A Method for Interference Mitigation in Space Communications Scheduling

Yen F. Wong James L. Rash

NASA Goddard Space Flight Center, Greenbelt, Maryland

ABSTRACT

Increases in the number of user spacecraft and data rates supported by NASA's Tracking and Data Relay Satellite System (TDRSS) in the S and Ku bands could result in communications conflicts due to mutual interference. More attention must be paid to this problem in terms of communications scheduling. A method based on consideration of all relevant communications parameters has been developed to mitigate interference while minimizing unnecessary scheduling restrictions on both the TDRSS network and user resources. This method calculates required separation angles at TDRS and produces potential interference intervals, which can be used in the production of schedules free of unacceptable interference. The method also can be used as the basis for analysis, evaluation, and optimization of user schedules with respect to communications performance. This paper describes the method and its proposed application to scheduling in space communications. Test cases relative to missions operating at Ku-band, including Space Shuttle, are discussed.

Key Words: Interference mitigation, space communications, scheduling, S/I

1. INTRODUCTION

Scheduling of user spacecraft communications via the geosynchronous data relay satellites of NASA's Tracking and Data Relay Satellite System (TDRSS) must increasingly be concerned with the effects of mutual interference among users (Refs. 1-3). The ultimate objective is to schedule interference-free communications while minimizing constraints imposed on both users and network resources. This objective cannot be accomplished absent the capability to analyze, evaluate, and optimize user schedules with respect to communications performance. Consideration of the effect of communications factors such as signal to interference level ratio (S/I), bit error rate (BER) margin degradation, and power received is beyond the scope of current TDRSS network scheduling systems, giving rise to the need for a new generation of scheduling systems incorporating interference mitigation capabilities, especially in the late 1990's and beyond.

This has led to the development, within the Communications Link Analysis and Simulation System (CLASS) at NASA Goddard Space Flight Center (GSFC), of a method for interference mitigation in space communications scheduling. CLASS is a software tool used for the prediction and evaluation of TDRSS/user spacecraft communications link performance. CLASS considers all communications channel parameters that affect link performance, including interference (Ref. 4).

The U. S. Air Force and the Jet Propulsion Laboratory have been using computer-generated predictions of interference as a scheduling constraint to avoid interference at a ground station receiving signals from two spacecraft and at two or more user spacecraft in the beam of a transmitting ground station (Ref. 5). Recently, NASA has begun evaluating predicted potential interference intervals, obtained as described below, as an adjunct to schedules generated by a partially-automated TDRSS network scheduling system; monitoring in the TDRSS network control center has revealed very few instances of unpredicted interference (Ref. 6).

The next section presents a TDRS telecommunications overview. Following sections describe a communications performance model; an approach to interference mitigation via required separation angles and potential interference intervals; and an interference mitigation procedure for scheduling. Then, illustrative test cases are presented, with discussion, followed by a summary.

2. TDRSS TELECOMMUNICATIONS OVERVIEW

NASA's TDRSS consists of a space segment and a ground segment. The ground segment of TDRSS consists of a ground terminal at White Sands, New Mexico. The operational space segment consists of a user transponder on each user spacecraft and three in-service satellites in geostationary orbit at 41, 171, and 174 degrees west longitude.

TDRSS provides telecommunications in S band via single access (SA) and multiple access (MA) services, and in Ku band via the SA service. Forward links (signals from the ground station via TDRS to a user) operate at data rates from 0.1 Kbps to 25 Mbps, and return links (signals from a user to the ground station via TDRS) operate at data rates from 0.1 Kbps to 300 Mbps (Ref. 7).

3. A MODEL FOR COMMUNICATIONS PERFORMANCE IN THE PRESENCE OF MUTUAL INTERFERENCE

In this paper, interference mitigation concerns only user return channels and single interferers. Multiple simultaneous interferers are not considered.

