired effect of minimizing force model errors over the calibration area. By constraining the orbit in the same place on successive revolutions by including data in the solution only from the calibration area one can cause the force model error propagating with the frequency of the orbit to be minimized at the time of tracking. Figure 2 presents a typical case of a GEOS-II orbit showing the geopotential error propagation for an arc of the length described. Note that the dominant force model errors are of the period of the orbit and have been minimized over the calibration area for this arc length.

The ORAN (Martin, 1970) error analysis system, which simulates a Bayesian least-squares adjustment, was used to create Figure 2. Twenty-five percent of two independently recovered geopotential models (APL 3.5 and SAO M-1; Martin and Roy, 1972) was propagated as a representation of gravity model error. Figure 2 indicates that, as anticipated, the orbital error over the calibration area due to the geopotential is only a very few meters.

FIGURE 2.

GEOS–II SATELLITE GEOPOTENTIAL ERROR PROPAGATION FOR TYPICAL CASE OF TWO PASSES OVER THE CALIBRATION AREA WITH AUSTRALIAN TRACKING NOT USED IN THE SOLUTION



This arc length was also employed to evaluate various geopotential models. In a number of cases, ranging instruments located in Australia also tracked GEOS-II on the same revolutions as the calibration area tracking. The orbit, when passed through the Australian data unweighted in the solution, revealed the amplitude of geopotential error sources. Figure 2 shows that along track error due to geopotential errors would be large over Australia. The along track error was measured by estimating the apparent timing errors in the residuals of the Australian data.

Two state of the art gravity models were compared. They were:

- The SAO Standard Earth II [SEII], Gaposchkin and Lambeck, 1970, and

- The Goddard Earth Model 1 [GEM1], Lerch, et al., 1972.

Table 2 presents a comparison of the recovered timing errors over Australia when these gravity models are used. GEM1 was found to produce significantly smaller along track errors by almost a factor of two. Therefore, the GEM1 geopotential model was initially adopted for our station recovery. As our work progressed, the GEM6 model (Lerch, 1974) became available. Part of the Australian data analysis was repeated indicating comparable performance for this model with GEM1. However, since GEM6, unlike GEM1, used a large amount of metric data including GRARR, laser, doppler and C-Band observations, it was this model which was employed for our final station recovery solution.

TABLE 2.
TIMING ERRORS OVER
AUSTRALIA USING REFERENCE
ORBITS DETERMINED WITH GEM1
AND THE STANDARD EARTH II
GRAVITY MODELS

Station	Epoch Time GMT YYMMDD HHMM	apparent timing errors (msec) SE II	GEM1
Woomera(4946)	690201 2146	-42.8	-18.8
Woomera(4946)	690202 2206	-6.9	-2.1
Woomera(4946)	690203 0843	14.6	-0.9
Woomera(4946)	690204 2241	6.9	5.5
Woomera(4946)	690205 0734	3.4	-0.7
Woomera(4946)	690205 0902	10.7	5.4
Woomera(4946)	690207 0957	3.2	2.9
Carnarvon(7054)	690207 0956	7.3	7.5
Carnarvon(7054)	690207 2342	-62.2	-34.4
Carnarvon(7054)	690208 1019	7.2	-2.7
Woomera(4946)	690211 2116	-44.1	-30.1
Woomera(4946)	690211 2306	-14.3	-12.0
Woomera(4946)	690212 0755	-16.5	-1[illegible]
Woomera(4946)	690212 0945	-11.8	[illegible]
RSS		93.86	[illegible].59

DETAILS OF THE SOLUTION

During most of the January/February period and all of the October period, the Eastern Test Range radars (Merritt, Grand Turk, and Antigua) tracked GEOS-II only during the daylight hours. Therefore, of necessity, most of the arcs selected for our solution were from the daylight hours. This prevented us from including any laser data in our solution since only two daylight passes were available which were simultaneous with the selected best C-Band tracks and this was not enough data to recover the laser positions.

We were fortunate however, for given the nodal rate of the GEOS-II satellite, the daylight passes taken in January/February were in the opposite direction from those in October (the later being South to North while Jan/Feb were North to South). This provided us with favorable cancellation of the remaining geopotential error and good geometry for station recovery. Passes were selected on both sides of all the stations in both directions.

Various data reduction experiments were performed to ensure that this data was corrected for known or suspected problems. The Wallops data required correction for timing errors of integer hundreds of milliseconds. The Bermuda observations from station 4740 were found to be inconsistent with the data from the other sites and since they were largely redundant with the data from 4760 they were deleted from the solution. The GODLAS laser data were found to have timing errors of about 10 msecs from February 5th through the 14th.

Eighteen arcs were selected for our solution. Table 3 presents a list of the selected arcs. In all, over 120 passes of radar data were used having a data sampling rate of 1 point/10 seconds. The final solution had over 6000 range observations and had an RMS of fit of 1.4 m. Residual plots are presented in Appendix A.

TABLE 3. DATA ARCS SELECTED FOR C–BAND RADAR STATION ESTIMATION SOLUTION

ARC NO.	DATE AND HOUR OF EPOCH		NUMBER OF OBSERVATIONS	RMS OF FIT (M)
1	JANUARY 28, 1969	9 HOURS	308	1.6
2	JANUARY 31, 1969	8 HOURS	270	1.7
3	FEBRUARY 1, 1969	8 HOURS	212	1.3
4	FEBRUARY 1, 1969	22 HOURS	349	1.4
5	FEBRUARY 2, 1969	9 HOURS	297	1.6
6	FEBRUARY 2, 1969	23 HOURS	254	1.5
7	FEBRUARY 4, 1969	21 HOURS	271	1.9
8	FEBRUARY 8, 1969	23 HOURS	381	1.9
9	FEBRUARY 12, 1969	0 HOURS	256	1.4
10	FEBRUARY 12, 1969	8 HOURS	248	1.9
11	SEPTEMBER 26, 1969	15 HOURS	455	1.3
12	OCTOBER 8, 1969	16 HOURS	342	1.1
13	OCTOBER 9, 1969	17 HOURS	310	1.2
14	OCTOBER 10, 1969	15 HOURS	337	1.4
15	OCTOBER 13, 1969	16 HOURS	366	1.4
16	OCTOBER 16, 1969	15 HOURS	461	1.2
17	OCTOBER 17, 1969	16 HOURS	525	1.0
18	OCTOBER 24, 1969	16 HOURS	453	1.3
		TOTAL	6095	1.4

RESULTS

Table 4 presents the values for the C-Band station position recovery. The GEM6 gravity model was used for this final solution. The treatment of the C-Band biases are discussed in the following paragraphs.

The C-Band Biases

The C-Band instruments have range biases which are significant when compared to their 1 to 1.5 meter noise level. A good general model for a C-Band range observation would be:

$$R_0 = R + \Delta R_1 + \Delta R_2 + \xi$$

where:

R_0 is the observed range

R is the true range

ΔR_1 is a bias term associated with very changeable errors so that

$$\Delta R_1 = \Delta r_1 + \Delta r_2 + ..$$

where Δr_N are factors such as:

Δr_1 = errors due to thermal changes in the system

TABLE 4 RECOVERED C-BAND STATION LOCATIONS

	STATION			GEODETIC LATITUDE			EAST LONGITUDE			HEIGHT
LOCATION	RADAR TYPE	NAME	NUMBER	DEG	MIN	SECS	DEG	MIN	SECS	(m)
ANTIGUA	FPQ-6	ETRANT	4061	17	08	37 156	298	12	27 192	-19 88
GRAND TURK	TPQ-18	ETRGRT	4081	21	27	45 370	288	52	4 940	-29 17
MERRITT ISLAND	TPQ-18	ETRMRT	4082	28	25	29 015	279	20	8 282	-36 94
BERMUDA	FPQ-6	NBER05	4760	32	20	52.800	295	20	47 648	-31.10
WALLOPS ISLAND	FPS-16	NWALI8	4840	37	50	28 955	284	30	53 648	-43.65
WALLOPS ISLAND	FPQ-6	NWALI3	4860	37	51	37 072	284	29	26 536	-40 74

a_e = 6378155m, 1/f = 298 255

Δr_2 = random calibration errors, etc.

ΔR_2 is a bias term associated with long term ranging errors caused by unchanging systematic errors so that

$\Delta R_2 \simeq \Delta r_p + \Delta r_s \ldots$

where Δr_x are factors such as:

Δr_p = a pulse width/bandwidth-mismatch problem

Δr_s = an error to the surveyed ranging calibration target (or if the target is large, such as a water tank, an error to the tracking point) etc.

and

ξ is noise. If ΔR_1 is small, the range measurements will be stable although they still may be biased.

Error analysis was performed and indicated that the station coordinates and all of the biases could be simultaneously adjusted. An initial station recovery solution was made having all biases recovered independently for each individual pass of data. The recovered biases seemed very consistent from the Bermuda FPQ-6 (4760) and both Wallops radars. The systematic errors for these range passes exceeded the random errors at these sites making their observations very stable. We took advantage of this stability. The station recovery error analysis was again performed but this time having the biases from Bermuda (4760), and both Wallops stations (4840 and 4860) adjusted on an arc-by-arc basis.

The results from the error analyses are presented in Table 5. The error sources modeled were:

GM_E:	1 ppm error assumed
Gravity:	25% of the difference between the APL 3.5 and SAO M-1 models.
Timing:	0.1 msec error at all sites.
Refraction:	5% error in tropospheric refraction (an error of 17 units of the refractivity N_s).

The sites were adjusted with respect to Bermuda. Table 5 indicates that superior results would be obtained if the Wallops and Bermuda biases could be adjusted on an arc by arc basis. This error analysis indicated that the 2m level of station recovery could be achieved. This station solution (which is quoted in Table 4) was then performed.

Table 6 presents the actual differences in the recovered station positions when the bias treatment was modified as previously discussed. The agreement in station recovery is consistent with the ORAN error analysis. We therefore were satisfied that our treatment of the C-Band biases did not adversely contaminate our station recovery. Our error analysis indicated that the 2m level of station positioning accuracy had been achieved at all sites. Our error analysis is probably conservative since the gravity model error propagated was scaled to the Standard Earth II and this model has been shown in Table 2 to be significantly less accurate (in the environment of this arc length) than either GEM1 or GEM6. Gravity model error is still the dominant error source for this work.

Table 7 presents the values of all the recovered biases from the adopted solution.

TABLE 5. ESTIMATED RELATIVE STATION RECOVERY UNCERTAINTY (METERS)

		ALL BIASES ADJUSTED PASS-BY-PASS	BIASES FROM WALLOPS AND BERMUDA ADJUSTED ARC-BY-ARC WITH ALL OTHERS PASS-BY-PASS
ANTIGUA	ϕ	1.2	0.8
(4061)	λ	5.4	1.9
	h	2.2	1.9
GRAND TURK	ϕ	1.9	0.9
(4081)	λ	3.8	2.1
	h	2.0	2.5
MERRITT ISL.	ϕ	4.3	1.3
(4082)	λ	1.6	1.0
	h	1.5	2.4
WALLOPS	ϕ	2.6	0.7
(4840)	λ	2.9	0.7
	h	1.5	1.6
WALLOPS	ϕ	2.7	0.7
(4860)	λ	3.0	0.6
	h	1.0	1.5

TABLE 6. DIFFERENCES IN RECOVERED STATION COORDINATES.
SOLUTION WITH ALL BIASES ADJUSTED PASS–BY–PASS MINUS
SOLUTION WITH BERMUDA AND WALLOPS BIASES
SOLVED FOR ON AN ARC BASIS

STATION		DIFFERENCE IN METERS		
NAME	NUMBER	ϕ	λ	HEIGHT
ETRANT	4061	−0.15	−0.79	0.37
ETRGRT	4081	0.22	−0.69	1.59
ETRMRT	4082	−0.86	−2.72	−0.10
NWALI8	4840	−0.61	0.21	1.28
NWALI3	4860	0.06	−0.51	−0.24

TABLE 7 RANGE BIASES RECOVERED IN STATION ESTIMATION SOLUTION

	STATION					
ARC NO.	4061	4081	4082	4760	4840	4860
1	− 1.6		8.7	15.6*		5 7*
	8.0		−12.0			
2	−36.6			13 0*	7.6*	
	− 4.2	5.7				
3				16.0*		11.0*
	−10.0					
4	8.7			18.0*	4.8*	6.2*
5	− 1.4			20.0*	5.7*	7.6*
	− 0.0					
6	− 6.8			14.9*	6.5*	8.5*
7		[illegible]		18.7*		
		5.0	5 7			6.4
8	12.0		8.4	17.5*		6.2*
			14.0		12.0	
9	0.8		2.7	12.4	5.0*	
			− 1.9			
10	− 5.7			8.8*		− 8.2*
	− 6.4		−41.0			
11	18.0			18.0*		
	− 0.0	−14.0				
12		4.0	6.0		− 0.3*	
		− 0.7	3.3			
13		− 1.6	4.1			2.1*
			2.3			
14	4.7	11.9	9.5			− 7.7
	4.3				− 1 6	
15	11.2	4.3		− 8.5*	− 0 6*	
16				−11.1*	1.4*	1 7*
	− 8.3		− 6.2			
17		− 3.9		− 7.2*		0 2*
		− 4.6	0.0			
18		11.8	4.6	− 0 2*	1.2*	
		3.3	− 0.8			

**Biases adjusted on arc basis from two passes of data.

The stability of the Bermuda and Wallops radars are presented in Figures 3, 4, and 5. In these figures the bias values with their estimated uncertainties are presented for the successive arcs of data used in the solution except for arc 11 which is two weeks from any other data set.

The bias recovery for the Wallops FPS-16 (Figure 3) deserves special mention. Early in 1969 a Frequency Shift Reflector (FSR) was installed at Wallops Island. Unfortunately the results from this point source target were unavailable during the January and February period. Therefore, this range data contained zero-set range errors due to calibrating against a physically large reference range target. The magnitude of this error was determined by zero-setting the range with the range target and then calibrating this against the FSR. The apparent target size error found for the FPS-16 was 7.9m. This bias agrees extremely well with the values obtained from the station recovery solution (Figure 3). The October data set was corrected for this bias in the preprocessing. The bias recovered from the station solution had a mean of 0 meters during October. For all the radars it is not surprising to find that the mean bias values changed from February to October, since normal preventive maintenance could be expected to have this effect.

Again, the stations were adjusted with respect to Bermuda. The error analysis indicated that any errors in the Bermuda position with respect to the center-of-mass would map virtually one to one into the recovered positions from the other sites. Therefore, this did not effect our relative station positioning. In order to ensure center-of-mass recovery for the C-Band station coordinates, initial solutions were performed permitting Bermuda's height to adjust. The longitude and latitude were held unadjusted from center-of-mass values obtained from Marsh et al, 1973a.

FIGURE 3.

WALLOPS FPS–16 (4840) BIAS RECOVERY WITH ERROR ANALYSIS ESTIMATE OF UNCERTAINTY

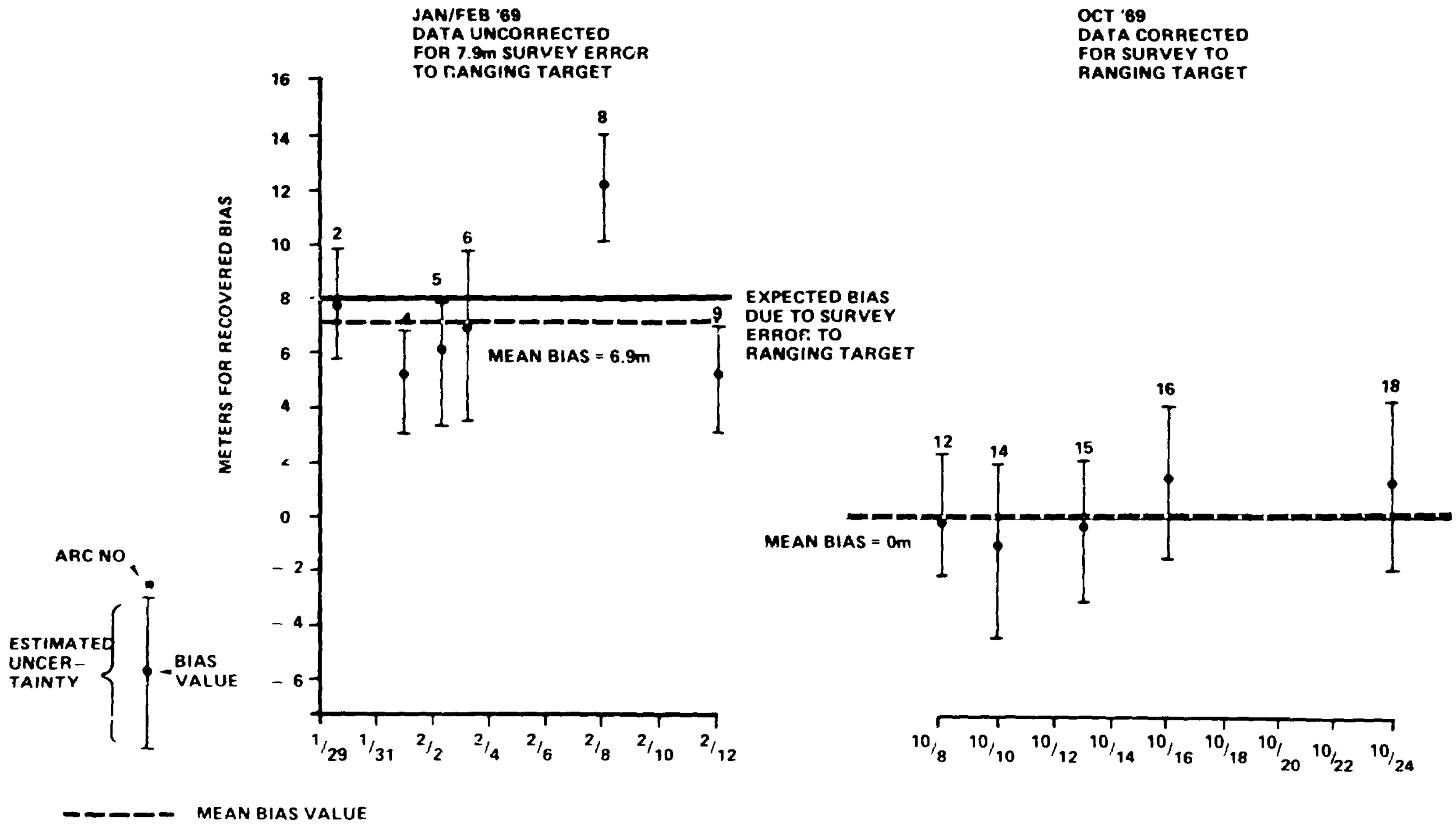


FIGURE 4. WALLOPS FPQ–6 (4860) BIAS RECOVERY WITH ERROR ANALYSIS ESTIMATES OF UNCERTAINTY

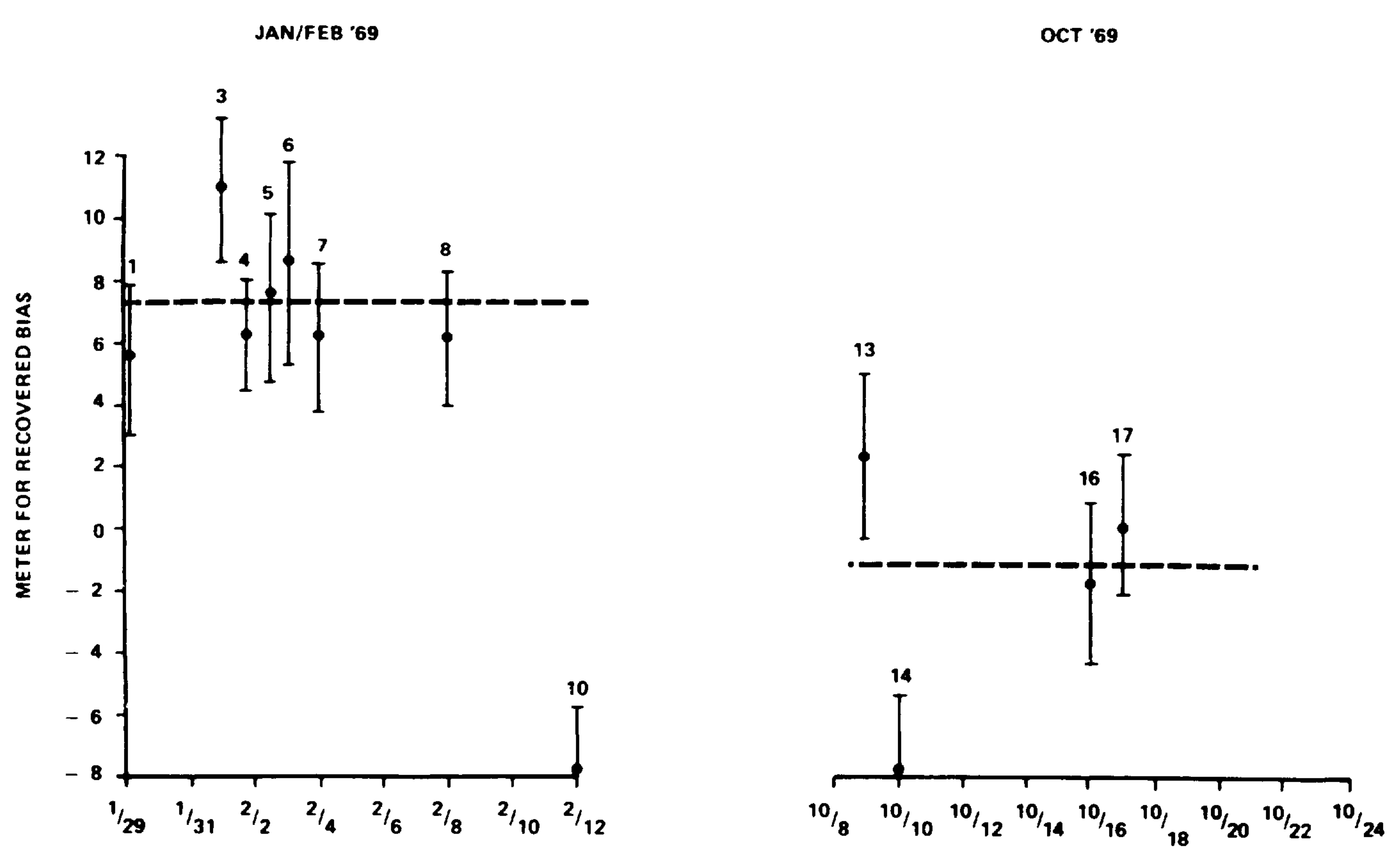
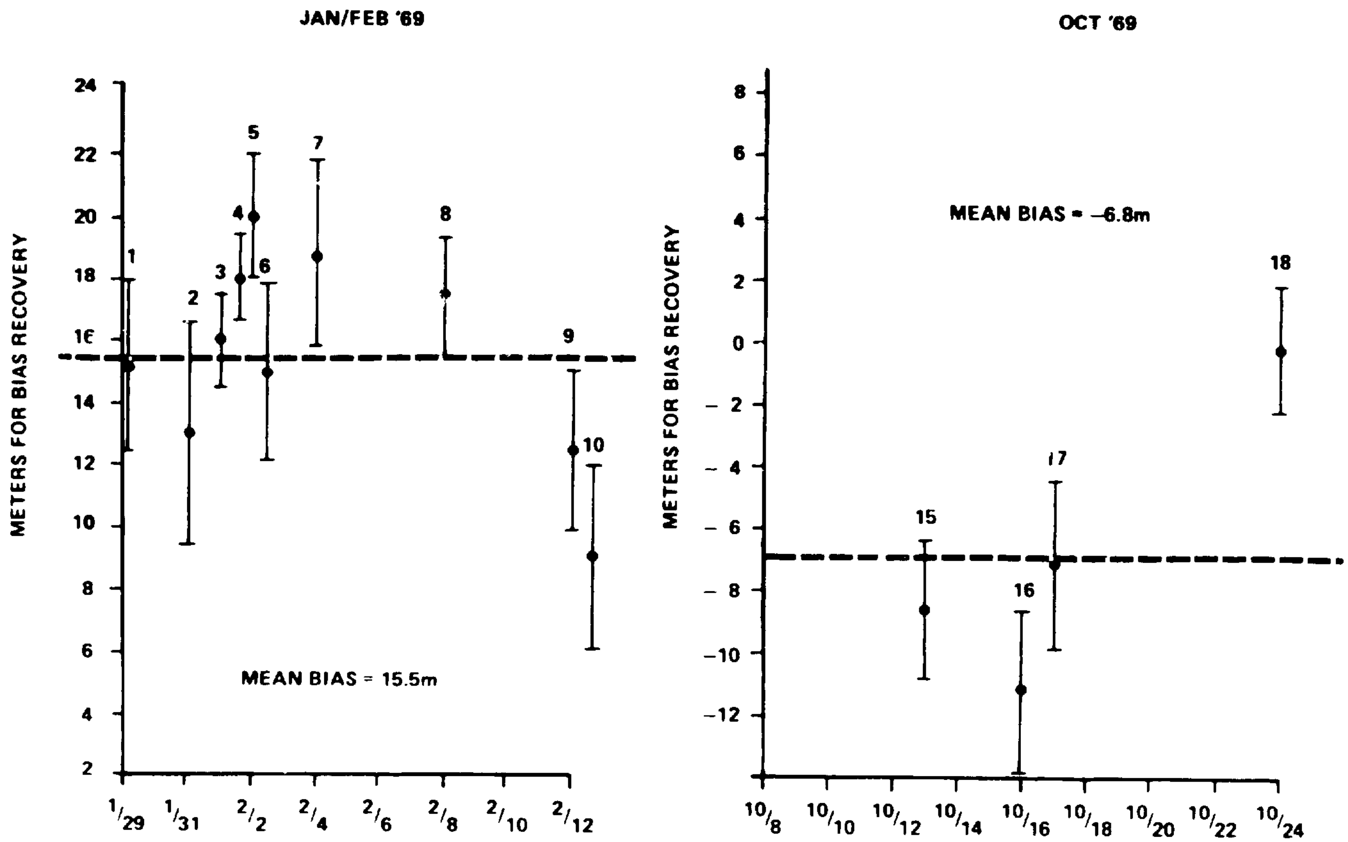


FIGURE 5.

