

INDEPENDENT TRACKING COORDINATION PROGRAM

824 Connecticut Avenue
Washington 6, D. C.

July 20, 1964

Dr. Thomas L. K. Smull
Director
Office of Research Grants and Contracts
National Aeronautics and Space Administration
Washington, D.C. 20546

Re: Research Grant NSG 35-60

Dear Dr. Smull:

Our last regular report was forwarded to you under date of April 20, 1964 and covered the period from 1 November 1963 to March 31, 1964.

Enclosed please find report covering activities for the period 1 April through 30 June, 1964.

[REDACTED]

Respectfully

Norton Goodwin
Norton Goodwin
Program Director

Enclosures:
Exhibits A through H

**UNPUBLISHED
PRELIMINARY DATA**

AM [REDACTED]
[REDACTED]
[REDACTED]

REPORTS CONTROL No. 2



INDEPENDENT TRACKING COORDINATION PROGRAM -

SUMMARY OF PROGRESS AND REPORT OF ACTIVITIES - 1 April to 30 June, 1964

I. TRACKING and ACQUISITION DATA

A. Observations and Reports of Fix

1. PHOTOTRACK observations have been received at SPACON during the period, as follows:

60 091	-	6	64 004A	-	13
63 047A	-	8	64 005A	-	4
63 053A	-	2			

2. According to summary reports received at this office, a number of visual reports of fix have been supplied to independent research programs on satellites. At the present time the majority of such reports are not being relayed to SPACON.

3. During the period, the following observations have been received from independent tracking sources overseas and forwarded to Goddard Space Flight Center:

60 091	-	15	63 038B	-	1
60 053	-	2	038C	-	1
61 Alpha 1		2	043A	-	1
62 A Ypsi		4	053A	-	1
62 Kappa 1		5	055B	-	1
62 B Kappa 1		3	64 001A	-	2
63 03A	-	5	004A	-	35
63 04A	-	2	006A	-	3
63 14A	-	2	010A	-	1
63 27A	-	4	010B	-	1
63 30A	-	3	011A	-	8
			64 028B	-	4

B. Acquisition Data

1. Mean Orbital Elements

Reports of Fix are of primary interest to individuals or centers conducting orbit studies on the particular satellites on which data is given. Individual observations are of little use in satellite acquisition. Mean orbital elements are the result of an analysis of a series of fixes and are of use to anyone wishing to acquire a satellite for observation purposes. An important element of the long-range goals of the Independent Tracking Coordination Program has been to develop sources of acquisition data of this type, not only from official tracking agencies but also from competent individuals and groups.

B. 1. (cont.)

Heretofore, the primary sources of mean orbital data, other than the principal tracking centers, have been individuals with extraordinary interests and/or computer resources, such as W. P. Overbeck, Director of the Savannah River Laboratories and Herman Michielsen, Senior Staff Scientist, Lockheed Missiles and Space Company. During the quarter, the ITCP received for the first time sets of mean orbital data which were based on independent analysis of independent observations carried out by a team of individuals with limited computer resources and no background training in orbit analysis of this kind. These results were reported in our Announcement Card issued 18 June 1964, copy of which is enclosed as Exhibit B.

It will be noted that the mean orbital elements supplied by Gregory Roberts and Arthur Arnold were based solely on observations made at Durban, South Africa. The data obtained by Roberts and Arnold are of use to anyone in the world having an interest in acquiring 1963-14A or 1962 Kappa I during a period from 30 to 60 days after issue. The analytical procedures were carried out with the aid of a desk calculator, following methods suggested in W. P. Overbeck's, "A Letter to Gregory Roberts", which has been published as part of the ITCP Program.

In the case of the more stable satellites, ways for describing the orbit and mean motion in terms of "gear ratio elements" have been developed. "Gear ratio elements" simplify long-term analysis of mean satellite motion. They also supply data in a form which permits acquisition of the more stable satellites from one to two years after the epoch of the elements. They will be described in bulletins to be issued during the next quarter.

2. Daily Satellite Ephemerides

An alternative method for communicating acquisition data of particular interest in the shorter-lived or more erratic satellites is the daily satellite ephemeris. Such an ephemeris, giving predicted orbital arguments for 00h G.M.T. for each day of a 50-day period on six satellites was issued during the period. It is typical of the kind of daily ephemeris that has been proposed for routine preparation at Goddard Space Flight Center, and was, in this instance, prepared by W. P. Overbeck. A copy of the Daily Ephemerides is attached hereto as Exhibit C. Ephemeris data on three of the satellites (58 001A, 59 001A and 59 007A) were based on Smithsonian Astrophysical Observatory mean orbital data. Data on the remaining three (60 006A, 60 013B, and 63 047A) were based on observations made by W. P. Overbeck. The ephemeris contained on its reverse side tables of eccentricity functions for the current value of eccentricity of each of the satellites listed on the obverse side. True anomaly (PRV) and radius ratio (RAD) were given as functions of mean anomaly (PRM). These elements were issued on April 5, 1964 in conjunction with a bulletin on "Work Sheets for Conversion of Satellite Data to Rationalized Orbital Elements" (Exhibit D). Further details are given in Section V of this Report.

II. Support of Inflation Studies.

There were no satellite inflations during the quarter. To date, none of the photographic records showing traces of ECHO II (1964 004A) that have come to our attention give evidence of apparent brightness fluctuations attributable to surface anomalies of the structure. Arrangements have been made to keep the satellite under photographic surveillance to determine when and if brightness fluctuations of this type become evident.

III. Satellite Trackers' Handbook.

Satellite tracking techniques and methods for orbit analysis continue to develop at such a pace as to make it undesirable at this point to attempt to "freeze" the material into the form of a handbook. Advances in tracking methods, graphic forms and worksheets, and suggested procedures continue to be issued in bulletin form. The individual bulletins are related to one another and to the present literature through common systems of notation and terminology, and also through adherence to and systematic development of decimal notation for describing angles, as well as times of events.

IV. Rationalized Tables of Trigonometric Functions

During the quarter copies of "SEVEN PLACE COSINES, SINES AND TANGENTS FOR EVERY TENTH MICROTURN" were distributed to addressees and participants in the Independent Tracking Coordination Program. A copy of these tables of trigonometric functions with rationalized arguments is attached hereto as EXHIBIT F. The availability of these tables vastly simplifies desk calculator tracking methods.

V. Derivation of Rationalized Orbital Elements from Daily Satellite Ephemerides, SATOR Code Messages, and NORAD/SPADATS "4-line" Elements.

Rationalized orbital elements present data on the motion of an artificial earth satellite in an optimum form for making predictions. The derivation of rationalized orbital elements from data in other standard formats is routine. In ITCP Bulletin of 5 April, 1964, examples are given of the derivation of rationalized orbital elements from a variety of sources (Exhibit D). Computation work sheets to be used as guides for obtaining rationalized orbital elements from a daily ephemeris were provided, sample copy of which is enclosed herewith - Work Sheet A - and is marked Exhibit D-1. Work Sheet B for obtaining rationalized orbital elements from modified orbital elements is attached hereto and is marked Exhibit D-2. A copy of Work Sheet C for conversion of NORAD/SPADATS "4-line elements" to rationalized orbital elements is attached hereto also and is marked Exhibit D-3. Work Sheet C (Exhibit D-3) provides for derivation of PRM_1 (first time derivative of mean anomaly) from the anomalistic period which is given in such elements to the nearest hundredth of a minute only. An improved Work Sheet permitting derivation of mean motion values to higher precision from the "Semi-Major Axis" values given in NORAD/SPADATS "4-line" elements is in preparation and will be issued when a conversion table has been computed and is available.

VI. Rules for Advancing the Epoch of Rationalized
Orbital Elements and Other Aids to Precise Computation.

Rationalized orbital elements may be routinely advanced to a subsequent epoch without loss of precision. Rules for computing rationalized orbital elements for a new epoch are described in ITCP Bulletin of 7 April, 1964, (EXHIBIT E) which gives an example of the necessary computations in work sheet form. Copies of blank Work Sheet C were supplied with the Bulletin (EXHIBIT E-1).

ITCP Bulletin of 7 April also gives rules for error-free combination of polar angles and for obtaining the negative of an angle. Drafting aids to make accurate overlays, including a table for locating arc centers on ITCP Chart #532 are supplied. The same bulletin briefly discusses the availability of circular slide rules for five significant figures, the relative merits of used desk calculators, and the availability of hand calculators which permit computation to eight significant figures.

VII. Digital Computer Program for Station Predictions (ZAYIN).

The methods of prediction, observation and analysis which have been consistently recommended by the Independent Tracking Coordination Program have been based on obtaining fixes at or near the time of local culmination. This is the instant when an artificial earth satellite transits the meridian from the mean orbit pole through the observer's station. For radio observers, this instant is practically undistinguishable from the instant of doppler inflection. Satellite observations at local culmination permit dealing with the effects of the earth's pear shape (third zonal harmonic) in a particularly efficient way and limit the problem of passing from mean to true anomaly in making a prediction. From a computation point-of-view, a method which requires conversion from true to mean anomaly is much more efficient.

A method for predicting positions of artificial earth satellites at the point of local culmination for desk calculator was described in detail in "A Letter to Gregory Roberts". These methods have been refined into a digital computer program of great efficiency by W. P. Overbeck, and described in a Bulletin dated May 14, 1964 entitled, "ZAYIN: A Computer Program For Predicting Positions of Artificial Satellites at the Point of Local Culmination", (EXHIBIT G), copy of which is attached hereto. ZAYIN uses rationalized orbital elements as input and accomplishes rejection of unobservable or unacceptable passes with a minimum of non-productive computation. ZAYIN computes the apparent positions of artificial earth satellites at the point of culmination. It is designed for use by the optical observer who wishes to make the type of observation that is most useful in the determination of orbital characteristics. It examines all revolutions of the satellite which occur between any two selected dates. It rejects those passes which are below the horizon, which occur while the observer is in daylight or for which the point of culmination is inside the Earth's shadow. For passes that are not rejected, it prints out predictions in both alt-azimuth form and in celestial coordinates, together with other data that is useful in setting the observing instrument or in adjusting the predictions when observation indicates that this is necessary. A number of observatories, including the Dominion

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Observatory, Ottawa, Canada, are now using ZAYIN as a means for satisfying requirements for station predictions on visually observable passes on artificial earth satellites. Copies of the program in deck form are being made available.

VIII. Long-term Tracking Techniques for Stable Satellites.

In the case of the more stable satellites, tracking procedures and orbit analysis can be greatly simplified by expressing the motion of the orbit and of perigee as functions of mean motion, rather than as functions of time. Element sets of this kind have been named "Gear Ratio Elements" by W. P. Overbeck, who is largely responsible for their development. ITCP Bulletin of June 11, 1964 reproduces Overbeck's paper entitled, "Gear Ratio Orbital Elements for Tracking Artificial Earth Satellites". (EXHIBIT H)

An important aspect of gear ratio elements is that they offer a technique for orbit analysis which permits the casual observer to become an authoritative source of long-range acquisition data on stable satellites. It also permits the improvement of mean orbital data currently being supplied by the official tracking agencies so as to be useful for satellite acquisition over extended periods of time.

One of the prime objectives in the Independent Tracking Coordination Program has been to reduce the amount of data on a given satellite required for acquisition by an independent observer and to reduce the frequency of communications on a specific satellite required for such purposes. It appears that the gear ratio type of data package permits use of a smaller data package at less frequent intervals than any that have been advanced so far. Although particularly appropriate for the longer-lived satellites, gear ratio elements convey the essential information required for the shorter-lived satellites and may, therefore, be of interest for general adoption for the exchange of satellite acquisition information.

IX. Requirements for a Passive Geodetic Satellite.

The above topic was discussed by a panel on April 27, 1964 at the 1964 International Conference of the Society of Photographic Scientists and Engineers held in New York City. Copies of the final program of the Conference were furnished as EXHIBIT M to Report of April 20, 1964. It is anticipated that J. Hewitt's paper, "A 24-in. f/1 Schmidt System for Precision Measurement of Satellite Positions" will appear in the forthcoming issue of PHOTOGRAPHIC SCIENCE AND ENGINEERING, the SPSE Journal.

X. Matrix Methods

At the same meeting on April 27, 1964, Mr. Norton Goodwin, Director of ITCP read a paper entitled, "Apparent Place Determination of Photographic Star Images". A number of requests for preprints of this paper have been received to date. It is anticipated that the subject matter will appear in an ITCP Bulletin in the near future.

XI. Announcements and Bulletins**A. Summary of Post Card Announcements on Radio-transmitting Satellites Distributed during Period 1 April - 30 June, 1964**

<u>Date</u>	<u>No. Dist.</u>	<u>Identity of Satellites</u>		
4/8	691	64 004A 64 005A	62 060A 63 024A	63 054A 64 003A
4/23	321	64 004A 64 005A	62 060A 64 001B	58 002B 64 015A
5/7	321	64 004A 64 005A	62 060A 63 038C	63 024A 63 049C
5/21	678	64 004A 64 010A	62 060A 63 024A	64 006B 62 015A
6/5	318	64 004A 62 060A	64 006B 63 024A	63 054A 62 015A
6/18	627	64 006B 63 024A 63 014A 64 004A	64 010A 63 054A 62 010A 64 005A	64 015A 62 015A 60 009A 63 053A

B. Summary of Post Card Announcements on Brighter Satellites

4/2	465	64 004A 60 009A	64 005A 61 004A	63 053A 58 001A
4/11 16	478 465	64 004A 60 009A 63 047A	61 004A 63 053A	60 009A 58 001A
5/1	463	64 009A 64 005A	60 006A 63 053A	58 001A 60 009B
5/15	463	60 009A 64 005A	60 006A 63 053A	58 001A 60 009B
5/29	467	64 004A 60 009A	64 005A 63 053A	58 001A 60 009B
6/11	465	64 006B 64 005A	64 004A 60 006A	60 009A 63 053A
6/25	465	60 009A 58 001A	64 005A 62 015A	60 009B 59 007A

END OF REPORT

EXHIBITS ATTACHED TO THIS REPORT :

- A. Financial Report, Quarter ending 30 June, 1964 (Forms 1030-1031)
- B. Modified Orbital Announcement Card dated June 18, 1964 giving acquisition data supplied by independent observers in Durban, South Africa.
- C. Daily Ephemerides on Six Satellites with Eccentricity Tables, issued April 5, 1964
- D. Bulletin dated April 5, 1964 describing in detail Computation Work Sheets for Conversion of Satellite Data to Rationalized Orbital Elements
 - D(1) Work Sheet A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides
 - D(2) Work Sheet B: Rational Orbital Elements from Modified Orbital Elements
 - D(3) Work Sheet C: Conversion of NORAD-SPADATS "4-line" Elements to R.O.E.
- E. Bulletin of April 7, 1964 containing Rules and information on Advancing the Epoch and Drafting Aids to Making Accurate Overlays
 - E(1) Work Sheet D: For Advancing the Epoch of Rationalized Orbital Elements
- F. Tables of Trigonometric Functions: "SEVEN PLACE COSINES, SINES AND TANGENTS FOR EVERY TENTH MICROTURN"
- G. Bulletin dated May 14, 1964: ZAYIN: A Computer Program for Predicting Positions of Artificial Satellites at the Point of Local Culmination.
- H. Bulletin dated June 11, 1964: "Gear Ratio" Elements for Tracking Artificial Earth Satellites.

EXHIBIT B

MODIFIED ORBITAL ELEMENTS 1 Jun	BRIGHT	64 006B	64 010A	64 015A	63 024A	63 054A	62 015A
	OBJECT	Elek 2	Cosmos	25 Ariel	2 Tiros 7	Tiros 8	Ariel
	NAME	Norad	Norad	GSFC	Norad	Norad	GSFC
	SOURCE	14 Jun	16 Jun	15 Jun	13 Jun	13 Jun	12 Jun
	EPOCH of	01H	08H	00H	16H	14H	18H
	perigee	14M64	56M53	49M10	53M36	33M38	39M96
	(UT)	60A20	49A02	51A66	58A23	58A50	53A86
	INCLIN.	350A16	323A52	010A61	113A60	250A74	091A29
	NODE W.	-04M24	-25M23	-20M06	-18M74	-17M97	-19M43
	MPD = 1D	073A30	276A21	020A66	144A25	350A03	282A06
PERIGEE	change/P	+A017	+A303	+A214	+A093	+A086	+A172
A. PERIOD	156M386	91M434	101M195	97M439	99M370	100M551	
change/P	-M00000	-M00031	-M00009	-M00001	-M00001	-M00001	
ECCEN.	U82847	U01347	U07331	U00256	U00235	U05417	
P. RADIUS	4326#0	4121#5	4142#2	4347#2	4405#3	4209#7	
freq. X6/S	19T430	90T022	136T447	136T233	136T233	136T406	
REMARKS	90T225			136T921	136T924		
R. A. NODE	290A87	075A27	265A00	041A77	229A53	089A82	

MODIFIED ORBITAL ELEMENTS 18 Jun	BRIGHT	-28.8	-26,-30	-4	+3	-8,-20	-16,-28
	OBJECT	63 014A	62 010A	60 009A	64 004A	64 005A	63 053A
	NAME	Atl.Agena	Midas 5	Echo 1	Echo 2	Saturn 5	Expl 19
	SOURCE	Durban*	Durban*	Norad	SAO	SAO	SAO
	EPOCH of	19 Jun	19 Jun	13 Jun	20 Jun	20 Jun	20 Jun
	perigee	00H	10H	09H	01H	02H	01H
	(UT)	17M346	45M045	38M15	45M66	05M79	10M28
	INCLIN.	87A310	86A705	47A30	81A47	31A45	78A62
	NODE W.	080A316	060A070	009A93	014A22	338A94	024A61
	MPD = 1D	-04M3164	-04M5056	-17M15	-07M18	-29M78	-07M78
PERIGEE	292A181	116A440	061A89	135A79	135A65	161A05	
change/P	-A11702	-A13042	+A255	-A13272	+A66797	-A15244	
A. PERIOD	166M4257	152M9816	114M328	108M714	94M237	115M594	
change/P	-M00000	-M00000	-M00030	-M00010	-M00033	-M00019	
ECCEN.	U00660	U02906	U05459	U02347	U03343	U11288	
P. RADIUS	6180#87	5716#51	4584#2	4579#3	4118#8	4333#6	
freq. X6/S	Tumbling	Tumbling		136T020			
REMARKS	very slower.	13 sec.		136T170			
R. A. NODE	191A1843	008A9299	036A34	280A32	320A64	261A06	

*Elements supplied by Gregory Roberts and Arthur Arnold,
62 Dragonwyck, 7 St. Georges Street, Durban, South Africa.

DAILY SATELLITE EPHEMERIDES

JNL	58001A	59001A	59007A	60006A	60013B	63047A
	SAO 38471	SAO 38471	SAO 38471	WPC 38466	WPO 38442	WPO 38468
	NRG.09132CG1358.4	NRG.09132CG1358.4	NRG.09260CG1595.3	NRG.09174CG 16.7	NRG.07848CG 14.5.9	NRG.08433CG 6.51.3
	CP 7358.1 13T	CP 8299.1 11T	CP 8492.4 11T	CP 6862.3 15T	CP 7443.8 13T	CP 7502.8 13T
38K	RNT	NRP	PRM	RNT	NRP	PRM
490	.03150.17290.11714	.57393.62860.41004	.28622.67181.44787	.26293.12637.63320	.06470.09028.08906	.11800.06189.41026
491	.04848.19417.87293	.58645.64330.89005	.29809.68541.53852	.20304.15321.90152	.00170.01302.40203	.13426.06358.71111
492	.00245.21543.62901	.59897.65800.37006	.30996.69900.62917	.30436.18026.16986	.09071.63706.91500	.15105.90527.12567
493	.08243.23669.38537	.61148.67270.85008	.32183.71260.71983	.32507.20721.43822	.71268.66030.42797	.16754.92695.48023
494	.09540.25795.14202	.62400.68740.33010	.33370.72620.81050	.34579.23415.70658	.72265.68354.94092	.18403.94864.83480
495	.11638.27922.89895	.63651.70210.81013	.34557.73979.90118	.36651.26110.97496	.74961.70618.45392	.20022.97032.18937
496	.13335.30048.65617	.64903.71680.29017	.35744.75339.99186	.38722.28800.24336	.70658.73022.96689	.21700.99201.54395
497	.15033.32174.41368	.66154.73150.77020	.36931.76698.08255	.40794.31495.51176	.70354.75326.47987	.23349.01370.09853
498	.16730.34301.17147	.67406.74620.25025	.38118.76058.17325	.42866.34194.78018	.80051.70650.99284	.24995.03238.25311
499	.18428.36427.92955	.68658.76090.73029	.39305.79418.26396	.44937.36888.04862	.81747.99744.20382	.26647.05707.00710
500	.20125.38554.68792	.69909.77560.21035	.40492.80777.35467	.47009.39503.31706	.83444.82298.01879	.28296.07876.96230
501	.21823.40680.44657	.71161.79030.69040	.41679.82137.44539	.49080.42278.58552	.85140.84622.53176	.29944.10044.31690
502	.23221.42807.20551	.72412.80500.17047	.42866.83497.53612	.51152.44972.85399	.86003.86945.04474	.31593.12213.67121
503	.25219.44934.96473	.73664.81970.65053	.44053.84856.62686	.52224.47607.12248	.86204.09269.25712	.33242.14382.02012
504	.26916.47050.72424	.74916.83440.13061	.45240.86216.71760	.55229.50361.39098	.90230.91293.07009	.34891.10250.38073
505	.28614.49187.48403	.76167.84920.61068	.46427.87576.80836	.57367.53056.65949	.91927.93917.58367	.36540.18719.73535
506	.30312.51314.24411	.77419.86380.09076	.47614.88935.89912	.59439.55751.92802	.93023.96241.09604	.38189.20888.08997
507	.32010.53441.00448	.78670.87850.57085	.48801.90295.98988	.61510.58445.19656	.94220.98065.00902	.39837.23026.44460
508	.33708.55567.76513	.79922.89320.05094	.49988.91655.08066	.63582.61140.46511	.97010.00889.12260	.41486.25225.79924
509	.35406.57694.52607	.81174.90790.53104	.51175.93014.17144	.65654.63835.73368	.98100.03213.03577	.43135.27394.15308
510	.37104.59821.28730	.82425.92260.01114	.52362.94374.26223	.67725.66529.00226	.00409.05527.14855	.44784.29562.20822
511	.38802.61948.04881	.83677.93230.49125	.53549.95734.35303	.69797.69224.27085	.02100.07861.66153	.46433.31731.86317
512	.40500.64075.81060	.84928.95201.97136	.54736.97093.44384	.71869.71919.53945	.03802.10185.17451	.48082.33900.21782
513	.42198.66203.57269	.86180.96671.45148	.55923.98453.53465	.73940.74613.80807	.05499.12509.68748	.49730.36068.57248
514	.43896.68330.33506	.87432.98141.53160	.57110.99812.62947	.76012.77308.20040	.07190.14033.20040	.51379.38270.92144
515	.45594.70457.09771	.88683.99511.41172	.58297.01172.71630	.78063.80003.34535	.08992.17157.71344	.53028.40400.28101
516	.47292.72584.86065	.89935.01081.69185	.59484.02532.80713	.80155.82697.61401	.10289.19421.22642	.54677.42574.63048
517	.48990.74711.62388	.91186.02551.37199	.60671.03891.89798	.82227.85392.88268	.12282.21804.73940	.56326.44743.99116
518	.50688.76839.38739	.92438.04021.85213	.61858.05251.98883	.84290.88080.15137	.14902.24128.22238	.57974.46911.34204
519	.52386.78966.15119	.93690.05491.33228	.63045.06611.07969	.86370.90701.42007	.17000.26042.76520	.59623.49080.70025
520	.54085.81093.91527	.94941.06961.81243	.64232.07970.17059	.88442.93470.68878	.19102.28706.27834	.61272.51249.05222
521	.55783.83221.67964	.96193.08431.29258	.65419.09330.26143	.90513.96170.95750	.21907.31100.79132	.62921.53471.40991
522	.57481.85348.44920	.97444.09901.77274	.66606.10690.35231	.92585.98865.22624	.20760.33424.30430	.64570.55586.70462
523	.59180.87476.20934	.98696.11371.75291	.67793.12049.44320	.94657.01560.49499	.22462.35748.81728	.66219.57755.11932
524	.60878.89603.97447	.99948.12841.73308	.68980.13409.53410	.96720.04255.76376	.24101.38072.33020	.67807.59923.47403
525	.62576.91731.73999	.01199.14311.21325	.70167.14769.62500	.98800.06949.03254	.25358.40396.84324	.69516.62092.82875
526	.64275.93859.50579	.02451.15781.69343	.71354.16128.71591	.00872.09644.30133	.27554.42720.35622	.71165.64261.18347
527	.65973.95986.27187	.03702.17251.17362	.72541.17488.80683	.02943.12339.57014	.29221.45044.08920	.72814.66429.53819
528	.67672.98114.03825	.04954.18721.05381	.73728.18848.89776	.05015.15033.83895	.30947.47378.83828	.74463.68598.09292
529	.69370.00242.80491	.06206.20191.13400	.74915.20207.98870	.07087.17728.10779	.32644.49692.89516	.76112.70767.24766
530	.71069.02370.57185	.07457.21661.61420	.76102.21567.07964	.09150.20423.37663	.34340.52016.40815	.77700.72930.00240
531	.72767.04498.33908	.08709.23131.09440	.77289.22927.17059	.11230.23171.64549	.36070.24639.92113	.79409.73104.95714
532	.74466.06626.10660	.09960.24601.57461	.78476.24286.26155	.13302.25812.91436	.37733.26003.43411	.81050.77273.31109
533	.76164.08754.87440	.11212.26071.05483	.79663.25646.35251	.15373.28507.18325	.39430.58987.94709	.82707.79442.66664
534	.77863.10882.64249	.12464.27541.53505	.80850.27006.44349	.17445.31201.45215	.41127.61311.46008	.84356.81610.02140
535	.79562.13010.41086	.13715.29011.01527	.82037.28365.53447	.19217.33890.72106	.42323.63615.97308	.86002.83779.03109
536	.81261.15138.17952	.14967.30481.49550	.83224.29725.62546	.21589.36591.98998	.44220.65959.48604	.87653.85948.73093
537	.82959.17266.94847	.16218.31951.97573	.84411.31085.71645	.23660.39285.25892	.46210.68223.99903	.89302.88116.08971
538	.84658.19394.71770	.17470.33422.45597	.85598.32445.80745	.25732.41980.52787	.47913.70607.51201	.90951.90285.44048
539	.86357.21523.48722	.18722.34892.93622	.86785.33804.89847	.27804.44675.79684	.49009.72931.02500	.92000.92454.79227
540	.88056.23651.25703	.19973.36362.41646	.87972.35164.98003	.29875.47370.06581	.51300.75215.53798	.94249.94622.15005