The proposed method to achieve interference mitigation uses BER margin degradation, formulated as a function of signal to interference level ratio (S/I), as the basic parameter for determination of channel communications performance for a link in the presence of interference (Ref. 8). The calculation of BER margin degradation includes all relevant parameters, such as PN or non-PN coding, frequency separation between desired user and interferer, channel coding, data rate (bandwidth) difference between desired user and interferer, and implementation loss.

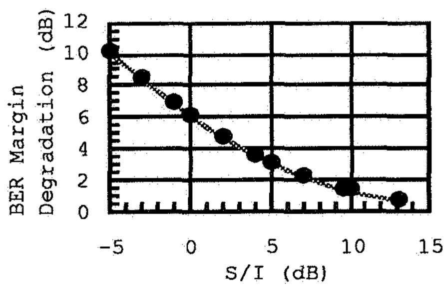

Fig. 1. Computed relationship between BER margin degradation and S/I. The desired user is Space Shuttle Orbiter using channel 3, 50 Mbps coded, and the interferer is operating at 50 Mbps (I+Q). Both are Ku band users. The desired user and interferer links are cross polarized with an assumed polarization rejection of the interfering signal of 15 dB on the TDRS SA antenna boresight.

Fig. 1 shows the relationship between BER degradation and S/I in a representative case. In general, degradation is computed by simulation, with S/I as an input parameter. Nonnegative BER margin is considered to correspond to acceptable communications performance when a link is degraded by interference.

The signal to interference level ratio S/I in dB at TDRS is defined as a function of the separation angle α between the desired user and the interferer as seen from TDRS:

$$\frac{S}{I}(\alpha) = (P_d+G(0)) - (P_i+G(\alpha)+R(\alpha)) \qquad \text{[Eq. A]}$$

where P_d = the worst case (maximum range, given actual orbits) TDRS received power at unity antenna gain for the desired user (in dB) including the loss due to the nonperfect polarization match between the TDRS and desired user antennas. It is assumed that the desired user is on the TDRS antenna boresight and that the desired user's antenna is pointing toward TDRS. P_d includes contributions from stochastic sources such as multipath (vehicle, earth, and atmospheric) and RFI.

P_i = the best case (minimum range, given actual orbits) TDRS received power at unity antenna gain for the interferer (in dB).

G = the TDRS antenna gain (in dB) as a function of the angle α. Spatially, G is assumed to be dependent only on the angle α.

R = the polarization rejection of the interferer's signal at the TDRS antenna (in dB) as a function of angle α. R always has a negative value when rejection is present (interferer oppositely polarized), and is zero otherwise. Spatially, R is assumed to be dependent only on the angle α.

Since only G and R are functions of α, Eq. (A) leads immediately to the following for any α_1 and α_2, each an allowed value of α:

$$\frac{S}{I}(\alpha_2)-\frac{S}{I}(\alpha_1) = -[G(\alpha)+R(\alpha)]_{\alpha=\alpha_1}^{\alpha=\alpha_2} \qquad \text{[Eq. B]}$$

From Eq. (B), S/I can be expressed as follows:

$$\frac{S}{I}(\alpha) = -[G(\alpha)+R(\alpha)] + \frac{S}{I}(\alpha)+[G(0)+R(0)] \qquad \text{[Eq. C]}$$

which indicates that S/I, as a function of separation angle α, depends on the quantity $G(\alpha)+R(\alpha)$. This quantity, TDRS antenna gain plus polarization rejection, is referred to as the *adjusted TDRS antenna gain.*

CLASS makes available a simplified model for polarization rejection at the TDRS SA antenna, which is adequate for our purposes. In Fig. 2 the model is applied to an oppositely polarized user in Ku band (referred to as User A in the numerical example in Section 6), where it is assumed that the TDRS SA antenna boresight polarization rejection is 15 dB. Note that according to this model the polarization rejection is zero for all angles off boresight beyond the first null of the antenna gain pattern (approximately 0.3 degrees in Ku band).

The TDRS SA antenna gain pattern envelope in Ku band, without polarization rejection adjustment, is shown in Fig. 3(a), representing the main beam, first null, and first sidelobe, with a logarithmic relation for the remainder of the pattern.