BERMUDA FPQ–6 (4760) BIAS RECOVERY WITH ERROR ESTIMATE OF UNCERTAINTY



The recovered height for Bermuda agreed to less than 1m with the gravimetric geoid (Marsh, Vincent, 1973b). We were therefore confident that we had a satisfactory Bermuda height as a reference point for our solution. Any error in the Bermuda longitude was not viewed as a problem since this merely established a longitude reference for the calibration area. However, a center-of-mass latitude error at Bermuda would map into all stations nearly equally and therefore, would cause a systematic error in ϕ with respect to the center-of-mass. The accuracy quoted in the Marsh (op cit, 1973a) solution for Bermuda ϕ is 3m, and this uncertainty cannot be neglected. However, the relative station positioning is not affected.

Our error analysis indicated that it was desirable to hold at least one station height unadjusted in the solution for this greatly lowered our sensitivity to variations in errors resulting from our adoption a priori of a value of GM_E. A solution using a value of 398601.2 Km^3/sec^2 for GM_E and allowing Bermuda's height to adjust was compared with our final solution which held Bermuda's height fixed and used a value of 398600.8 Km^3/sec^2. After removing a difference of about 7 m in recovered height, the RMS agreement was 31, 24 and 25 cm in X, Y and Z, respectively.

Results Compared To One-Day Arc Solution

We took an additional precaution to ensure center-of-mass recoverability. A solution using one-day arcs was also performed. Bermuda was again held unadjusted. The data which was selected was largely independent of the data used in the short arc recovery. The night-time GODLAS laser data was also included with the GODLAS position being adjusted. Since this data set was largely independent of the data used in the short arc recovery, we had a very small amount of data in this one-day arc solution from Grand Turk and Antigua. The solution was therefore performed removing this Antigua and Grand Turk data since satisfactory station recovery from these sites was viewed as unlikely given their limited data sets. Table 8 presents the differences in X, Y and Z between the short arc and one-day arc solutions. The recovered value for GODLAS is presented in Table 9 and is compared with the Marsh (op cit 1973a) recovery which used the same value of GM_E and was in the same longitude system. The agreement between the short arc and the one-day arc length recoveries is very good. We were also very satisfied with our recovered GODLAS position.

TABLE 8. DIFFERENCES BETWEEN SHORT ARC AND ONE–DAY ARC SOLUTIONS IN METERS

STATION	NUMBER	ΔX (m)	ΔY (m)	ΔZ (m)
BERMUDA	4760	0.	0.	0. *held unadjusted
MERRITT	4082	−0.29	−0.09	−3.73
WALLOPS	4840	0.05	−0.30	−1.11
WALLOPS	4860	0.71	−0.12	−1.33

TABLE 9. RECOVERED VALUES FOR GODLAS LASER STATION 7050

		LATITUDE			LONGITUDE			HEIGHT
	NUMBER	DEG	MIN	SEC	DEG	MIN	SEC	(METERS)
ONE-DAY ARC RECOVERY	7050	39	01	14.183	283	10	19.013	4.15
MARSH et al 1973	7050	39	01	14.268	283	10	18.955	2.46
DIFFERENCE				−0.″085			0.″058	1.69

Comparison With Other Investigators

In an investigation such as this one it is often very useful to compare the station recovery results obtained with those of some independent investigations. Extensive comparisons were made to further assess the accuracy of the C-Band short arc recovery. The other investigators who were selected for comparison are presented below, along with a brief description of their solutions.

- Marsh, Douglas, Klosko, 1973:
  A global solution for stations using optical and laser measurements.

- Lerch et al, 1974:
  GEM6: a global solution using GRARR, laser, Doppler, C-Band and optical observations recovering station coordinates and the GEM6 gravity model.

- Martin and Walls, 1973:
  Narrow-band VLBI techniques were employed to recover values for the S-Band radars tracking the Lunar Excursion Module.

- Walls, Boulware and Schanzle, 1973:
  S-Band station recovery from the tracking data taken on Mariner 9.

- Marsh and Vincent, 1973:
  A gravimetric geoid combining satellite and surface measurements.

- Ballew, 1974:
  A Gravimetric Geoid for GEOS-C Test Area based on satellite and surface measurements produced by the Defense Mapping Agency Aeronautical Center (DMAAC).

- Brooks 1972:
  A global solution using C-Band observations taken on GEOS-II for station coordinates.

- Wolf Research and Development Corporation, 1972 (Brooks):
  A solution in which the Grand Turk radar (4081) was recovered with respect to the Antigua radar (4061) held fixed at the Brooks (1972) value. The solution also recovered the geodetic position of a ship over the Puerto Rican Trench.

- Air Force Eastern Test Range, 1974:
  Positions from the most recent "AFETR Geodetic Coordinates Manual."

Figure 6 presents the geoid heights recovered by the various investigators. In order to account for the different values of GM_E employed, Figure 7 presents a plot of the geoid heights for the other stations relative to the geoid height from Bermuda for each investigator. The gravimetric geoids agree very well with C-Band short arc values for geoid height except in the case of Bermuda relative to Wallops. In this latter case, all investigators who presented adjusted station coordinates are in substantial disagreement with the geoids as can be seen in Figure 7. The uncertainty quoted for the Marsh-Vincent gravimetric geoid is 2-4 m. The RMS agreement between the C-Band short arc solution and this gravimetric geoid is 2.8 m. The C-Band solution is even in closer agreement with the DMAAC geoid, especially at Antigua. Antigua is located in an area of large geoidal slope and DMAAC's use of 15'x15' versus the Marsh-Vincent's 1°x1° reduction may account for the difference seen. The RMS agreement between DMAAC and the C-Band solutions is 2.7m. The agreement between the Lerch solution and our solution is especially good.

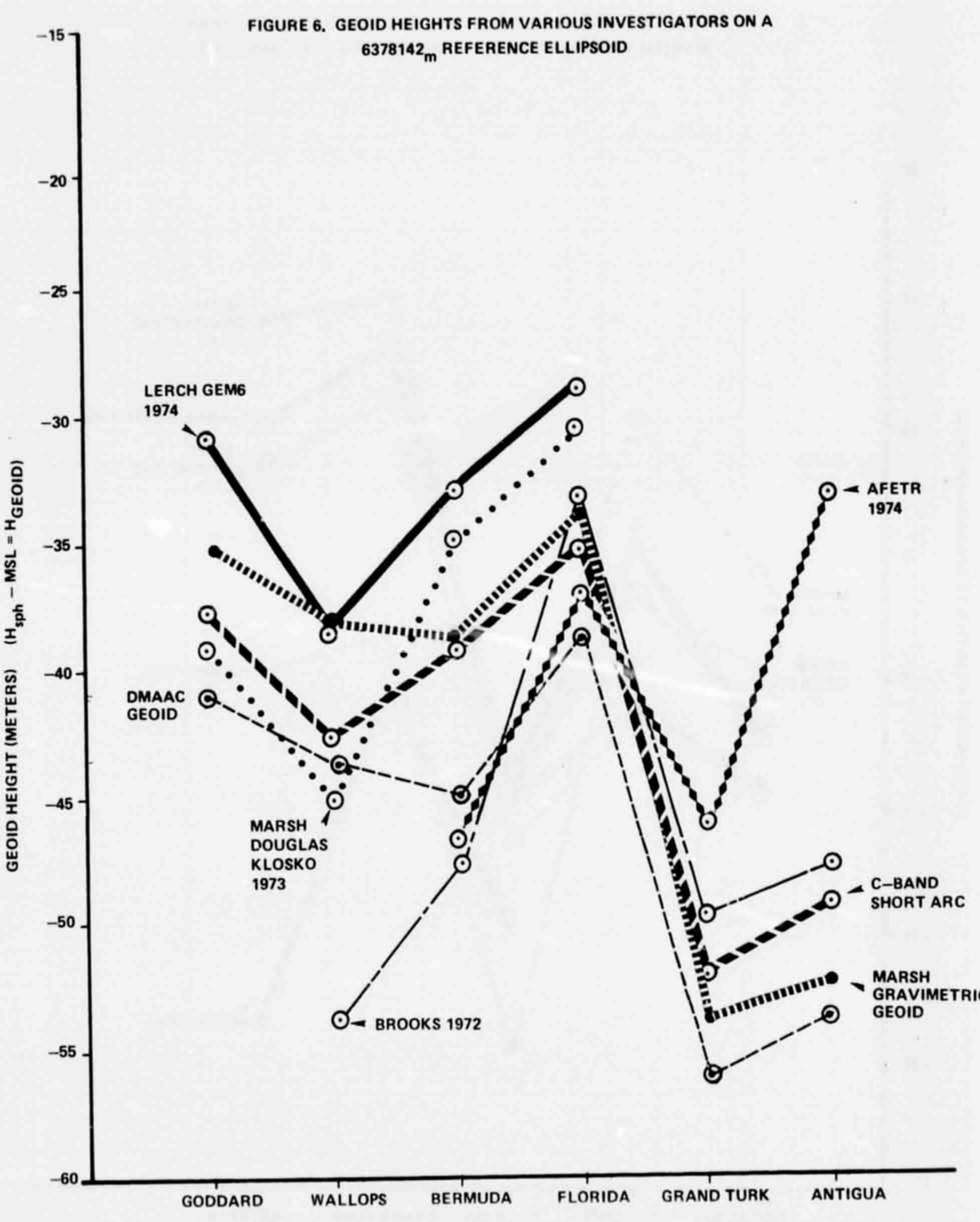


FIGURE 6. GEOID HEIGHTS FROM VARIOUS INVESTIGATORS ON A
6378142m REFERENCE ELLIPSOID
GEOID HEIGHT (METERS) (Hsph – MSL = HGEOID)
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
LERCH GEM6
1974
DMAAC
GEOID
MARSH
DOUGLAS
KLOSKO
1973
BROOKS 1972
AFETR
1974
C–BAND
SHORT ARC
MARSH
GRAVIMETRIC
GEOID
GODDARD
WALLOPS
BERMUDA
FLORIDA
GRAND TURK
ANTIGUA

FIGURE 7. GEOID HEIGHT RELATIVE TO BERMUDA FROM VARIOUS INVESTIGATORS (BERMUDA'S GEOID HEIGHT MINUS OTHER SITE)

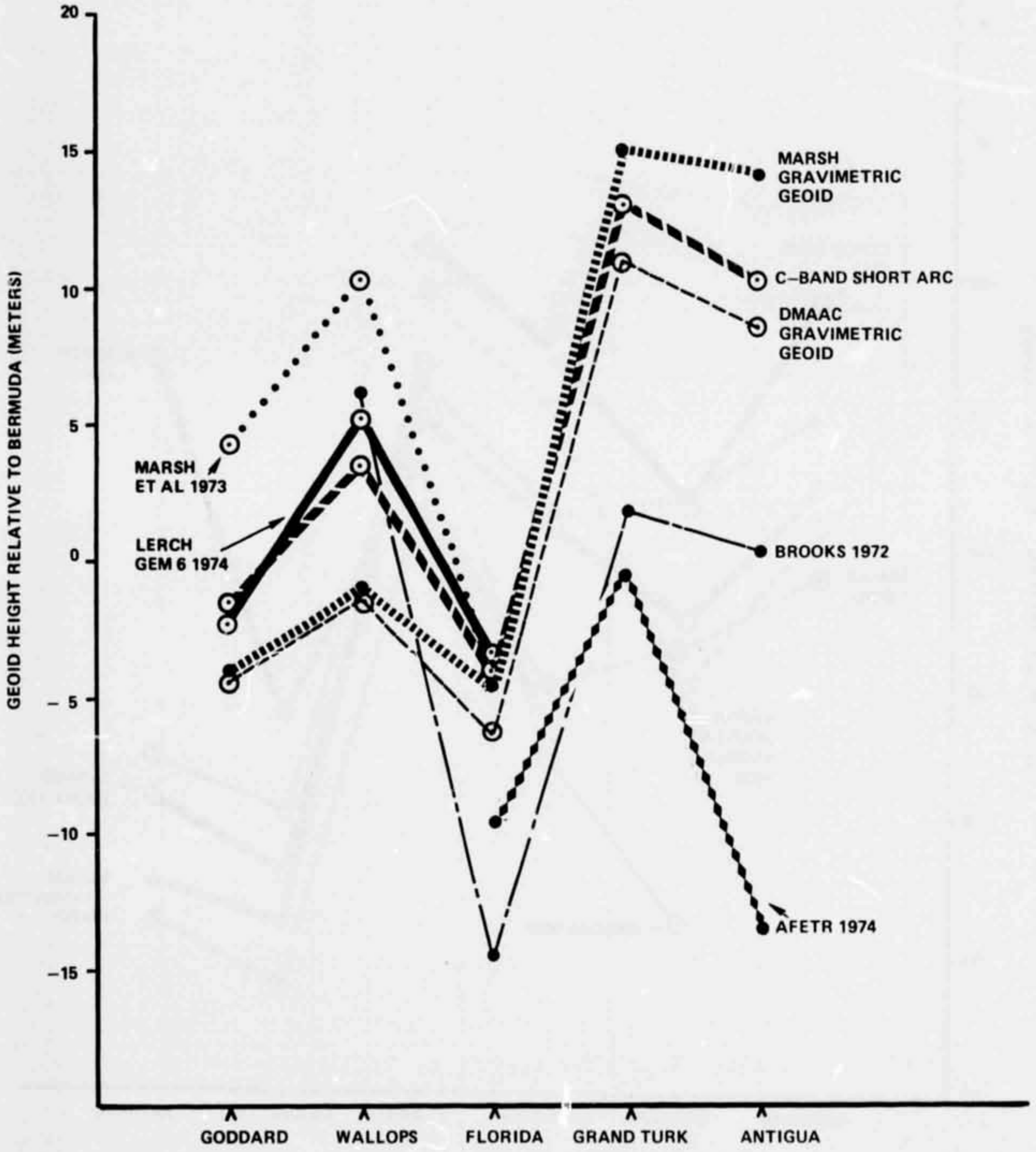


Table 10 presents the various recoveries for the Merritt Island station with respect to Bermuda. The compared quantities are relative spin axis distances and relative longitudes. In the cases of relative spin axis distances, the C-Band results show good agreement with the other investigators. In the case of longitudes our agreement is best with the solutions with the smallest quoted uncertainties. Table 11 compares the relative positioning of Grand Turk with respect to Antigua obtained from the Puerto Rican Trench Experiment and our C-Band short arc solution.

Finally, the C-Band results have been compared to the North American Datum surveys. Since the Wallops radars were solved for independently*, a comparison can be made of their relative recovery with respect to their surveyed values. Table 12 presents these results.

The North American Datum has recently been evaluated by using very precise traverses. A chord was measured up the East Coast of the United States. The C-Band recovered chord length is compared with this traverse in Table 13.

Table 14 presents a comparison of the North American Datum chord from Wallops Island to Goddard Space Flight Center with the values recovered in the present analysis.

*This comparison is especially interesting since 13 of the 22 passes taken by 4860 were <u>not</u> simultaneous with data taken by the other Wallops radar (4840).

TABLE 1Ƈ. RELATIVE SPIN AXIS DISTANCES AND RELATIVE LONGITUDES IMPLIED BY VARIOUS INVESTIGATORS BETWEEN BERMUDA AND MERRITT ISLAND

INVESTIGATOR	RELATIVE SPIN AXIS DISTANCE (BER–MER) (METERS)	C–BAND RESULT – OTHER
Marsh (opt/las)	−219951.59 ± 4m	− 1.6 m
Lerch (opt, dop, las, CBND)	−219955.08 ± 6m	1.9 m
Martin (LEM)	−219938.76 ± 9m	− 14.4 m
Walls (Mariner 9)	−219948.97 ± 7m	− 4.2 m
Brooks	−219957.23 ± 7m	4.1 m
AFETR	−219953.50 ± 9m	0.3 m
C–Band Short Art	−219953.17 ± 3m	

	RELATIVE LONGITUDES IN DEGREES (BER–MER)	C–BAND RESULT – OTHER
Marsh	16°0109778 ± 4m	−".154 or −4.2 m
Lerch	16°0109639 ± 6m	−".104 or −2.8 m
Martin	16°0110056 ± 7m	−".254 or −6.9 m
Walls	16°0110211 ± 7m	−".310 or −8.4 m
Brooks	16°011056 ± 7m	−".434 or −11.8 m
AFETR	16°011043 ± 9m	−".389 or −10 5 m
C–Band Short Arc	16°0109350 ± 3m	

TABLE 11. RELATIVE LATITUDE, LONGITUDE AND HEIGHT FOR GRAND TURK AND ANTIGUA OBTAINED FROM THE PUERTO RICAN TRENCH EXPERIMENT AND THE C–BAND SHORT ARC RECOVERY

	RELATIVE LATITUDE (GRT–ANT)	RELATIVE LONGITUDE (GRT–ANT)	RELATIVE SPHEROID HEIGHT (GRT–ANT)
PUERTO RICAN TRENCH EXPERIMENT	4.319000°	−9.3395278°	−7.95 m
C–BAND SHORT ARC	4.318947°	−9.3395139°	−9.29 m
DIFFERENCE	5.7 m	−1.5 m	1.34 m

TABLE 12. STATIONS 4840 AND 4860 RELATIVE RECOVERY COMPARED TO THE SURVEYED VALUES IN CENTIMETERS

	$\Delta\phi$ (cm)	$\Delta\lambda$ (cm)	Δh (cm)
4840–4860	–3	–73	–37

TABLE 13. CHORD LENGTH COMPARISON BETWEEN MERRITT ISLAND AND WALLOPS

CHORD	PRECISE TRAVERSE	C–BAND SHORT ARC	Δ
4082 TO 4860	1149612.0 m	1149609.2 m	2.8 m

TABLE 14. CHORD LENGTH COMPARISON BETWEEN WALLOPS ISLAND AND GODDARD SPACE FLIGHT CENTER

CHORD	NAD SURVEY	C–BAND SHORT ARC	Δ
7050 TO 4840	175728.61 m	175730.21 m	–1.6 m

CONCLUSIONS

The station recovery presented in this paper is believed to satisfy the GEOS-C requirement of better than 2m relative accuracy in each coordinate (1σ) for sites located in the GEOS-C altimeter calibration area. This conclusion is supported by our error analysis and comparisons with other investigators.

The techniques employed in this recovery experiment have wide-range implications for future GEOS-C experiments. The C-Band radars are all-weather instruments and unlike lasers, are not adversely affected by climatic conditions. Therefore, a geodetic parameter recovery experiment can be planned, analyzed, scheduled and the experimentor can be virtually certain that the necessary tracking data will be obtained by such radar systems. In addition, given that the techniques described within this report do not rely on global tracking support, a given experiment can be optimized without this difficult consideration. There will be a number of C-Band radars deployed on the European Datum for GEOS-C. The expected locations include Germany, France, Spain, Norway, and England. Radar data taken on GEOS-C should be similarly employed to recover accurate baselines for the reduction and improvement of the ED 1950.