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{0}$	
@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			<hr/>				<hr/>	<hr/>
Δ JNL =	$\frac{d}{t}$		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$	Δ PRM = $\frac{t}{t}$	

divide each item by above value of Δ JNL

$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$	$PRM_1 =$	$\frac{t}{t}$
-----------	---------------	-----------	---------------	-----------	---------------

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{0}$	
@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			<hr/>				<hr/>	<hr/>
Δ JNL =	$\frac{d}{t}$		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$	Δ PRM = $\frac{t}{t}$	

divide each item by above value of Δ JNL

$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$	$PRM_1 =$	$\frac{t}{t}$
-----------	---------------	-----------	---------------	-----------	---------------

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{0}$	
@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{t}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			<hr/>				<hr/>	<hr/>
Δ JNL =	$\frac{d}{t}$		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$	Δ PRM = $\frac{t}{t}$	

divide each item by above value of Δ JNL

$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$	$PRM_1 =$	$\frac{t}{t}$
-----------	---------------	-----------	---------------	-----------	---------------

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{d}0$	
@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			Δ JNL =		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$
					divide each item by above value of Δ JNL			
					$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$
							$PRM_1 =$	$\frac{t}{t}$

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{d}0$	
@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			Δ JNL =		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$
					divide each item by above value of Δ JNL			
					$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$
							$PRM_1 =$	$\frac{t}{t}$

WORK SHEET A: For Obtaining Rationalized Orbital Elements from Rationalized Daily Ephemerides

No.	-	-	NGR = $\frac{t}{d}$	CG =	. km	CP =	. km	
			CG/CP =			Whole turns in PRM per day =	$\frac{t}{d}0$	
@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
-(@	JNL =		$\frac{d}{d}$	:	TNR =	$\frac{t}{t}$	NRP = $\frac{t}{t}$	PRM = $\frac{t}{t}$
			Δ JNL =		Δ TNR =	$\frac{t}{t}$	Δ NRP =	$\frac{t}{t}$
					divide each item by above value of Δ JNL			
					$TNR_1 =$	$\frac{t}{t}$	$NRP_1 =$	$\frac{t}{t}$
							$PRM_1 =$	$\frac{t}{t}$

WORKSHEET B: Rationalized Orbital Elements from Modified Orbital Elements
(items in square brackets are line No.'s of items listed in M.O.E.'s)

No.	= [1]								#0
JNE	= epoch: from [4]	= day	mo.	yr,	obtain	mjd	=	d.000000	
		+([5]/24	= h/24h/day				=	d.)	
		+([6]/1440	= m. /1440m/day				=	d.)	
							=	<u>d.</u>	#1
NGR	= inclination = [7]/360°/t	=	°	/360°/t			=	t.	#2
CG/CP	= eccentricity = [14]						=	.	#3
CP	= semi-major axis = [15] (1.60935 km/sm)/(1.000000 - #3)						=	. km	#4
	= (. sm) (1.60935 km/sm)/(0.)						=	. km	#5
CG	= semi-major axis times eccentricity = (#3)(#4)						=	. km	#5
TNR ₀	= mean time of orbit pole at epoch						=	t.	
	TNL ₀ = fractional part of #1						=	t.	
	-(ANL ₀ = [8]/360°/t	=	°	/360°/t			=	t.)	
	= TNA ₀						=	t.	
	-(TNA						=	t.250000)	
	<u>TNR₀</u>						=	t.	#9
TNR ₁	= 1 st time derivative of mean time of orbit pole						=	t.	(ENL) #11
	= [9]/1440	=	m.	/1440m/t			=	t.	
	Argument of perigee at epoch (from ascending node)						=	t.	#12
	= (#10)/360°/t	=	°	/360°/t			=	t.	
NRP ₀	= argument of perigee at epoch (from north point of orbit)						=	t.	#13
	= (#12) - t.250000						=	t.	
NRP ₁	= 1 st time derivative of argument of perigee = (#16)[11]/360						=	t.	(ENL) #14
	= (#16)(° /360°/t) = (t.)(t.)						=	t.	
PRM ₀	= mean anomaly at epoch						=	t.000000	#15
PRM ₁	= 1 st time derivative of mean anomaly = 1440m/[12]						=	t.	(ENL) #16
	= 1440m/ m. /t						=	t.	
PRM ₂	= $\frac{1}{2}$ 2 nd time derivative of mean anomaly = -(#16) ³ [13]/2880						=	t.	(ENL) ² #17
	= -(.)(m.)/2880 = . /2880						=	t.	

Additional copies available from: ITCP, 824 Conn. Ave., Wash., D.C. 20006.

WORKSHEET C: Conversion of NORAD-SPADATS "4-line Elements" to R.O.E.
 (items in square brackets are line No. and item No. of items in NORAD elements)

No.	= [0,3]	=	-	-	#0
JNE	= epoch = [1,3]	=	d	.	#1
NGR	= inclination = [2,3]/360°/t = ° /360°/t	=	t	.	#2
CG/CP	= eccentricity = [2,6]	=	.	.	#3
CP	= semi-major axis = [1,4](a) = . (6378.17 km)	=	.	km	#4
CG	= semi-major axis times eccentricity = (#3)(#4)	=	.	km	#5
QNT ₀	= celestial longitude of midnight from pole of ecliptic at epoch = t540608 + t.002738(#1 - 38400d.000000) = t540608 + t.002738(d) = t.540608 + t.	=	t.	.	#6
QNT ₁	= 1 st time derivative of longitude of mean midnight	=	t.0027379093(ENL)	.	#7
TNR ₀	= mean time of the orbit pole at epoch QNR ₀ = [2,5]/360°/t = ° /360°/t -QNT ₀ = #6 ----- =TNR ₀	=	t.	.	#8
TNR ₁	= 1 st time derivative of mean time of orbit pole QNR ₁ = [3,5]/360°/t = ° /360°/t -(QNT ₁ ----- = TNR ₁	=	t.	(ENL)	#10
		=	t.002738(ENL)	.	#11
	Argument of perigee at epoch (from ascending node) = [2,4]/360°/t = ° /360°/t	=	t.	.	#12
NRP ₀	= Argument of perigee at epoch (from north point of orbit) = #12 - t.250000	=	t.	.	#13
NRP ₁	= 1 st time derivative of argument of perigee = [3,4]/360°/t = ° /360°/t	=	t.	(ENL)	#14
PRM ₀	= mean anomaly at epoch = [3,3]/360°/t = ° /360°/t - (#12 - ((*)(#8) (*))=(-1) if #2>t.25 -----	=	t.	)	#15
		=	t.	.	#15
PRM ₁	= 1 st time derivative of mean anomaly = 1440/[2,7] = 1440m/ m /t	=	t.	(ENL)	#16
PRM ₂	= 1/2 2 nd time derivative of mean anomaly = -(#16) ² [3,7]/2880 = -(.)(.)/2880 = . /2880	=	t.	(ENL) ²	#17

WORKSHEET C: Conversion of NORAD-SPADATS "4-line Elements" to R.O.E.
 (items in square brackets are line No. and item No. of items in NORAD elements)

No.	= [0,3]	=	-	-	#0
JNE	= epoch = [1,3]	=	d	.	#1
NGR	= inclination = [2,3]/360°/t = ° /360°/t	=	t	.	#2
CG/CP	= eccentricity = [2,6]	=	.	.	#3
CP	= semi-major axis = [1,4](a) = . (6378.17 km)	=	.	km	#4
CG	= semi-major axis times eccentricity = (#3)(#4)	=	.	km	#5
QNT ₀	= celestial longitude of midnight from pole of ecliptic at epoch = t.540608 + t.002738(#1 - 38400d.000000) = t.540608 + t.002738(d) = t.540608 + t.	=	t.	.	#6
QNT ₁	= 1 st time derivative of longitude of mean midnight	=	t.0027379093(ENL)	.	#7
TNR ₀	= mean time of the orbit pole at epoch QNR ₀ = [2,5]/360°/t = ° /360°/t -QNT ₀ = #6 ----- =TNR ₀	=	t.	.	#8
TNR ₁	= 1 st time derivative of mean time of orbit pole QNR ₁ = [3,5]/360°t = ° /360°/t -(QNT ₁) ----- = TNR ₁	=	t.	(ENL)	#1
		=	t.002738(ENL)	.	#1
	Argument of perigee at epoch (from ascending node) = [2,4]/360°/t = ° /360°/t	=	t.	.	#1
NRP ₀	= Argument of perigee at epoch (from north point of orbit) = #12 - t.250000	=	t.	.	#1
NRP ₁	= 1 st time derivative of argument of perigee = [3,4]/360°/t = ° /360°/t	=	t.	(ENL)	#1
PRM ₀	= mean anomaly at epoch = [3,3]/360°/t = ° /360°/t - (#12) - ((*)(#8)) (*)=(-1) if #2>t.25 -----	=	t.	.	#1
PRM ₁	= 1 st time derivative of mean anomaly = 1440/[2,7] = 1440m/ m /t	=	t.	(ENL)	#1
PRM ₂	= 1/2 2 nd time derivative of mean anomaly = -(#16) ² [3,7]/2880 = -(.)(.)/2880 = . /2880	=	t.	(ENL) ²	#1

Phone: Sterling 3-4100

INDEPENDENT TRACKING COORDINATION PROGRAM

824 Connecticut Avenue
Washington 6, D. C.

BULLETIN

April 5, 1964

WORK SHEETS FOR CONVERSION OF SATELLITE DATA
TO RATIONALIZED ORBITAL ELEMENTS

COMPUTATION WORK SHEETS which may be used as guides for obtaining rationalized orbital elements from various sources are discussed below. Blank copies are supplied herewith. Additional work sheets may be obtained from this office upon request. Please specify which work sheets are required.

Rationalized Orbital Elements from Daily Ephemeris: Example
Given

	63047A	WPO 38468	
	NGR=08433	CG 651.3	
JNL	CP 7502.8	13T	
38K	KNT	NRP	PRM
518	57755	57755	11932
519	55522	55522	76462
520	64570	64570	76462
521	66219	66219	76462
522	64570	55586	76462
523	66219	57755	11932

(Extract from Daily Ephemerides supplied by W. P. Overbeck 3 April 1964.)

**WORK SHEET A: For Obtaining Rationalized Orbital Elements from
Rationalized Daily Ephemerides**

No. 63-047-01 NGR = 08433 CG = 651.3 km CP = 7502.8 km
CG/CP = .086812 Whole turns in PRM per day = 13.0

@ JNL = 38523.^d.000000: TNR = - 06219 NRP = 57755 PRM = 11932
-(@ JNL = 38522.^d.000000: TNR = - 64570 NRP = 55586 PRM = 76462)

Δ JNL = 1.^d.000000 Δ TNR = - .01649 Δ NRP = .02169 Δ PRM = 13.35470

divide each item by above value of Δ JNL

TNR₁ = - .01649 NRP₁ = .02169 PRM₁ = 13.35470



Decoding SATOR Messages: Description of Code

SATOR (Modified Orbital Elements for Prediction Purposes)

Code word: SATOR

<u>Symbolic form:</u>	SATOR	aabbc	deeff	ggggZ	hhhhX	NOWES	iiii
	jkkkk	ARPER	11111	mnnnX	PERIOD	ooooo	
	ppppp	ECCEN	qqqqq	PERRA	rrrrr	RAFRE	
	sssss	(sssss repeated as necessary)			RADEG	ttttt	

Key:

- aa = last two digits of year satellite launched
- bb = Greek letter designation, 01 = Alpha, 02 = Beta, etc.
- c = component
- d = reference time (epoch): last digit of numerical notation for month; i.e. 1 = January or November, 2 = February or December, 3 = March, etc.
- ee = reference time (epoch): date
- ff = reference time (epoch): hour
- gggg = reference time (epoch): minutes and hundredths of minutes
- Z = Universal time, Greenwich Mean Time
- hhhh = inclination in degrees and hundredths of degrees. If the orbit inclination is negative (satellite fired westward) group is preceded by NEGAT
- X = always an X
- NOWES = sub-indicator for geographical longitude of northbound node west of Greenwich at reference time
- iiii = longitude of northbound node in degrees and hundredths of degrees
- j = 1 if plus: when the "prime sweep interval" is one day plus a certain number of minutes
- 2 if minus: when the "prime sweep interval" is one day minus a certain number of minutes
- This is equivalent to saying that the same portion of the orbit plane will reappear at the same location a certain number of minutes earlier each day.
- kkkk = number of minutes and hundredths of minutes by which "prime sweep interval" differs from one day or 1440 minutes. This is another way of expressing the relative "westward motion" of the orbit plane.
- ARPER = sub-indicator (argument of perigee) angular distance of perigee from node at reference time. For modified orbital elements, this is also the position of the satellite in the ellipse at reference time (mean anomaly at epoch is always equal to zero in this system)
- 11111 = angular distance of perigee and satellite from northbound node, measured in the direction of satellite travel in degrees and hundredths of degrees
- m = 1 for plus, if perigee moves in the same direction as satellite travel
- 2 for minus, if perigee moves in the direction opposite to satellite travel
- nnn = average decimal fraction of a degree which perigee moves per period, measured in thousandths of a degree
- X = always an X
- PERIOD = sub-indicator for perigee-to-perigee period (anomalistic period)
- ooooo = perigee-to-perigee period (anomalistic period) in minutes and thousandths of a minute. If first two digits are less than 85 it should be understood that 100 should be added in order to arrive at the correct period (period cannot be less than about 88 minutes). Should the period be greater than 185 minutes a special notation will be made in the message.
- ppppp = average per period change in perigee-to-perigee period, measured as a decimal fraction in one hundred thousandths of a minute
- ECCEN = sub-indicator for eccentricity
- ggggg = eccentricity, measured as a decimal fraction in one hundred thousandths
- PERRA = sub-indicator for radial distance of satellite from center of earth at perigee
- rrrrr = radial distance of satellite from center of earth at perigee, measured in miles and tenths of miles
- RAFRE = sub-indicator for radio frequencies currently being transmitted from satellite
- sssss = radio frequency in megacycles and hundredths of megacycles
- RADEG = sub-indicator for right ascension of the ascending node expressed in degrees and hundredths of degrees in order that this message may also serve the needs of those who prefer traditional orbital elements (Note that this sub-indicator and the following code group represent a revision of the code appearing in the Fifth Supplement to the Draft Manual)
- ttttt = degrees and hundredths of degrees of right ascension (Note that right ascension is given in degrees and hundredths of degrees rather than hours and minutes)

(From Satellite Report #7, National Academy of Sciences, National Research Council, p. 49-50)

Decoding SATOR Messages: Example

Given the following SATOR code message:

PART IV.					
SATOR	6354A	32716	5450Z	5850X	NOWES
	29152	21798	ARPER	24051	PERIOD
	99369	00001	ECCEN	00268	PERRA
	RAFRE	36.20	00000	RADEG	14726
					44038

(From Bulletin 9 1963-54A 716 Part IV, from NASA Goddard Space Flight Center. Data Source NORAD)

Modified Orbital Elements from above SATOR code message:

					Line					
					No.					
BRIGHT	+3	-4	-8	-20	-8	-24	-16	-28	-28	0
OBJECT	64 004A	63-054A	64 006A	61 004A	63 053A	58 001A				1
NAME	Echo 2	Tiros 8	Saturn 5	Expl 9	Expl 19	Expl 19				2
SOURCE	Norad	Norad	Norad	SAO	SAO	SAO				3
EPOCH of	28 Mar	27 Mar	29 Mar	04 Apr	28 Mar	04 Apr				4
perigee	02H	16H	12H	00H	00H	01H				5
(UT)	09M28	54M50	07M07	17M48	37M97	05M72				6
INCLIN.	81A46	58A50	31A44	38A94	78A60	35A50				7
NODE W.	228A85	291A52	323A76	932A71	212A36	292A71				8
MPD = 1D	-07M19	-17M98	-29M52	-24M77	-07M78	-24M77				9
PERIGEE	329A37	240A51	01A51	383A79	327A03	144A51				10
change/P	-A186	+A086			-A15539	+A086				11
A. PERIOD	108M853	99M369			115M711	108M853				12
change/P	-M00009	-M00001								13
ECCEN.	U02377	U00268			U11238	U00268				14
P. RADIUS	4530#1	4403#8			4530#1	4403#8				15
freq. X6/S	136T020	136T233								16
REMARKS	136T170	136T924								17
R. A. NODE	349A00	147A26								18

Rationalized Orbital Elements from Modified Orbital Elements: Example
 Given above Modified Orbital Elements:

WORKSHEET B: Rationalized Orbital Elements from Modified Orbital Elements
 (items in square brackets are line No.'s of items listed in M.O.E.'s)

No.	= [1]					63-054-01	#0	
JNE	= epoch: from [4] = 30 day 03 mo. 1964 yr, obtain mjd	=	38481	d	000000			
	+([5]/24 = 16h/24h/day	=		d	666667)			
	+([6]/1440 = 54 ^m .50/1440m/day	=		d	037847)			
		=	38481	d	704514	#1		
NGR	= inclination = [7]/360°/t	=	58°50	/360°/t	=	t	162500 #2	
CG/CP	= eccentricity = [14]	=	.00268		=		#3	
CP	= semi-major axis = [15] (1.60935 km/sm)/(1.000000 - #3)	=	7106.30	km	#4			
	= (4403.8 sm) (1.60935 km/sm)/(0.99732)							
CG	= semi-major axis times eccentricity = (#3)(#4)	=	19.04	km	#5			
TNR ₀	= mean time of orbit pole at epoch							
	TNL ₀ = fractional part of #1	=	t	704514				
	-(ANL ₀ = [8]/360°/t	=	291°52	/360°/t	=	t	809778)	
	= TNA ₀	=	t	394736				
	-(TNA	=	t	250000)				
	TNR ₀	=	t	644736	#9			
TNR ₁	= 1 st time derivative of mean time of orbit pole							
	= [9]/1440	=	-17 ^m .98	/1440m/t	=	-	t	012486(ENL) #11
	Argument of perigee at epoch (from ascending node)							
	= (#10)/360°/t	=	240°51	/360°/t	=	t	668083 #12	
NRP ₀	= argument of perigee at epoch (from north point of orbit)							
	= (#12) - t	250000	=	t	418083	#13		
NRP ₁	= 1 st time derivative of argument of perigee = (#16)[11]/360							
	= (#16)(0°00/360°/t)	=	(14 4914)(t	0002389)	=	t	003462(ENL) #14	
PRM ₀	= mean anomaly at epoch	=	t	000000	#15			
PRM ₁	= 1 st time derivative of mean anomaly = 1440m/[12]							
	= 1440m/ 96 ^m .500/t	=	14 ^t .49144	(ENL)	#16			
PRM ₂	= $\frac{1}{2}$ 2 nd time derivative of mean anomaly = -(#16) ³ [13]/2880							
	= -(3041.2)(-1 ^m .90001)/2880	=	.030432/2880	=	t	.106-4 (ENL) ²	#17	

Rationalized Orbital Elements from NORAD-SPADATS "4-line" Elements: Example
Given:

```

((((
0 716 009 1963-54A      US  64 03 27  9 03 28 261
1 716 009 38481.72737050 01.11416577 -.953515-06 -.240759-10 178
2 716 009 058.4979 240.5085 147.2553 .0026835 0099.36 000721 179
3 716 009 147.0132 01.2459 -03.5655 -.853-06 -.127-3 001411 136
))))

```

(From Element sets for NASA issued 29 March 64, Data Source NORAD)

WORKSHEET C: Conversion of NORAD-SPADATS "4-line Elements" to R.O.E.
(items in square brackets are line No. and item No. of items in NORAD elements)

No.	= [0,3]	=	#0
JNE	= epoch = [1,3]	=	#1
NGR	= inclination = [2,3]/360°/t	=	#2
CG/CP	= eccentricity = [2,6]	=	#3
CP	= semi-major axis = [1,4](a)	= (6378.17 km)	#4
CG	= semi-major axis times eccentricity = (#3)(#4)	=	#5
QNT ₀	= celestial longitude of midnight from pole of ecliptic at epoch = t540608 + t002738(#1 - 384000000000)	=	#6
QNT ₁	= 1 st time derivative of longitude of mean midnight	= t.0027379093(ENL)	#7
TNR ₀	= mean time of the orbit pole at epoch QNR ₀ - [2,5]/360°/t - QNT ₀ = #6	=	#8
	= TNR ₀	=	#9
TNR ₁	= 1 st time derivative of mean time of orbit pole QNR ₁ = [3,5]/360°/t - (QNT ₁	=	#10
	= TNR ₁	=	#11
	Argument of perigee at epoch (from ascending node) = [2,4]/360°/t	=	#12
NRP ₀	= Argument of perigee at epoch (from north point of orbit) = #12 - t.250000	=	#13
NRP ₁	= 1 st time derivative of argument of perigee = [3,4]/360°/t	=	#14
PRM ₀	= mean anomaly at epoch = [3,3]/360°/t - (#12 - ((*)(#8) (*))=(-1) if #2>.25	=	#15
PRM ₁	= 1 st time derivative of mean anomaly = 1440/[2,7] = 1440m/ m /t	=	#16
PRM ₂	= 1/2 2 nd time derivative of mean anomaly = -(#16) ² [3,7]/2880 = - () () /2880	=	#17

DRAFTING AIDS TO MAKING ACCURATE OVERLAYS

In ITCP Bulletin of January 15, 1964 (1. 11) mention was made of an

"inexpensive yardstick compass such as #978 of Eugene Dietzgen Co., 2425 Sheffield, Chicago, Illinois 60614, which could be purchased for less than \$15 and which is useful in preparing accurate overlays for meridional stereographic nets."

Our attention has been drawn to the Keuffel and Esser Mark 1 Beam Compass, Item No. 55-1806, which is also available at less than \$15. It is available at most drafting and surveying supply houses and is distributed by Keuffel and Esser, Hoboken, New Jersey. Three 8" beams are supplied with this unit and additional beams are available.

ACCURATE LOCI for the centers of arcs to be swung with a beam compass can rapidly be found with the table given below. Distances in millimeters from the net center are given.

Location of Arc Centers for Preparing Accurate Overlays of Mean Orbit Plane and of Observer's Parallel
On ITCP Chart #532

ORBIT PLANE ARC CENTER			OBSERVER CIRCLE CENTER		
NGR (turns)	Center On X Axis (mm)	NGR (turns)	NGO (turns)	Center On Y Axis (mm)	NGO (turns)
.00	00.0	.50	.00	160.3	.50
.01	10.1	.49	.01	160.6	.49
.02	20.3	.48	.02	161.6	.48
.03	30.6	.47	.03	163.2	.47
.04	41.2	.46	.04	165.5	.46
.05	52.1	.45	.05	168.5	.45
.06	63.5	.44	.06	172.4	.44
.07	75.4	.43	.07	177.2	.43
.08	88.1	.42	.08	182.9	.42
.09	101.7	.41	.09	189.9	.41
.10	116.5	.40	.10	198.1	.40
.11	132.6	.39	.11	208.0	.39
.12	150.5	.38	.12	219.9	.38
.13	170.7	.37	.13	234.2	.37
.14	193.8	.36	.14	251.5	.36
.15	220.6	.35	.15	272.7	.35
.16	252.6	.34	.16	299.2	.34
.17	291.6	.33	.17	332.7	.33
.18	340.7	.32	.18	376.5	.32
.19	404.9	.31	.19	435.5	.31
.20	493.4	.30	.20	518.7	.30
.21	624.3	.29	.21	644.6	.29
.22	840.3	.28	.22	855.5	.28
.23	1268.9	.27	.23	1279.0	.27
.24	2547.9	.26	.24	2552.9	.26
.25	-----	.25	.25	-----	.25

ACUARC RULER

It is obvious from the above table that many of the arcs of circles which one would like to draw on a stereographic net overlay are too large for beam compasses of practical radius. The ACUARC ruler is a flexible template that can be adjusted to approximate curves of any radius from about 7" to infinity. It is extremely useful in fitting arcs of circles through three or four points plotted on a net overlay. It is sold by many drafting and mapping supply houses and is manufactured by Hoyle Engineering Company, Barstow, California, U.S.A. The list price is \$10.00.

SLIDE-RULE MULTIPLICATION AND DIVISION TO FIVE SIGNIFICANT FIGURES

The Atlas slide rule is an ingenious device for multiplying and dividing to five significant figures. In addition to a circular scale around the periphery of the disc, the slide rule contains a spiral scale of 25 coils occupying most of the face of the slide rule, which is about 21 cm in diameter. For those who do not have access to a desk calculator or a hand calculator, such as the CURTA described below, the Atlas Slide Rule will prove a very useful aid to computation. It is distributed by Eugene Dietzgen Co., 2425 Sheffield, Chicago, Illinois, 60614, U.S.A., and is available from most drafting and surveying supply houses. It is listed as Dietzgen Part No. 1797A at a \$13.50 list price.

USED DESK CALCULATORS

Greater than 5-place accuracy requires access to a desk calculator or at least a hand calculator. Used and/or reconditioned desk calculators with automatic division features and sufficient register dials to compute to 8 significant figures are available through most stationery and office supply sales outlets, including those of the larger department stores (e.g. Macy's in New York City). In general, a used desk calculator with few features, but in good condition, will prove to be a better buy than a used desk calculator in fair condition with many special features at the same price.

CURTA HAND CALCULATOR

The CURTA hand calculator, while not as convenient as a good electric-powered desk calculator, can be used to solve problems to 8 significant figures. One version with more limited registers is offered but is not considered to be as good a buy. These items are not toys, they are precision equipment and command a substantial price - about \$165. They are available through some of the larger stationery stores and are listed in the Montgomery Ward catalog under Automobile Rally Accessories.