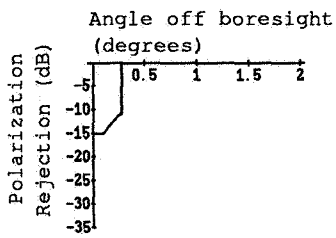

Fig. 2. Example of an assumed CLASS model of polarization rejection as a function of angle off boresight.

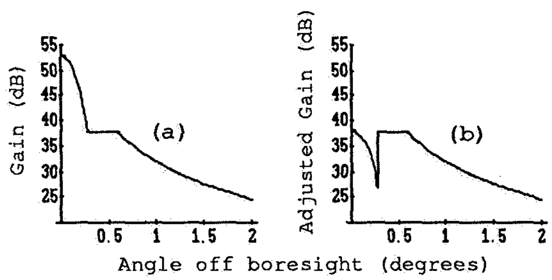

Fig. 3. TDRS SA antenna gain pattern envelope as modeled in CLASS: (a) without polarization rejection adjustment, and (b) adjusted by polarization rejection of a cross polarized signal (see Fig. 2).

Fig. 3(b) shows an example (in which the interferer is User A) of the adjusted antenna gain, [G+R], in which the gain of the TDRS SA antenna is adjusted by the polarization rejection of an oppositely polarized user antenna. This figure results from adding the graphs shown in Figures 3(a) and 2.

With Eq. (C), the graph of S/I can be obtained from the negated adjusted TDRS antenna gain pattern, –[G+R], shifted vertically by a constant (the boresight value of S/I plus the boresight value of [G+R]).

The negated TDRS antenna gain pattern envelopes for a representative case are shown in Figures 4(a) and 4(b), with and without polarization rejection, respectively. These graphs are the negation of the graphs in Fig. 3.

In general, due to the possibility of complex models for gain and polarization rejection, the negated adjusted antenna gain curve, –[G+R], will have multiple relative minima. The global minimum value of the curve may correspond to more than one value for the separation angle α (interferer's angle off boresight). We let α^* denote the least such value of α. Since, in general, the boresight value of –[G+R] may be greater than the global minimum, α^* is not necessarily zero.

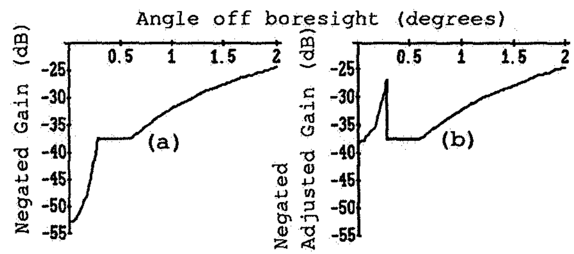

Fig. 4. Negated TDRS SA antenna gain pattern envelopes obtained as the negative of the graphs in Fig. 3. The global minimum of each curve occurs at boresight ($\alpha = 0$).

The graph of S/I is shown in Fig. 5 for representative cases (to be described later, in Table 4). By reference to the relationship between S/I and BER margin degradation (see Fig. 1), and with knowledge as to the maximum amount of BER degradation that can be tolerated by a given desired user signal, the S/I graph (Fig. 5) offers the means of finding a separation angle between the user spacecraft as seen from TDRS such that no unacceptable interference can occur. This is the basis of the method proposed in this paper for mutual interference mitigation.

3.1 Worst S/I

As the interferer moves off boresight, the interferer's received power changes in a manner dictated by the negated adjusted antenna gain curve (Fig. 4). When –[G+R] reaches a local minimum, the interferer's power reaches a local maximum. Since the desired user remains on boresight, P_d remains constant. Therefore, as –[G+R] reaches its global minimum (for example, at $\alpha = \alpha^*$), the value of S/I also reaches its global minimum. This minimum S/I is the "worst S/I", and so we have, by Eq. (C), $(S/I)_{worst} = (S/I)(\alpha^*)$, and

$$\left(\frac{S}{I}\right)_{worst} = -[G(\alpha^*)+R(\alpha^*)] + \frac{S}{I}(0) + [G(0)+R(0)]$$

Note that if $\alpha^* = 0$, the worst S/I is simply boresight S/I: $(S/I)_{worst} = (S/I)(0)$.