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APPENDIX A: RESIDUALS FROM C-BAND STATION RECOVERY SOLUTION

STATION KEY FOR RESIDUAL PLOTS

SYMBOL	STATION NAME	LOCATION	RADAR INSTRUMENT
○	ETRANT	ANTIGUA, WEST INDIES ASSOCIATED STATES	FPQ–6
☆	ETRMRT	MERRITT ISLAND, FLORIDA	TPQ–18
★	NBERO5	BERMUDA	FPQ–6
●	ETRGRT	GRAND TURK, BAHAMA ISLANDS	TPQ–18
■	NWALI8	WALLOPS ISLAND, VIRGINIA	FPS–16
□	NWALI3	WALLOPS ISLAND, VIRGINIA	FPQ–6

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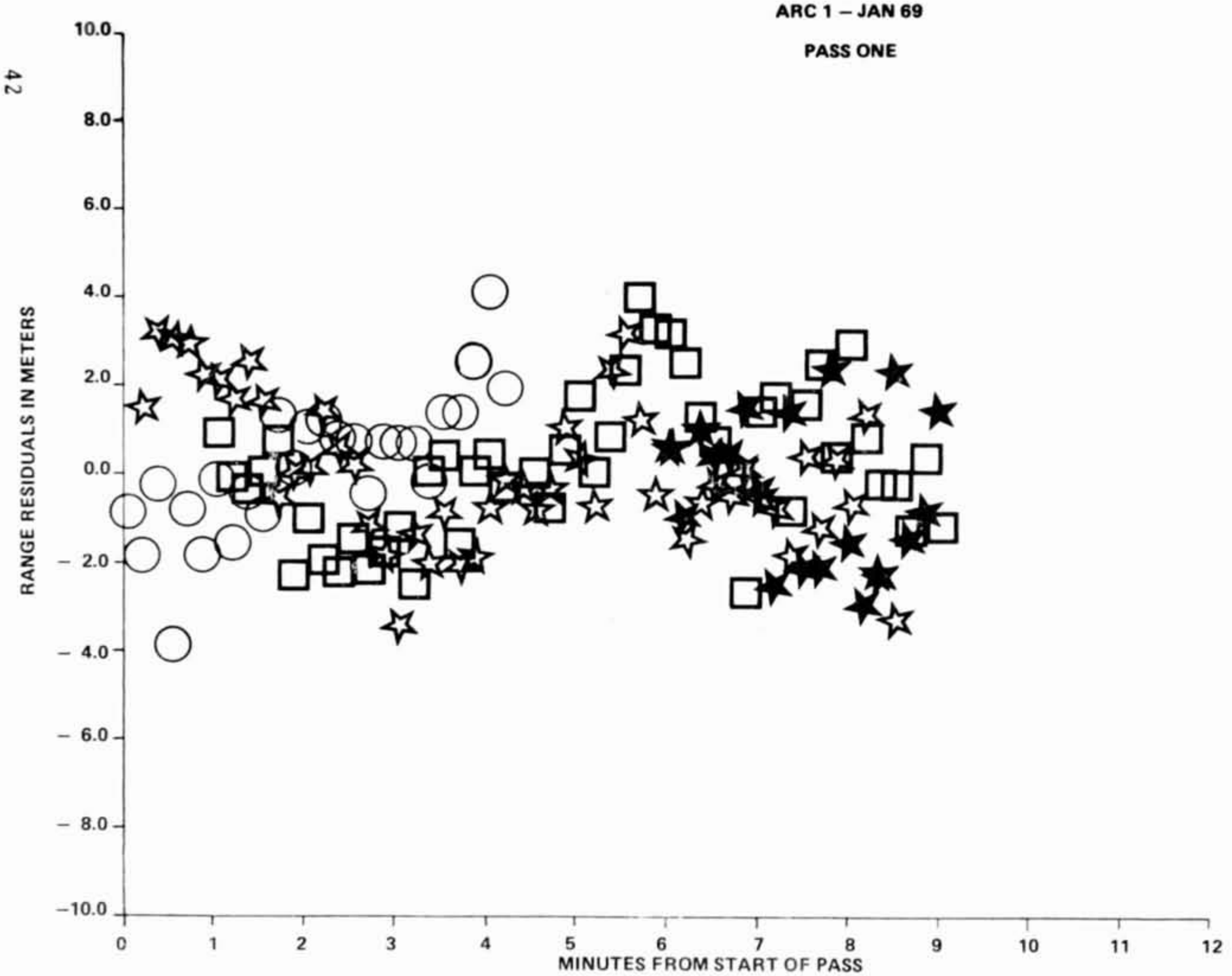

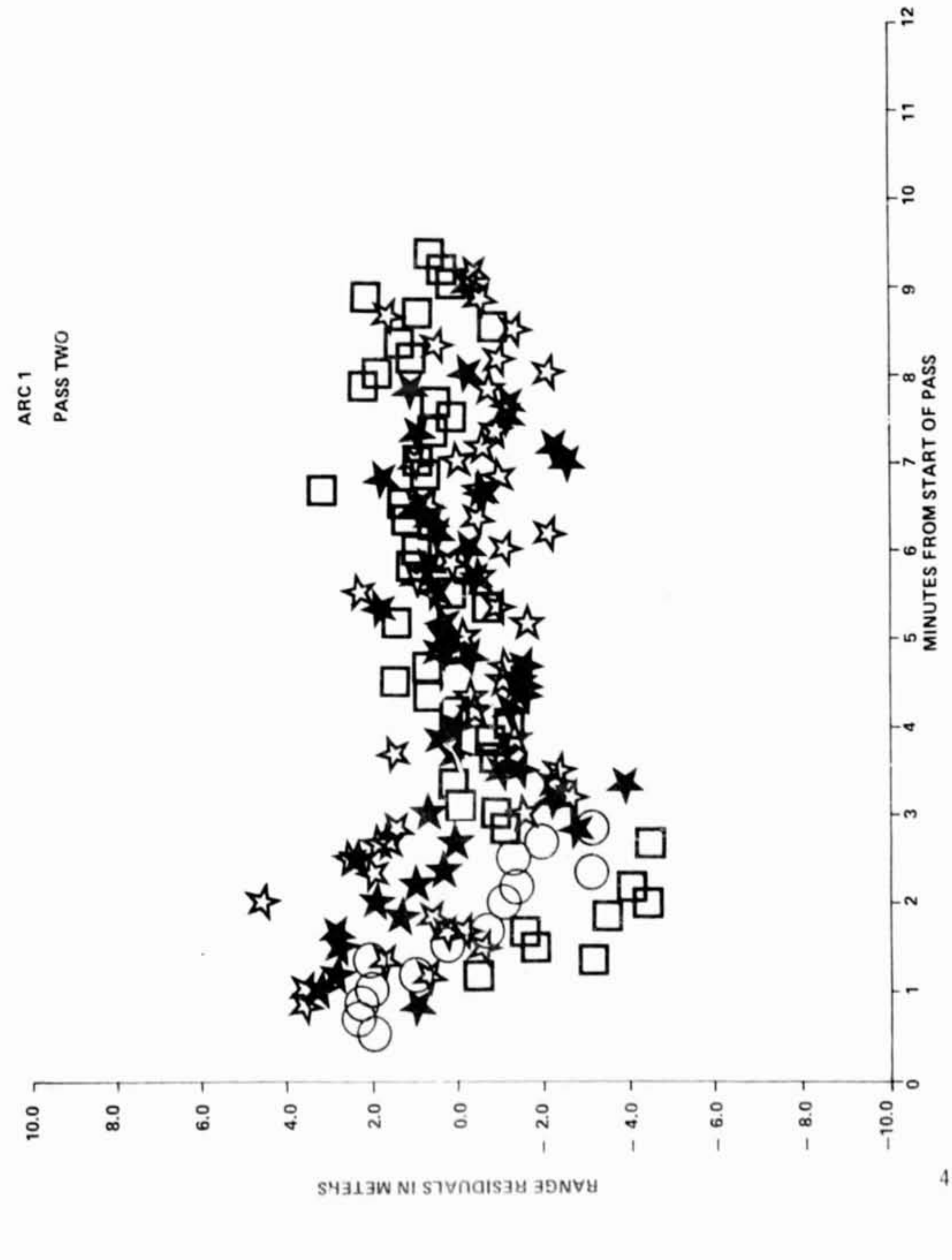
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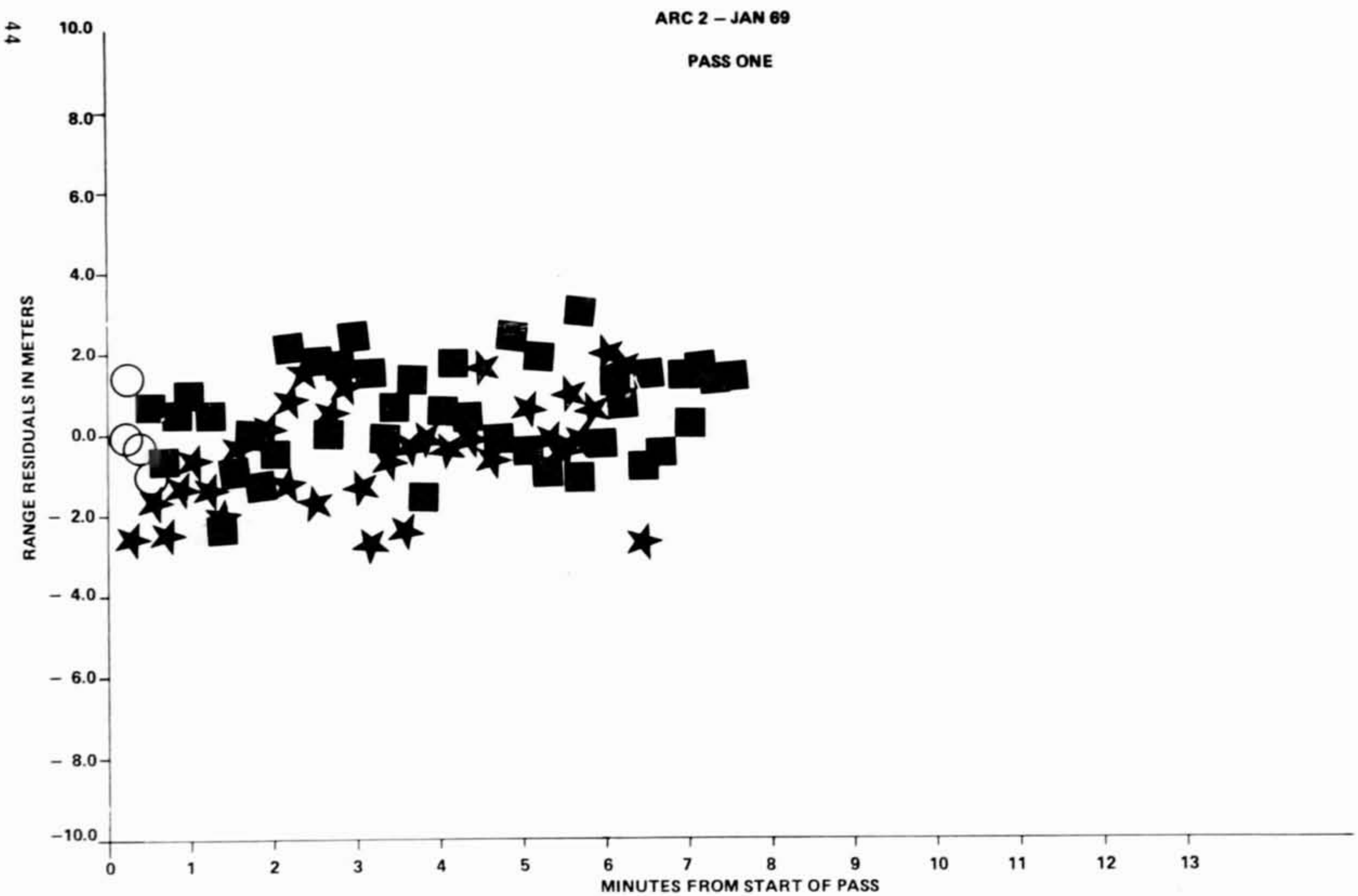
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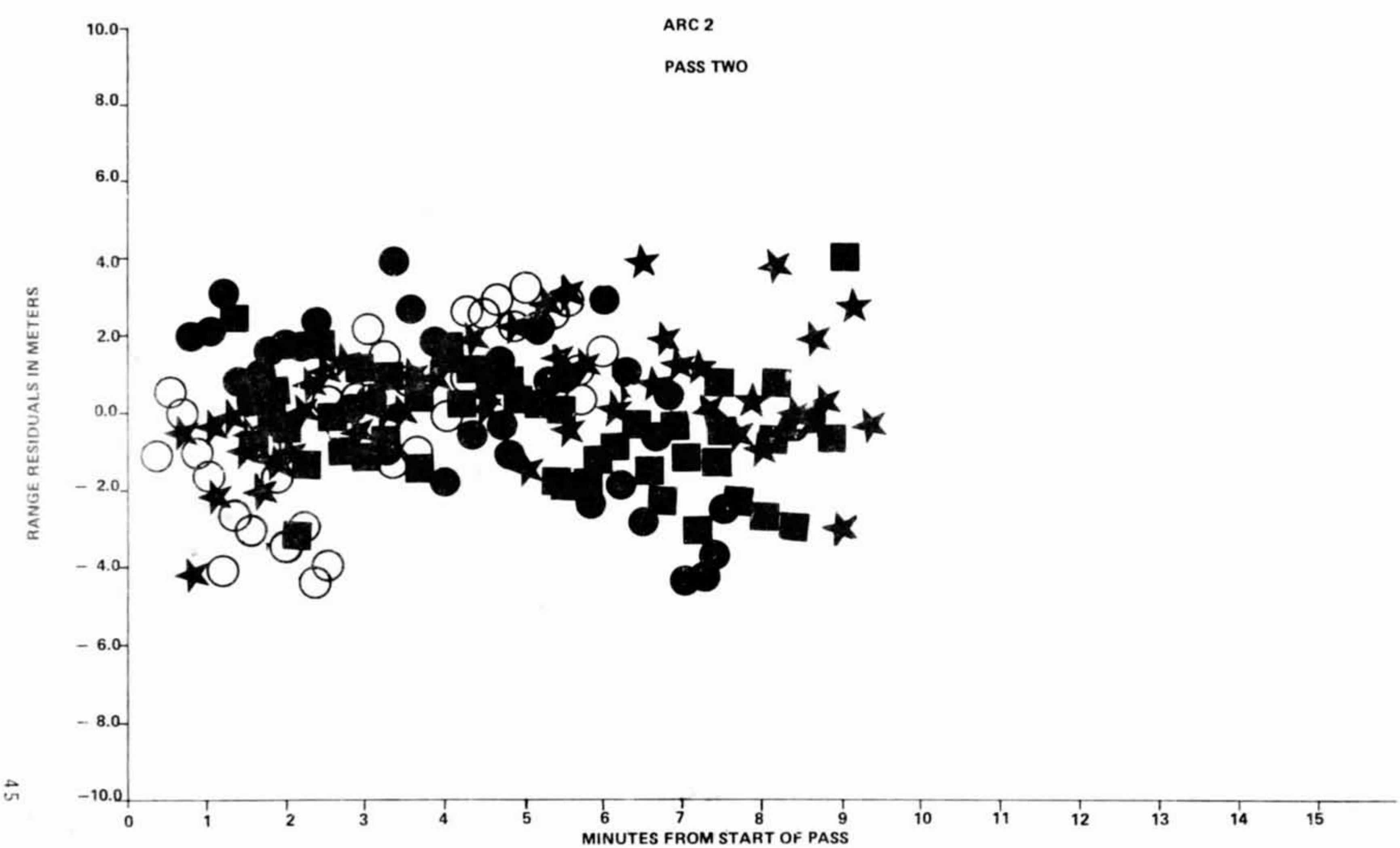
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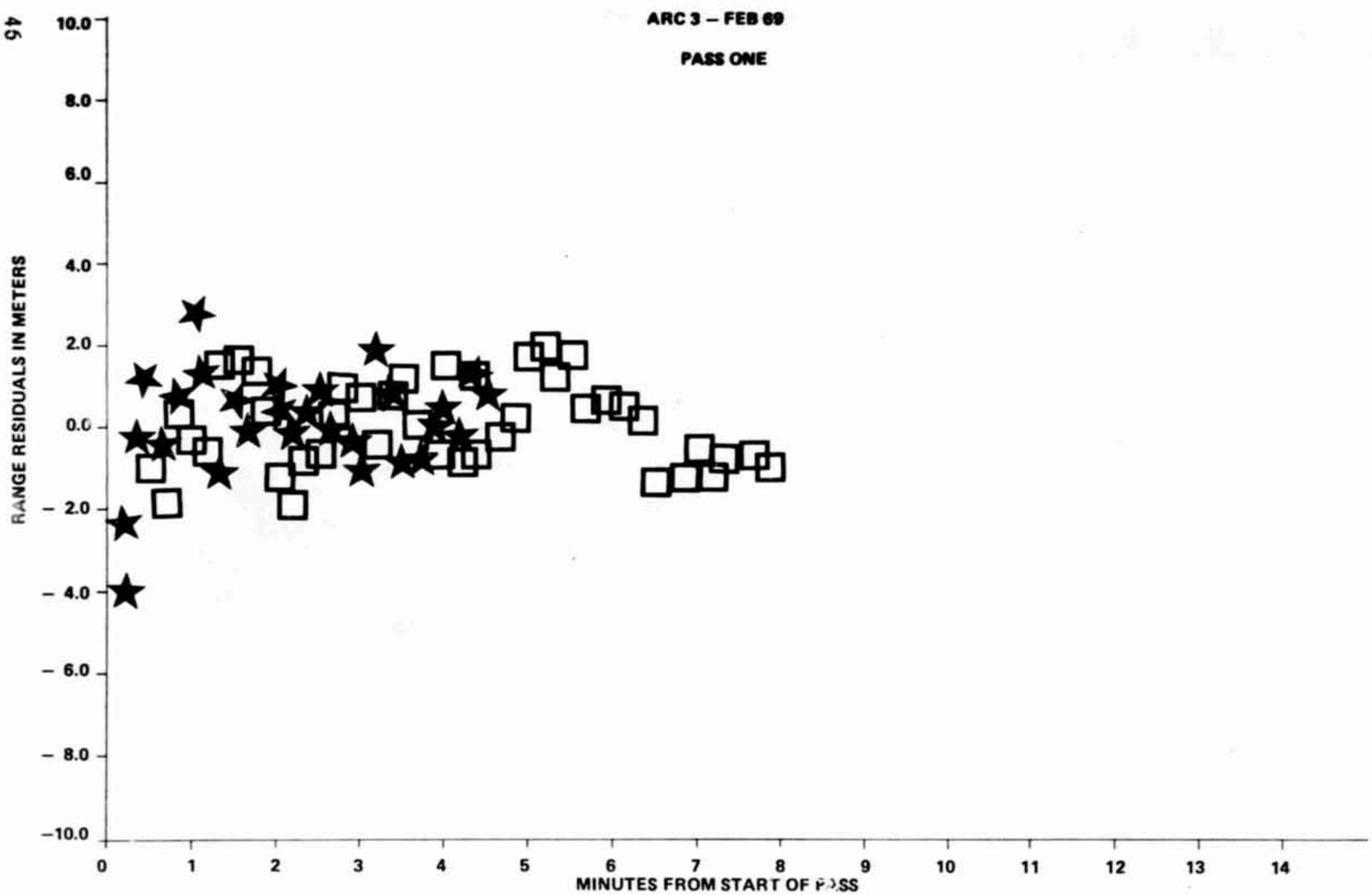
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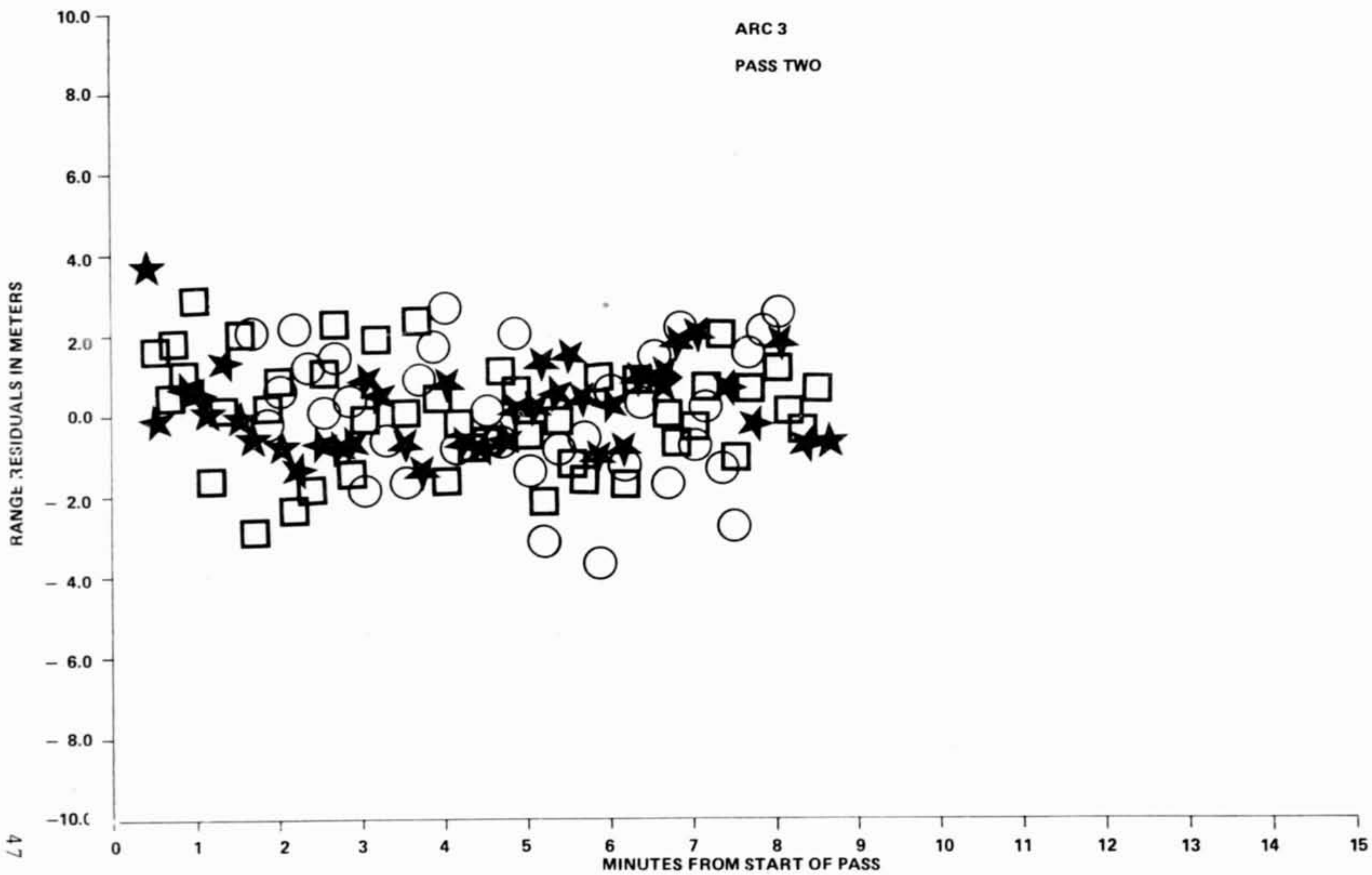
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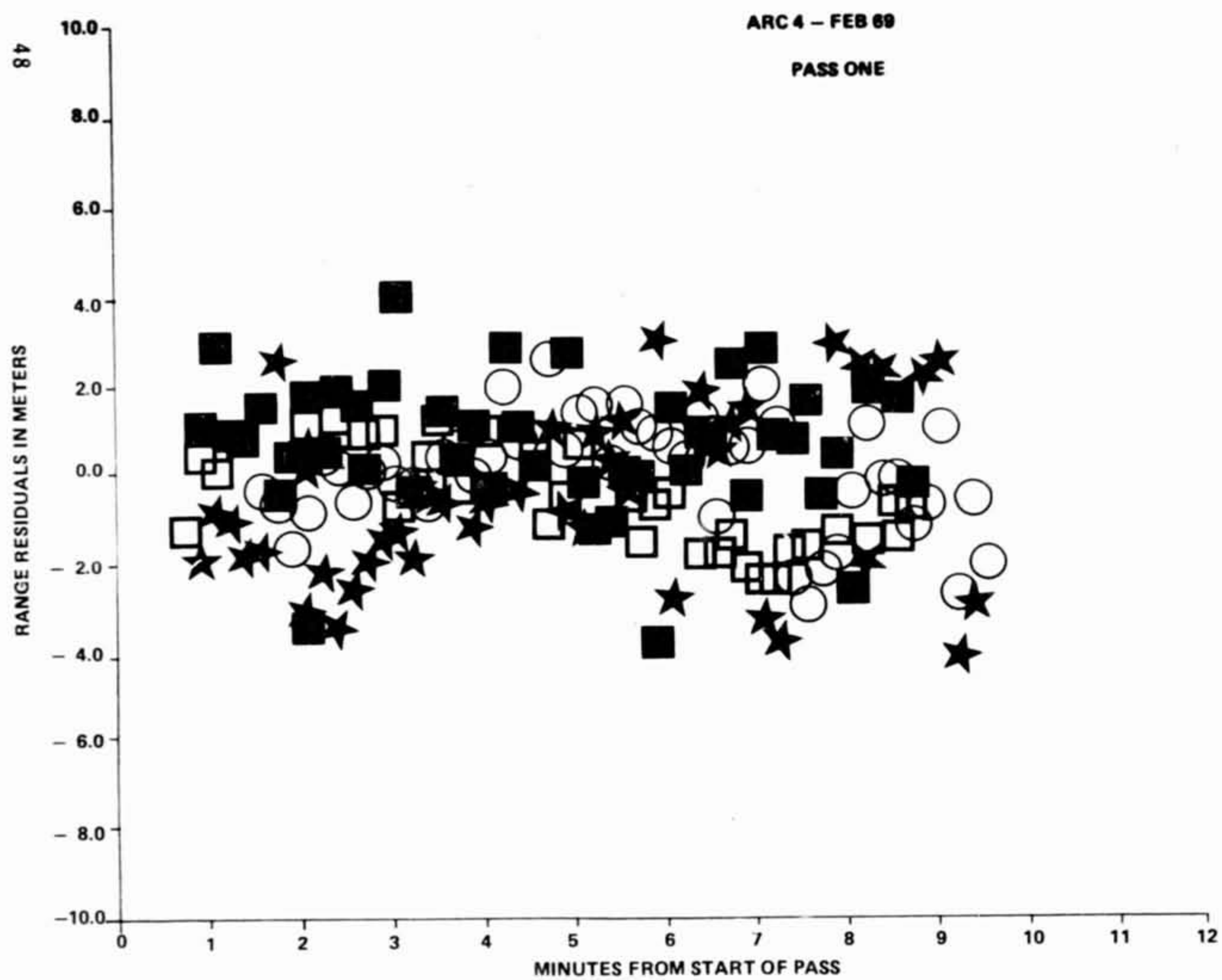

