PHASE II FINAL REPORT

6 October 1974 to 6 December 1974

TYPICAL TELEOPERATOR TIME DELAY PROFILES

R. D. Wetherington and J. R. Walsh

Contract NAS8-30919
Control No. 1-4-40-43057 (1F)
Time Delay Profiles for Teleoperator

6 December 1974

Prepared for
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

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FOREWORD

This report was prepared by the Engineering Experiment Station of the Georgia Institute of Technology under contract number NAS8-30919 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration.

The work was carried out under the direct supervision of Mr. J. R. Walsh, Project Director, and under the general supervision of Mr. D. W. Robertson, Chief of the Communications Division. The report describes the results of a two month effort to investigate typical time delay profiles expected in a teleoperator communication system.

ABSTRACT

This report presents the results of the second phase of a study on time delays in communications systems applicable to the teleoperator program. Phase I covered the sources of time delays and their magnitudes. Phase II covers estimates of the maximum time delays that will be encountered and presents time delay profiles for (1) ground control to teleoperator in low earth orbit, (2) ground control to teleoperator in geosynchronous orbit, and (3) low earth orbit control to teleoperator in low earth orbit.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

Chapter 4

Chapter 5

LIST OF FIGURES (continued)

LIST OF TABLES

PAGE

Chapter 2

Chapter 3

Chapter 5

1. INTRODUCTION

The teleoperator program will provide NASA with satellite service vehicles which have remotely controlled manipulator arms. Control of the manipulator arms will be directed by a human operator from a control console, and this console may be located at a ground site, aboard a spacecraft orbiting near teleoperator, or aboard a spacecraft in an entirely different orbit. In either case, operation of the system will require a two way communication link between the human operator and teleoperator. The up-link will carry command data for effecting manipulator movements; the return link will carry monitoring data which will verify the movements with the major portion of the return data being video data. Obviously when the human operator moves a control, the entire round-trip transmission path must be negotiated before he can observe any response. Since the transmission path may be lengthy, an appreciable time delay may be involved. It is toward specifying the time delay profiles for various control station positions and teleoperator orbits that this portion of the project effort was directed.

Phase I of this program, previously reported [1], consisted of a survey and evaluation of possible sources of time delay. To briefly review the major results of Phase I, it was found that the delays that occur can be subdivided into three general classes: (1) signal processing delays, (2) transmission delays, and (3) hardware delays. Each of these classes may subdivide into several subclasses. Thus, signal processing may consist of transformation of signal form, data buffering, error checking, etc. Transmission delays encompasses delays over communications lines as well as propagation delays for radio links. Hardware delays are those associated with passing signals through amplifiers, filters, etc. with no basic change in the signal type and may occur at several points in the communications link. Of these three general sources of time delay, the major delays were found to be associated with signal processing and transmission time. Hardware delays are usually of the order of microseconds for each piece of equipment. The total for all hardware components in the link could well be expected to be of the order of one millisecond. Such a delay will be insignificant in comparison with processing and transmission delays.

Signal processing delays present uncertainties in two areas. First is the initial processing of the control system sensor output signals to form drive signals for the teleoperator function motors. Sensors attached to the controls activated by a human operator will produce analog output signals. The analog signals will be converted to digital form for input to a computer, and the computer will operate on these digital inputs (a form of matrix inversion) to form drive signals for eight different function motors which control the movement of a single manipulator arm. In a test set-up at MSFC, this processing time from analog-to-digital conversion of the sensor outputs to drive signal output from the digital computer is approximately 75 milliseconds. This delay time is highly dependent on the particular computer being used and the construction of the processing software. A change of computer hardware or reprogramming of the processing algorithm could change the processing time. However, it should be noted that even if hardware or software changes affect this delay time it will be a fixed quantity in an operational system.

Most of the uncertainty in time delays associated with transmission time occur in considering point-to-point links on the ground. It is presumed that when the teleoperator control station is located on the ground and remote from the TDRS tracking station communication between the two will be via the NASCOM network. In the present mode of operation most data transmitted by NASCOM is formed into standardized 1200 bit blocks with the 1200 bits including a preamble header and a check sum at the end. Buffering delays occur in accumulating the entire block before transmission or at any intermediate point at which the validity of the data is checked. It appears likely that for processing delays of this type estimates based on the present system will give a good upper bound estimate. The actual delays in the 1980 time frame may well be less since changes are being considered that will reduce the processing time. Many NASCOM personnel feel that the network will be operating in a "bent pipe" mode by 1980, and the delays due to blocking, buffering, and error checking will be eliminated.

Another source of time delay uncertainty in NASCOM transmissions arises from the lack of precise control over message facilities and routing. NASCOM traffic is generally carried over commercial common carrier links which are obtained on a dedicated twenty-four hour per day basis. However, the commercial carrier may switch physical facilities at any time that difficulties occur on a particular configuration.

The remaining major source of delay is the propagation time associated with radio transmissions. These delays may be among the largest and most variable in the entire link, particularly when the mission geometry requires that the signal be relayed through one or more synchronous satellites. However, propagation delays can be accurately estimated for all mission geometries including the variations that will occur due to satellite motion.

Phase II of this study, reported here, deals with determining the largest time delays that are likely to occur in earth-orbit operation of teleoperator and with developing time delay profiles for three control/teleoperator configurations. Maximum time delays are considered for various communication network configurations and maximum time delay figures are given. Delay situations are considered for the cases of land line and communication satellite connection of the ground control station to the TDRSS ground station.

Three basic configurations of control station and teleoperator are considered. These are (1) ground station control to teleoperator in low earth orbit, (2) ground control to teleoperator in geosynchronous orbit, and (3) low earth orbit control to teleoperator in low earth orbit. Each of the cases are discussed in this report. Time delay profiles for cases (1) and (3) have been generated for selected orbits. Delay figures are given for case (2) for which the delay profile is very nearly a constant with the only delay variations being those produced by "synchronous" satellite movement due to orbit inclination or eccentricity.

2. MAXIMUM DELAYS

2.1 Delay Factors

A survey of time delays in communications systems that will affect teleoperator was carried out in Phase I of this program [1]. The results of the survey are summarized in Table 2-1, taken from Reference 1. Scanning the data presented in Table 2-1, it is obvious that the major delay factors are (1) signal processing, (2) signal propagation through space, and (3) signal transmission. Unfortunately, none of these delays can be precisely determined at this time for the following reasons:

(1) Plans for the 1980 time frame for the NASCOM network (assumed to be the media for point-to-point ground communication) are not completely defined at this time. Indicated trends are that signal processing time may be reduced or eliminated and that satellite relay between ground stations may be introduced.

(2) Specific mission orbits for teleoperator are not defined.

(3) Initial processing (matrix inversion) time delays depend on the computer hardware and the processing algorithm. Changes in either may change the 75 millisecond delay currently experienced in the laboratory mock-up.

These factors make it unfeasible to determine the maximum time delay for teleoperator configurations with absolute accuracy. However, reasonable bounds on time delays that are likely to occur can be established and estimates of the maximum delay that will occur can be made.

2.2 Fixed Delays

Time delays due to two sources will be essentially fixed and will apply to all orbit configurations. The major delay of this type is that due to signal processing of the control console outputs into usable drive signals (matrix inversion). The time delay required for matrix processing will depend on the computer hardware and the processing algorithm used. In the present

TABLE 2-1

SUMMARY OF COMMUNICATION SYSTEM TIME DELAYS (APPROXIMATE VALUES)

Cause	Range of Values
Processing	
Matrix Inversion	≃ 75 msec.
Switching	tens to hundreds of μsec
Formating	up to 1/2 sec. (Apollo)
Error protection	tens to hundreds of μsec.
Forward error correction	several constraint lengths.
Propagation (one way)	
Ground to synchronous orbit	120 to 140 msec.
Synchronous to low earth orbit (up to 2000 km)	110 to 160 msec.
Ground to low earth orbit (up to 2000 km)	0.5 to 18 msec.
Transmission (surface lines)	
Loaded cable	63 μsec/km
Unloaded cable	13 μsec/km
Coaxial cable & microwave link	4 to 5 μsec/km
Hardware	
Transistor amplifiers	2 to 3 nanosec
TWT's	tens of nanosec
Filters	tens of nanosec to hundreds of μsec
Total delay for all hardware	< 1.0 msec.

laboratory teleoperator test set-up at MSFC, this processing delay is 75 milliseconds. This figure will be used as an estimate of processing delay for matrix inversion for all configurations.

The other source of "fixed" delay is that due to hardware and, actually, is not fixed. The magnitudes of hardware delays are relatively small, and it is estimated that they will total no more than 1.0 millisecond for any link configuration. Consequently, hardware delays will be estimated as fixed at 1.0 millisecond.

2.3 Maximum Delay Estimates

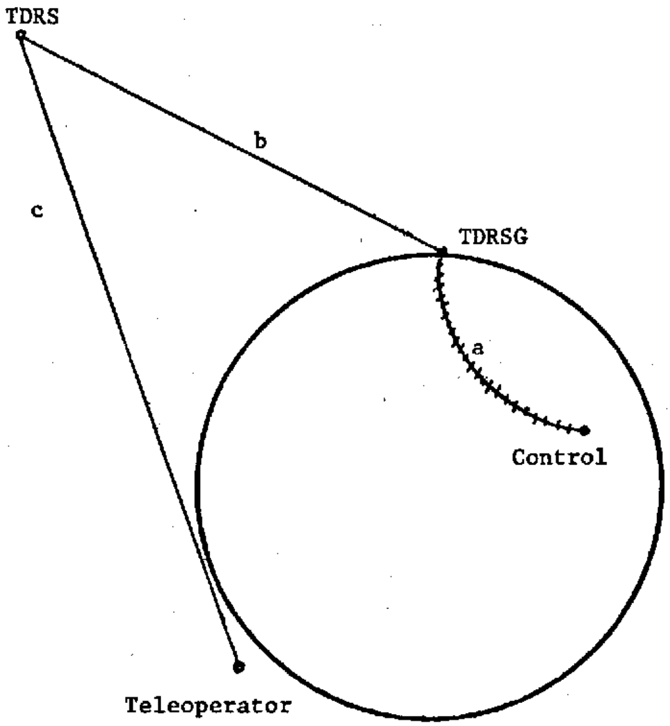
Of the various orbital geometry/communication link configurations that may occur in teleoperator missions, the maximum time delay will probably occur on links requiring two satellite relays. Such links may occur in two cases (1) ground control to teleoperator in low earth orbit with point-to-point ground communication being relayed through a commercial satellite, and (2) low earth orbit control to teleoperator in low earth orbit with both control and teleoperator relaying through one of the TDRS satellites.

The first of these is a variation of ground control to teleoperator in low earth orbit that may apply in 1980. In the present NASCOM operation, the point-to-point ground communication would be by land lines. However, it is considered quite possible that by 1980 some intracontinental communications will use satellite relays. To cover both possibilities, estimates of maximum time delays have been prepared for both modes of operation.

Figure 2-1 presents the link configuration and estimated delay summary for ground control to teleoperator in low earth orbit with the ground link being via cable. In this and following figures, TDRSG denotes the ground station for relaying signals to TDRS satellites.

The cable delay assumes a maximum total length of 8000 km, and delay is based on the CCIR formula [2];

$$\text{Delay} = 12 + (0.004 \times D_{km}), \quad \text{millisec} \qquad (2\text{-}1)$$



Summary of Estimated Delays

Path	Description	Media	Delay, millisec
a	Control - TDRSG	Land Line	44
b	TDRSG-TDRS	RF Prop.	134
c	TDRS-Teleop	RF Prop.	157
		Total One-Way	335
		Two-Way	670
		Fixed Delays (75 msec matrix inversion, 1.0 msec hardware)	76
		Total Estimated Delay	746

Figure 2-1. Link Configuration and Estimated Maximum Time Delays for Ground Control to Teleoperator in Low Earth Orbit, with Ground Link via Land Line.

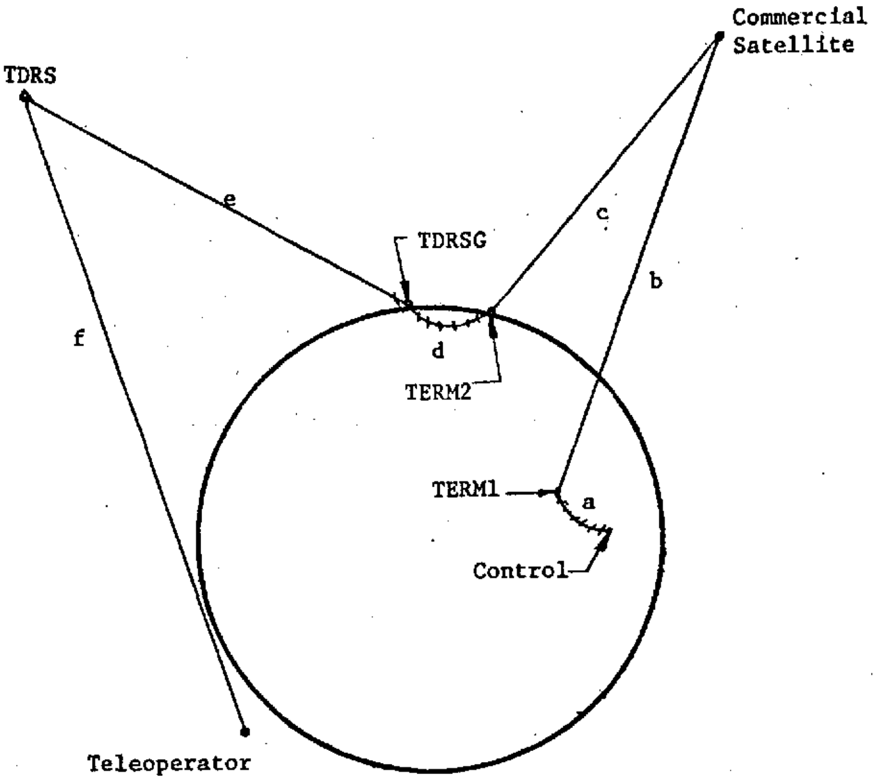
The 8000 km length may appear somewhat large, but this length is assumed to cover passing the signal through the NASCOM switching center at GSFC.

Propagation delays are based on the proposed locations for the satellites and the TDRSS ground station and on computed maximum delay to low earth orbits having altitudes between 300 km and 3000 km.

Figure 2-2 shows the configuration and delay summary when the point-to-point ground communication is by commercial satellite relay. It is assumed that some cable run will exist between the control point and the first satellite terminal (TERM1), and a delay based on a 1000 km cable length was estimated. A similar allowance was used for the cable connecting the second satellite terminal (TERM2) to TDRSG. Propagation delays were made as before; the somewhat smaller delays on the paths to and from the commercial satellite are due to assuming the satellite to be approximately on the meridian passing through the center of the continental U. S.

Figure 2-3 shows the geometry and delay estimates for low earth orbit control to teleoperator in low earth orbit. It is assumed that in this operational mode,control will relay through TDRS to the TDRS ground station and that TDRSG will immediately turn the signal around and relay it through a TDRS satellite (which may or may not be the same TDRS that relayed control's signal) to teleoperator.

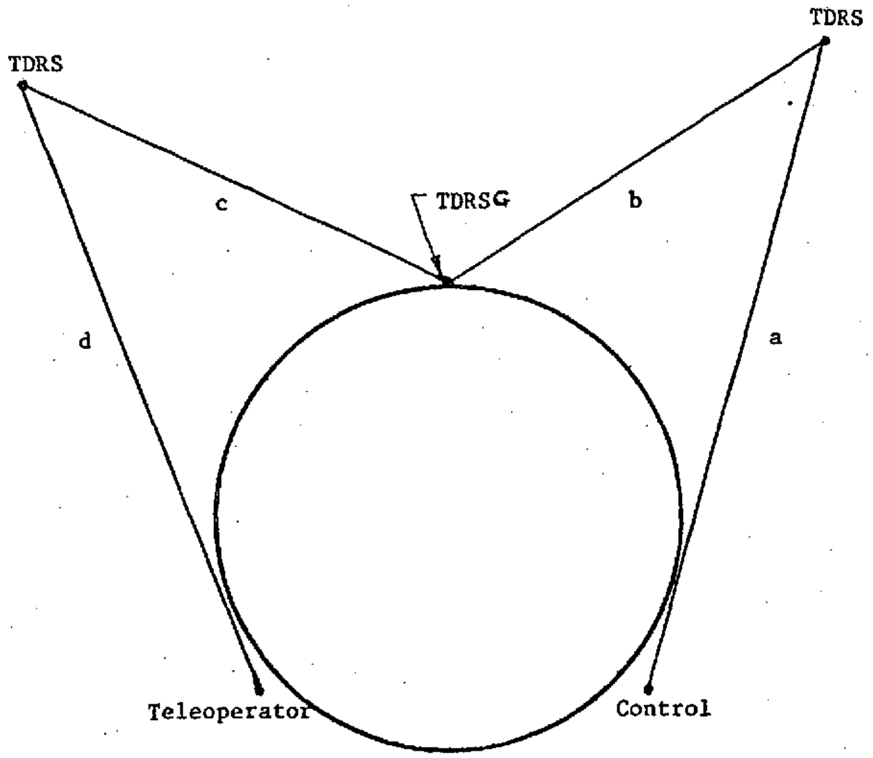
A remotely possible configuration that could produce even longer delays is not presented since it is deemed unlikely to be used. This configuration could occur if (1) satellite relay of intracontinental signals becomes a reality, and (2) NASCOM retains its present policy of routing all traffic through the central switching center at GSFC. It would then be possible for two relays through commercial satellites to occur, one relaying from control to GSFC, and the other relaying from GSFC to TDRSG. Such a configuration would produce a maximum delay approximately 480 milliseconds longer than that tabulated in Figure 2-2, or a total maximum delay of 1702 milliseconds.



Summary of Estimated Delays

Path	Description	Media	Delay, millisec
a	Control-TERM1	Land Line	16
b	TERM1-CSAT	RF Prop.	125
c	CSAT-TERM2	RF Prop.	125
d	TERM2-TDRSG	Land Line	16
e	TDRSG-TDRS	RF Prop.	134
f	TDRS-Teleop	RF Prop.	157
		Total One-Way	573
		Two-Way	1146
	Fixed Delays (75 msec matrix inversion, 1.0 msec hardware)		76
		Total Estimated Delay	1222

Figure 2-2. Link Configuration and Estimated Maximum Time Delays for Ground Control to Teleoperator in Low Earth Orbit, with Ground Link via Commercial Satellite Relay.



Summary of Estimated Delays

Path	Description	Media	Delay, millisec
a	Control-TDRS	RF Prop.	157
b	TDRS-TDRSG	RF Prop.	134
c	TDRSG-TDRS	RF Prop.	134
d	TDRS-Teleop	RF Prop.	157
		Total One-Way	582
		Two-Way	1164
	Fixed Delays (75 msec matrix inversion, 1.0 msec hardware)		76
		Total Estimated Delay	1240

Figure 2-3. Link Configuration and Estimated Maximum Time Delays for Low Earth Orbit Control to Teleoperator in Low Earth Orbit.

3. GROUND TO LOW EARTH ORBIT DELAYS

3.1 Approach

The determination of time delay profiles for ground control of teleoperator in low earth orbit requires that many cases be considered since an endless variety of orbits and communications link configurations are possible. The particular orbits in which teleoperator will operate have not been specified. Also, it is unlikely that specific orbits will be pre-determined. Teleoperator's function as a "service vehicle" may require that it rendezvous with any satellite in space; hence, the range of possible orbits encompasses all of the orbits of other vehicles.

As a practical matter, it was necessary to limit the orbits to be considered to a relative few and to automate the process of calculating the profiles. A computer program was constructed for carrying out the computations and presenting the results graphically on automated plots. The program includes routines for calculating earth rotation vs time, orbital motion, and distances and propagation times. Using the program, profiles were calculated for a number of specific orbits which provide a range of satellite altitudes and orbital inclinations. The following sections describe the structure of the program, the particular orbits considered, and presents the profiles.

3.2 Orbit-Earth Geometry

Conventional orbital geometry was adapted and is illustrated in Figure 3-1. A three dimensional rectangular coordinate system is positioned in space with the origin at the earth's center, the X-axis aligned with Aries (T), and the XY plane coincident with the equatorial plane. In this reference frame an orbit is described in terms of its eccentricity, ε; its radius at perigee, (R); the longitude (relative to T) of the ascending node, Ω; the inclination, i, of the orbital plane relative to the equatorial plane; the argument of perigee, ω; and the time, t, at which the body is at perigee.

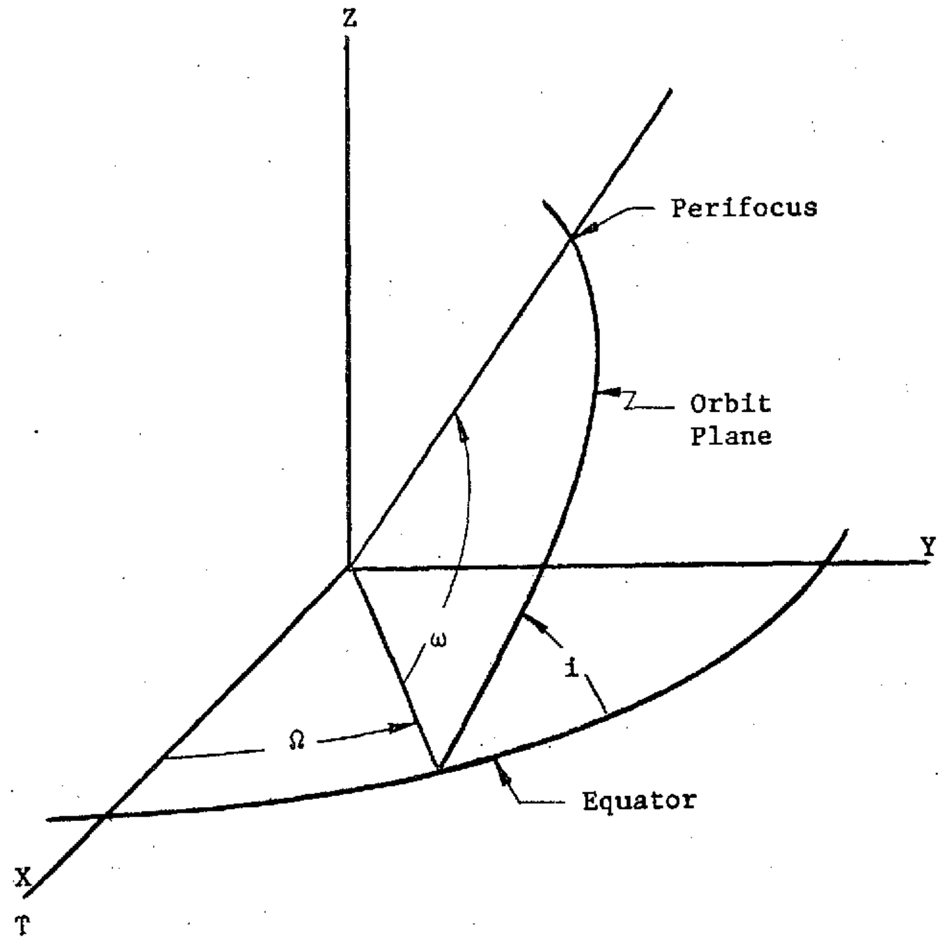


Figure 3-1. Reference Coordinate System Showing Definition of the Orientation Angles i, ω, and Ω.

An earth rotation routine was constructed to enable continuous determination of the location of ground stations within the coordinate system. Initial orientation of the earth within the reference frame required standardizing the system at some point in time. Since the teleoperator program schedule calls for operation in 1980, the time origin was fixed at January 0, 1980. At this instant of time the Greenwich meridian will be located 99.814° east of T.

3.3 Communications Configuration

The assumed communications system consists of the two TDRS vehicles, a ground based TDRS station, plus a ground based STDN station which could communicate with teleoperator directly during overpasses. Communications links between the teleoperator control point and the two ground stations would be via the NASCOM network.

Positioning of both ground stations was somewhat arbitrary; a final decision on the future location of the TDRS ground station (TDRSG) has not been reached, but the vicinity of White Sands, N. M. appears to be the likely choice. For calculation purposes, the TDRSG was assumed to be located at Lat. 33° N and Long. 107° W, approximately the center of the White Sands Missile Range.

For the STDN station Rosman (ROS), N. C. was chosen on the basis of its proximity to GSFC. If the current practice of funneling all NASCOM traffic through GSFC still exists in 1980, the STDN station nearest GSFC would be a likely choice.

The two TDRS satellites were assumed to be precisely synchronous at their proposed longitudes of 41° W and 171° W and to have orbits of 0° inclination. Table 3-1 summarizes the earth-based coordinates applicable at time $t = 0$, and Figure 3-2 shows the longitudes relative to T.

3.4 Program Description

The program consisted of a main and several subroutines for making orbital calculations, earth position calculations, and time delay calculations.

TABLE 3-1

COORDINATES OF GROUND STATIONS AND SATELLITES USED IN TIME DELAY PROFILES

Station/Satellite	Latitude	Longitude
ROS	35° 11' 46" N	277° 07' 27" E 85° 52' 33" W
TDRS-G	33° 00' 00" N	253° 00' 00" E 107° 00' 00" W
TDRS-E	0°	319° 00' 00" E 41° 00' 00" W
TDRS-W	0°	189° 00' 00" E 171° 00' 00" W
T (t = 0)	----------	260° 11' 11" E 99° 48' 49" W

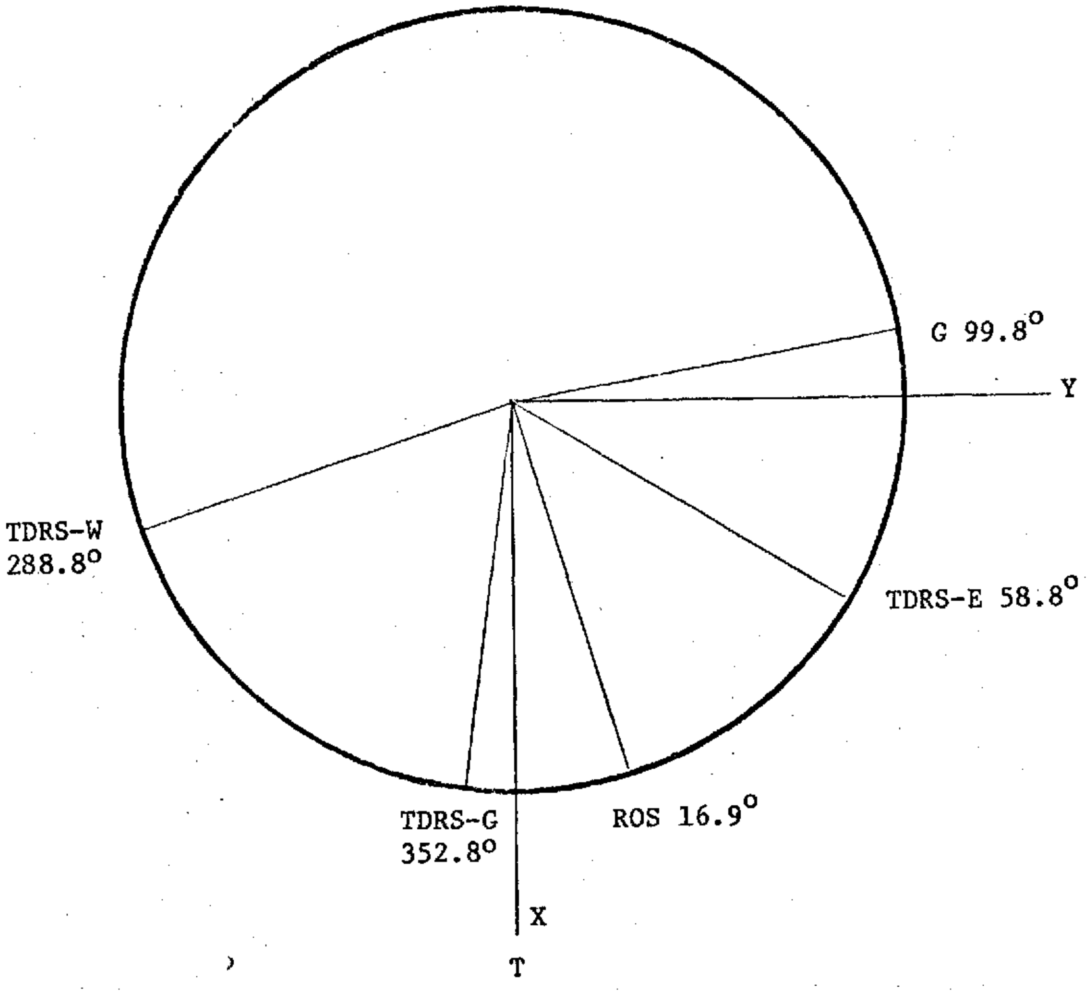


Figure 3-2. View from Positive Z Axis at t = 0 Showing Meridians of Interest. Numbers are East Longitudes Measured from T.

The program was designed for interactive operation from a remote terminal. Input parameters consisted of two ground delays (one for ROS and one for TDRSG) specifying the total delay in milliseconds between the control point and the ground station antenna, five orbit parameters (eccentricity, altitude in kilometers, plus Ω, ω, and i in degrees), and the time duration in hours and minutes. In the absence of any specific basis for choosing mission dates, all the delay profiles were calculated from $t = 0$ (0000 hours, January 1, 1980).

Communications link decisions and handover logic was incorporated in the program. The decisions can be summarized as follows:

(1) Direct earth-teleoperator contact through ROS any time the elevation of teleoperator as seen from ROS exceeds 5°. Handover occurs at 5° elevation.

(2) When relaying through the TDRS satellites, handover from the west satellite (TDRS-W) to the east satellite (TDRS-E), or vice versa, occurs at the mid-meridian between the two. This is at 254° E in the western hemisphere; also at 74° E for the eastern hemisphere provided the satellite altitude is great enough.

(3) In the eastern hemisphere, low altitude orbits will lose contact with both satellites in the shadow region centered around the 74° E meridian. Loss of contact on entering the shadow region, and acquisition on leaving it, is based on the position at which a straight line between teleoperator and the appropriate TDRS just grazes the earth. It is assumed that no communication exists while teleoperator is in the shadow region.

The program nominally calculates the positions of teleoperator, the appropriate ground station, and either TDRS satellite in use, at one minute intervals of time, and then calculates the time delay and the position (latitude and longitude) of teleoperator. When a handover is indicated, the one minute interval is subdivided to determine the time of handover to the nearest second. Delays on both pre-handover and post-handover links are calculated for the time of handover.

The program generates printed listings of the delays as a function of time, along with the latitude and longitude of teleoperator, and indicates the link configuration in use. A sample of the printed output is shown in Figure 3-3. However, to make the profiles more readily apparent an automated plotting routine was constructed to enable graphical display of the profiles. The plots display time delay vs mission time. The delays shown are total round trip delays from the ground station antenna for command data up and video data back. It was decided not to include the ground delays between teleoperator control and the ground communications stations in the plotted delay. These delays will vary for different control point locations and different ground net configurations. They will usually be fixed for a mission, barring difficulties that require altering the ground link configuration during a mission. Thus, the profiles shown display the variations in time delay that occur on the earth-space radio links. The appropriate fixed delay for signal processing and ground links can be added to the delays shown to obtain a complete profile.