INDEPENDENT TRACKING COORDINATION PROGRAM

824 Connecticut Avenue
Washington 6, D. C.

BULLETIN

ZAYIN: A COMPUTER PROGRAM FOR PREDICTING POSITIONS OF ARTIFICIAL SATELLITES AT THE POINT OF LOCAL CULMINATION

W. P. Overbeck

May 14, 1964

Introduction

This paper describes an automatic prediction program, ZAYIN, which computes the apparent positions of artificial earth satellites at the point of local culmination. It is designed for use by the optical observer who wishes to make the type of observation that is most useful in the determination of orbital characteristics. It examines all revolutions of the satellite which occur between any two selected dates. It rejects those passes which are below the horizon, which occur while the observer is in daylight or for which the point of culmination is inside the Earth's shadow. For passes that are not rejected, it prints out predictions in both alt-azimuth form and in celestial coordinates, together with other data that is useful in setting the observing instrument or in adjusting the predictions when observation indicates that this is necessary.

ZAYIN uses Rationalized Orbital Elements as input. These were initially described in an ITCP publication, "A Letter to Gregory Roberts", and have been further discussed in subsequent ITCP Bulletins. A Bulletin of April 5, 1964, tells how to derive such elements from the information available from a variety of sources. The output of ZAYIN is also, primarily, in rationalized format and is arranged to facilitate mailing of predictions from a central computing facility to distant observing stations.

ZAYIN is one of a group of programs which, together, comprise a complete data processing system for satellite tracking, including such functions as; computation of perturbations, preparation of tabular aids for desk calculator computation and the reduction and analysis of observations. The data card format and the subroutines used in ZAYIN are designed to be applicable to all programs in this system.

The unique feature of ZAYIN is that it accomplishes its rejection of unacceptable passes, with a minimum of non-productive computation, in the coordinate system of the orbit pole, rather than that of the Earth's North Pole. A fast subroutine for coordinate transformation, POLO, makes it possible to do this expeditiously. ZAYIN also includes an "internal counter" system that permits the program to make its own decisions as to whether certain steps in the computation are necessary.



Symbols, Units and Fortran Names

With few exceptions, the Fortran names used in ZAYIN are derived from the three-letter symbols which have been consistently used in the ITCP reference material. To maintain this consistency, we will use the same three-letter symbols in the ensuing description of ZAYIN, even though they differ from the Fortran names. It is believed that the reader can learn to recognize the differences without confusion. Where it is necessary to use Fortran names in the discussion, they will be underlined and will also include the Fortran convention of writing the letter "O" with a slash, as "ø", to distinguish it from the numeral, zero.

The Fortran names require a fourth, prefix letter to differentiate between fixed-point and floating-point variables. We have given this prefix letter an added significance as follows:

- I The letter "I" is used to designate the integral portion of a number. For example, the mean anomaly, PRM, may include both full and fractional turns, as in PRM = 1179.283492. In this case, the name, IPRM, would have the value, 1179, representing only the full turns.
- A The fractional portion of a number such as that above, would have the prefix "A". In the above example, APRM would have the value, .283492. In ZAYIN, names that begin with "A", such as APRM, ANGR, ANRP, etc., represent the amplitude of the angle that is represented by the last three letters in the name.
- S The prefix "S" will represent the sine of an angle. Thus, when the angle is named ANGR its sine will be named SNGR.
- C Similarly, "C" designates the cosine, so that CNGR is the cosine of ANGR.
- D The prefix "D" designates a difference or a derivative. Such a name will usually require further definition.

The units of angular measure in ZAYIN are decimal turns; units of time are decimal days and units of distance are kilometers. Throughout the program and subroutines, the letter "Z" always represents the constant, 2 pi, needed as a conversion factor between turns and radians wherever the standard trigonometric Library Functions are used.

Input

The input data for ZAYIN is arranged on a series of punched cards as described below. For each card, we give the full 72 column format, in which blank spaces are indicated by the letter "b". The field assigned to each Fortran variable is underlined. The numbers used in these examples correspond to an actual case and, in a succeeding description of the output, the same case is used so that the numbers may be directly compared.

Control Card

1
b38475b38535bbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbb
JNL1 JNL2

This card gives the Modified Julian Dates, JNL, for starting, JNL1, and ending, JNL2, of the series of predictions.

C Card

0.157250b-0.227057b6372.07bbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbb0VERBECKbbb
ANGØ ALNØ GO IDEN IDEN1

The C card gives the observer's position, including his polar distance, NGO, his longitude, LNO, and his radius, GO, from the Earth's center. It also provides 46 spaces for alphanumeric data that may be needed for identification or as an aid in addressing and mailing predictions. This information is transferred from input to output in blocks of 5 characters, such as IDEN and IDEN1. As written, ZAYIN transfers only two such blocks but it may be easily changed to transfer more information.

A Card

1
38466.02459357b.091739b06862.26b0016.75b21157.572844b15.26800111.665E-05
JNE AJNE ANGR CP CG IPRMO AFRMO APRM1 APRM2

This card contains a portion of the orbital elements for one satellite and includes all of the information needed in calculating the principal perturbations of its motion. Thus, for some programs, this is the only card needed. The first item is the epoch of the elements, JNE, divided into an integral portion, JNE, and a fractional portion, AJNE. (The "I" prefix is not used for the integral portion because the letter "J" already defines it as a fixed point variable.) The next three items include the inclination, NGR, the semimajor axis, CP, and the displacement of the orbit center, CG. The remaining items are coefficients of the equation for the mean anomaly, PRM, which, with the above values, would be written:

$$PRM = 21157.572844 + 15.26800111(ENL) + .665E-05(ENL)^2$$

For some programs, the second term coefficient, APRM1, is split into integral and fractional portions but ZAYIN does not require this.

B Card

1
-.766253b-.02071577b-.783E-08b+.480335b+.02694540b+.117E-07b.00E-05-3.53
ATNRO ATNR1 ATNR2 ANRPO ANRP1 ANRP2 RGW GD

The B card contains the remaining orbital element data, starting with coefficients for the two equations:

$$TNR = - 0.766253 - 0.02071577(ENL) - .783E-08(ENL)^2$$

$$NRP = + 0.480335 + 0.02694540(ENL) + .117E-07(ENL)^2$$

It also includes the values necessary in correcting for the effects of the Earth's pear shape; RGW, which happens to be insignificant for this case, and GD.

The full stack of data cards for a run of ZAYIN starts with the Control Card and C Card and may then include any number of pairs of A and B Cards, one pair for each satellite for which predictions are desired. A single blank card is then added at the end of the stack.

TABLE I, EXAMPLE OF OUTPUT OF ZAYIN

OVERDECK		38466.024594 CP= 6862.26 CG= 16.75 NGR=.091739 RGW=0. GD=-3.53									
JNL1=38475		21157.572844 15.26800108 0.665E-05 NRP 0.480335 0.02694540 0.117E-07 TNR-0.766253 -0.02071577-0.783E-08									
JNL UT	GNX NGX	RA DECL	NOR OGX	NRO RGO	GV PRM	ONX NXR	DMDT DRGX	SLAN COGS	I/J K/L	M/N	
481.44057	.10950	20 37.7	.09244	.84110	6844.6	.1324	14.546	.3235	49	0 1	
10 34 25	.36707	-42.145	.24241	.19763	.94563	.1060	-1.445	.2133	42	0 91	
482.42134	.09208	20 12.6	.09210	.84190	6845.7	.1315	14.545	.3207	8	0 1	
10 6 43	.36679	-42.045	.24180	.19812	.92012	.1054	-1.454	.2785	5	0 105	
483.40210	.07461	19 47.4	.09176	.84270	6847.1	.1306	14.544	.3178	8	0 1	
9 39 1	.36647	-41.930	.24113	.19861	.89460	.1048	-1.462	.3652	5	0 119	
485.43245	.04856	19 9.9	.06420	.89732	6846.3	.0687	14.506	.1541	16	2 1	
10 22 43	.33300	-29.880	.18736	.22728	.89451	.0617	-2.171	.2141	10	0 148	
486.41321	.03092	18 44.5	.06372	.89816	6848.1	.0676	14.505	.1523	8	1 1	
9 55 1	.33184	-29.464	.18594	.22763	.86901	.0610	-2.182	.2983	4	0 162	
489.42455	.99409	17 51.5	.02774	.95721	6849.3	.0112	14.458	.0754	24	6 1	
10 11 20	.22148	10.267	.06504	.24523	.84699	.0235	-1.959	.2386	12	0 205	
490.40530	.97699	17 26.9	.02717	.95809	6851.6	.0106	14.457	.0754	8	2 1	
9 43 38	.21936	11.029	.06287	.24538	.82151	.0231	-1.921	.3162	3	0 219	
493.41679	.98389	17 36.8	.98726	.01955	6853.4	.9978	14.447	.0711	24	9 1	
10 0 10	.18254	24.285	.02537	.24821	.80186	.9883	0.959	.2571	9	0 262	
494.39754	.96715	17 12.7	.98668	.02044	6856.0	.9976	14.446	.0715	8	3 1	
9 32 27	.18341	23.971	.02625	.24813	.77634	.9878	0.997	.3328	2	0 276	

496.42818	.96335	17	7.2	.94919	.07982	6856.0	.9576	14.483	.1109	16	8	1
10 16 34	.29900	-17.639	.14741	.23587	.78101	.9557	2.412	.1824	4	0	305	
497.40893	.94601	16	42.2	.94868	.08067	6858.6	.9568	14.483	.1124	8	4	1
9 48 51	.30008	-18.029	.14866	.23559	.75544	.9551	2.402	.2658	1	0	319	
505.04729	.69688	10	43.5	.05456	.91391	6871.6	.0484	14.485	.1223	64	38	1
1 8 5	.30734	-20.642	.15704	.23373	.38154	.0485	-2.342	.2662	6	0	428	
508.05863	.67179	10	7.4	.01704	.97384	6869.5	.0038	14.445	.0739	24	12	1
1 24 25	.19001	21.595	.03293	.24758	.36026	.0153	-1.232	.2949	6	0	471	
509.03936	.65497	9	43.2	.01647	.97471	6867.3	.0035	14.445	.0735	8	3	1
0 56 40	.18893	21.984	.03184	.24768	.33463	.0148	-1.198	.1973	2	0	485	
511.07006	.68062	10	20.1	.97707	.03530	6867.9	.9929	14.449	.0754	16	6	1
1 40 52	.20490	16.235	.04808	.24643	.34052	.9801	1.624	.3323	6	0	514	
512.05079	.66363	9	55.6	.97651	.03616	6865.5	.9925	14.450	.0753	8	2	1
1 13 8	.20670	15.589	.04991	.24630	.31490	.9797	1.665	.2414	3	0	528	
515.06207	.63124	9	9.0	.93990	.09554	6863.9	.9406	14.496	.1396	24	6	1
1 29 22	.32216	-25.977	.17431	.23019	.29308	.9444	2.251	.2886	12	0	571	
516.04280	.61358	8	43.6	.93942	.09635	6861.2	.9395	14.497	.1411	8	1	1
1 1 37	.32357	-26.487	.17597	.22987	.26746	.9437	2.243	.1930	4	0	585	
518.07311	.58656	8	4.6	.91088	.15127	6862.1	.8766	14.539	.2966	16	2	1
1 45 16	.36362	-40.903	.23559	.20228	.26766	.9002	1.526	.3231	10	0	614	
519.05383	.56898	7	39.3	.91054	.15204	6859.4	.8756	14.540	.2992	8	0	1
1 17 31	.36406	-41.061	.23638	.20182	.24200	.8995	1.518	.2343	5	0	628	
534.40009	.16480	21	57.3	.07194	.88352	6875.2	.0832	14.512	.1894	127	1	2
9 36 7	.34310	-33.515	.20162	.22107	.56102	.0720	-1.962	.2118	90	0	847	

Output

An example of the output of ZAYIN, obtained with the above input data, is shown in Table I. The table will extend through as many pages as are needed to reach the ending date, JNL2. For each satellite, a fresh page is started. The format is arranged so that the most important data is to the left of the vertical line, where the sheet can be trimmed to fit the standard $6\frac{1}{2}$ " mailing envelope. The alphanumeric identification data is printed at the upper left, where it will match a transparent window in the envelope.

The input orbital element data is reproduced at the upper right. Here, it may be seen that, in transferring the coefficient, APRM1, as a single, floating-point number, we lose the identity of the last digit. This is not important to ZAYIN.

Immediately below the identification, we print the starting date, JNL1. The purpose of this is to eliminate need for printing the first two digits in the succeeding table of predictions.

Each prediction occupies two lines and the numbers are arranged in pairs, upper and lower, which correspond to the upper and lower column headings. In most cases, the numbers in each pair have a functional relationship as indicated in the following discussion:

- JNL Both numbers represent the predicted time of culmination transit.
UT The upper is expressed as the integral and fractional Modified Julian Date (with the first two digits removed) and the lower is the Universal Time in hours, minutes and seconds.
- QNX This is the predicted apparent position in rationalized celestial
NGX coordinates, including the polar angle, QNX, and polar distance, NGX.
- RA This is the same predicted position as above but is expressed in star
DECL chart coordinates of Right Ascension and Declination for the epoch of the prediction. For precise work, these must be corrected for precession of the coordinate system from the epoch of the charts.
- NOR This is equivalent to an alt-azimuth prediction for the point of
OGX culmination but is expressed in rationalized coordinates with the observer's geocentric zenith (obtained by projection from G through O) as the pole. NOR is the polar angle of the orbit pole and OGX is the zenith distance. These values are not corrected for effects of atmospheric refraction.
- NRO These represent the coordinates of the observer relative to the orbit
RGO pole. They are of interest to the observer who wishes to select those observations which will be most useful in determining the location of the orbit pole.
- GV These numbers give the radius and mean anomaly of the satellite at the
PRM point of culmination. They are useful in selecting the most meaningful observations. They may be used in combination with other data to determine brightness and apparent rates of motion.

ONX These values are used in setting an instrument that employs an
NXR equatorial mounting. ONX corresponds to the "local hour angle" of the
 point of culmination and NXR determines the apparent "bearing angle"
 or direction of travel of the satellite, as viewed in celestial
 coordinates.

DMDT DMDT is the rate of change of mean anomaly of the satellite, with
DRGX respect to time, at the point of culmination. DRGX is the rate at
 which the angle, RGX, changes with respect to time. These values
 may be used in setting the proper rate of motion for a camera which,
 like the Baker-Munn camera, follows the motion of the satellite. They
 may also be used in calculating corrections which should be applied
 to the predicted positions when the predicted timing is found to be
 in error.

SLAN SLAN is a Fortran variable that corresponds to the ratio of slant
COGS range to radius. Multiplied by GV, it gives the slant range and
 aids the observer in estimating brightness. COGS is the cosine of
 the angle, OGS, between the observer and the Earth's shadow center.
 For predictions that fall in the twilight zone, it is useful in
 estimating darkness of the sky so that the observer can decide
 whether observation of a faint satellite is feasible.

The remaining three columns contain numbers that are not related to the prediction. However, they are pertinent to a later discussion of the performance of the computer program. As described below, they indicate what the program has done in the interval between predictions.

I/J I represents the number of passes rejected, after the preceding prediction, because they were below the observer's horizon. J represents the number rejected because they occurred while the observer was in daylight, even though they were above the horizon.

K/L K represents the number of passes rejected because the culmination point was inside the Earth's shadow although they were above the horizon and occurred while the observer was in darkness. L represents passes that were not rejected but which had to be returned for more precise computation because the estimated mean anomaly was substantially different from that predicted by the equation for mean anomaly, PRM.

M/N M is the number of returns for recomputation needed in refining the prediction to six-digit precision. N is the total number of synodic revolutions tested, up to the current prediction and including previous predictions. It is a cumulative count so that, as indicated by the final entry, the entire table involves the examination of 847 synodic revolutions, plus a few more that would have occurred between the final prediction and the ending date, JNL2.

In discussion of the Main Program, we will again refer to these counts to explain how they control the routing of the computation and how they provide a measure of the performance of the program.

Subroutines

The following discussion represents a functional description of each of the subroutines, starting with an example of the necessary CALL statement. Internal detail of some of these subroutines is given in separate Appendices. In each CALL statement, the underlined arguments are the "input" arguments, whose values must be supplied by the Main Program. The remaining arguments are the output arguments, for which values are supplied by the subroutine.

CALL FRACT (A, ARNØ)

FRACT is a very brief subroutine that usually precedes an entry into POLO or other subroutines and operations that involve trigonometric functions. It extracts the fractional portion of a decimal number and expresses it in the range from - 0.5 to + 0.5. In ZAYIN, the input argument for FRACT usually has a temporary name, such as A or B. The CALL statement defines the permanent name for storage (in this case, it is ARNØ). As an example of the operation of this subroutine, we might start with the number:

$$A = 2412.849236$$

FRACT would extract the fractional portion, .849236, and, because this is outside the required range, it would subtract 1.0 to obtain - 0.150764, which would be returned to the Main Program as the value for ARNØ. Use of this subroutine permits us to combine several angles without concern as to whether or not they accumulate to more than a full revolution.

CALL POLO (ANGØ, SNGØ, CNGØ, ANGR, SNGR, CNGR, ARNØ, SRNØ, CRNØ, ARGØ, SRGØ, CRGØ, AØRN, SØRN, CØRN, ANØR, SNØR, CNØR)

POLO is the "workhorse" of ZAYIN, solving all problems in spherical trigonometry through coordinate transformation. The three underlined input arguments are supplied by the Main Program and POLO supplies the remaining 15 arguments. The chart on page 8 gives the rules for naming the arguments for POLO and also helps to explain what POLO does. The above CALL statement represents a case in which we wish to transform the coordinates of an observer, O, from the Earth's North pole, N, to the orbit pole, R, with the Earth's center, G, as the center of both coordinate systems. Examining the definitions given in the upper right portion of the chart, it may be seen that this requires the following substitutions:

$$3 = Ø \quad 1 = N \quad 2 = R \quad 0 = G$$

These substitutions are then made in the list of "Call Names" given in the lower portion of the chart to obtain the arguments as listed above in the CALL statement. The order of letters obtained from this substitution automatically defines the direction of measurement of each polar angle. The subroutine contains its own switching system to route each computation through the shortest path. A complete description, flow diagram and Fortran listing for POLO are included in an ITCP Bulletin of November 19, 1962, on "Fortran Programs for Preparation of Tabular Aids to Satellite Tracking".

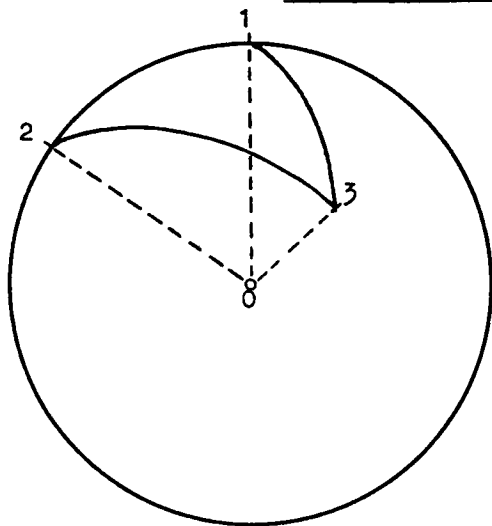
CALL SHADO (JNL, AJNL, ANGS, ATNS, AQNT)

SHADO also requires FRACT and POLO as internal subroutines. From a given input date, for which the integral portion is JNL and the fractional portion is AJNL, SHADO computes the Earth's true anomaly and transforms it from the pole of the ecliptic, Q, to the North pole, N, providing the coordinates of the Earth's shadow center, NGS and TNS. It also supplies the fractional value of the Tropical Year, QNT. Details of SHADO are given in Appendix B. An understanding of the problem with which it deals can be obtained from an ITCP Bulletin of March 28, 1964, on "Time as a Measure of Direction in Space".

CALL KEPLR (APRV, CP, CG, APRM, DPRM, RADR, DRAD)

KEPLR contains Kepler's equations and computes the mean anomaly, PRM, and the ratio of radius to semimajor axis, RADR, from given input values of the true anomaly, PRV, and eccentricity, as derived from CG and CP. It also computes the rate of change of mean anomaly, DPRM, and rate of change of radius ratio, DRAD, per unit change in true anomaly.

Naming of Variables used as Arguments in POLO



Definitions:

- 3 A point whose coordinates are to be transformed.
- 1 Pole of coordinate system in which coordinates of 3 are known.
- 2 Pole of coordinate system in which coordinates of 3 are desired.
- 0 Common center of both coordinate systems.

Note: All angles must be expressed in decimal revolutions (turns) and in the range from - 0.5 to + 0.5

<u>Call Name</u>	<u>Dummy Name</u>	<u>Description:</u>
<u>A103</u>	A	Polar distance of point 3 from pole 1
<u>S103</u>	B	Sine of polar distance, 103
<u>C103</u>	C	Cosine of polar distance, 103
<u>A102</u>	D	Polar distance of pole 2 from pole 1
<u>S102</u>	E	Sine of polar distance, 102
<u>C102</u>	F	Cosine of polar distance, 102
<u>A213</u>	G	Polar angle of point 3 from pole 2, measured about pole 1
<u>S213</u>	H	Sine of polar angle, 213
<u>C213</u>	Ø	Cosine of polar angle, 213
<u>A203</u>	P	Polar distance of point 3 from pole 2
<u>S203</u>	Q	Sine of polar distance, 203
<u>C203</u>	R	Cosine of polar distance, 203
<u>A321</u>	S	Polar angle of pole 1 from point 3, measured about pole 2
<u>S321</u>	T	Sine of polar angle, 321
<u>C321</u>	U	Cosine of polar angle, 321
<u>A132</u>	V	Polar angle of pole 2 from pole 1, measured about point 3
<u>S132</u>	W	Sine of polar angle, 132
<u>C132</u>	X	Cosine of polar angle, 132

Note: The underlined variables; A103, A102 and A213 represent the input data, which must be supplied from the main program. All other values are computed by POLO. In the CALL statement, the variables must be listed in the above order.

Main Program

The following description is based on the Flow Diagram of Figure 1 but also requires reference to the Fortran statement list in Table II. Numbers in the Flow Diagram boxes correspond to the statement numbers. Although the program is a continuously flowing sequence of operations, it is written in six "Parts", each of which completes a major portion of the logic. Within each Part, the statements are numbered consecutively.

PART I reads the input data and establishes the output format. It also establishes the control pattern as that of a "one station - many satellite" program, predicting for any number of satellites in one computer run but for only one observing location. Minor changes in this part of the program will convert it to a "one satellite - many station" or "many satellite - many station" program.

As written, ZAYIN starts by reading the Control Card and C Card (statements 10 - 13) to find the range of prediction dates and the observer's location. It then reads the A Card for the first satellite. As indicated in the Flow Diagram, the program returns to this point for additional satellites and, if there are none, it is routed to the END through statement 16.

Continuing with a given satellite, ZAYIN reads the B Card (statements 17 and 18) and then proceeds to print the headings for the output table of predictions (statements 19 - 32).

PART II establishes initial values of program variables and the value of one constant, Z, (statement 40).

The independent variable in ZAYIN is ENL, the time elapsed since the epoch of the orbital elements. Its initial value is determined (statements 41 and 42) from the starting date, JNL1. Statement 43 then finds the maximum value, ENLM, from the ending date, JNL2.

The average interval between times of local culmination is equal to the "synodic period", SYNP. This is the reciprocal of the mean rate of revolution of the satellite relative to the observer, measured in turns per day. Statement 44 adds all of the rates involved: APRM1, the mean anomalous motion of the satellite; ANRP1, the motion of the perigee; ATNR1, the motion of the orbit pole and $-1\frac{1}{2}$ /day for the motion of the observer. Statement 45 then find the reciprocal to define the value of SYNP.

The internal counters; I, J, K, L, M and N, are all set to zero in this part of the program. The necessary statements are placed in an order that depends on the points at which various return loops are to enter.

One of the time-saving features of ZAYIN is that it computes the coordinates of the Earth's shadow center no more frequently than necessary, once at the start of the program and once as a part of the completion of each prediction. The initial values are supplied, in statements 48 and 49, for the starting date, JNL1.

Considerable time is saved in ZAYIN by rejecting "impossible" passes prior to a final computation of the satellite radius, GV. Statement 55 allows the program to start with the initial assumption that the satellite is at its apogee radius, CP + CG.