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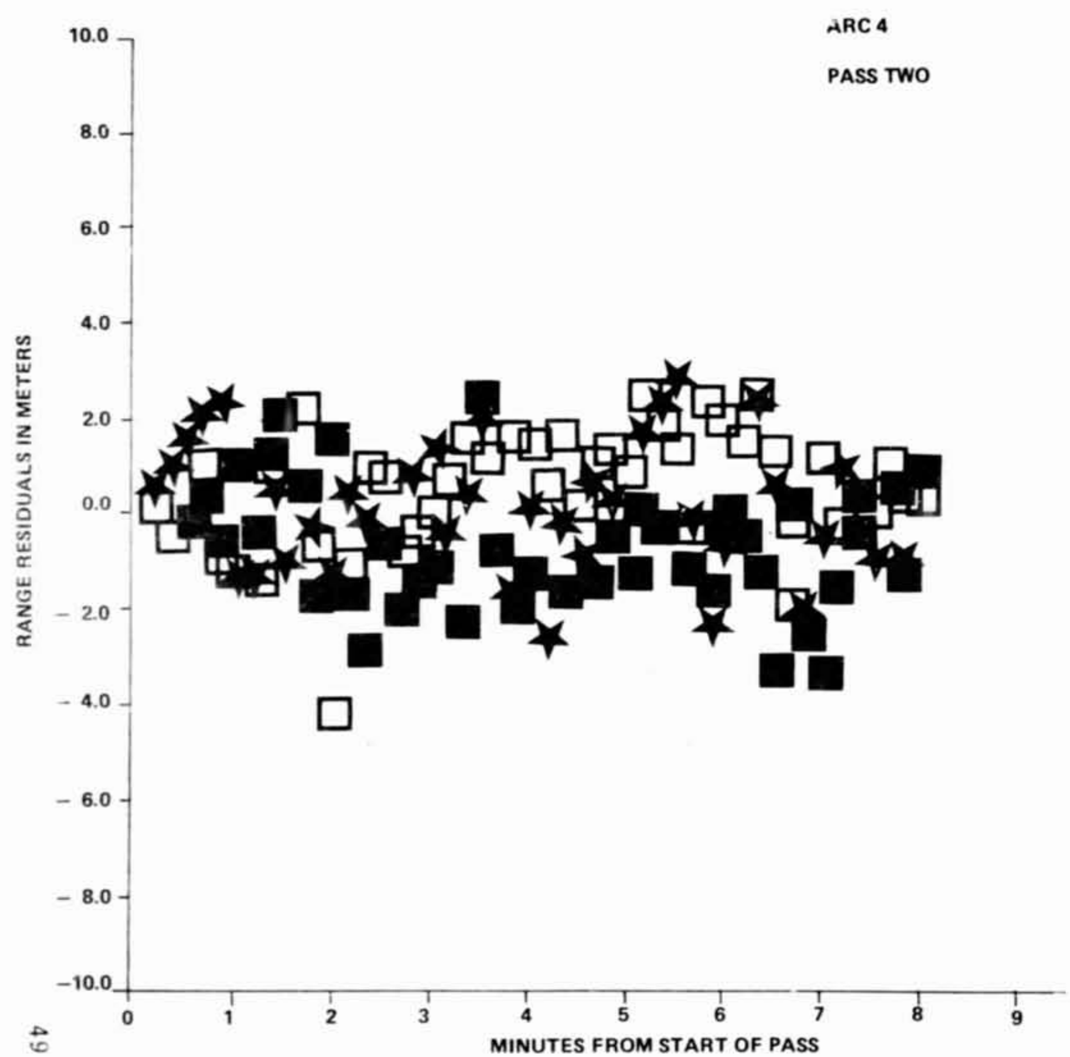
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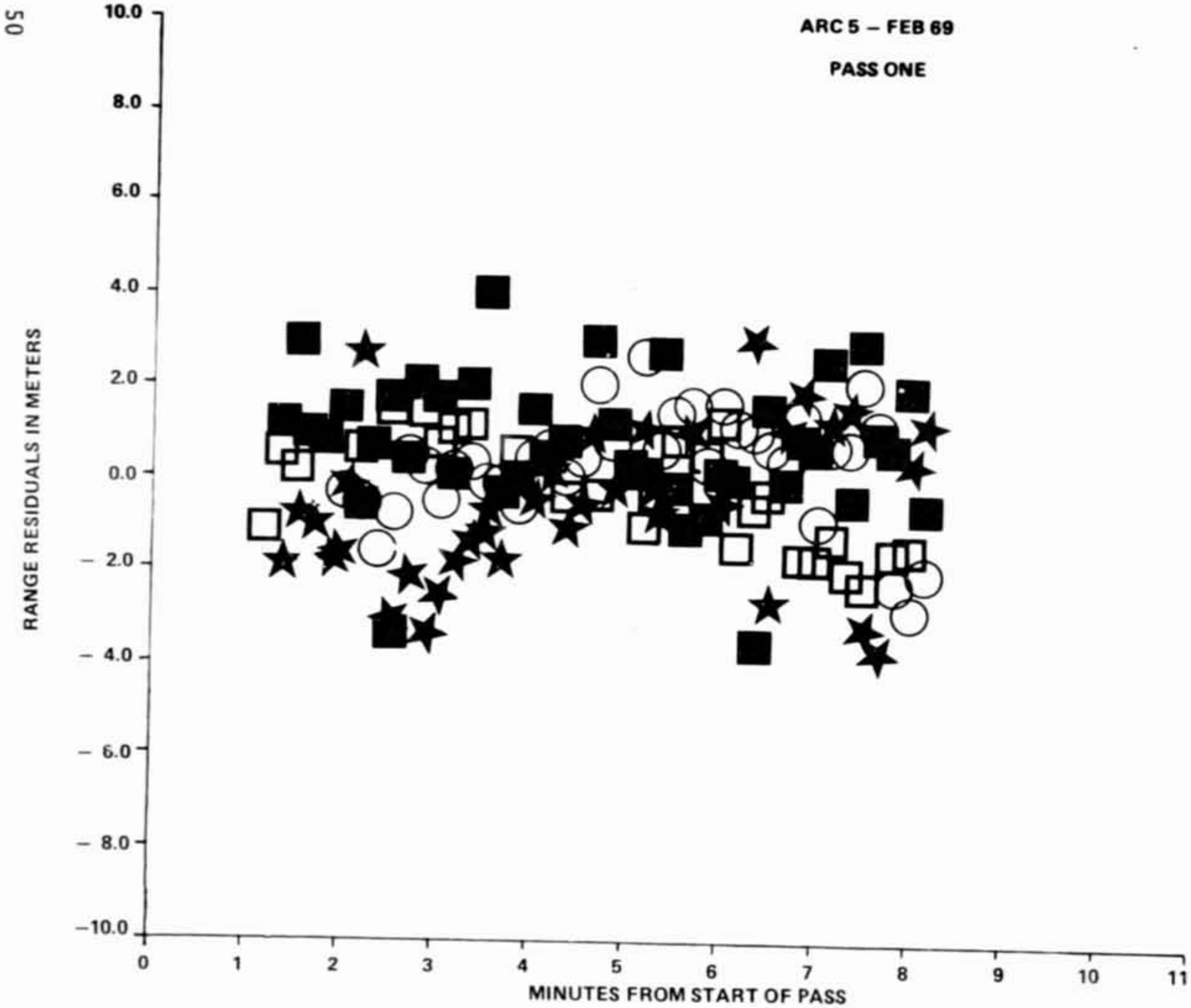
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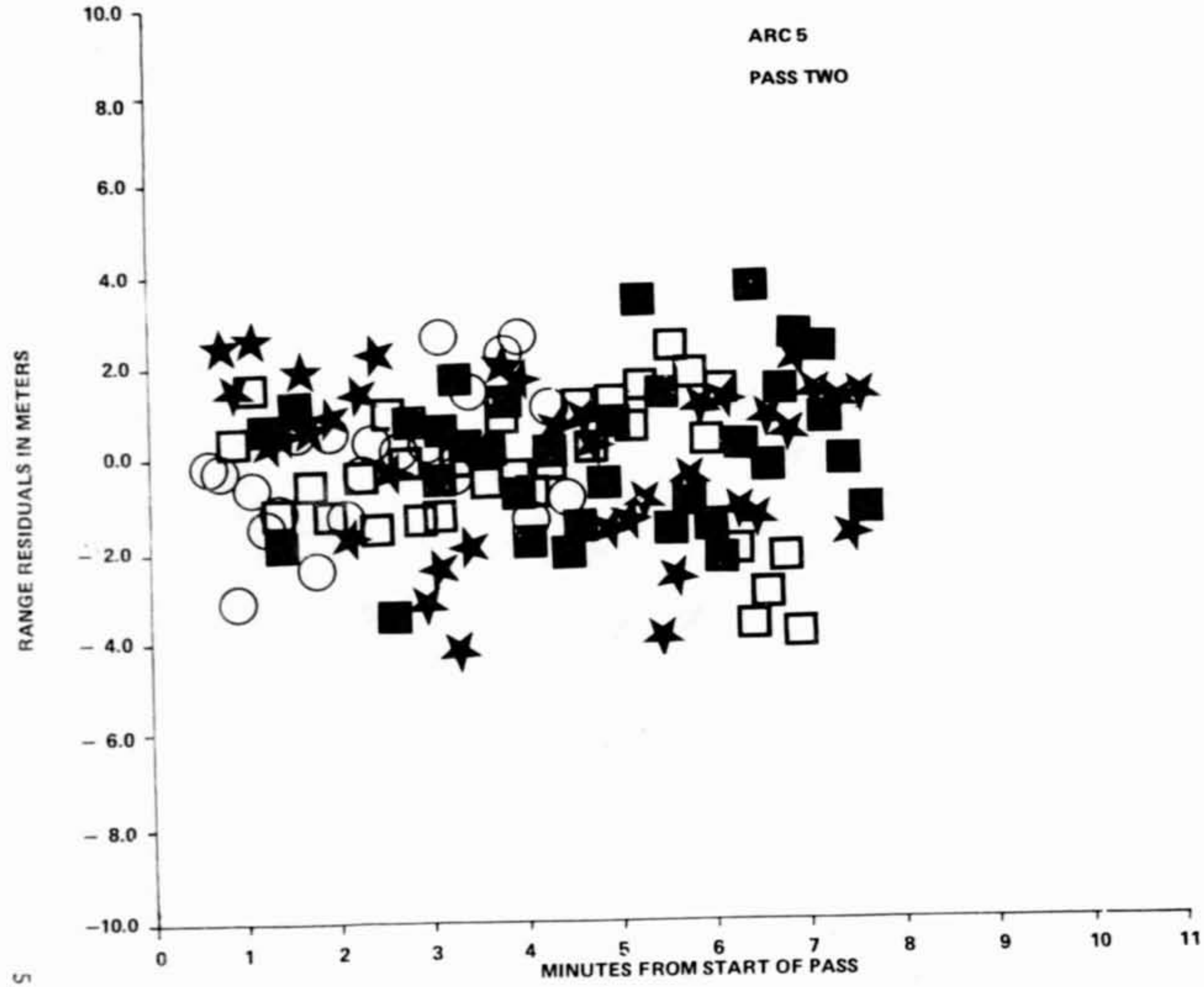
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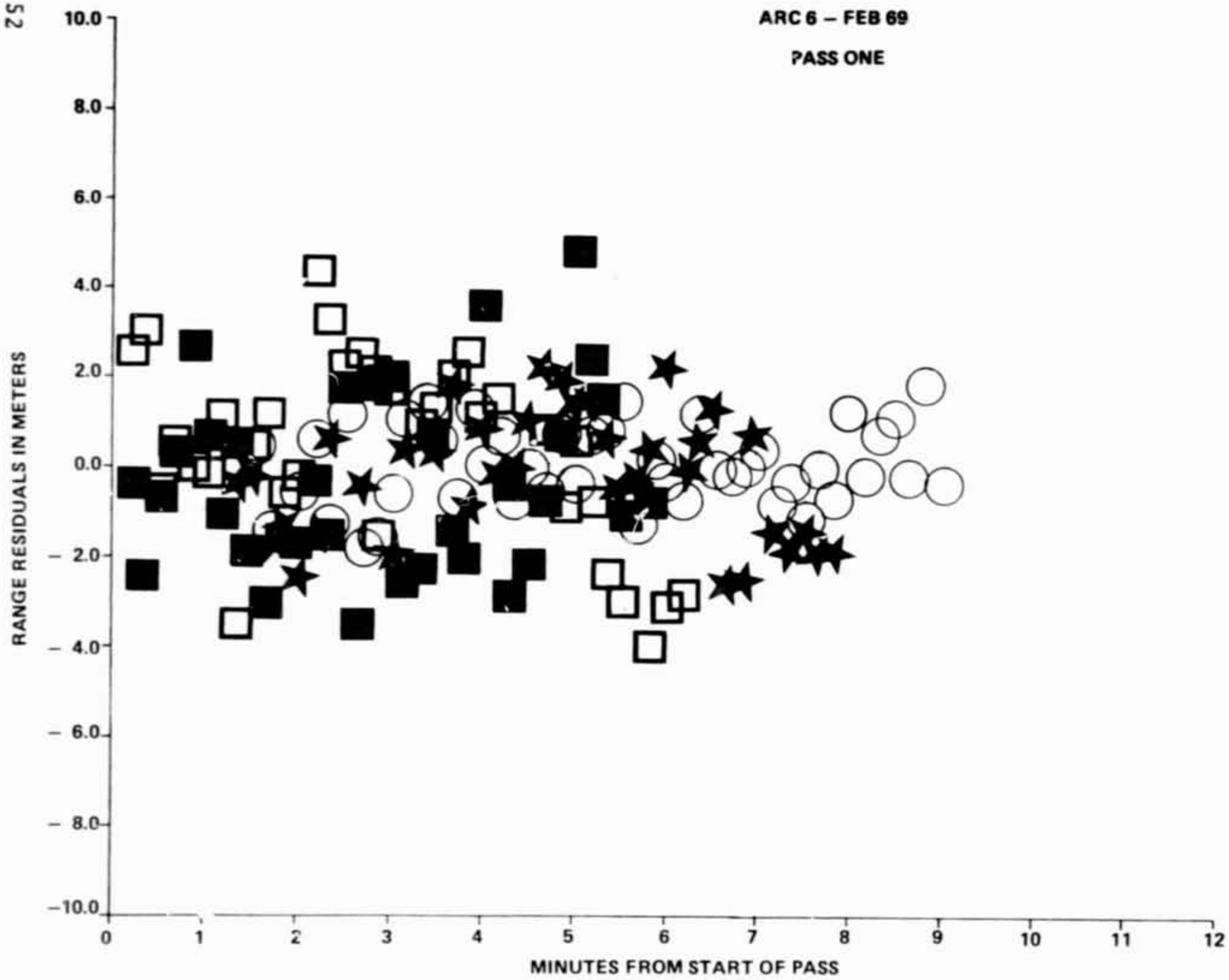
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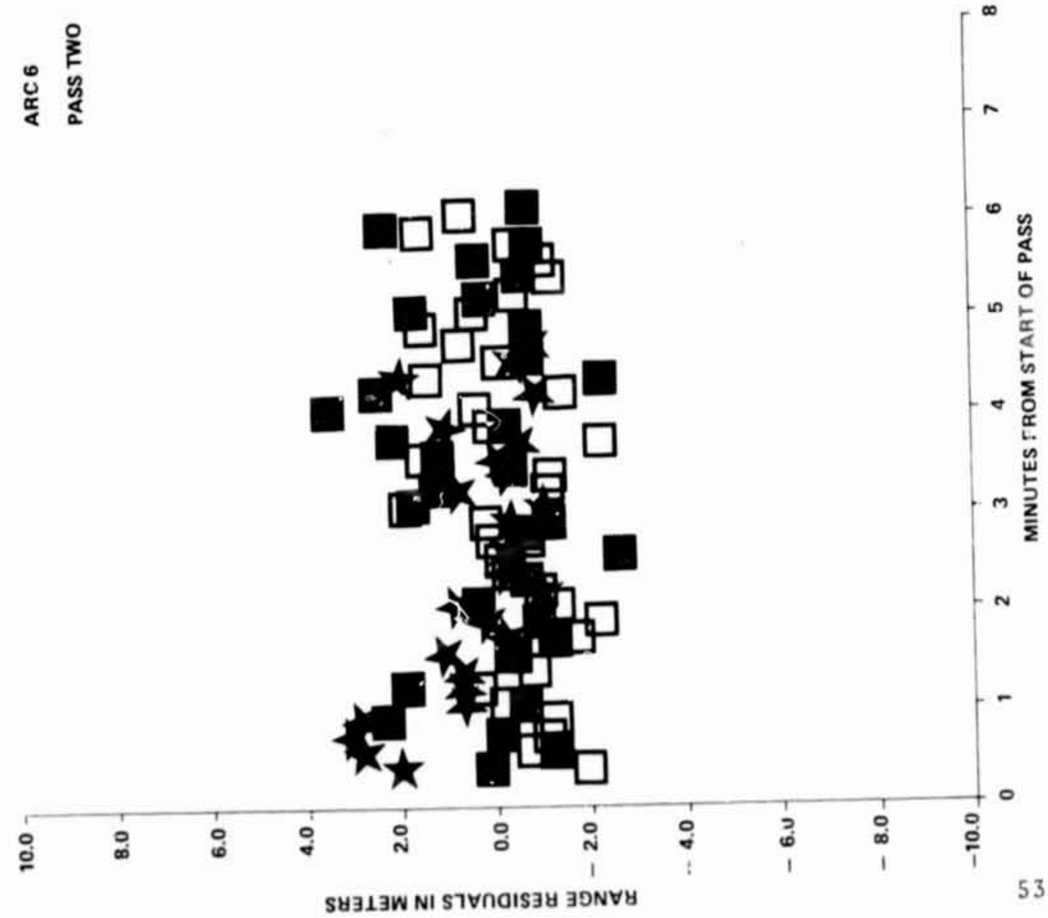
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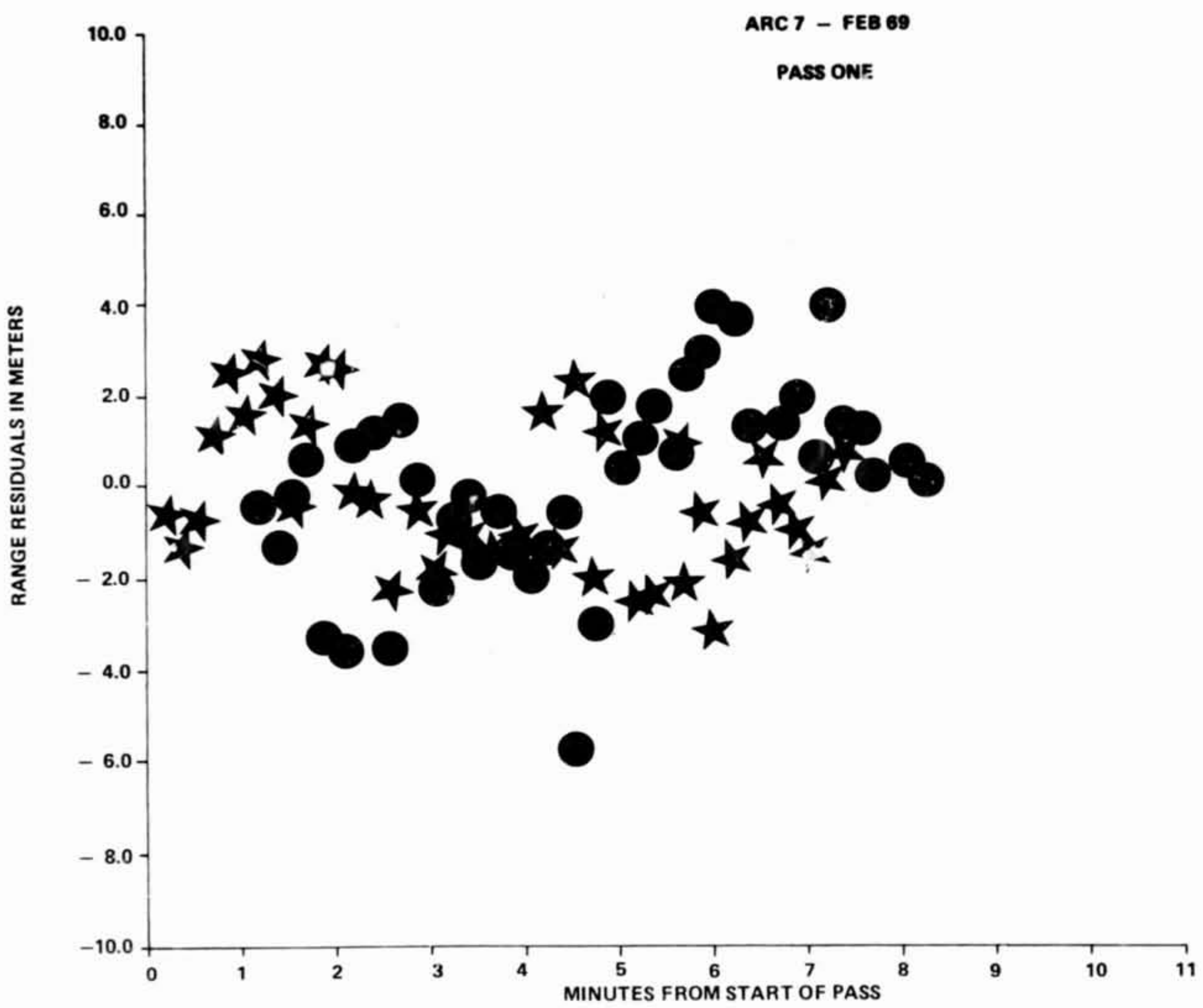
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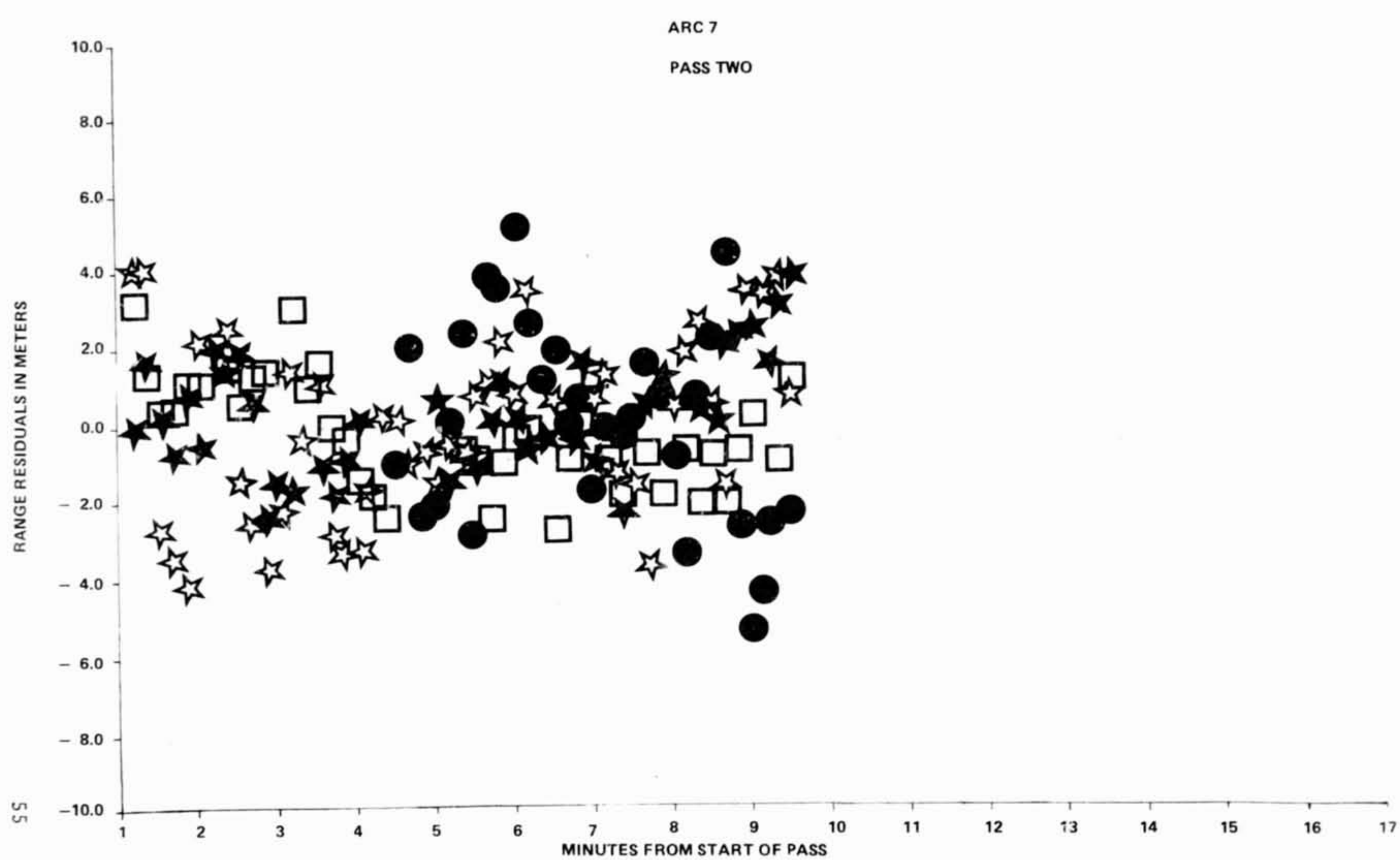