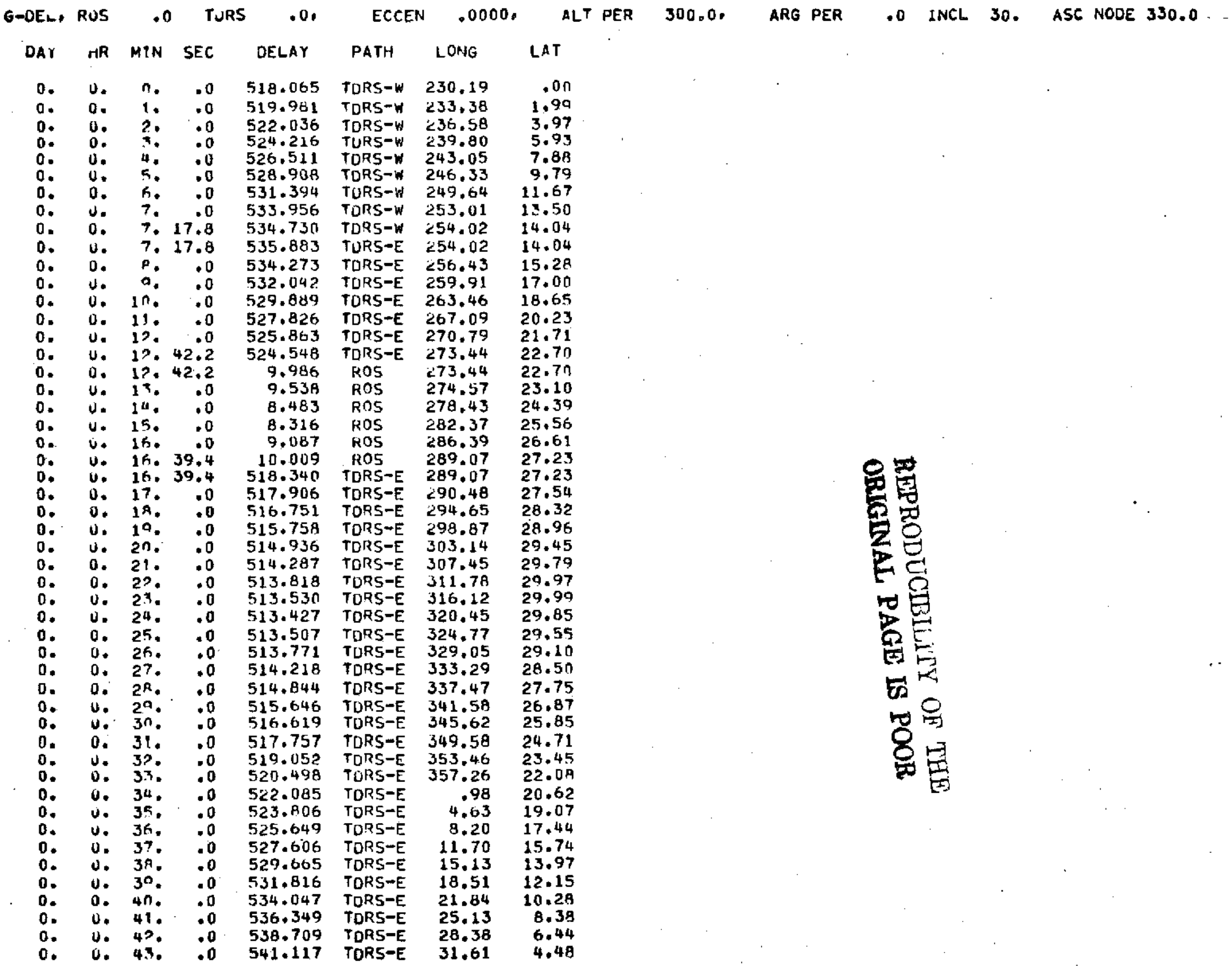
The horizontal time axis was scaled to provide a maximum time interval of 2.5 hours, sufficient for displaying a full orbit for low earth orbit vehicles. The program permits plotting of successive 2.5 hour increments so that longer missions can be shown.

The vertical axis is broken with the lower section scaled for displaying delays for direct contact between ROS and teleoperator. The upper section is scaled for relay through a TDRS vehicle. By omitting time delays between these ranges (which could not occur anyway), the variations in time delay can be shown in greater detail.

The communication path is indicated at the beginning of each trace by the codes ROS, TDRS-E, or TDRS-W. Entry into the shadow region is indicated by the word SHADOW. The vertical line immediately ahead of each code word marks the transition time.

3.5 Delay Profiles

With only limited information available on specified planned orbits, profiles were calculated for three assumed orbital altitudes (300 km, 1000 km,



```
G-DEL, ROS    .0   TDRS    .0,     ECCEN   .0000,    ALT PER   300.0,    ARG PER     .0  INCL  30.   ASC NODE 330.0

 DAY    HR  MIN  SEC     DELAY     PATH     LONG       LAT

  0.    0.   0.    .0   518.065   TDRS-W   230.19       .00
  0.    0.   1.    .0   519.981   TDRS-W   233.38      1.99
  0.    0.   2.    .0   522.036   TDRS-W   236.58      3.97
  0.    0.   3.    .0   524.216   TDRS-W   239.80      5.93
  0.    0.   4.    .0   526.511   TDRS-W   243.05      7.88
  0.    0.   5.    .0   528.908   TDRS-W   246.33      9.79
  0.    0.   6.    .0   531.394   TDRS-W   249.64     11.67
  0.    0.   7.    .0   533.956   TDRS-W   253.01     13.50
  0.    0.   7. 17.8   534.730   TDRS-W   254.02     14.04
  0.    0.   7. 17.8   535.883   TDRS-E   254.02     14.04
  0.    0.   8.    .0   534.273   TDRS-E   256.43     15.28
  0.    0.   9.    .0   532.042   TDRS-E   259.91     17.00
  0.    0.  10.    .0   529.889   TDRS-E   263.46     18.65
  0.    0.  11.    .0   527.826   TDRS-E   267.09     20.23
  0.    0.  12.    .0   525.863   TDRS-E   270.79     21.71
  0.    0.  12. 42.2   524.548   TDRS-E   273.44     22.70
  0.    0.  12. 42.2     9.986    ROS     273.44     22.70
  0.    0.  13.    .0     9.538    ROS     274.57     23.10
  0.    0.  14.    .0     8.483    ROS     278.43     24.39
  0.    0.  15.    .0     8.316    ROS     282.37     25.56
  0.    0.  16.    .0     9.087    ROS     286.39     26.61
  0.    0.  16. 39.4    10.009    ROS     289.07     27.23
  0.    0.  16. 39.4   518.340   TDRS-E   289.07     27.23
  0.    0.  17.    .0   517.906   TDRS-E   290.48     27.54
  0.    0.  18.    .0   516.751   TDRS-E   294.65     28.32
  0.    0.  19.    .0   515.758   TDRS-E   298.87     28.96
  0.    0.  20.    .0   514.936   TDRS-E   303.14     29.45
  0.    0.  21.    .0   514.287   TDRS-E   307.45     29.79
  0.    0.  22.    .0   513.818   TDRS-E   311.78     29.97
  0.    0.  23.    .0   513.530   TDRS-E   316.12     29.99
  0.    0.  24.    .0   513.427   TDRS-E   320.45     29.85
  0.    0.  25.    .0   513.507   TDRS-E   324.77     29.55
  0.    0.  26.    .0   513.771   TDRS-E   329.05     29.10
  0.    0.  27.    .0   514.218   TDRS-E   333.29     28.50
  0.    0.  28.    .0   514.844   TDRS-E   337.47     27.75
  0.    0.  29.    .0   515.646   TDRS-E   341.58     26.87
  0.    0.  30.    .0   516.619   TDRS-E   345.62     25.85
  0.    0.  31.    .0   517.757   TDRS-E   349.58     24.71
  0.    0.  32.    .0   519.052   TDRS-E   353.46     23.45
  0.    0.  33.    .0   520.498   TDRS-E   357.26     22.08
  0.    0.  34.    .0   522.085   TDRS-E      .98     20.62
  0.    0.  35.    .0   523.806   TDRS-E     4.63     19.07
  0.    0.  36.    .0   525.649   TDRS-E     8.20     17.44
  0.    0.  37.    .0   527.606   TDRS-E    11.70     15.74
  0.    0.  38.    .0   529.665   TDRS-E    15.13     13.97
  0.    0.  39.    .0   531.816   TDRS-E    18.51     12.15
  0.    0.  40.    .0   534.047   TDRS-E    21.84     10.28
  0.    0.  41.    .0   536.349   TDRS-E    25.13      8.38
  0.    0.  42.    .0   538.709   TDRS-E    28.38      6.44
  0.    0.  43.    .0   541.117   TDRS-E    31.61      4.48
```

Figure 3-3. Sample of Printed Output.

```
G-DEL, ROS    .0    TDRS    .0,     ECCEN    .0000,    ALT PER   300.0,    ARG PER    .0  INCL  30.   ASC NODE 330.0

  DAY    HR  MIN  SEC     DELAY     PATH     LONG      LAT

   0.    0.  44.   .0    543.561   TDRS-E   34.81     2.50
   0.    0.  45.   .0    546.031   TDRS-E   38.01      .52
   0.    0.  46.   .0    548.516   TDRS-E   41.20    -1.47
   0.    0.  47.   .0    551.006   TDRS-E   44.40    -3.45
   0.    0.  48.   .0    553.489   TDRS-E   47.62    -5.42
   0.    0.  49.   .0    555.957   TDRS-E   50.85    -7.37
   0.    0.  50.   .0    558.399   TDRS-E   54.12    -9.30
   0.    0.  51.   .0    560.807   TDRS-E   57.43   -11.18
   0.    0.  51.  5.6    561.030   TDRS-E   57.74   -11.36
   0.    0.  51.  5.6   ********   SHADOW   57.74   -11.36
   0.    0.  52.   .0   ********   SHADOW   60.78   -13.03
   0.    0.  53.   .0   ********   SHADOW   64.19   -14.82
   0.    0.  54.   .0   ********   SHADOW   67.65   -16.56
   0.    0.  55.   .0   ********   SHADOW   71.18   -18.23
   0.    0.  56.   .0   ********   SHADOW   74.79   -19.82
   0.    0.  57.   .0   ********   SHADOW   78.47   -21.33
   0.    0.  58.   .0   ********   SHADOW   82.23   -22.75
   0.    0.  59.   .0   ********   SHADOW   86.07   -24.06
   0.    1.  -1. 54.4   ********   SHADOW   89.62   -25.16
   0.    1.  -1. 54.4    559.790   TDRS-W   89.62   -25.16
   0.    1.   0.   .0    559.536   TDRS-W   89.99   -25.27
   0.    1.   1.   .0    556.794   TDRS-W   93.99   -26.35
   0.    1.   2.   .0    554.008   TDRS-W   98.06   -27.31
   0.    1.   3.   .0    551.189   TDRS-W  102.21   -28.13
   0.    1.   4.   .0    548.348   TDRS-W  106.42   -28.81
   0.    1.   5.   .0    545.498   TDRS-W  110.67   -29.34
   0.    1.   6.   .0    542.649   TDRS-W  114.97   -29.72
   0.    1.   7.   .0    539.816   TDRS-W  119.30   -29.94
   0.    1.   8.   .0    537.010   TDRS-W  123.64   -30.00
   0.    1.   9.   .0    534.245   TDRS-W  127.98   -29.90
   0.    1.  10.   .0    531.535   TDRS-W  132.30   -29.65
   0.    1.  11.   .0    528.892   TDRS-W  136.59   -29.24
   0.    1.  12.   .0    526.331   TDRS-W  140.84   -28.67
   0.    1.  13.   .0    523.865   TDRS-W  145.04   -27.96
   0.    1.  14.   .0    521.508   TDRS-W  149.17   -27.11
   0.    1.  15.   .0    519.274   TDRS-W  153.23   -26.13
   0.    1.  16.   .0    517.175   TDRS-W  157.21   -25.02
   0.    1.  17.   .0    515.225   TDRS-W  161.11   -23.79
   0.    1.  18.   .0    513.435   TDRS-W  164.93   -22.45
   0.    1.  19.   .0    511.817   TDRS-W  168.68   -21.01
   0.    1.  20.   .0    510.382   TDRS-W  172.34   -19.48
   0.    1.  21.   .0    509.140   TDRS-W  175.93   -17.87
   0.    1.  22.   .0    508.098   TDRS-W  179.44   -16.19
   0.    1.  23.   .0    507.265   TDRS-W  182.90   -14.44
   0.    1.  24.   .0    506.645   TDRS-W  186.29   -12.63
   0.    1.  25.   .0    506.245   TDRS-W  189.63   -10.78
   0.    1.  26.   .0    506.066   TDRS-W  192.93    -8.88
   0.    1.  27.   .0    506.111   TDRS-W  196.19    -6.95
   0.    1.  28.   .0    506.378   TDRS-W  199.42    -4.99
   0.    1.  29.   .0    506.868   TDRS-W  202.63    -3.02
```

Figure 3-3. (Concluded)

and 3000 km). For each altitude three inclination angles (0^o, 30^o, and 60^o) were used. In addition the profile for a tentative planned retrograde orbit [3] of altitude 380 km and inclination 103^o was calculated.

All of the orbits were assumed to be circular (eccentricity = 0). The position of teleoperator at t = 0 coincides with the ascending node of the orbit; the position of the ascending node was chosen on each inclined orbit so that the first pass was within tracking range of ROS. Delay profiles for equatorial orbits were calculated only for a 2½ hour interval since sequential orbits generate identical profiles. For the inclined orbits, longer profiles were generated to show the changes on successive orbits.

Table 3-2 summarizes the data for each of the profiles produced, and the profiles are shown in Figures 3-4 to 3-13.

3.6 Limits of Delays and Delay Rates

For the orbits shown for ground control of teleoperator in low earth orbit, the time delay for the round trip space propagated signal can be read directly from Figures 3-4 to 3-13. The maximum and minimum delay values for space propagation can be read directly from the graphs by reading the highest and lowest delays shown. To obtain the maximum and minimum values for the complete profile, the round trip transmission time on the ground communications link plus the fixed delays (matrix inversion processing delays and hardware delays) must be added to the values read from the figures.

The rate-of-change of time delay is also easily obtained from the figures by measuring the slope of the curve and multiplying by a constant. The appropriate constant would depend on the scaling of the graphs. For Figures 3-4 to 3-13, which have identical scaling, the rate of change of time delay is

$$r = 4.45 \times 10^{-5} \tan \theta \qquad (3\text{-}1)$$

where θ is the angle between the delay line and the horizontal. Equation (3-1) is dimensionless; note that both axes of the graphs are calibrated

TABLE 3-2

SUMMARY OF GROUND TO LOW EARTH ORBIT PROFILES

Orbit Number	Altitude km	Inclination degrees	Ascending Node E. Long*	Duration hrs.-min.	Figure Number
1	300	0	0	2 30	3-4
2	300	30	330	12 30	3-5
3	300	60	0	12 30	3-6
4	1000	0	0	2 30	3-7
5	1000	30	330	12 30	3-8
6	1000	60	0	12 30	3-9
7	3000	0	0	2 30	3-10
8	3000	30	330	12 30	3-11
9	3000	60	0	12 30	3-12
10	380	103	26	10 0	3-13

* Relative to ♈

in units of time; hence, (3-1) expresses r as seconds change in delay per second of real time.

A more convenient expression for rate-of-change of time delay might be to rescale (3-1) so that the increment of delay and the increments of real time are in different units. Scaling delays in milliseconds and elapsed time in minutes, the rate of change in delay can be expressed as

$$r_1 = 2.67 \tan \theta \quad \text{(millisec/minute)} \tag{3-2}$$

Table 3-3 summarizes the maximum delays and delay rates obtained from the delay profiles shown in Figures (3-4) to (3-13). The values have been categorized by orbit altitude and separate delays and delay rates tabulated for relay through TDRS satellites, and for direct contact with the ground station (ROS).

TABLE 3-3

MAXIMUM DELAYS AND DELAY RATES FROM COMPUTED PROFILES

Orbit Altitude (kilometers)	TDRS Relay		ROS-Teleop	
	Max. Delay (msec)	Max. Rate (msec/min)	Max. Delay (msec)	Max. Rate (msec/min)
300	562	2.97	11	2.67
1000	573	2.77	22	2.49
3000	583	2.40	42	1.67
380 Retrograde	564	3.08	12	2.92

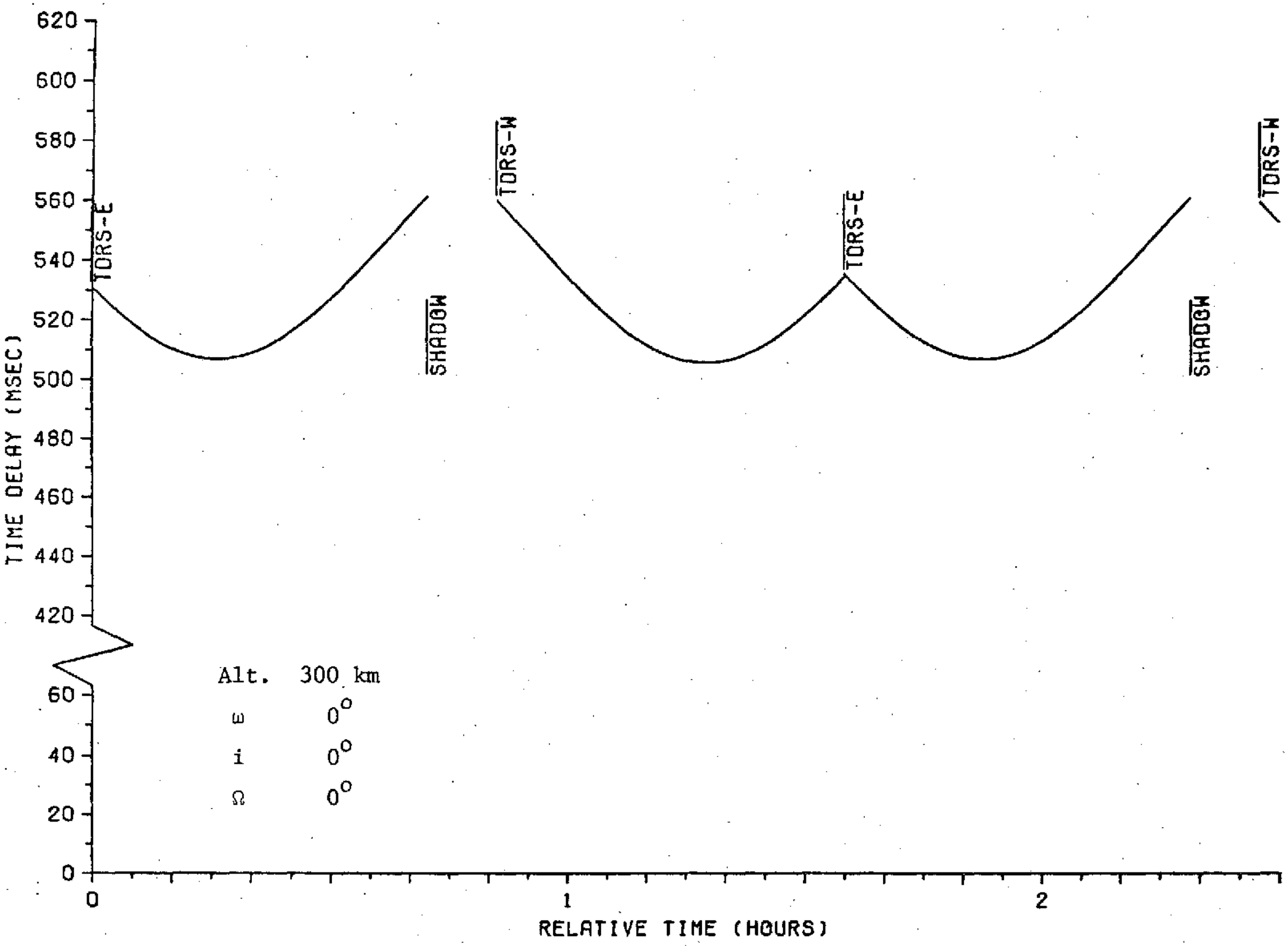


Figure 3-4. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 300 km, Inclination 0°.

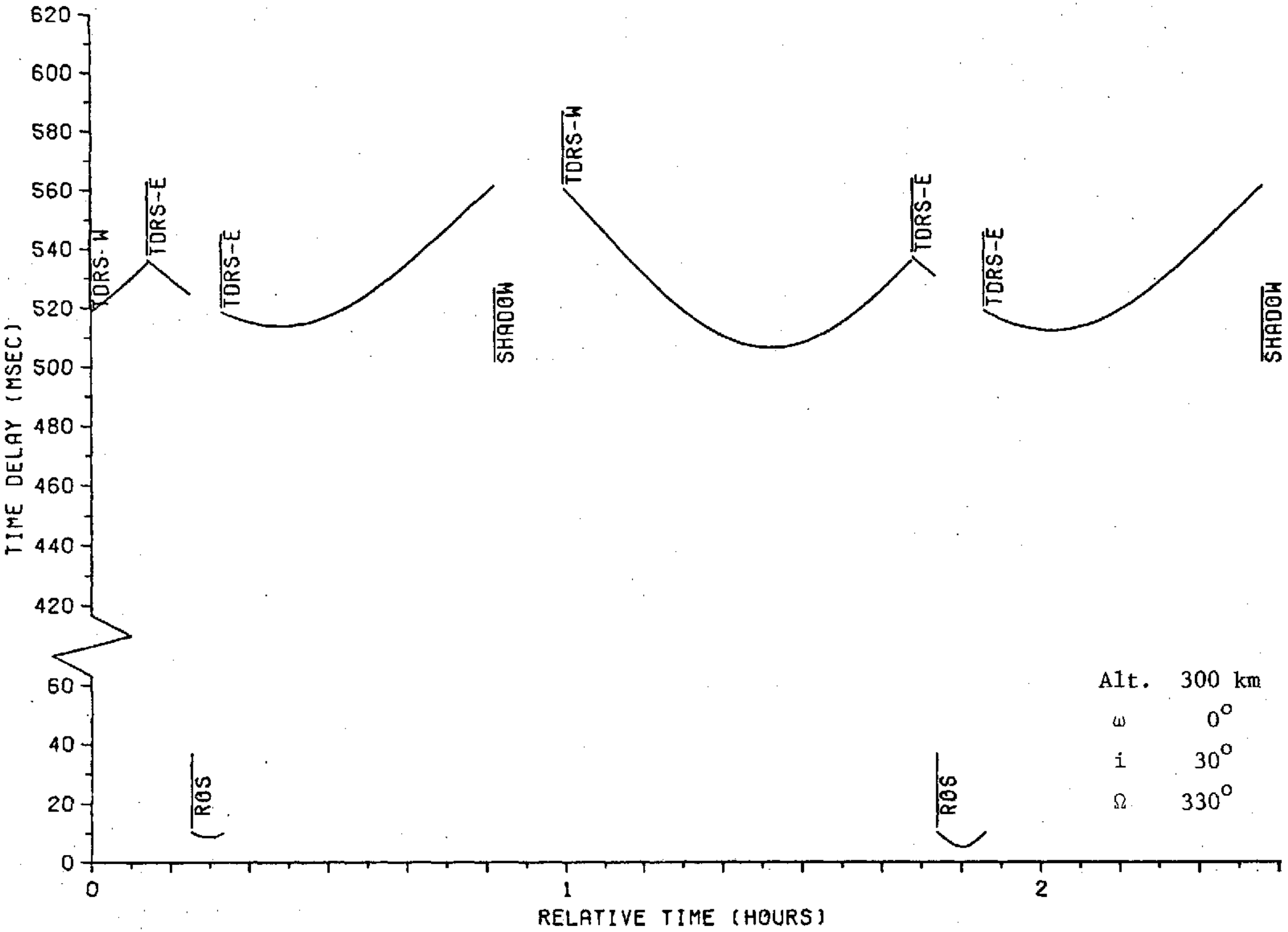


Figure 3-5. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 300 km, Inclination 30°.

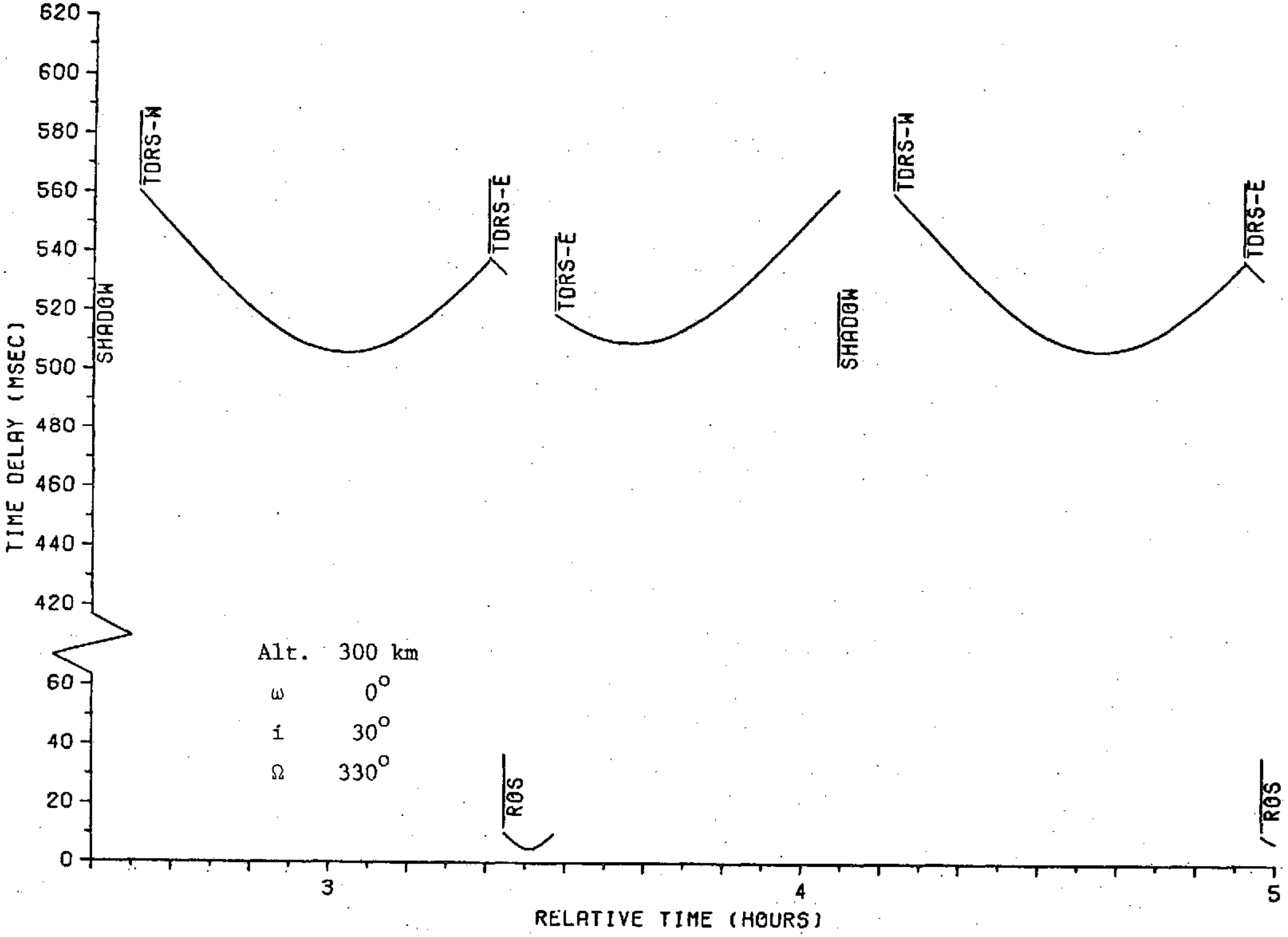


Figure 3-5. (Continued)

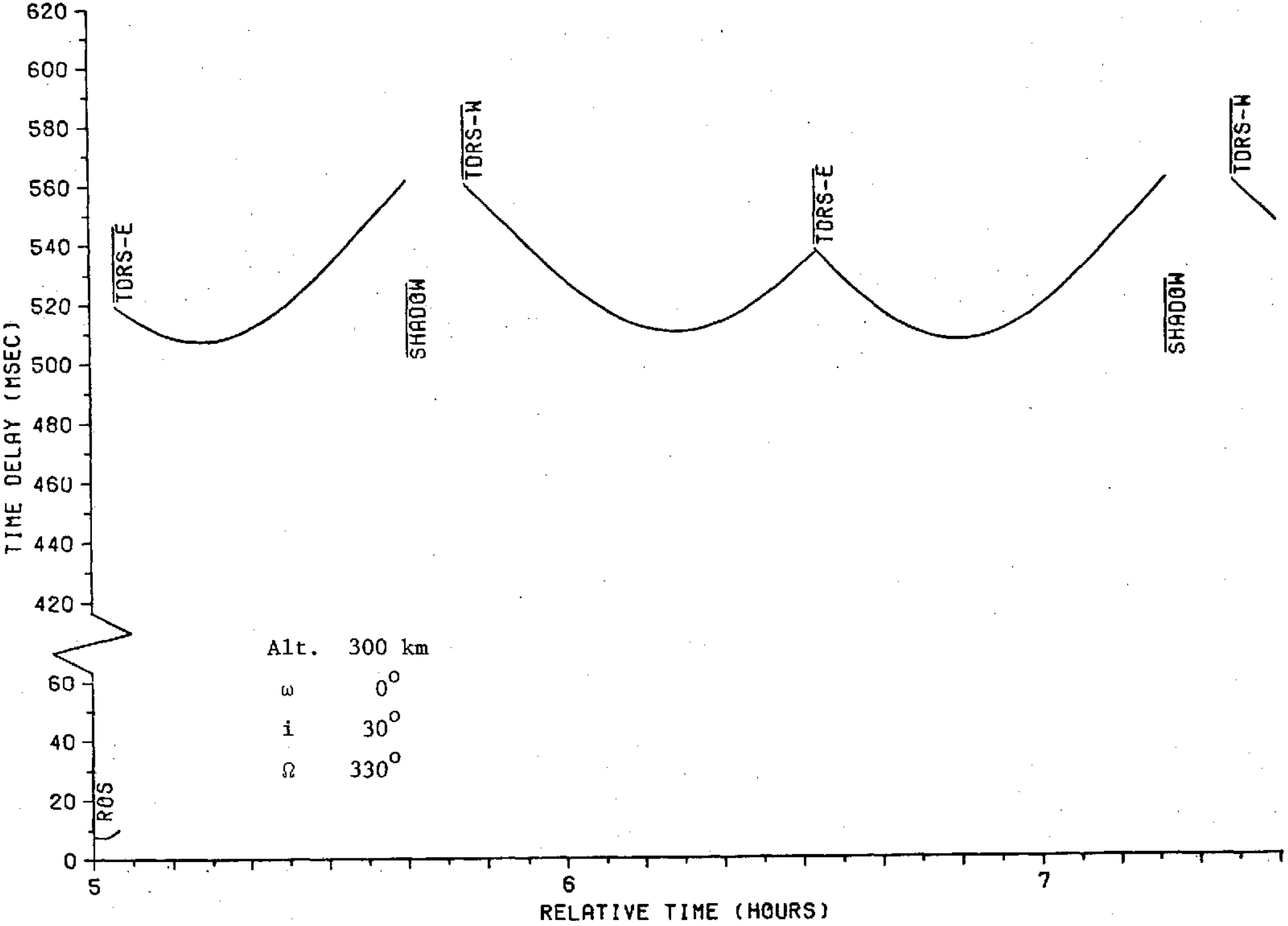


Figure 3-5. (Continued)

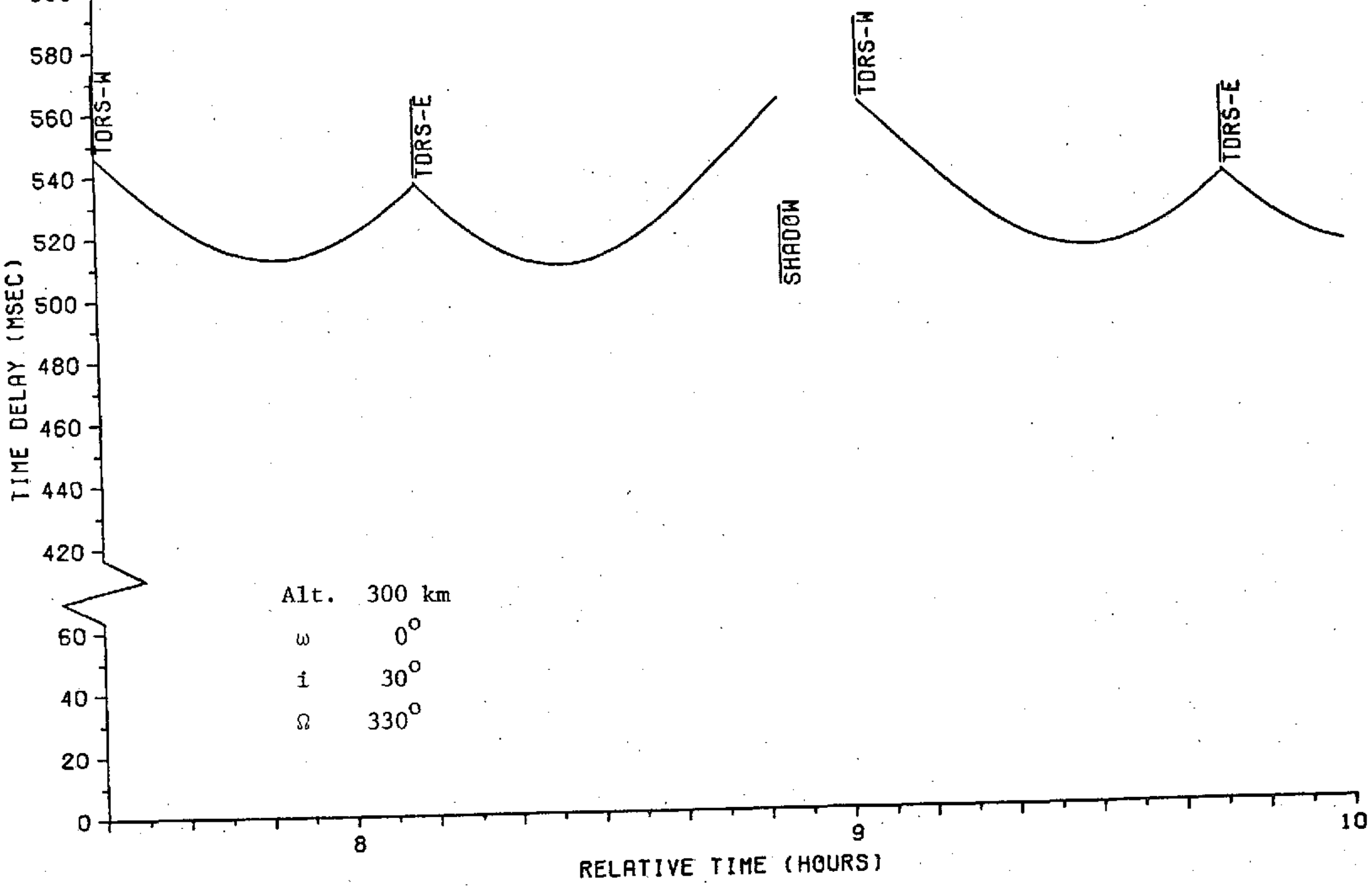


Figure 3-5. (Continued)