3.2 Required S/I

Required S/I is defined as the value of S/I such that the degradation of the desired user signal equals the worst acceptable channel margin. The required S/I for any given combination of desired user and interferer links is highly dependent on the specific signal structure, and is obtained by computer simulation. The worst S/I may or may not be less than the required S/I. If the worst S/I *is* less than the required S/I, then unacceptable mutual interference is possible for certain separation angles.

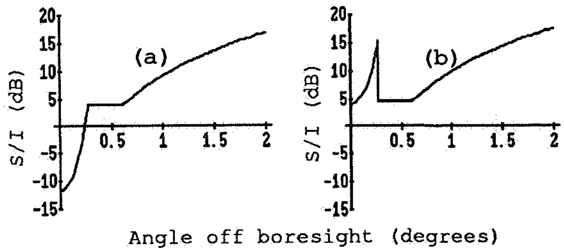

Fig. 5. S/I as a function of interferer's angle off boresight: (a) for a representative case where desired user and interferer have the same polarization but different signal levels, and (b) for the same case, except that the desired user and the interferer are oppositely polarized, showing the effect of TDRS antenna gain and polarization rejection on the interfering signal. Note that these curves have the shape of the negated TDRS antenna gain curve (unadjusted and adjusted, respectively (see Fig. 4)) shifted vertically by the value of the constant terms in Eq. (C).

4. INTERFERENCE MITIGATION VIA SEPARATION ANGLE AND POTENTIAL INTERFERENCE INTERVALS

4.1 Required separation angle

Since the desired user is assumed to be on the TDRS antenna boresight, and since antenna gain decreases off boresight, a sufficient variation of the interferer's separation angle provides discrimination between the signals, reduces the interference level, and increases the S/I level ratio. In the case where the worst S/I is less than the required S/I (that is, where interference is possible), the required S/I corresponds to specific separation angles that can be read directly from the graph of S/I (see Fig. 5). Note that, due to the possibility of multiple lobes in the adjusted antenna gain graph (and therefore multiple lobes in the graph of S/I), there may be multiple disjoint ranges of separation angle providing at least the necessary value of S/I. The largest of all the angles where S/I is equal to the required S/I is defined as the *required separation angle*. For purposes of user spacecraft communications scheduling, it must be assumed that any smaller separation angle will correspond to an unacceptable level of interference.

4.2 Potential interference intervals

A *potential interference interval* is defined as any time interval during which the separation angle between the two user spacecraft is less than the required separation angle as described above. During such intervals, unacceptable interference could occur if the given pair of links of the two spacecraft are active via the same TDRS. The potential interference intervals, therefore, would constrain any interference mitigation scheduling process by specifying when the two links should not be used simultaneously for communications to a given TDRS. A method to determine which of the two links should not be scheduled during any potential interference interval is part of the algorithm used by the scheduler and is beyond the scope of this paper.

Calculation of potential interference intervals is straight forward, given user orbits and required separation angles.

5. A PROCEDURE FOR INTERFERENCE MITIGATION IN SCHEDULING

A procedure is suggested for producing schedules free of unacceptable interference while minimizing restrictions on use of network and user resources. This procedure is based on a model, described above, for communications performance in the presence of interference, which permits calculation of required separation angles, by which potential interference intervals are obtained. The procedure is summarized as follows:

(1) For every pair of desired and interfering signals, determine –[G+R] as a function of α (the separation angle at a given TDRS between the desired user and the interferer), where G is the TDRS antenna gain envelope and R is the polarization rejection of the interfering signal at the TDRS antenna. R is assumed to be zero if the desired user and interferer have the same polarization.

(2) For every pair of desired and interfering signals, determine the smallest separation angle, α^*, that corresponds to the global minimum value of the function –[G+R].