FORTTRAN Listing for ZAYIN Main Program Parts I and II

```

C           ZAYIN
C           PART I
10 READ 11,JNL1,JNL2
11 FØRMAT(2I6)
12 READ 13,ANGØ,ALNØ,GØ,IDEN,IDEN1
13 FØRMAT(F8.6,F10.6,F8.2,34X,2A5)
14 READ 15,JNE,AJNE,ANGR,CP,CG,IPRM,APRMO,APRM1,APRM2
15 FØRMAT(I5,F9.8,F8.6,F9.2,F8.2,I6,F7.6,F12.8,E8.3)
16 IF(JNE)172,172,17
17 READ 18,ATNRO,ATNR1,ATNR2,ANRPO,ANRP1,ANRP2,RGW,GD
18 FØRMAT(F8.6,F11.8,E10.3,F9.6,F11.8,E10.3,E8.2,F5.2)
19 WRITE ØUTPUT TAPE 6,20,IDEN,IDEN1,JNE,AJNE,CP,CG
20 FØRMAT(1H1,5X,2A5,7X,I5,F7.6,4H CP=,F8.2,4H CG=,F7.2)
21 WRITE ØUTPUT TAPE 6,22,ANGR,RGW,GD
22 FØRMAT(25X,4HNGR=,F7.6,5H RGW=,E8.2,4H GD=,F5.2//)
23 WRITE ØUTPUT TAPE 6,24,IPRM,APRMO,APRM1,APRM2
24 FØRMAT(25X,I5,F7.6,F12.8,E10.3)
25 WRITE ØUTPUT TAPE 6,26,ANRPO,ANRP1,ANRP2
26 FØRMAT(25X,3HNRP,F9.6,F12.8,E10.3)
27 WRITE ØUTPUT TAPE 6,28,JNL1,ATNRO,ATNR1,ATNR2
28 FØRMAT(2X,5HJNL1=,I5,13X,3HTNR,F9.6,F12.8,E10.3//)
29 WRITE ØUTPUT TAPE 6,30
30 FØRMAT(4X,61HJNL      QNX      RA      NØR      NRØ      GV      ØNX      DMD
1T      SLAN)
31 WRITE ØUTPUT TAPE 6,32
32 FØRMAT(5X,72HUT      NGX      DECL      ØGX      RGØ      PRM      NXR      DRGX
1      CØGS I/J K/L M/N)

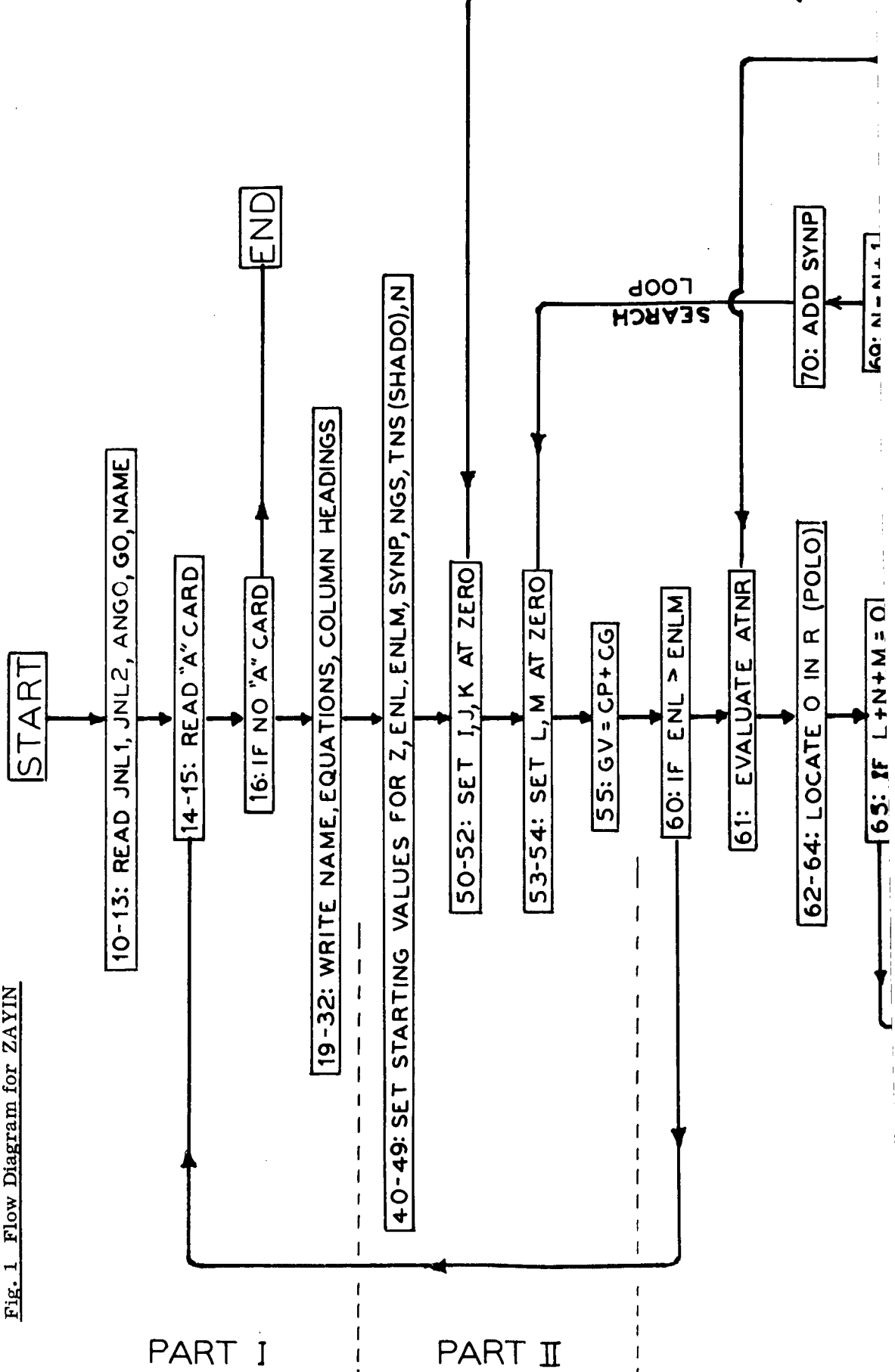
```

```

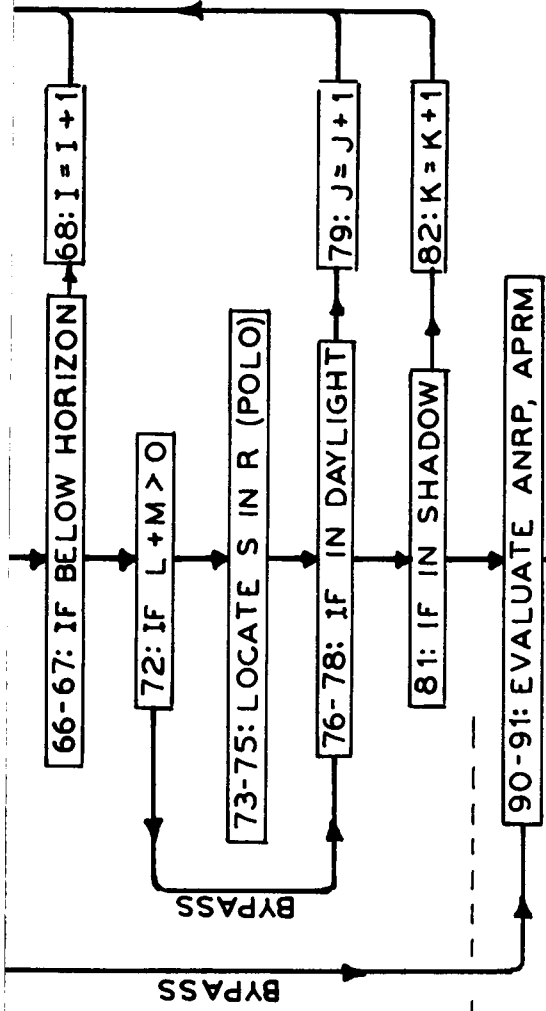
C           PART II
40 Z=6.28318531
41 A=JNL1-AJNE
42 ENL=A+AJNE
43 ENLM=JNL2-JNE
44 A=APRM1+ANRP1+ATNR1-1.
45 SYNP=1./A
46 N=0
47 N=0
48 AJNL=0.
49 CALL SHADØ(JNL1,AJNL,ANGS,ATNS,AQNT)
50 I=0
51 J=0
52 K=0
53 L=0
54 M=0
55 GV=CP+CG

```

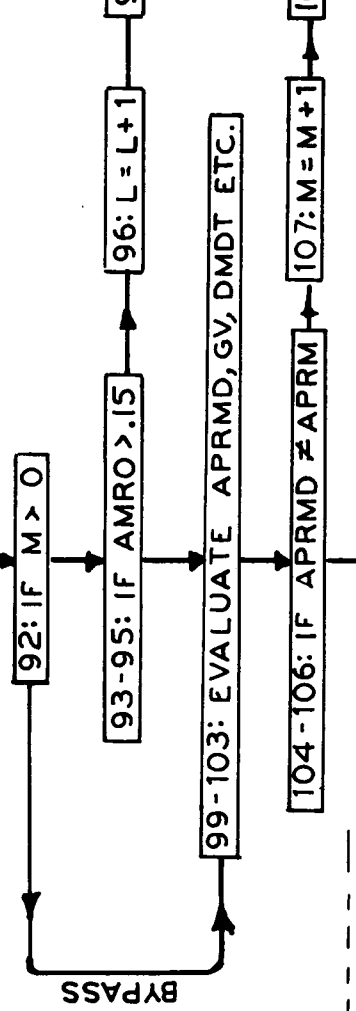
Fig. 1 Flow Diagram for ZAYIN



PART III

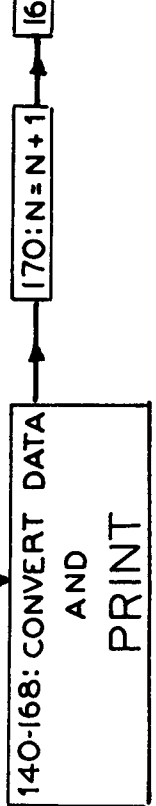


PART IV



PART V - [120-136: COMPLETE PREDICTION. FIND NEW VALUES OF NGS, TNS, QNT]

PART VI



REITERATION LOOP

PART III starts with statement 60, which sends ZAYIN back for another satellite if ENL exceeds the maximum value, ENLM. It then includes the principal components of a "search loop", which searches for acceptable passes. The action of this loop can be better understood with the aid of a preliminary review of the geometry for the general situation, Figure 2, and for the rejection criteria, Figure 3.

Figure 2 is a view of the Earth from the direction of the orbit pole, R. The orbit then lies in the plane of the paper and its inclination is represented by the polar distance, NGR, of the Earth's North pole, N, from the orbit pole. In this view, the observer's circular path is tilted and his relationship to the orbit is described by the direction coordinates, NRO and RGO, and his radius, GO.

In Figure 3(a), it may be seen that, if the sine of the angle, RGO, is greater than GO/GV , the satellite will be above the observer's horizon. For preliminary screening, we can apply this criterion without knowing whether the satellite is actually at the point, V, and without knowing its exact radius, GV. To avoid unnecessary rejections, we can assume that GV has its maximum value, $CP + CG$.

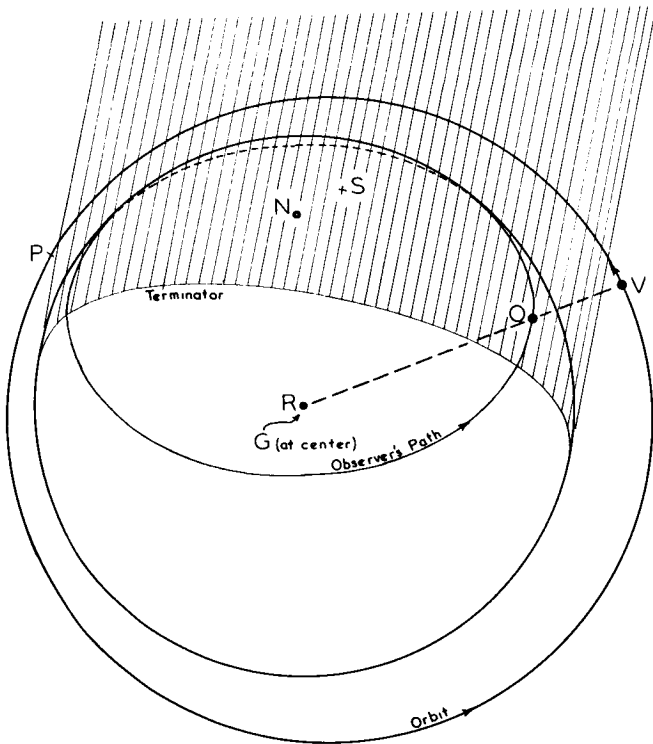


Fig. 2. Requirements for Optical Observation at the Point of Local Culmination

In this diagram, the Earth is visible from the orbit pole, R, and the Earth's center, G, is the center of the coordinate system. The orbit is in the plane of the paper and its inclination is represented by the polar distance, NGR, of the Earth's North Pole, N. The polar angle, NRO, of the observer, O, must equal the polar angle, NRV, of the satellite, V. For successful optical observation, the observer's polar distance, RGO, must be such that the satellite will be above his horizon (see Fig. 3(a)). The position of the Earth's shadow center, S, must be such that the observer is on the shadowed side of the terminator (see Fig. 3(b)) and the satellite is outside the cylindrical region defined by the Earth's shadow (see Fig. 3(c)).

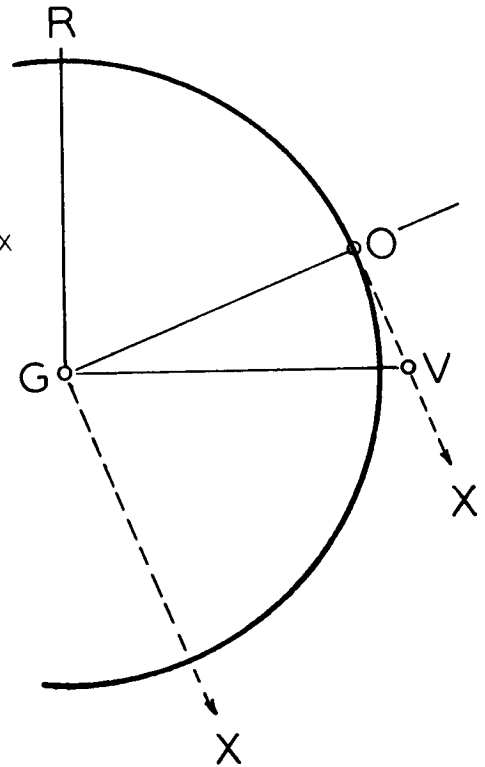


Fig. 3 (a) Criterion for Rejection

For the limiting case, the satellite, V, is on the horizon of the observer, O. The angle, OVG, is equal to the angle, RGO, and the sine of either OVG or RGO is GO/GV . Thus, if the sine of RGO is less than GO/GV , the satellite will be below the observer's horizon.

Returning to Figure 2, the position of the Earth's shadow center, S, may be defined by the direction coordinates, NRS and RGS. The question as to whether the observer is in daylight depends on the angle, SGO.

As illustrated in Figure 3(b), the cosine of SGO must be positive and, if we wish to insure that the observer is well inside the twilight zone, we can specify a minimum value. As written, ZAYIN requires that the observer be at least $0^{\circ}028'$ away from the "terminator", or edge of the shadow. This criterion is independent of the exact location of the satellite.

Looking, again, at Figure 2, it may be seen that the coordinates of the satellite would be: NRV, RGV and GV. RGV is always equal to $0^{\circ}25'$. At the point of culmination, NRV will be equal to NRO and, again, we may assume that GV has the maximum value, CP + CG.

As shown in Figure 3(c), the satellite must be outside the cylinder defined by the Earth's shadow, regardless of whether the angle, SGV, is greater or less than $0^{\circ}25'$. This requires that the sine of SGV be greater than GO/GV. Again, the assumption that GV = CP + CG is one that avoids unnecessary rejections.

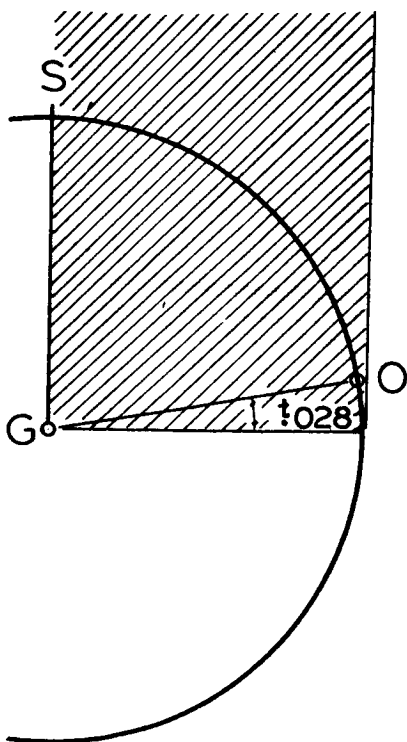


Fig. 3 (b) Criterion for Rejection

If the angle, SGO, is greater than $0^{\circ}25'$, the observer will be in sunlight. To ensure that his sky is reasonably dark, we require that he be about $0^{\circ}028'$ away from the edge of the shadow. Thus, if the cosine of SGO is negative, or less than 0.174, the circumstances are considered to be unsatisfactory.

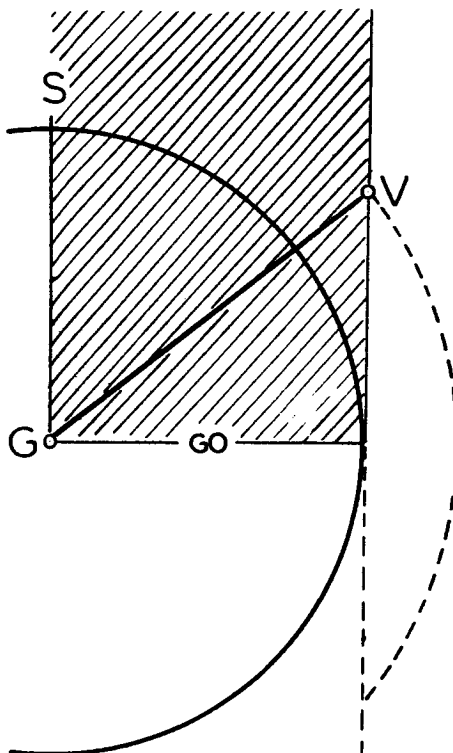


Fig. 3 (c) Criterion for Rejection

If the sine of the angle, SGV, is less than GO/GV, the satellite will be inside the cylinder defined by the Earth's shadow. On the side towards the Sun, it will then be below the horizon for any observer who is inside the shadow. On the side away from the Sun, it will be inside the shadow and will not be illuminated.

Returning to the Flow Diagram and Fortran listing, we should, temporarily, ignore the "bypass" lines at statements 65 and 72 because these are best related to the functions of Part IV of the program. The first task is then to locate the position of the observer, O, in the coordinates of the orbit pole, R. This is done in four steps:

- a. Evaluate TNR from the TNR equation (statement 61).
- b. Sum the necessary polar angles to find NRO (statement 62).
- c. Call FRACT to express NRO in the proper range (statement 63).
- d. Call POLO to transform O from N to R (statement 64). This statement is the example that was used in the functional description of POLO, above.

The criterion of Figure 3(a) is then applied in statements 66 and 67. ~~SRG~~ - ~~GO~~/GV is given the name, P_{OGX}, only because its value is useful at a later point in the program. If the pass is rejected (below the horizon), we add 1 to the "I" counter (statement 68). Returning through the search loop, we add 1 to the "N" counter and advance ENL by one synodic period (statements 69 and 70).

For the passes that are above the horizon, we then find the coordinates of the shadow center, S, in the same manner as used above; summing the polar angles (statement 73), placing in the proper range (statement 74) and transforming coordinates (statement 75). Statements 76 and 77 then represent two applications of the Law of Cosines, which are written in an order that economizes on computing time. Written in full, statement 76 would be:

$$\cos SGV = \cos RGS \cos RGV + \sin RGS \sin RGV \cos SRV$$

but RGV is always 0.25 and, at the point of culmination, SRV will equal SRO so that the equation reduces to:

$$\cos SGV = \sin RGS \cos SRO$$

Similarly, statement 77 could be written in full as:

$$\cos SGO = \cos RGS \cos RGO + \sin RGS \sin RGO \cos SRO$$

Having already evaluated the product, $\sin RGS \cos SRO$, we can write:

$$\cos SGO = \cos RGS \cos RGO + \sin RGO \cos SGV$$

The criterion of Figure 3(b) is then applied in statement 78 and, if the pass is rejected (in daylight), we add 1 to the "J" counter (statement 79) and, in returning through the search loop, add 1 to "N" and SYNP to ENL.

For surviving passes, the criterion of Figure 3(c) is applied in statement 81. For those rejected here (in shadow), we add 1 to the "K" counter, 1 to "N" and SYNP to ENL.

Much of the speed of ZAYIN is due to the effectiveness of this search loop. On the average, half of the passes will be rejected because they are below the horizon. (In Table I, there are a total of 480 "I" rejections in the 847 passes examined.) For this reason, the "I" reject path has been kept

as short as possible. Of the remaining passes, approximately half (240 in Table I) will occur with the observer in daylight. Thus, the "J" path is just outside the "I" path. For a low-flying satellite, as was selected for our example in Table I, many passes that are otherwise acceptable will lie inside the Earth's shadow (106 in Table I). The fact that ZAYIN rejects these prior to final computation of the satellite position is an important time-saving feature. It should be noted that the assumption that $GV = CP + CG$ is one that is designed to save all possible passes. This leads to some unnecessary computer work in that a few of these may be, later, rejected in Part IV. An alternative assumption would be that the satellite is at perigee radius where $GV = CP - CG$. Such an assumption would minimize computer work and would select only those passes that are easiest to observe. If ZAYIN were to be used in predicting for a large number of observing stations, such an assumption might be preferred.

FORTRAN Listing for ZAYIN Main Program Part III

C

```

60 IF(ENL-ENLM)61,61,14
61 ATNR=ATNRO+ATNR1*ENL+ATNR2*ENL**2
62 A=-ATNR+AJNE+ENL+ALNØ
63 CALL FRACT(A,ARNØ)
64 CALL PØLØ(ANGØ,SNGØ,CNGØ,ANGR,SNGR,
   ONGR,ARNØ,SRNØ,CRNØ,ARGØ,SRGØ,
   1CRGØ,AØRN,SØRN,CØRN,ANØR,SNØR,CNØR)
65 IF(L+M+N)90,90,66
66 PØGX=SRGØ-GØ/GV
67 IF(PØGX)68,68,72
68 I=I+1
69 N=N+1
70 ENL=ENL+SYNP
71 GØ TØ 53
72 IF(L+M)73,73,76
73 A=ATNS-ATNR
74 CALL FRACT(A,ARNS)
75 CALL PØLØ(ANGS,SNGS,CNGS,ANGR,SNGR,
   ONGR,ARNS,SRNS,CRNS,ARGS,SRGS,
   1CRGS,ASRN,SSRN,CSRN,ANSR,SNSR,CNSR)
76 CSGV=SRGS*CØSF((ASRN-AØRN)*Z)
77 CSGØ=CRGØ*CRGS+SRGØ*CSGV
78 IF(CSGØ-.173648)79,79,81
79 J=J+1
80 GØ TØ 69
81 IF(SQRTF(1.-CSGV**2)-GØ/GV)82,82,90
82 K=K+1
83 GØ TØ 69

```

PART IV is concerned with matching the polar angle, NRV , of the satellite with that of the observer, NRO (see Figure 2). It starts by evaluating NRP (statement 90) and PRM (statement 91) from the orbital element equations. Ignoring the bypass at statement 92, the sum of NRP and PRM is compared with NRO in statements 93, 94 and 95. If there is an appreciable difference (the value, 0.15 , was selected arbitrarily), the value of ENL is adjusted according to the formula in statement 97 and, adding 1 to the "L" counter, we return to statement 61 to try again. This returns the case to the search loop to redetermine the coordinates of the observer, O . The pass must again pass the rejection criteria but, this time, it is not necessary to redetermine the coordinates of S , which change rather slowly. Statement 72 permits us to bypass statements 73 through 75.

As indicated by Table I, very few passes are returned through "L". Such returns occur occasionally if the satellite has very high orbital eccentricity. Most cases advance to statements 99, 100 and 101, where we determine the mean anomaly, $APRMD$, that is equivalent to the polar angle, PRO , between the perigee, P , and observer, O , (see Figure 2). This is done by using PRO as the input value of true anomaly for KEPLR.

Statement 102 is the first determination of the actual radius, GV , and includes a small adjustment, $GD \cos NRO$, for effects of the pear shape.

Statement 103 determines the rate of change, $DMDT$, of the computed value of mean anomaly as a function of time. It includes effects of motion of the satellite, the perigee, the orbit pole and the observer.

The desired value of mean anomaly, $APRMD$, is then compared with that predicted by the orbital element equation in statement 91, $APRM$. This requires three statements; 104, 105 and 106, using FRACT because we are interested in only the fractional portion. If the difference represents more than 0.000001 in timing, we add 1 to the "M" counter, adjust ENL by an amount determined from the difference in mean anomaly and its rate of change, $DMDT$, and return to statement 61 to try again. The accurate determination of $DMDT$ in statement 103 is an important factor in keeping the number of these returns to a minimum. As indicated in Table I, at least one return through "M" is usually necessary but the count is very rarely higher than 2.

In returning through "M", it is necessary, again, to pass all rejection criteria and, this time, with the correct value of GV . It is here that an occasional pass will be rejected after having progressed all the way through Part IV.

Use of the synodic period, $SYNP$, as a first approximation from each time of local culmination to the next is valid only after finding one correct time of culmination. This explains the bypass at statement 65, which requires that there must have been at least one adjustment at "L" or "M" or one complete prediction to bring the observer and satellite into "synchronism" before the rejection criteria can be applied.

The bypass at statement 92 insures that the rough adjustment of mean anomaly in statement 97 is applied only once. If this adjustment is made too closely, and if it is permitted to remain in effect, the program can go into a state of sustained recycle when there is a substantial difference between true anomaly and mean anomaly at the culmination point.

On completing Part IV, ZAYIN has fully established the situation shown in Figure 2, with NRV , for the satellite, substantially equal to NRO , for the observer. The observer, satellite and orbit pole are lined up on the same great circle.

FORTRAN Listing for ZAYIN Main Program Part IV

C

```
90 ANRP=ANRPO+ANRP1*ENL+ANRP2*ENL**2
91 APRM=APRMO+APRM1*ENL+APRM2*ENL**2
92 IF(M)93,93,99
93 A=-APRM-ANRP-AORN
94 CALL FRACT(A,AMRØ)
95 IF(ABSF(AMRØ)-.15)99,99,96
96 L=L+1
97 ENL=ENL+AMRØ/(APRM1+ANRP1-(1.-ATNR1)*SNGØ*CNØR/SRGØ)
98 GØ TØ 61
99 A=-ANRP-AØRN
100 CALL FRACT(A,APRØ)
101 CALL KEPLR(APRØ,CP,CG,APRMD,DPRM,RADR,DRAD)
102 GV=CP*RADR+GD*GØRN
103 DMDT=APRM1+ANRP1-DPRM*(1.-ATNR1)*SNGØ*CNØR/SRGØ
104 A=APRMD-APRM
105 CALL FRACT(A,B)
106 IF(ABSF(B)-DMDT*.1E-05)120,120,107
107 M=M+1
108 ENL=ENL+B/DMDT
109 GØ TØ 61
```

PART V finishes the prediction after the exact time of culmination has been found in Part IV. The order of the statements in Part V is not as logical as it could be and, although this does not affect the computer, we will discuss them in an order that should be easier for the reader to understand.

The alt-azimuth prediction in column 4 of Table I is already partly completed. The value of NOR has been stored as a part of the coordinate transformation in statement 64. Statement 120 completes the calculation of OGX, which was partially done in statement 66.

The next task is the conversion to celestial coordinates. These are first determined with relation to the orbit pole, R. In Figure 2, it may be seen that NRX is equal to NRO (already determined) and, in Figure 3(a), it may be seen that RGX will be equal to RGO + OGX, as done in statement 121. These coordinates, NRX and RGX, must then be transformed to the N pole, as is done in statement 130, providing values of RNX and NGX. To express the polar angle as QNX, we need a value of QNT, obtained with statements 124 through 129. We make the necessary summation of angles and adjust to the proper range in statements 131 through 134. The call of SHADO, in statement 129 not only provides the required value of QNT but also provides revised values of TNS and NGS for use with the next prediction.