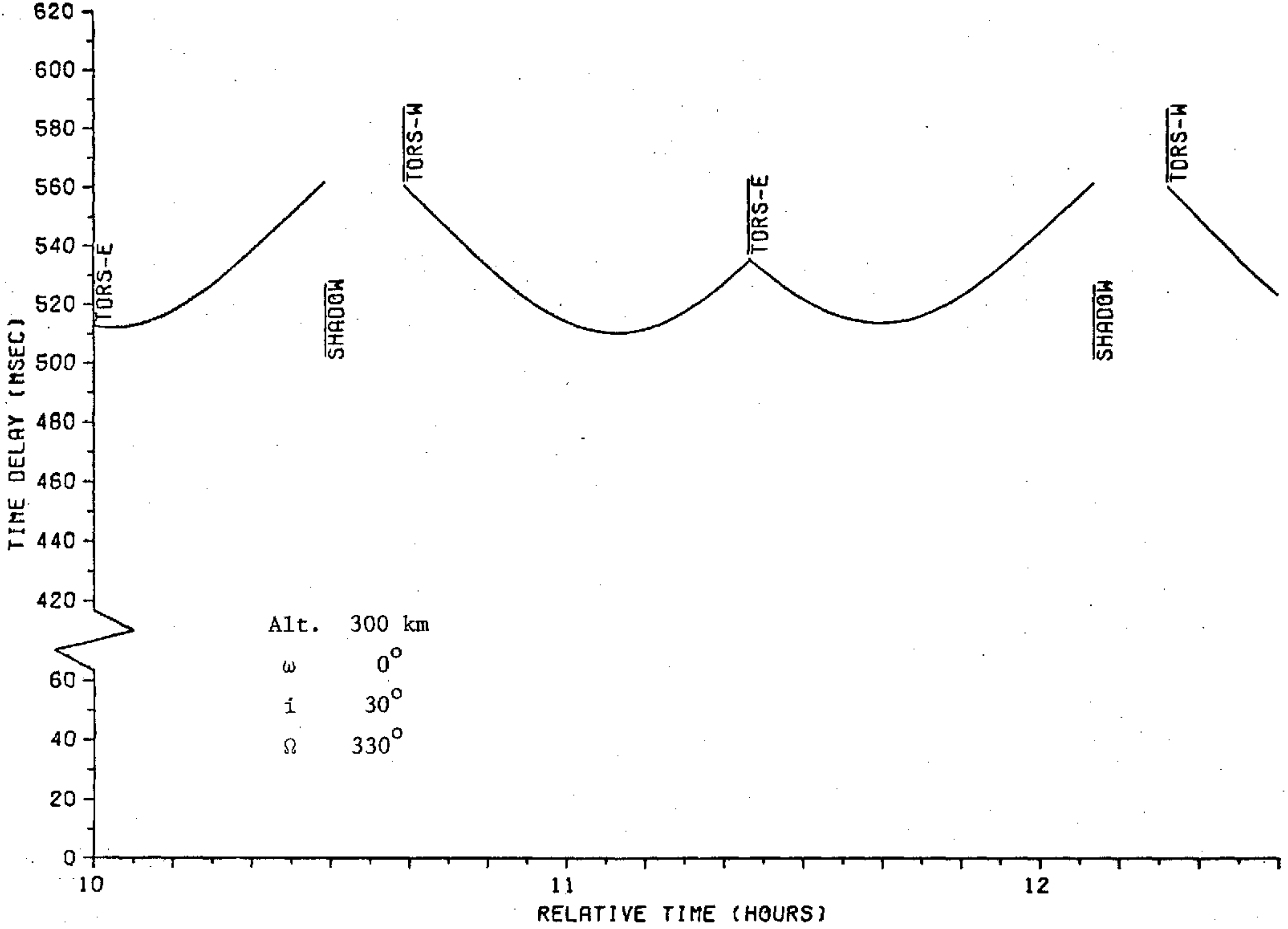


Figure 3-5. (Concluded)

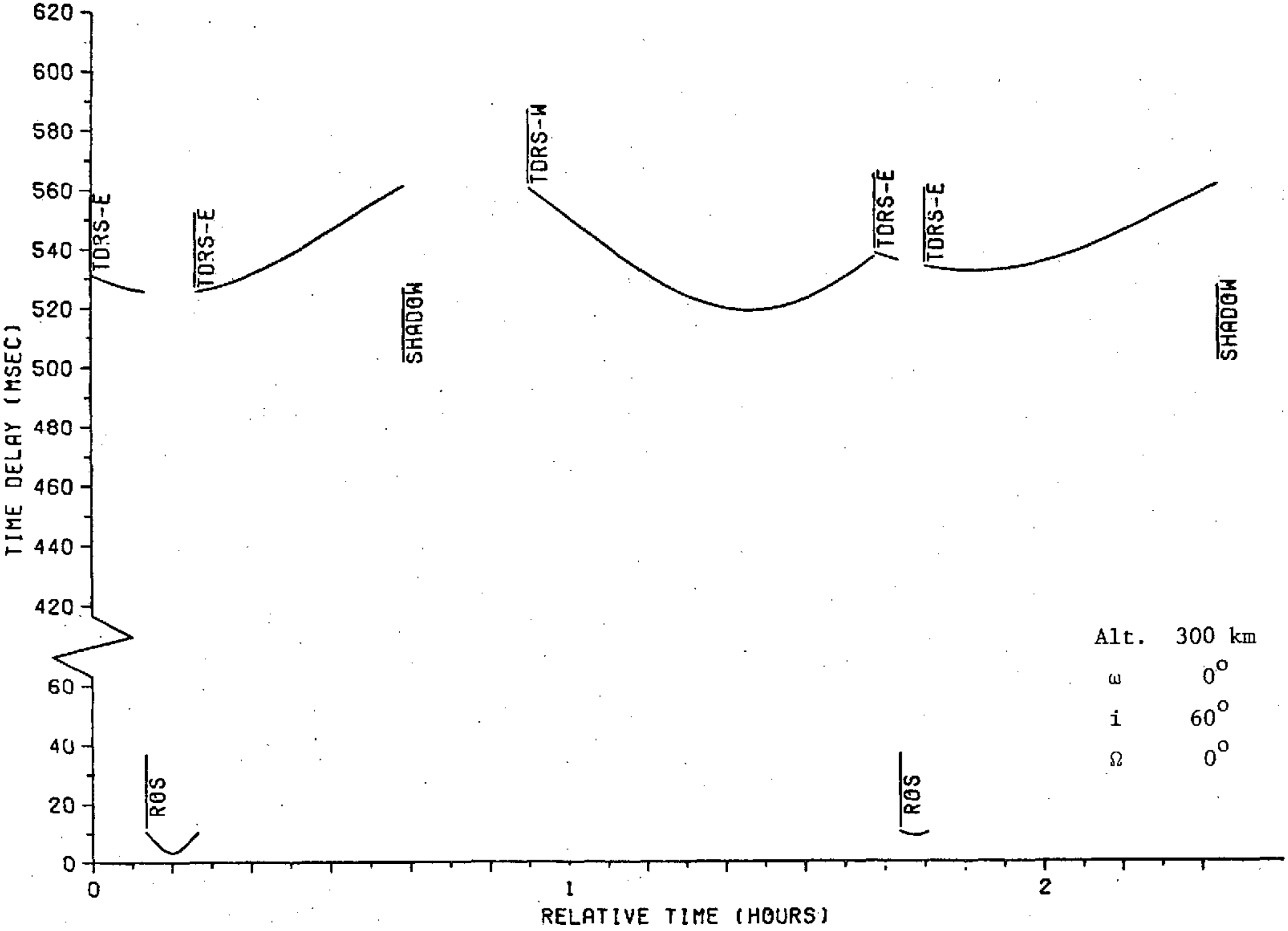


Figure 3-6. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 300 km, Inclination 60°.

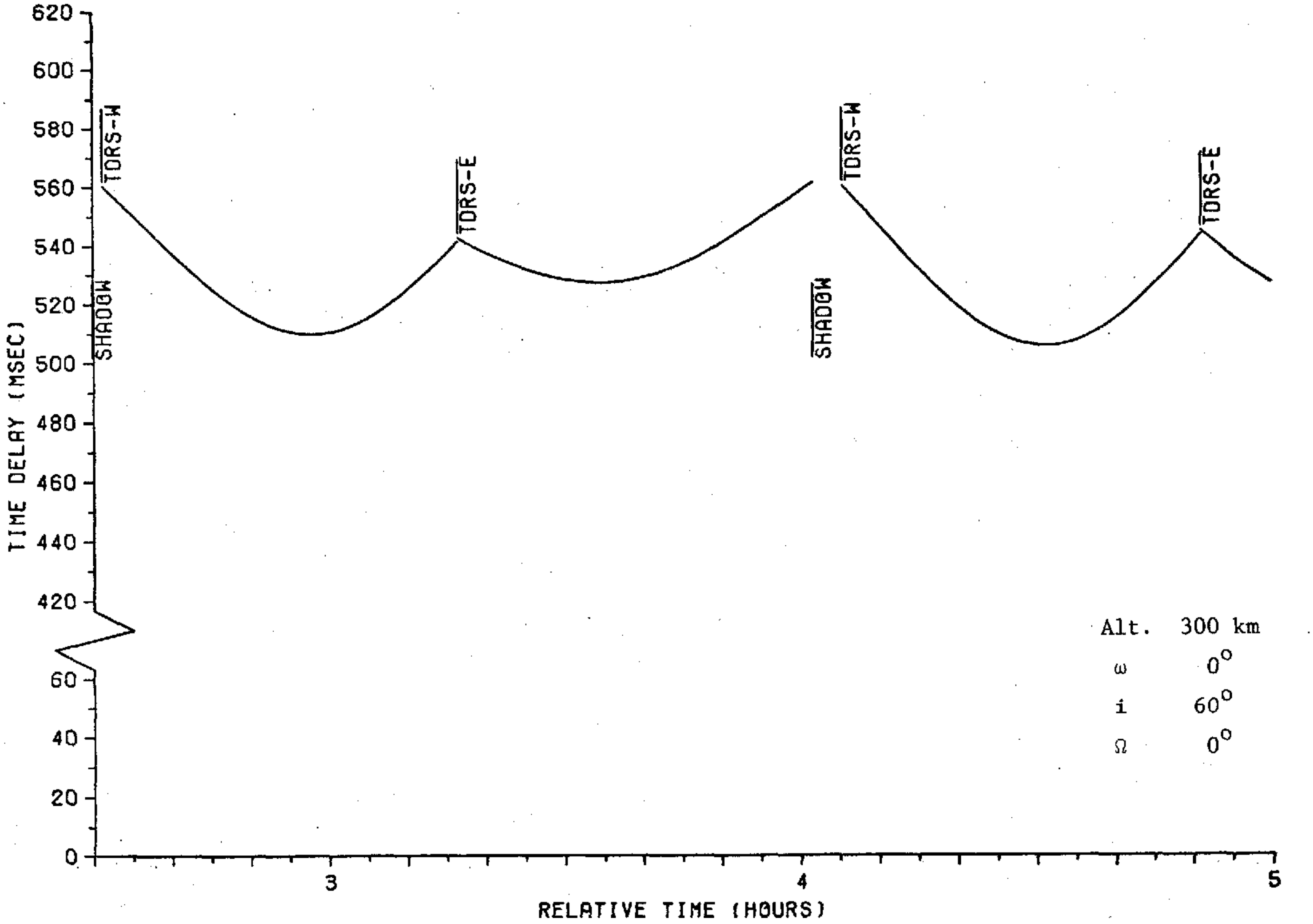


Figure 3-6. (Continued)

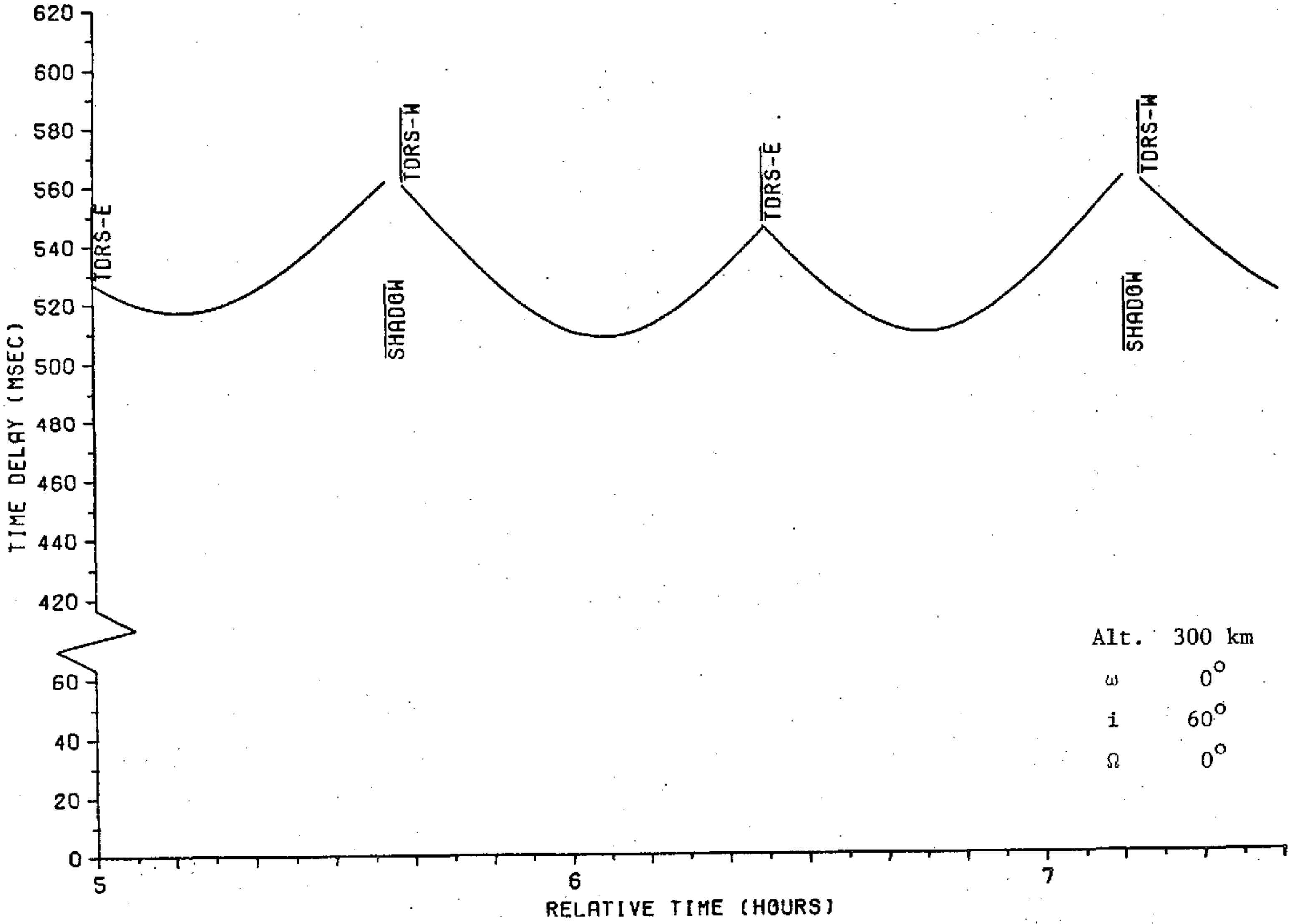


Figure 3-6. (Continued)

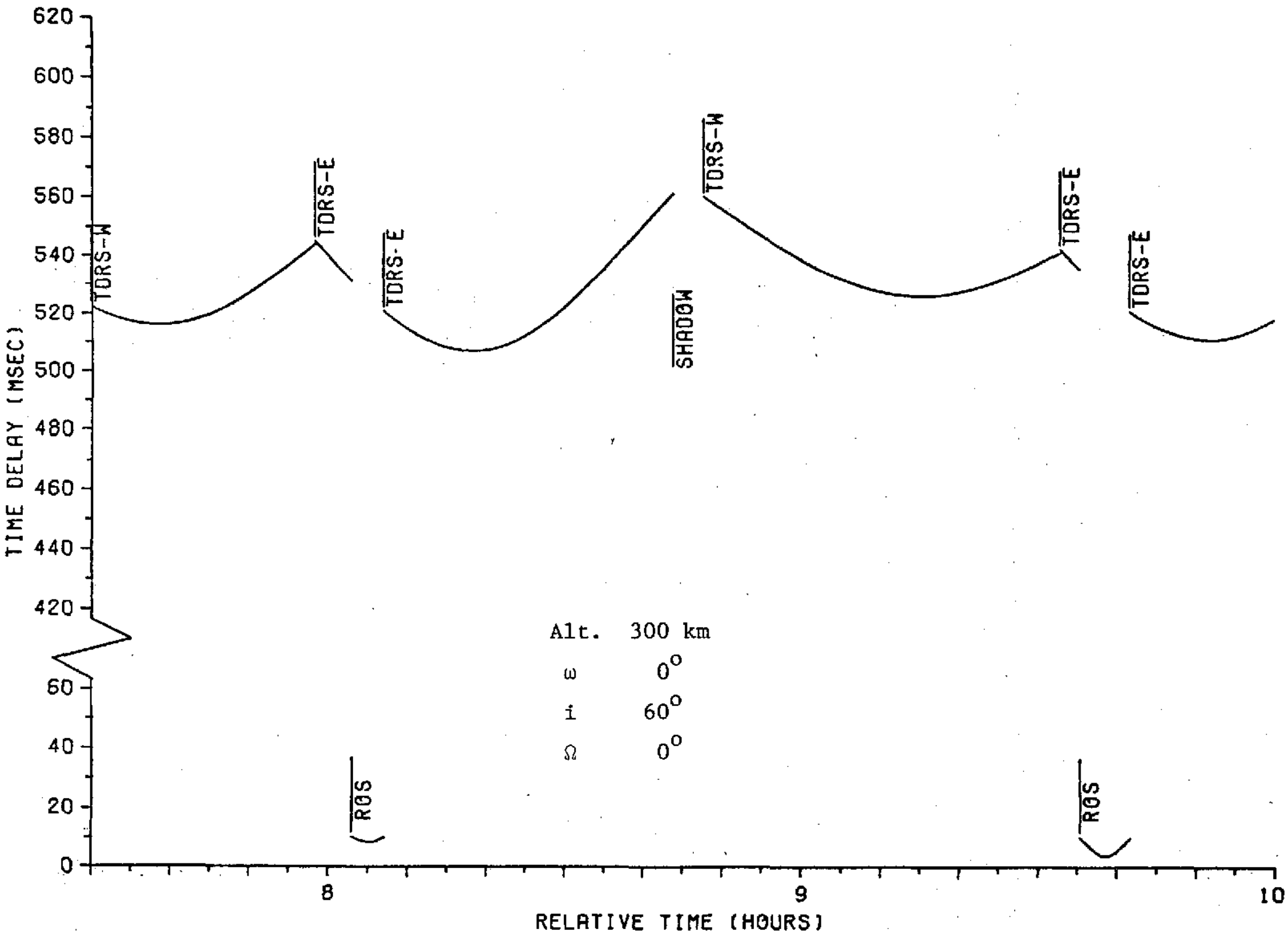


Figure 3-6. (Continued)

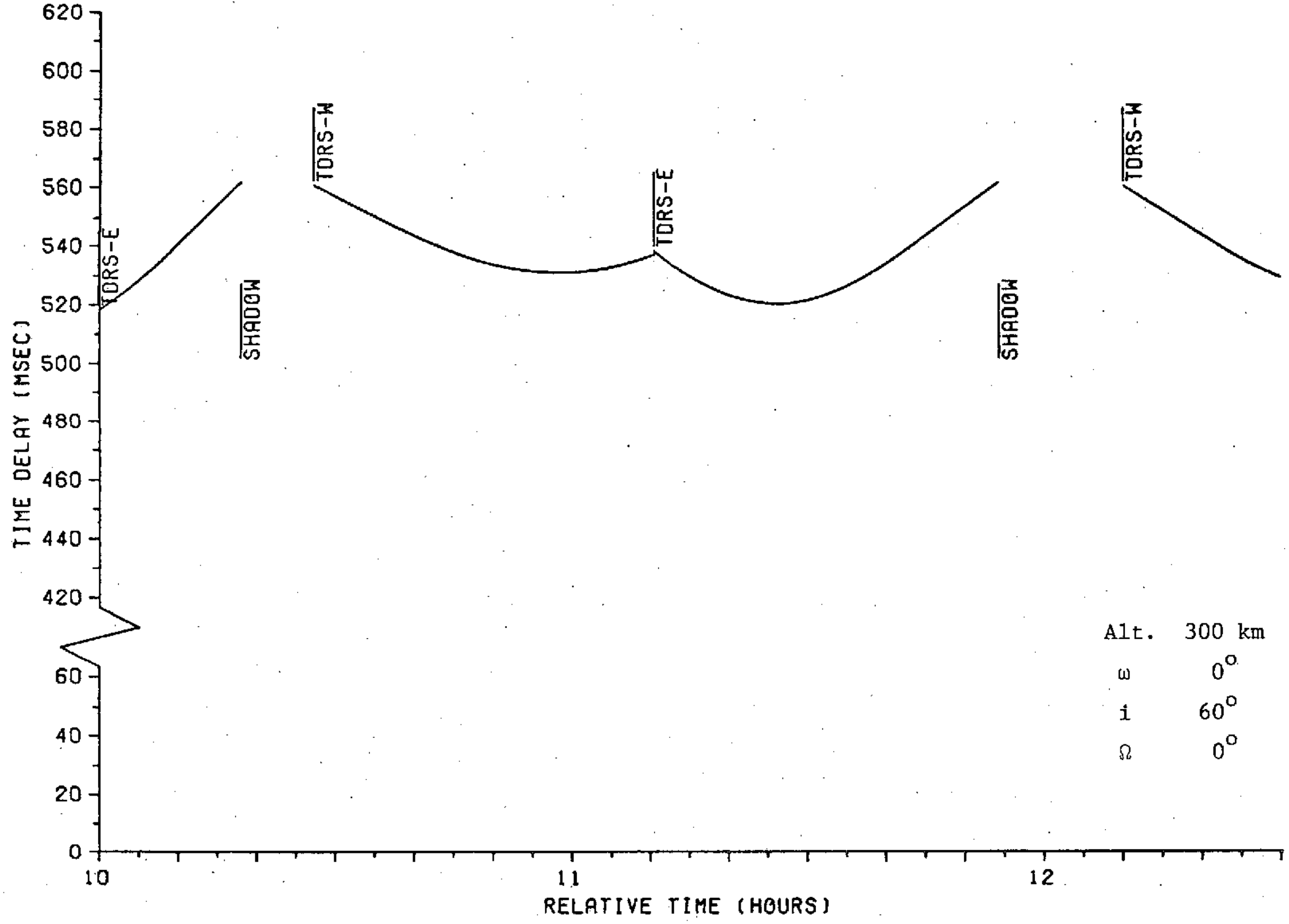


Figure 3-6. (Concluded)

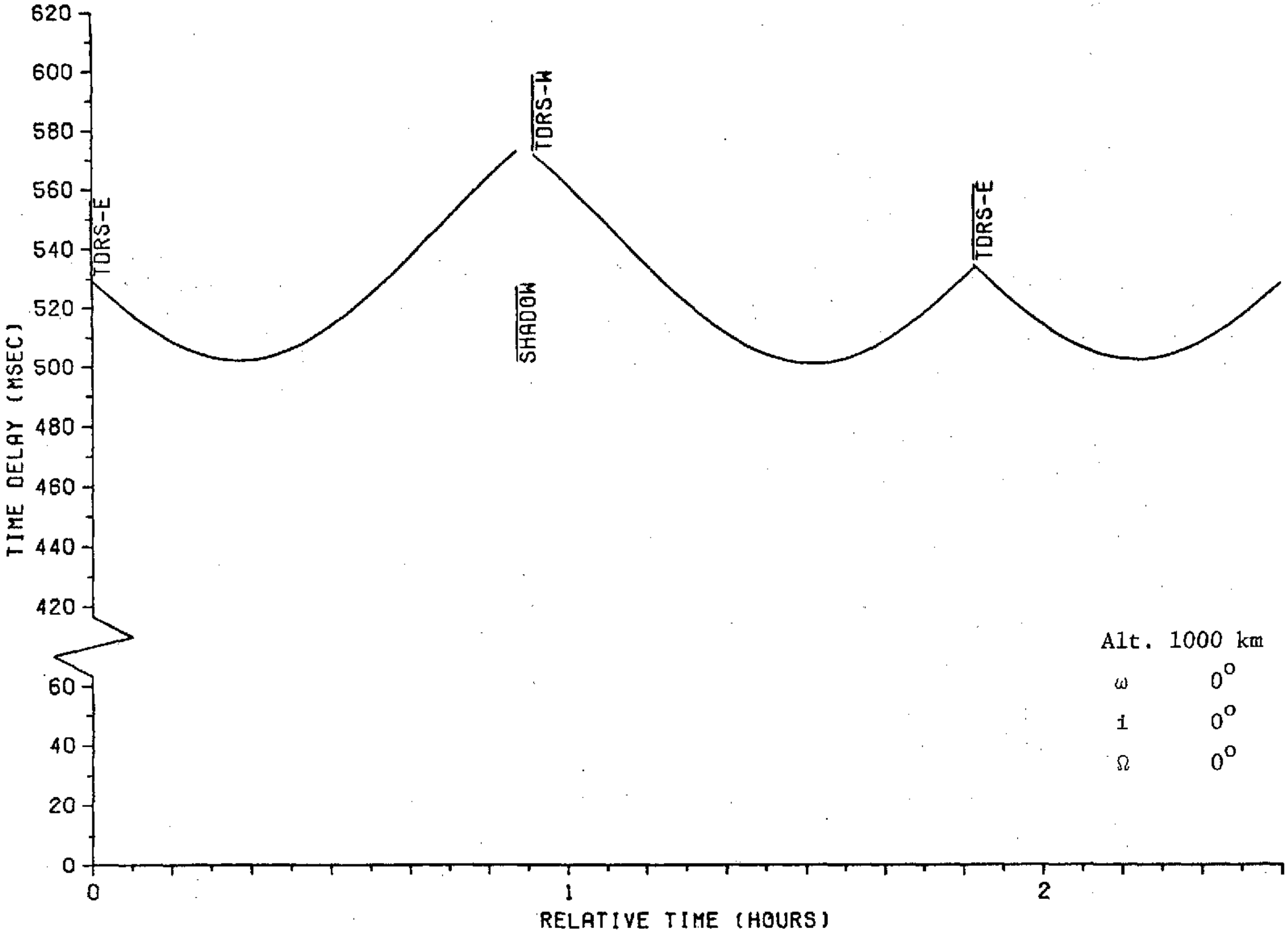


Figure 3-7. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 1000 km, Inclination 0°.

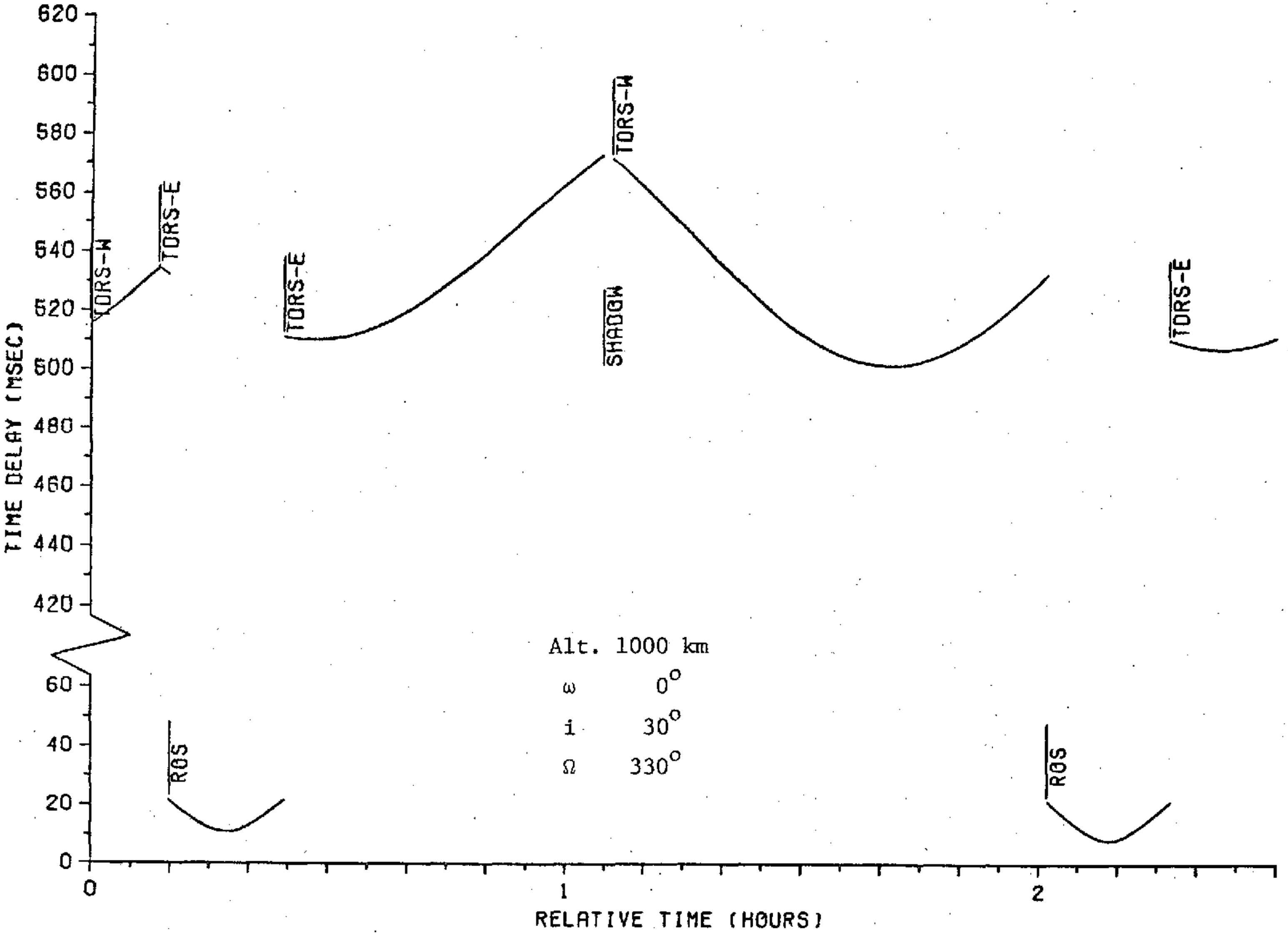


Figure 3-8. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 1000 km, Inclination 30°.