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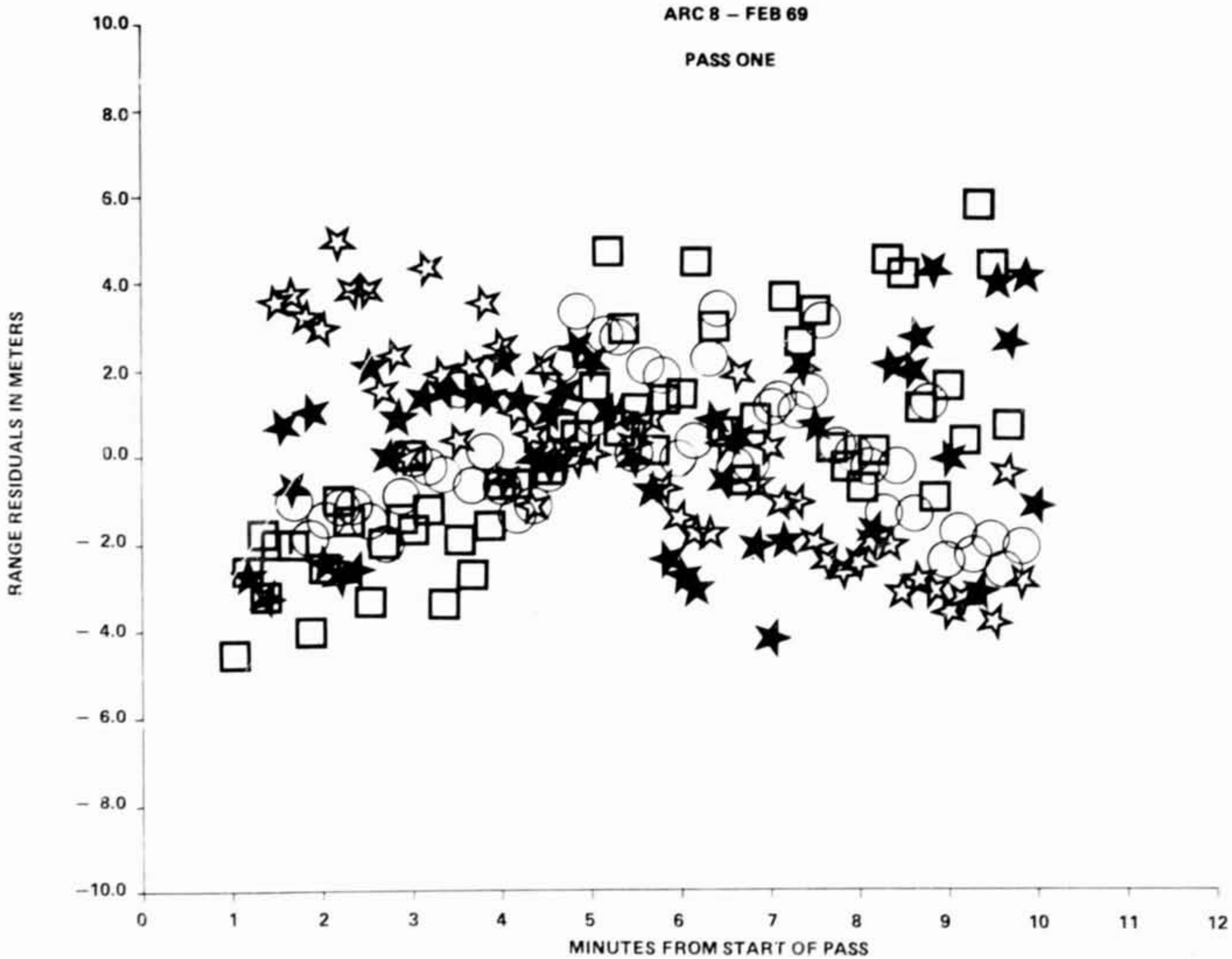
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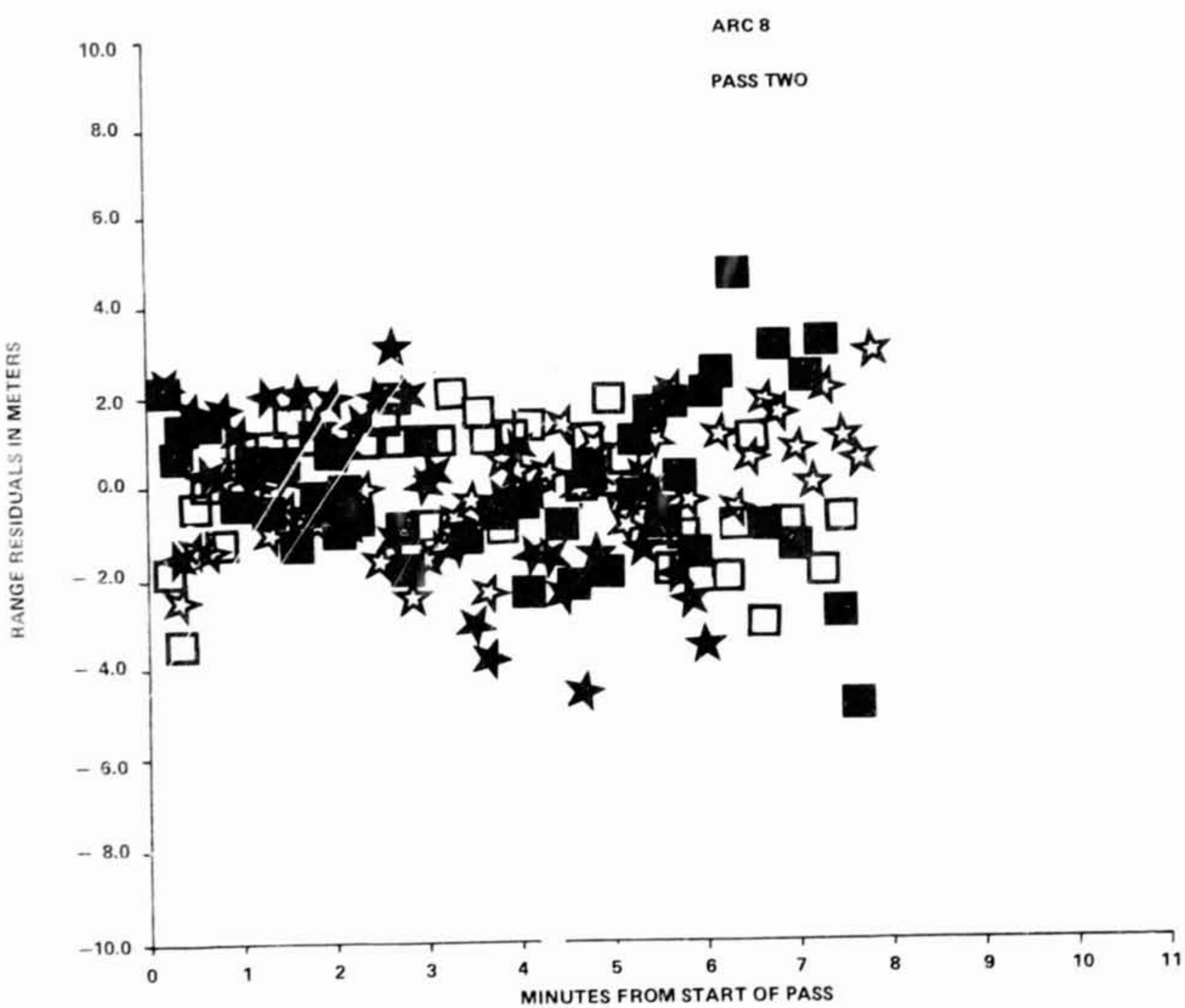

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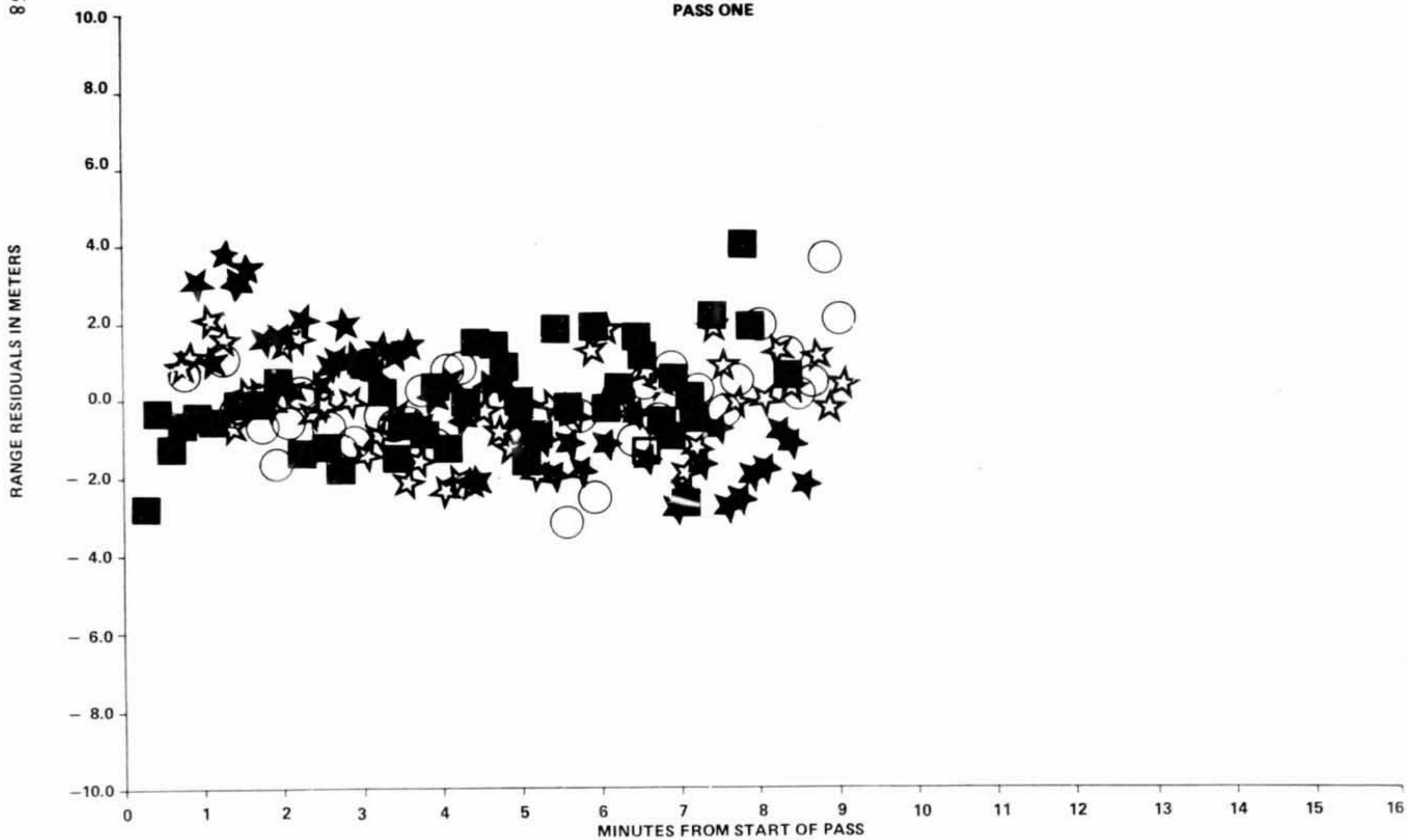