Miscellaneous computations are included in statement 122, which computes the ratio of slant range to radius, SLAN; statement 123, which computes the rate of change of RGX with time; statement 135, which computes the local hour angle, ONX, and statement 136, which simply reverses the sign of ORN so that it can be printed out as NRO.

On completion of Part V, all of the real work of prediction is done and values of 98 variables that are involved in the prediction are in storage. At this point, we can make any decision that we like as to which values we wish to have in the output record.

PART VI is then concerned only with the conversion of data to the particular form desired for the printout of Table I. Statements 140 through 146 convert decimal days to Universal Time in hours, minutes and seconds. Statements 147 through 153 convert the value of QNX to hours and minutes in Right Ascension. Statement 154 converts NGX to degrees of Declination. Statements 154 through 164 cause all negative decimal fractions to be expressed as positive decimal fractions, simply to save space in the output format by eliminating minus signs. Statements 165 through 168 do the printing.

Finally, statement 169 adds one synodic period, statement 170 adds 1 to the "N" count and statement 171 sends ZAYIN back to look for the next observable pass.

Program Performance

ZAYIN has been tested with a variety of satellites, covering the full range of values of inclination and eccentricity. It works equally well for both northern hemisphere and southern hemisphere observing locations. The example used for Table I was chosen to illustrate the performance through a full revolution in TNR, the Local Mean Time of the Orbit Pole, for a low-flying satellite, which makes relatively few observable passes (60 06 A). The nature of the satellite is apparent from the rather large number of passes rejected because they are below the horizon (I) or inside the shadow (K). The only known limitation of the program is that it will not operate dependably if one attempts to predict for a period much beyond 100 days from the epoch of the orbital elements. This is a result of handling the mean motion, PRM1, as a single floating point number, rather than breaking it into integral and fractional parts and using double precision in multiplying it by ENL. The multiplication then results in uncertainty in the sixth decimal digit so that, in attempting to balance to 0.000001, the program can fall into a sustained loop. This is not a serious limitation but the user should be aware of its existence.

Tracing through the rejects, as well as the predictions in Table I, one finds that the entire computation includes:

- 1261 coordinate transformations using POLO
- 43 orbital computations using KPLR
- 22 determinations of the Earth's shadow position with SHADO

plus the computations called for in many cycles through the Main Program. Using the IBM 704, which is now regarded as a slow machine, the entire job, plus printout on magnetic tape, requires about 95 seconds. A faster machine could do it in about 16 seconds. This proves, at least, that there are a great many microseconds in one second.

FORTRAN Listing for ZAYIN Main Program Parts V and VI

```

C          PART V
120 AØGX=ATANF(CRGØ/PØGX)/Z
121 ARGX=ARGØ+AØGX
122 SLAN=ABSF(CRGØ/SINF(AØGX*Z))
123 DRGX=-(1.-ATNR1)*SNGØ*SNØR/SLAN
124 A=ENL+AJNE
125 IB=A
126 JNL=JNE+IB
127 B=IB
128 AJNL=A-B
129 CALL SHADØ(JNL,AJNL,ANGS,ATNS,AQNT)
130 CALL PØLØ(ARGX,SRGX,CRGX,ANGR,SNGR,CNGR,AØRN,SØRN,CØRN,ANGX,SNGX,
1    CNGX,ARNX,SRNX,CRNX,ANXR,SNXR,CNXR)
131 A=AQNT+ATNR+ARNX
132 CALL FRACT(A,AQNX)
133 IF(AQNX)134,135,135
134 AQNX=AQNX+1.
135 AØNX=-ARNØ+ARNX
136 ANRØ=-AØRN

```

```

C          PART VI
140 A=24.*AJNL
141 IUTH=A
142 B=IUTH
143 B=60.*(A-B)
144 IUTM=B
145 C=IUTM
146 IUTS=60.*(B-C)
147 B=AQNX-.25
148 IF(B)149,150,150
149 B=B+1.
150 B=24.*B
151 IRAH=B
152 C=IRAH
153 RAM=60.*(B-C)
154 DECL=360.*( .25-ANGX)
155 IF(ANØR)156,157,157
156 ANØR=ANØR+1.
157 IF(AØGX)158,159,159
158 AØGX=AØGX+1.
159 IF(ANRØ)160,161,161
160 ANRØ=ANRØ+1.
161 IF(AØNX)162,163,163
162 AØNX=AØNX+1.
163 IF(ANXR)164,165,165
164 ANXR=ANXR+1.
165 WRITE ØUTPUT TAPE 6,166,JNL,AJNL,AQNX,IRAH,RAM,ANØR,ANRØ,GV,AØNX,
1    1DMDT,SLAN,I,K,M
166 FØRMAT(1X,I3,F6.5,1X,F6.5,I3,F5.1,1X,F6.5,1X,F6.5,F7.1,1X,F5.4,
1    1F7.3,1X,F5.4,3I4)
167 WRITE ØUTPUT TAPE 6,168,IUTH,IUTM,IUTS,ANGX,DECL,AØGX,ARGØ,APRM,
1    1ANXR,DRGX,CSGØ,J,L,N
168 FØRMAT(1X,3I3,1X,F6.5,F8.3,1X,F6.5,1X,F6.5,1X,F6.5,1X,F5.4,F7.3,
1    11X,F5.4,3I4//)

```

Continuation of PART VI

```

169 ENL=ENL+SYNP
170 N=N+1
171 ØØ TØ 50
172 END FILE 6
    REWIND 6
    STØP 7777
    END(2,0,1,0,1)

```

(See continuation, above.)

Appendix A. FORTRAN Listing for FRACT

```
C          FRACT
          SUBROUTINE FRACT(A,B)
10 I=A
11 C=I
12 D=A-C
13 IF(ABS(D)-.5)19,19,14
14 IF(D)15,19,17
15 B=1.+D
16 GO TO 20
17 B=D-1.
18 GO TO 20
19 B=D
20 RETURN
```

Comments

"A" is the input argument and may be any decimal number that includes both integral and fractional parts. The output argument, "B", will correspond to the fractional part and, if this is greater than 0.5 in magnitude (statement 13), 1.0 is subtracted (statement 17). Thus, the output argument is always in the range from -0.5 to +0.5. The object deck for FRACT will consist of only two cards.

Appendix B. FORTRAN Listing for SHADO

```
C          SHADØ
          SUBROUTINE SHADØ(I,A,B,C,D)
10  G=I-38200
11  H=G+A
12  ANQM=0.493026+.273791E-02*H
13  AQNT=ANQM+0.5
14  ANQP=0.034201+.13E-06*H
15  E=ANQM-ANQP
16  CALL FRACT(E,APQM)
17  Z=6.28318531
18  APQM=APQM*Z
19  APQE=APQM+.01673572*SINF(APQM)+.14004E-03*SINF(2.*APQM)
20  APQM2=APQE-.01673572*SINF(APQE)
21  APQE=APQE+(APQM-APQM2)/(1.-.01673572*CØSF(APQE))
22  F=CØSF(APQE/2.)
23  IF(F)26,24,26
24  APQS=.5
25  GØ TØ 27
26  APQS=2.*ATANF(1.01687813*SINF(APQE/2.)/F)/Z
27  E=ANQP+APQS
28  CALL FRACT(E,ANQS)
29  AQGN=.06513206
30  AQGS=.25
31  CALL PØLØ(AQGS,SQGS,CQGS,AQGN,SQGN,CQGN,ANQS,SNQS,CNQS,B,SNGS,
            1CNQS,ASNQ,SSNQ,OSNQ,AQSN,SQSN,CQSN)
32  E=-AQNT-ASNQ
33  CALL FRACT(E,C)
34  J=AQNT
35  P=J
36  D=AQNT-P
          RETURN
```

Discussion

Equations in SHADO use the Modified Julian Date, 38200, as the epoch. Thus, they should be periodically revised. These include statement 12, which computes the Earth's mean polar angle, NQM, and statement 14, which computes the perigee position.

Statement 19 makes a first approximation of the eccentric anomaly, using equation (45) from page 161 of Moulton's "Celestial Mechanics". Statement 20 computes the corresponding mean anomaly. Statement 21 then uses Moulton's equation (47), page 162, to obtain a closer approximation of the eccentric anomaly. For the Earth's orbital eccentricity, this second approximation is sufficient.

SHADO then computes the true anomaly, (statement 26) and then transforms the Earth's position from the pole of the ecliptic, Q, to the North celestial pole, N, using POLO. Statement 29 gives the value used for obliquity of the ecliptic.

Appendix C. FORTRAN Listing for KEPLR

```
C          KEPLR
          SUBROUTINE KEPLR(W,B,C,D,E,F,G)
           9 A=W
          10 H=C/B
          11  $\phi=1.-H$ 
          12 P=1.+H
          13 Q=SQRTF( $\phi/P$ )
          14 R=SQRTF( $\phi*P$ )
          15 IF(A)21,16,24
          16 D=0.
          17 F= $\phi$ 
          18 E=F* $\phi/R$ 
          19 G=0.
             S=1.
          20 G $\phi$  T $\phi$  44
          21 S=-1.
          22 A=-A
          23 G $\phi$  T $\phi$  25
          24 S=1.
          25 IF(A-.5)34,26,31
          26 D=.5
          27 F=P
          28 E=F*P/R
          29 G=0.
          30 G $\phi$  T $\phi$  44
          31 A=1.-A
          32 T=-1.
          33 G $\phi$  T $\phi$  35
          34 T=1.
          35 Z=6.28318531
          36 U=A*Z/2.
          37 V=2.*ATANF(Q*SINF(U)/C $\phi$ SF(U))
          38 D=(V-H*SINF(V))/Z
          39 F=1.-H*C $\phi$ SF(V)
          40 E=F**2/R
          41 G=S*T*Z*E*H*SINF(2.*U)/R
          42 IF(T)43,44,44
          43 D=1.-D
          44 D=S*D
             RETURN
```

Discussion

KEPLR uses conventional orbital formulae, which are included in statements 37 through 40. The remaining statements are concerned with establishing constants and with the routing of trivial solutions. The input true anomaly, W , may have any value in the range of -1π to $+1\pi$.

INDEPENDENT TRACKING COORDINATION PROGRAM

824 Connecticut Avenue
Washington 6, D. C.

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BULLETIN

"Gear Ratio" Orbital Elements

for

Tracking Artificial Earth Satellites

W. P. Overbeck

June 8, 1964

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INTRODUCTION

One of the main problems facing those who attempt to supply satellite prediction data is the rapid rate at which this data becomes obsolete. The principal reason for this is the erratic nature of the accelerations due to atmospheric drag, solar wind and radiation pressure. There is no way to eliminate this problem completely but there is a way to isolate it and express it in a form such that it can be more easily controlled by the independent observer.

In 1958, I used a tracking method that I called the "gear ratio method", because it treats the components of satellite motion as though they were coupled to one another like the gears in a gear train. I discarded this method because its performance seemed erratic. However, it was particularly useful in its application to long-term extrapolation from each observation to the next. Remembering this particular quality, I resurrected the Gear Ratio



method for use in a recent effort to track ECHO II through daytime optical observation. The results were surprisingly successful, particularly when the method was coupled with refinements that have been developed during the period since 1958. In its modernized form, the Gear Ratio method is found to have the following advantages:

1. With few exceptions, the characteristics of any satellite that is now in orbit can be expressed in a "permanent" set of Gear Ratio Orbital Elements which can be easily kept up-to-date with no further information other than that derived by the observer from his own observations.
2. With careful measurement by an experienced observer, the Gear Ratio Elements will give very precise prediction over periods as long as 2 to 3 years. Relatively little analytical effort is required in the interpretation of observations.
3. Gear Ratio Elements can also be used and kept up-to-date by a beginner who does not care for precision or who is not equipped for precise measurement. Under such usage, the Gear Ratio Elements do not deteriorate. The effects of measurement error are not cumulative.

The ECHO balloon satellites are the principal exceptions to the above comments in that additional refinements are needed for precise prediction. However, the ability to obtain dependable, though rough, predictions is retained. The Gear Ratio Elements appear to be the best way to provide a long-term, though incomplete, description of the behavior of such satellites.

The following discussion is in two parts. The first of these reviews the background of theory and experimental evidence from which the Gear Ratio Elements are derived. The second part explains a few applications of the Gear Ratio Elements to satellite tracking problems. The discussion assumes that the reader is familiar with other recent publications of the Independent Tracking Coordination Program.

THE DERIVATION OF GEAR RATIO ELEMENTS

a. Basic Orbital Elements

If the Earth were a perfect sphere, if it had no atmosphere and if there were no other nearby massive objects, such as the Sun and Moon, the behavior of an artificial satellite could be permanently described by a set of six numbers, known as the "orbital elements". The nature of these elements is illustrated in Figure 1.

In this diagram, we view the Earth from the direction of the orbit pole, R, so that the orbit lies in the plane of the paper, which also includes the Earth's center, G, (hidden under R). The inclination of the orbit is represented by the polar distance, NGR, between the Earth's North pole, N, and the orbit pole. Its value, expressed in turns, is one of the six elements.

Using the pole of the ecliptic, Q, as a reference direction, the location of R is further defined by the polar angle, QNR, expressed in turns and measured about the North pole. The value of QNR is a second orbital element.

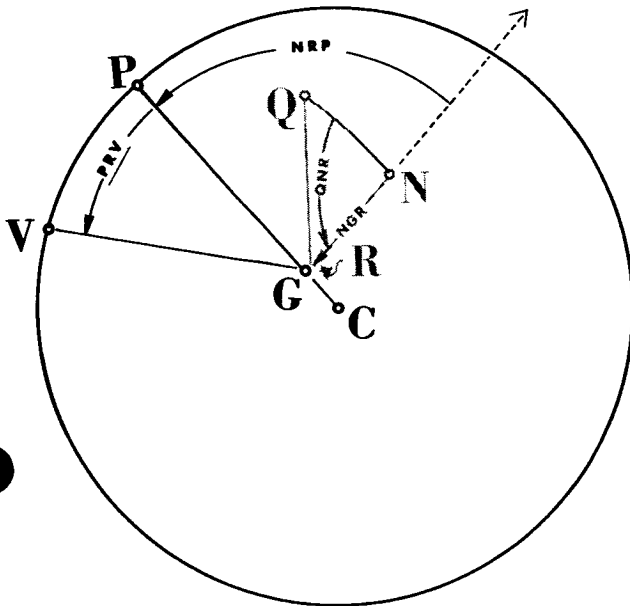
The point in the orbit nearest to the Earth's center is the perigee, P, and its position is defined by a third orbital element, the value of the polar angle, NRP, also measured in turns.

The above three elements define the orientation of the orbit which, according to Kepler's First Law, must then be drawn as an ellipse, with one of its foci at the Earth's center. The size and shape of the ellipse can then be defined in terms of its semimajor axis, CP, and the displacement, CG, of its center from the Earth's center. The value of CP, in kilometers, is a fourth orbital element and the eccentricity, CG/CP, is the fifth.

Finally, if we select an instant at which the satellite is at the perigee, we need supply only one more number, the corresponding epoch, JNE, as a sixth orbital element.

Such economy in description is seldom necessary and it is customary to expand this group of numbers so that we can specify initial positions of the satellite other than at the perigee. A more general situation would be that in which the satellite is at a point, V. This may be defined in terms of a polar angle, PRV, known as the "true anomaly". Kepler's Laws are then used in providing a description of the variation of this angle as a function of time.

Fig. 1. Definition of Orbital Elements:



Points and directions in the plane of the orbit are represented in black and are mapped in the plane of the paper. Points which lie above the plane of the orbit, and the angles between them, are shown in grey.

QNR: The right-handed polar angle measured from the pole of the ecliptic Q, around the North Pole, N, to the mean pole of the orbit, R. This value, together with the Polar distance, NGR, determines the orientation of orbit's coordinate system relative to that in which the observer's position is defined.

NGR: The polar distance from the North Pole, N, measured at the center of its earth, G, to mean orbit pole, R.

NRP: "Argument of perigee from the North point of the orbit" = The right-handed polar angle measured from the North Pole, N, around the mean orbit pole, R, to perigee, P.

P: Perigee, the point in the orbit closest to G, the center of the earth.

V: The center of mass of the satellite.

PRV: "True anomaly" = The right-handed polar angle measured from perigee, P, around the mean orbit pole, R, to the center of mass of the satellite.

C: Center of elliptical orbit

CG: Distance from center of orbit, C, to center of Earth, G.

CP: "Semi-major axis" = Distance from center of orbit, C, to perigee, P.

CG/CP = Eccentricity of orbit.

b. Treatment of Kepler's Laws by Tabulation of Eccentricity Functions

As indicated above, Kepler's First Law defines the orbit as an ellipse, with one focus at the Earth's center. This can be expressed in the equation:

$$\frac{GV}{CP} = \frac{1 - e^2}{1 + e \cos(\text{PRV})} \quad (1)$$

in which e is the eccentricity, CG/CP . The ratio of satellite radius to semi-major axis, GV/CP , is the "radius ratio". For any given value of eccentricity, we can compute values of the radius ratio as a function of true anomaly and can tabulate these, as in the fourth column of Table I. We can also use a derivative of equation (1) to calculate the rates of change of radius ratio, as listed in the fifth column.

With the assumptions made earlier (spherical Earth, no atmosphere, no Sun or Moon), the satellite would continue to travel around its orbit forever, completing each revolution in exactly the same time interval. This can be expressed, according to Kepler's Third Law, in the equation:

$$n^2(\text{CP})^3 = .75402\text{E}+14 \quad (2)$$

in which n is the "mean motion", in revolutions per day, and CP is measured in kilometers. The constant, $.75402\text{E}+14$ (electronic computer format for $.75402 \times 10^{14}$), applies only to earth satellites and would be different for satellites of other planets.

The true angular motion of the satellite, $d(\text{PRV})/dt$, will vary from the mean motion, being faster at perigee and slower at apogee. To simplify the description of this motion, it is compared with that of a fictitious object, M , which travels around R at a constant rate, $d(\text{PRM})/dt$, which is equal to the mean motion, n . Kepler's Second Law permits us to define a "velocity ratio", or ratio of true motion to mean motion, in the equation:

$$\frac{d(\text{PRV})}{d(\text{PRM})} (GV/CP)^2 = \sqrt{1 - e^2} \quad (3)$$

This differential equation can be solved, uniquely, for PRM as a function of PRV . A solution for PRV as a function of PRM requires successive approximations. We have tabulated values of PRM in the second column of Table I and have inverted equation (3) to obtain inverse values of the velocity ratio, as listed in the third column. The entire table is then called a table of "eccentricity functions" because it applies to only one value of eccentricity. Now that we have electronic computers to produce them, it is much more convenient to interpolate in such tables than to use the basic equations.

Such equations, or tables, provide an artifice which permits us to describe the motion of the satellite in the simple time equation:

$$\text{PRM} = \text{PRM}_0 + \text{PRM}_1(\text{ENL}) \quad (4)$$

in which PRM_0 is the initial value at any epoch, JNE . PRM_1 is equal to the mean motion, n , and ENL is the elapsed time since epoch. Presumably, one might then determine the value of PRM at any time and then translate to PRV . A table using PRM as the argument would therefore seem more useful. However, such a table is more costly, in terms of computational time and effort. Instead, we use a prediction procedure in which we, first, select a position, PRV . We then translate to PRM and use equation (4) to determine the time.

TABLE I

Mean Anomaly (PRM) and Other Values
Tabulated as Functions of True Anomaly (PRV)
Where Eccentricity (CG/CP) = .019607

<u>PRV</u>	<u>PRM</u>	<u>d(PRM)</u> <u>d(PRV)</u>	<u>Radius</u> <u>Ratio</u>	<u>d(R.R.)</u> <u>d(PRV)</u>
0.00	0.000000	0.961356	0.980393	0.000000
0.01	0.009614	0.961429	0.980430	0.007438
0.02	0.019229	0.961647	0.980542	0.014851
0.03	0.028847	0.962011	0.980727	0.022211
0.04	0.038470	0.962518	0.980986	0.029494
0.05	0.048098	0.963168	0.981317	0.036674
0.06	0.057734	0.963957	0.981719	0.043724
0.07	0.067378	0.964884	0.982191	0.050621
0.08	0.077032	0.965945	0.982731	0.057339
0.09	0.086697	0.967137	0.983337	0.063853
0.10	0.096375	0.968456	0.984007	0.070140
0.11	0.106066	0.969897	0.984739	0.076177
0.12	0.115773	0.971456	0.985530	0.081940
0.13	0.125496	0.973126	0.986377	0.087407
0.14	0.135236	0.974903	0.987277	0.092557
0.15	0.144994	0.976780	0.988227	0.097370
0.16	0.154772	0.978750	0.989223	0.101824
0.17	0.164570	0.980807	0.990262	0.105903
0.18	0.174388	0.982943	0.991340	0.109588
0.19	0.184229	0.985151	0.992452	0.112863
0.20	0.194092	0.987422	0.993596	0.115712
0.21	0.203977	0.989748	0.994765	0.118122
0.22	0.213887	0.992120	0.995956	0.120080
0.23	0.223820	0.994530	0.997165	0.121576
0.24	0.233777	0.996967	0.998386	0.122600
0.25	0.243759	0.999423	0.999616	0.123146
0.26	0.253766	1.001889	1.000848	0.123206
0.27	0.263797	1.004354	1.002078	0.122777
0.28	0.273853	1.006808	1.003302	0.121858
0.29	0.283933	1.009242	1.004514	0.120448
0.30	0.294038	1.011645	1.005709	0.118551
0.31	0.304166	1.014008	1.006883	0.116169
0.32	0.314318	1.016321	1.008031	0.113309
0.33	0.324492	1.018575	1.009148	0.109981
0.34	0.334689	1.020759	1.010229	0.106195
0.35	0.344907	1.022864	1.011270	0.101964
0.36	0.355146	1.024881	1.012267	0.097302
0.37	0.365404	1.026801	1.013215	0.092228
0.38	0.375682	1.028617	1.014110	0.086761
0.39	0.385976	1.030319	1.014949	0.080922
0.40	0.396288	1.031900	1.015727	0.074735
0.41	0.406614	1.033354	1.016442	0.068225
0.42	0.416954	1.034672	1.017091	0.061418
0.43	0.427307	1.035851	1.017670	0.054344
0.44	0.437671	1.036883	1.018177	0.047032
0.45	0.448044	1.037765	1.018610	0.039514
0.46	0.458426	1.038492	1.018966	0.031822
0.47	0.468813	1.039062	1.019246	0.023990
0.48	0.479206	1.039470	1.019446	0.016053
0.49	0.489602	1.039716	1.019566	0.008044
0.50	0.500000	1.039798	1.019607	0.000000

With the aid of equation (4), we can write what are called "unperturbed orbital elements" as follows, using values for a particular satellite, 1960 Nu 2, to provide a numerical example:

Unperturbed Orbital Elements,
1960 Nu 2

JNE = 38442.028710
 NGR = .078483
 CP = 7443.85
 CG = 145.95
 PRM = .654629 + 13.51296031(ENL)
 QNR = .804751
 NRP = .475764

For such elements, the epoch, JNE, may have any selected value. The meticulous reader may find that, in the above elements, the value of $n^2(CP)^3$ does not agree exactly with equation (2). The above values include corrections for the gravitational perturbations discussed below. However, equation (2) is quite adequate for a first approximation.

c. Cumulative Effects of Gravitational Perturbations

The Earth is not a perfect sphere but resembles, more nearly, an oblate spheroid, having an equatorial radius of 6378.17 km. and polar radius of 6356.79 km. Through observation of artificial satellites, it has also been found that the Earth is slightly pear-shaped, having more mass to the South of the equator than to the North. In addition, its equatorial cross-section is elliptical, with the maximum radius (at about 0°06' W) being about 0.17 km. greater than the minimum. In theory, these differences from a spherical figure may be treated as extra masses which exert extra "perturbing" forces on the satellite, giving rise to perturbations in its motion.

The most important perturbations are those that are due to the oblateness. In prediction, these must be considered. However, it is usually possible to neglect effects of the elliptical equator and, except in precise prediction, those of the pear shape. The most noticeable effect of the oblateness is the precession of the orbit pole which, in a manner similar to the precession of a gyroscope, moves in a circular path about the Earth's North pole. This motion can be expressed in an equation:

$$QNR = QNR_0 + QNR_1(ENL) \quad (5)$$

in which the value of the coefficient, QNR_1 , can be approximated from the formula:

$$QNR_1 = - \frac{.66037E+5}{p^2} (PRM_1) \cos(NGR) \quad (6)$$

in which p is equal to $CP(1 - e^2)$.

For the Gear Ratio Elements, we regard the ratio, QNR_1/PRM_1 , as the first of two gear ratios. Motion of the satellite is so coupled to that of the orbit pole that, for each mean revolution of the satellite, the pole is moved by the amount:

$$\frac{\Delta QNR}{\Delta PRM} = \frac{QNR_1}{PRM_1} = - \frac{.66037E+5}{p^2} \cos(NGR) \quad (7)$$

In equating this to $\Delta QNR/\Delta PRM$, we indicate that it is applicable to large, as well as small changes in PRM.

A second effect of the oblateness is observed as a motion of the perigee so that the polar angle, NRP, may be described by a time equation:

$$NRP = NRP_0 + NRP_1(ENL) \quad (8)$$

For this equation, an approximate value of NRP_1 may be obtained from:

$$NRP_1 = \frac{.66037E+5}{p^2} (PRM_1) (2 - 2.5 \sin^2(NGR)) \quad (9)$$

The second gear ratio is obtained by dividing equation (9) by equation (6) to obtain:

$$\frac{\Delta NRP}{\Delta QNR} = \frac{NRP_1}{QNR_1} = - \frac{2 - 2.5 \sin^2(NGR)}{\cos(NGR)} \quad (10)$$

which is also applicable to large, as well as small changes. It should be noted that this ratio depends only on the inclination, NGR.

These equations have been described as yielding "approximate" values and, in the preceding section, we also indicated that equation (2) gives a first approximation. In "Smithsonian Contributions to Astrophysics", Vol. 6, p 67, Kozai gives more complete formulae than those of equations (2), (6) and (9). We have obtained excellent results by using the Kozai formulae to compute the rates of motion and by deriving the ratios from these rates.