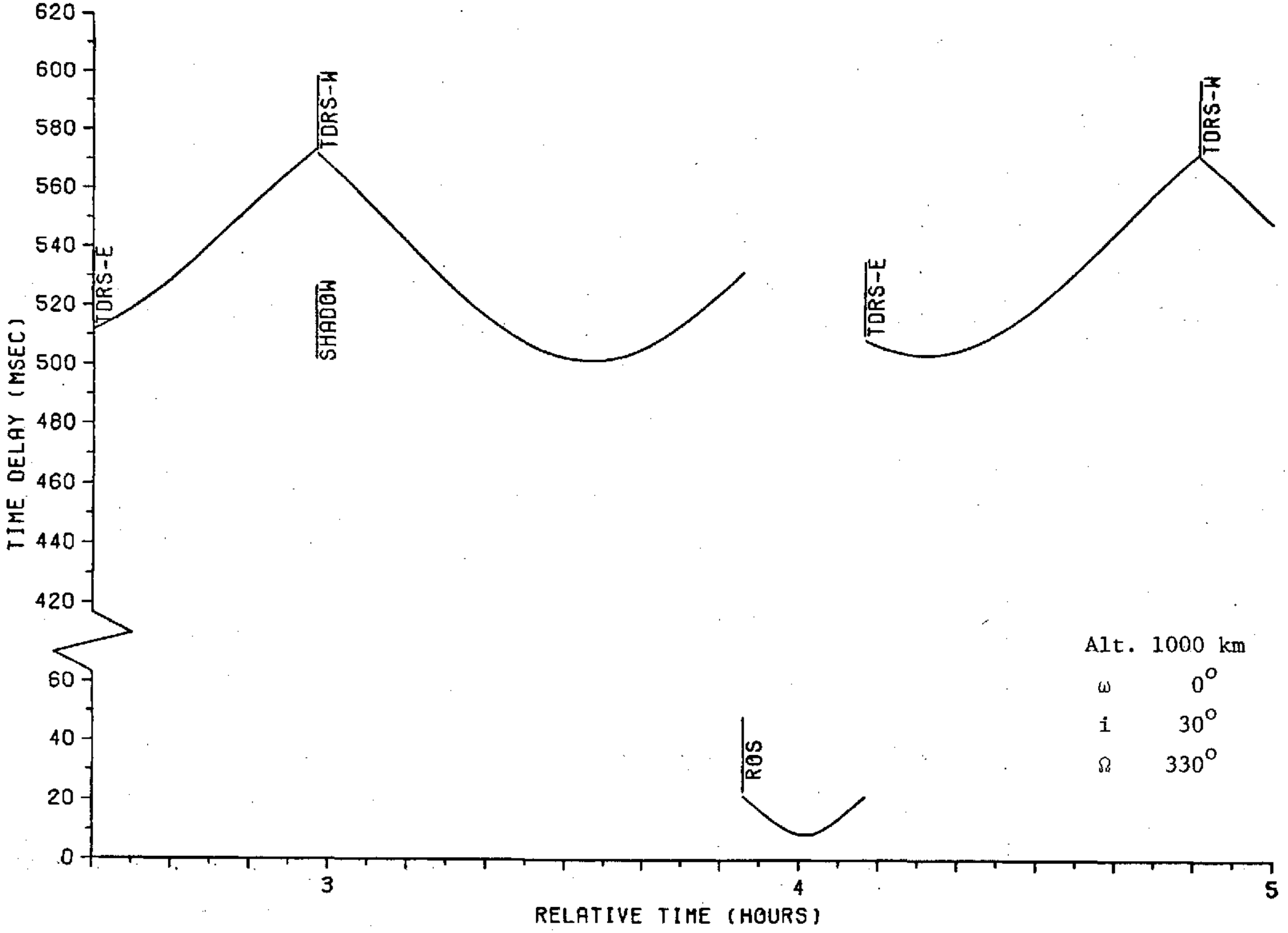


Figure 3-8. (Continued)

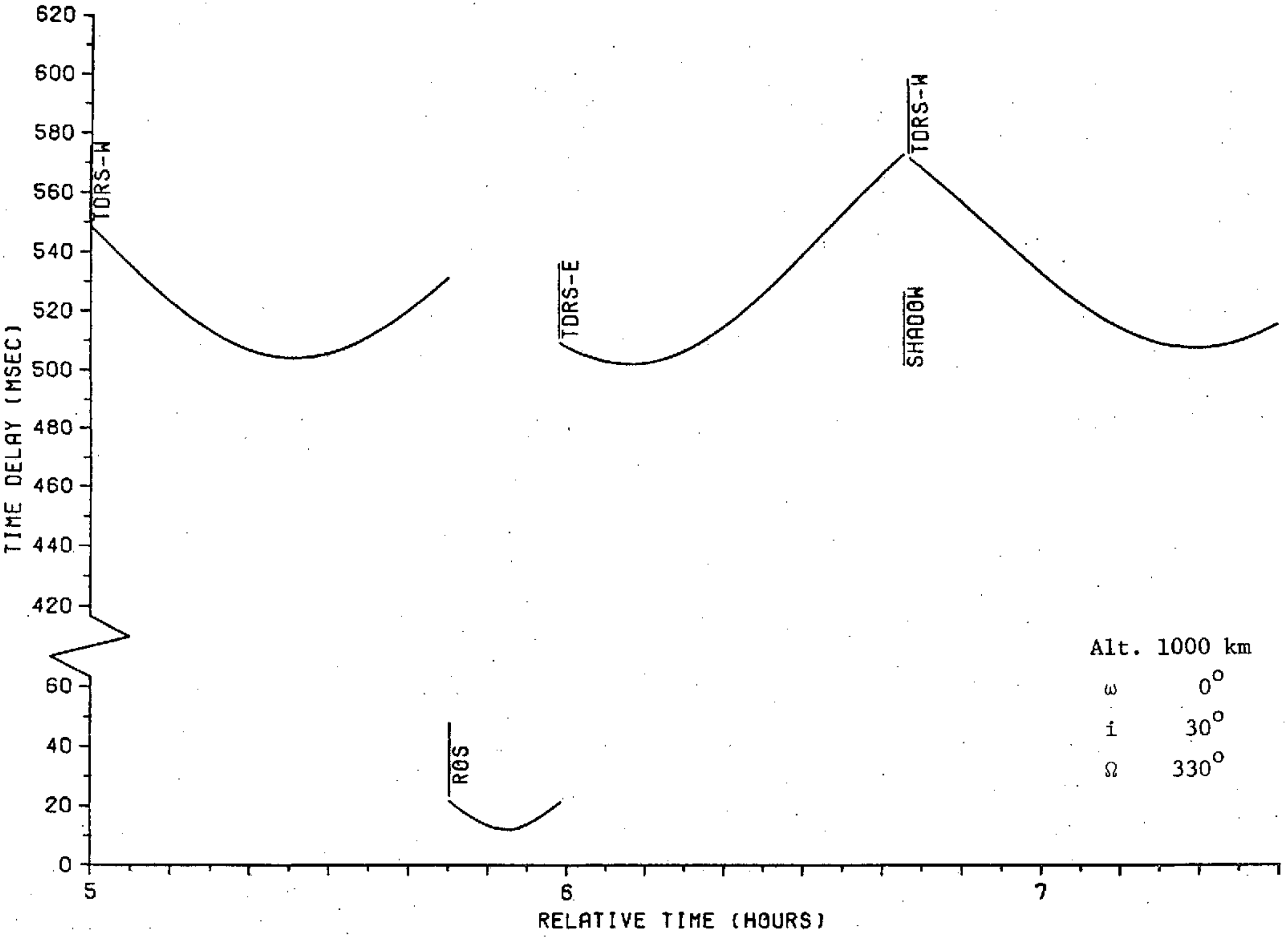


Figure 3-8. (Continued)

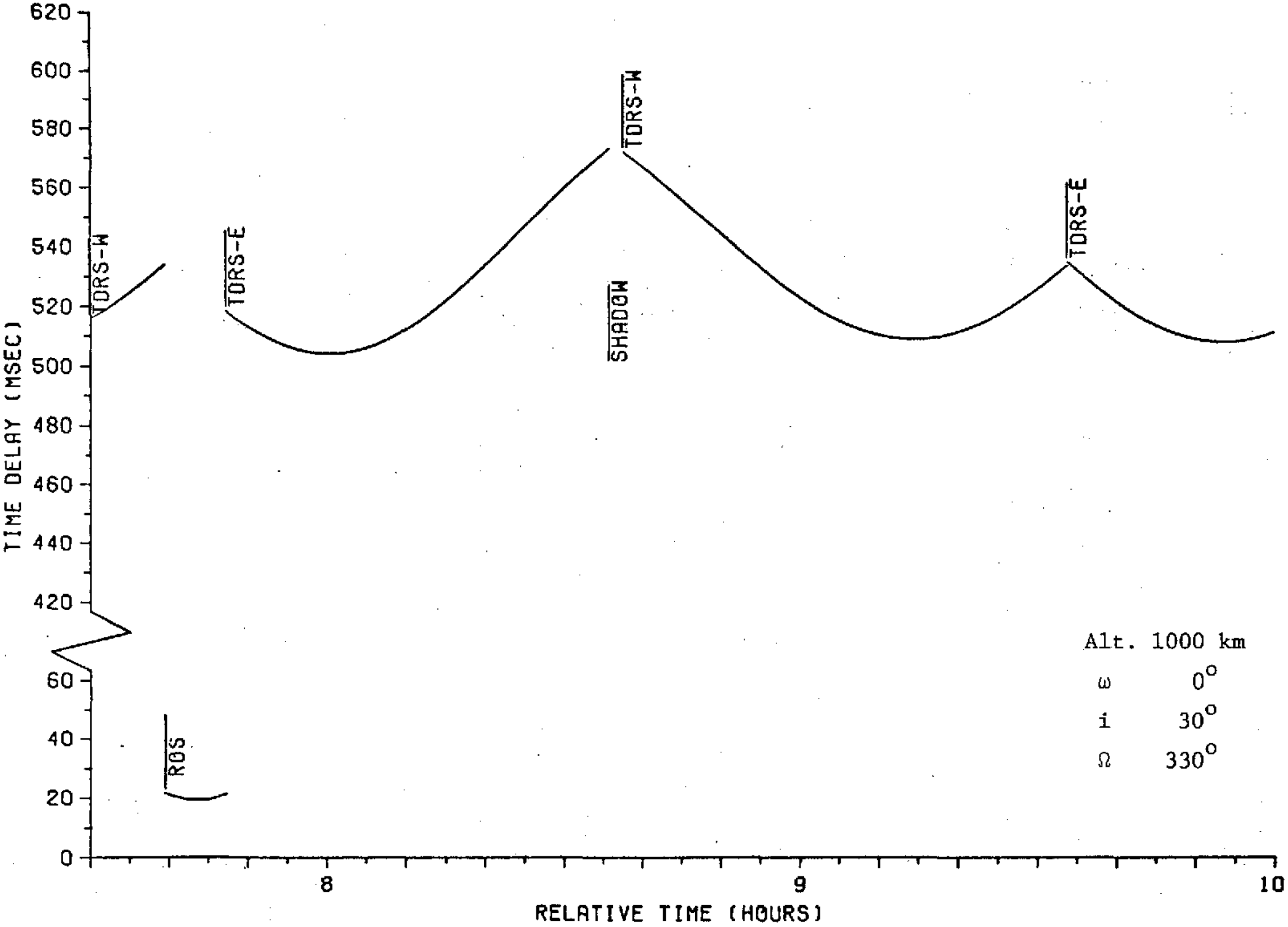


Figure 3-8. (Continued)

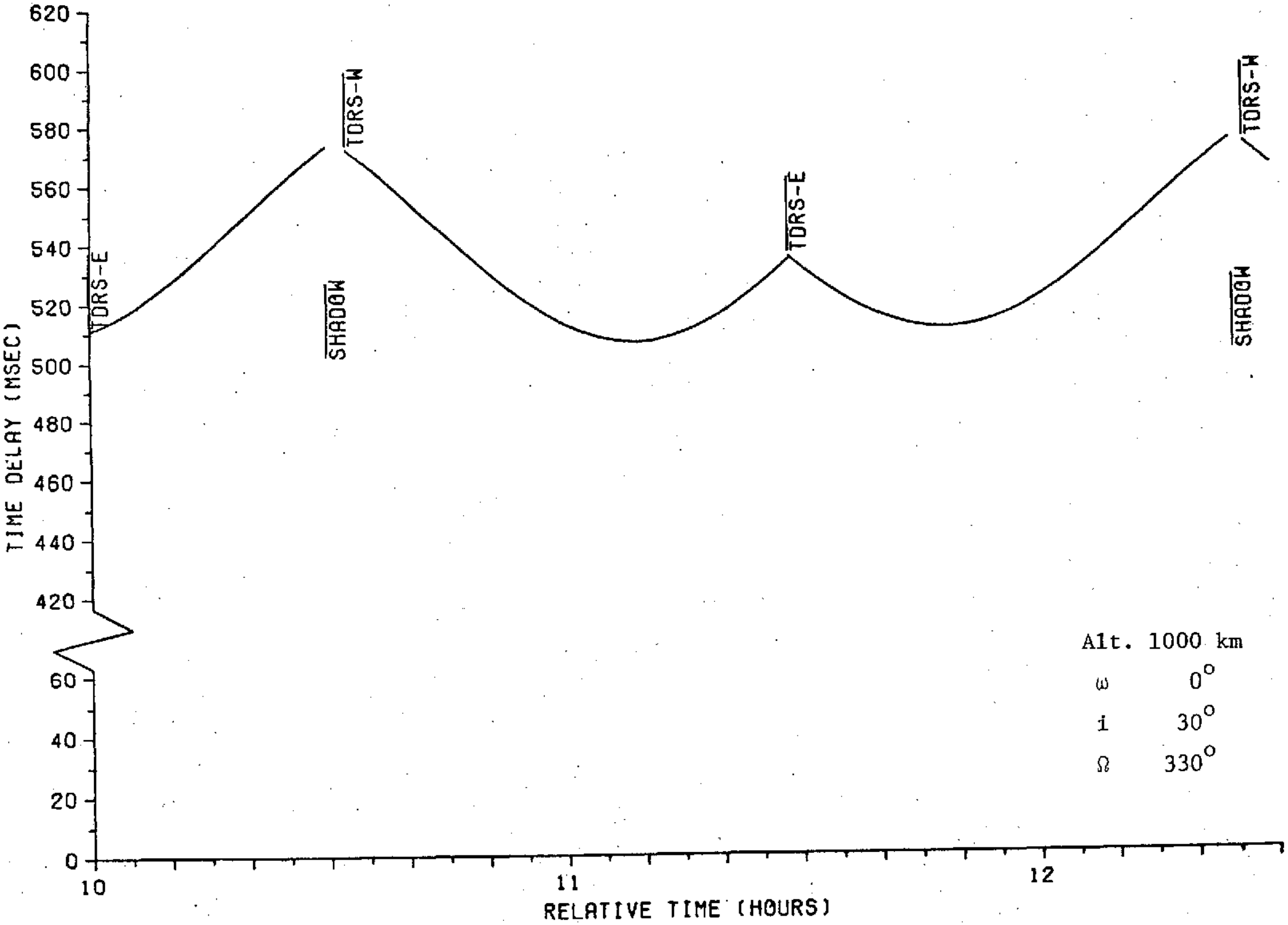


Figure 3-8. (Concluded)

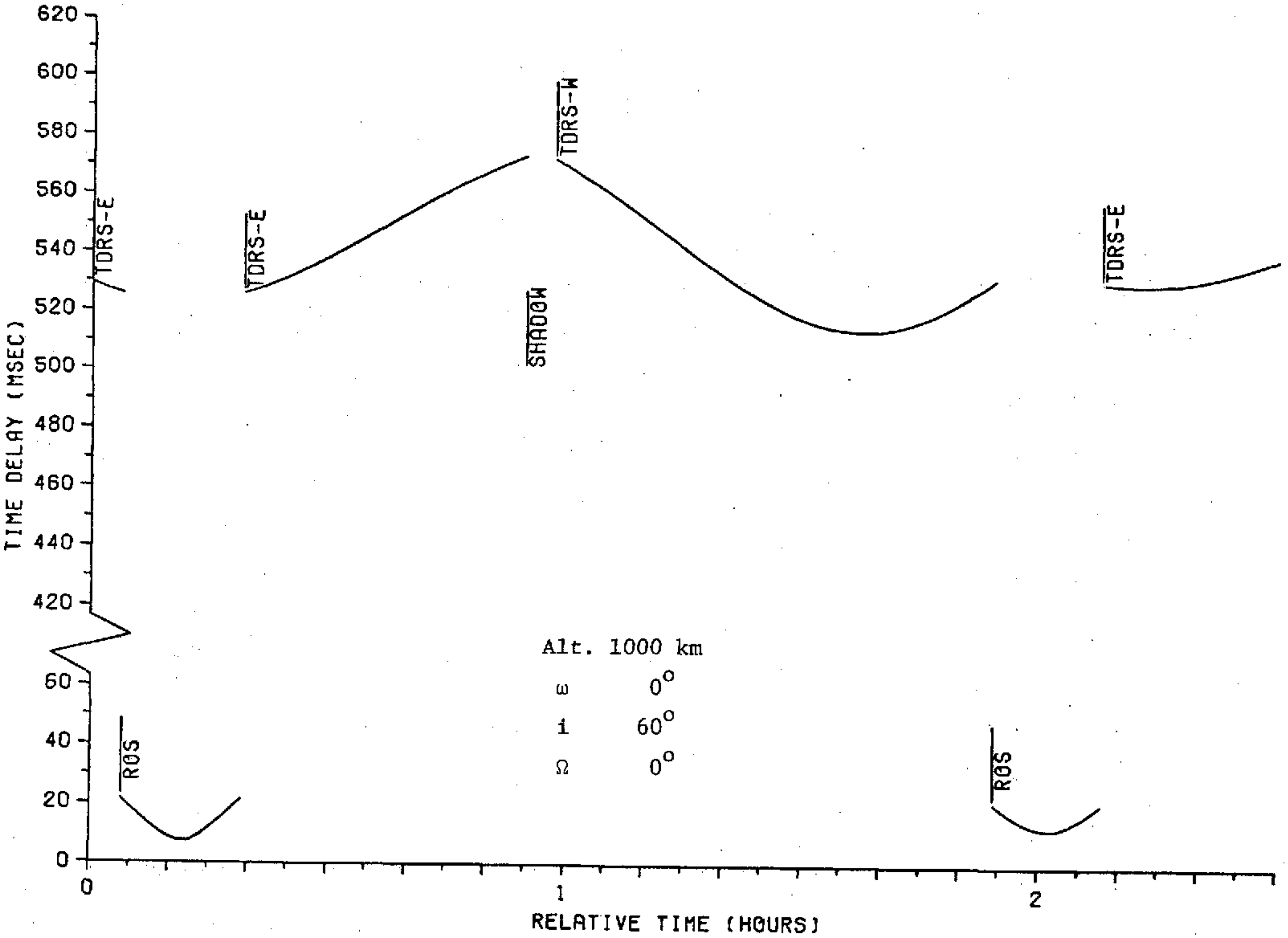


Figure 3-9. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 1000 km, Inclination 60°.

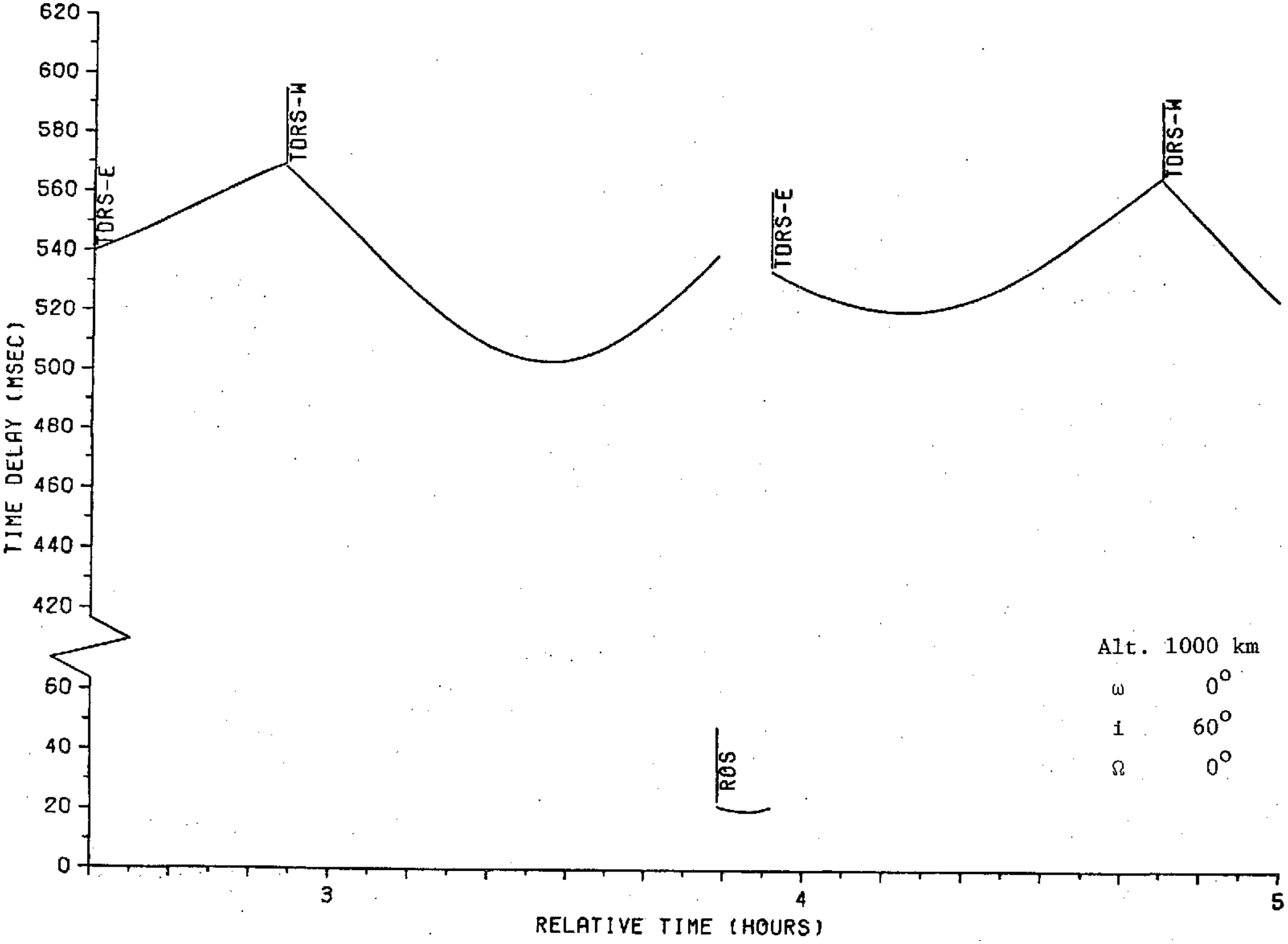


Figure 3-9. (Continued)

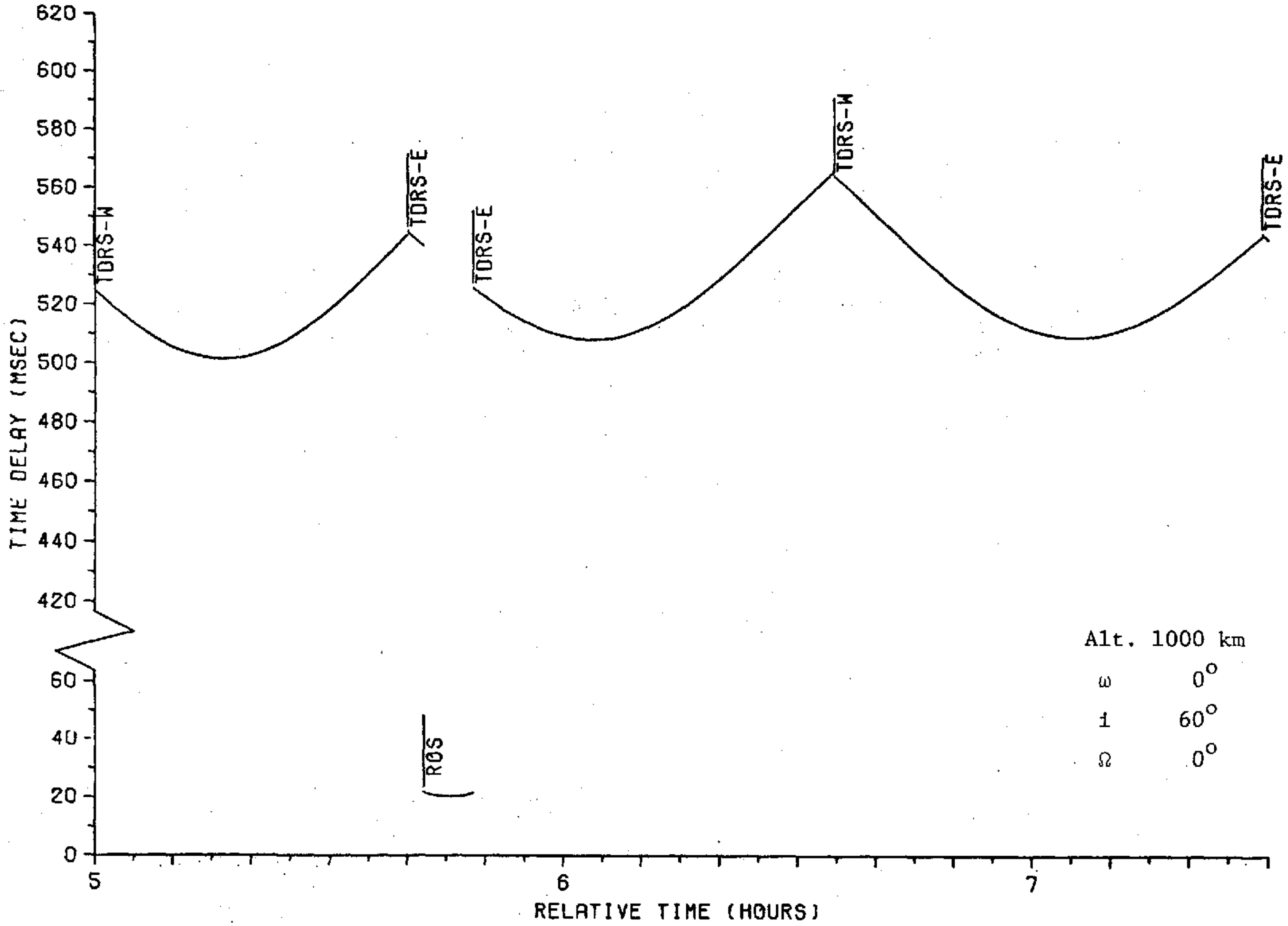


Figure 3-9. (Continued)

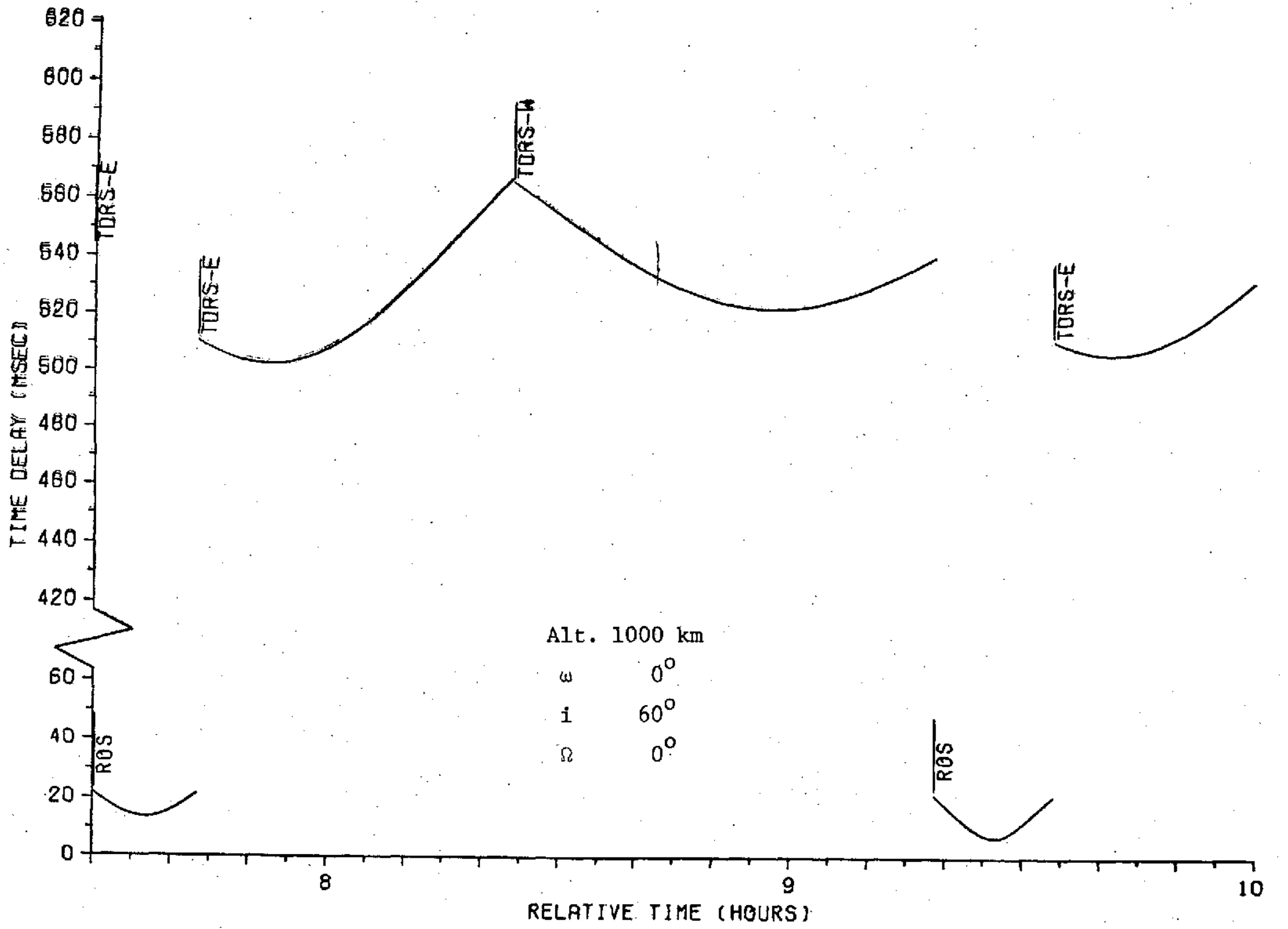


Figure 3-9. (Continued)

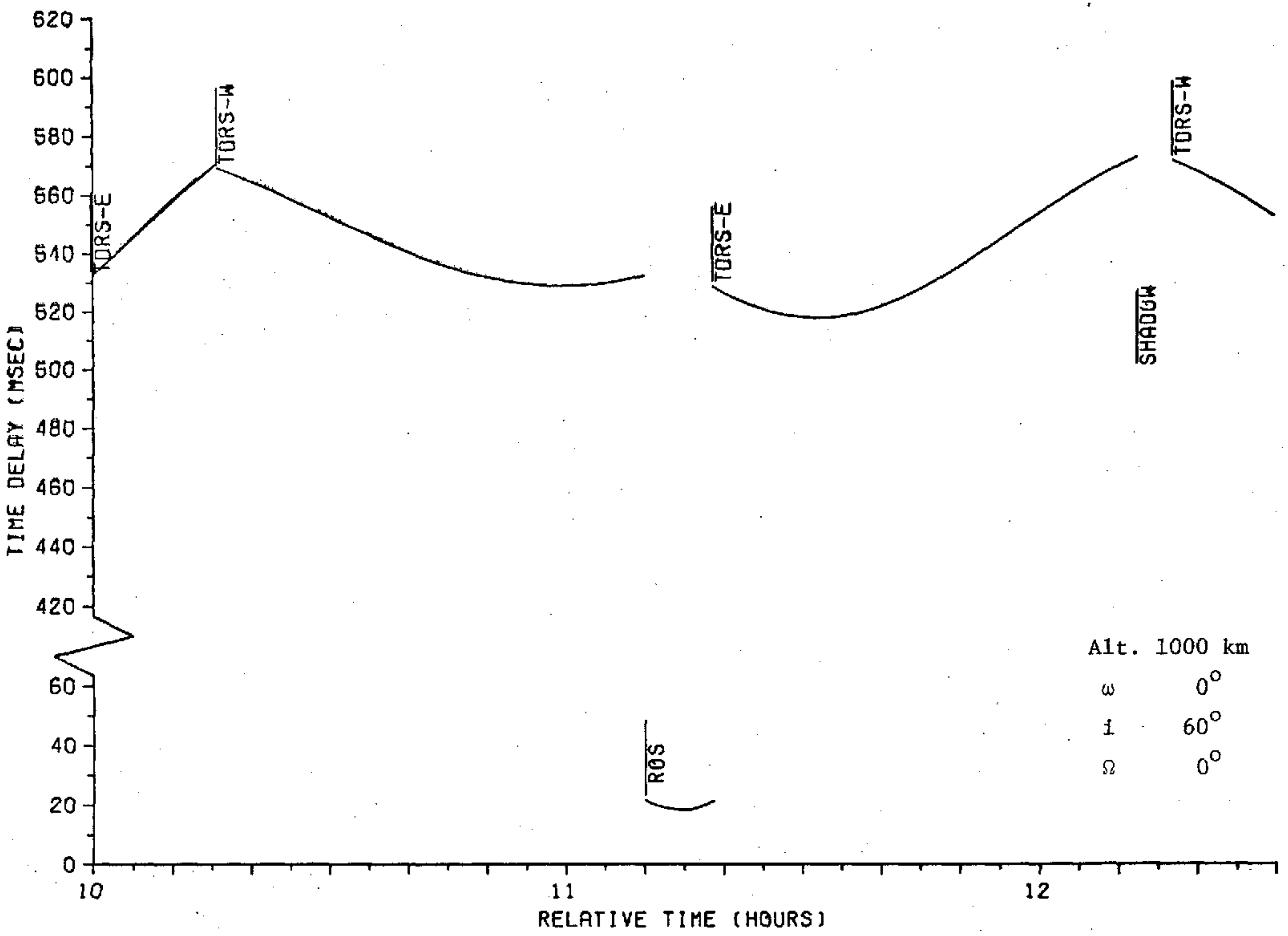


Figure 3-9. (Concluded)