(3) For every pair of desired and interfering signals, determine S/I, the signal to interference level ratio, as a function of α, given by Eq. (A) above. Calculate $(S/I)(\alpha^*) = -[G+R](\alpha^*) + (S/I)(0) + [G+R](0)$. This is the *worst S/I*.

(4) For every pair of desired and interfering signals, determine by computer simulation the degradation of the desired signal that corresponds to the worst S/I determined in step (3). This is the desired signal's *worst degradation*. Identify all signal pairs where the desired signal's worst degradation exceeds the desired user's worst acceptable channel margin. Unacceptable mutual interference is possible for these signal pairs.

(5) For every pair of desired and interfering signals where interference is potentially unacceptable as determined in step (4), determine by computer simulation the *required S/I*, that is, the S/I for which the degradation is equal to the desired signal's worst acceptable channel margin.

(6) For every pair of desired and interfering signals where interference is potentially unacceptable as found in step (4), calculate, from the S/I graph, the required separation angle (the largest separation angle between desired user and interferer that provides the required S/I as determined in step (5)).

(7) For every pair of desired and interfering signals where interference is unacceptable as determined in step (4), and on the basis of the separation angles obtained in step (6), find all *potential interference intervals*, that is, intervals during which unacceptable interference is possible. These calculations involve the actual orbits of the given spacecraft and the TDRSs.

(8) Use the potential interference intervals from step (7) as a constraint to a scheduler for generating schedules free of unacceptable interference. The effect of this constraint is to preclude the scheduling of at least one member of any pair of desired/interferer links via a given TDRS during any potential interference interval associated with that pair of links.

The first four steps can be used as a screening process to isolate the cases where unacceptable interference could occur. Steps (5) and (6) would be applied in all such cases, as an intermediate process prior to execution of a scheduler. Step (7) would be performed prior to every run of an interference mitigation scheduling system (step (8)).

6. APPLICATION OF THE METHOD: A NUMERICAL EXAMPLE

The proposed method has been applied to study interference between the Space Shuttle Orbiter (SSO) and TDRSS users operating at high data rates in Ku band.

All the users in this example operate with a carrier frequency of 15.0034 GHz, unspread.

Table 1 presents the Shuttle link parameters. SSO operates with Right Circular Polarization (RCP). Channels 1 and 2 are rate 1/2 convolutional coded and channel 3 is uncoded (Ref. 9).

User A link parameters are shown in Table 2. User A operates with Left Circular Polarization (LCP) at data rates of 300 Mbps and 50 Mbps. Table 3 presents the link characteristics for User B operating with RCP at a data rate of 300 Mbps.

The illustrative example discussed below considers two cases. In each case, the Shuttle, as the desired user, suffers from interference.

6.1 Interference analysis results

Table 4 presents the results of an example interference analysis for two cases.

In Case 1, the SSO (COLUMBIA) channel 3 (50 Mbps) experiences interference from User B's 300 Mbps link (I + Q). The worst S/I is less than the required S/I by 17.8 dB. The required separation angle can be obtained directly from the appropriate S/I graph (Fig. 5(a)): for the required S/I of 6.2 dB, the required separation angle is 0.74 degrees. There is no unacceptable interference in Case 1 for SSO channels 1 and 2.

In Case 2, where the interferer is the User A 50 Mbps link (I + Q), the worst S/I (4.0 dB) is less than the required S/I (9.0 dB) by 5.0 dB, and from Fig. 5(b) the required separation angle is seen to be 0.92 degrees. A comparison of Case 2 with Case 1 might seem to present an apparent inconsistency: as the interferer EIRP is nearly the same in both cases, and as the desired user in Case 2 is cross polarized relative to the interferer, it would seem reasonable to conclude that the required separation angle should be smaller than in Case 1. However, in Case 2, the interfering signal is "in-band", so that all of the interferer's power affects the desired channel, making the required S/I greater than that in Case 1. Also (see Fig. 2), it is clear why the advantage of cross polarization does not apply in Case 2, since the largest separation angle corresponding to the required S/I (see Fig. 5) is beyond the first null of the TDRS SA antenna. No unacceptable interference exists in Case 2 for SSO channels 1 and 2.