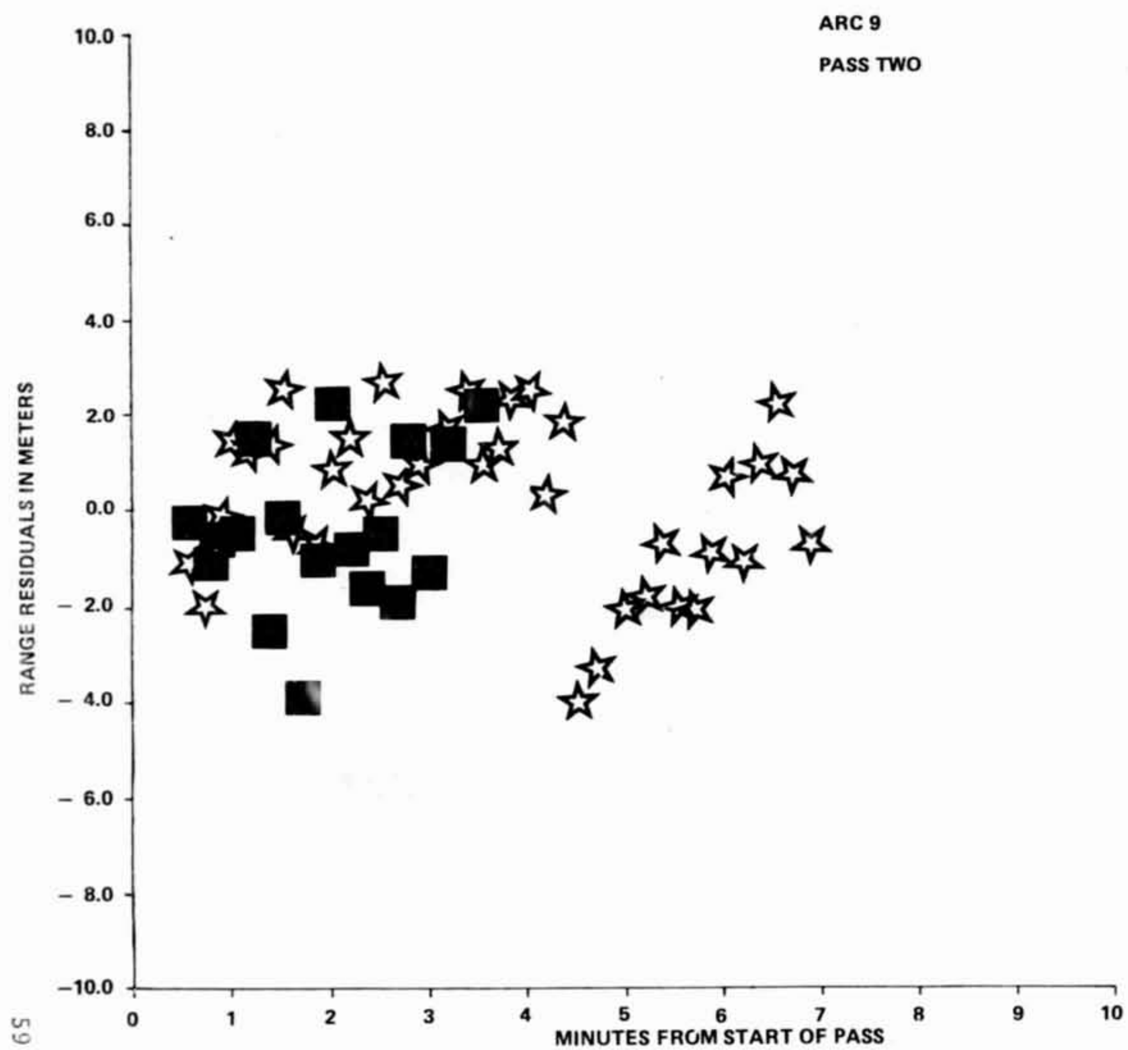
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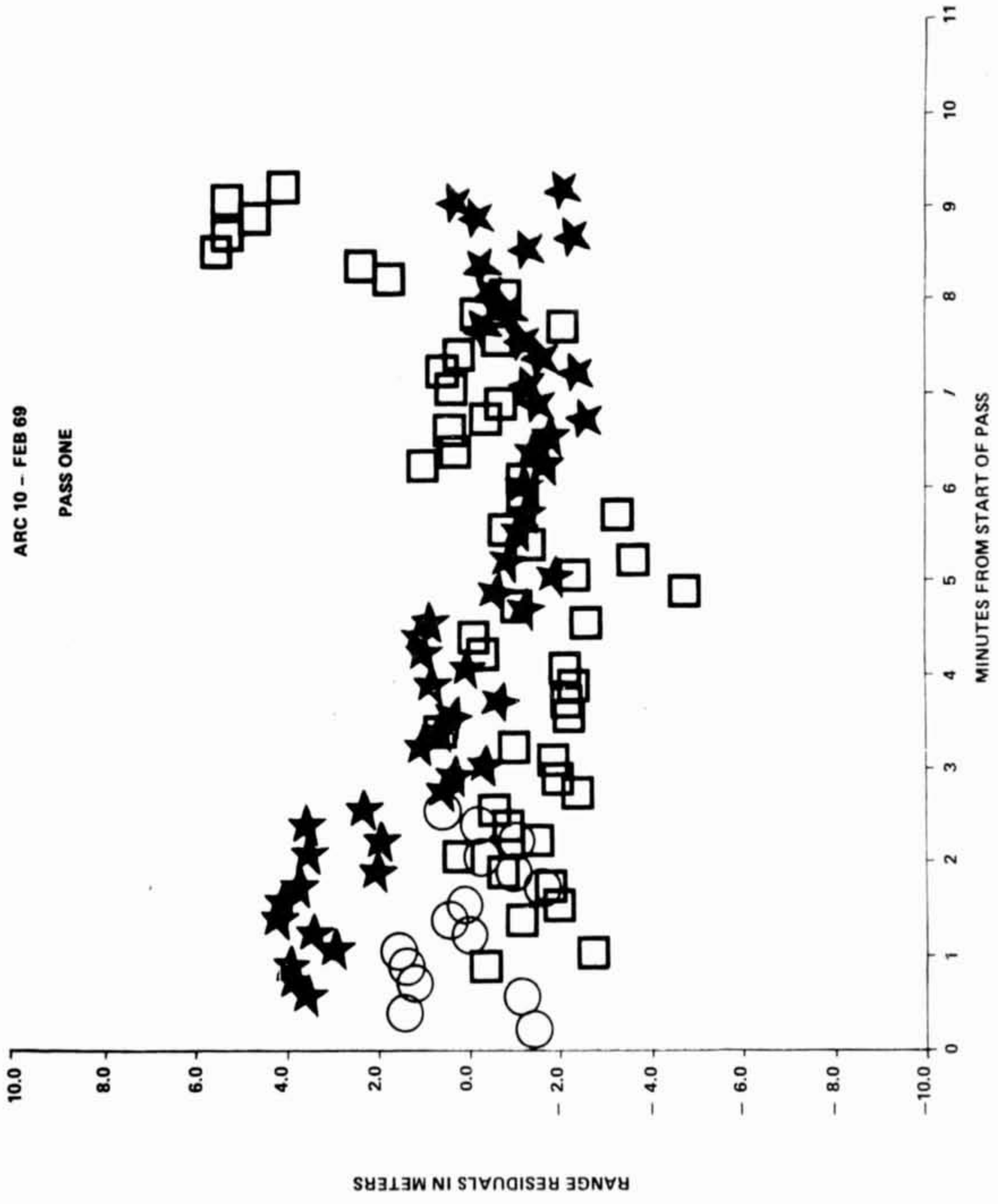
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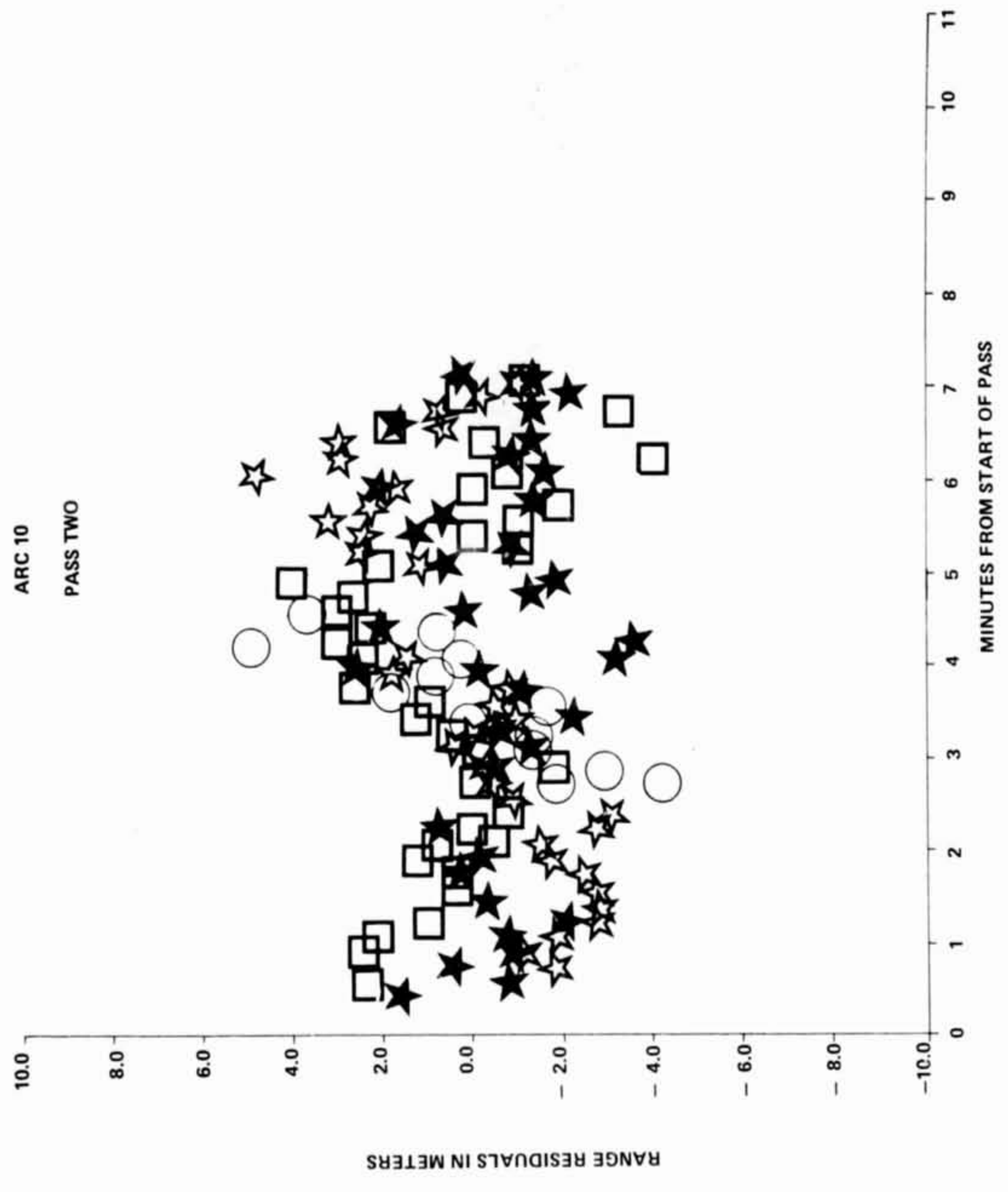
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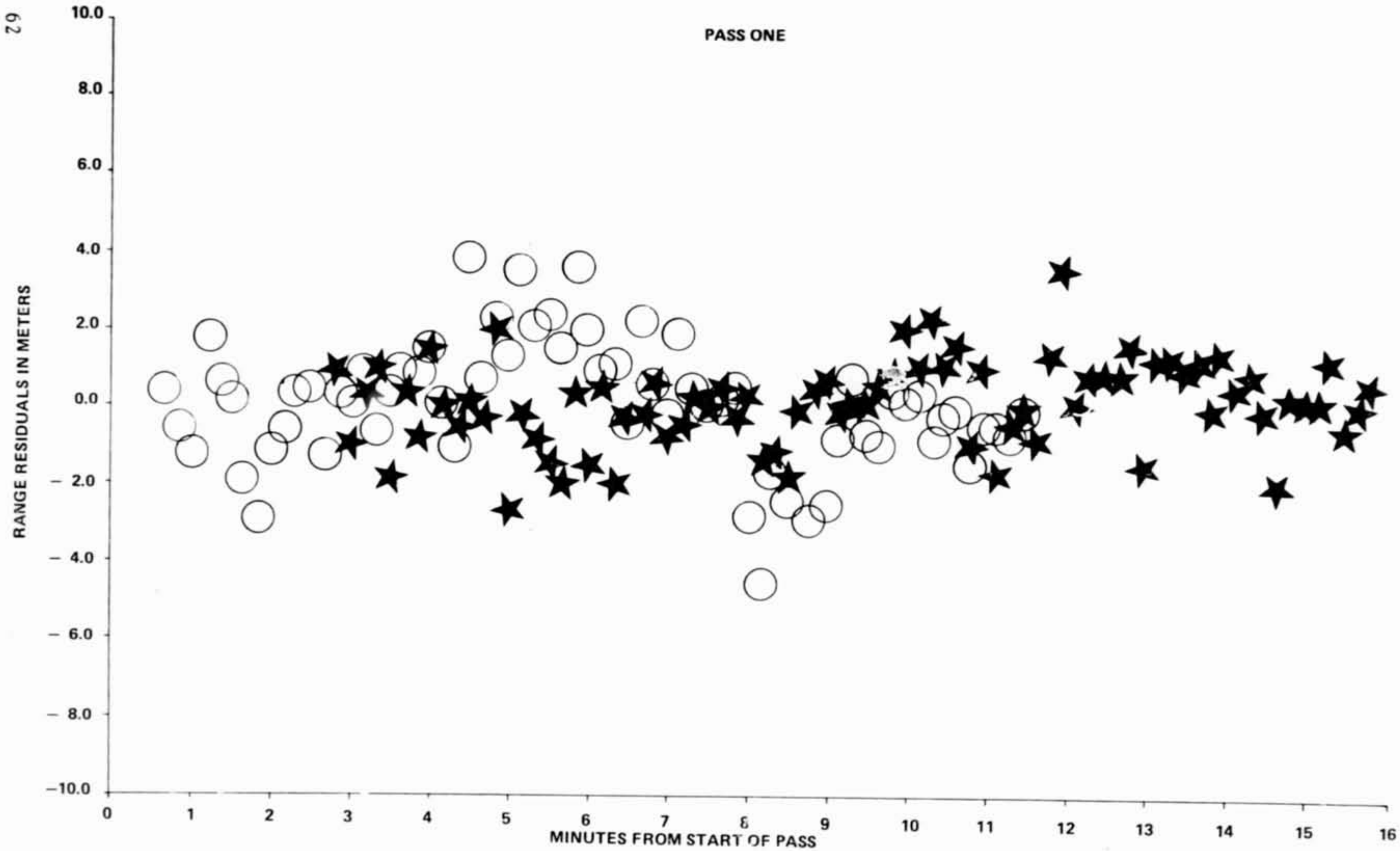
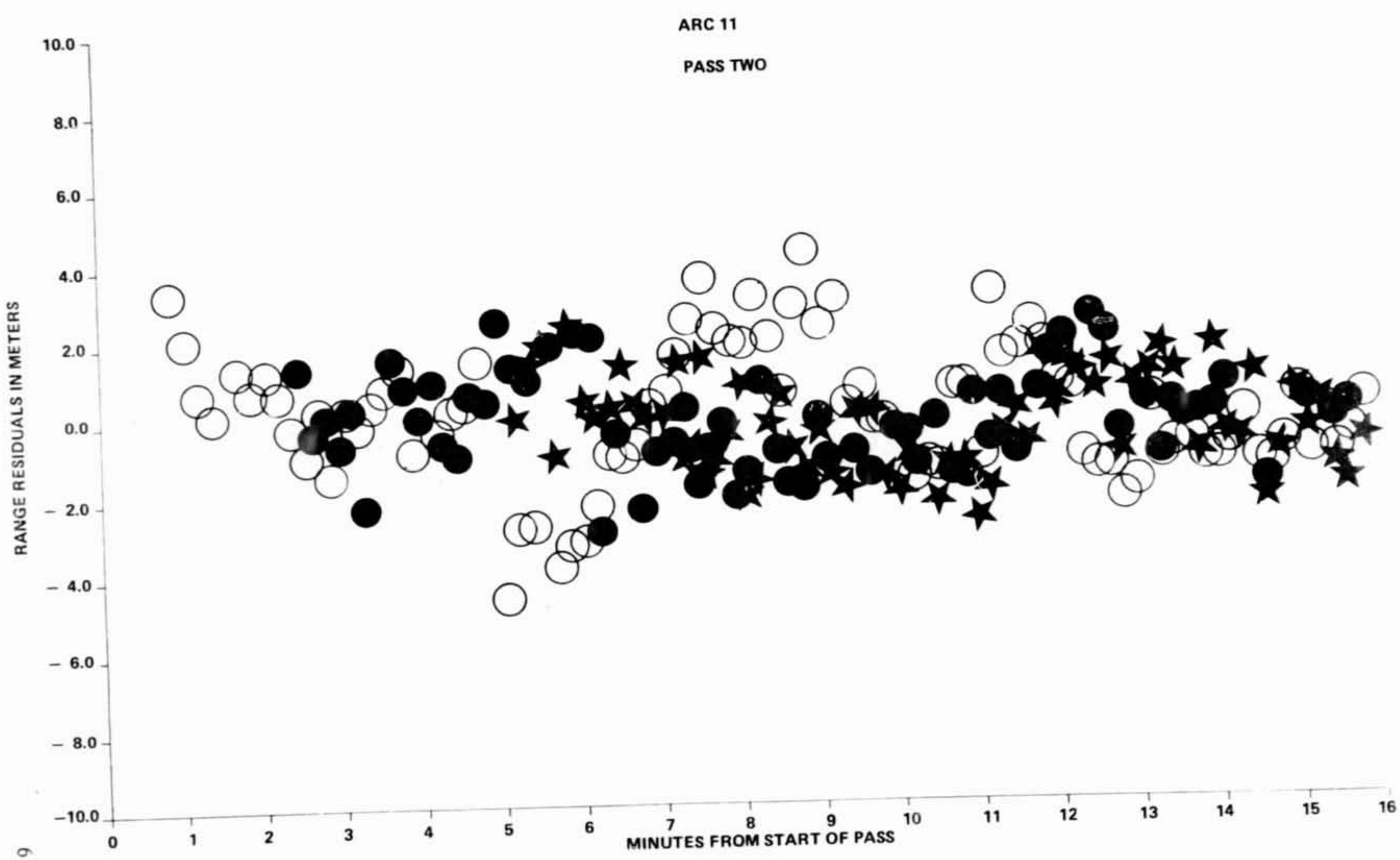
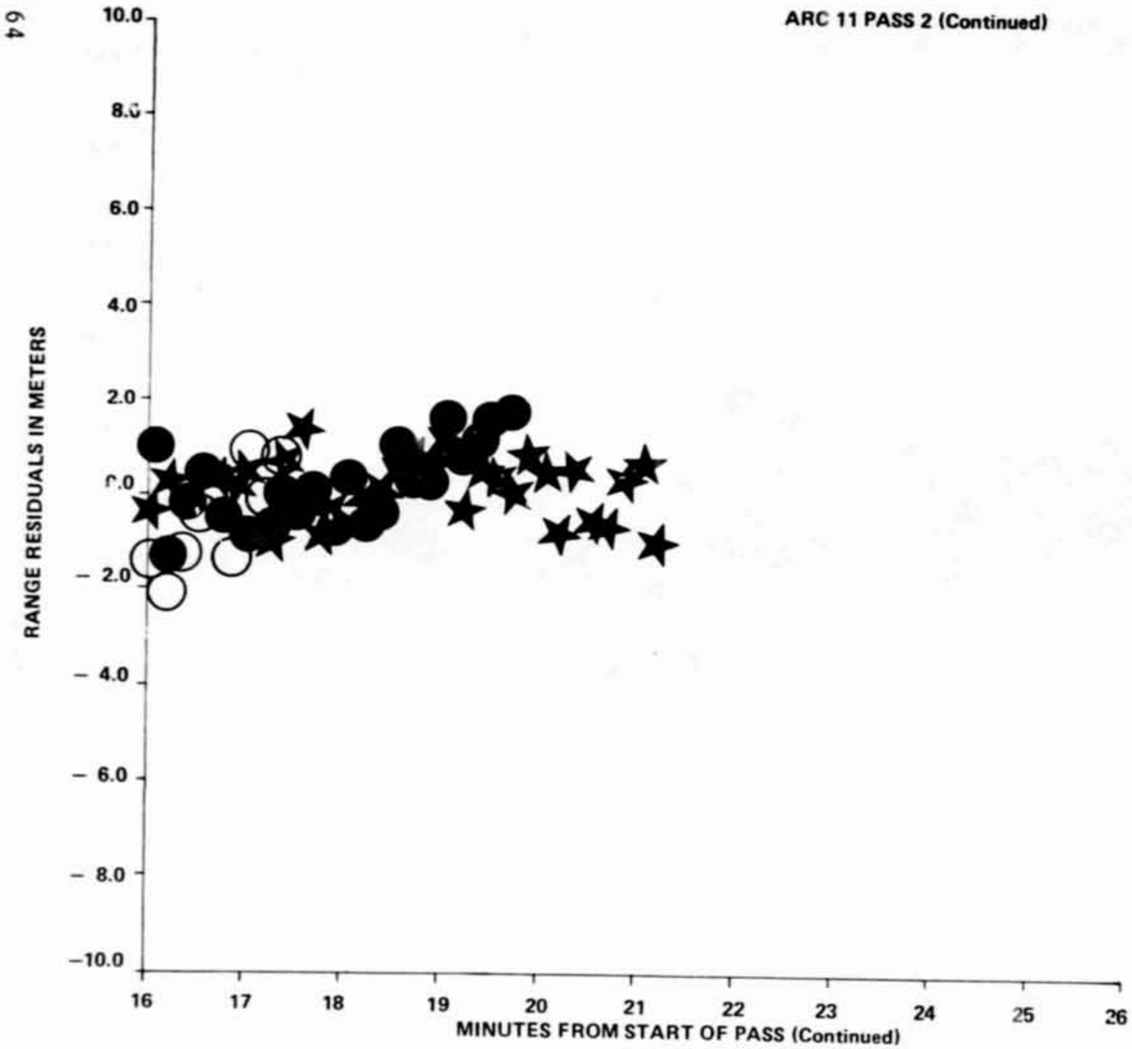
ARC 11 — SEPT 69