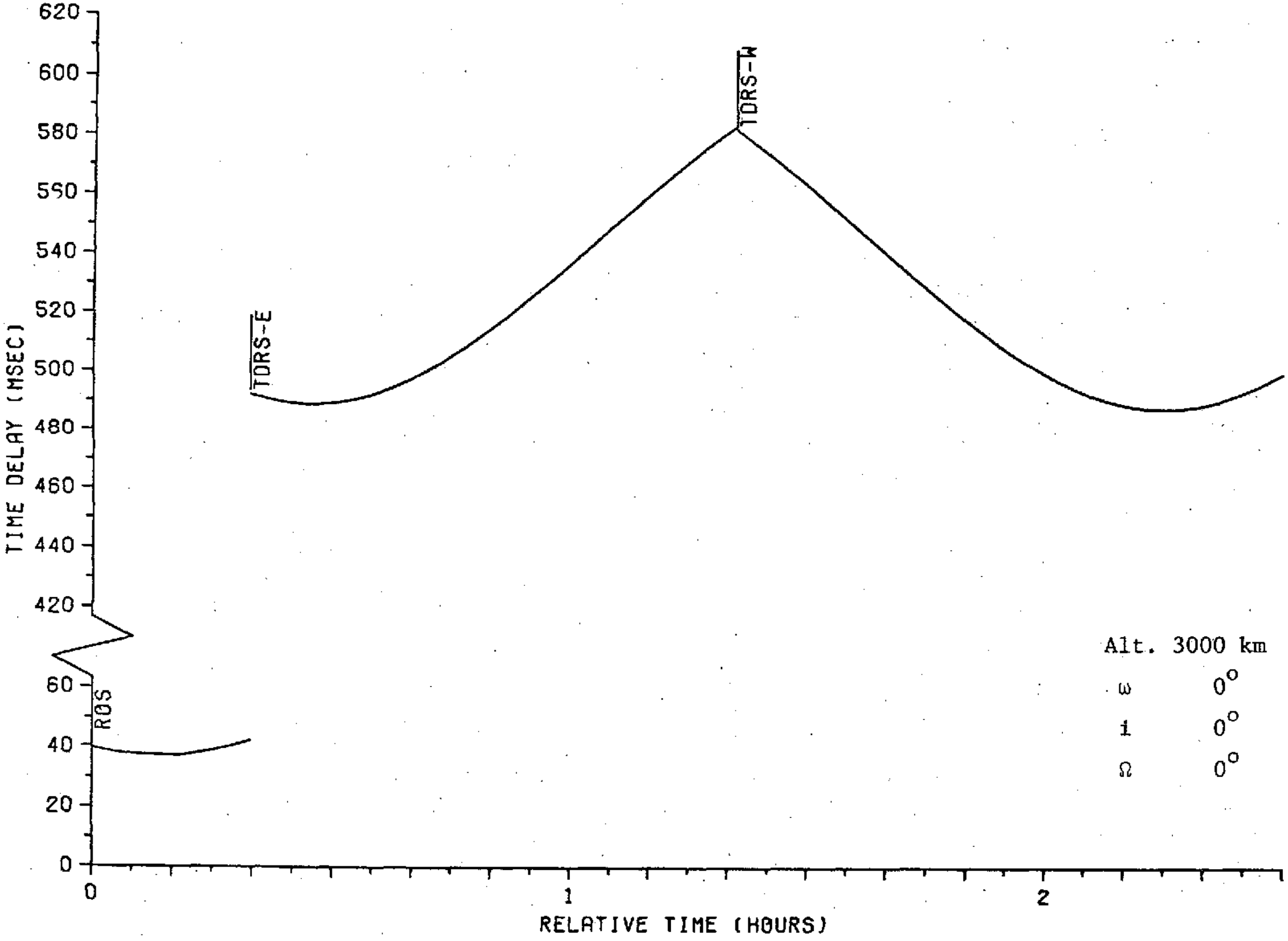


Figure 3-10. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 3000 km, Inclination 0°.

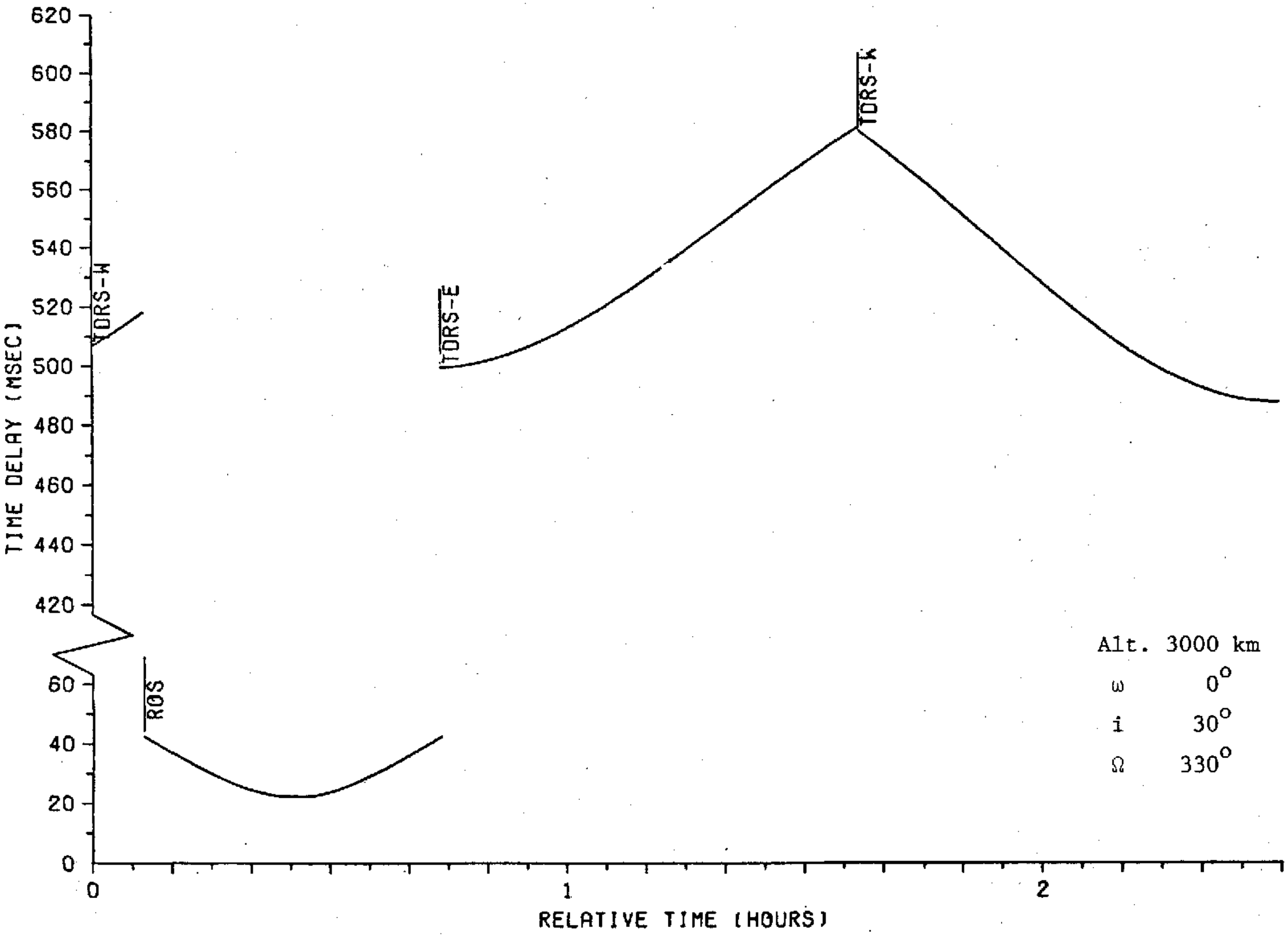


Figure 3-11. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 3000 km, Inclination 30°.

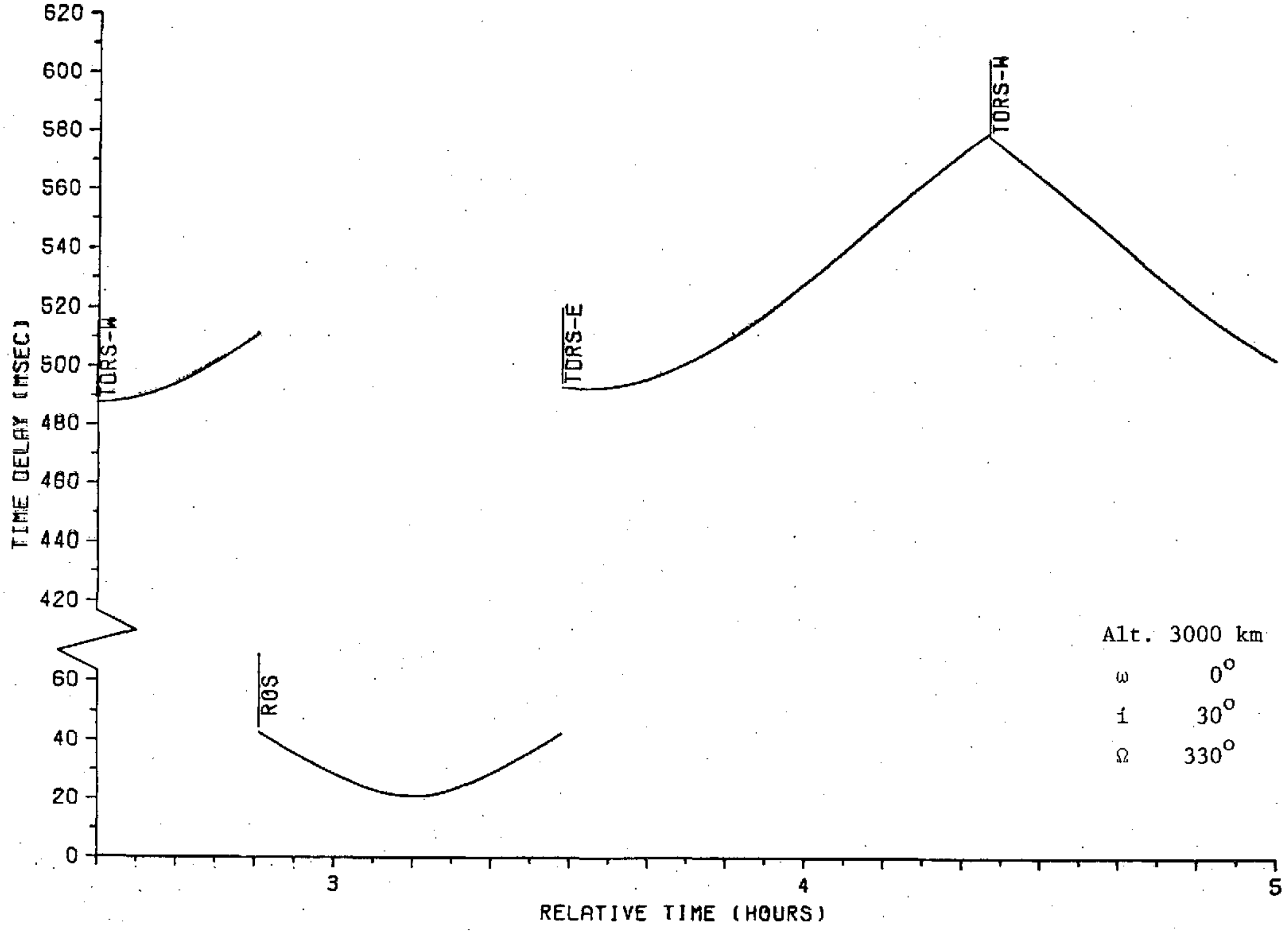


Figure 3-11. (Continued)

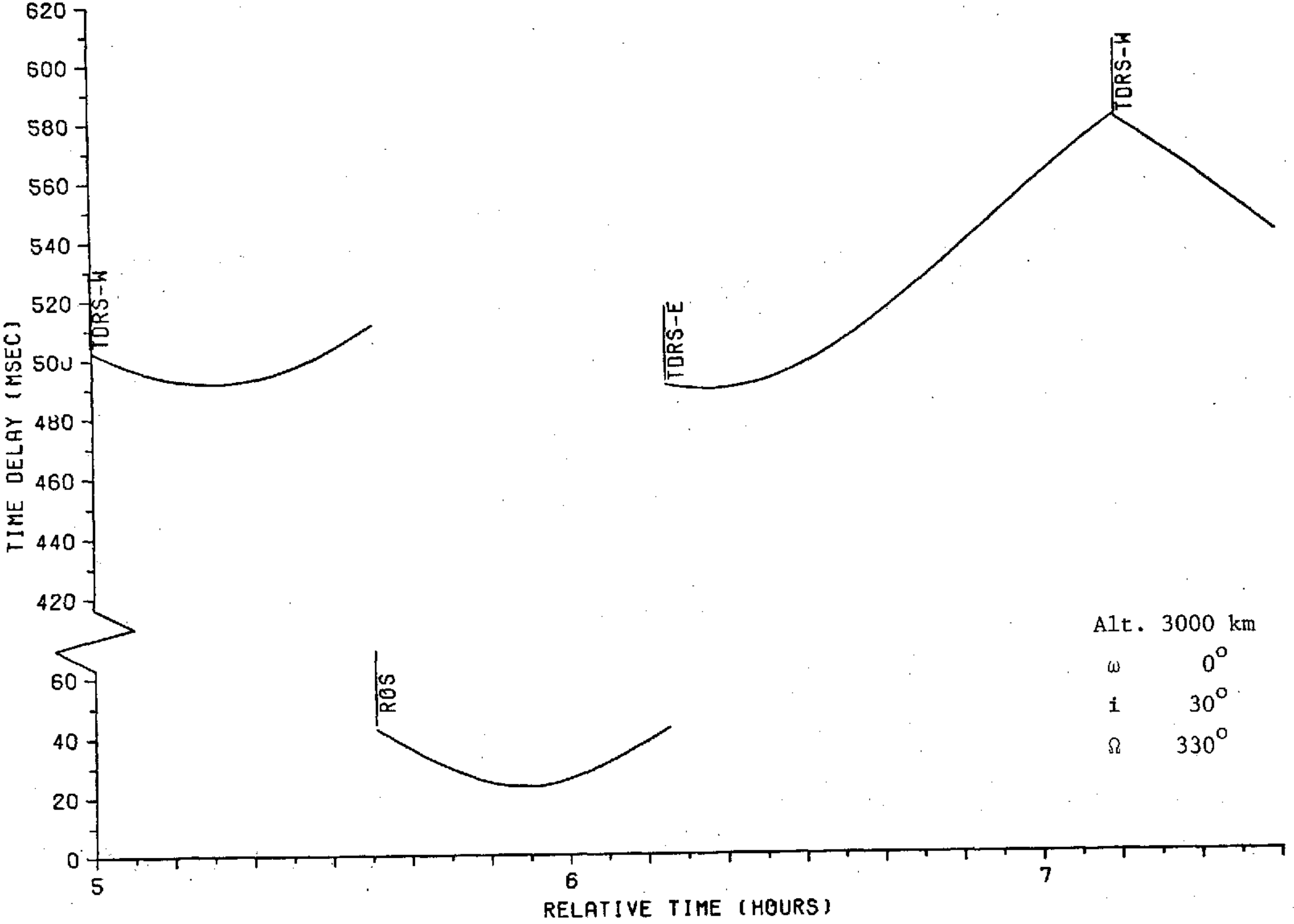


Figure 3-11. (Continued)

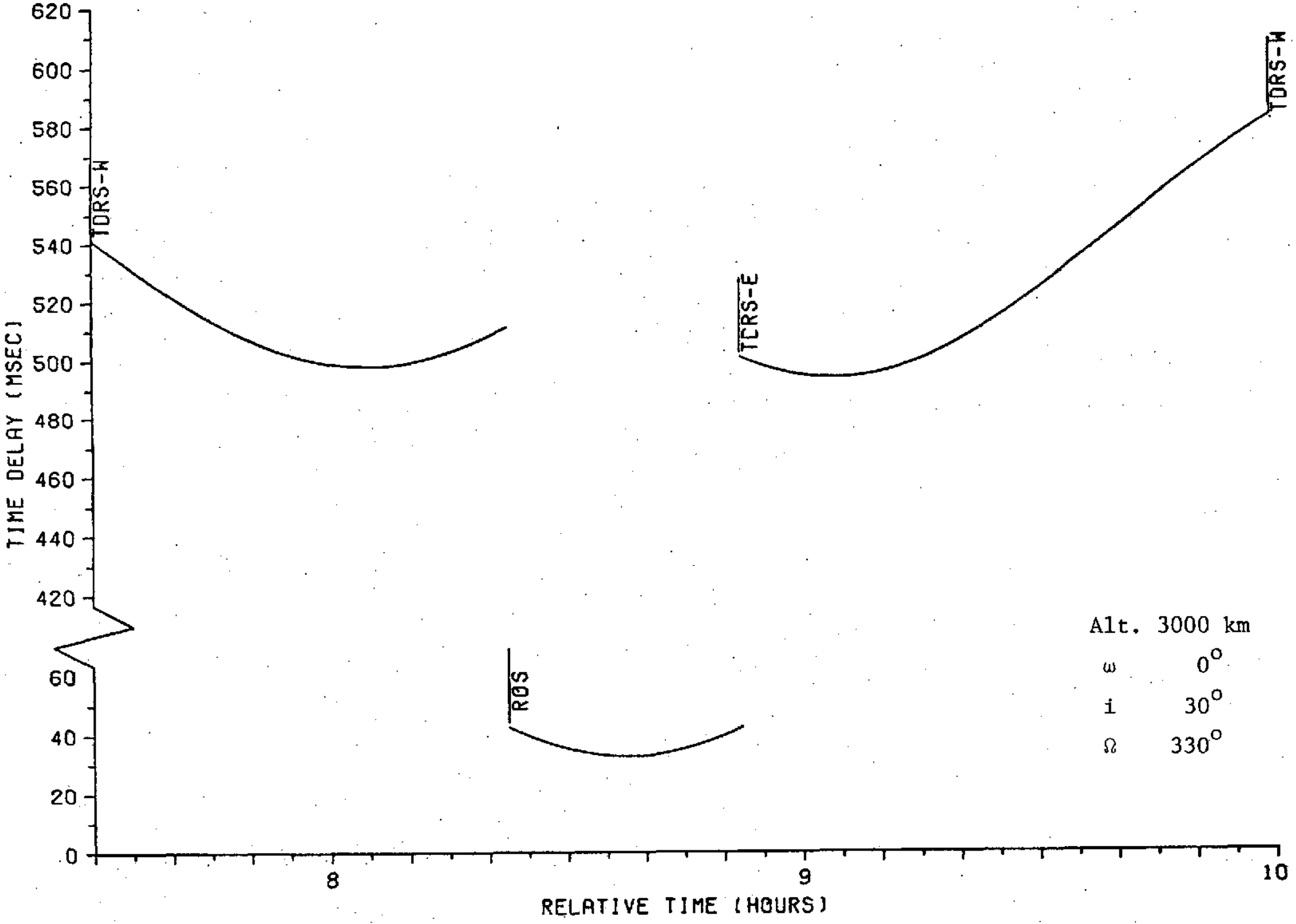


Figure 3-11. (Continued)

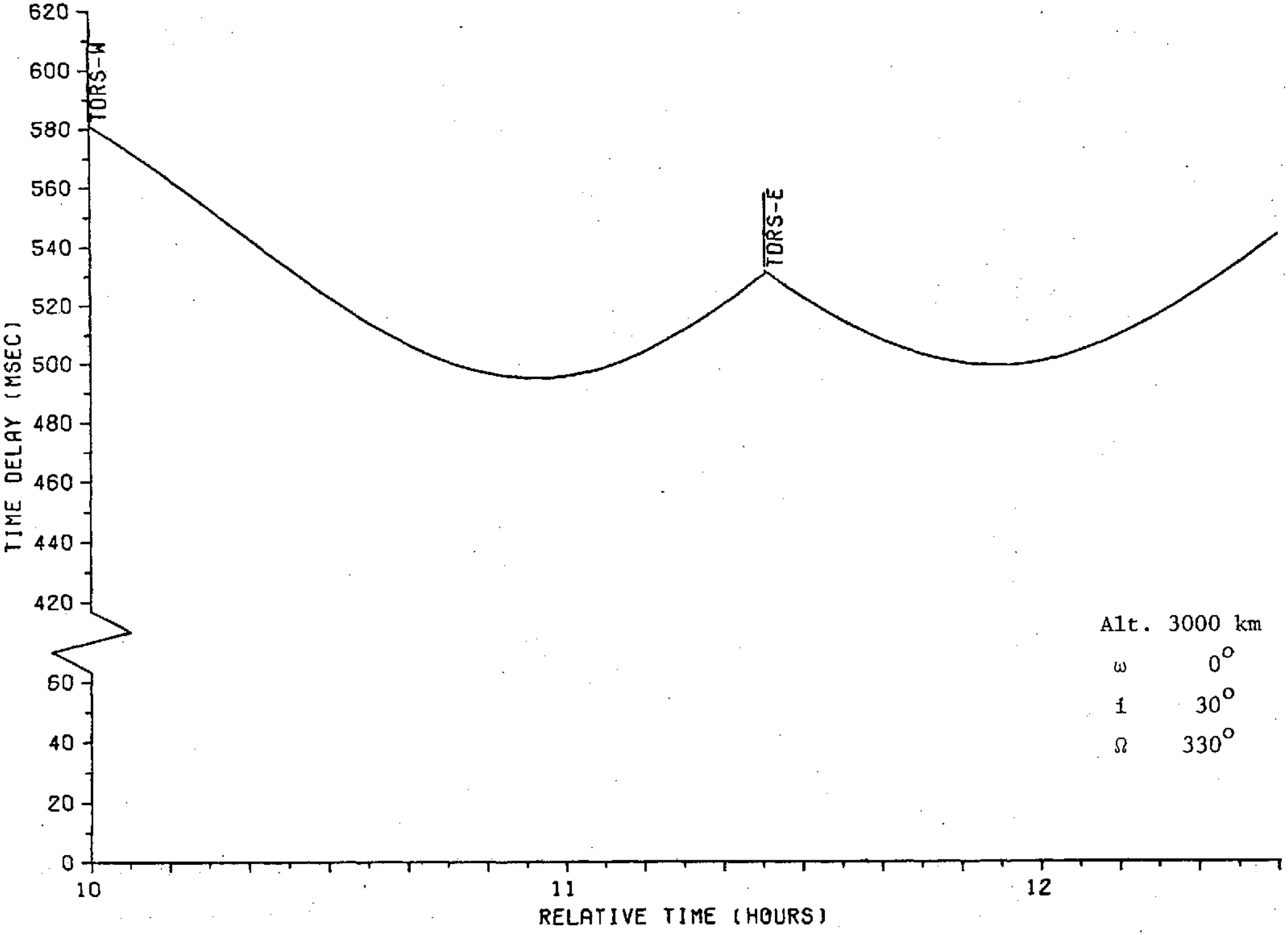


Figure 3-11. (Concluded)

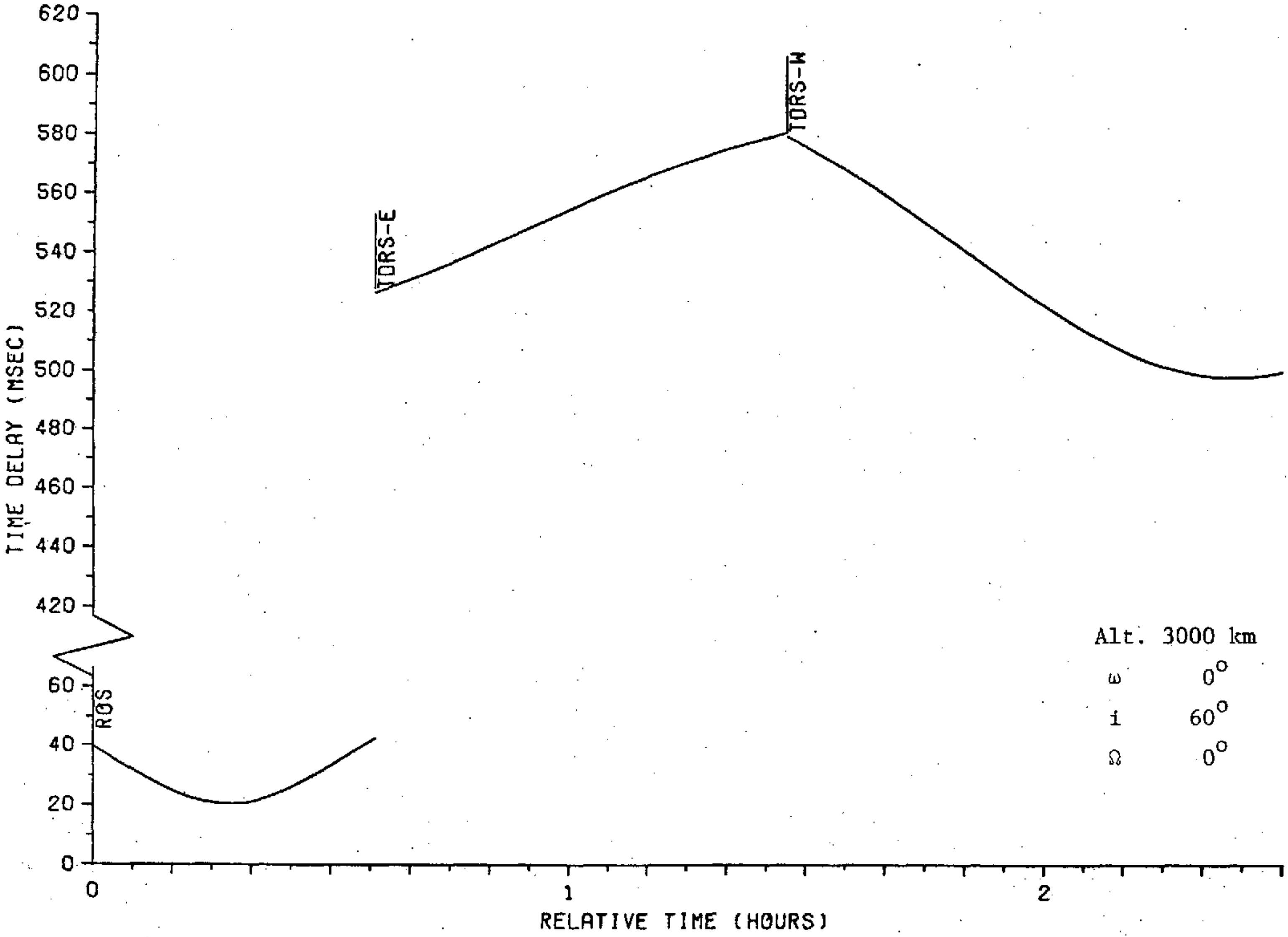


Figure 3-12. Time Delay Profile for Ground Control to Teleoperator in Low Earth Orbit, Altitude 3000 km, Inclination 60°.