Unacceptable interference in Case 2 does not occur between the User A 300 Mbps link (I + Q) and SSO channels 1, 2, or 3.

6.2 Potential Interference Intervals

Potential interference intervals depend on the choice of orbits for user spacecraft. Fig. 6 illustrates this dependency by showing the intervals for two choices for the user orbital elements. The only difference between these choices is the value for the mean anomaly. For the choice illustrated in Fig. 6(a), the difference in the mean anomaly is zero degrees; for the choice illustrated in Fig. 6(b), it is 20 degrees. The total of the potential interference intervals goes from 100% of the in-view time (Fig. 6(a))—approximately 813 minutes during the 24 hour scheduling period—to 7.5% of the in-view time (Fig. 6(b))—approximately 61 minutes. Thus, the potential interference intervals become shorter and less numerous as the orbital spacing of the users increases. If, indeed, the mean anomalies differ by more than approximately 48 degrees, with all other factors in this example remaining the same, unacceptable interference becomes impossible, and potential interference intervals no longer exist.

7. SUMMARY

It is proposed that an interference mitigation scheduling system must reflect consideration of communications performance, and it is argued that the use of BER degradation as a function of S/I is a sufficient basis for an interference mitigation scheduling system.

In general, scheduling may involve any number of user spacecraft. The scope of the approach presented in this paper is limited to the case of single interferers.

This paper presents a model of communications performance as affected by the presence of mutual interference. The model formulates communications performance in terms of S/I, which is considered as a function of the interferer's angle off the receiving antenna boresight. Required separation angles for interference mitigation can be calculated based on this functional relationship, and these angles then can be used to determine potential interference intervals.

Potential interference intervals are proposed for use as a constraint in an interference mitigation scheduling system. By guaranteeing acceptable BER degradation for all desired user/interferer link combinations, except during potential interference intervals associated with those link combinations, the proposed procedure guarantees schedules to be free of unacceptable mutual interference. Potential interference intervals also can be useful as the basis for evaluating and optimizing (with respect to communications performance) user schedules produced by any scheduling system.

Table 1. Space Shuttle Orbiter Link Characteristics

CHANNEL	DATA RATE (Kbps)	EIRP (dBW)	LINK MARGIN (dB)
Channel 1: Subcarrier Q	192	39.4	19.0
Channel 2: Subcarrier I	2,000	43.6	13.5
Channel 3: Baseband	50,000	51.0	1.5

Table 2. User A Link Characteristics

CHANNEL	DATA RATE (Mbps)	EIRP (dBW)	LINK MARGIN (dB)
I	150	57.1*	3.0
Q	150	57.1*	3.0
I	25	57.1*	10.8
Q	25	57.1*	10.8

Table 3. User B Link Characteristics

CHANNEL	DATA RATE (Mbps)	EIRP (dBW)	LINK MARGIN (dB)
I	150	57.7**	3.6
Q	150	57.7**	3.6

* The minimum EIRP required to achieve a 3 dB margin for a 300 Mbps user.

** The minimum EIRP required to achieve a 3.6 dB margin for a 300 Mbps user.

Table 4. Analysis results for channels with unacceptable interference.

		Case 1	Case 2
Desired User	User ID	COLUMBIA	COLUMBIA
	Channel	3	3
	Polarization	RCP	RCP
	Worst Acceptable Channel Margin	1.5	1.5
Interferer	User ID	User B	User A
	Polarization	RCP	LCP
S/I	Required (dB)	6.2*	9.0*
	Worst (dB)	-11.6	4.0
Worst Degradation (dB)		**	3.5*
Required Separation Angle (deg.)		0.74	0.92

* Obtained by computer simulation.