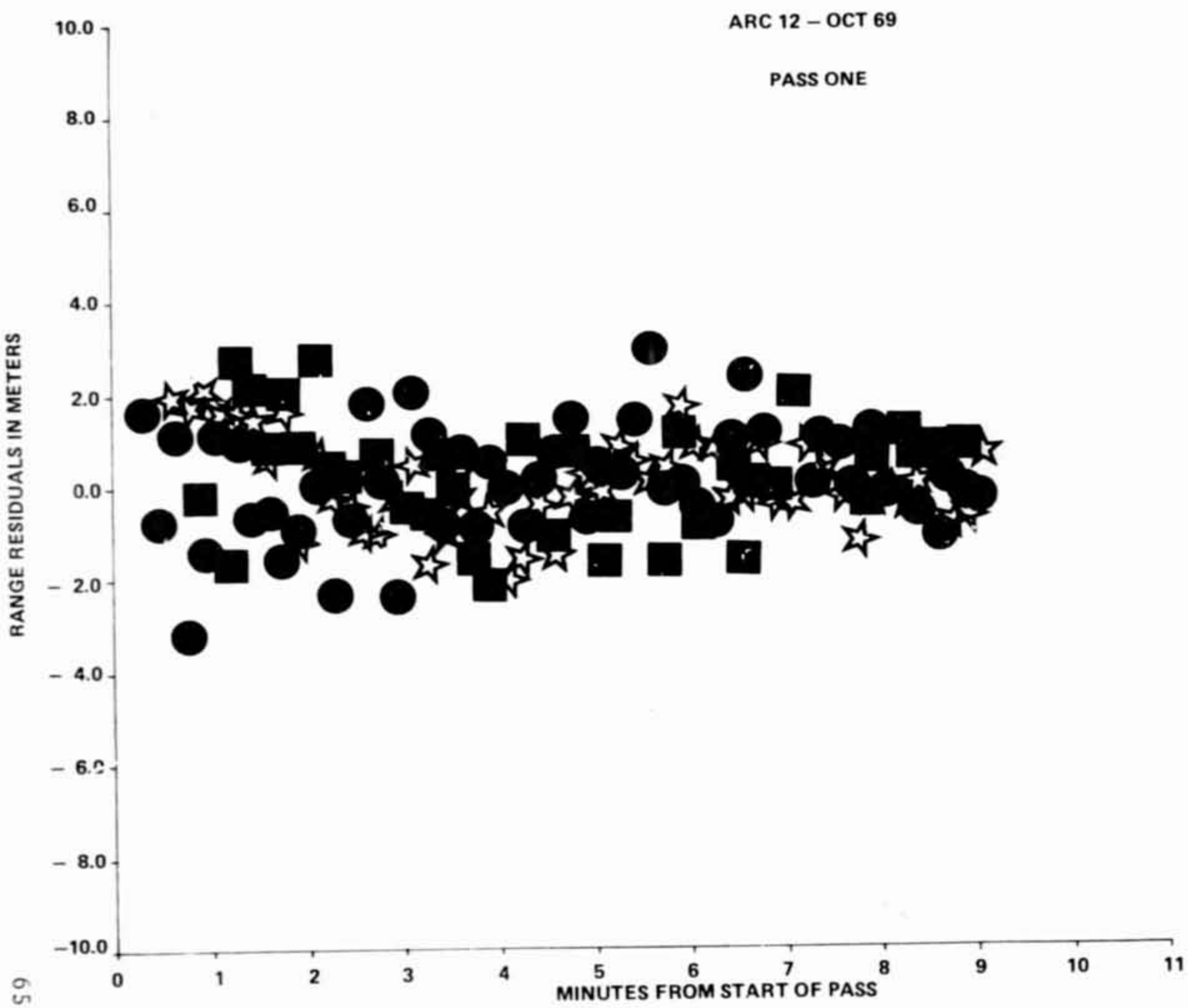
PASS ONE



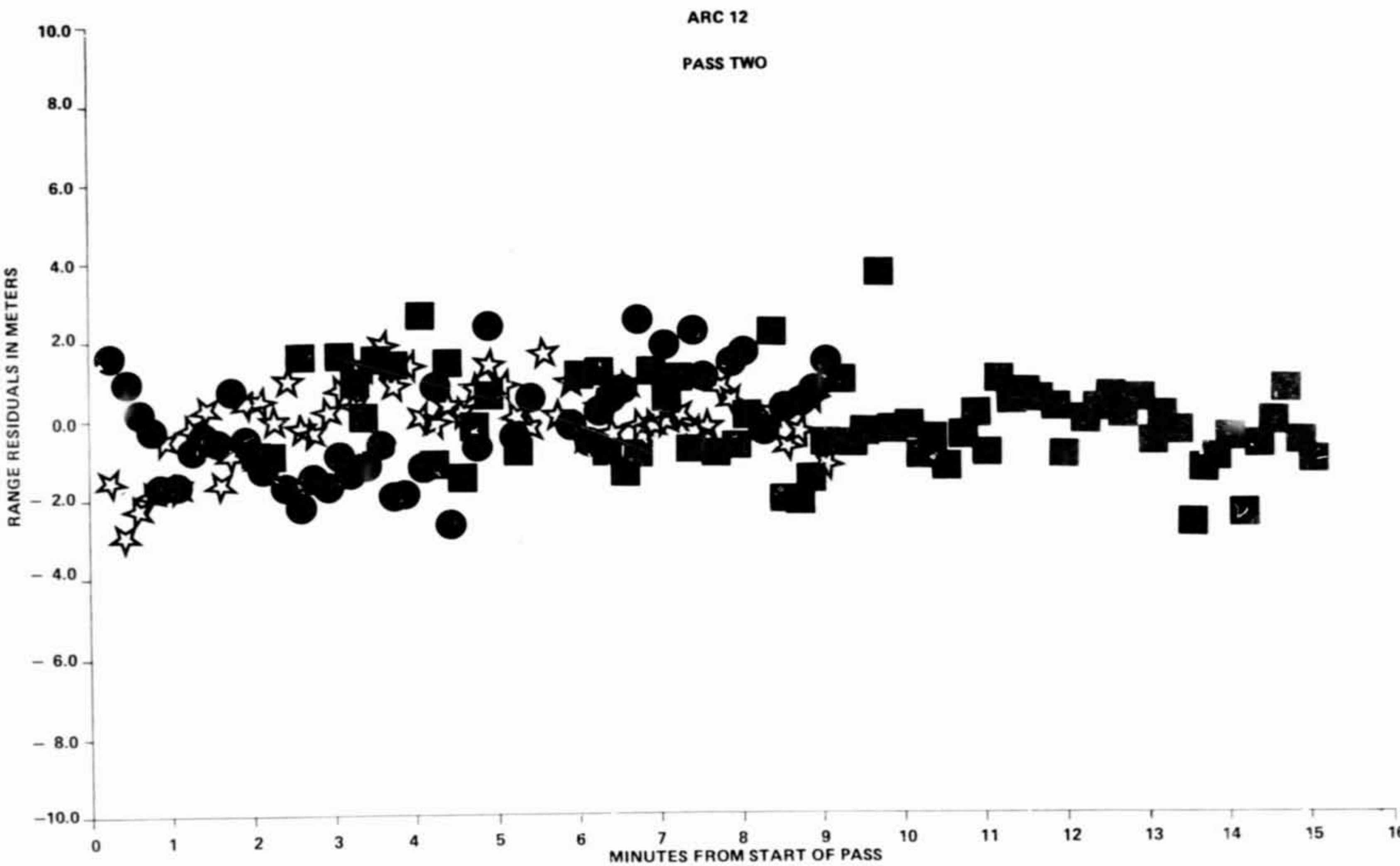

ARC 11
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS

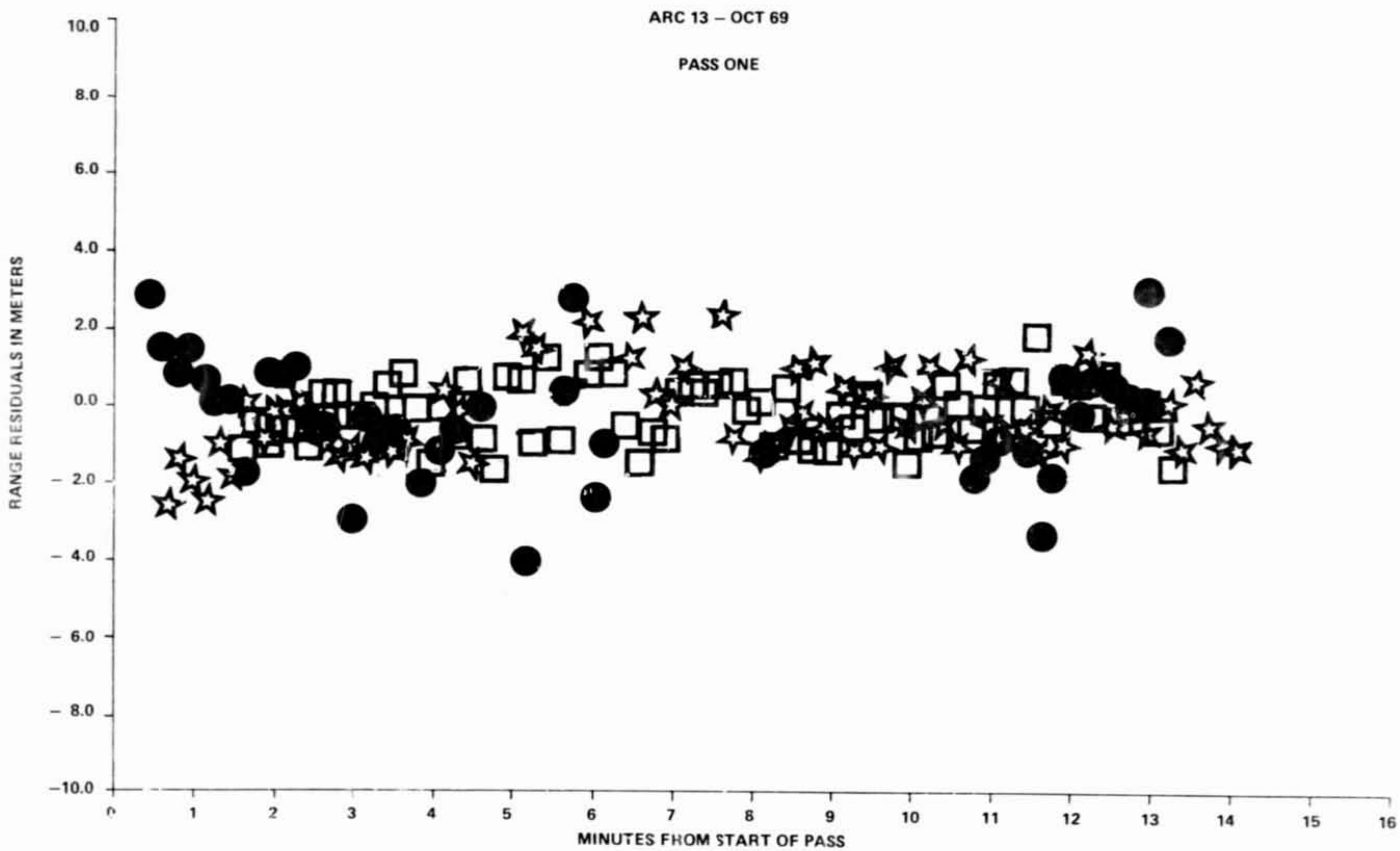


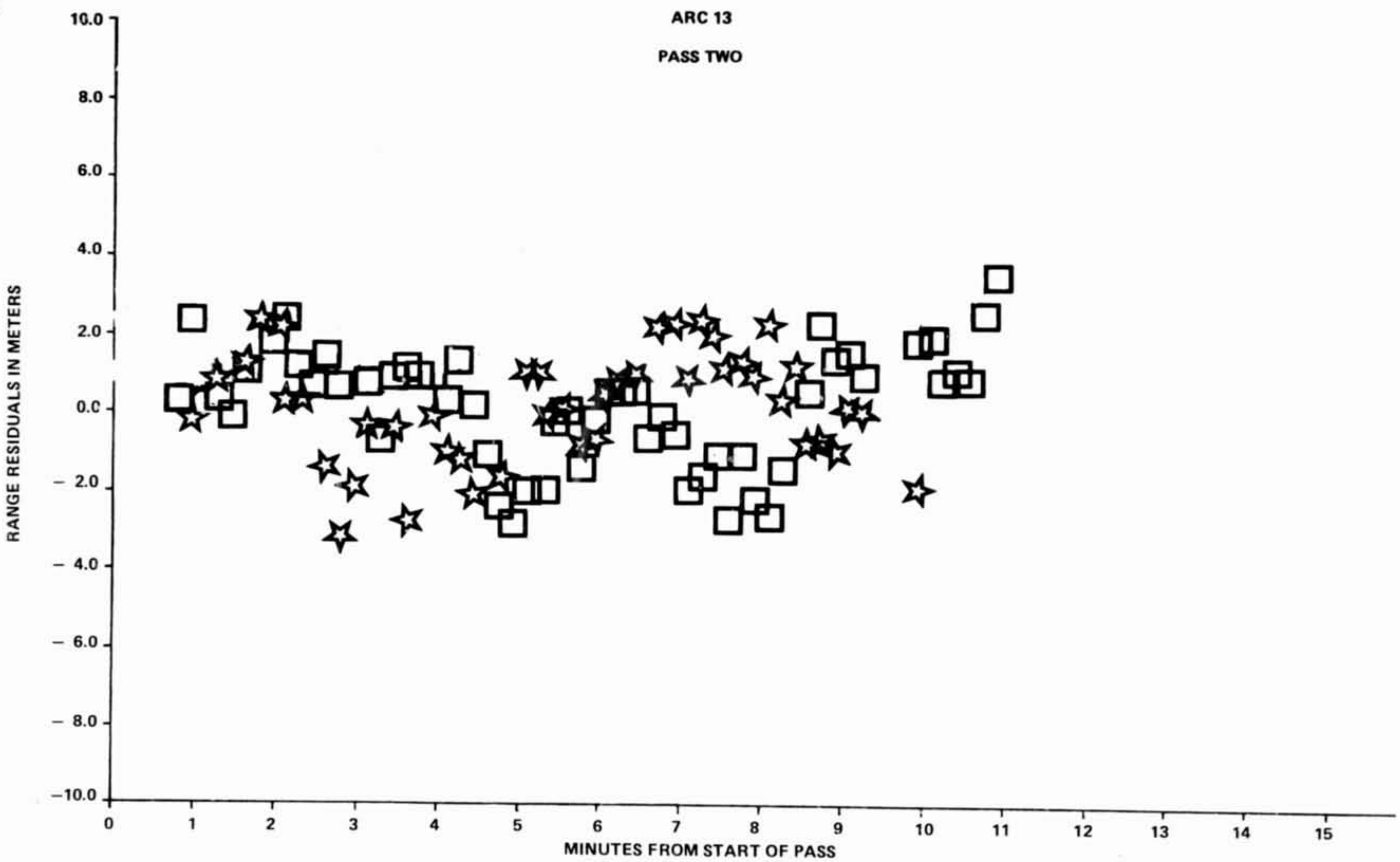
ARC 11 PASS 2 (Continued)
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
16
17
18
19
20
21
22
23
24
25
26
MINUTES FROM START OF PASS (Continued)



ARC 12 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
MINUTES FROM START OF PASS

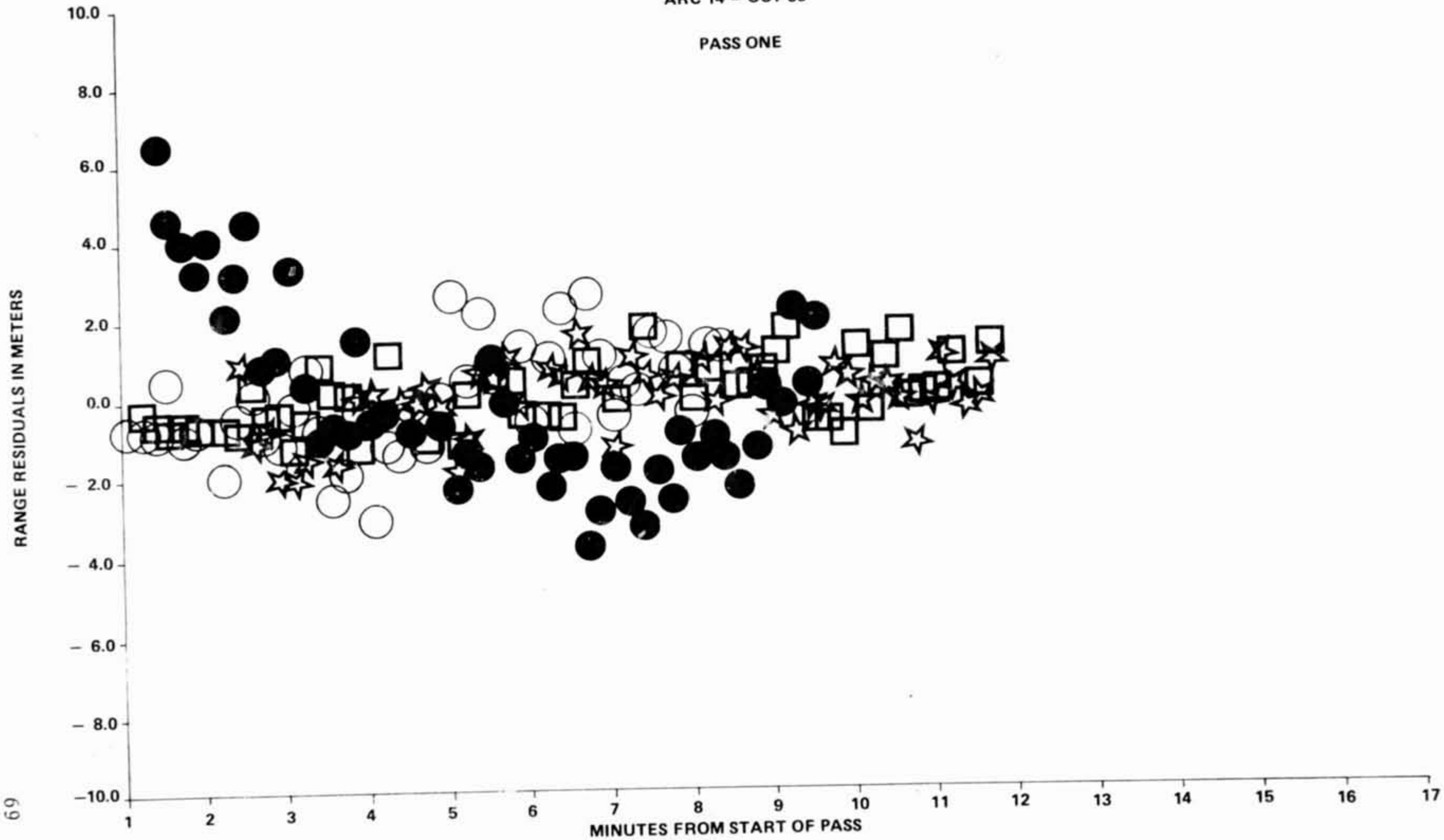

ARC 12
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS

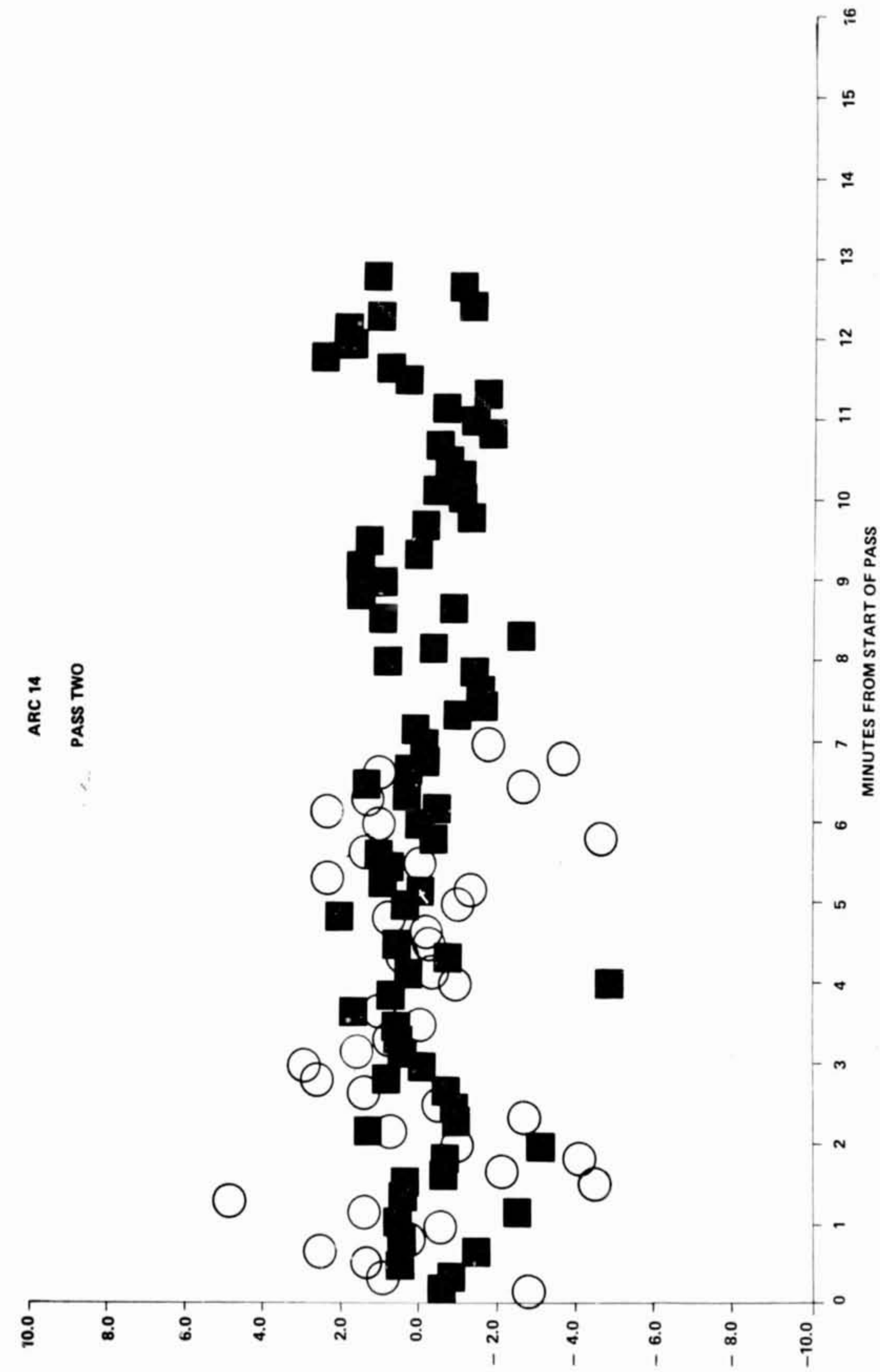

ARC 13 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS

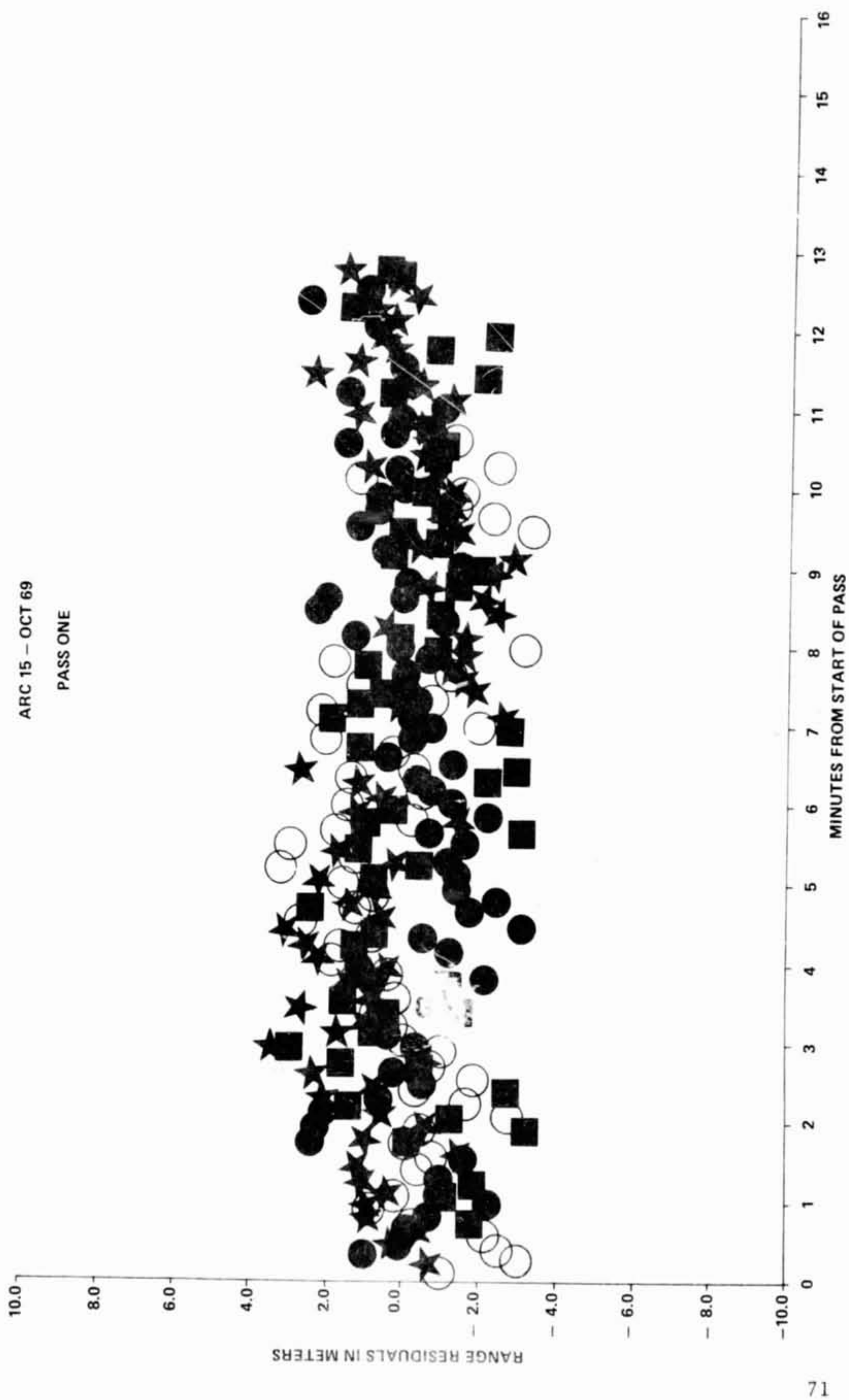

ARC 13
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
MINUTES FROM START OF PASS