In writing orbital elements to include the effects of oblateness, the normal practice is to express QNR and NRP in terms of time equations, such as equations (5) and (8). However, the Gear Ratio Elements would be written:

$$JNE = 38442.028710$$

$$NGR = .078483$$

$$CP = 7443.85$$

$$CG = 145.95$$

$$PRM = .654629 + \Delta PRM$$

$$QNR = .804751 - .001052884(\Delta PRM)$$

$$NRP = .475764 - 1.6333966(\Delta QNR)$$

and we might then supply an auxiliary prediction equation which, at this stage, would be written:

$$\Delta PRM = 13.51296031(ENL)$$

However, it should be noted that the prediction information can be expressed in forms other than the above equation. It can be expressed as a table of values of PRM as a function of time, as a graph or in the form of periodic announcements of observed values.

d. Acceleration Effects

The effects of atmospheric drag and radiation pressure make it necessary to add another term to equation (4) so that it becomes:

$$PRM = PRM_0 + PRM_1(ENL) + PRM_2(ENL)^2 \quad (11)$$

in which the acceleration coefficient, PRM_2 , is usually of a magnitude that can be most conveniently expressed in microturns per day².

When the perigee radius (CP - CG) is about 6900 km. or less, the acceleration will be primarily due to atmospheric drag. PRM_2 will be positive and may range from 10 to 1,000 $\mu\text{t}/\text{d}^2$ for reasonably long-lived satellites. As a satellite approaches the end of its lifetime, PRM_2 may increase rapidly to values as great as 100,000 $\mu\text{t}/\text{d}^2$.

If the perigee radius is greater than 6900 km., the effects of radiation pressure become significant and may result in either positive or negative values of PRM_2 , generally of the order of $\pm 1 \mu\text{t}/\text{d}^2$. The ECHO satellites are a notable exception, being abnormally sensitive to both radiation pressure and atmospheric drag. For these satellites, typical values of PRM_2 might range from - 500 to + 2,000 $\mu\text{t}/\text{d}^2$.

In any case, the acceleration coefficient is highly variable and can seldom be predicted with an accuracy much better than $\pm 50\%$. So, in writing an equation for long-term prediction, we usually use a mean value that has been determined from observations over a substantial period. In addition to yielding the best possible predictions, this value also serves as an indicator of the length of time that the mean anomaly equation remains useful. For example, if we expect the equation to give values of PRM that are accurate to ± 0.1 , its accuracy begins to become questionable when the acceleration term approaches this value or when:

$$ENL \text{ is equal to or greater than } \sqrt{.01/PRM_2}$$

The acceleration affects other orbital elements because the mean motion, n , is variable, as indicated by:

$$n = \frac{d(PRM)}{d(ENL)} = PRM_1 + 2PRM_2(ENL) \quad (12)$$

which may be derived from equation (11). As indicated by preceding formulae, this variation can affect the semimajor axis, the eccentricity and the rates of motion of both orbit pole and perigee.

The resulting rate of change of the semimajor axis is usually quite small so that the effects of acceleration are best treated by occasional recomputation or adjustment according to the equation:

$$\Delta(CP) = - \frac{2(CP)}{3n} \Delta n \quad (13)$$

The theory for estimating relationships between acceleration and eccentricity is rather unsatisfactory, except for after-the-fact analysis. However, in his book, "Satellites and Scientific Research", King-Hele presents some useful formulae which apply to satellites having moderately high acceleration (about $.5E-3$ or more) and for which the initial eccentricity is between 0.2 and 0.02. Expressed in our symbols, one of these formulae estimates the lifetime, t_L , of the satellite as:

$$t_L = \frac{3 e_0 (PRM_1)}{8 (PRM_2)} \text{ (days)} \quad (14)$$

in which e_0 is the initial value of eccentricity. The variation of eccentricity with time can then be expressed by:

$$e = e_0 \sqrt{1 - (ENL)/t_L} \quad (15)$$

where ENL is the elapsed time since the epoch of the initial value.

For lesser acceleration, corresponding to a perigee radius greater than about 6900 km., the above formulae become meaningless. Experience indicates that one may as well adopt the most convenient assumption; that the eccentricity remains constant until the observations indicate that a change is necessary. (This excludes effects of the pear shape, which we handle through geometric adjustment of predictions and observations, rather than as a cyclic variation in eccentricity.) Again, the ECHO satellites are an important exception in that they undergo large, cyclic variations in eccentricity as a result of radiation pressure.

Theory becomes even less satisfactory in predicting the effects of acceleration on the motion of the orbit pole and perigee. Generally, the theory requires that additional terms, dependent on $(ENL)^2$, be added to equations (5) and (8). However, it is difficult to derive satisfactory values for the necessary coefficients, QNR_2 and NRP_2 .

COMPARISON OF THEORETICAL GEAR RATIOS
WITH THOSE OBSERVED OVER LONG PERIODS

For the Gear Ratio Elements, we have made two simplifying assumptions. First, the ratio between motion of the orbit pole and mean motion of the satellite is assumed to follow the equation:

$$\frac{\Delta QNR}{\Delta PRM} = A + B(\Delta PRM) \quad (16)$$

in which A and B are constants to be determined empirically. Second, the ratio between motion of the perigee and that of the pole is assumed to remain a single-valued constant. To test these assumptions, we have studied records for several satellites, with the results indicated in the following Table II.

TABLE II
Study of Observed Gear Ratios

<u>Satellite</u>	<u>Perigee Radius</u>	<u>$\Delta QNR/\Delta PRM$</u>		<u>$\Delta NRP/\Delta QNR$</u>	<u>Revolutions Examined</u>
		<u>A</u>	<u>B</u>		
64 005 A	6636.02	-.001193673	-.239E-8	-1.545815	1800
1958 Alpha	6718.51	-.001033630	-.639E-9	-1.493730	15600
1959 Alpha 1	6938.64	-.000851741	negligible	-1.5033958	8700
1959 Eta	6894.33	-.000823397	negligible	-1.4888692	8500
1960 Zeta 1	6844.96	-.001177486	negligible	-1.4988108	22000
63 047 A	6851.30	-.001029629	negligible	-1.5771681	1600
1960 Nu 2	7297.90	-.001052884	negligible	-1.6333966	19000

Values of B less than .1E-12 were considered negligible. In no case was there a significant departure from a single value for $\Delta QNR/\Delta NRP$.

These results should not be viewed with surprise because they represent an after-the-fact fit to data that is limited in precision and the implied acceleration effects are not greatly different than those that would be predicted by other means. The only conclusions that we wish to draw are:

1. For satellites having a perigee radius of the order of 6900 km. or more, constant values for both $\Delta QNR/\Delta PRM$ and $\Delta NRP/\Delta QNR$ may be used over periods of time as long as 2 to 3 years.
2. For satellites having a perigee radius less than 6900 km., the ratio, $\Delta NRP/\Delta QNR$, remains constant and the ratio, $\Delta QNR/\Delta PRM$, can be closely approximated as a linear function of ΔPRM .

These conclusions apply to mean rates of motion. Periodic variations due to the pear shape are treated separately.

Obviously, a long period of observation is needed to establish accurately measured values of these ratios. However, we can use the Kozai formulae to calculate initial values and, as indicated by the following Table III, these values are adequate to serve for several hundred revolutions.

TABLE III
Comparison of Observed and Theoretical Gear Ratios

Satellite	$\Delta QNR/\Delta PRM$		$\Delta NRP/\Delta QNR$	
	Observed	Theoretical	Observed	Theoretical
1960 Zeta 1	-.001177486	-.00117730	-1.4988108	-1.4988108
1960 Nu 2	-.001052884	-.00105213	-1.6333974	-1.6334171
63 047 A	-.001029629	-.00102906	-1.5771681	-1.5771675

Thus the final form of the Gear Ratio Elements for 1960 Nu 2 might be written:

$$JNE = 38442.028710$$

$$NGR = .078483$$

$$CP = 7443.85$$

$$CG = 145.95$$

$$PRM = 16624.654629 + \Delta PRM$$

$$QNR = .804751 - .001052884(\Delta PRM) - 0.0(\Delta PRM)^2$$

$$NRP = .475674 - 1.6333966(\Delta QNR)$$

This term is shown only to indicate where it is placed, when its value is significant.

This differs from the form written previously only in the addition of the integral number of turns, since launching, to PRM_0 . This is useful in coordinating different sets of elements that are derived at different times. The auxiliary prediction equation may now be written as:

$$\Delta PRM = 13.51296031(ENL) + .127E-6(ENL)^2$$

and it must be recognized that the values of CP and CG will require occasional revision.

The usefulness of the Gear Ratio Elements will become more apparent in the following description of various applications. However, at this point, it should be noted that their basic characteristic is that they use PRM as the independent variable, rather than ENL. In essence, the mean anomaly, PRM, is the satellite's measure of time, just as our time, JNL, is based on mean revolutions of the Earth about the Sun. The prediction equation is simply a means of translating between the two systems of time.

APPLICATIONS OF GEAR RATIO ELEMENTS

a. Use of Gear Ratio Elements to Furnish Rationalized Orbital Elements for Prediction

It is possible to make predictions directly from the Gear Ratio Elements. However, to take advantage of other ITCP publications on the subject of prediction, the Gear Ratio Elements can be converted to the normal form of Rationalized Orbital Elements. Using the above 1960 Nu 2 elements as an example, we first add the ΔPRM equation to PRM_0 to obtain:

$$PRM = 16624.654629 + 13.51296031(ENL) + .127E-6(ENL)^2 \quad (17)$$

The ΔPRM equation is then multiplied by the $\Delta QNR/\Delta PRM$ ratio and added to QNR_0 to obtain:

$$QNR = .805751 - .01422758(ENL) - .134E-9(ENL)^2 \quad (18)$$

and the ΔQNR portion of this is multiplied by the $\Delta NRP/\Delta QNR$ ratio and added to NRP_0 to obtain:

$$NRP = .475764 + .02323928(ENL) + .218E-9(ENL)^2 \quad (19)$$

It should be noted, here, that the coefficients of $(ENL)^2$ in equations (18) and (19) are slightly less than we would have derived from a more elaborate, but rather uncertain theory. Evidently, this difference from past practice has little practical significance.

To make equation (18) easier to use, we usually combine it with an equation for QNT. Using methods outlined in previous ITCP Bulletins, the applicable equation would be:

$$QNT = .655678 + .00273791(ENL) \quad (20)$$

and, combining with equation (18), we have:

$$TNR = .149073 - .01696549(ENL) - .134E-6(ENL)^2 \quad (21)$$

Equations (17), (19) and (21) are those normally used with the Rationalized Orbital Elements. The values of JNE, NGR, CP and CG can be copied directly from the Gear Ratio Elements to complete the full set of Rationalized Orbital Elements.

b. Use of Gear Ratio Elements in Simplified Satellite Tracking for Casual as well as Meticulous Observers

For tracking, we replace the PRM equation by a "Revolutions Log", a device that was first used in satellite tracking by Arthur S. Leonard. Equation (17) can be expanded into a table of values of PRM , with first and second differences, as shown in Table IV.

TABLE IV

Tentative Revolutions Log for 1960 Nu 2
(based on equation (17), above)

<u>JNL</u>	<u>PRM</u>	<u>1st Diff.</u>	<u>2nd Diff.</u>
38440	16597.240752		.0000254
		135.1296158	
38450	16732.370368		.0000254
		135.1296412	
38460	16867.500009		.0000254
		135.1296666	
38470	17002.629676		.0000254
		135.1296920	
38480	17137.759368		.0000254
		135.1297174	
38490	17272.889085		.0000254
		135.1297428	
38500	17408.018828		.0000254

The usual practice is to write these values in pencil so that they can, later, be erased and replaced by observed values.

Using a 10 day interval, the values in the third column will be 10 times the mean motion, n , and those in the fourth column will be 200 times the acceleration coefficient. As outlined in previous ITCB Bulletins, predictions may be made by interpolation in such a table. Its form is comparable to that of the Daily Satellite Ephemerides.

The prediction procedure involves the calculation of a time, JNL, at which the satellite is expected to appear at a particular position such as the point of local culmination. For this position, we will have calculated a value of PRM. The observation then represents a measurement of the actual time at which the satellite appeared at, or very near this position. As a meticulous observer, I will have measured this time to ± 0.0000001 . I will then use this actual time to recalculate the position and will correct for differences between the calculated and actual point of observation. I will also make corrections for effects of the pear shape and the ellipticity of the equator. All of this is done with the objective of obtaining a measured value of PRM that is accurate to about ± 0.000001 .

Another observer, Mr. X, may either be less meticulous or may lack the means for making precise observations. He may simply use the predicted value of PRM as a measured value to correspond with his measurement of the time. We can assume that his accuracy is ± 0.000001 in timing and ± 0.001 in PRM. Let us then assume that Mr. X and I both start tracking 1960 Nu 2, using the above table and the Gear Ratio Elements. For convenience, we will also assume that his location is the same as mine and that he makes each observation at the same time that I do. After about 60 days, our records of observations might compare as shown in Table V.

TABLE V

RECORD OF OBSERVATIONS

Comparing Log of a Meticulous Observer (W.P.O.)
with Log of a Casual Observer (Mr. X)

<u>JNL</u>	<u>Predicted PRM</u>	<u>W. P. O.</u>		<u>Mr. X</u>	
		<u>PRM</u>	<u>Resid.</u>	<u>PRM</u>	<u>Resid.</u>
38462.40113315	16899.946438	16899.946518	+80	16899.9469	+400
38482.05088329	17165.472894	17165.473397	+503	17165.4732	+300
38484.04727861	17192.450126	17192.450724	+598	17192.4512	+1100
38485.08494712	17206.472112	17206.472747	+635	17206.4728	+700
38486.04369964	17219.427707	17219.428390	+683	17219.4280	+300
38494.02957430	17327.340616	17327.341718	+1102	17327.3416	+1000
38495.06723367	17341.362480	17341.363653	+1173	17341.3642	+1700
38497.06365582	17368.340068	17368.341367	+1299	17368.3410	+900

We can assume that Mr. X's values of JNL will be the same as mine (in the first column) except that they will include only five digits to the right of the decimal.

In the above table, each "residual" column represents the difference between the observed values and the predicted values, which are in the second column. As we proceed, Mr. X and I will both plot these residuals against time, as shown in Figure 2.

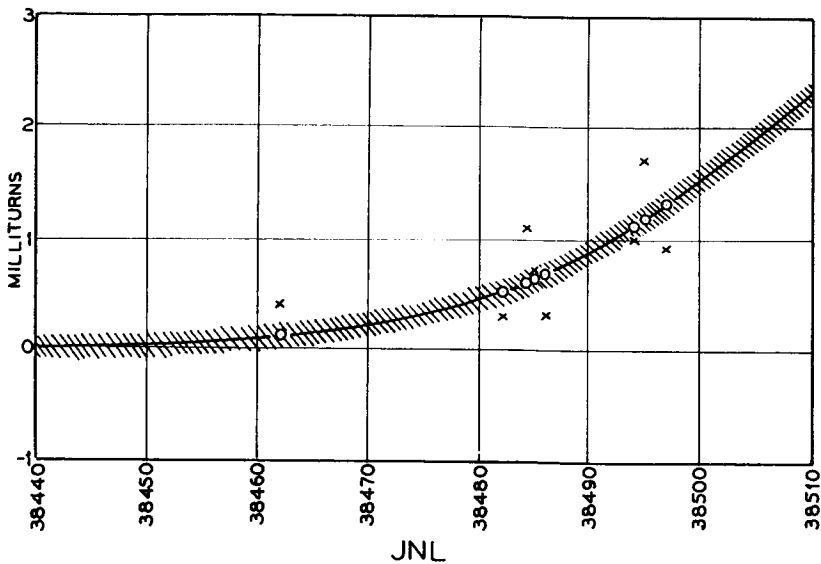


Fig. 2. Plot of residuals in NRM obtained by a meticulous observer (O) as compared with those of a casual observer (X). Data from Table V.

On JNL = 38500, Mr. X and I both decide to review the situation and bring our orbital elements up to date. We both draw a smooth curve through the data points. My curve is represented by the solid line and Mr. X's curve will probably fall somewhere within the shaded area.

Our next step is to correct the values of PRM in the Revolutions Log by amounts equal to the ordinates of this curve for the dates used in the Log. A comparison of the results that we obtain might be as shown in Table VI.

TABLE VI
Corrected Revolutions Logs of
Meticulous and Casual Observer Compared

JNL	W. P. O. Log			Mr. X's Log		
	PRM	1st Diff.	2nd	PRM	1st	2nd
38440	16597.240752		.000036	16597.2408		.0000
38450	16732.370378	135.129626	.000085	16732.3704	135.1296	.0001
38460	16867.500089	135.129711	.000068	16867.5001	135.1297	.0001
38470	17002.629871	135.129782	.000157	17002.6299	135.1298	.0001
38480	17137.759810	135.129939	.000216	17137.7598	135.1299	.0003
38490	17272.889965	135.130155	.000228	17272.8900	135.1302	.0001
38500	17408.020348	135.130383	-----	17408.0203	135.1303	-----
		135.130583	.000200		135.1305	.0002
38510	17543.150931	135.130783	.000200	17543.1508	135.1307	.0002
38520	17678.281714			17678.2815		

In both cases, we have extrapolated the table ahead by selecting a mean value for the second difference and adding it in for two more 10 day intervals. Thus, the portion of each Log below the dashed line represents a new "tentative" Log, with which we continue to predict for subsequent observations.

At the same time that we revise the Log, Mr. X and I will both derive new orbital elements and we will assume that we select the date, JNL = 38510. As compared with the previous Gear Ratio Elements, the data that we will work from will be:

Data Required for Revision of Elements

	<u>W. P. O.</u>	<u>Mr. X</u>
JNL	38510.0	38510.0
PRM	17543.150931	17543.1508
Δ PRM	918.496302	918.4962

The new Gear Ratio Elements that we derive will be:

New Gear Ratio Elements Derived from Casual and Meticulous Observations Compared

	<u>W. P. O.</u>	<u>Mr. X</u>
JNE	38510.0	38510.0
NGR	.078483	.078483
CP	7443.46	7443.46
CG	145.95	145.95
PRM	17543.150931 + Δ PRM	17543.1508 + Δ PRM
QNR	.837681 - .001052884 (Δ PRM)	.837681 - .001052884 (Δ PRM)
NRP	.055373 - 1.6333966 (Δ QNR)	.055373 - 1.6333966 (Δ QNR)

If I were to write an auxiliary prediction equation, it would be:

$$\Delta \text{PRM} = 13.5130683(\text{ENL}) + .100\text{E}-5(\text{ENL})^2$$

Whereas Mr. X's prediction equation would be:

$$\Delta \text{PRM} = 13.51306(\text{ENL}) + .1\text{E}-5(\text{ENL})^2$$

Thus, it may be seen that the main difference between my results and those of Mr. X is that I have more quantitative information as to the acceleration that has taken place and my prediction data will be more accurate in timing. However, the new Gear Ratio Elements that we derive will not be significantly different. Insofar as tracking is concerned, I could have abandoned the satellite for 70 days, leaving it to Mr. X. At the end of that time, I would have found his elements acceptable in recovering it. So, Mr. X easily qualifies as an Independent Satellite Tracker. (We once defined a "tracker" as a man who can keep track of satellites by himself.)

It should be noted that the above example is fictitious in that it was necessary to show a rather sudden increase in acceleration in order to make the residuals large enough to clearly illustrate the method of correction. 1960 Mu 2 would never show such a drastic change. If actual data had been used, the curve of Figure 2 would have been very close to the time axis. I would have made very small corrections, plotting the curve on a larger scale, and Mr. X would have concluded that there was no need to make corrections.

c. Use of Gear Ratio Elements to Improve Tracking Agency Data for Long Term Predictions

In using data issued by the official tracking agencies, one should recognize its limitations. The principal objective of the agency is to provide good short-term prediction. Observations are analyzed in batches to derive the best orbital elements to fit current observations and these are then extrapolated one or two weeks ahead. Before these elements begin to deteriorate, the agency will have a new batch of observations, a new analysis and a fresh set of elements. Thus, there is little reason to aim for long-term accuracy of any one set of elements.

There are a number of methods by which tracking agency data can be "smoothed" to obtain more uniform and better long-term performance. However, in smoothing the data, one should understand which items are likely to be most accurate and which should be regarded with suspicion. First, the rates of motion given for orbit pole and perigee are usually theoretical, rather than measured values. As a result, one sometimes obtains better values by comparing successive sets of elements, rather than by using those stated in the official bulletins. The remaining items are then comparable to those that we have described as "unperturbed" orbital elements and can be discussed, in order of decreasing accuracy, as follows:

- JNE The tracking agencies measure time very precisely so that there need never be any doubt as to the precision of the stated epoch.
- CP The semimajor axis is derived from measurement of the mean motion and this value should always be quite precise.
- NGR The inclination is relatively easy to measure and does not change rapidly. After the first week or two that a satellite is in orbit, tracking agency values for NGR will stabilize to within about ± 30 microturns of the correct value.
- QNR This value is also relatively easy to measure but more observations are needed in finding a correct value. So, the accuracy will generally be about ± 100 microturns for SAO elements and not quite this good for NORAD elements.
- CG This depends on eccentricity and the ability to obtain a good measurement varies with the orientation of the orbit. In prediction elements, the values seem to have a "scatter" of about ± 0.0005 .
- NRP The perigee position is the most difficult to measure, particularly if the eccentricity is low. Errors can be of the order of ± 1500 microturns. Tracking agency data will also contain the variations due to the pear shape. For long-term, smoothed elements, we must separate these variations.
- PRM Accuracy in measurement of mean anomaly is affected by the accuracy of the perigee position, which serves as the reference point. It should be realized that, by adding NRP and PRM to obtain NRM, we can usually obtain a more accurate measure of the satellite position because NRM is measured from a fixed reference point.

Table VII then illustrates how we can use the Gear Ratio Elements to improve tracking agency data. In this case, we have used Ephemeris VI data, issued by the Smithsonian Astrophysical Observatory. Once we have established values for the gear ratios, the only data that we need accept from the SAO ephemerides are the values of JNE, NGR and NRM. In effect, we use SAO just as we used Mr. X, to keep track of how many times the satellite goes by and when. Thus, the first two columns of the table are similar to the Revolutions Log, except that, for convenience, we have used the 14 day interval that corresponds to the dates for which the Ephemeris VI is issued.

To start the table, we initially used the SAO values of NRM, to find temporary ratios, $\Delta QNR/\Delta NRM$ and $\Delta NRP/\Delta QNR$, that would give a reasonably good fit to the SAO values for QNR and NRP. This made it possible to establish a few of the calculated values, QNR(WPO) and NRP(WPO). The calculated NRP(WPO) values could then be subtracted from the NRM(SAO) values to obtain some starting values for PRM(WPO). With these, we derived the equations shown at the upper left. For convenience, these were based on an initial value of zero for PRM. Based on this start, we now fill in new values in the table according to the following procedure:

Procedure Used in Preparing Table VII

1. From each new issue of Ephemeris VI, we enter the values of JNL and NRM(SAO) in columns 1 and 2.
2. We extrapolate the value of NRP(WPO) forward, using the tabulated 1st and 2nd difference to obtain a tentative value for NRP.
3. The tentative value of NRP is subtracted from NRM(SAO) to obtain a tentative value for PRM(WPO).
4. The tentative value of PRM(WPO) is then used to calculate final values of QNR(WPO) and NRP(WPO) that are entered in columns 7 and 11.
5. The final NRP(WPO) is subtracted from NRM(SAO) to obtain the final value for PRM(WPO). This final value seldom varies from the tentative value by more than a few microturns so that it is not necessary to recalculate QNR(WPO) and NRP(WPO).
6. The first and second differences are then filled in for PRM (columns 4 and 5), QNR (columns 8 and 9) and NRP (columns 12 and 13).
7. The SAO values of QNR(SAO) and NRP(SAO) are entered in columns 6 and 10 for comparison.

Columns 14 and 15 illustrate how we can keep track of the variation in semimajor axis. The first entry in this column was calculated from the mean motion, corresponding to 1/14 of the value entered in column 4 of the same row. Succeeding values are obtained by subtracting the numbers listed as ΔCP in column 14. The ΔCP values are obtained with the equation shown above the table, in which $\Delta\Delta PRM$ represents the 2nd difference in PRM. The constant in this equation, - 21.5601, is 1/14 of the value obtained with equation (13).

Columns 16 and 17 compare the SAO values for eccentricity with those calculated from the King-Hele equations (14) and (15). Equation (14) gives a lifetime, t_L , of 629 days from JNL = 38436, indicating that this satellite should reenter the Earth's atmosphere on or about November 1, 1965. It should be a very spectacular sight because this is the rocket that is filled with sand.

As indicated, the QNR(SAO) values agree with the calculated QNR(WPO) values quite well and, as anticipated, the NRP(SAO) values do not show as good agreement. The calculated values are definitely better for long-term prediction and have given more accurate predictions of position angles.

With the 14 day interval, one must divide first differences by 14 to obtain daily motion and must divide 2nd differences by $2 \times (14)^2$ or 392 to obtain the acceleration coefficients. For example, if we wish to write Rationalized Orbital Elements for the epoch, JNE = 38534, we first interpolate in the table to obtain:

	Base Value	1st Diff.	2nd Diff.
PRM	1680.019530	213.676191	.090684
QNR	-.520363	-.256775	-.000328
NRP	.213694	.396927	.000507

We then divide 1st differences by 14 and 2nd differences by 392 to write:

$$\begin{aligned} \text{PRM} &= 1680.019530 + 15.2625851(\text{ENL}) + .231\text{E}-3(\text{ENL})^2 \\ \text{QNR} &= -.520363 - .0183411(\text{ENL}) - .837\text{E}-6(\text{ENL})^2 \\ \text{NRP} &= .213694 + .0283519(\text{ENL}) + .129\text{E}-5(\text{ENL})^2 \end{aligned}$$

For comparison, the SAO equations for the same epoch may be written:

$$\begin{aligned} \text{PRM} &= 1680.02241 + 15.263657(\text{ENL}) + .259\text{E}-3(\text{ENL})^2 \\ \text{QNR} &= -.520369 - .018324(\text{ENL}) \\ \text{NRP} &= .210816 + .027669(\text{ENL}) \end{aligned}$$

This comparison helps to illustrate several points:

1. The two sets of elements describe the same initial position because the NRM values for each are nearly equal, .233224 vs .233226.
2. The principal difference in long-term prediction will be due to the difference in mean motion. The value obtained from the Gear Ratio Elements will usually be better because it must fit the past history.
3. While the rates of motion of the orbit pole agree quite well, the rates of motion of the perigee differ substantially. This may be ascribed to possible effects of the pear shape on the SAO analysis.