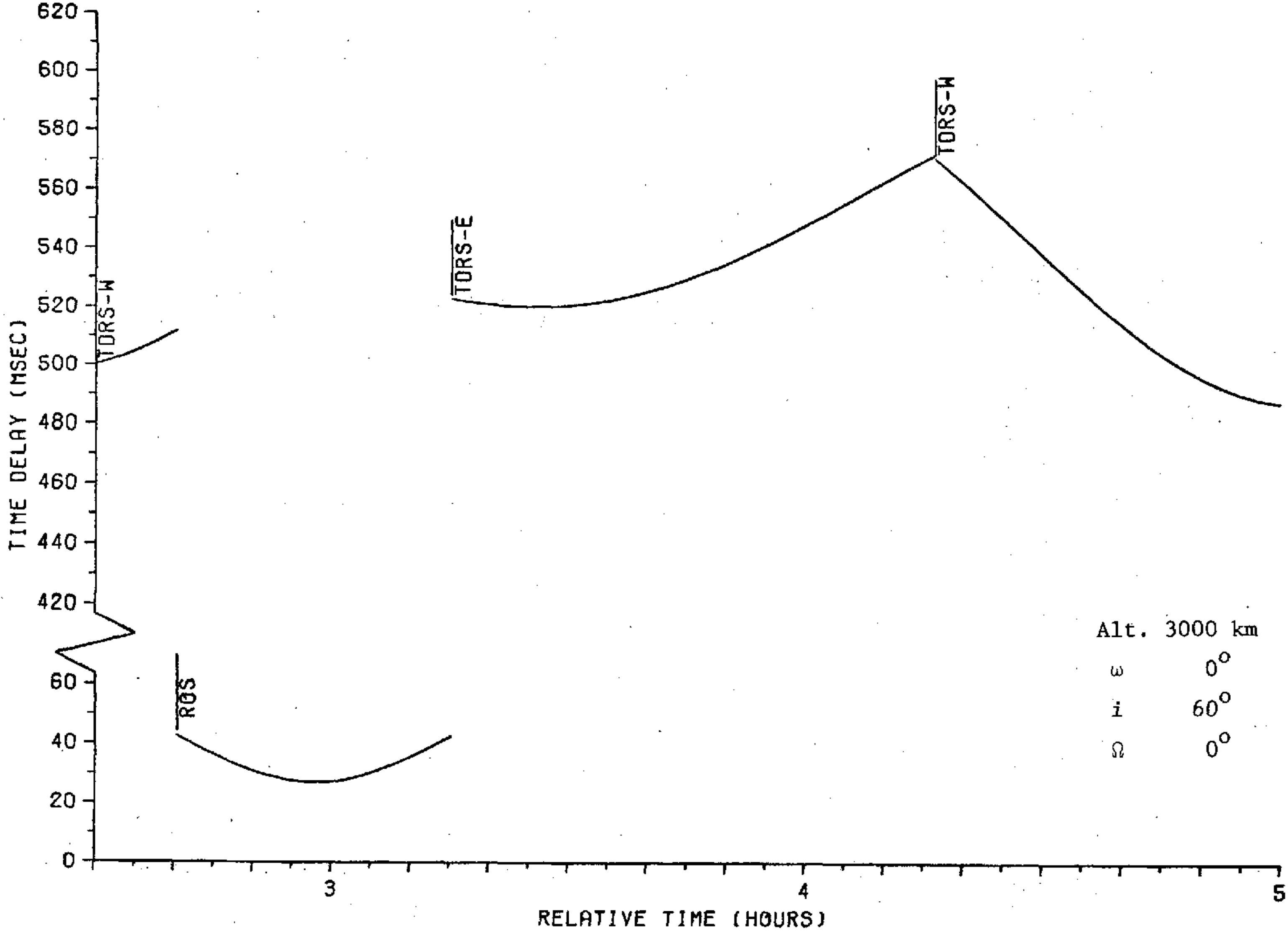


Figure 3-12. (Continued)

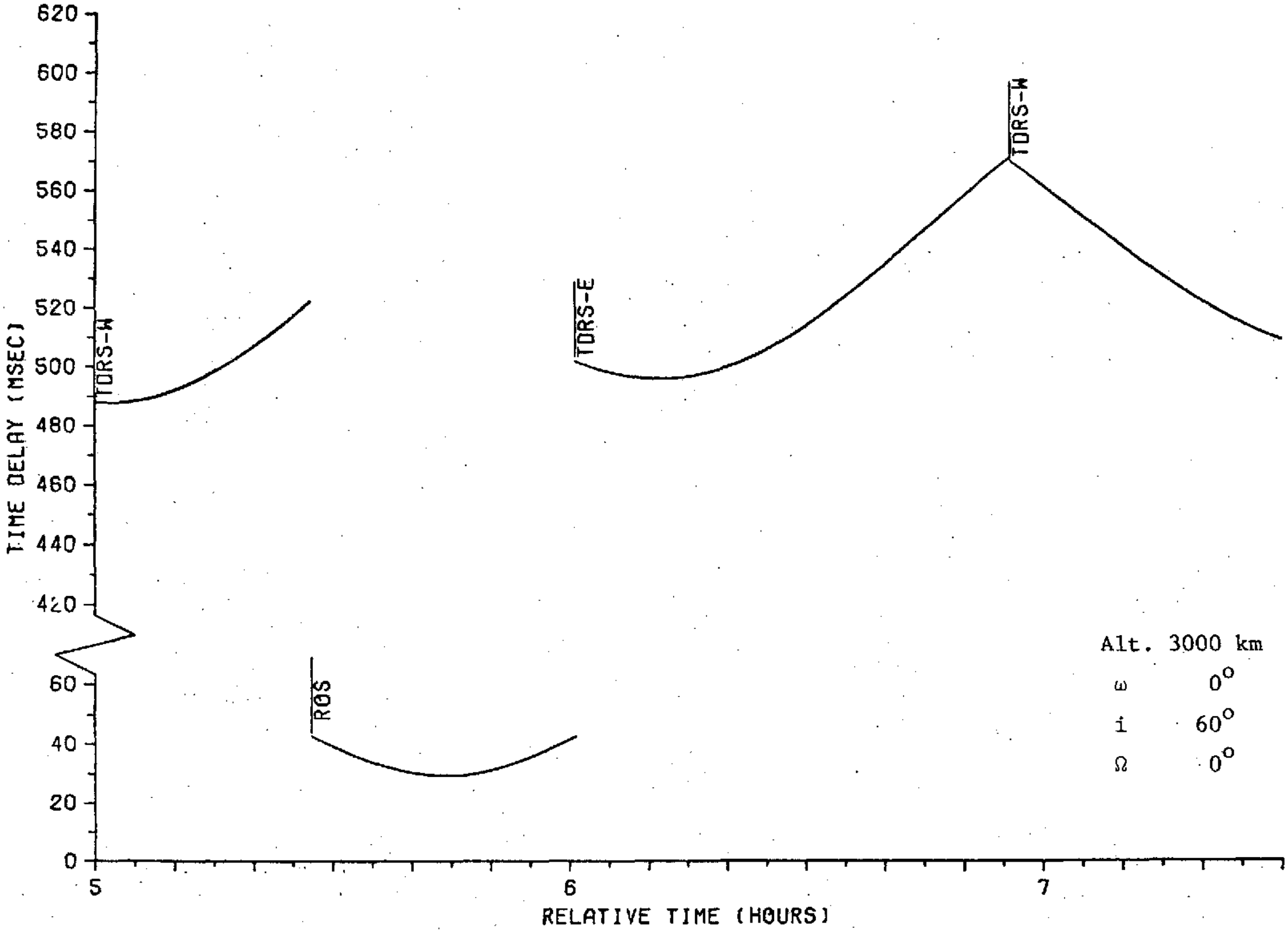


Figure 3-12. (Continued)

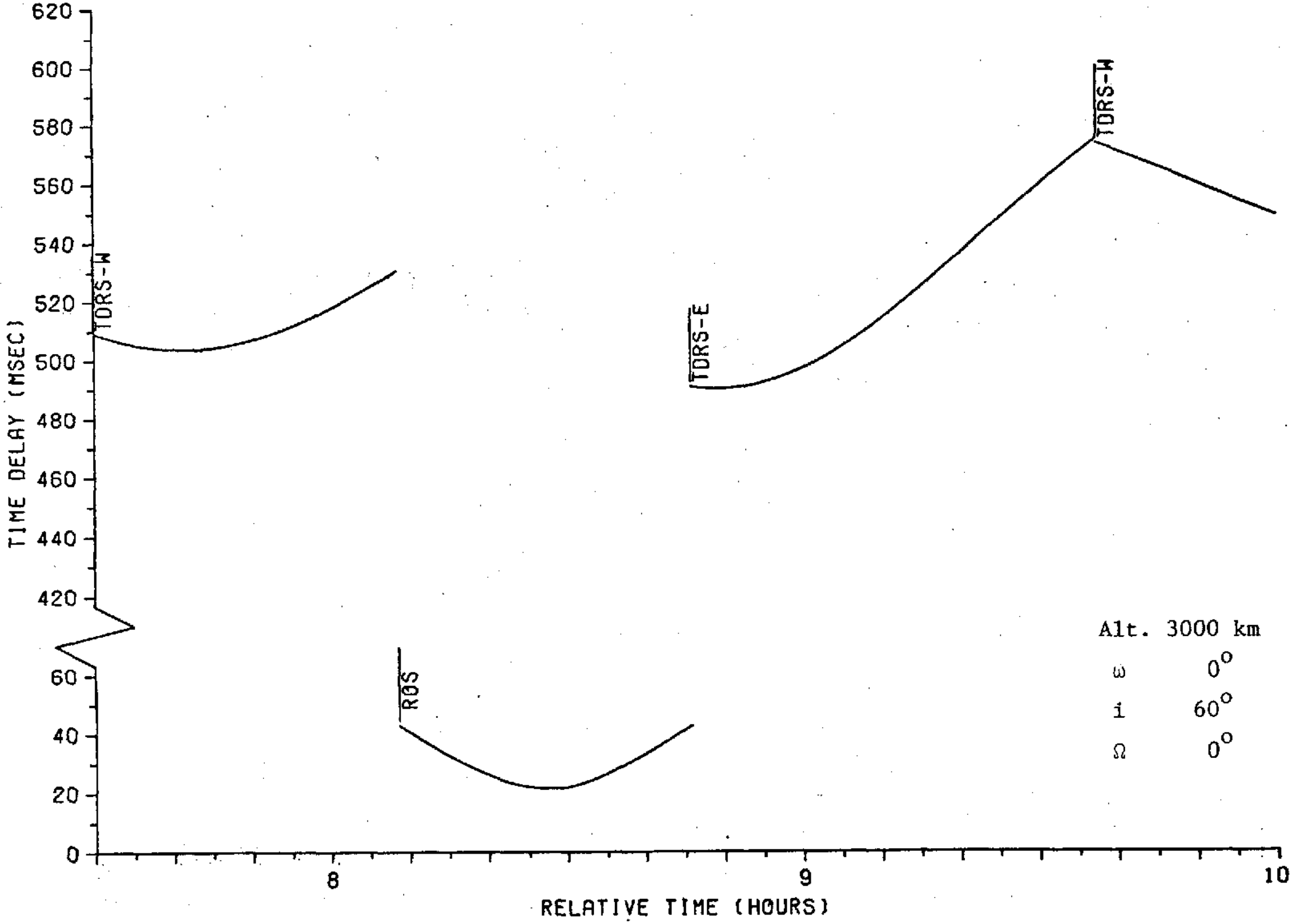


Figure 3-12. (Continued)

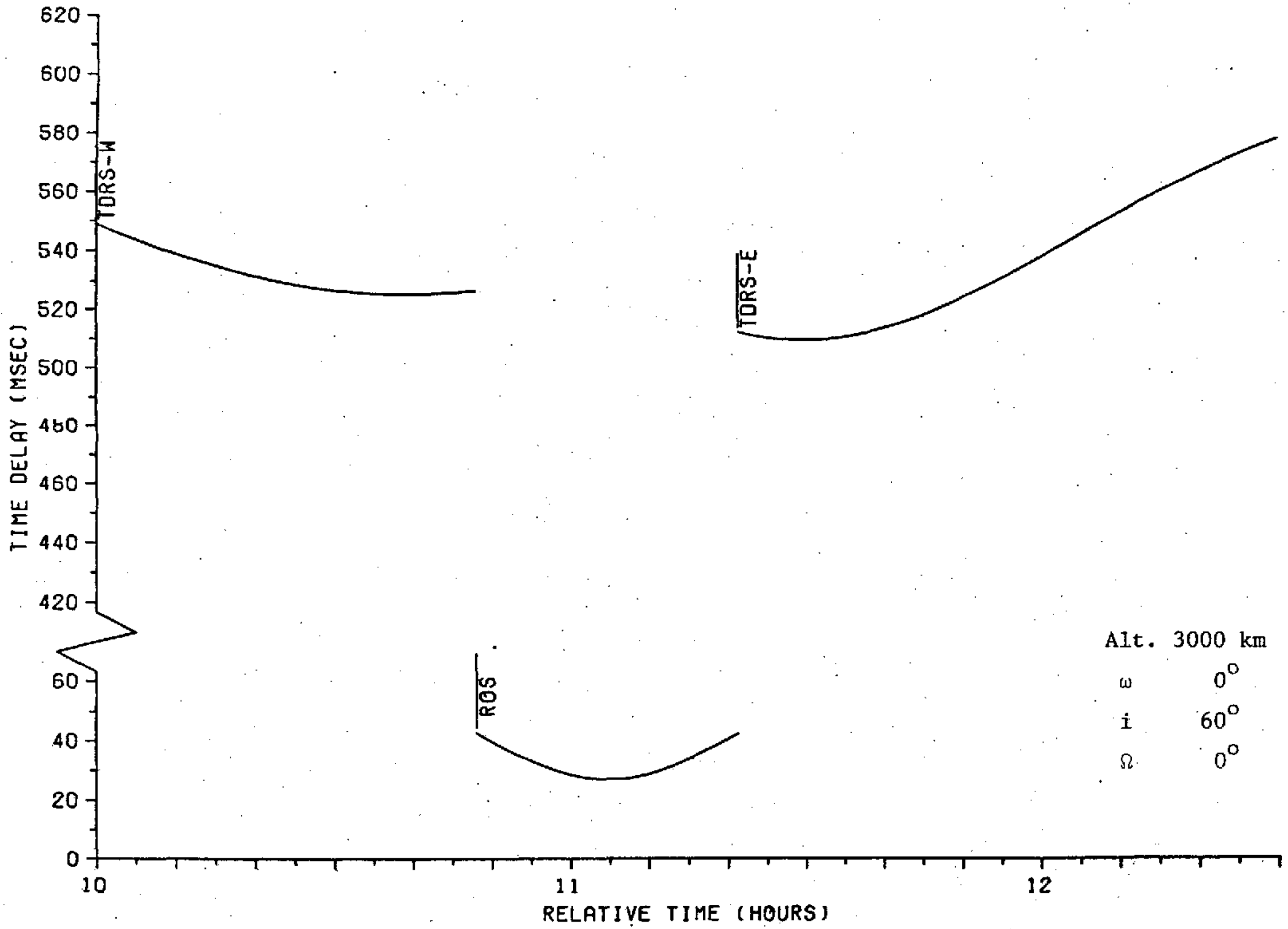


Figure 3-12. (Concluded)

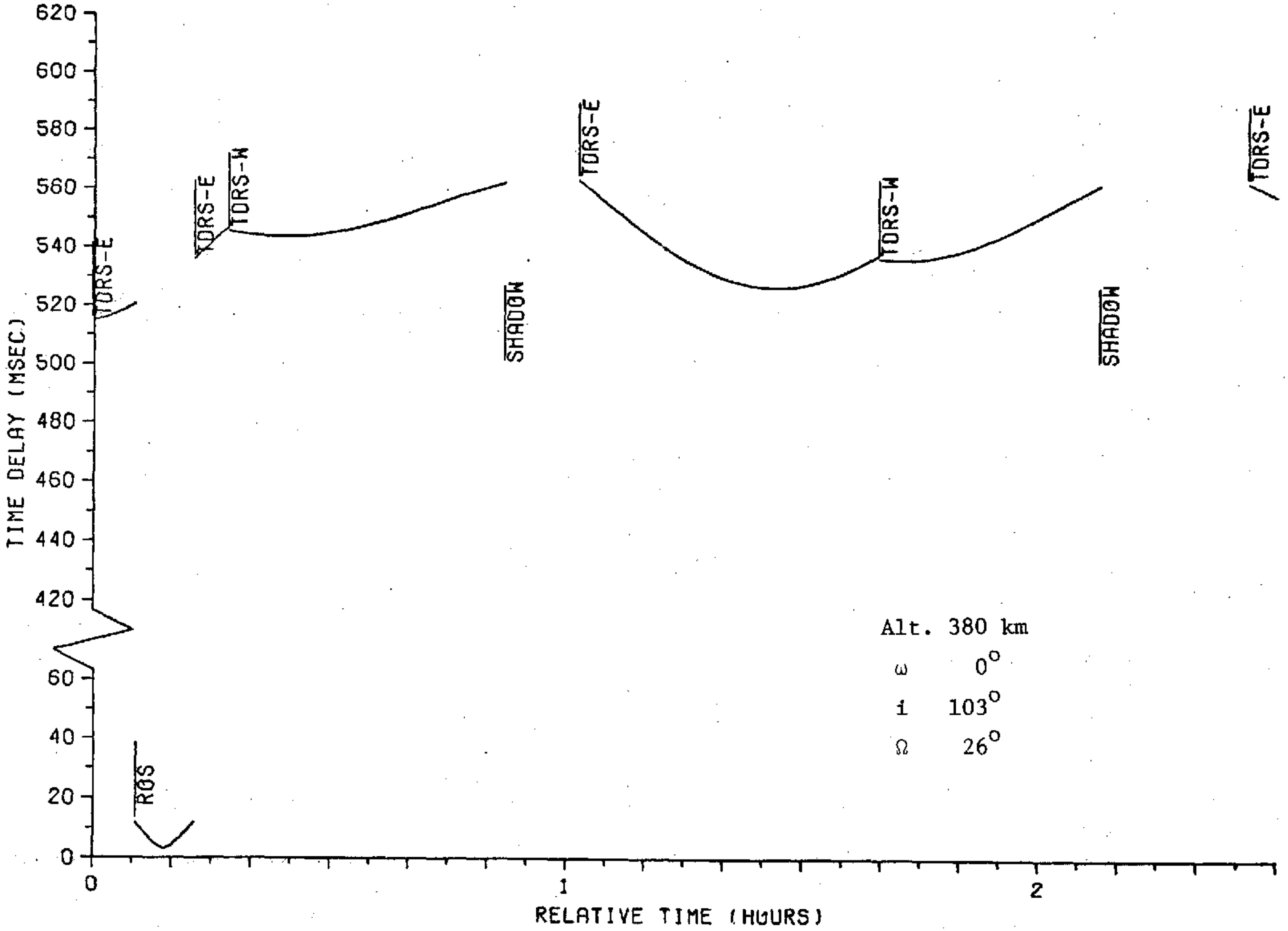


Figure 3-13. Time Delay Profile for Ground Control to Teleoperator in Low Earth Circular Orbit, Altitude 380 km, Inclination 103°.

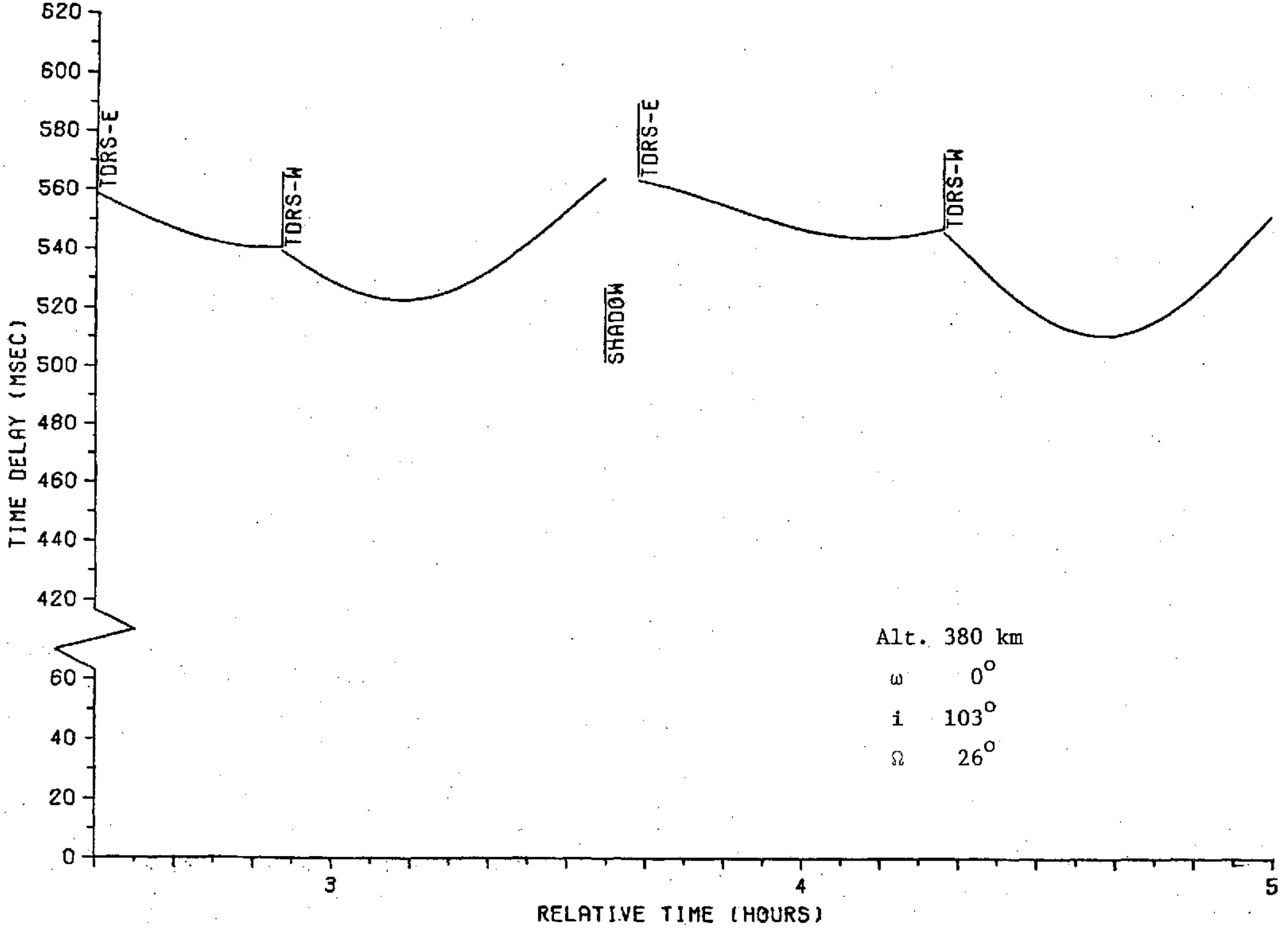


Figure 3-13. (Continued)

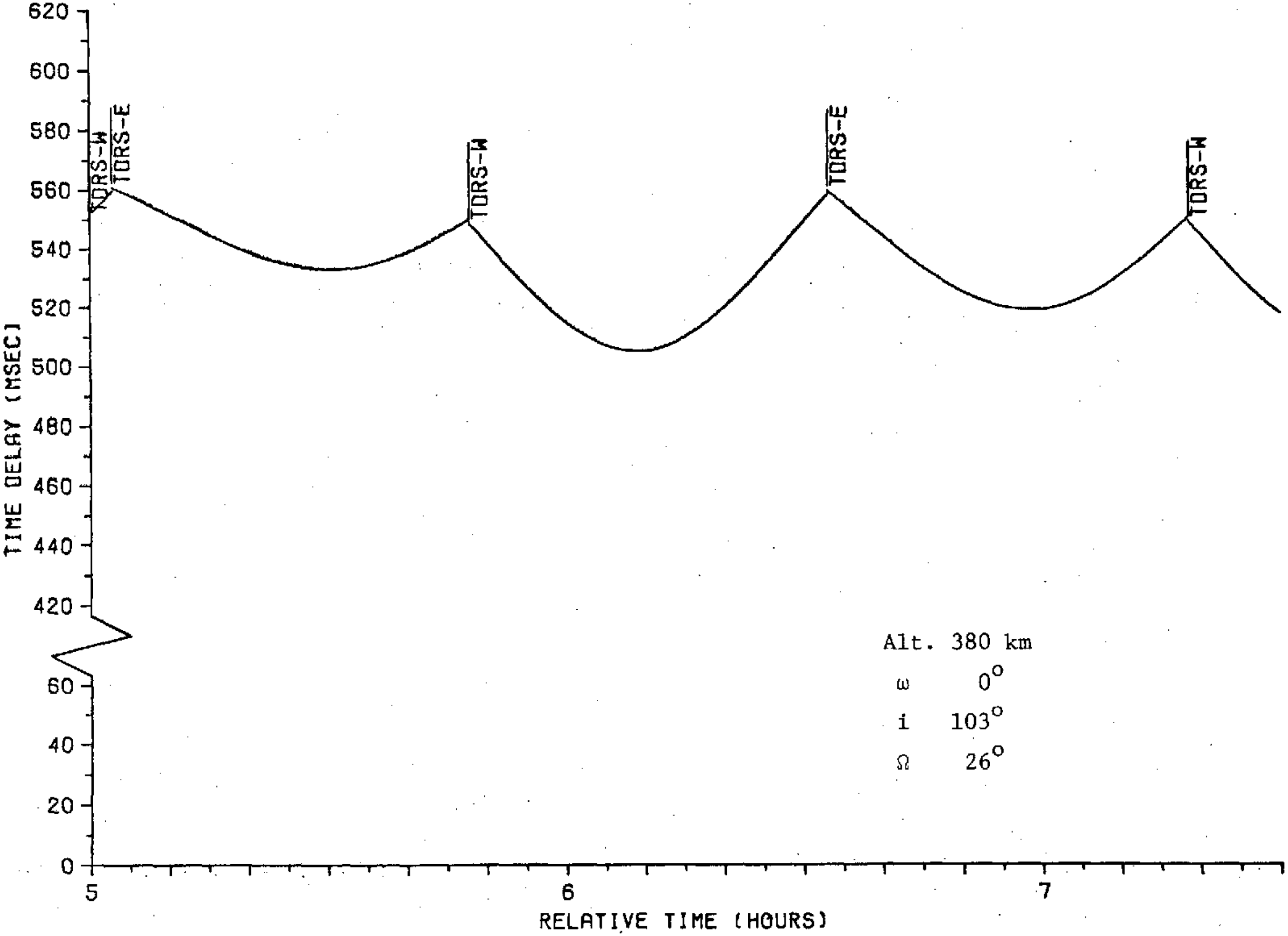


Figure 3-13. (Continued)

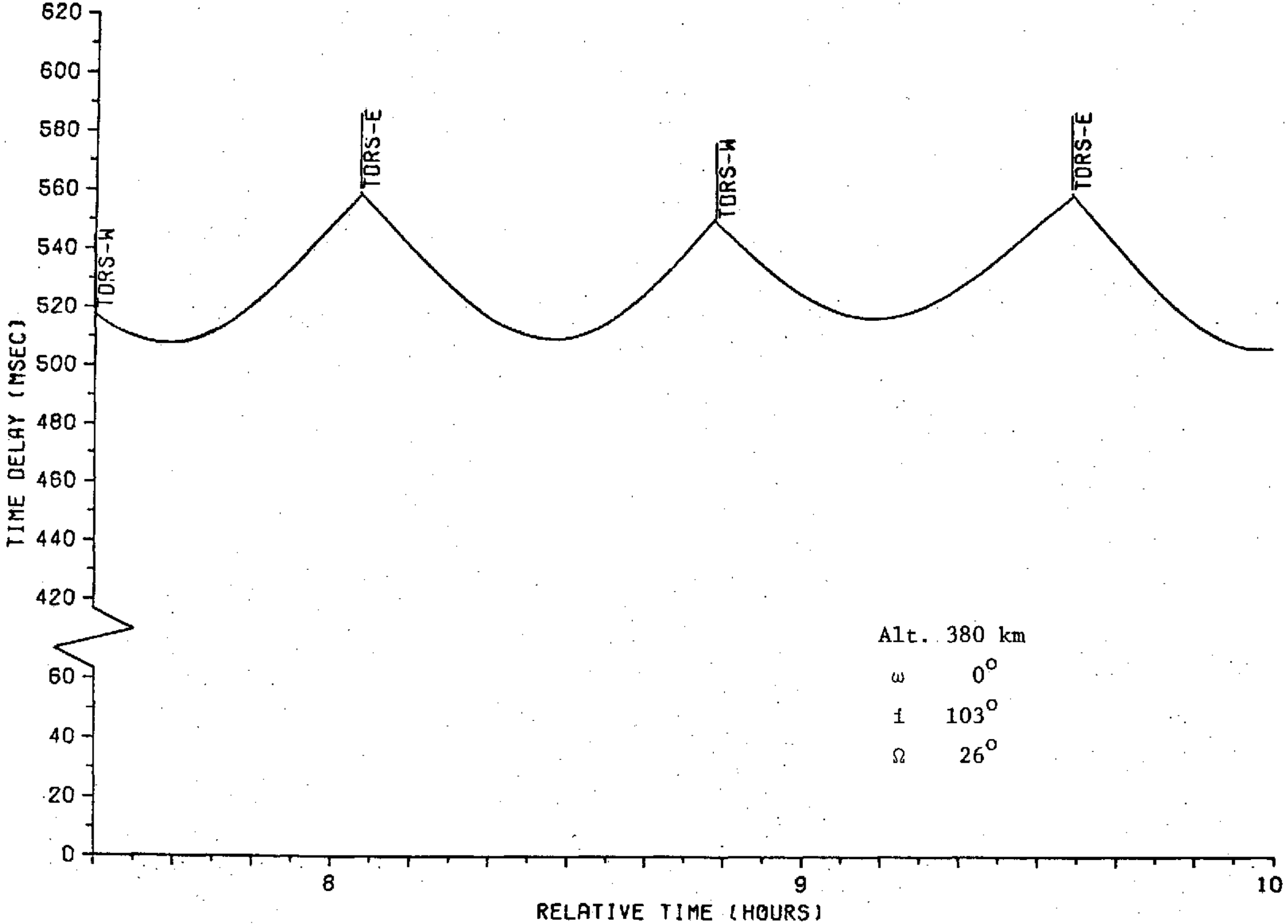


Figure 3-13. (Concluded)

4. GROUND TO TELEOPERATOR IN GEOSYNCHRONOUS ORBIT

The propagation time from a ground control station to a teleoperator in a geosynchronous orbit is essentially fixed. Small variations do exist which are caused by the complicated movement of a geosynchronous satellite with respect to the earth. Movement of the satellite can be caused by inclination of the orbital plane, which produces a north and south oscillation of the satellite, or by eccentricity of the orbit which produces radial movement of the satellite. These motions can produce a diurnal variation of several milliseconds in transmission time, the amount depending on the orbit inclination angle and eccentricity.

Another cause of variation in transmission delay through a "synchronous" satellite is a general east or west drift of the satellite. This drift results in a slow change of the satellite's longitudinal position with time. For commercial communication satellites variations in delay due to drift would probably not exceed several milliseconds before the satellite is repositioned.

Variations due to the satellite motion should represent only a small portion of the total delay encountered in transmission to and from a geosynchronous satellite.

The one way propagation time to or from a geosynchronous satellite is shown in Figure 4-1 as a function of elevation angle from the ground station to the satellite. The total time required for transmission of a command and receipt of a response would be twice the values shown in the figure. The propagation times to and from the satellite are minimum when it is directly overhead and amount to approximately 240 msec. The maximum time would occur at the minimum usable elevation angle; assuming this angle to be 5 degrees, the maximum delay time is approximately 276 msec.

Values of processing delay and transmission delay required to get the signals to and from the satellite ground terminal must be added to the above propagation delay figures. For example, land line and cable transmission to and from GSFC to Carnarvon would add a total of 246 msec to the above delay figures, while a satellite link between the same two points would add 608 msec (two way) [1].

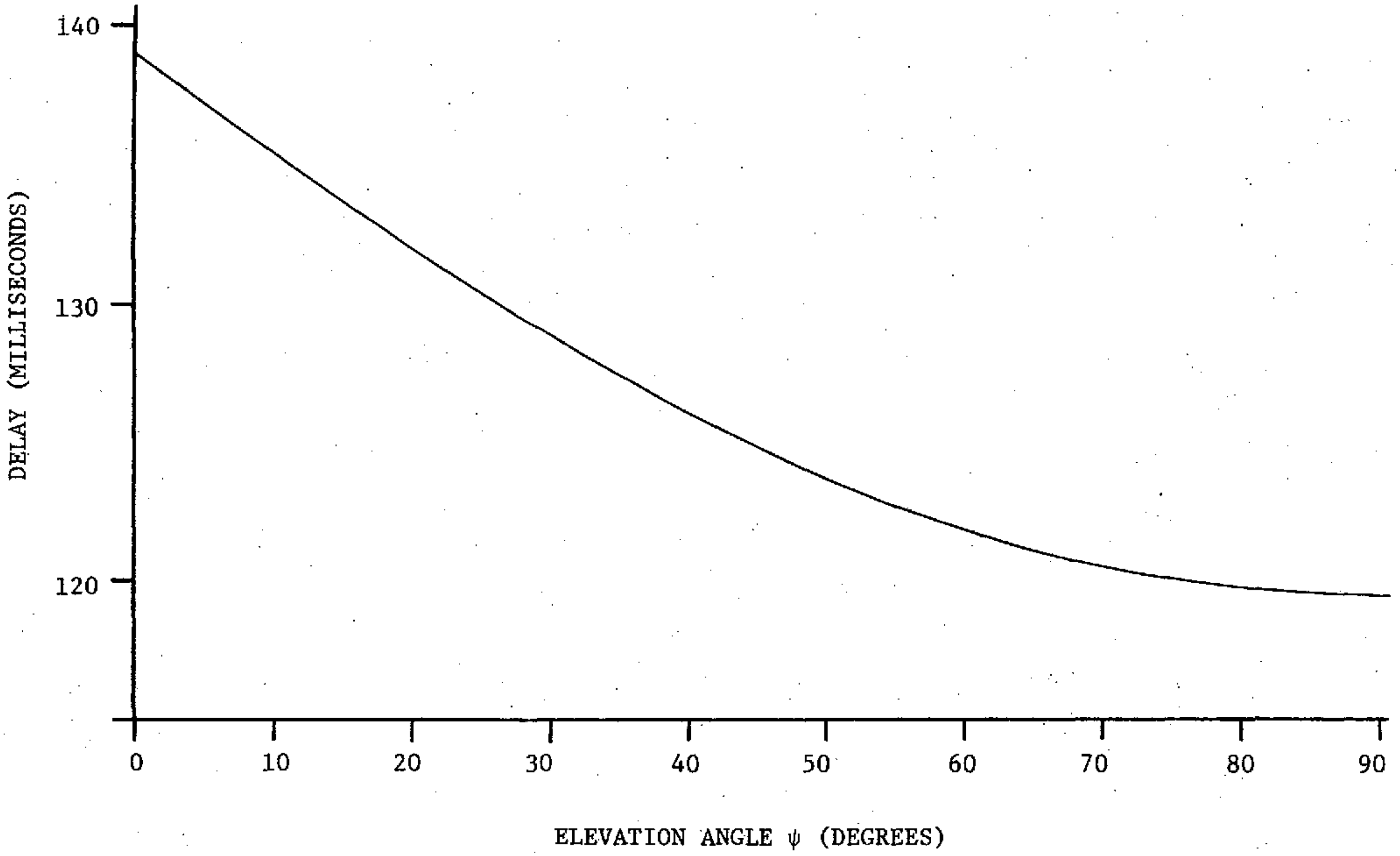


Figure 4-1. Propagation Delay For One-Way Transmission Between An Earth Station And a Geosynchronous Satellite (Altitude 35800 km) As a Function of the Elevation Angle of the Line-of-Site at an Earth Station.

5. LOW EARTH ORBIT TO LOW EARTH ORBIT DELAYS

5.1 Approach

Time delay profiles were also generated for the case where teleoperator is in low earth orbit and the control console is aboard another satellite in low earth orbit. Modifications were made to the computer program developed for computing ground to low earth orbit profiles in order to adapt it to generating these profiles and producing graphs of the results. These modifications include (1) providing for another orbiting vehicle and introducing calculations for low earth orbit to low earth orbit delays, (2) dropping ROS and the direct ground station to low earth orbit link, and (3) rescaling the graph to accommodate the longer time delays associated with these profiles.