** Degradation is much greater than 1.5 dB.

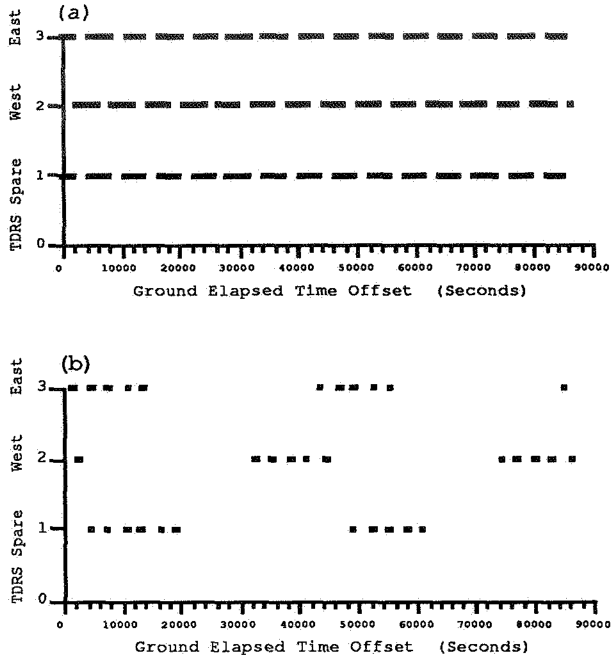

Fig. 6. Potential Interference Intervals at (1) TDRS Spare, (2) TDRS West, and (3) TDRS East when the desired user is SSO COLUMBIA and the interferer is User A. A period of 24 hours is represented. Each user spacecraft orbit is approximately 90 minutes in duration. (a) The users have identical orbits, so that the separation angle is always zero degrees during TDRS view periods. (b) The users have identical orbits except for a difference of 20 degrees in their mean anomalies. In each orbit there are two times when they are separated by less than the required separation angle: once just after they both appear above the horizon as seen by the TDRS, and once just before they both disappear below the horizon.

8. ACKNOWLEDGMENTS

The authors would like to acknowledge CLASS Project Manager Robert Godfrey of NASA/GSFC for originating the concept of an interference mitigation scheduling system for CLASS. We would also like to thank Nancy Smith and Ron Vento of NASA/GSFC, Farzad Ghazvinian and Masoud Toufanian of LinCom Corporation, and David Wampler of Stanford Telecommunications for valuable technical support. Finally, we would like to express appreciation to our supervisor, Frank Stocklin, for supporting our efforts on this project.

9. REFERENCES

1. NASA Goddard Space Flight Center. December, 1990. Space Network Mission Model and Network Loading (Update, March 1992). Presentation by A. Levine, GSFC/Code 534.2, to NASA management. Greenbelt, Maryland.
2. Computer Sciences Corporation. February, 1990. *Network Control Center User Planning System System Requirements Document*, 514-4SRD/0389. Greenbelt, Maryland.
3. Welti, G., Christopher, P., and Griffin, M. March, 1990. *ATDRSS Self Interference Assessment*, Technical Report TR0007, Stanford Telecommunications, Inc. Reston, Virginia.
4. NASA Goddard Space Flight Center. September, 1989. *Communication Link Analysis and Simulation System*, CLASS No. 101. Greenbelt, Maryland.
5. Sollfrey, W. October 21-24, 1984. Interference problems for nongeostationary satellites. In *Conference Record, Military Communications Conference* (Milcom '84), McLean, Virginia, Vol. 3, pp. 384-388.
6. Wampler, D. and Kaplan, T. March 23, 1992. *ACRS Performance Evaluation*, Technical Report 028-1DW92, Stanford Telecommunications, Inc. Reston, Virginia.
7. NASA Goddard Space Flight Center (1988). *Space Network (SN) Users' Guide*, STDN No. 101.2, Revision 6. Greenbelt, Maryland.
8. Bhargava, V. K., Haccoun, D., Matyas, R., and Nuspl, P. P. 1981. *Digital Communications by Satellite*. New York, NY: John Wiley & Sons.
9. NASA Goddard Spaoce Flight Center. January 30, 1989. Memo, To: Distribution, From: GSFC Code 531.1, Subject: STS Link Calculations. Greenbelt, Maryland.