An incidental benefit of the table of Gear Ratio Elements is that we begin to see the pattern of acceleration. The early period, between 38436 and 38492, is one in which the perigee is in sunlight. From 38506 through 38548 it is in darkness, where the atmospheric drag is reduced. The entire cycle should extend through about 137 days.

The values in the first row of Table VII represent my extrapolation back to the time of launching, JNL = 38423.686866. These values place the orbit directly over Cape Canaveral and allow the real satellite a few minutes to rise from the launching pad to meet its mathematical model.

d. Gear Ratio Elements for Keeping Track of the ECHO Satellites

Radiation pressure causes large, cyclic changes in eccentricity for the ECHO satellites, ranging up to 0.05 for ECHO I and 0.025 for ECHO II. This phenomenon leads to apparent irregularities in the motion of the perigee. For example, as the eccentricity passes through zero, the perigee position must jump from one side of the orbit to the other. These variations also lead to cyclic changes in the rate of motion of the orbit pole because, as indicated by equation (6), this rate is affected by the eccentricity. These effects of radiation pressure are coupled with large, irregular variations in acceleration. Thus, it becomes virtually impossible to describe the overall behavior of the ECHO satellites with a simple set of long-term equations.

One can devise means for accurate prediction for these satellites over short periods of time. However, the most useful application of the Gear Ratio Elements to this type of satellite appears to be that of providing a means for rough prediction that remains valid over long periods of time. With this objective in mind, we can make the Gear Ratio Elements simpler, rather than more complicated.

We start with the basic assumption that the eccentricity is zero and that there is no perigee position. We then need only one gear ratio, that between the orbit pole position, QNR, and the mean polar angle, NRM, of the satellite. With these assumptions, we can write Gear Ratio Elements for the two ECHO satellites as follows:

Gear Ratio Elements for Tracking ECHO Satellites

ECHO I

$$JNE = 38541.0$$

$$NGR = .131381$$

$$CP = 7806.94$$

$$NRM = 5704.0997 + \Delta NRM$$

$$QNR = .272361 - .000733181(\Delta NRM)$$

ECHO II

$$JNE = 38548.0$$

$$NGR = .226400$$

$$CP = 7547.40$$

$$NRM = 1697.8462 + \Delta NRM$$

$$QNR = .819782 - .000171478(\Delta NRM)$$

For ECHO I, the integral number of turns was taken from an arbitrary starting point. For ECHO II, the count is taken from the time of launching.

Auxiliary prediction equations, using the same epoch as for each set of elements, would be:

$$\text{For ECHO I: } \Delta NRM = 12.595787(ENL) + .174E-4(ENL)^2$$

$$\text{For ECHO II: } \Delta NRM = 13.238029(ENL) + .893E-4(ENL)^2$$

These will be somewhat less dependable than for other satellites, due to the rather rapid changes in acceleration.

Such Gear Ratio Elements can be kept up to date partly through observation and partly through the use of data from any other source. As an example, the ITCP issued Modified Orbital Elements on June 4, 1964, including the following data for ECHO II:

OBJECT	64 004A	
NAME	ECHO II	
SOURCE	SAO	
EPOCH of	06 Jun	} → JNL = 38552.104410
perigee	02 H	
(UT)	30M35	
INCLIN	81A50	
NODE W	000A17	
MPD=1D	-07M17	
PERIGEE	155A79	→ NRP = .182750
change/P	-A16391	
A Period	108M720	
change/P	-M00012	
EGGEN	U02317	
P RADIUS	4580#8	
R A NODE	291A77	

Of this data, we need only the two values indicated for JNL and NRP. (The NRP value is obtained by dividing the argument of perigee, 155°79, by 360 and subtracting 0.25).

Modified Orbital Elements are always written for an epoch at which PRM is zero so that the above value of NRP is also equal to NRM. Using the ECHO II prediction equation, the full value of NRM can readily be identified as:

$$\text{NRM} = 1752.182750 \quad \text{for} \quad \text{JNL} = 38552.104410$$

and these values can be regarded as equivalent to any observation that the tracker might obtain through his own effort.

As a check on the effectiveness of the Gear Ratio Elements, we can use the above data to compute QNR in:

$$\text{QNR} = .819782 - .000171478(1752.182750 - 1697.846200)$$

from which the result (0.810464) should be numerically equal to the value given in the Modified Orbital Elements for the Right Ascension of the Node (291°77)

Based on past history, the above Gear Ratio Elements for the ECHO satellites should give satisfactory prediction for a year or more and should thus provide a good beginner's exercise in tracking, when coupled with graphical methods of prediction such as those involving the Rationalized Wulff Net.

CONCLUSIONS

Obviously, Gear Ratio Elements are not truly "permanent" in that they must ultimately deteriorate due to lack of arithmetical precision. However, they are correct in principle in that motion of the orbit pole and perigee is more properly a function of motion of the satellite, rather than of time.

It is evident that they provide a more enduring model of satellite behavior, permitting the tracker to continue for a much longer period before adjustments become necessary. Since starting this investigation of their performance, I have continued tracking three satellites, each for about 200 days, and have continued to obtain accurate predictions for each from a single set of Gear Ratio Elements. During the entire period, the process of bringing the elements up to date and making new predictions has been completely automatic. It now appears that the same elements will continue to be satisfactory for at least one year.

INDEPENDENT TRACKING COORDINATION PROGRAM

824 Connecticut Avenue
Washington 6, D. C.

BULLETIN

7 April 1964

CONTENTS: Rules for Combining Polar Angles

Rules for the Negative of an Angle

Worksheet for Advancing Epoch of Rationalized Orbital Elements

Drafting Aids to Making Accurate Overlays

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More Significant Figures with Used Desk Calculators

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Rules for Combining Polar Angles

The predictable way in which the 3-letter "names" of polar angles change under addition and subtraction is illustrated in the work sheets.

IN GENERAL: Polar angles may properly be combined if, and only if, they have a common pole (common middle letter-identity) and another identity in common.

If the INITIAL identity of one is the same as the TERMINAL identity of the other, the SUM ANGLE will have the remaining initial and terminal identities; for example:

$$ABC + CBD = ABD$$

If the INITIAL identities are the same, the INITIAL identity of the REMAINDER ANGLE will be the remaining identity of the subtrahend; for example:

$$ABD - ABC = CBD$$

If the TERMINAL identities are the same, the TERMINAL identity of the REMAINDER ANGLE will be the remaining identity of the subtrahend; for example:

$$ABD - CBD = ABC$$

Rule for the Name of the Negative of an Angle

If an angle is defined by the three-letter symbols, ABC, then the angle, CBA is the negative of ABC, for example:

$$-ABC = CBA$$



WORKSHEET FOR ADVANCING EPOCH: Example

Data used in the example given below was taken from the Work Sheet B example discussed in ITCP Bulletin 5 April 1964. Additional copies of Work Sheets are available on request to this office. Please specify which Work Sheets are desired.

WORK SHEET D: For Advancing the Epoch of Rationalized Orbital Elements

No. = \dots
 JNE = new epoch = \dots d
 -(JNE = old epoch = \dots d)
 = Δ NE = interval = \dots d $(\Delta$ NE)² = \dots

Transmits: \dots mc/s
 \dots mc/s

NGR = \dots CG = \dots km CP = \dots km CG/CP = \dots

$TNR_0 = \dots$	$TNR_1 = \dots (ENL)$	$TNR_2 = \dots (ENL)^2$
+ $TNR_1(\Delta$ NE) = \dots	+2 $TNR_2(\Delta$ NE) = \dots	
+ $TNR_2(\Delta$ NE) ² = \dots		
<hr/>	<hr/>	<hr/>
= $TNR_0 = \dots$	$TNR_1 = \dots (ENL)$	$TNR_2 = \dots (ENL)^2$

$NRP_0 = \dots$	$NRP_1 = \dots (ENL)$	$NRP_2 = \dots (ENL)^2$
+ $NRP_1(\Delta$ NE) = \dots	+2 $NRP_2(\Delta$ NE) = \dots	
+ $NRP_2(\Delta$ NE) ² = \dots		
<hr/>	<hr/>	<hr/>
= $NRP_0 = \dots$	$NRP_1 = \dots (ENL)$	$NRP_2 = \dots (ENL)^2$

$PRM_0 = \dots$	$PRM_1 = \dots (ENL)$	$PRM_2 = \dots (ENL)^2$
+ $PRM_1(\Delta$ NE) = \dots	+2 $PRM_2(\Delta$ NE) = \dots	
+ $PRM_2(\Delta$ NE) ² = \dots		
<hr/>	<hr/>	<hr/>
= $PRM_0 = \dots$	$PRM_1 = \dots (ENL)$	$PRM_2 = \dots (ENL)^2$

WORK SHEET D: For Advancing the Epoch of Rationalized Orbital Elements

No.	=	-	-			
JNE	=	new epoch	=	d		Transmits: . mc/s
-(JNE)	=	old epoch	=	d		. mc/s
<hr/>						
= ENE	=	interval	=	d	(ENE) ² =	.

NGR = t . CG = . km CP = . km CG/CP = .

TNR ₀	=	t				
+ TNR ₁ (ENE)	=	t				
+ TNR ₂ (ENE) ²	=	t				
<hr/>						
=	TNR ₀	=	t			

TNR ₁	=	t	(ENL)	TNR ₂	=	t	(ENL) ²	
+2 TNR ₂ (ENE)	=	t						
<hr/>								
=	TNR ₁	=	t	(ENL)	TNR ₂	=	t	(ENL) ²

NRP ₀	=	t				
+ NRP ₁ (ENE)	=	t				
+ NRP ₂ (ENE) ²	=	t				
<hr/>						
=	NRP ₀	=	t			

NRP ₁	=	t	(ENL)	NRP ₂	=	t	(ENL) ²	
+2 NRP ₂ (ENE)	=	t						
<hr/>								
=	NRP ₁	=	t	(ENL)	NRP ₂	=	t	(ENL) ²

PRM ₀	=	t				
+ PRM ₁ (ENE)	=	t				
+ PRM ₂ (ENE) ²	=	t				
<hr/>						
=	PRM ₀	=	t			

PRM ₁	=	t	(ENL)	PRM ₂	=	t	(ENL) ²	
+2 PRM ₂ (ENE)	=	t						
<hr/>								
=	PRM ₁	=	t	(ENL)	PRM ₂	=	t	(ENL) ²

WORK SHEET D: For Advancing the Epoch of Rationalized Orbital Elements

No.	=	-	-				
JNE	=	new epoch =		d		Transmits:	. mc/s
-(JNE)	=	old epoch =		d	)		. mc/s
= ENE	=	interval =		d	(ENE) ² =		.

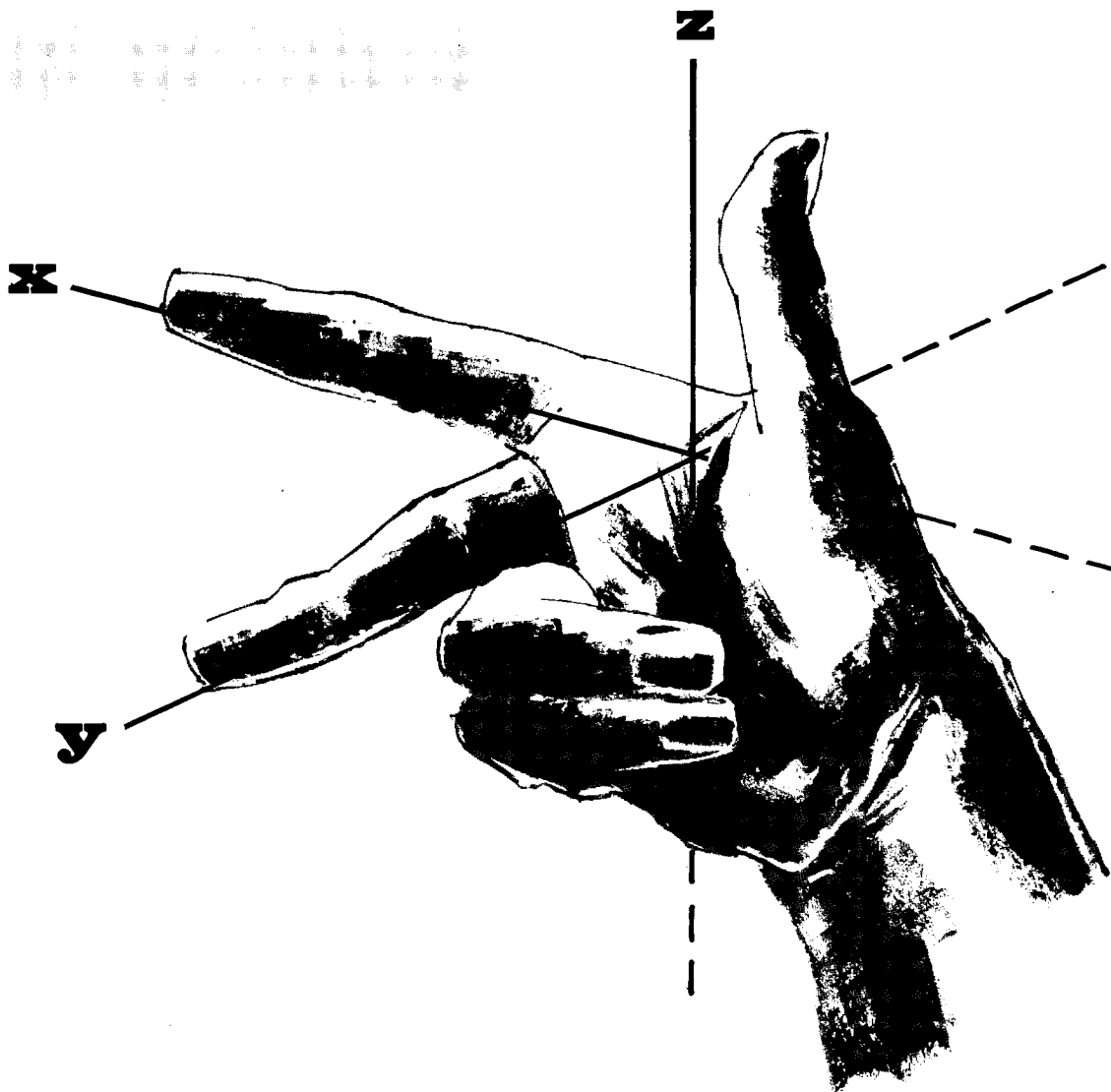
NGR = t . CG = . km CP = . km CG/CP = .

TNR ₀	=	t					
+ TNR ₁ (ENE)	=	t	+2 TNR ₂ (ENE)	=	t	(ENL)	TNR ₂ = t (ENL) ²
+ TNR ₂ (ENE) ²	=	t					
<hr/>							
=	TNR ₀	=	t	TNR ₁	=	t	(ENL) TNR ₂ = t (ENL) ²

NRP ₀	=	t					
+ NRP ₁ (ENE)	=	t	+2 NRP ₂ (ENE)	=	t	(ENL)	NRP ₂ = t (ENL) ²
+ NRP ₂ (ENE) ²	=	t					
<hr/>							
=	NRP ₀	=	t	NRP ₁	=	t	(ENL) NRP ₂ = t (ENL) ²

PRM ₀	=	t					
+ PRM ₁ (ENE)	=	t	+2 PRM ₂ (ENE)	=	t	(ENL)	PRM ₂ = t (ENL) ²
+ PRM ₂ (ENE) ²	=	t					
<hr/>							
=	PRM ₀	=	t	PRM ₁	=	t	(ENL) PRM ₂ = t (ENL) ²

SEVEN PLACE COSINES, SINES AND TANGENTS FOR EVERY TENTH MICROTURNO



Seven Place
Cosines, Sines and Tangents
For Every Tenth Microturn

Norton Goodwin, *Director*

*Independent Tracking Coordination Program
Society of Photographic Scientists and Engineers*

NOTE ON PHOTOGRAPHIC TYPOGRAPHY

These tables were photographically composed from digital computer tape records. The particular typefaces in which these tables are set are Spartan Book Condensed Large and Spartan Heavy Condensed Large. The selection was made from trial copy composed in a variety of fonts.

Typography was prepared by a commercial printer on a conventional photocomposition unit controlled by perforated paper tapes. The control tapes were produced by a converter unit designed to process magnetic tape records into a form suitable for general-purpose phototypesetting machines.

Acknowledgment is made of the assistance of Robert H. Blechen, Computer Sciences Department, The Rand Corporation, in securing a magnetic tape record of the tabular values, edited in the specified page format, and to Donald Rollert and Carl Rosencrown, Graphic Systems Engineering Department, Mergenthaler Linotype Company for their concern in converting the magnetic tape record to Linofilm tape.

PREFACE

THESE TABLES differ from trigonometric tables now available in that the sine and cosine values of a given argument appear on opposite pages, and in that decimal fractions of the period of these functions are the arguments. They were designed to facilitate routine desk-calculator transformations of the coordinates of artificial earth satellites in particular. They should prove generally advantageous in any area, such as space navigation or electrical engineering, involving cyclical coordinate changes.

The prime source of these tables is a subtabulation performed by Dr. E. C. Bower based on key values obtained from Francois Callet's "Tables Portatives de Logarithmes." Values have been correctly rounded from an accuracy of one unit in the fifteenth decimal place.

The arrangement of values in the one customary in logarithmic tables. Each page lists five hundred arguments at ten micro-turn intervals. The first two significant figures of the argument identify particular pages, the next two identify particular rows, and the last significant figure identifies a particular column. To facilitate "reading up," a tenth column is provided which gives the same value as the zeroth column in the succeeding row.

Complete values are given only in the zeroth column. In the remaining columns, unless the value is printed in boldface, the missing first two significant figures are those of the first complete value in the same row, or higher. If the value is printed in boldface, the missing first two significant figures are those of the first value in the succeeding row.

Tabular values of cosines and sines of from $t00000$ to $t25000$ are given. Since $\arctan a/b = \operatorname{arccot} b/a$, tangents are only given for from $t00000$ to $t12500$ and cotangents for from $t12500$ to $t25000$. All tabulated values are positive. Rules for determining the senses and magnitudes of the various functions in the remaining three quadrants are given in an Appendix.

Washington, March, 1964

NORTON GOODWIN

	0	1	2	3	4	5	6	7	8	9	10		
00	1.00	00000	00000	00000	00000	00000	00000	99999	99999	99999	99998	99998	99
01	.99	99998	99998	99997	99997	99996	99996	99995	99994	99994	99993	99992	98
02		99992	99991	99990	99990	99989	99988	99987	99986	99985	99983	99982	97
03		99982	99981	99980	99979	99977	99976	99974	99973	99971	99970	99968	96
04		99968	99967	99965	99964	99962	99960	99958	99956	99955	99953	99951	95
05		99951	99949	99947	99945	99942	99940	99938	99936	99934	99931	99929	94
06		99929	99927	99924	99922	99919	99917	99914	99911	99909	99906	99903	93
07		99903	99900	99898	99895	99892	99889	99886	99883	99880	99877	99874	92
08		99874	99870	99867	99864	99861	99857	99854	99851	99847	99844	99840	91
09		99840	99837	99833	99829	99826	99822	99818	99814	99810	99807	99803	90
10		99803	99799	99795	99791	99787	99782	99778	99774	99770	99765	99761	89
11		99761	99757	99752	99748	99743	99739	99734	99730	99725	99720	99716	88
12		99716	99711	99706	99701	99696	99692	99687	99682	99677	99672	99666	87
13		99666	99661	99656	99651	99646	99640	99635	99630	99624	99619	99613	86
14		99613	99608	99602	99596	99591	99585	99579	99573	99568	99562	99556	85
15		99556	99550	99544	99538	99532	99526	99520	99513	99507	99501	99495	84
16		99495	99488	99482	99476	99469	99463	99456	99449	99443	99436	99430	83
17		99430	99423	99416	99409	99402	99395	99389	99382	99375	99368	99360	82
18		99360	99353	99346	99339	99332	99324	99317	99310	99302	99295	99287	81
19		99287	99280	99272	99265	99257	99249	99242	99234	99226	99218	99210	80
20		99210	99203	99195	99187	99179	99170	99162	99154	99146	99138	99130	79
21		99130	99121	99113	99104	99096	99088	99079	99071	99062	99053	99045	78
22		99045	99036	99027	99018	99010	99001	98992	98983	98974	98965	98956	77
23		98956	98947	98938	98928	98919	98910	98901	98891	98882	98872	98863	76
24		98863	98854	98844	98834	98825	98815	98805	98796	98786	98776	98766	75
25		98766	98756	98747	98737	98727	98716	98706	98696	98686	98676	98666	74
26		98666	98655	98645	98635	98624	98614	98603	98593	98582	98572	98561	73
27		98561	98550	98540	98529	98518	98507	98496	98485	98475	98464	98452	72
28		98452	98441	98430	98419	98408	98397	98385	98374	98363	98351	98340	71
29		98340	98329	98317	98305	98294	98282	98271	98259	98247	98235	98224	70
30		98224	98212	98200	98188	98176	98164	98152	98140	98128	98115	98103	69
31		98103	98091	98079	98066	98054	98041	98029	98016	98004	97991	97979	68
32		97979	97966	97953	97941	97928	97915	97902	97889	97876	97863	97850	67
33		97850	97837	97824	97811	97798	97785	97772	97758	97745	97732	97718	66
34		97718	97705	97691	97678	97664	97651	97637	97623	97610	97596	97582	65
35		97582	97568	97554	97540	97526	97512	97498	97484	97470	97456	97442	64
36		97442	97428	97413	97399	97385	97370	97356	97341	97327	97312	97298	63
37		97298	97283	97269	97254	97239	97224	97209	97195	97180	97165	97150	62
38		97150	97135	97120	97105	97089	97074	97059	97044	97029	97013	96998	61
39		96998	96982	96967	96951	96936	96920	96905	96889	96873	96858	96842	60
40		96842	96826	96810	96794	96778	96762	96746	96730	96714	96698	96682	59
41		96682	96666	96650	96633	96617	96601	96584	96568	96551	96535	96518	58
42		96518	96502	96485	96468	96452	96435	96418	96401	96384	96367	96350	57
43		96350	96333	96316	96299	96282	96265	96248	96231	96213	96196	96179	56
44		96179	96161	96144	96126	96109	96091	96074	96056	96039	96021	96003	55
45		96003	95985	95967	95950	95932	95914	95896	95878	95860	95842	95823	54
46		95823	95805	95787	95769	95751	95732	95714	95695	95677	95658	95640	53
47		95640	95621	95603	95584	95565	95547	95528	95509	95490	95471	95452	52
48		95452	95433	95414	95395	95376	95357	95338	95319	95300	95280	95261	51
49		95261	95242	95222	95203	95183	95164	95144	95125	95105	95085	95066	50
	10	9	8	7	6	5	4	3	2	1	0		

	0	1	2	3	4	5	6	7	8	9	10		
00	.00	00000	00628	01257	01885	02513	03142	03770	04398	05027	05655	06283	99
01		06283	06912	07540	08168	08796	09425	10053	10681	11310	11938	12566	98
02		12566	13195	13823	14451	15080	15708	16336	16965	17593	18221	18850	97
03		18850	19478	20106	20734	21363	21991	22619	23248	23876	24504	25133	96
04		25133	25761	26389	27018	27646	28274	28903	29531	30159	30788	31416	95
05		31416	32044	32673	33301	33929	34557	35186	35814	36442	37071	37699	94
06		37699	38327	38956	39584	40212	40841	41469	42097	42726	43354	43982	93
07		43982	44610	45239	45867	46495	47124	47752	48380	49009	49637	50265	92
08		50265	50894	51522	52150	52779	53407	54035	54663	55292	55920	56548	91
09		56548	57177	57805	58433	59062	59690	60318	60947	61575	62203	62831	90
10		62831	63460	64088	64716	65345	65973	66601	67230	67858	68486	69114	89
11		69114	69743	70371	70999	71628	72256	72884	73513	74141	74769	75398	88
12		75398	76026	76654	77282	77911	78539	79167	79796	80424	81052	81681	87
13		81681	82309	82937	83565	84194	84822	85450	86079	86707	87335	87963	86
14		87963	88592	89220	89848	90477	91105	91733	92362	92990	93618	94246	85
15		94246	94875	95503	96131	96760	97388	98016	98644	99273	99901	00529	84
16	.01	00529	01158	01786	02414	03042	03671	04299	04927	05556	06184	06812	83
17		06812	07440	08069	08697	09325	09954	10582	11210	11838	12467	13095	82
18		13095	13723	14351	14980	15608	16236	16865	17493	18121	18749	19378	81
19		19378	20006	20634	21263	21891	22519	23147	23776	24404	25032	25660	80
20		25660	26289	26917	27545	28173	28802	29430	30058	30687	31315	31943	79
21		31943	32571	33200	33828	34456	35084	35713	36341	36969	37597	38226	78
22		38226	38854	39482	40110	40739	41367	41995	42623	43252	43880	44508	77
23		44508	45136	45765	46393	47021	47649	48278	48906	49534	50162	50791	76
24		50791	51419	52047	52675	53304	53932	54560	55188	55817	56445	57073	75
25		57073	57701	58330	58958	59586	60214	60843	61471	62099	62727	63356	74
26		63356	63984	64612	65240	65868	66497	67125	67753	68381	69010	69638	73
27		69638	70266	70894	71523	72151	72779	73407	74035	74664	75292	75920	72
28		75920	76548	77177	77805	78433	79061	79689	80318	80946	81574	82202	71
29		82202	82831	83459	84087	84715	85343	85972	86600	87228	87856	88484	70
30		88484	89113	89741	90369	90997	91625	92254	92882	93510	94138	94766	69
31		94766	95395	96023	96651	97279	97907	98536	99164	99792	00420	01048	68
32	.02	01048	01677	02305	02933	03561	04189	04818	05446	06074	06702	07330	67
33		07330	07958	08587	09215	09843	10471	11099	11728	12356	12984	13612	66
34		13612	14240	14868	15497	16125	16753	17381	18009	18637	19266	19894	65
35		19894	20522	21150	21778	22406	23035	23663	24291	24919	25547	26175	64
36		26175	26804	27432	28060	28688	29316	29944	30572	31201	31829	32457	63
37		32457	33085	33713	34341	34970	35598	36226	36854	37482	38110	38738	62
38		38738	39366	39995	40623	41251	41879	42507	43135	43763	44392	45020	61
39		45020	45648	46276	46904	47532	48160	48788	49417	50045	50673	51301	60
40		51301	51929	52557	53185	53813	54442	55070	55698	56326	56954	57582	59
41		57582	58210	58838	59466	60095	60723	61351	61979	62607	63235	63863	58
42		63863	64491	65119	65747	66376	67004	67632	68260	68888	69516	70144	57
43		70144	70772	71400	72028	72656	73285	73913	74541	75169	75797	76425	56
44		76425	77053	77681	78309	78937	79565	80193	80821	81450	82078	82706	55
45		82706	83334	83962	84590	85218	85846	86474	87102	87730	88358	88986	54
46		88986	89614	90242	90870	91499	92127	92755	93383	94011	94639	95267	53
47		95267	95895	96523	97151	97779	98407	99035	99663	00291	00919	01547	52
48	.03	01547	02175	02803	03431	04059	04687	05315	05943	06571	07199	07827	51
49		07827	08455	09083	09712	10340	10968	11596	12224	12852	13480	14108	50
	10	9	8	7	6	5	4	3	2	1	0		