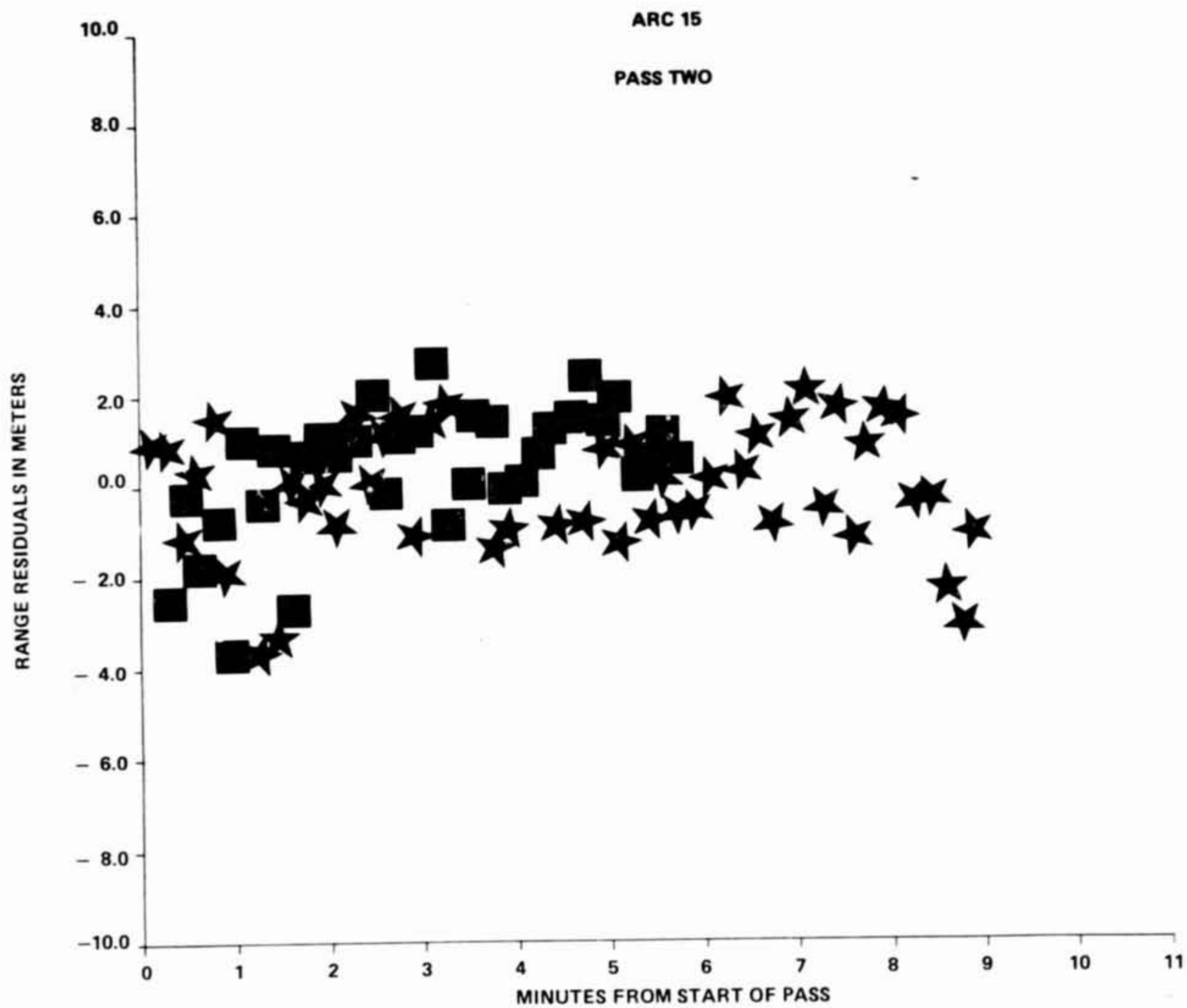
ARC 14 – OCT 69

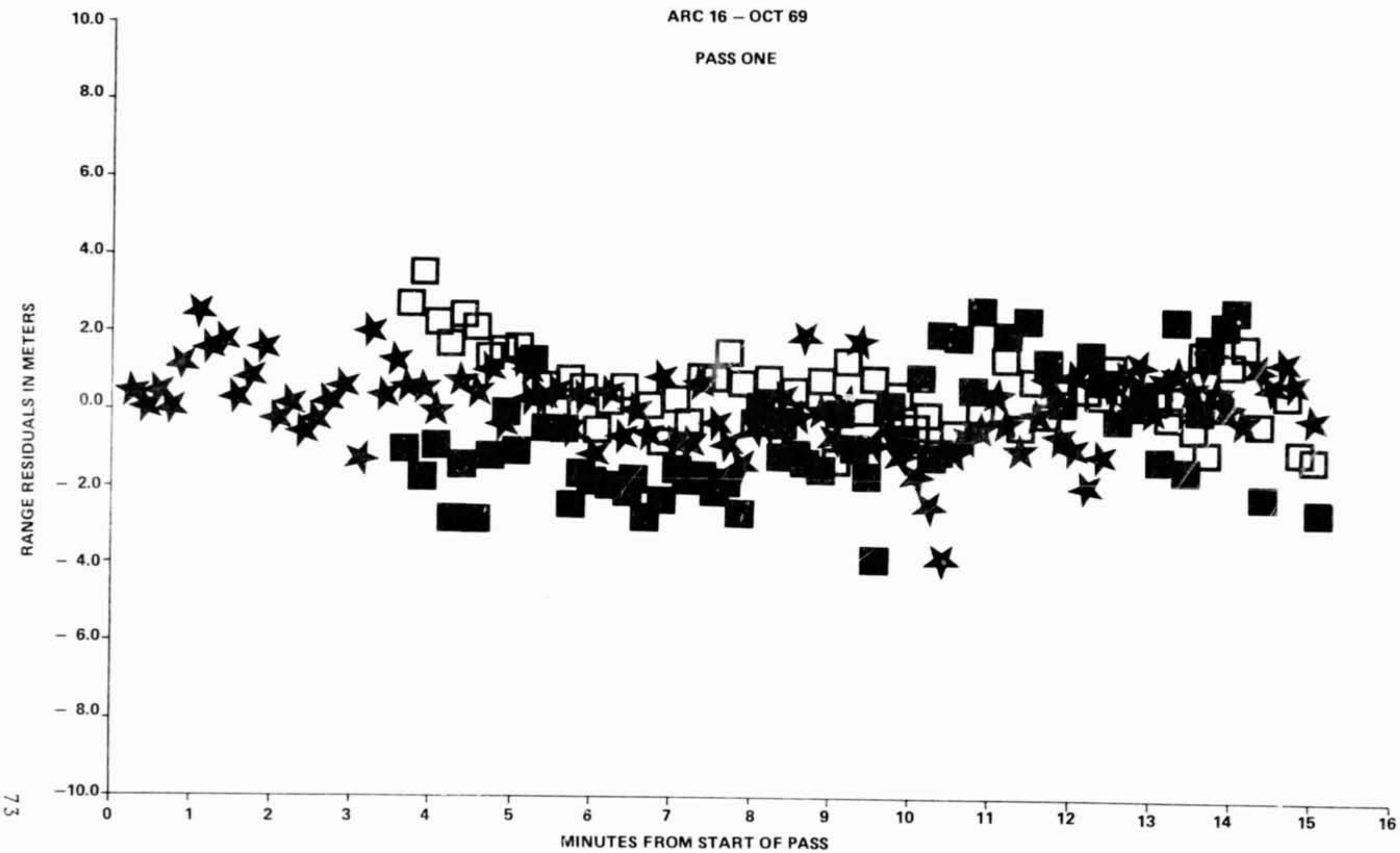
PASS ONE

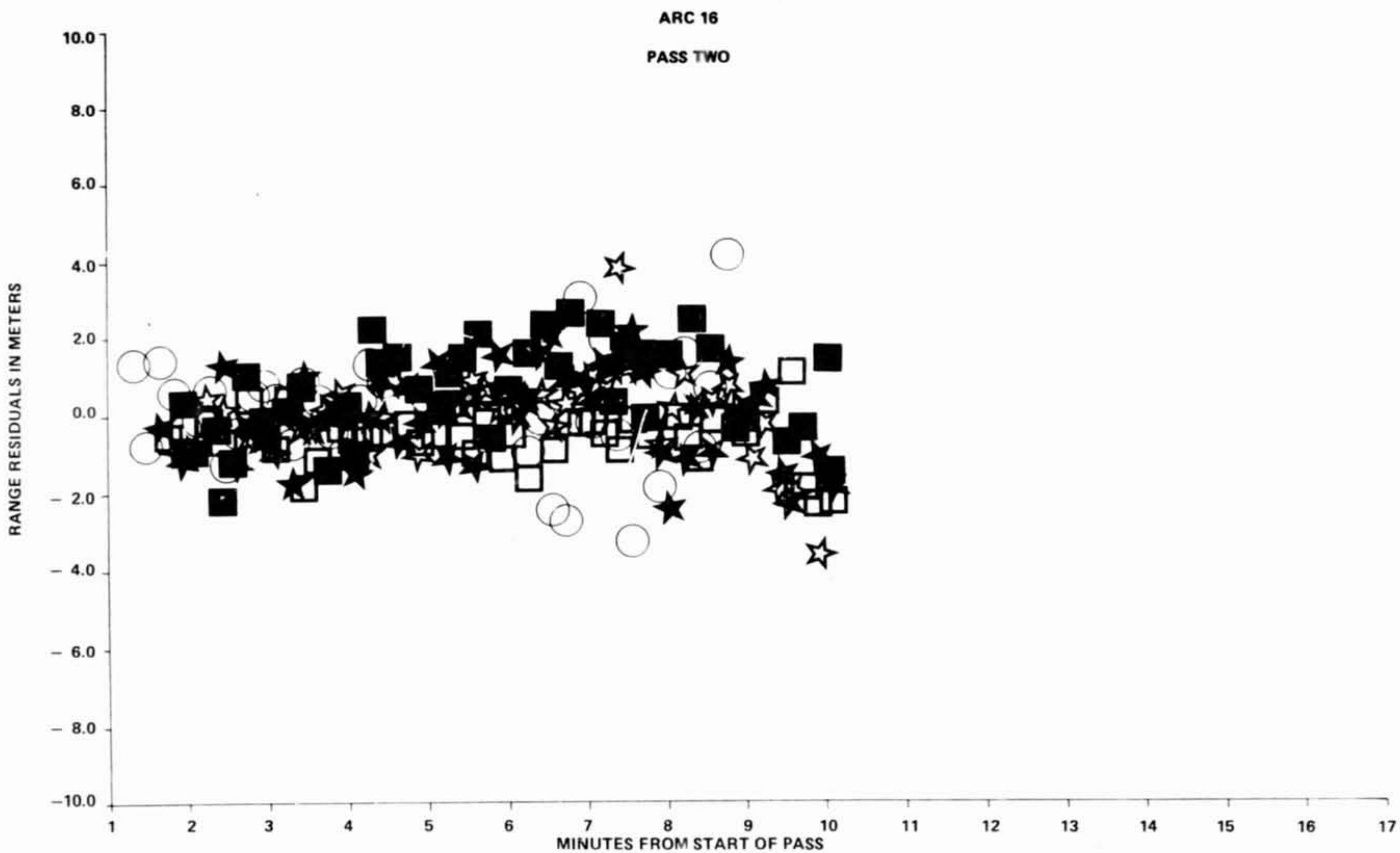


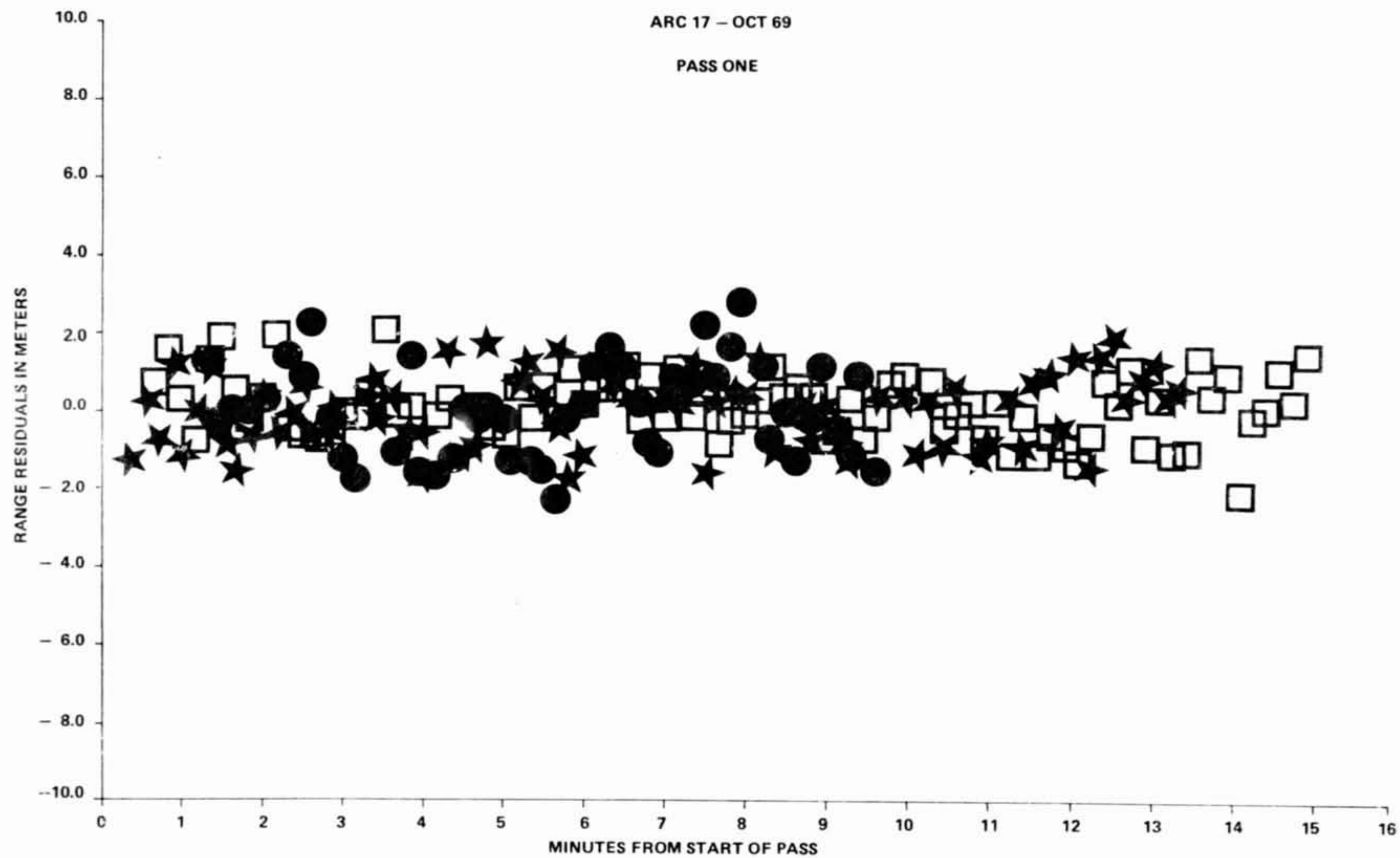

ARC 14
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
MINUTES FROM START OF PASS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


ARC 15 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS


ARC 15
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
MINUTES FROM START OF PASS

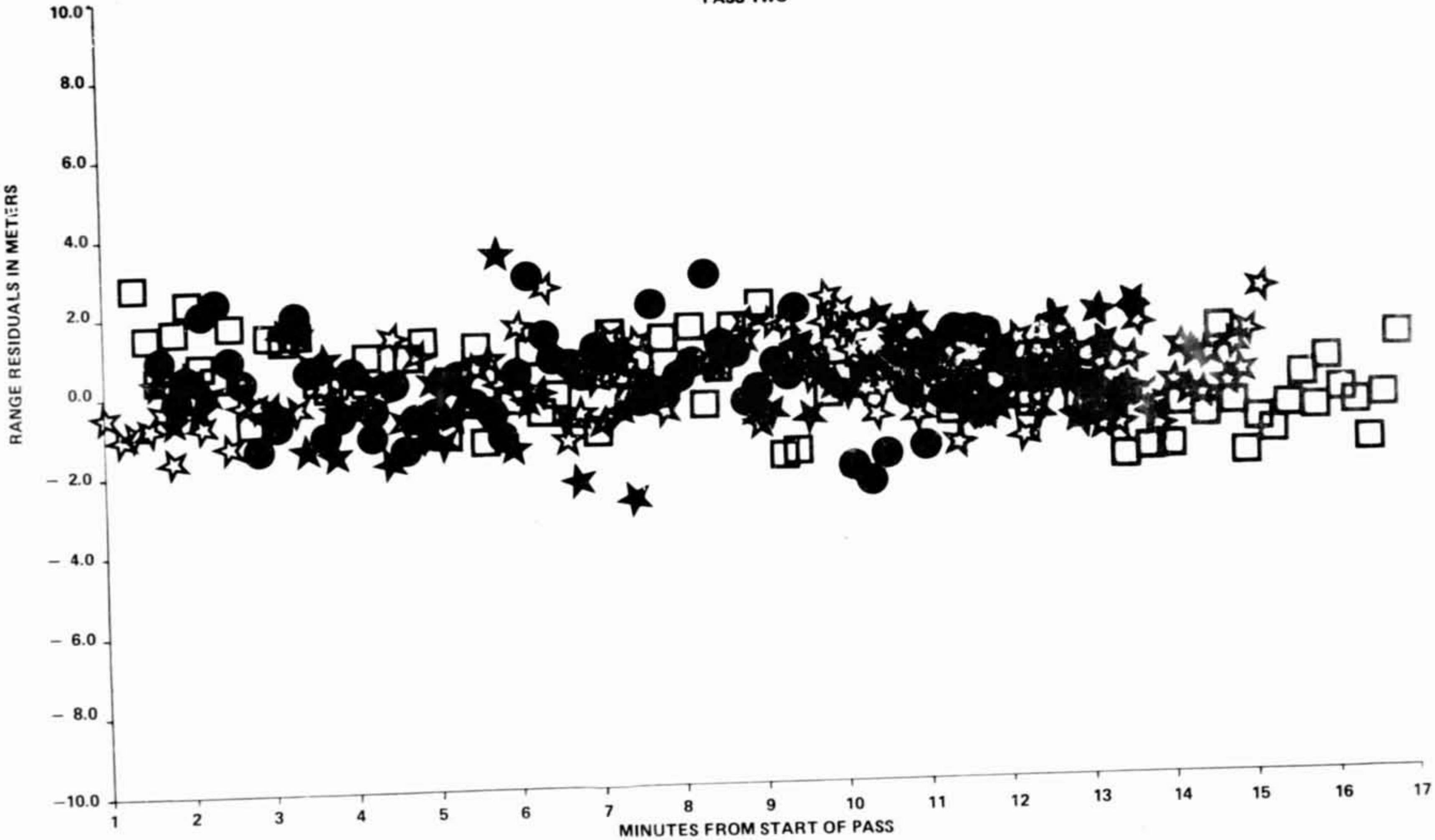

ARC 16 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS

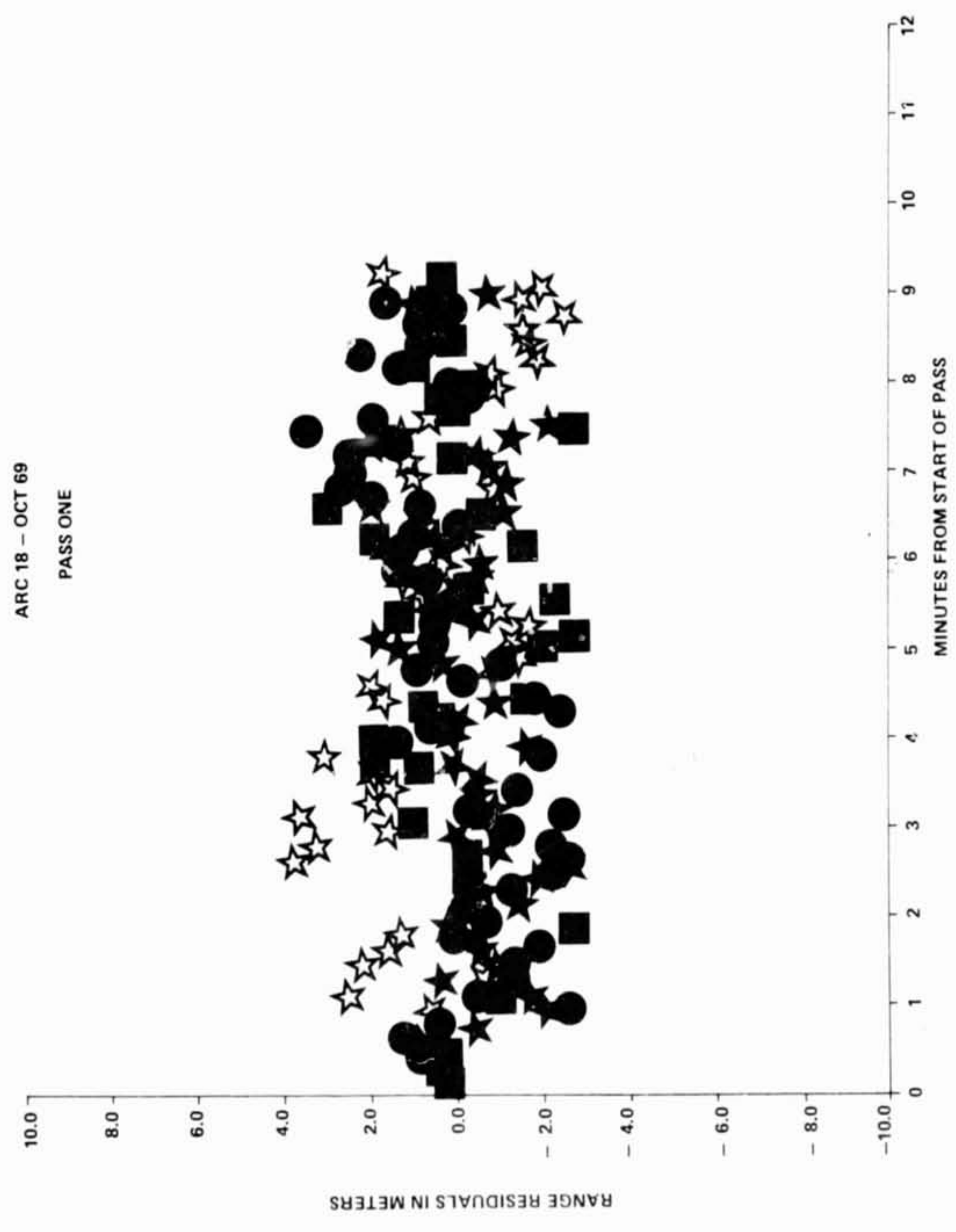

ARC 16
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
MINUTES FROM START OF PASS


ARC 17 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MINUTES FROM START OF PASS

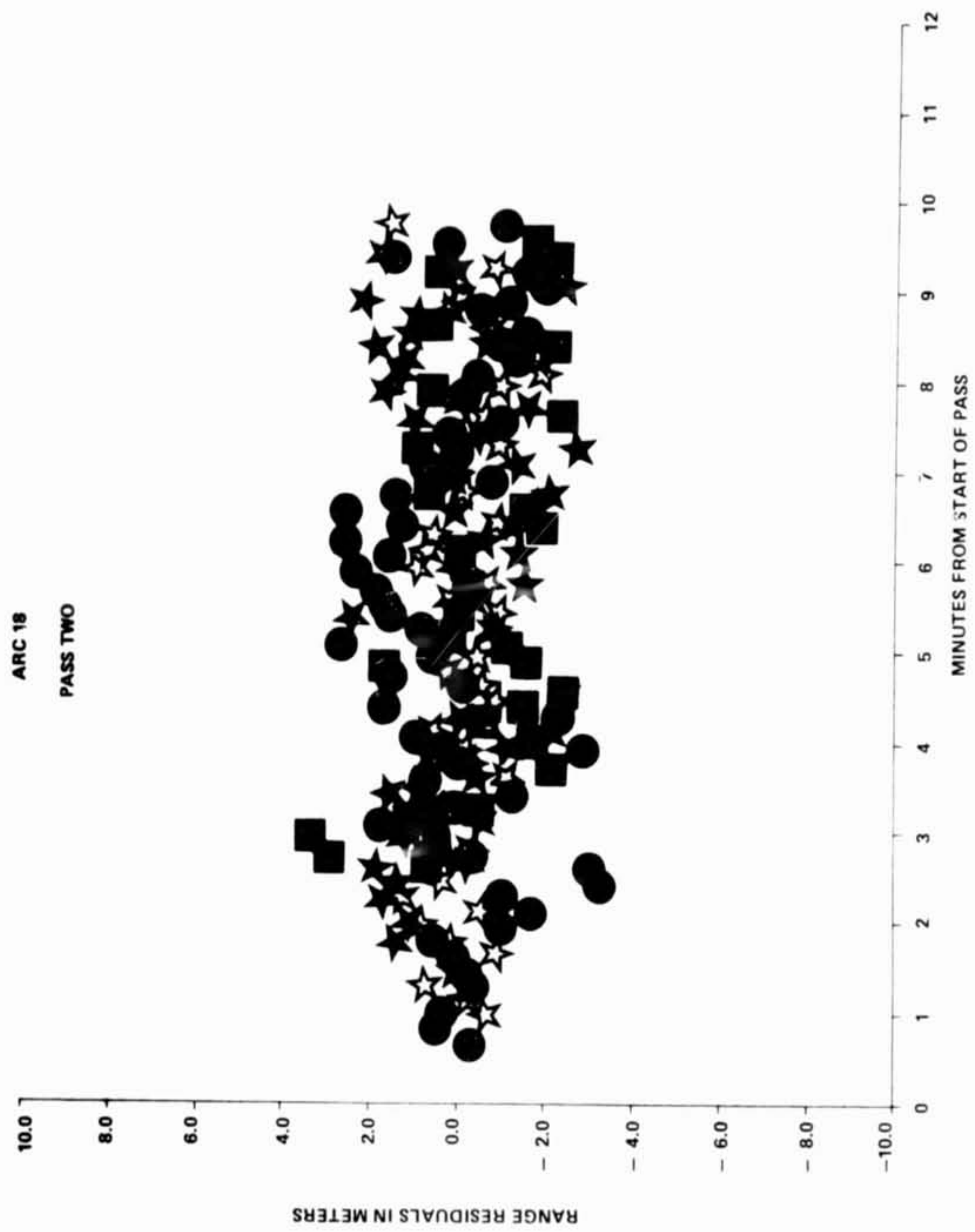
ARC 17

PASS TWO





ARC 18 – OCT 69
PASS ONE
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
MINUTES FROM START OF PASS



ARC 18
PASS TWO
RANGE RESIDUALS IN METERS
10.0
8.0
6.0
4.0
2.0
0.0
– 2.0
– 4.0
– 6.0
– 8.0
–10.0
0
1
2
3
4
5
6
7
8
9
10
11
12
MINUTES FROM START OF PASS