5.2 Program Description

The two satellite programs operate in a very similar manner to that of the ground to low earth orbit program. Satellite positions, separation distances, and time delays are calculated at one minute intervals. When a handover occurs, the time period is divided down to locate the time of handover to the nearest second.

Handover logic for the two satellite programs is as follows:

(1) Highest priority communication is control to teleoperator direct; this mode is used at all times when an unobstructed line of sight between control and teleoperator exists.

(2) When direct communication is lost, each low earth orbit vehicle relays through the nearest TDRS satellite. It is assumed that this communication method requires transmitting the signal from the TDRS satellite to the TDRS ground station (TDRSG) for turn-around and relay to the other vehicle, though both low orbit vehicles may be relaying through the same TDRS satellite.

(3) When in relay mode, handovers for each low earth orbit vehicle are made independently of the other. Handovers from TDRSE to TDRSW (or vice versa) occur on crossing the central meridian between the two TDRS satellites. Entry into or departure from the shadow region centered around 74° E. longitude is also sensed.

In addition to altering the scaling on the output graphs, a change was made in the link/mode identification word printed at the beginning of each delay segment so that the status of both low orbit satellites could be encoded. The two low earth orbit vehicles are identified by a single letter, C for control and T for teleoperator. When in relay mode each of these identifiers is followed by one of three characters, E denoting relay through TDRSE, W denoting relay through TDRSW, and * denoting that the vehicle is in the shadow region. When line of sight between control and teleoperator exists, the word DIRECT appears on the plotter output.

5.3 Delay Profiles

A summary of the delay profiles generated is given in Table 5-1. Only circular orbits were used. Included are two profiles for altitudes of 300 and 310 km with the orbit planes separated by 30° and 60°; one profile for both vehicles in equatorial orbit, one at 300 km and one at 3000 km; and 5 profiles for altitudes of 400 and 500 km with both orbits inclined at 28.5°. The latter 5 show different starting positions for the same physical orbit pair; hence, they present different profiles that would be experienced on a single mission of the type expected in the early test of the free flying teleoperator [4]. Each low earth orbit vehicle started from its ascending node at $t = 0$ except for orbit 8. Note that $\omega = 180^{\circ}$ for this orbit places teleoperator at the descending node and 20° east of control at $t = 0$.

5.4 Maximum Delays and Delay Rates

Rate-of-change of delay can be obtained from Figures 5-1 to 5-8 by measuring the slopes of the delay profiles and computing the rate from

$$\gamma = 5.33 \tan \theta. \quad \text{(millisec/minute)} \qquad (5\text{-}1)$$

The constant in (5-1) differs from that in (3-2) due to the different delay scaling on the two types of profiles.

A summary of the maximum delays and maximum delay rates obtained from Figures 5-1 to 5-8 are given in Table 5-2.

TABLE 5-1

SUMMARY OF LOW EARTH ORBIT TO LOW EARTH ORBIT PROFILES

	Control				Teleoperator				
Orbit Number	Alt. km	i Deg.	Ω Deg.	ω Deg.	Alt. km	i Deg.	Ω Deg.	ω Deg.	Figure Number
1	300	0	0	0	310	30	0	0	5-1
2	300	0	0	0	310	60	0	0	5-2
3	300	0	0	0	3000	0	0	0	5-3
4	400	28.5	0	0	500	28.5	0	0	5-4
5	400	28.5	30	0	500	28.5	0	0	5-5
6	400	28.5	60	0	500	28.5	0	0	5-6
7	400	28.5	120	0	500	28.5	0	0	5-7
8	400	28.5	0	0	500	28.5	200	180	5-8

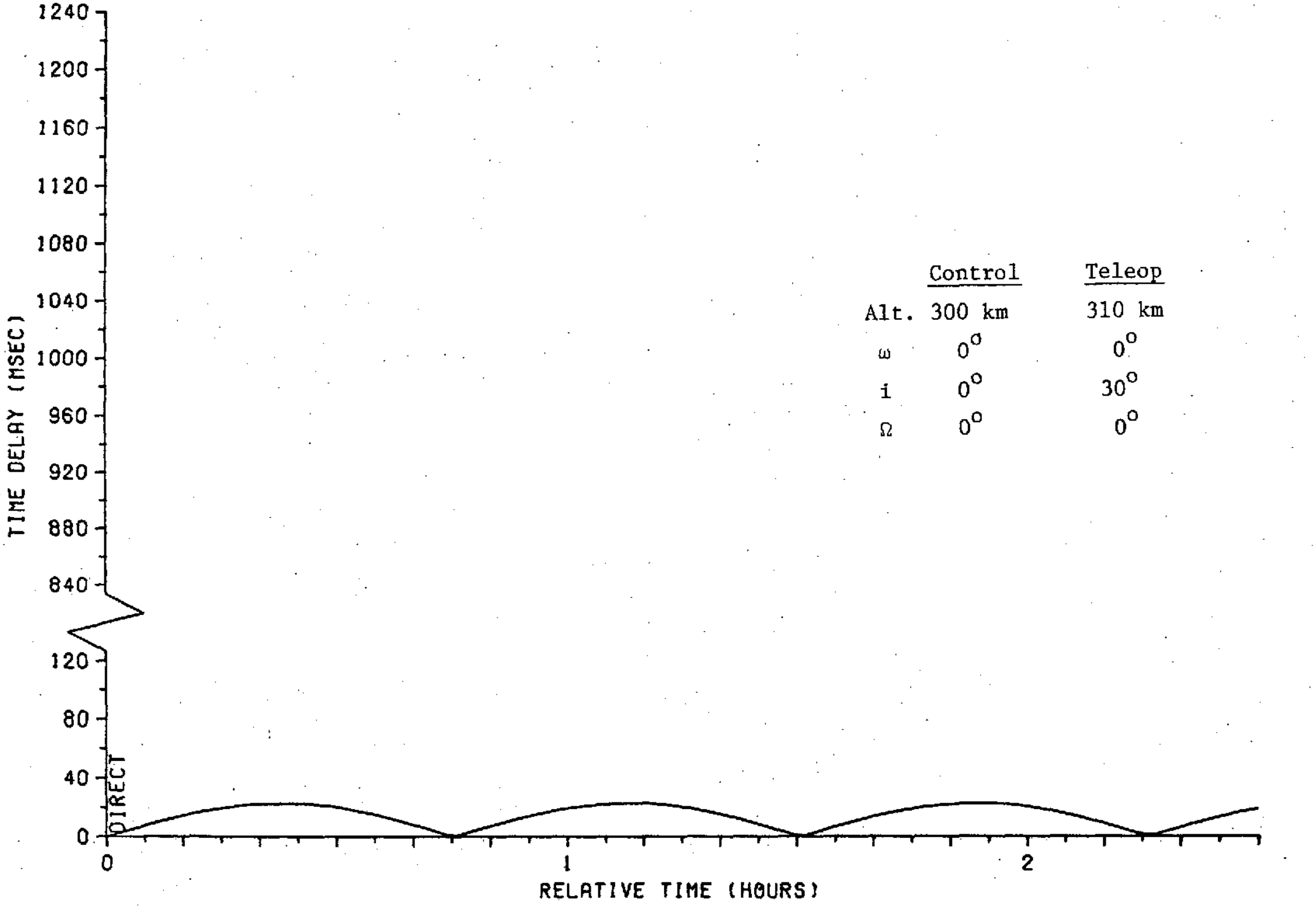


Figure 5-1. Time Delay Profile for Low Earth Orbit Control (Altitude 300 km, Inclination 0°) to Teleoperator in Low Earth Orbit (Altitude 310 km, Inclination 30°).

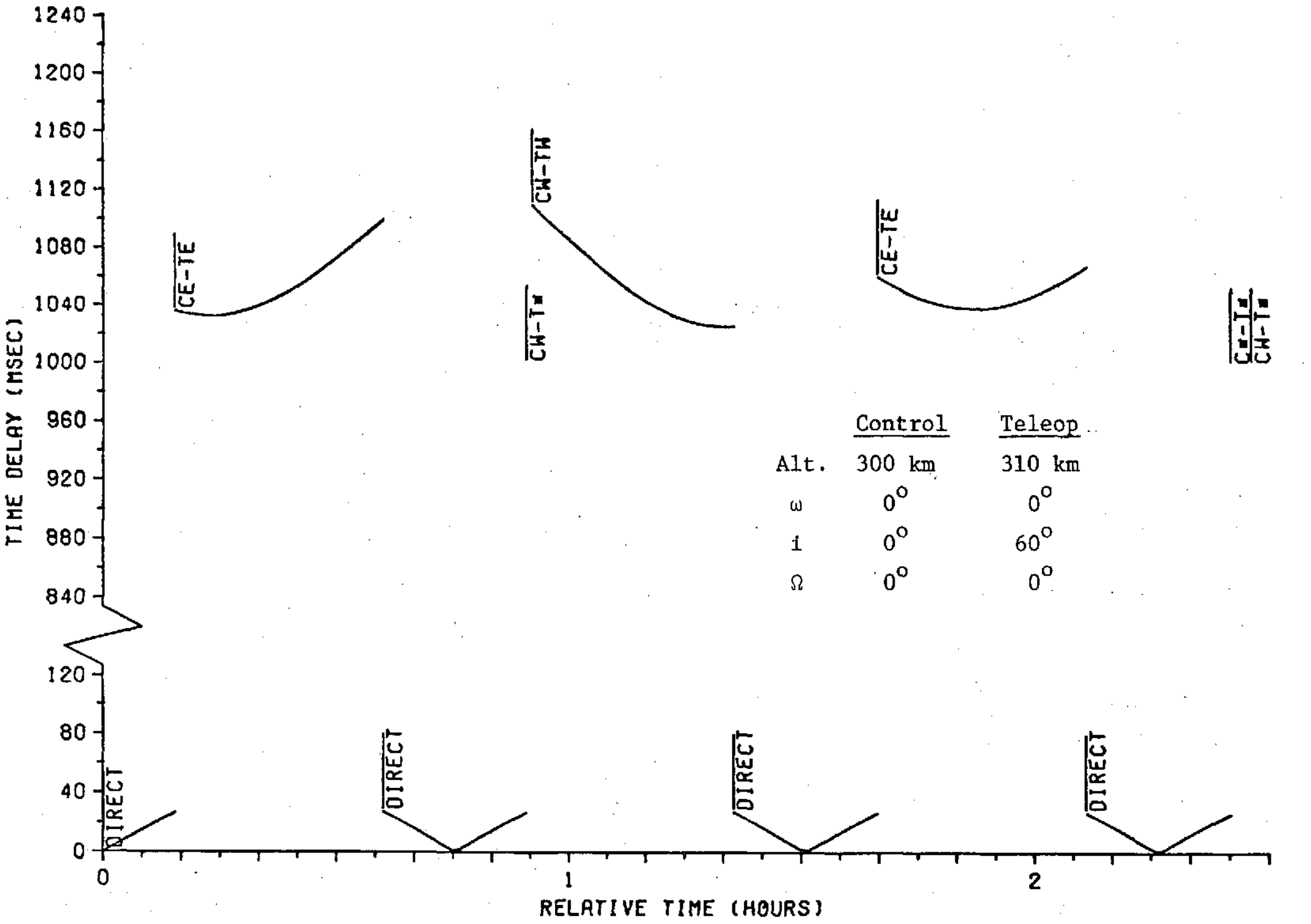


Figure 5-2. Time Delay Profile for Low Earth Orbit Control (Altitude 300 km, Inclination 0°) to Teleoperator in Low Earth Orbit (Altitude 310 km, Inclination 60°).

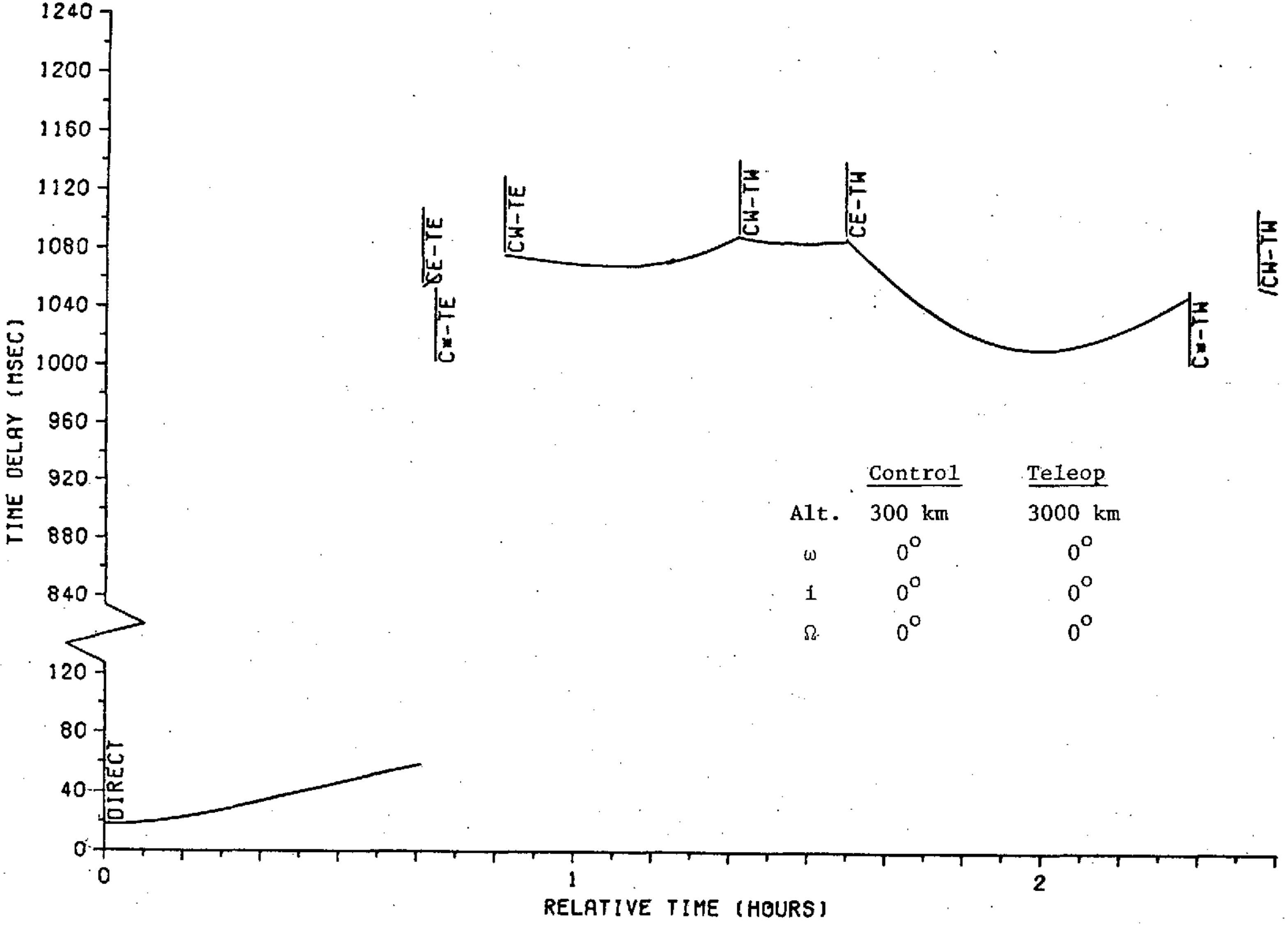


Figure 5-3. Time Delay Profile for Low Earth Orbit Control (Altitude 300 km, Inclination 0°) to Teleoperator in Low Earth Orbit (Altitude 3000 km, Inclination 0°).

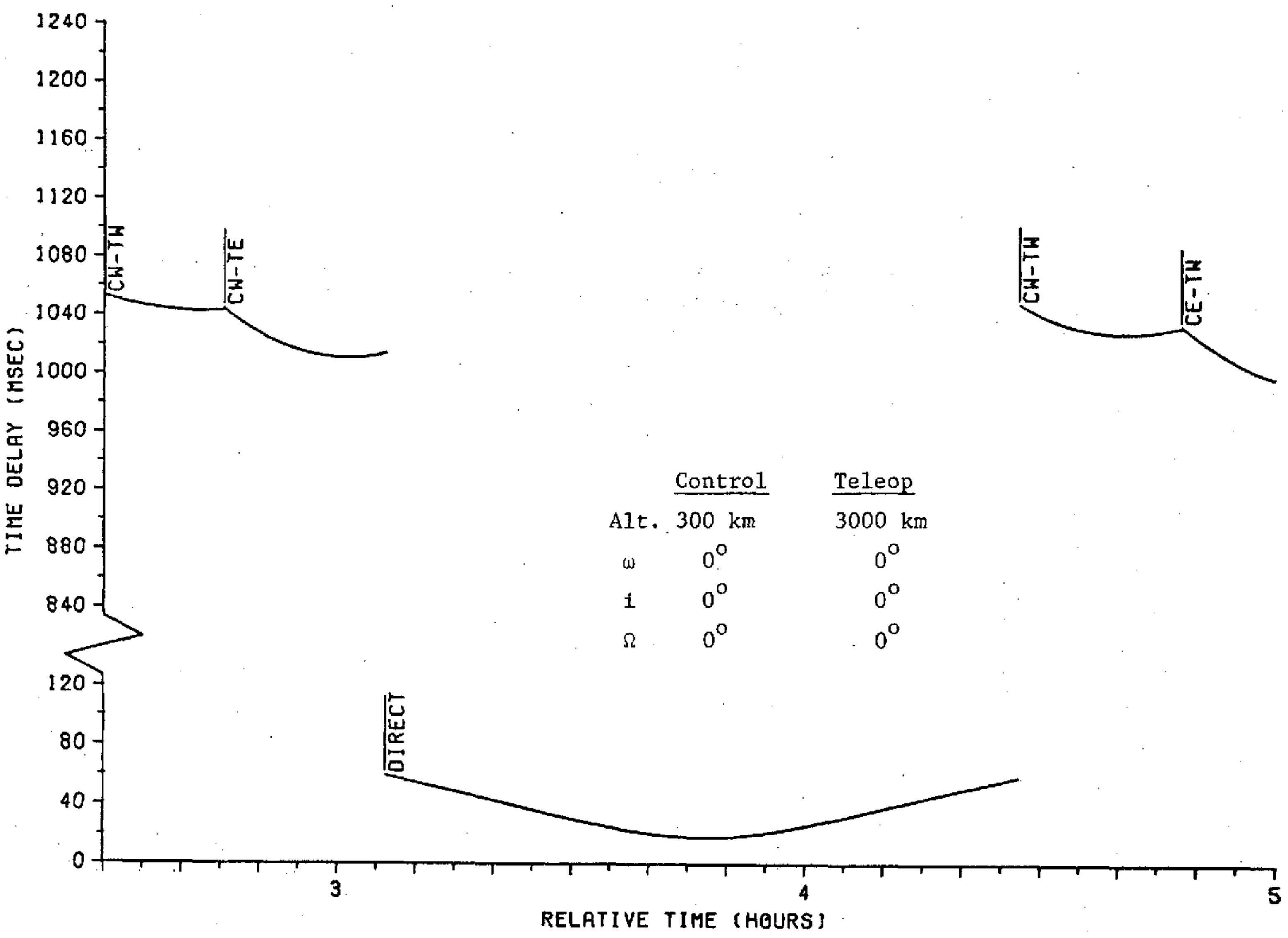


Figure 5-3. (Concluded)

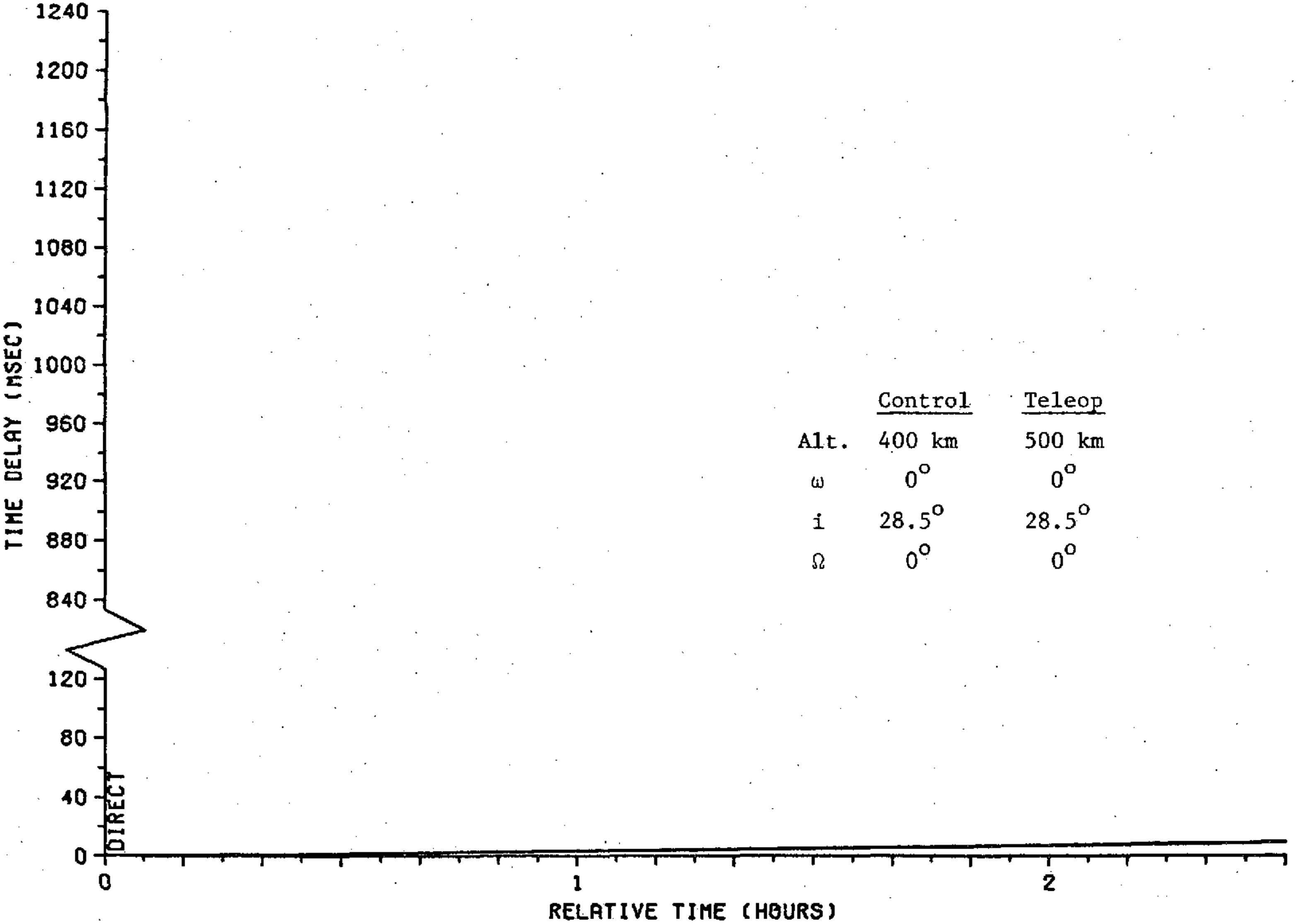
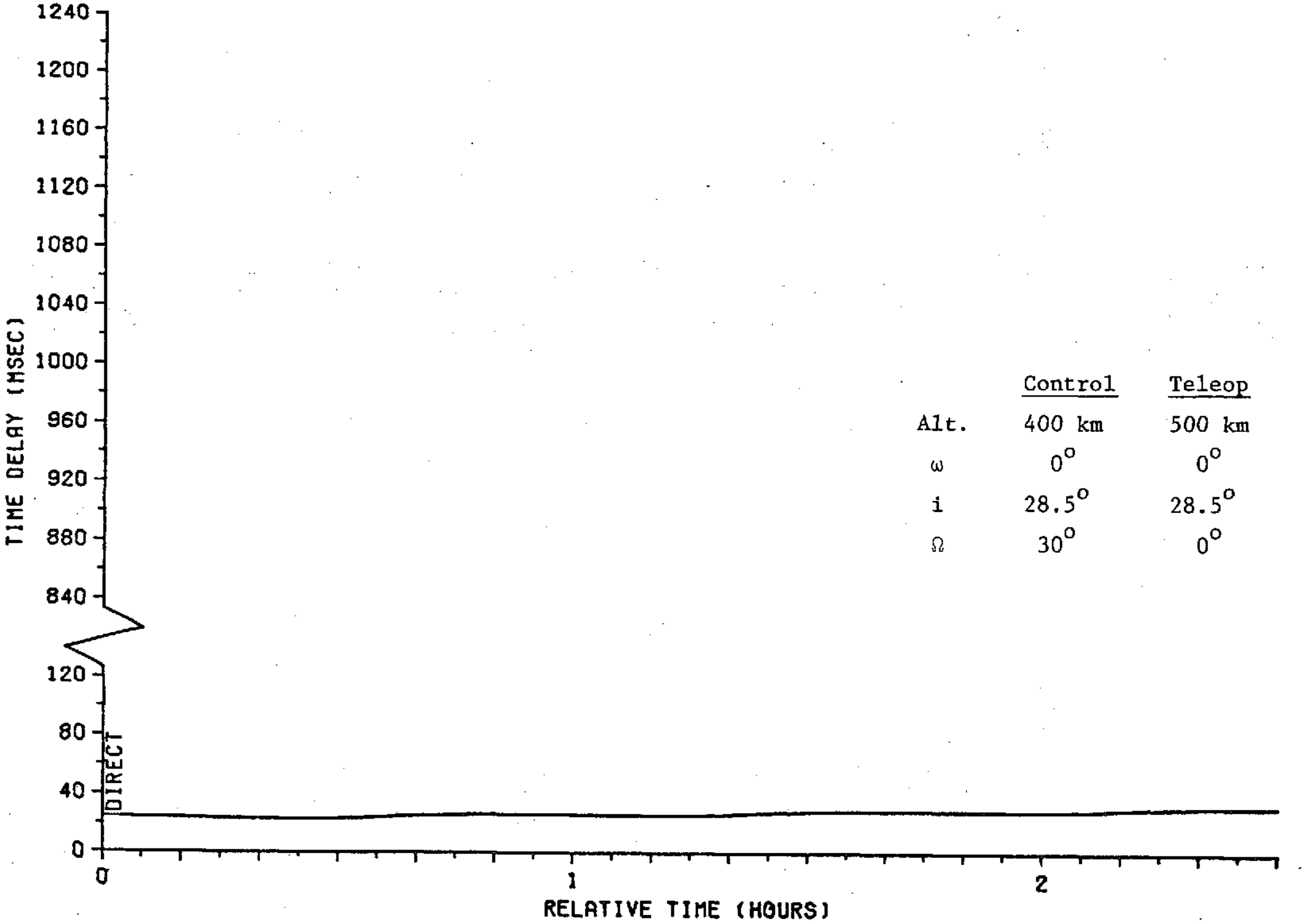
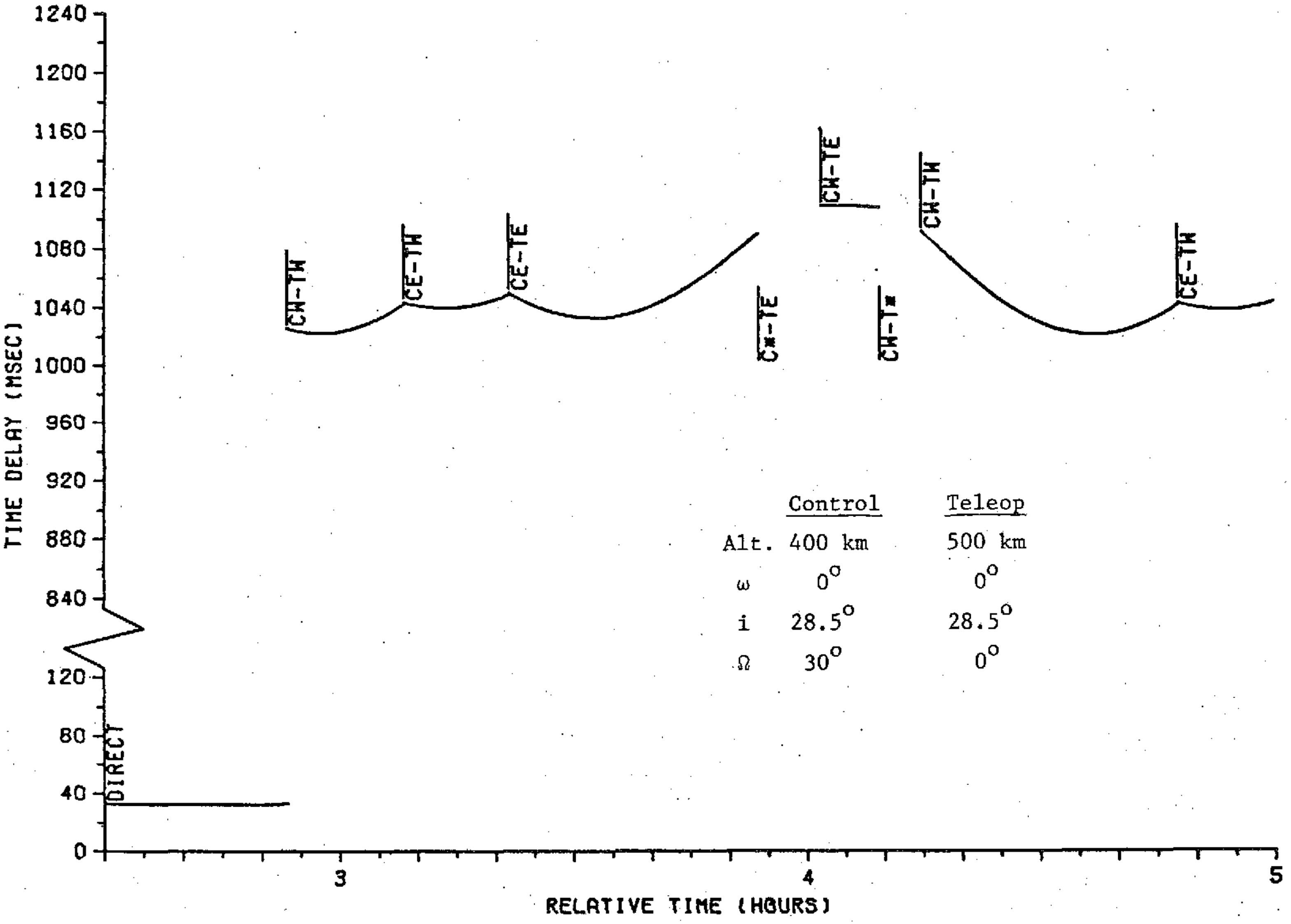


Figure 5-4. Time Delay Profile for Low Earth Orbit Control (Altitude 400 km, Inclination 28.5°) to Teleoperator in Low Earth Orbit (Altitude 500 km, Inclination 28.5°); Longitude Separation 0° at t = 0.