	0	1	2	3	4	5	6	7	8	9	10	
50	.99 95066	95046	95026	95006	94986	94966	94946	94926	94906	94886	94866	49
51	94866	94846	94826	94806	94785	94765	94745	94724	94704	94683	94663	48
52	94663	94642	94622	94601	94581	94560	94539	94518	94498	94477	94456	47
53	94456	94435	94414	94393	94372	94351	94330	94308	94287	94266	94245	46
54	94245	94223	94202	94180	94159	94138	94116	94094	94073	94051	94029	45
55	94029	94008	93986	93964	93942	93920	93899	93877	93855	93833	93810	44
56	93810	93788	93766	93744	93722	93699	93677	93655	93632	93610	93587	43
57	93587	93565	93542	93520	93497	93474	93452	93429	93406	93383	93360	42
58	93360	93338	93315	93292	93269	93246	93222	93199	93176	93153	93130	41
59	93130	93106	93083	93060	93036	93013	92989	92966	92942	92918	92895	40
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62	92413	92389	92364	92340	92315	92290	92266	92241	92216	92191	92167	37
63	92167	92142	92117	92092	92067	92042	92017	91992	91966	91941	91916	36
64	91916	91891	91865	91840	91815	91789	91764	91738	91713	91687	91661	35
65	91661	91636	91610	91584	91558	91533	91507	91481	91455	91429	91403	34
66	91403	91377	91351	91325	91298	91272	91246	91220	91193	91167	91140	33
67	91140	91114	91087	91061	91034	91008	90981	90954	90928	90901	90874	32
68	90874	90847	90820	90793	90766	90739	90712	90685	90658	90631	90604	31
69	90604	90576	90549	90522	90494	90467	90440	90412	90385	90357	90329	30
70	90329	90302	90274	90246	90219	90191	90163	90135	90107	90079	90051	29
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73	89483	89454	89425	89396	89367	89338	89309	89280	89251	89222	89193	26
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77	88299	88268	88238	88208	88177	88146	88116	88085	88055	88024	87993	22
78	87993	87962	87931	87901	87870	87839	87808	87777	87746	87714	87683	21
79	87683	87652	87621	87590	87558	87527	87496	87464	87433	87401	87370	20
80	87370	87338	87306	87275	87243	87211	87179	87148	87116	87084	87052	19
81	87052	87020	86988	86956	86924	86892	86859	86827	86795	86763	86730	18
82	86730	86698	86665	86633	86601	86568	86535	86503	86470	86437	86405	17
83	86405	86372	86339	86306	86273	86240	86208	86175	86141	86108	86075	16
84	86075	86042	86009	85976	85942	85909	85876	85842	85809	85775	85742	15
85	85742	85708	85675	85641	85607	85574	85540	85506	85472	85438	85404	14
86	85404	85370	85336	85302	85268	85234	85200	85166	85132	85097	85063	13
87	85063	85029	84994	84960	84925	84891	84856	84822	84787	84753	84718	12
88	84718	84683	84648	84614	84579	84544	84509	84474	84439	84404	84369	11
89	84369	84334	84298	84263	84228	84193	84157	84122	84086	84051	84016	10
90	84016	83980	83944	83909	83873	83837	83802	83766	83730	83694	83658	09
91	83658	83622	83587	83551	83514	83478	83442	83406	83370	83334	83297	08
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93	82932	82896	82859	82822	82785	82748	82712	82675	82638	82601	82564	06
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97	81433	81395	81357	81318	81280	81241	81203	81164	81126	81087	81048	02
98	81048	81010	80971	80932	80893	80855	80816	80777	80738	80699	80660	01
99	80660	80621	80582	80542	80503	80464	80425	80385	80346	80307	80267	00
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TAN t00--

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03		18850	19478	20106	20735	21363	21991	22620	23248	23876	24504	25133	96
04		25133	25761	26389	27018	27646	28274	28903	29531	30159	30788	31416	95
05		31416	32044	32673	33301	33929	34558	35186	35814	36443	37071	37699	94
06		37699	38328	38956	39584	40213	40841	41469	42098	42726	43354	43983	93
07		43983	44611	45239	45868	46496	47124	47753	48381	49009	49638	50266	92
08		50266	50894	51523	52151	52779	53408	54036	54664	55293	55921	56549	91
09		56549	57178	57806	58434	59063	59691	60319	60948	61576	62204	62833	90
10		62833	63461	64089	64718	65346	65974	66603	67231	67859	68488	69116	89
11		69116	69744	70373	71001	71630	72258	72886	73515	74143	74771	75400	88
12		75400	76028	76656	77285	77913	78541	79170	79798	80427	81055	81683	87
13		81683	82312	82940	83568	84197	84825	85453	86082	86710	87338	87967	86
14		87967	88595	89224	89852	90480	91109	91737	92365	92994	93622	94251	85
15		94251	94879	95507	96136	96764	97392	98021	98649	99278	99906	00534	84
16	.01	00534	01163	01791	02420	03048	03676	04305	04933	05561	06190	06818	83
17		06818	07447	08075	08703	09332	09960	10589	11217	11845	12474	13102	82
18		13102	13731	14359	14987	15616	16244	16873	17501	18129	18758	19386	81
19		19386	20015	20643	21271	21900	22528	23157	23785	24413	25042	25670	80
20		25670	26299	26927	27556	28184	28812	29441	30069	30698	31326	31955	79
21		31955	32583	33211	33840	34468	35097	35725	36354	36982	37610	38239	78
22		38239	38867	39496	40124	40753	41381	42010	42638	43266	43895	44523	77
23		44523	45152	45780	46409	47037	47666	48294	48922	49551	50179	50808	76
24		50808	51436	52065	52693	53322	53950	54579	55207	55836	56464	57093	75
25		57093	57721	58350	58978	59606	60235	60863	61492	62120	62749	63377	74
26		63377	64006	64634	65263	65891	66520	67148	67777	68405	69034	69662	73
27		69662	70291	70919	71548	72176	72805	73433	74062	74690	75319	75947	72
28		75947	76576	77204	77833	78461	79090	79718	80347	80975	81604	82233	71
29		82233	82861	83490	84118	84747	85375	86004	86632	87261	87889	88518	70
30		88518	89146	89775	90404	91032	91661	92289	92918	93546	94175	94803	69
31		94803	95432	96060	96689	97318	97946	98575	99203	99832	00460	01089	68
32	.02	01089	01718	02346	02975	03603	04232	04860	05489	06118	06746	07375	67
33		07375	08003	08632	09261	09889	10518	11146	11775	12404	13032	13661	66
34		13661	14289	14918	15547	16175	16804	17432	18061	18690	19318	19947	65
35		19947	20576	21204	21833	22461	23090	23719	24347	24976	25605	26233	64
36		26233	26862	27491	28119	28748	29376	30005	30634	31262	31891	32520	63
37		32520	33148	33777	34406	35034	35663	36292	36920	37549	38178	38806	62
38		38806	39435	40064	40692	41321	41950	42579	43207	43836	44465	45093	61
39		45093	45722	46351	46979	47608	48237	48865	49494	50123	50752	51380	60
40		51380	52009	52638	53266	53895	54524	55153	55781	56410	57039	57668	59
41		57668	58296	58925	59554	60183	60811	61440	62069	62698	63326	63955	58
42		63955	64584	65213	65841	66470	67099	67728	68356	68985	69614	70243	57
43		70243	70872	71500	72129	72758	73387	74015	74644	75273	75902	76531	56
44		76531	77159	77788	78417	79046	79675	80303	80932	81561	82190	82819	55
45		82819	83448	84076	84705	85334	85963	86592	87221	87849	88478	89107	54
46		89107	89736	90365	90994	91622	92251	92880	93509	94138	94767	95396	53
47		95396	96024	96653	97282	97911	98540	99169	99798	00427	01055	01684	52
48	.03	01684	02313	02942	03571	04200	04829	05458	06087	06716	07344	07973	51
49		07973	08602	09231	09860	10489	11118	11747	12376	13005	13634	14263	50
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COT t24--

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02		54626	55084	55541	55998	56456	56913	57371	57828	58285	58742	59200	97
03		59200	59657	60114	60571	61028	61485	61942	62399	62856	63313	63770	96
04		63770	64227	64684	65141	65598	66055	66512	66968	67425	67882	68338	95
05		68338	68795	69252	69708	70165	70621	71078	71534	71991	72447	72904	94
06		72904	73360	73817	74273	74729	75185	75642	76098	76554	77010	77466	93
07		77466	77923	78379	78835	79291	79747	80203	80659	81115	81571	82026	92
08		82026	82482	82938	83394	83850	84305	84761	85217	85672	86128	86584	91
09		86584	87039	87495	87950	88406	88861	89317	89772	90227	90683	91138	90
10		91138	91593	92049	92504	92959	93414	93869	94325	94780	95235	95690	89
11		95690	96145	96600	97055	97510	97965	98420	98874	99329	99784	00239	88
12	.69	00239	00694	01148	01603	02058	02512	02967	03422	03876	04331	04785	87
13		04785	05240	05694	06149	06603	07057	07512	07966	08420	08875	09329	86
14		09329	09783	10237	10691	11145	11600	12054	12508	12962	13416	13870	85
15		13870	14324	14778	15231	15685	16139	16593	17047	17500	17954	18408	84
16		18408	18861	19315	19769	20222	20676	21129	21583	22036	22490	22943	83
17		22943	23397	23850	24303	24757	25210	25663	26116	26570	27023	27476	82
18		27476	27929	28382	28835	29288	29741	30194	30647	31100	31553	32006	81
19		32006	32459	32912	33364	33817	34270	34723	35175	35628	36080	36533	80
20		36533	36986	37438	37891	38343	38796	39248	39700	40153	40605	41058	79
21		41058	41510	41962	42414	42867	43319	43771	44223	44675	45127	45579	78
22		45579	46031	46483	46935	47387	47839	48291	48743	49195	49646	50098	77
23		50098	50550	51002	51453	51905	52357	52808	53260	53711	54163	54614	76
24		54614	55066	55517	55969	56420	56872	57323	57774	58225	58677	59128	75
25		59128	59579	60030	60481	60933	61384	61835	62286	62737	63188	63639	74
26		63639	64090	64541	64991	65442	65893	66344	66795	67245	67696	68147	73
27		68147	68597	69048	69499	69949	70400	70850	71301	71751	72202	72652	72
28		72652	73102	73553	74003	74453	74904	75354	75804	76254	76704	77154	71
29		77154	77605	78055	78505	78955	79405	79855	80305	80754	81204	81654	70
30		81654	82104	82554	83004	83453	83903	84353	84802	85252	85702	86151	69
31		86151	86601	87050	87500	87949	88399	88848	89297	89747	90196	90645	68
32		90645	91095	91544	91993	92442	92891	93341	93790	94239	94688	95137	67
33		95137	95586	96035	96484	96933	97382	97830	98279	98728	99177	99626	66
34		99626	00074	00523	00972	01420	01869	02317	02766	03215	03663	04112	65
35	.70	04112	04560	05008	05457	05905	06353	06802	07250	07698	08146	08595	64
36		08595	09043	09491	09939	10387	10835	11283	11731	12179	12627	13075	63
37		13075	13523	13971	14419	14866	15314	15762	16210	16657	17105	17553	62
38		17553	18000	18448	18895	19343	19791	20238	20685	21133	21580	22028	61
39		22028	22475	22922	23370	23817	24264	24711	25158	25606	26053	26500	60
40		26500	26947	27394	27841	28288	28735	29182	29629	30075	30522	30969	59
41		30969	31416	31863	32309	32756	33203	33649	34096	34542	34989	35436	58
42		35436	35882	36329	36775	37221	37668	38114	38560	39007	39453	39899	57
43		39899	40346	40792	41238	41684	42130	42576	43022	43468	43914	44360	56
44		44360	44806	45252	45698	46144	46590	47036	47481	47927	48373	48819	55
45		48819	49264	49710	50155	50601	51047	51492	51938	52383	52829	53274	54
46		53274	53719	54165	54610	55055	55501	55946	56391	56836	57281	57727	53
47		57727	58172	58617	59062	59507	59952	60397	60842	61287	61732	62176	52
48		62176	62621	63066	63511	63956	64400	64845	65290	65734	66179	66624	51
49		66624	67068	67513	67957	68402	68846	69290	69735	70179	70624	71068	50
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02		81078	80648	80217	79786	79355	78924	78494	78063	77632	77201	76770	97
03		76770	76339	75908	75477	75046	74615	74184	73752	73321	72890	72459	96
04		72459	72027	71596	71165	70733	70302	69871	69439	69008	68576	68145	95
05		68145	67713	67281	66850	66418	65987	65555	65123	64691	64260	63828	94
06		63828	63396	62964	62532	62100	61668	61236	60804	60372	59940	59508	93
07		59508	59076	58644	58211	57779	57347	56915	56482	56050	55618	55185	92
08		55185	54753	54320	53888	53455	53023	52590	52158	51725	51292	50860	91
09		50860	50427	49994	49561	49129	48696	48263	47830	47397	46964	46531	90
10		46531	46098	45665	45232	44799	44366	43933	43500	43067	42633	42200	89
11		42200	41767	41333	40900	40467	40033	39600	39166	38733	38299	37866	88
12		37866	37432	36999	36565	36131	35698	35264	34830	34397	33963	33529	87
13		33529	33095	32661	32227	31793	31359	30925	30491	30057	29623	29189	86
14		29189	28755	28321	27887	27452	27018	26584	26150	25715	25281	24846	85
15		24846	24412	23978	23543	23109	22674	22239	21805	21370	20936	20501	84
16		20501	20066	19631	19197	18762	18327	17892	17457	17022	16587	16153	83
17		16153	15718	15282	14847	14412	13977	13542	13107	12672	12237	11801	82
18		11801	11366	10931	10495	10060	09625	09189	08754	08318	07883	07447	81
19		07447	07012	06576	06140	05705	05269	04833	04398	03962	03526	03090	80
20		03090	02654	02219	01783	01347	00911	00475	00039	99603	99167	98730	79
21	.71	98730	98294	97858	97422	96986	96550	96113	95677	95241	94804	94368	78
22		94368	93931	93495	93059	92622	92185	91749	91312	90876	90439	90002	77
23		90002	89566	89129	88692	88255	87819	87382	86945	86508	86071	85634	76
24		85634	85197	84760	84323	83886	83449	83012	82575	82137	81700	81263	75
25		81263	80826	80388	79951	79514	79076	78639	78201	77764	77327	76889	74
26		76889	76451	76014	75576	75139	74701	74263	73826	73388	72950	72512	73
27		72512	72074	71637	71199	70761	70323	69885	69447	69009	68571	68133	72
28		68133	67694	67256	66818	66380	65942	65503	65065	64627	64188	63750	71
29		63750	63312	62873	62435	61996	61558	61119	60681	60242	59803	59365	70
30		59365	58926	58487	58049	57610	57171	56732	56293	55855	55416	54977	69
31		54977	54538	54099	53660	53221	52782	52342	51903	51464	51025	50586	68
32		50586	50147	49707	49268	48829	48389	47950	47510	47071	46632	46192	67
33		46192	45752	45313	44873	44434	43994	43554	43115	42675	42235	41795	66
34		41795	41356	40916	40476	40036	39596	39156	38716	38276	37836	37396	65
35		37396	36956	36516	36076	35635	35195	34755	34315	33874	33434	32994	64
36		32994	32553	32113	31673	31232	30792	30351	29911	29470	29029	28589	63
37		28589	28148	27707	27267	26826	26385	25944	25504	25063	24622	24181	62
38		24181	23740	23299	22858	22417	21976	21535	21094	20653	20211	19770	61
39		19770	19329	18888	18446	18005	17564	17122	16681	16240	15798	15357	60
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41		10940	10499	10057	09615	09173	08731	08289	07847	07405	06963	06521	58
42		06521	06079	05637	05195	04753	04311	03869	03426	02984	02542	02099	57
43		02099	01657	01215	00772	00330	99887	99445	99003	98560	98117	97675	56
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46		88817	88374	87931	87487	87044	86601	86157	85714	85271	84827	84384	53
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75		99300	00448	01597	02746	03895	05044	06194	07343	08492	09642	10792	24
76	.91	10792	11942	13092	14242	15392	16543	17693	18844	19995	21146	22297	23
77		22297	23448	24600	25751	26903	28055	29207	30359	31511	32663	33816	22
78		33816	34968	36121	37274	38427	39580	40733	41886	43040	44193	45347	21
79		45347	46501	47655	48809	49964	51118	52273	53427	54582	55737	56892	20
80		56892	58047	59203	60358	61514	62670	63825	64982	66138	67294	68450	19
81		68450	69607	70764	71920	73077	74234	75392	76549	77707	78864	80022	18
82		80022	81180	82338	83496	84654	85813	86971	88130	89289	90448	91607	17
83		91607	92766	93925	95085	96244	97404	98564	99724	00884	02045	03205	16
84	.92	03205	04366	05526	06687	07848	09009	10170	11332	12493	13655	14817	15
85		14817	15979	17141	18303	19465	20628	21790	22953	24116	25279	26442	14
86		26442	27605	28769	29932	31096	32260	33423	34588	35752	36916	38081	13
87		38081	39245	40410	41575	42740	43905	45070	46236	47401	48567	49733	12
88		49733	50899	52065	53231	54397	55564	56730	57897	59064	60231	61398	11
89		61398	62566	63733	64901	66068	67236	68404	69572	70741	71909	73078	10
90		73078	74246	75415	76584	77753	78922	80092	81261	82431	83601	84771	09
91		84771	85941	87111	88281	89452	90622	91793	92964	94135	95306	96477	08
92		96477	97649	98820	99992	01164	02336	03508	04680	05852	07025	08197	07
93	.93	08197	09370	10543	11716	12889	14063	15236	16410	17583	18757	19931	06
94		19931	21106	22280	23454	24629	25803	26978	28153	29328	30504	31679	05
95		31679	32855	34030	35206	36382	37558	38734	39911	41087	42264	43441	04
96		43441	44617	45795	46972	48149	49326	50504	51682	52860	54038	55216	03
97		55216	56394	57573	58751	59930	61109	62288	63467	64646	65825	67005	02
98		67005	68185	69365	70544	71725	72905	74085	75266	76446	77627	78808	01
99		78808	79989	81170	82352	83533	84715	85897	87079	88261	89443	90625	00
		10	9	8	7	6	5	4	3	2	1	0	

	0	1	2	3	4	5	6	7	8	9	10	
00	.93 90625	91808	92990	94173	95356	96539	97722	98905	00089	01272	02456	99
01	.94 02456	03640	04824	06008	07192	08377	09561	10746	11931	13116	14301	98
02	14301	15486	16672	17857	19043	20229	21415	22601	23787	24973	26160	97
03	26160	27346	28533	29720	30907	32095	33282	34469	35657	36845	38033	96
04	38033	39221	40409	41597	42786	43975	45163	46352	47541	48731	49920	95
05	49920	51109	52299	53489	54679	55869	57059	58249	59440	60630	61821	94
06	61821	63012	64203	65394	66586	67777	68969	70160	71352	72544	73736	93
07	73736	74929	76121	77314	78507	79699	80892	82086	83279	84472	85666	92
08	85666	86860	88054	89248	90442	91636	92831	94025	95220	96415	97610	91
09	97610	98805	00000	01196	02391	03587	04783	05979	07175	08371	09568	90
10	.95 09568	10764	11961	13158	14355	15552	16750	17947	19145	20342	21540	89
11	21540	22738	23936	25135	26333	27532	28730	29929	31128	32328	33527	88
12	33527	34726	35926	37126	38326	39526	40726	41926	43127	44327	45528	87
13	45528	46729	47930	49131	50332	51534	52735	53937	55139	56341	57543	86
14	57543	58746	59948	61151	62354	63556	64760	65963	67166	68370	69573	85
15	69573	70777	71981	73185	74389	75594	76798	78003	79208	80412	81618	84
16	81618	82823	84028	85234	86439	87645	88851	90057	91264	92470	93676	83
17	93676	94883	96090	97297	98504	99711	00919	02126	03334	04542	05750	82
18	.96 05750	06958	08166	09375	10583	11792	13001	14210	15419	16628	17838	81
19	17838	19047	20257	21467	22677	23887	25098	26308	27519	28730	29941	80
20	29941	31152	32363	33574	34786	35997	37209	38421	39633	40845	42058	79
21	42058	43270	44483	45696	46909	48122	49335	50549	51762	52976	54190	78
22	54190	55404	56618	57832	59047	60261	61476	62691	63906	65121	66336	77
23	66336	67552	68768	69983	71199	72415	73632	74848	76064	77281	78498	76
24	78498	79715	80932	82149	83367	84584	85802	87020	88238	89456	90674	75
25	90674	91893	93111	94330	95549	96768	97987	99206	00426	01645	02865	74
26	.97 02865	04085	05305	06525	07746	08966	10187	11408	12629	13850	15071	73
27	15071	16293	17514	18736	19958	21180	22402	23624	24847	26069	27292	72
28	27292	28515	29738	30961	32185	33408	34632	35856	37080	38304	39528	71
29	39528	40752	41977	43202	44426	45651	46877	48102	49327	50553	51779	70
30	51779	53005	54231	55457	56683	57910	59136	60363	61590	62817	64045	69
31	64045	65272	66500	67727	68955	70183	71411	72640	73868	75097	76325	68
32	76325	77554	78783	80013	81242	82472	83701	84931	86161	87391	88621	67
33	88621	89852	91082	92313	93544	94775	96006	97238	98469	99701	00933	66
34	.98 00933	02165	03397	04629	05861	07094	08327	09559	10792	12026	13259	65
35	13259	14492	15726	16960	18194	19428	20662	21896	23131	24366	25600	64
36	25600	26835	28071	29306	30541	31777	33013	34249	35485	36721	37957	63
37	37957	39194	40430	41667	42904	44141	45379	46616	47854	49091	50329	62
38	50329	51567	52805	54044	55282	56521	57760	58999	60238	61477	62717	61
39	62717	63956	65196	66436	67676	68916	70156	71397	72638	73878	75119	60
40	75119	76360	77602	78843	80085	81326	82568	83810	85053	86295	87537	59
41	87537	88780	90023	91266	92509	93752	94996	96239	97483	98727	99971	58
42	99971	01215	02460	03704	04949	06194	07439	08684	09929	11174	12420	57
43	.99 12420	13666	14912	16158	17404	18650	19897	21144	22390	23637	24885	56
44	24885	26132	27379	28627	29875	31123	32371	33619	34867	36116	37365	55
45	37365	38614	39863	41112	42361	43611	44860	46110	47360	48610	49860	54
46	49860	51111	52361	53612	54863	56114	57365	58617	59868	61120	62372	53
47	62372	63624	64876	66128	67381	68633	69886	71139	72392	73645	74899	52
48	74899	76152	77406	78660	79914	81168	82423	83677	84932	86187	87442	51
49	87442	88697	89952	91207	92463	93719	94975	96231	97487	98743	00000	50
	10	9	8	7	6	5	4	3	2	1	0	

APPENDIX

COSINES AND SINES map directions in right-handed rectangular coordinates. It is impossible to be right-handed or left-handed in two dimensions. The Z axis around which directions are mapped on the back cover is normal to the plane of the paper at the intersection of the X and Y axes. By definition, positive rotation carries points on the positive X axis around toward the positive Y axis. In right-handed coordinates, the positive direction along the Z axis is the direction in which the thumb of the right hand would point if the fingers of the right hand were curled around the Z axis in the sense of positive rotation. The positive Z axis must therefore project upward from the back cover toward the viewer.

WHOLE TURNS added to or subtracted from rotation around the Z axis have no effect on directions in the X-Y plane. The direction determined by any finite rotation around Z may be defined by an angle ϕ in the range $\pm \frac{1}{2}$ turn from the positive X axis.

THE FIGURE on the back cover maps all possible directions around the Z axis as the collection of points at unit distance from Z in the plane of the paper. These points are defined both in terms of the angle, ϕ , and in terms of the corresponding x, y right-handed rectangular coordinates. By definition:

$$\begin{array}{ll} \cos \phi = x & \sin \phi = y \\ \cot \phi = x/y & \tan \phi = y/x \end{array}$$

THESE TABLES map cosines, sines, cotangents, and tangents in the range of positive values of ϕ up to $\frac{1}{4}$ turn. The following rules for determining the sense and magnitude of cosine and sine for any value of ϕ may be verified from the figure on the back cover:

$$\cos \phi \text{ is negative if, and only if, } |\phi| > t25; \quad (1)$$

$$\sin \phi \text{ is negative if, and only if, } \phi \text{ is negative;} \quad (2)$$

$$|\cos| \phi = |\sin| \phi \pm t25; \text{ and } |\sin| \phi = |\cos| \phi \pm t25; \text{ and,} \quad (3)$$

$$|\cot| \phi = |\tan| \phi \pm t25, \text{ and } |\tan| \phi = |\cot| \phi \pm t25 \quad (4)$$

NOTE: When a symbol is represented between vertical brackets, thus: $|A|$, only the magnitude of the object, A , is specified.

$$|A| \text{ is always taken as positive, and } |A| = \sqrt{A^2}$$