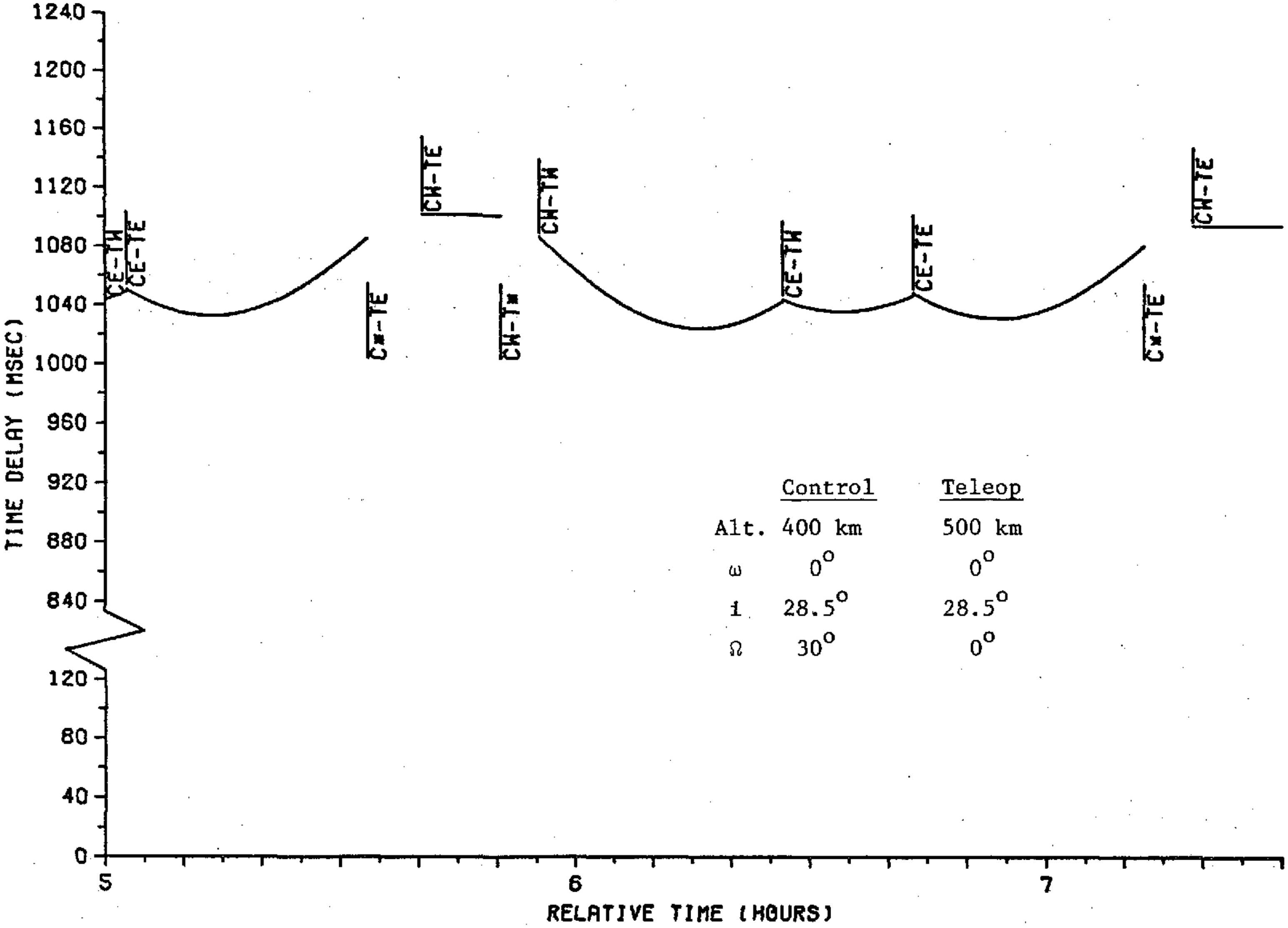
	Control	Teleop
Alt.	400 km	500 km
ω	0°	0°
i	28.5°	28.5°
Ω	30°	0°

Figure 5-5. Time Delay Profile for Low Earth Orbit Control (Altitude 400 km, Inclination 28.5°) to Teleoperator in Low Earth Orbit (Altitude 500 km, Inclination 28.5°); Longitude separation 30° at t = 0.



	Control	Teleop
Alt.	400 km	500 km
ω	0°	0°
i	28.5°	28.5°
Ω	30°	0°

Figure 5-5. (Continued)



	Control	Teleop
Alt.	400 km	500 km
ω	0^o	0^o
i	28.5^o	28.5^o
Ω	30^o	0^o

Figure 5-5. (Continued)

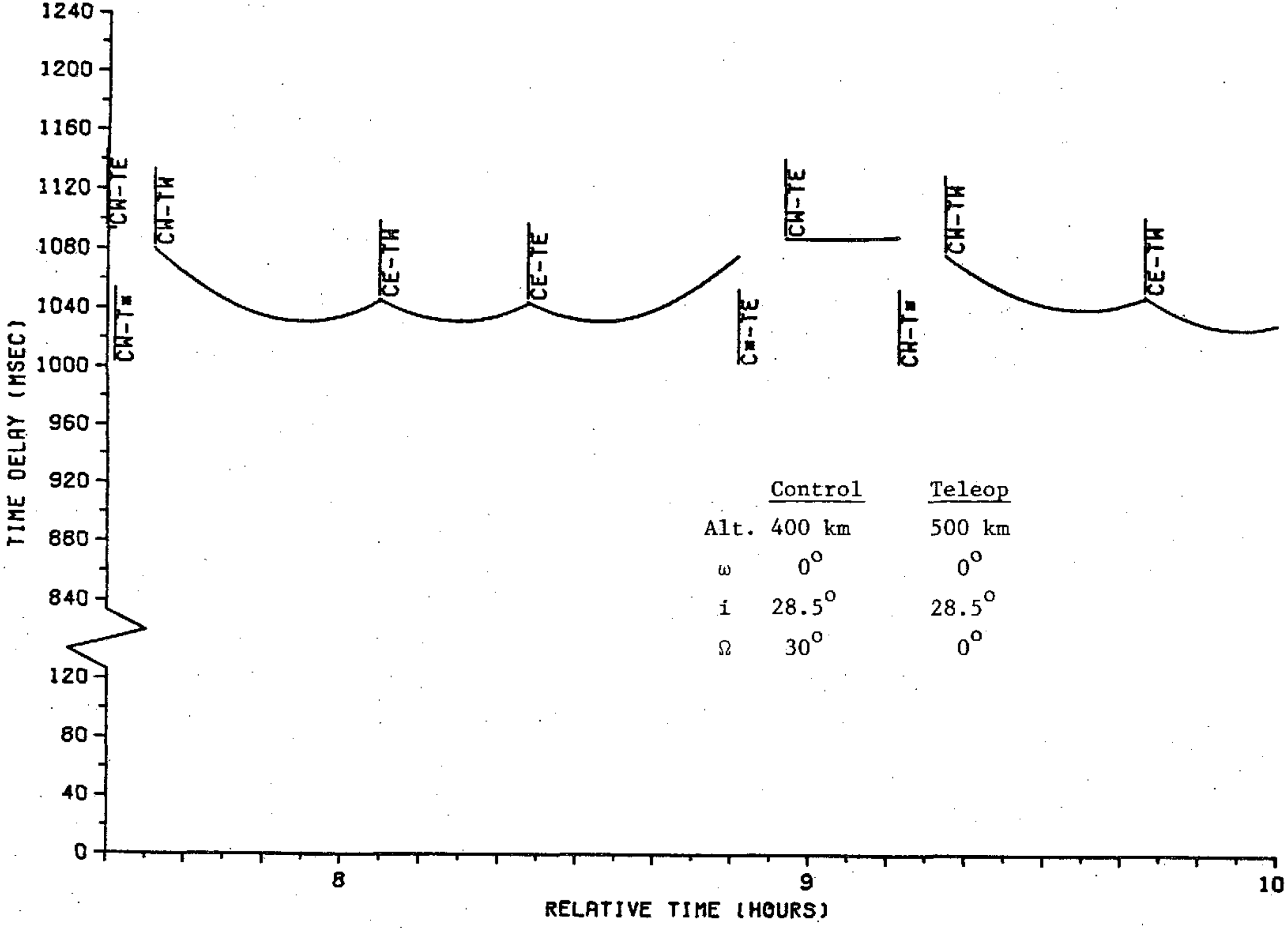


Figure 5-5. (Concluded)

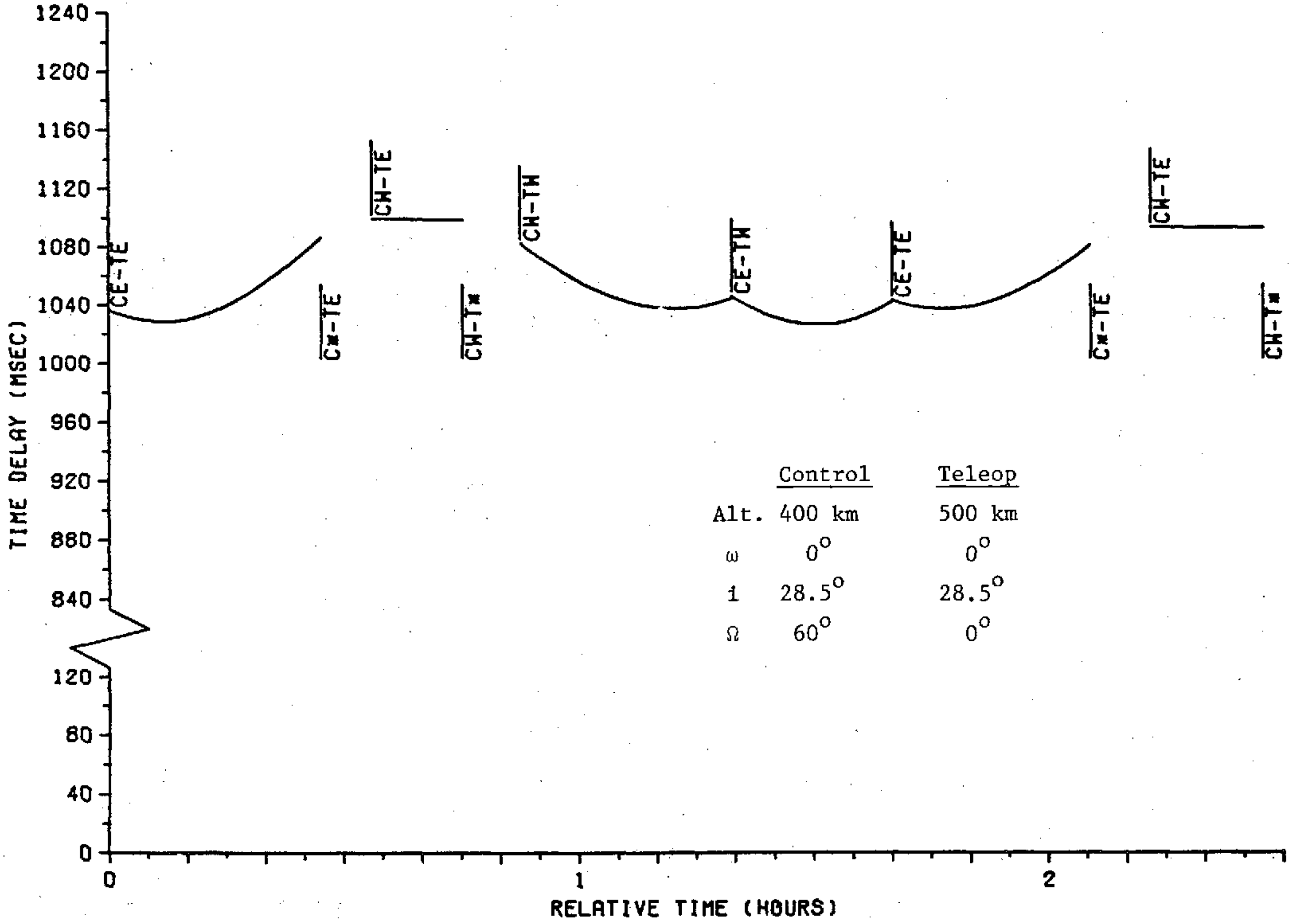


Figure 5-6. Time Delay Profile for Low Earth Orbit Control (Altitude 400 km, Inclination 28.5°) to Teleoperator in Low Earth Orbit (Altitude 500 km, Inclination 28.5°); Longitude separation 60° at t = 0.

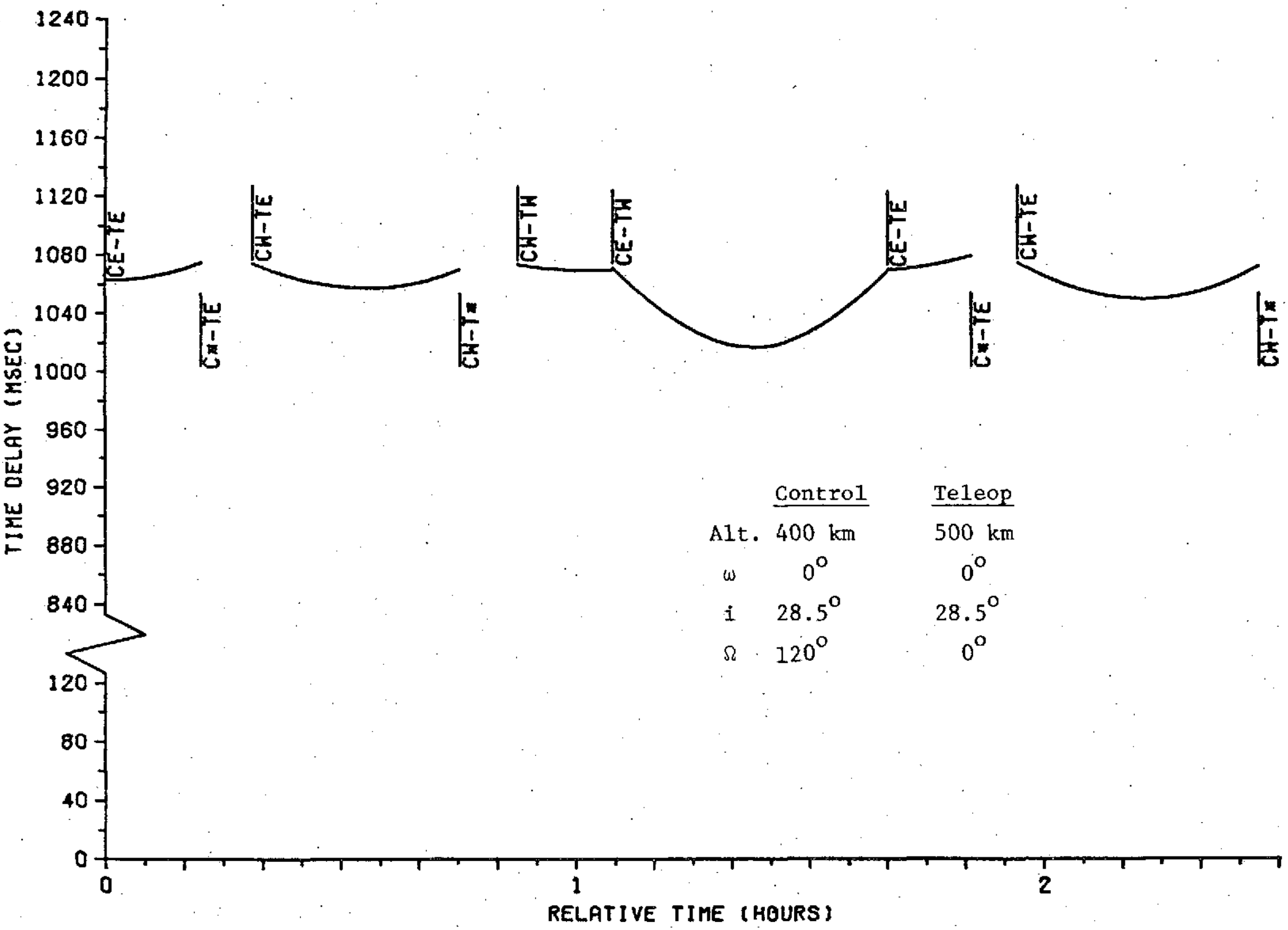


Figure 5-7. Time Delay Profile for Low Earth Orbit Control (Altitude 400 km, Inclination 28.5°) to Teleoperator in Low Earth Orbit (Altitude 500 km, Inclination 28.5°); Longitude separation 120° at t = 0.

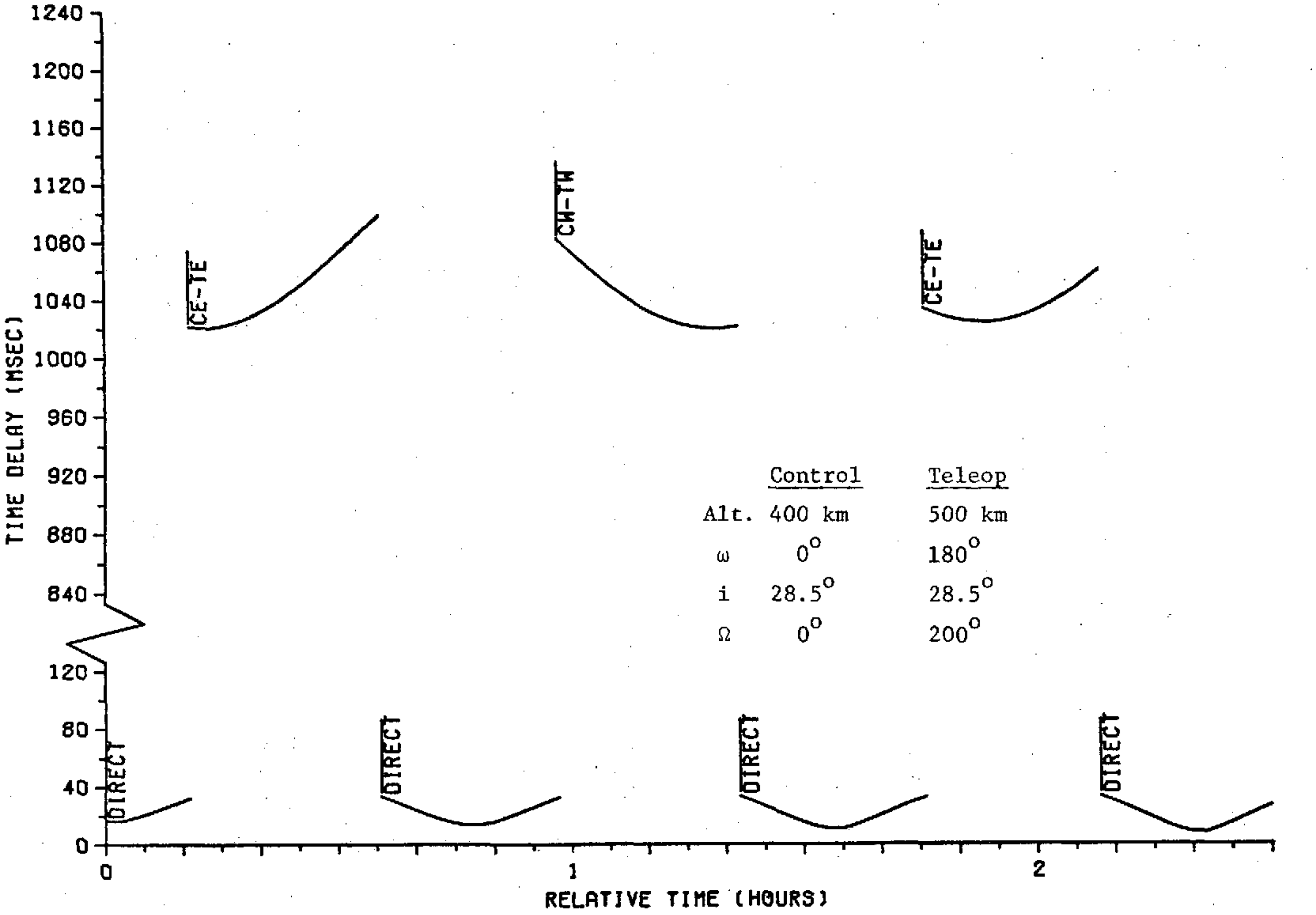


Figure 5-8. Time Delay Profile for Low Earth Orbit Control (Altitude 400 km, Inclination 28.5°) to Teleoperator in Low Earth Orbit (Altitude 500 km, Inclination 28.5°); Longitude separation 20° at t = 0, inclinations in opposite directions.

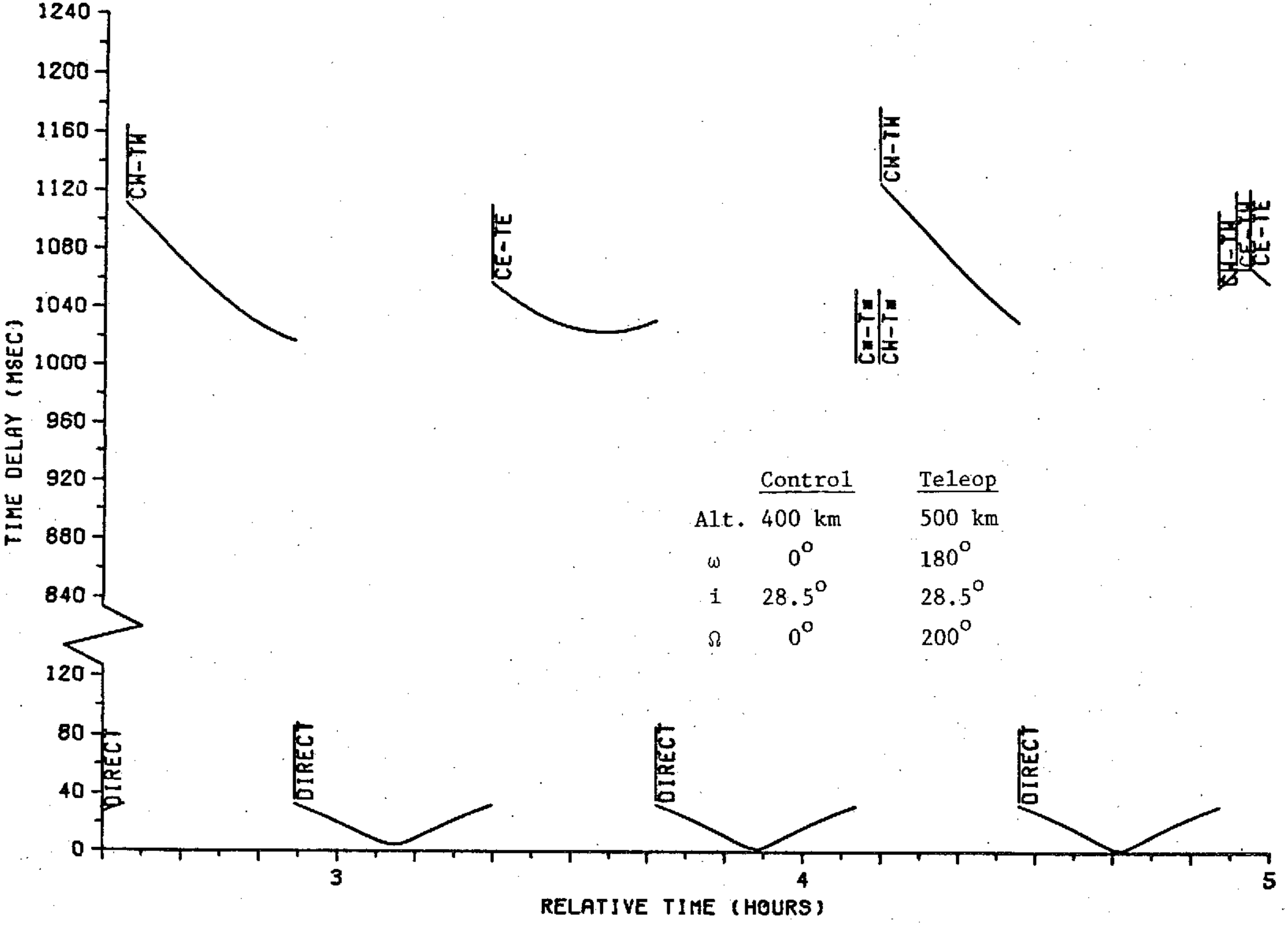


Figure 5-8. (Continued)

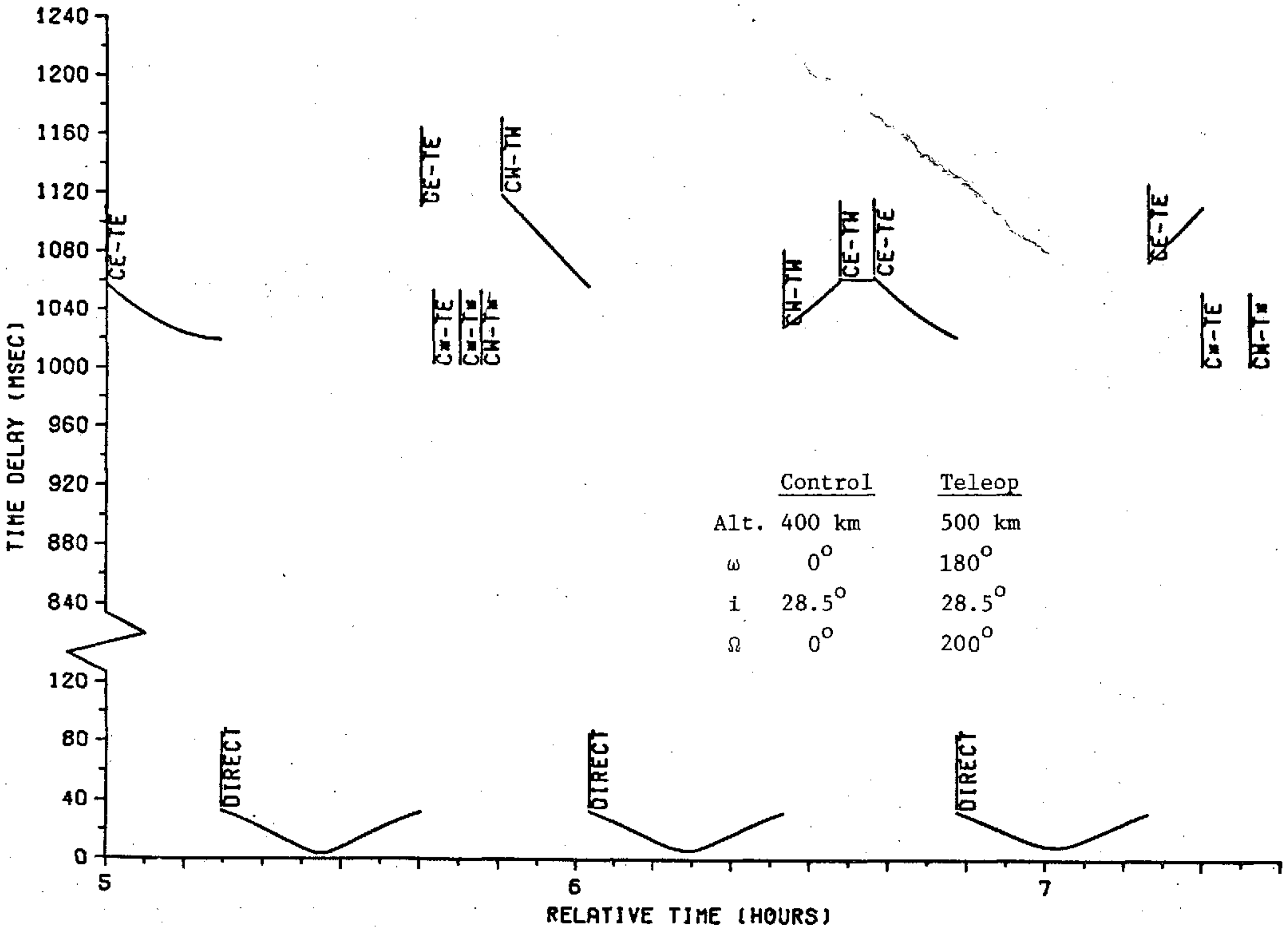
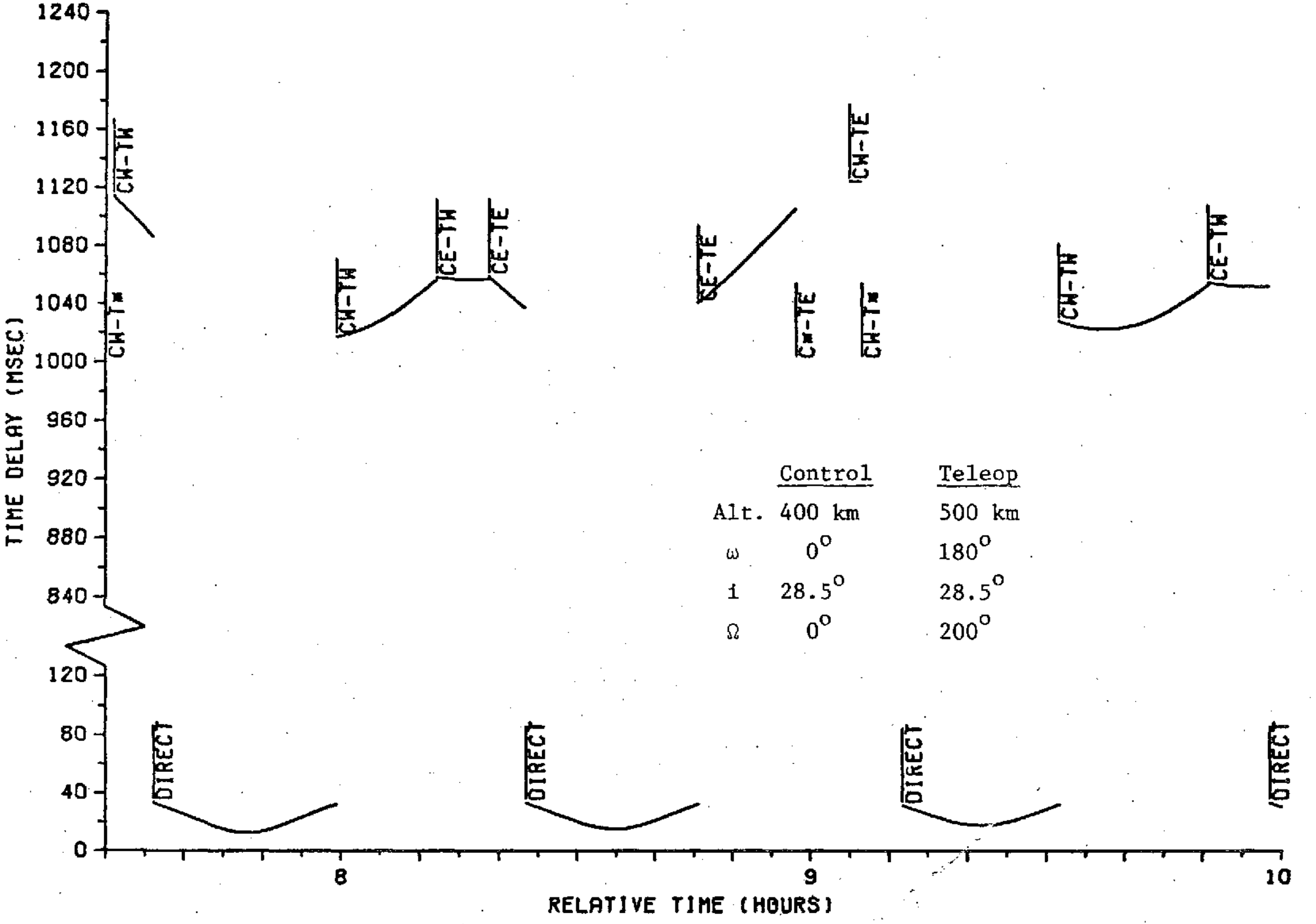


Figure 5-8. (Continued)



	Control	Teleop
Alt.	400 km	500 km
ω	0^o	180^o
i	28.5^o	28.5^o
Ω	0^o	200^o

Figure 5-8. (Concluded)

TABLE 5-2

MAXIMUM DELAYS AND DELAY RATES
FROM COMPUTED PROFILES

	TDRS Relay		Direct Com	
Orbit Altitudes	Max. Delay (msec)	Max. Rate (msec/min)	Max. Delay (msec)	Max. Rate (msec/min)
300, 310	1108	4.72	26	3.02
300, 3000	1088	4.72	60	1.33
400, 500	1126	5.93	34	2.60

6. CONCLUSIONS

Time delays have been examined and time delay profiles defined for two-way (command signals up, video signals returned) communications for teleoperator vehicles with three orbital configurations. These were (1) ground control to teleoperator in low earth orbit, (2) ground control to teleoperator in geosynchronous orbit, and (3) low earth orbit control to teleoperator in low earth orbit. The largest delays and rate of change of delay are associated with the first and last categories. Missions of orbital configuration (2) will generally be subject to smaller delays and very small rates-of-change.

For the orbits considered, the maximum delay (exclusive of an estimated 76 millisec fixed delay) was 1126 millisec for a low earth orbit to low earth orbit configuration. Maximum rate of change of delay of 5.93 millisec/min occurred for the same configuration.

It is worth noting that on the profiles produced and shown graphically, no discontinuity in delay time occurs in connection with handovers between the east and west TDRS satellites. This type performance depends on the proper choice of handover times. For the profiles shown, handovers between east and west relay satellites were made on the meridian half-way between the positions of the two TDRS vehicles. If any other handover point were used, a discontinuity in delay will occur on handover.

For the ground to low earth orbit profiles shown in Figures 3-3 to 3-12, it is obvious that direct communication with teleoperator from a single ground station (ROS in this case) will have very limited usefulness. Direct contact with a ground station can be effected only on those orbits that bring the vehicle near the ground station. Even for these orbits, the time interval over which direct contact can be made is only a few minutes, and presents the problem associated with two handovers with a marked time discontinuity on each. Since it is envisioned that typical teleoperator missions will be from many minutes to many hours, it is questionable whether any advantage will be gained from switching to direct ground-to-teleoperator communication for such short intervals. It is recommended that serious consideration be given to abandoning the direct ground to low earth orbit mode of communication and limit communication from the ground to low earth orbit teleoperators to synchronous satellite relay.

In developing the time delay profiles presented here, the computations necessarily had to be limited to a sampling of possible orbit configurations. Since teleoperator's function as a service vehicle may require that it assume the orbit of any other satellite in space, it is recommended that a general purpose delay profile computer routine be completed and implemented on MSFC computers so that delay profiles for anticipated future missions can be generated.

7. REFERENCES

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